

**The Response Of *Amaranthus cruentus* L. To Water Application Using Drip And
Sprinkler Irrigation Systems.**

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AGE/91/2839

FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

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CERTIFICATION

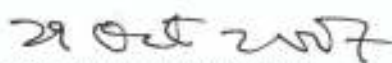
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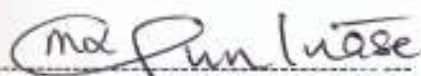
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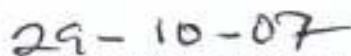
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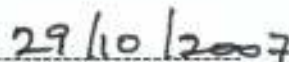
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Date

DEDICATION

**This research work is dedicated to the glory of the Lord most high and
to the benefit of all rural farmers**

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To God be the glory great thing He has done.

ABSTRACT

Prince's feather *Amaranthus cruentus*, a staple leafy vegetable grown in the humid region of sub-Saharan Africa is widely known for its nutritional and medicinal importance. Its cultivation is however mostly limited to the wet seasons of the year. This is largely due to: inadequate water supply and rapid depletion of moisture from soil during dry seasons, and lack of reliable and relevant data on crop water requirement at the different stages of development and their relationship to yield. Dearth of knowledge about appropriate use of modern irrigation systems has also hindered successes that would have been made at improving *Amaranth* production during off seasons. Dry season farmers (mostly Fadama farmers) often use intuition and other non scientific methods to apply water to crop and this often leads to under-irrigation or over-irrigation of crops.

Therefore, this study was aimed at determining the response of *Amaranthus cruentus* to different water application levels using sprinkler and drip irrigation systems and as well determine the water-yield relationship for the crop with a view to proposing the most effective irrigation method for its optimum yield under a controlled moisture supply in the study area.

A two (2) year field experiment was carried out to investigate the growth, yield and water use pattern of *Amaranthus cruentus* under limited water supply. The experiment was carried out at the Research and training Farm site of the Department of Agricultural Engineering, Federal university of Technology, Akure. A preliminary investigation was carried out on the soil physical and chemical characteristics, climate variations and water resource of the study site to determine its potentials for dry season farming. A 2 x 3 x 3 combination of two irrigation methods (Drip and sprinkler systems), three(3) crop phenological stages (Emergence, vegetative/fruiting, maturity)and three water stress levels (50-59, 60-69 and 70 KPa).The treatments were twice replicated using a randomized complete block design (RCBD). Measurements taken on the field during experiment include soil moisture

content using the gravimetric method, soil bulk density, the soil hydraulic change using mercury tensiometers, overland flow during occasional rainfalls in the field by use of developed and celebrated runoff meter, deep drainage from the field using hydraulic lysimeter. Measured crop parameters include the plant height, the leaf area and leaf area index (LAI), the number of leaves and *Amaranthus cruentus* yield. Weather variables such as solar radiation, minimum and maximum relative humidity, minimum and maximum temperature and wind speed from the field were measured with the aid of automatic mini-meteorological station installed some 200 m away from the site of experiment. Soil, crop and meteorological data collected were subjected to statistical analysis such as Analysis of variance (ANOVA), mean, standard deviation and linear and multiple regression analysis. Results obtained from the experiment showed that the soil hydraulic charge (θ) is higher during the dry season experiment of 2005 than 2006. Soil moisture depletion during the wet season experiment was close to zero most times at the different soil depths; hence no irrigation was necessary during the wet season experiment. Also, the variations in volumetric moisture content showed an increase in moisture regime down the soil profile. Moisture was readily available for crop use in the treatments that was well watered (STI and DTI). However, as crop reaches maturity and senescence, soil moisture storage for all treatments is reduced due to reduction in canopy at full crop maturity. Consumptive use of crop (Evapotranspiration) was highest (9.96 mm/day) in drip plots DT1 and DT2 at the peak of the dry season (57-64 DOY). Reduced radiation at the onset of raining season brought about reduced evapotranspiration to as low as 0.30 mm/day. The value of crop factor k_c for *Amaranthus cruentus* on function of day of the year reduced marginally at the earlier stage of crop growth but rose sharply during the productive stage of the crop. At late season during crop senescence, crop factor k_c maintained nearly constant values. The coefficient of correlation between crop consumptive use and the growth stage of *Amaranthus* (emergence to maturity) was highest

(0.94) in sprinkler plot ST6. Crop yield model based on equation calibrated on *Amaranthus cruentus* yield showed good agreement with the field data. The correlation coefficient (R) of the model output and the measured yield was significantly high (0.86). Linear regression analysis carried out on yield on function of cumulative moisture stored at the vegetative stage of the crop showed that the coefficient of determination between crop yield and soil moisture stored was higher (R=0.84) on drip plots than on sprinkler plots (R=0.74) at $P<0.05$. Simulated crop growth and soil water balance showed a significantly high agreement with field determined growth and actual evapotranspiration of *Amaranthus cruentus*. The WaSim model simulated crop growth and crop cover adequately well, the coefficient of determination ($R^2 = 9.9$) is high. Findings from this research are useful for careful planning of irrigation to meet crop water demand during off seasons most especially in areas of limited rainfall occurrences.

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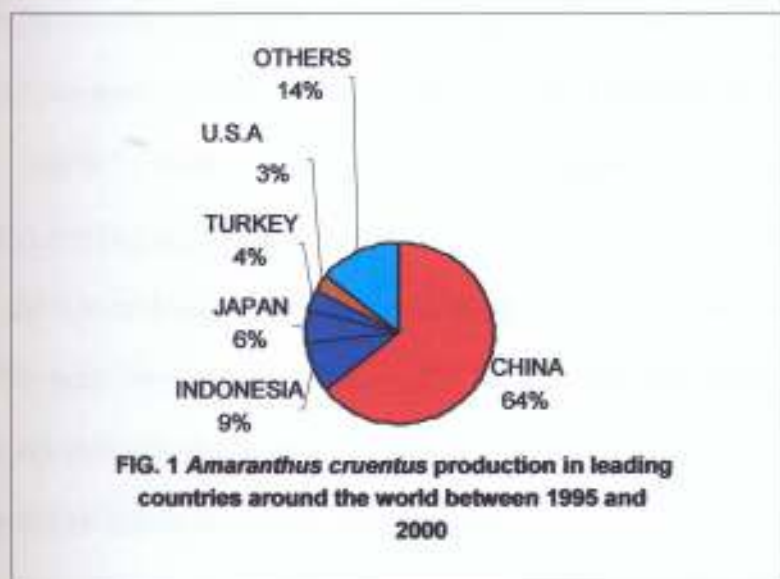
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CHAPTER ONE

1 INTRODUCTION

1.1 General Introduction

The earliest archeological record of pale seeded grain Amaranth is that of *Amaranthus cruentus* popularly called 'Tete Arowojeja'. The crop was found in Tehuacan Puebla, Mexico, about 400 BC (Pal and Khoshoo, 1974; Saver, 1979) making it one of the oldest known food crops. It originated in Central and South America (Grubben and Van Stolen 1981). Figure 1 shows the distribution of *Amaranthus* production in leading countries around the world.



Source: Mc Pherson, 1982

Amaranthus spp has been valued since ancient times for its nutritional and ornamental qualities. *Amaranthus cruentus* is cultivated as a grain crop in Guatemala.in Mexico. Grain Amaranth is used chiefly for making 'alegria candies' from popped seeds and molasses (Early, 1977) and for the preparation of 'atole' a drink from roasted and powdered seeds mixed with syrup and water (Oke, 1983). One of the highest protein



grains with medicinal attributes, Amaranth has excellent potential in health, food and nutrition market.

Amaranth's sweet, nutty flavour compliment a range of cereal products, and its starch could replace fat in processed foods. *Amaranthus cruentus* belong to the very useful leafy amaranths of the third world. Amaranth is high in protein, lysine, calcium, iron and fibre; all of which are useful as functional ingredient in cereal products. Amaranth oil are high in "squalene", a powerful antioxidant used as a dietary supplement for diabetes and those suffering from hypertension and metabolic disorders (Teutonico and Knorr, 1985).

Amaranth oil is of great value. It contains about 77% of non-saturated fatty acids (about 50% of lino-lenic and lion leic acid, squarlene and vitamin E in the rare form of tocotrienol which takes part in the biosynthesis of cholesterol (<http://amaranth.twoday.net/topics/kontack/>).

It is active in all human organs; normalizes the metabolism and makes better the immunity. The main characteristics of the oil is its harmless and effectiveness for the prophylactic and treatment of diseases:

Amaranth oil has the following characteristics:

- Strengthens immunizing function;
- Improves organism's resistance to disease;
- Makes recovery from injury faster;
- Improves the resistance against radioactive and x-ray irradiation;
- Retards the effect of skin opening and development of wrinkles;
- Improves mental performance, memory functions;

- Reduces the feeling of tiredness and psychic stress;
- Helps to regulate the conversion of fats, especially cholesterol;
- Extinguishes free oxygen radicals.

Wide use of Amaranth oil is explained by its unique active biological matter: amino acids, micro-elements, minerals, vitamins, proteins, polyunsaturated fatty acids, choline, gall acids, spirits, steroids and squalene. Squalene is said to have properties that ward off cancer producing substances in the body. It also fights against bacteria, fungi, herpes and other viruses, and improve auto-immune disorders. Shark oil has a 1% squalene content, while the content of Amaranth oil is 8%. Amaranth oil has antibacterial, anti-tumor, and burn-and wound-healing properties. Animal test also show that Amaranth lowers blood serum cholesterol, and some varieties contain up to 3% rutin. Squalene also prevents the development of lung cancer of individual exposed to inhalation of smoke with high content of tar substances. Regular intake of Amaranth improves mental performance, memory functions and improves also the resistance against psychic stress.

In the humid tropics, *Amaranthus cruentus* is the most cultivated leafy vegetable (Mc Pherson, 1982). The vegetable is very rich in vitamin A and it contributes to a balance diet a significant amount of beta-carotene and ascorbic acid (Vitamin C), iron and calcium. Despite the nutritional and medicinal importance of the crop, efforts to improve its production have been hampered by inadequate knowledge on how best the crop could be produced especially in the off-season. In the southern part of Nigeria, irrigation practice is not wide spread. The reason for this are due to unfavourable agricultural policy, lack of awareness of the benefits of irrigation, lack of irrigation facilities and poor

dissemination of the few research findings to farmers and other interest groups (Alatise, 2002). Hence, the need for relevant data for effective crop-water management at the field level cannot be over-emphasized.

In the past decades, the development of dynamic crop growth simulation models has made substantial progress. However, the developed models possess different level of complexity depending on specific requirements. Moreover, some of the available models consist of empirical relationships, which require a local calibration and validation (Whisler *et al.*, 1986; Bennie *et al.*, 1988; Singels and De Jager, 1991; Smith, 1992; Annandale *et al.*, 1996; Crosby, 1996). Walker *et al.* (1995) published a comprehensive review of wheat models, and Mottram and De Jager (1994), provided an overview of soil-water balance and reference evapotranspiration models. Advantages and disadvantages of several models were also described by Hank and Ritchie, (1991).

Most water balance simulation models commonly used world-wide have benefited from many years of development and validation. However, different purposes (applications) require different packaging of the models. Many of the existing models were developed for research use where the emphasis is on the validity of the output and rigour in the scientific understanding of packages, and for educational use which have a much greater demand on the ease of use of the interface, simple parameterization and clear visualization of results, and less on the accuracy of the production. It is important that a model responds to simulated conditions in the right direction and the correct order of magnitude, but relative changes in the output are more important in conveying the understanding of the system than absolute predictions (Hess and Counsell, 2000). Many

of the existing models therefore are unsuitable for research purpose, or can only be used once extensive training in the use of the software has been completed.

Computer simulation models are increasingly being used as teaching tools and as a replacement for, or adjunct to traditional field or laboratory exercises. Among the most recently developed is the water simulation model (WaSim), a daily water balance model that simulates the soil water in response to different management strategies and environmental scenerios (Hess and Counsell, 2000). Many benefits have been cited among which are: speed, controlling the environment, performing impossible, or undesirable experiments, focus on the learning experience, substituting for physical resources and tutor's time synthesizing expertise, loaming and sensitivity analysis, distance and self learning and observing obscure processes. Little information is available on the use of WaSim in the tropical condition.

Although there is little quantitative information in the literature from environmental sciences, computer assisted learning in other disciplines has been quantified experimentally. Comparative studies have shown that computer aided learning is at least as effective as traditional methods, and in many cases has positive benefits in terms of motivation and retention.

The aim of this study is to quantify the response of *Amaranthus cruentus* to water application by two irrigation systems and to calibrate and validate a soil water simulation model (WaSim).

1.2 Importance of Water to Crops

Water is very essential in the plant system. It is a major structural constituent held in cells, which add bulk, affect form through turgor development and is responsible for

many of the physical and structural characteristics of the plants. The amount of water directly involved in photosynthesis reactions is very small. However, biochemical reactions and transport processes in plants require an adequate aqueous environment. Also, in the process of transpiration, it cools leaves exposed to solar radiation, hence; it acts as a buffer against high temperature injury (Jensen, 1980).

Water requirement for crops are not constant, but increases as the plant grows. When planning for irrigation, one must determine both the seasonal and peak water requirement for the crop to be irrigated. In addition to the peak water use period, many crops have certain stages of growth when significant yield or quality reduction will occur if adequate soil moisture levels are not maintained. Irrigation not only must be timed to minimize periods of water stress, but also not exceed the available root zone storage, except as needed for leaching of excess salts.

Crop production, especially in the south-western part of Nigeria is largely limited to the rainy season of the year. With the increasing need of the growing population, there is an urgent need for increased production of food and industrial raw materials by transforming the existing largely traditional or subsistence agriculture into modern agriculture through intensive mechanization (Smith, 2000). One way to accomplish this is to have supplemental irrigation during the growing season and hence total or complete irrigation during off-season. A detailed knowledge of irrigation water requirements, its magnitude, its temporal and spatial variability is essential for the assessment of water resources and storage requirements, the capacity of irrigation systems, optimal allocation of water to crops and for the decision making in operation of irrigation systems (Oguntunde, 2004).

1.3 Objectives of the Research

The objectives of the research are to:

- i. investigate the growth, water use pattern and yield of *Amaranthus cruentus* grown under drip and sprinkler irrigation systems.
- ii. establish the variations in the consumptive use of *Amaranthus cruentus* grown under rain-fed and irrigated conditions.
- iii. determine the input parameters and validation a soil water balance model (WaSim) for *Amaranthus cruentus*.

1.4 Justification for the Study

Few researches have been focused on the field determination of the consumptive use of vegetables and other crops in the sub-Saharan Africa. Thus, limited data is available on the actual quantity of water required for the production of crops from the period of establishment to maturity in order to prevent water stress or over irrigation of crop on the field. These data are needful in the development of crop models and the establishment of water management strategies for maximum crop production. Since effective irrigation strategies or models depend on the quality of input data, the research work will generate these needed data in the case of *Amaranthus* and lead to the development of reliable production functions (models).

1.5 Research Hypothesis

Amaranthus cruentus responds to water application in a way that its growth and yield can be predicted and thus modeled. Hence, well defined production functions can be established.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Irrigation Scheduling Strategies and Time Scale

Irrigation scheduling is the process of determining when to irrigate and how much water to apply per irrigation (James, 1993). Proper scheduling is essential for the efficient use of water, energy, and other production inputs, such as fertilizer. It allows irrigations to be coordinated with other farming activities including cultivations and chemical applications.

Plant root depth, canopy development, growth habits and nutrients requirements in a given climate largely determine the irrigation schedule, and soil infiltration characteristics determine water application rates. Among the benefits of proper irrigation scheduling are: improved crop yield and/or quality, water and energy conservation, and lower production costs.

Several techniques exist for establishing irrigation schedules based on soil, plant and evaporative measurements. There is a crude method based on experience and/or visual observation of soil and/or plant characteristic; other modern methods have also been documented. According to Shae *et al.*, (1999), irrigation scheduling can be classified into major categories as shown in Figure 2. Effective scientific irrigation scheduling techniques are based on well defined production functions or model which has been established for a particular crop. There are two possibilities (Deumier *et al.*, 1996): real time irrigation scheduling systems (high value crops) and strategy in the choice of crops (agricultural crops).

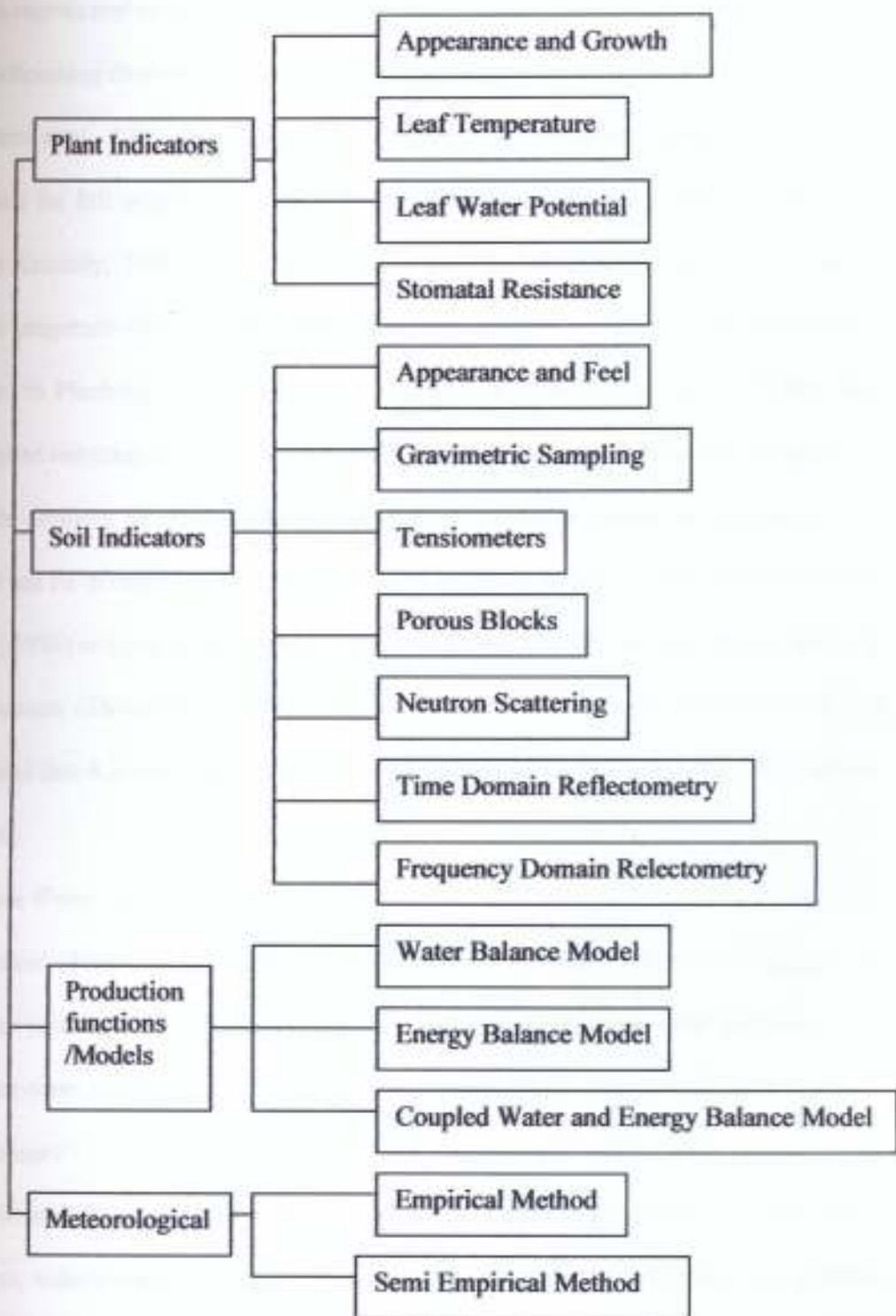


Figure 1.2: Irrigation Scheduling Techniques

As regards real time irrigation systems, Reference evapotranspiration (ET_{ref}) for the forthcoming days can be directly estimated from meteorological service forecasts (Cabelguerne et al., 1996; Specty and Isberie, 1996). In some other cases, historical data can be used for full season irrigation scheduling based on long-term average data (De Jager and Kennedy, 1996; Specty and Isberie, 1996). The first one seems to be more adapted to temperate climate with rapidly changing weather conditions. The time step is seven days in Plauborg et al. (1996) and five days in Cabelguerne *et al.* (1996), who recommended resetting data day after day due to the unreliability of five-day forecasts.

The problem of rainfall arises when using calendars based on long-term data. Calendars can be determined assuming either no rain or average rainfall conditions (Hill and Allen, 1996) or by applying different percentages of probable rainfall during the crop growing season (Thoradeniya, 1995). The latter makes calculation more difficult and author thinks that it is necessary to evaluate the consequences in terms of transfer before application.

Use of Plant Water Stress Criteria

Instead of measuring or estimating, by means of a water balance, the amount of water in the rooted soil, it is possible to get messages from the plant itself indicating that the time has come to irrigate.

Plant Messages

Trunk or branch diameter change: Pepista' system (Huguet *et al.*, 1992) gave interesting information, mainly on trees, when it is possible to analyse the following two factors: mean trend in diameter growth and diurnal changes (Deurmier et al., 1996). As for other plant measurements, it is necessary to sample several trees. The main problem

encountered is that, sometimes, the same response is obtained with an excess and a lack of water. Furthermore small diurnal changes are also observed in the case of high water stress (as a result of important stomatal closure). For mild water stress conditions, diurnal changes depend on species and varieties, so it could be useful to have groups of crops exhibiting the same type of response before any possible transfer to farmers.

Leaf water potential: The main interest of this measurement lies in the possibility of linking values of pre-drawn leaf water potential to relative evapotranspiration. Itier *et al.* (1992) showed that it is possible for C3 plants such as wheat and tomato, but experiments performed since that time show that it is not the case for C4 plants such as corn and sorghum (Karterji and Itier, 1995). This technique presents other limitations such as the sampling needs which are too difficult for farmers and cannot be done automatically.

Sap flow: Sap measurement (Valancogne and Nasr, 1989) are sometimes included among the plant water stress criteria for irrigation scheduling. In fact, one can obtain relative ET values by measuring sap flow along the trunk and comparing trees under water shortage to well irrigated trees (Granier *et al.*, 1990; Allen and Grime, 1995). Two techniques are available: 1) the sap flux density technique (e.g. Cohen *et al.*, 1981); and 2) the mass flux technique (e.g. Sakuratani, 1981) the former is limited by the need to determine the cross-sectional area of the water conducting tissue. The latter is restricted to estimation of small trees' transpiration. Both techniques need tree sampling and, if badly used, can lead to necrosis of the trunk.

Temperature: Surface temperature measurements performed by means of infrared radiometers are mentioned in Mailhol *et al.* (1995). The stress degree day (SDD) was used (Idso *et al.*, 1981) to calibrate a model. The problems related to this index are: 1) it is not relative index, which means that threshold values need to be adjusted to each crop; and 2) it does not work correctly when small rainfall occurs during the drying cycle, because the question of knowing whether it must be reset or not is not solved.

These problems do not occur with the crop water stress index (CWSI) (Jackson *et al.*, 1981) but its use is limited by the problems related to the baselines definition (Idso, 1982). Despite efforts to simplify calculations (Itier *et al.*, 1993), and the continually decreasing price of Infrared radiometers, its use seems to be limited to industrial farms or advisers. Furthermore, both SDD and CWSI can be used only if weather conditions are not rapidly changing (wind and radiation) and only for fully developed crops (in order to avoid soil surface temperature influence on measurements).

Radiation: There are some possibilities of using the ratio of intercepted radiation in the near infrared over visible ranges to anticipate water shortage. This is the aim of some tools such as Piquhelios (Baldy, 1973). However, to use it, it is necessary to know the evolution of the optimum ratio.

Use of Models

Two types of models are presented for irrigation scheduling:

- (i) Models based on soil water balance, where irrigation starts when a threshold value of water content in the soil is reached (Pilote and Pilotman in Mailhol *et al.*, 1995; Cavazza *et al.*, 1996; Przybyla, 1995; Putu in De jager and

Kennedy, 1996; Hess, 1996; Bipode in Specty and Isberie, 1995; Irriguide in Bailey and Spackman, 1996).

- (ii) Mechanistic models, in which growth and yield are simulated and depend upon water status of the plants at different stages. (MODIS in Chang *et al.*, 1995; Markvand in Plauborg *et al.*, 1996; Epicphase in Cabelgueme *et al.*, 1996; Lunardi *et al.*, 1995; Hydra in Huygen *et al.*, 1995; Epic in Santos *et al.*, 1995; Tarjuelo *et al.*, 1995; Varlev *et al.*, 1996). Obviously, this last type of model includes a water balance sub-model generally similar to those mentioned above.

Models can be used either for strategic or tactical purposes. In the first case, the question is: how large an area to irrigate, which crops to plant and how to distribute the available water supply along the season (Huygen *et al.*, 1995). For agricultural crops, this is the major problem while real time irrigation scheduling is important for high value crops (Deumier *et al.*, 1996).

Models, per se, seem to be difficult to run for farmers. Irrigation simulators originated from these models could be easier to use. Deumier *et al.* (1996) present one software (LORA), which makes it possible for farmers to find the optimal crop planning on irrigated farms, and two irrigation simulators (MIRA and IRMA), designed for testing of management decisions. Most often, decisions rules result from collaboration between farmers and researchers. For real-time irrigation scheduling, Plauborg *et al.* (1996) present the Markvand, a model being used by 200 farmers in Denmark, while Bailey and Spackman (1996) indicated that their package is currently being used by over 300 farms



in the United Kingdom. Speety and Isberie (1996) present some examples of irrigation warning in France and the results of an inquiry among users.

2.2 Crop Consumptive Use and Evapotranspiration (ET) Models

The combined water that is transferred to the atmosphere through evaporation (E) and transpiration (T) processes is known as evapotranspiration (ET). Apart from the water availability in the top soil, the evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil surface. This fraction decreases over the growing period as the crop develops and the crop canopy shades more and more of the ground area. When the crop is well developed and completely covers the soil, transpiration becomes the main process (Jensen *et al.*, 1990). However, consumptive use refers to the total amount of moisture required for crop growth and development excluding its catabolic activity.

2.2.1. Methods of estimating evapotranspiration (ET)

For irrigation scheduling and hydrologic studies, it is often necessary to estimate evapotranspiration. This is because of the stochastic nature of rainfall coupled with the need for efficient utilization of water in crop production. Evapotranspiration is not easy to measure. Specific devise and accurate measurements of various physical parameters or the soil water balance in lysimeters are required to determined evapotranspiration (Allen *et al.*, 1998).

Different measurement techniques for ET include: Soil water balance, energy balance and microclimatological methods, lysimeters, ET computed from meteorological data, ET estimate from pan evaporation.

(a) Soil Water Balance

Evapotranspiration can be determined by measuring the various components of the soil water balance. The method consists of assessing the incoming and out coming water flux into the crop root zone over some time period. Irrigation (I) and rainfall (P) add water to the root zone. Part of I and P might be lost by surface runoff (R_o) and by deep percolation (DP) that will eventually recharge the water table. Water might also be transported upward by capillary rise (CR) from a shallow water table towards the root zone or even transferred horizontally by subsurface flow in (SF_{in}) or out of (SF_{out}) the root zone. In many situations, however, except under conditions with large slopes, SF_{in} and SF_{out} are minor and can be ignored. Soil evaporation and crop transpiration deplete water from the root zone.

If all fluxes other than evapotranspiration (ET) can be assessed, the evapotranspiration can be deduced from the change in soil water content (ΔSW) over the time period.

$$ET = I + P - R_o - DP + CR \pm \Delta SF + \Delta SW \quad 2.1$$

where ET = evapotranspiration (mm)

I = irrigation (mm)

P = precipitation (mm)

R_o = runoff (mm)

DP = deep percolation (mm)

CR = capillary rise (mm)

ΔSF = change in subsurface flow (mm)

ΔSW = change in soil moisture storage (mm)

Some fluxes such as subsurface flow, deep percolation and capillary rise from a water table and difficult to assess and short time periods cannot be considered. The soil water balance method can usually only give ET estimate over long periods of the order of week-long or ten-day periods.

(b) Energy Balance and Microclimatological Methods

Evaporation of water requires relatively large amount of energy, either in the form of sensible heat or radiant energy. Therefore the evapotranspiration process is governed by energy exchange at the vegetation surface and is limited by the amount of energy available. Because of this limitation, it is possible to predict the evapotranspiration rate by applying the principle of energy conservation. The energy arriving at the surface must equal the energy leaving the surface for the same time period. All fluxes of energy should be considered when deriving an energy balance equation. The equation form an evaporating surface can be written as:

$$R_n - G - \lambda ET - H = 0 \quad 2.2$$

Where, R_n is the net radiation, H the sensible heat, G the soil heat flux and λET the latent heat flux. The various terms can be either positive or negative. The equation components can be measured remotely with sensing technologies or on the ground with Bowen Ratio or Eddy Correlation equipment as described by Brown et al. (2001):

$$ET = \frac{\Delta}{\Delta + \gamma} \left[(R_n - G) + \frac{PC_p}{\Delta} H(u) (D_{so} - D_s) \right] \quad 2.3$$

Where $R_n - G$ = available energy (MJ/m^2) for the canopy, comprised of net radiation, R_n and the soil heat flux, G ; $H(u)$ = exchange coefficient (m/s) between the surface level and a reference level above the canopy but taken inside the conservative boundary sub-

layers; D_s and D_a (KPa) = vapour pressure deficits (VPD) for the surface level and the reference level, respectively; ρ = atmospheric density (Kg/m^3), C_p = specific heat of moist air ($\text{J/kg}^\circ\text{C}$); Δ = slope of the saturation vapour pressure curve (Pa°C); and γ = psychrometric constant (Pa°C). Equation 2.3 is viewed as a definition for ET rather than a predictor of ET, since it cannot produce estimates for reasons given below (Pereira et al., 1999).

To obtain evapotranspiration with equation 2.3, the most difficult term to estimate is D_s , representing the vapour pressure deficit at the evaporative surface (Oguntunde, 2004). The bulk of literature on the estimation and measurements of ET over different land covers and climatic conditions have demonstrated the large variation in complexity of the evapotranspiration process. Hence, models ranging from the simple to the physically based have been formulated that describe the processes involved at various levels of complexity with different forms of assumptions (Shuttleworth and Wallance, 1985). The most widely applied of these models was developed by Penman and modified by Monteith (1965). It combines the energy balance of the land surface with the concept of a species dependent surface resistance for water vapour release.

Another method of estimating evapotranspiration is the mass transfer method. This approach considers the vertical movement of small parcels of air (eddies) above a large homogenous surface. The eddy transport materials (water vapour) and energy (heat, momentum) from and towards the evaporating surface. By assuming steady state conditions and that the eddy transfer coefficients for water vapour are proportional to those for heat and momentum; the evapotranspiration rate can be computed from the vertical gradients of air temperature and water vapour via the Bowen ratio. Other direct

measurement methods use gradients of wind speed and water vapour. These methods and other methods such as eddy covariance require accurate measurement above the surface. Therefore, their application is restricted to primarily research situations.

(c) **Lysimeters**

By isolating the crop root zone from its environment and controlling the processes that are difficult to measure, the different terms in the soil water balance equation can be determined with great accuracy. This is done in lysimeters where the crop grows in isolated tanks field with either disturbed or undisturbed soil. The bottoms of the micro-lysimeters are capped and returned to the soil. The amount of water lost by evapotranspiration is determined daily by weighing the micro-lysimeters at sunrise and at sunset. Lascano (2001) noted that obtaining accurate soil evaporation measurements with micro-lysimeters is an art. Using many spatially distributed replications of micro-lysimeters will help to capture the average soil evaporation that occurs within the plant/soil environment.

A requirement of lysimeter is that the vegetation both inside and immediately outside of the lysimeter be perfectly matched (same height and leaf area index). This requirement has historically not been closely adhered to in a majority of lysimeter studies and has resulted in severely erroneous and unrepresentative ET_e and K_e data. As lysimeters are difficult and expensive to construct and as their operation and maintenance require special care, their use is limited to specific research purposes.

2.2.2 Potential and Reference Evapotranspiration

Potential ET is the maximum rate of which water, if available, can be removed from soil and plant surfaces. Penman (1948) defined potential evapotranspiration as the

evapotranspiration rate of a short green crop, completely shading the ground, of uniform height and never short of water.

The evaporation from a reference surface, not short of water is called the reference crop evapotranspiration or reference evapotranspiration and it's denoted as ET_0 (Allen *et al.*, 1998). They went further to remark that the reference surface is a hypothetical grass reference crop with specific characteristics. The use of other denominations such as potential ET strongly discouraged due to the ambiguity in their definitions (Smith *et al.*, 1996). The concept of the reference evapotranspiration was introduced to study the evaporative demand of the atmosphere independently of the crop type, crop development and management practices. As water is abundantly available at the evapotranspiring surface, soil factors do not affect ET. Relating ET to a specific surface provides a reference to which ET from other surfaces can be related. It necessitates the definition of a separate ET level for each crop and stage of growth. Values measured or calculated at different locations or in different seasons are comparable as they refer to the ET from the same reference surface (Pereira *et al.*, 1999).

The only factor affecting ET_0 are climatic parameters. Consequently, ET_0 is a climatic parameter and can be computed from weather data. ET_0 expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors. The FAO-Penman Monteith method is recommended as the sole method for determining ET (Allen *et al.*, 1998). The method has been selected because it closely approximates grass ET_0 at the location evaluated. It is physically based on, and explicitly incorporated both physiological and aerodynamic

parameters. Moreover, procedures have been developed for estimating missing climatic parameters.

2.2.3 Need for a Standard ET_0 Method

A large number of more or less empirical methods have been developed over the last 50 years by numerous scientists and specialist world wide to estimate evapotranspiration from climatic variables. Relationships were often subject to vigorous local calibrations and proved to have limited global validity. Testing the accuracy of the methods under a new set of conditions is laborious, time-consuming and costly, and yet evapotranspiration data are frequently needed at short notice for project planning or irrigation scheduling design. To meet this need, guidelines were developed and published in the FAO Paper No 56 (Allen *et al.*, 1998). To accommodate users with difference data availability, four methods were presented to calculate the reference crop evapotranspiration (ET_0): the Blaney – Criddle radiation, modified Penman and Pan evaporation methods. The modified Penman method was considered to offer the best results with minimum possible error in relation to a living grass reference crop. It was expected that the Pan method would give acceptable estimates, depending on the location of the Pan. The radiation method was suggested for areas where available climatic data include measured air temperature and sunshine, cloudiness or radiation, but not measured wind speed and air humidity. Finally, the publication proposed the use of the Blaney-Criddle method for areas where available climatic data cover air temperature data only (Allen *et al.*, 1994).

These climatic methods to calculate ET_0 were all calibrated for ten-day or monthly calculations, not for daily or hourly calculations. The Blaney-Criddle method

was recommended for periods of one month or longer. For the Pan method, it was suggested that calculations should be done for periods of ten days or longer. Users have not always respected these conditions and calculations have often been done on daily-time steps. The analysis of the performance of the various calculation methods reveals the need for formulating a standard method for the computation. The analysis of the performance of the various calculation methods reveals the need for formulating a standard method for the computation of ET_0 . The FAO-Penman-Monteith method is recommended as the sole standard method. It is a method with strong likelihood of correctly predicting ET_0 in a wide range of locations and climates and has provision for application in data-short situation. The use of older FAO or other reference ET methods is no longer encouraged.

2.2.4 Crop Evapotranspiration under Standard Conditions (ET_c)

Pereira *et al.* (1999) defined crop evapotranspiration under standard conditions, denoted as ET_c , as the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions. The amount of water required to compensate the evapotranspiration loss from the cropped field is defined as crop water requirement. Although, the values for crop evapotranspiration and crop water requirement are identical, crop water requirement refers to the amount of water that needs to be supplied, while crop evapotranspiration refers to the amount of water that is lost through evaporation and transpiration (Smith *et al.*, 1996).

The irrigation water requirement basically represents the different between the crop water requirement and effective precipitation. This also includes additional water for

leaching of salts and to compensate for non-uniformity of water application (Walter *et al.*, 2000). Crop evapotranspiration can be calculated from climatic data and by integrating directly the crop resistance, albedo and air resistance factors in the Penman-Monteith approach. As there is still a considerable lack of information for different crops, the Penman-Monteith method is used for the estimation of the standard reference crop to determine its evapotranspiration rate, i.e. ET_0 . Experimentally determined ratios of ET_c/ET_0 , called crop coefficient (K_c) are used to relate ET_c to ET_0 or

$$ET_c = K_c ET_0 \quad 2.4$$

Difference in leaf anatomy, stomata characteristics, aerodynamic properties and even albedo cause the crop evapotranspiration to differ from the reference crop evapotranspiration under the same climatic conditions. Due to variations in the crop characteristics throughout its growing season, K_c for a given crop enlarges from sowing till harvest.

2.2.5 Crop Evapotranspiration under Non-Standard Conditions (ET_c adj)

The crop evapotranspiration under non-standard condition (ET_c adj) is the evapotranspiration from crops grown under management and environmental conditions that differ from the standard conditions (Kruegar *et al.*, 2001). When cultivating crops in fields the real crop evapotranspiration may deviate from ET_c due to non-optimal conditions such as the presence of pests and diseases, soil salinity, low soil fertility, water shortage or water logging. This may result in scanty plant growth, low plant density and may reduce the evapotranspiration rate below ET_c .

The crop evapotranspiration under non-standard condition is calculated by using a water stress coefficient K_s and/or by adjusting K_c for all kinds of other stresses and environmental conditions on crop evapotranspiration.

2.2.6 Some ET Prediction Models

Yearly Differential Model (Yd)

The yearly differencing model can be described mathematically as:

$$ET_{o,t} = ET_{o,t-12} + e_t \quad 2.5$$

where

$ET_{o,t}$ = Reference crop evapotranspiration during the month t ,

$ET_{o,t-12}$ = Reference crop evapotranspiration during the month $t - 12$, and

e_t = Prediction error in the month t .

This simple model predicts the reference crop evapotranspiration in such a way that it is equated with reference crop evapotranspiration during the same month of the previous years. The application of this method is even more important when there is a limited number of information about the previous values of reference crop evapotranspiration. Y_d model does not use either calibration or parameter estimation, and it is very simple to use. The successful application of this model is obtained through the domination of seasonal component of evapotranspiration time series.

Monthly Average Model (MAV)

Monthly average (MAV) model is described mathematically as:

$$ET_{a,j} = \frac{1}{N} \sum_{i=1}^N ET_{a,j-12} + e_i \quad 2.6$$

Where

N = Number of years of observation

A monthly value of reference crop evapotranspiration is obtained as an average value of reference crop evapotranspiration during the previous year in the corresponding month. This method decreases the influence that extreme years have on the prediction by averaging them in with the "usual years". MAV model needs a small calibration, and its parameters are easily calculated from the data set.

Auto Regressive Integrated Moving Average (ARIMA) Model

The Box-Jenkins method is one of the most widely used time series prediction method in practice. The method uses a systematic procedure to select an appropriate model from a rich family of models (ARIMA Models).

Auto Regressive (AR) models estimate values for the dependent variable X_t as a regression function of previous values, X_{t-1} , ———, X_{t-p} plus some random error e_t . Moving Average (MA) models give a series value X_t as a linear combination of some finite past random errors, $e_{t-1}, \dots, e_{t-q}$. P and q are referred to as orders of the models. AR (P) and MA (q) models can be combined to form an ARMA (p, q) model. This model can provide additional flexibility in describing time series.

Soil, Water, Atmosphere and Plant (SWAP) Model.

SWAP (Soil, Water, Atmosphere and Plant) model has been developed by Wageningen University and Alterra. The SWAP model is a physically based, detailed agro-hydrological model that simulates the relationships between soil, water, weather and plants. The core of the model is the Richards' equation where the transport of soil water is modeled by combining Darcys' law and the law of continuity. The program is designed to simulate the transport processes at field scale and during entire growing seasons. A simple or detailed crop model WOFOST (Doorenbos and Kassam, 1979) simulates crop

growth. The simple crop model is based on the linear production function of Doorenbos and Kassam (1979). WOFOST is a general crop model, which is capable of simulating the growth and development of the crop. Basically, daily meteorological data are used to calculate daily, potential evapotranspiration according to Penman-Monteith (Allen *et al.*, 1998). The model considers several management scenarios and various possibilities of irrigation scheduling criteria.

Other models

The detailed description of some other models is given in Tsuji *et al.* (1994) and IWMI working paper 22 (Ines *et al.*, 2001). The soil water balance in DSSAT is based on Ritchie's model where the concept of drained upper limit and drained lower limit of the soil is used as the basis of the available soil water (Ritchie 1972; Ritchie 1981a; Ritchie 1981b). The approach is simple water accounting in each layer considered in the soil profile (Ritchie, 1988). The strategies Evaluation of the Program in DSSAT allows users to evaluate the merits of simulated strategies and identify the best one. The program uses cumulative probability functions to develop and select the strategy with the preferred mean and variability characteristics. With this program users can determine the effectiveness of crop management strategies, the economic return of a new cultivar, or the suitability of a site for a specific crop. Using weather generators programs which generate coefficients from historical weather data, DSSAT can simulate the growth and development of a crop for up to 50 consecutive years. DSSAT allows up to 15 combinations of options to be simulated in a single experiment, generating in a few hours, amounts of data that traditionally required an agronomist's lifetime of work.

DSSAT also provides for validation of crop model outputs; thus allowing users to compare simulated outcomes with observed results. Crop model validation is accomplished by inputting the user's minimum data sets (MDS) running the model, and comparing outputs. By simulating probable outcomes of crop management strategies, DSSAT offers users information with which to rapidly appraise new crops, products, and practices for adoption.

2.3 WaSim Model

2.3.1 Description of WaSim Model

WaSim model was developed in UK by HR Wallingford and Cranfield University by Hess et al.(2000). Its original aim is to serve as a computer-based teaching and research package for the demonstration of issues involved in irrigation, drainage and salinity management. WaSim is a daily water balance model that simulates the soil water / salinity relationships in response to different management strategies (e.g. drainage designs and water management practices) and environmental scenarios (e.g. weather data, soil types, cropping patterns).

The water balance model is a one-dimensional, daily, soil water balance. It aims to simulate the soil water storage and rates of input (net rainfall and irrigation) and output (evaporation, transpiration and drainage) of water in response to climate. The upper boundary is the soil surface and the lower boundary is the impermeable layer. Water is stored between these two boundaries in five stores (layers):

- i. the surface (0 – 0.15 m) layer,
- ii. the active root zone (0.15 m – root depth),
- iii. the unsaturated layer below the root zone (root depth – watertable),

- iv. the saturated layer above drain depth (watertable – drain depth),
- v. the saturated layer below drain depth (drain depth –impermeable layer).

The boundary between layers ii and iii will change as the roots grow. Before plant roots reach 0.15 m; layer ii will have zero thickness. Similarly the boundary between layers iii and iv will fluctuate with the watertable. Soil water moves from upper layers to layers below only when the soil water content of the layer exceeds field capacity but the rate of drainage is a function of the amount of the excess water. Upward capillary rise occurs from the water table to the root zone.

The model requires daily reference evapotranspiration and rainfall data. An accompanying utility, WaSim ET is provided for calculating reference evapotranspiration from daily climate data using the Penman-Monteith, FAO Modified-Penman, or Penman methods. Climate data is imported from text files and screened for missing or out-of-range data. Data errors are then flagged and can be edited with WaSim.

Up to three crops (with fallow periods between) can be combined in a cropping pattern. For each crop, information is required on the cover development and rooting depths. Basic soil moisture characteristics are required, but typical guidance values provided. The crop and soil information is added to a database for future reference. Irrigation schedules are developed for individual crops. Irrigation may be scheduled in two ways;

- Rule based scheduling. The cropping season can be divided in to a maximum of 12 periods, during which different scheduling rules can be applied. The rules (e.g. irrigate at 25 mm soil water deficit and refill to field capacity) determine the timing of irrigation and the amounts to be applied.

- Calendar scheduling. Irrigations can be specified for fixed dates (e.g. apply 60 mm 30 days after planting) to simulate irrigation by a fixed calendar. This option can also be used to simulate the impact of an actual irrigation schedule. The scheduling criteria include the ability to suspend irrigation due to rainfall, or constrain the schedule due to limiting system capacity.

At the end of the simulation all calculated outputs relating to the climate, soil water, salinity, water table and crop status are written to an output file which can then be viewed, summarized and plotted using the results engine. This provides the flexibility to investigate any aspect of the simulation and produced customized graphs. The results of up to five simulations can be overlaid to compare scenarios and the graphed series can be exported to a spreadsheet for further analysis if required.

13.2 Principles of the WaSim Model

An existing model of evapotranspiration and selected empirical equations existing in the literature were assembled to simulate the crop actual evapotranspiration at different phenological stages. The model carries out a one-dimensional, daily soil water balance. It aims to simulate the soil water storage and rates of input (infiltration) and output (evapotranspiration and drainage) of water in response to climate; irrigation, and camel seepage where relevant. The boundary between the active root zone and unsaturated soil below the root zone will change as the roots grow. Before plant root reach 0.15 m, region of active root zone will have zero thickness. Similarly the boundary between the unsaturated will fluctuate with the water table (Hess *et al.*, 2000).

Inputs of Water

Inputs of water are from net rainfall, net irrigation and lateral seepage, where relevant. Net rainfall and irrigation are defined as the gross amounts, less interception losses, and surface runoff. Irrigation may or may not be subject to interception, depending on the application method.

Outputs of Water

The outputs of water from the profile are:

- i. Open water evaporation, E_o , occurs only if there is ponding of the soil surface. In this case, there is no transpiration.
- ii. Soil evaporation, E_s occurs from the soil surface layer only.
- iii. Plant transpiration, T_{so} , T_{sl} occurs from the soil surface layer and the active root zone layer.
- iv. Capillary rise from groundwater. Rather than redistribution of water from the water table to the unsaturated compartment and then to evaporation or transpiration, the model simulates a direct 'shortcut' from the groundwater to evaporation, E_{gw} and transpiration, T_{gw} .

2.3.3 Redistribution of Soil Water

Soil water moves from upper components to compartments below only when the soil water content of the compartment exceeds field capacity. In this case, the rate of drainage, q_0 to q_2 , is a function of the amount of excess water.

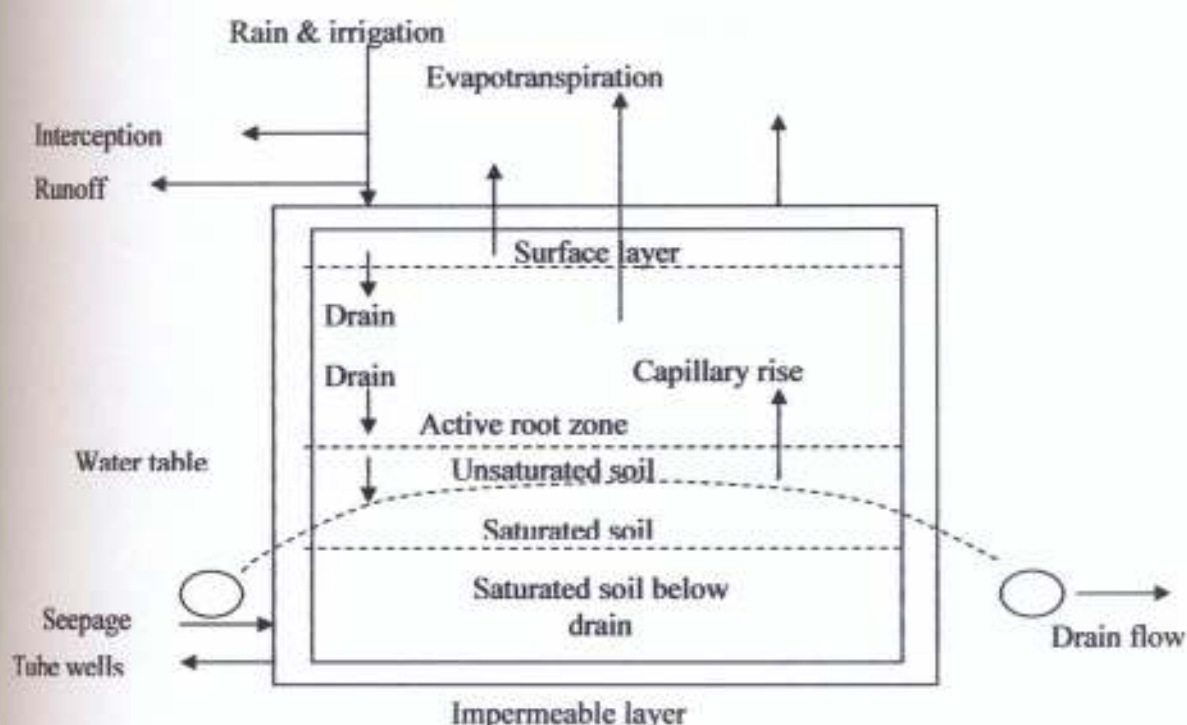


Fig. 2.1: Overview of the Soil Water Balance (Source: Hess, 2000)

2.3.4 Surface Conditions

The soil surface is divided into three components – plant cover, bare soil and mulch-and the evapotranspiration from each is modeled separated.

(a) Crop Cover Fraction

The crop cover fraction on a particular day is determined by linear interpolation between the dates of emergence i.e 20% cover, maximum cover, maturity and harvest. If the maximum cover fraction is less than 20%, then the first stage is ignored. Senescence is simulated by a linear reduction in crop fraction between maximum cover at maturity and zero at harvest.

(b) Mulch Cover Fraction

The fraction of the ground covered by mulch each day is determined by;

$$M_i = 1 - M_o - C_i \quad 2.7$$

Where

M_i = Cover fraction of mulch on day i

M_o = Cover fraction of mulch at planting

C_i = Cover fraction of crop on day i

i.e. the crop cover is assumed to expand over the mulch.

(c) Bare Soil Fraction

The fraction of the ground covered by bare soil each day is determined by;

$$B_i = 1 - M_i - C_i \quad 2.8$$

Where

B_i = bare soil fraction on day i

2.3.5 Available Water and Soil Water Deficit

(i) Root Depth

The root depth on a particular day is calculated from the following table:

Table 2.1: Calculation of Root Depth

Condition	Root depth
i) Planting depth	r_o
ii) Planting to maximum root depth	$r_{i-1} + \Delta_r$
iii) Maximum root depth to harvest	r_{max}
iv) After harvest	0

where

r_i = root depth on day i , m

Δ_r = daily root growth, m

r_o = planting depth, m

r_{max} = maximum root depth, m



The root growth on a particular day is determined from a sigmoidal root curve

(Borg and Grimes, 1986).

$$\Delta_r = [0.5 + 0.5 * \sin (0.03 * (t_p / n) - 1.47)] * (r_{\max} - r_o) \quad 2.9$$

Where

t_p = time since planting, (days)

n = duration of root growth, (days).

The root growth is limited by the water table, but is not reduced if a water table rises into an established root zone.

(ii) Available Water Capacity

$$F_c = \theta_{fc} * r_i * 1000 \quad 2.10$$

Where

F_c = water content of root zone at field capacity, mm

θ_{fc} = volume water fraction at field capacity,

r_i = root depth on day i, m

$$PWP = \theta_{pwp} * r_i * 1000 \quad 2.11$$

Where

PWP = water content of root zone at permanent wilting point, mm,

θ_{pwp} = volume water fraction at permanent wilting point.

r_i = root depth on day i, m.

$$TAWC = FC - PWP \quad 2.12$$

$$EAWC = TAWC * P \quad 2.13$$

Where

TAWC = total available water capacity of root zone, mm

P = fraction of total available water that is easily available,
Dimensionless

All soil parameters are weighted according to the fractions of the root zone in the top soil and subsoil where the physical characteristics may be different.

(c) Root Zone Deficit

The soil water deficit of the root zone is calculated from;

$$SWD = (\theta_{fc} - \theta) * r * 1000 \quad 2.14$$

Where

SWD = soil water deficit of root zone, mm

r = root depth, m

θ_{fc} = volume water fraction at field capacity, dimensionless

θ = volume water fraction of root zone, dimensionless.

2.3.6 Inputs

(a) Gross Rainfall and Irrigation

Gross rainfall on each day is read from the input data and irrigation may be given, or determined by the model according to scheduling rules. The irrigation plan determines whether irrigation applications are subject to inception loss or not. For example, drip irrigation would not be subject to interception, whereas sprinkler irrigation would.

(b) Interception Loss

Net rainfall (or irrigation) i.e. that part not intercepted by the crop canopy and directly evaporated, is estimated from;

$$P_n = P(1 - c) + (a + bP)c \quad (P > a)$$

$$P_n = P \quad (P \geq a) \quad 2.15$$

Where

P_n = net rainfall, mm

P = gross rainfall, mm

C = crop cover fraction (dimensionless)

a, b = empirical constants (dimensionless)

Thus, interception loss = $P - P_n$

23.7 Outputs

(a) Open Water Evaporation

Open water evaporation occurs only if there is ponded water on the surface. The rate of open water evaporation is proportional to the reference evapotranspiration.

$$E_{oi} = ET_{oi} / K_p \quad 2.16$$

Where,

E_{oi} = open water evaporation on day i , mm

ET_{oi} = reference evapotranspiration on day i , mm

K_p = open water evaporation (pan) coefficient, dimensionless = 0.80

(b) Soil Evaporation

i. Potential soil evaporation

The potential soil evaporation on any day is given by;

$$E_{soi} = ET_{oi} \quad 2.17$$

Where

ET_{soi} = Potential soil evaporation on day i , mm

ET_{oi} = Reference evapotranspiration on day i , m

ii. Actual soil evaporation

The evaporation from bare soil is calculated as a two stage process, following the method of Richie (1972).

Stage 1 starts on the first day after wetting and lasts until a maximum cumulative evaporation, U . During stage 1, evaporation is limited by the atmosphere, therefore;

$$E_{si} = E_{sat} \quad 2.18$$

Where,

E_{si} = soil evaporation on day i , mm d^{-1}

During stage 2, evaporation is limited by the wetness of the soil, and the evaporation rate is determined from the time since wetting,

$$E_{si} = \alpha t_2^{1/2} - \alpha (t_2 - 1)^{1/2} \quad 2.19$$

where,

E_{si} = soil evaporation on day i , mm

α = constant, $\text{mm d}^{-1/2}$

t_2 = time since the start of stage 2, d

Methods used to calculate t_2 following partial wetting and adjustment of soil evaporation on rain days are given in Richie (1972).

2.3.8 Crop Transpiration

(a) Potential Crop Transpiration

The potential crop transpiration on any day is given by;

$$T_{oi} = ET_{oi} * KC_{max} \quad 2.20$$

Where

T_{oi} = potential transpiration on day, i , mm

KC_{max} = ratio of potential to reference evapotranspiration at maximum cover.

(b) Actual Crop Transpiration

Actual plant transpiration per unit area of plant, assumed to occur at the potential rate whilst the root zone soil water content is between field capacity (F_c) and the easily available water capacity (EAWC). For excess water, it decreases linearly to zero when the root zone soil water content reaches saturation (SAT), for restricted water supply, it decreases linearly to permanent wilting point (PWP) and remains zero thereafter. This has been shown to be an acceptable simplification for irrigated condition (Ritchie, 1972).

Actual plant transpiration is then,

$$T_{ai} = T_{oi} * T_{ai} / T_{oi} \quad 2.21$$

Where,

T_{ai} = actual transpiration on day i , mm

T_{oi} = potential transpiration on day i , mm

A proportion of the rainfall will be readily available to the crop when rain falls on dry soil, even if the soil profile is at an otherwise limiting deficit. Therefore, a pool of 'available precipitation' is maintained in the soil that will be depleted preferentially, at the potential rate.

At the start of each day, any rainfall or irrigation on that day is added to the pool of available precipitation.

$$P'_i = P'_{i-1} + P_i + I_i \quad 2.22$$

During that day, all rainfall and irrigation are available at the potential rate. However, at the end of the day, the pool of available precipitation will have been depleted by an amount equal to the actual evapotranspiration. Also, a fraction of the day's

rainfall and irrigation would have been redistributed through the soil profile and will be available at the limited rate. Thus, at the end of the day,

$$P'_i = P'_{i-1} + \frac{P_i + I_i - ET_i}{2} \quad 2.23$$

Where

P'_i = available precipitation on day i, m

P_i = rainfall on day i, mm

I_i = irrigation on day i, mm

ET_i = actual evapotranspiration on day i, mm

The upper and lower limits of the pool of available precipitation are the easily available water capacity of the root zone and zero respectively.

Actual transpiration is adjusted for rain days and available precipitation by the following;

<i>Condition</i>	T_a	
$(T_a + P^l) \geq T_o$	T_o	
$(T_a + P^l) < T_o$	$T_a + P^l$	2.24

where

T_a = actual transpiration, mm

T_o = potential transpiration, mm

P^l = available precipitation, mm

2.3.9 Capillary Rise

The maximum contribution of groundwater to transpiration, T_{gw} , and evaporation, E_{gw} , are functions of the difference between the root depth (for transpiration) or soil surface (for evaporation) and the water table position and the hydraulic properties of the soil (Gardner, 1958).

— If the water table is below half of the root depth, ($Z > r/2$)

Then

$$e = 1000 \left[\frac{K}{\exp \left[c \left(Z_w - \frac{r}{2} \right) \right] - 1} \right] \quad 2.25$$

where

e = the potential contribution of groundwater to ET, mmd^{-1}

k = saturated hydraulic conductivity, md^{-1}

c = empirical parameter, m^{-1}

r = root depth, m

Z_w = depth to water table, m.

If the water table is above half the root depth, the soil is not limiting and, $e = 1000 \text{ mmd}^{-1}$.

The parameter c , is a soil texture/structure parameter that represents the relative importance of gravity and capillary forces during water movement in unsaturated soil.

Where movement is dominated by capillarity c which is small and difficult to estimate; but has been related to the hydraulic conductivity of the soil (Reynolds and Elrick, 1991);

$$c = 8.85K + 2.72 \quad 2.26$$

Where

c = empirical parameter, m^{-1}

K = saturated hydraulic conductivity, md^{-1} .

WaSim is very interactive and is user friendly, has minimal data requirements, good visualization of model calculations, a reasonable level of accuracy and flexibility in terms of the range of water management situations that can be simulated.

2.4 Review of Irrigation Systems

2.4.1 Overview of Drip Irrigation

Drip, or trickle irrigation, is a type of irrigation that slowly applies small amounts of water to parts of the plant root zone. Water is applied frequently, often daily, to maintain a favourable soil moisture condition and prevents moisture stress in the plant. In an effective irrigation system, water is distributed as close as possible to the plant root system.

When compared with overhead irrigation systems, drip irrigation accomplishes this process more efficiently. Furthermore, drip irrigation requires less water and less labour than other forms of irrigation (Benami and Ofen, 1993).

Advantages of Drip Irrigation System

- i. Smaller water sources can be used. Drip irrigation requires about half of the water needed by sprinkler or surface irrigation.
- ii. Lower operating pressures and flow rates result in reduced energy costs.
- iii. A higher degree of water control is attainable. Plant can be supplied with more precise amount of water.
- iv. Disease and insect damage is reduced because plant foliage stay dry.
- v. Labour and operating costs are usually reduced. Moreover, extensive automation is also a possibility.
- vi. Field operations may continue during the irrigation process because rows between plants remain dry.
- vii. There are fewer weed problems and less need for cultivation. Water is applied directly to the plant root zone. Therefore, water is not lost to weed growth in

unproductive areas, resulting in both better weed control and significant water savings.

- viii. Fertilizers can be applied through these types of systems. This can result in a reduction of fertilizer and fertilizer costs.
- ix. When compared with overhead sprinkler system, drip irrigation leads to less soil and wind erosion.
- x. Drip irrigation can be applied under a wide range of field conditions.

Disadvantages of Drip Irrigation System

- i. Drip irrigation is not adaptable for frost protection.
- ii. Rodent, insect, and human labour may cause damage to components and create potential sources of leaks.
- iii. When compared with sprinkler irrigation, water distribution in the soil is limited. Distribution of moisture should be a major design consideration.
- iv. Water filtration is a must because clean water is necessary to prevent clogging of the small emission holes found in this system.
- v. Drip irrigation is not suitable for closely planted crops such as alfalfa or cereal grains.

Components of Drip Irrigation System

A drip or trickle irrigation system includes the following six main components:

- i. **Delivery or Distribution System**
 - Mainline distribution to field, underground PVC pipe or above-ground PVC pipe or above-ground aluminium pipe.

- Sub-main or header line "Vinyl" hoses.
- Feeder tubes – Small Plastic tubes
- Drip lines – Turbulent flow drip tape or drip tape with internally attached emitters.

ii. **Filters**

- Sand – separate sand and heavy matter by swirling the water passing through them
- Media – most common; can filter poor quality water at high flow rates, but are expensive, heavy, and large
- Screen – most commonly used if the water source is relatively clean, but they are not capable of removing as much debris as a media filter
- Disk – possess the traits of both media and screen filters

iii. **Pressure Regulators**

- Fixed Outlet
- Adjustable Outlet

iv. **Valves or Gauges**

v. **Chemical Injectors**

- Positive displacement injectors – externally powered diaphragm, gear, piston, and roller pumps powered by gas, diesel, or electric; medium to high in cost
- Pressure differential injectors – pressurized mixing tanks and venture injectors; often simple in design

- Water – powered injectors – driven by the pressure of the irrigation system; piston and diaphragm types are available

vi. Controllers

- Manual
- Computer

Water Sources

Water sources may include municipally treated water, well water, pond or reservoir water, and ditch, stream, or river water. Clean water is especially important to successful drip irrigation. The small orifices found in the trickle emission devices can be clogged easily by physical and chemical contaminants found in the water (Elliot *et al.*, 2004). Groundwater from wells is generally of good quality and should be used when possible. Groundwater may contain sand or chemical precipitates. Surface water can be used but often contain bacteria, algae, and other aquatic life. Multistage filtration or chemical treatment of surface water is generally required (Lamont *et al.*, 2000). Usually, fast moving water contains higher levels of suspended particles, and reservoir or ponds contain a relatively small amount of these particles.

Maintenance

Line flushing is standard maintenance for drip irrigation systems. The amount of particle buildup in the lines will depend on the amount of suspended solids found within the water source (Keesen, 2003). Particle flushing of the lines will help to eliminate this buildup. A routine maintenance schedule of line flushing and inspection will aid in preventing emitter blockages. In addition, periodic flushing of the system during off season also helps eliminate blockages.

2.4.2 Sprinkler Irrigation

Sprinkler irrigation developed mainly after the Second World War with the introduction of light-weight, portable aluminum pipes (Benami and Ofen 1993). The first to be introduced on a large scale were systems with hand-moved laterals and impact-type, rotating sprinklers.

Sprinkler system comprises a network of pipes and sprinklers. The pipes convey water under pressure to the sprinkler inlets. At each sprinkler-nozzle the available pressure head is converted into a velocity head. The jets, ejected from the nozzles at a given initial velocity, break down into different-sized droplets which fall over an area around each sprinkler. In the absence of wind, or in light wind, the wetted area is circular in shape (Karmell, 1978).

The size of an area wetted by a single sprinkler and the distribution of water over it depends mainly on the operating pressure and the type, angle and diameter of the sprinkler-nozzle or nozzles. At a given pressure head, droplet size increases with nozzle diameter for a given nozzle, and droplet size increases as the pressure head drops. The larger droplets fall closer to the boundary of the wetted area while the finer droplets fall nearer the sprinkler. Other factors affecting the water distribution are: the driving mechanism, the speed of rotation, the height of the riser and the wind conditions.

Classification of Sprinkler Systems

Center-pivot sprinkler systems are classified according to pressure or nozzle type. Although there is no definite boundary between high, medium and low pressures, it is commonly accepted to have the following classifications:

- High-pressure systems have pressures of more than 50 KN/m^2 at the pivot,

- Medium-pressure systems have 35 to 50 KN/m^2 at the pivot.
- Low-pressure systems have less than 35 KN/m^2 at the pivot.

This is not as low as low-pressure systems. LEPA (Low-Energy Precision Application) and LDN (Low Drift Nozzle) can operate on pivot pressures of 15 to 25 KN/m^2 .

Nominal operating pressures at the sprinkler head or water-emitting devices are constant for a particular head:

- Nominal pressures for LEPA devices are 6 to 10 KN/m^2 .
- Spray nozzles, rotators and spinners are 10 to 25 KN/m^2 .
- Small impact heads with modified nozzles are 20 to 45 KN/m^2 .
- Small impact sprinklers with round nozzles are 30 to 60 KN/m^2 .
- Large impact sprinklers are 45 to 80 KN/m^2 .

The range for large impact sprinklers depends on nozzle type and size. Pressures needed at the pivot depend on pressure losses in the lateral due to friction losses and elevation differences along the lateral. To find the necessary pressure at the pivot work back from the last emitting device, add pressure losses or gains due to friction and elevation changes. Impact sprinklers usually operate at high to medium pressures, are installed on the lateral pipe, and irrigate over the crop. Spray and rotary nozzles operate at medium to low pressures, are installed on the lateral pipe or on drop tubes or pipes, and result in "down in the crop" irrigation. Irrigation down in the crop reduces evaporation and wind drift (Broner, 2002). There is a definite trend of higher application rates for lower pressures. Application rates can be as high as 254 to 355.6 mm per hour for spray nozzles and much higher for LEPA systems. A user should select a sprinkler package with an application rate that matches the soil's intake rate, satisfies crop water

requirements, and functions under local climatic conditions (wind). Proper tillage might overcome possible runoff problems (Brooner, 2002).

Sprinkler Distribution Pattern

The distribution pattern is a representation of the water depths measured in collecting cans spaced along the diameter of throw of a sprinkler. The distribution pattern, under no wind conditions, is more or less symmetrical about the sprinkler; the symmetry becomes distorted under strong wind conditions. Distribution patterns of sprinkler can become distorted if the operating pressure heads are too low or too high. If the pressure is too low, the wetted diameter is reduced and an excessive number of large droplet form. If too high, the diameter increases and a high percentage of droplets become too fine; this can result in excessive wind-drift and evaporation. In both cases there is impairment of the uniformity of water applications, even if the sprinklers are properly spaced. This highlights the importance of efficient design in order to ensure suitable pressure in all parts of the irrigated field.

Applications of Sprinkler Irrigation System

Although, they are normally designed to supply the irrigation requirements of the farms, sprinkler systems are also used for crop and soil cooling, frost protection, delaying fruit and bud development, controlling wind erosion, providing water for germinating seeds, application of agricultural chemicals, and land application of waste waters. Sprinkle irrigation is adaptable to many soil terrains. It can be successfully used to irrigate:

- i. Permeable soils that is difficult to irrigate using other application systems.

- ii. Lands with combinations of shallow soils and terrain that prevent proper land smoothening needed for other application systems.
- iii. Land having steep slopes and easily erodible soils.
- iv. Undulating terrain that would be too costly to smooth for use of other application systems.

However sprinkler system often leads to waste of scarce resource (water). Scattered application of water also promotes weeds growth around the planted crop. The sprinkler system is also not recommended under condition of high wind velocity as irrigation water is quickly drifted off the field where water application is desired.

The drip and sprinkler system of irrigation were used for this study based on the limited availability of water during the dry season. The two systems allows for conservative use of this limiteds natural resource.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Study Area

The research was carried out at the Teaching and Research farm of the Department of Agricultural Engineering, Federal University of Technology, Akure. Akure is located within the humid region of Nigeria at latitude $7^{\circ}16'N$; longitude $5^{\circ}13'N$. Akure has a population of about 483,300 out of the 140,003,542 inhabitant of Nigeria (Population census, March 2006 estimate). Akure has a land area of about 2,303 sq km and is situated within the Western upland area. The area has a general elevation of between 300 -700 meters above seas level. Local peaks rise to 1000 meters; other hill-like structures which are less prominent rise only a few hundred meters above the general elevations. The average annual population growth rate according to the 2004 estimate was 2.4%. Akure has been steadily increasing in population, putting pressure on the natural resources both land and water.

The climate in Akure is controlled primarily by the tropical continental air mass or North East Trade Winds and the tropical maritime TM air mass or South West Monsoon Wind. Rainfall is governed by the annual passage of the Inter-Tropical Convergence Zone (ITCZ), the meeting point of a dry northeastern low-pressure air mass and a moist southwestern high-pressure air mass. The northeastern movement of the ITCZ and the rain-bearing winds that accompany it mark the onset of the rainy season. Its southwestward movement and the accompanying harmattan winds mark the begging of the dry season. Annual rainfall and its reliability decrease from the south northwards. The pattern of rainfall is bimodal, the first peak occurring in June – July, and the second in

September, with dry spell in August (Adefolalu, 1972, 1973). The mean annual rainfall ranges between 1300mm to 1500mm. More than half of humid zone of Nigeria is covered by Pre-Cambrian basement complex (Rahaman, 1976 and Asiwaju Bello, 1999). It is principally composed of metamorphic and igneous materials. A gently rising ridge of quartzite occurs in the upstream part (north) of the area while pavement outcrops of biotite gneiss are found a few hundreds of meters downstream, (South of a perennial spring). There is a residual soil cover of dark reddish to light brown medium – grained lateritic material around the spring outlet. The spring falls within the fifth order of meinzers classification (Asiwaju – Bello, 1999 as reported in Alatisie, 2002). The soils are light textured, fine sandy loam to fine sandy clay loam. The soil is moderately well supplied organic matter and nutrients. Moisture holding capacity is moderately good. The soil of the environment is however subject to seasonal water logging for varying periods, but generally become dry during the dry seasons.

3.2 The Crop

A variety of grain amaranth (*Amaranthus cruentus*) was obtained from the National Institute of Horticulture (NIHORT), Ibadan to ensure the viability of the seeds used. Amaranth seeds used usually germinate quite readily and was planted shallow (i.e. at 1cm) depth. The variety used germinates within 3 – 4 days after planting and it is capable of attaining a height of up to 200 cm.

3.3 Hydrology and Water Supply at the Experimental Site

There is presence of a spring source which had been dammed about 200 m from the site of the experiment. Therefore, the water supply within the experimental site is mainly from two hand dug wells at the experimental site (WELL 1 and WELL 2) about

4.5m depth and located at the lower end farm site. The water source yield adequate water that could be supplied to the farm site provided pumping is carried out periodically. However, because of the difficulty in digging below the water level, the dug well does not penetrate the zone of saturation to a depth sufficient to produce a high yield. Analysis of water quality had been carried out by Alatisie (2002) to ascertain the amount of suspended and dissolved solids, the common cations, anions and other solutes. The results of water quality analysis are shown in Table 3.1, 3.2 and 3.3.

Table 3.1: Result of Physical Characteristics of the Well-Water on the Experimental Site

PARAMETERS	WELL 1	WELL 2
Colour	Colourless	Colourless
Odour	Odourless	Odourless
Taste	Inspid	Inspid
Conductivity (μmhos)	1.2×10^2	2.5×10^2
Turbidity (NTU)	ND	0.03

ND — Not detected.

Source: Alatisie, 2002

Table 3.2: Result of Chemical Properties of the Well-Water on the Experimental Site

PARAMETERS	WELL 1	WELL 2
pH	5.9	5.9
Alkalinity	264.3	101.67
Chloride	0.05	0.18
Hardness	14.0	6.0
Sulphate	ND	ND
Nitrate	ND	ND
Total solid	0.18	0.07
Total dissolved solid	0.07	0.004
Zinc	16.6	31.0
Iron	ND	ND
Magnesium	18.0	27.5
Copper	ND	ND
Sodium	60.1	83.0
Potassium	64.0	64.0
Calcium	11.3	12.2
Cadmium	ND	ND
Lead	ND	ND
Manganese	ND	ND

All parameters are measured in ppm unless otherwise stated.

Source: Alatisse, 2002.

Table 3.3: Result of Computed salinity of water from the wells at the Experimentation site

Parameters	Well 1	Well 2
Sodium Adsorption Ratio (SAR)	15.7	18.23
Exchangeable Sodium Percentage (ESP)	19.06	21.47
Cation Exchange Capacity (CEC)	0.05	0.17

Source: Alatisse, 2002

The parameters of the well water fall within the limit of tolerance for irrigation as recommended by FAO.

3.4 Treatments

Amaranthus cruentus seeds were planted on the field during dry and rainy seasons of 2004 -2006. These were repeated twice during the three year period of experiment.

3.4.1 Dry Season Experiment

There were a total of eighteen (18) treatments which were based on:

- i. Different levels of water application
- ii. Systems of irrigation
- iii. Phenological stages of the crop.

There were three levels of irrigation water treatment which were based on tensiometer readings adapted from James (1993) as shown in Table 3.4. There were two methods of irrigation: drip irrigation and mini- sprinklers (see Figure 4.1) and three phenological stages of the crop: emergence stage, vegetal/fruiting stage and the maturity stage.

Table 3.4: Irrigation Water Treatment on the Field

TREATMENT	DEFINITION
M1	Irrigation at 50 – 59 KPa of Tensiometer reading
M2	Irrigation of 60 – 69 KPa of Tensiometer reading
M3	Irrigation at 70 KPa and above

James (1993)



PLATE 1. Field grown *Amaranthus* under: (a) drip irrigation system at planting, (b) sprinkler irrigation system at planting, (c) drip irrigation plots at mid growing season, (d) sprinkler irrigation plots at the mid growing season

3.4.1.1 Experimental Design

A 50 m x 80 m portion of the farm site was ploughed and harrowed for effective seed bed formation and 10 m x 30 m part of the ploughed land was divided into eighteen (18) seed beds (micro-sprinkler plots) each 2.0 m long, 2.0 m wide and 0.15 m deep in and leaving 1m spacing between beds. Another 10.0 m x 12.0 m portion of the tilled land was formed into eighteen tied-ridges each 10.0 m x 0.4 m to form the drip plots. Eighteen (18) micro-sprinklers, one on each of the micro-sprinkler plots were installed at the centroid of the eighteen 2.00 m x 2.00 m plots. The micro-sprinkler are connected to separate supplies (0.04 m³ capacity reservoirs) placed adjacent to each of the beds at uniform pressure head of 2 m as shown in Figure 3.1.

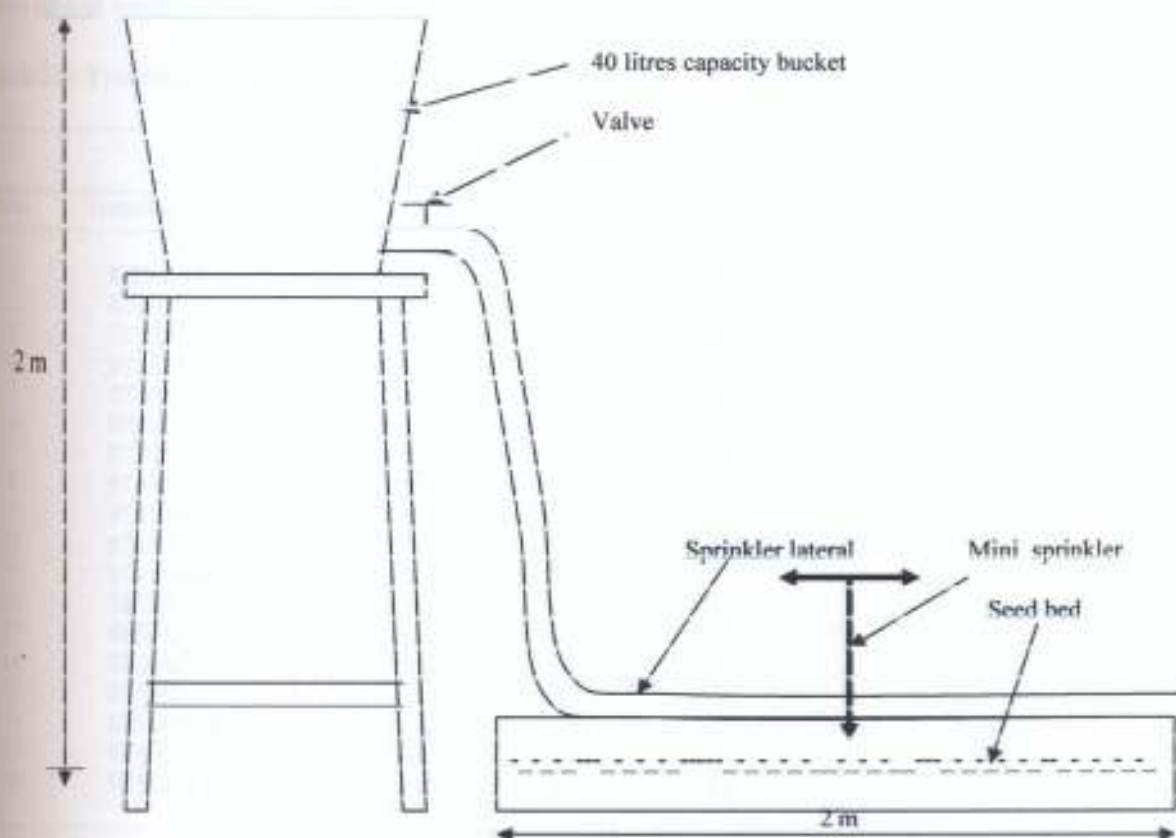


Figure 3.1 Layout of the sprinkler irrigation system in the field of experiment

The experiment was a $2 \times 3 \times 3$ combination of two (2) irrigation methods (Drip and Sprinkler systems), three (3) crop phenological stages(I, II, III) and three water stress levels (M1, M2, M3). A randomized complete block design (RCBD) was adopted as shown in Table 3.5. The treatments were replicated twice giving a total of 18 plots per irrigation system See Figure 3.2. Since two irrigation systems were used and therefore, there were altogether 36 plots. Water was applied daily at 6pm using the micro-sprinkler and drip irrigation systems during the first three weeks to maintain soil at field capacity. This is to prevent water stresses that are commonly experienced at the peak of the dry season. *Amaranthus* seeds were planted manually at a spacing of 20 cm between stands. Each plot was thinned at 2nd weeks after planting. Urea was applied about the rate of 45 KgNha⁻¹ based on soil research earlier carried out (Russel, 1980).

Table 3.5: Treatment Design

Plots	Treatment Code	Phenological Stages		
		I	II	III
1	ST1/DT1	M1	M1	M1
2	ST2/DT2	M1	M2	M2
3	ST3/DT3	M1	M2	M3
4	ST4/DT4	M2	M1	M2
5	ST5/DT5	M2	M2	M1
6	ST6/DT6	M2	M1	M3
7	ST7/DT7	M3	M1	M2
8	ST8/DT8	M3	M2	M1
9	ST9/DT9	M1	M3	M2
10	ST10/DT10	M1	M1	M1
11	ST11/DT11	M1	M2	M2
12	ST12/DT12	M1	M2	M3
13	ST13/DT13	M2	M1	M2
14	ST14/DT14	M2	M2	M1
15	ST15/DT15	M2	M1	M3
16	ST16/DT16	M3	M1	M2
17	ST17/DT17	M3	M2	M1
18	ST18/DT18	M1	M3	M2

M1 – well watered M2 – moderately stressed M3 – severely stressed

ST – Plots irrigated under sprinkler irrigation system DT – Plots irrigated under drip irrigation system

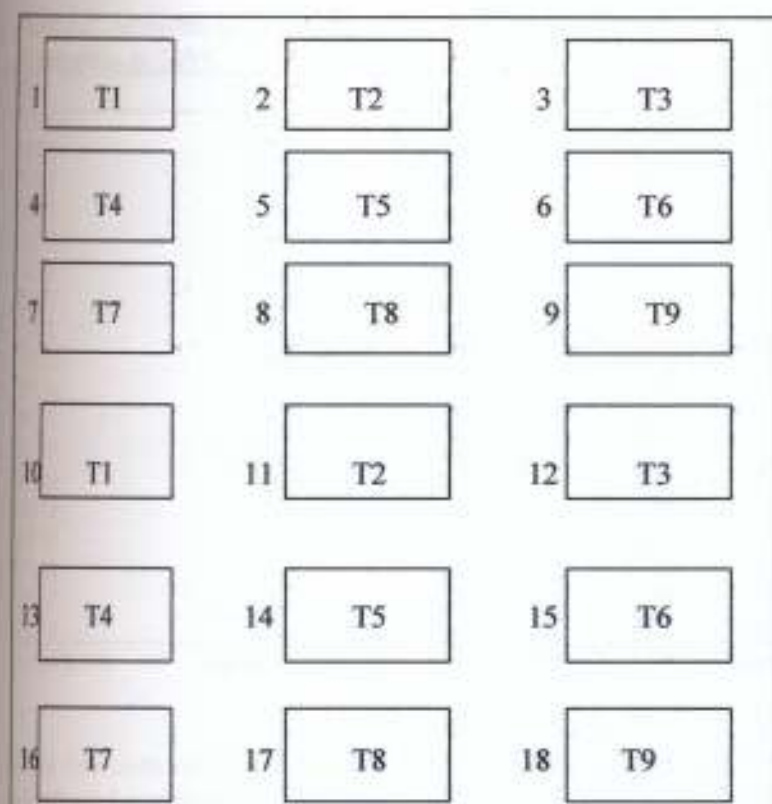


Figure 3.2. The layout of the irrigation plots

Table 3.6, 3.7, 3.8 and 3.9 below show the quantity of water that was added to each of the treatments during the two seasons of Amaranth production.

Table 3.6: Amounts of Moisture (mm) applied to sprinkler plots at different growth periods of Amaranthus in 2005.

Plots	I	II	III	Total
ST 1	144.0	150.0	140.0	434.0
ST 2	140.0	120.5	90.0	350.5
ST 3	125.2	150.0	60.0	335.2
ST 4	60.0	345.5	14.0	419.5
ST 5	101.0	82.4	30.0	213.4
ST 6	130.0	150.0	95.0	375.0
ST 7	100.0	80.5	24.0	204.5
ST 8	120.0	150.0	120.0	390.0
ST 9	25.0	150.0	40.0	215.0
ST 10	140.0	100.0	120.6	360.6
ST 11	105.0	150.0	25.0	280.0
ST 12	52.3	250.6	40.0	342.9
ST 13	45.0	310.5	20.0	375.5
ST 14	50.0	200.0	50.0	300.0
ST 15	40.0	206.4	46.5	292.9
ST 16	55.0	125.0	60.0	240.0
ST 17	135.0	125.0	120.0	380.0
ST 18	30.0	104.0	61.0	195.0

I – emergence II – vegetative/fruiting III – maturity ST – Sprinkler Treatment plot

Table 3.7: Amounts of Moisture (mm) applied to drip plots at different Growth periods of *Amaranthus* in 2005.

Pots	I	II	III	Total
DT 1	125.0	93.0	115.0	333.0
DT 2	115.0	90.5	85.0	290.5
DT 3	124.3	87.0	50.0	261.3
DT 4	95.0	47.5	80.0	222.5
DT 5	99.0	42.4	90.0	231.4
DT 6	115.0	40.0	35.0	290.0
DT 7	82.0	102.5	99.0	283.5
DT 8	80.0	147.0	73.0	300.0
DT 9	95.0	90.0	40.0	225.0
DT 10	86.0	42.0	110.6	238.6
DT 11	88.0	90.0	88.0	266.0
DT 12	96.3	45.6	50.0	191.9
DT 13	38.0	130.5	30.0	198.5
DT 14	40.0	110.0	40.0	190.0
DT 15	52.0	116.4	48.5	216.9
DT 16	65.0	105.0	62.0	232.0
DT 17	85.0	105.0	90.0	280.0
DT 18	38.0	95.0	54.0	187.0

I - emergence II - vegetative/fruiting III - maturity DT - Drip Treatment Plot

Table 3.8: Amounts of Moisture (mm) applied to sprinkler plots at different Growth periods of *Amaranthus* in 2006.

Pots	I	II	III	Total
ST 1	135.0	95.0	122.7	352.7
ST 2	130.0	90.5	98.0	318.5
ST 3	135.0	88.5	65.0	288.5
ST 4	120.0	60.5	110.0	290.5
ST 5	100.0	57.4	87.7	245.1
ST 6	110.6	67.0	52.4	230.0
ST 7	82.6	102.3	87.3	272.2
ST 8	85.0	128.5	93.5	307.0
ST 9	78.7	100.3	62.4	241.4
ST 10	96.0	81.5	129.6	307.1
ST 11	97.0	68.0	70.6	235.6
ST 12	83.5	60.2	51.0	194.7
ST 13	62.0	98.5	101.0	261.5
ST 14	32.6	74.2	70.6	187.4
ST 15	44.5	96.4	55.4	196.3
ST 16	35.0	75.2	97.0	207.2
ST 17	73.0	107.9	96.0	276.9
ST 18	72.0	62.3	53.3	187.6

I - emergence II - vegetative/fruiting III - maturity ST - Sprinkler Treatment plot

Table 3.9: Amounts of Moisture (mm) applied to drip plots at different Growth periods of *Amaranthus* in 2006.

Plot	I	II	III	Total
DT 1	100.0	90.0	125.6	315.6
DT 2	120.0	95.5	92.0	307.5
DT 3	128.0	85.5	45.0	258.5
DT 4	120.0	50.5	105.0	275.5
DT 5	105.0	48.4	80.7	234.1
DT 6	98.6	52.0	48.5	199.1
DT 7	87.5	98.3	95.3	281.1
DT 8	76.0	122.2	80.5	278.7
DT 9	76.4	64.0	42.4	172.8
DT 10	75.0	52.6	121.6	249.2
DT 11	77.0	58.0	75.6	210.6
DT 12	79.6	48.6	44.0	172.2
DT 13	50.3	90.5	108.0	248.8
DT 14	41.6	84.2	66.6	192.4
DT 15	33.5	106.4	47.4	187.3
DT 16	43.0	75.2	93.0	211.2
DT 17	50.0	97.9	86.0	233.9
DT 18	47.0	82.3	53.3	182.6
I – emergence	II – vegetative/fruiting		III – maturity	DT – Drip Treatment Plot

3.4.2 Wet Season Experiment

The 0.4 hectare experimental site was planted with *Amaranthus cruentus* during the rainy season following the traditional agricultural practices used by local farmers in the area. However, the plant was also thinned to have the same plant population as the experiment performed during the dry season.

3.5 MEASUREMENTS

3.5.1 Soil Measurements

Soil samples were collected from 0 – 15cm depth at six different locations on the experimental site to determine the soil physicochemical properties such as particle size distribution (i.e. sand, silt and clay contents), organic matter, soil pH, bulk density, percentage composition of nitrogen, phosphorus, potassium, calcium and magnesium using standard procedures.

Soil Bulk Density

Soil bulk density (gcm^{-3}) was determined by the core method (Blake and Hartage, 1986) using a 10.0cm long by 8.3cm diameter cylindrical metal core. Samples were dried at 105°C for 24 hours in a forced air oven, weighed and density calculated as sample dry weight (g) divided by sample volume (cm^3).

Soil Micro and Major Elements

The percentage nitrogen content of the soil was determined using the digestion method as described by Jackson (1962). Exchangeable potassium, calcium and magnesium were extracted using ammonium acetate (Jackson, 1962) and the individual cations of Ca^{2+} , Mg^{2+} , K^{+} were measured by Atomic Absorption Spectrometer (AAS) and flame photometer.

Soil Moisture Content and Hydraulic Charge

Soil moisture content were determined in each of the plot once a week at 10, 20, 30, 40, and 50cm soil depth in every plot using gravimetric method (Hillel, 1998). Hydraulic charge i.e. soil tension was determined using mercury tensiometer that effectively measures up to a maximum of 80 cbs. Tensiometers were installed at depths 10, 20, 30, 40, and 50cm on plots whose method of water application is based on tensiometer reading. Owing to limited number available, a few others were installed randomly on some other plots.

3.5.2 Micro-climate

Air Temperature and Air Relative Humidity within the crop canopy were monitored throughout the growing season. Meteorological data such as solar radiation, Maximum and Minimum Air Temperature, Maximum and Minimum Relative Humidity, Wind Speed and

Sunshine Hours during the growing season were obtained from a Meteorology station under the Department of Meteorology, located within the campus and about 200 m away from the site. A ten-year meteorological record was obtained from the Meteorology station and also from the Federal Ministry of Aviation, Akure for the estimation of Potential Evapotranspiration using Penman, Modified Penman-Monteith equation, Blaney-Morin Model and Thornthwaith approach. Raingauges were installed within the experimental field to measure Precipitations during the two seasons of experiment.

3.5.3 Measurement of Runoff

A runoff-meter was installed within the experimental field. The installed Runoff-meter is shown in Figure 4.4. The runoff-meter was automated and experiments were performed to calibrate the Runoff-meter that was developed during the study.

Development of an Automatic Runoff-meter

Overland flow (runoff) from the field was measured with the aid of a 1.00 m x 1.00 m x 30.00 cm digital runoff meter. The runoff meter was made from metal sheet plate (18 gauge) opened at both ends. The device permits the flow of water within the catchments area to a runoff collector (60 cm x 60 cm x 40 cm in dimension) through a 2.54 cm galvanized steel pipe (see Figure 4.4). The cover and the base of the runoff collector were tightly sealed to prevent leakage of stored runoff from the tank. The digital sensing device employs the use of a resistive sensor. The sensing device was connected via pins to the digital display (ICT7106). The sensor detected changes in water level in the collector pan and the analog quality was converted to a digital display.

Calibration curves based on linear regression equation are shown in Figure 4.5 a while Figure 4.5 b showed calibration curve based on a quadratic model. A summary of



the calibration statistics is presented in Table 3.10. Results showed that the sensor readings are almost linear with the manual observation with $R^2 > 0.94$ in both cases. The quadratic calibration curve showed a better fit with $R^2 > 0.98$. All the models are highly significant at $P < 0.0001$. Although linear fit showed high accuracy with their R^2 not statistically different from that of the quadratic model, the values of standard error (0.150 mm) is higher making it less acceptable to the non-linear equation which has SE of 0.079 mm. Linear model starting from the origin is theoretically favoured since no negative runoff depth was observed. Given the foregoing, calibration curve based of the quadratic model was adjudged best and then adopted for this electronic water level sensor.

Table 3.10: Summary of calibration statistics

S/N	Model	Overall Statistics		
		R^2	Standard error	Sig. level
1	Linear	0.9448	0.150	< 0.0001
2	Quadratic	0.9869	0.079	< 0.0001

R^2 is coefficient of determination; SE is standard error of estimates

The performance was further validated by measuring runoff simultaneously with the sensor and manually for the months of March and April. Runoff obtained from digital sensor conversion using the quadratic calibration equation were very similar to values from manual measurement as shown Figures 3.3a and 3.3b, for March and April, respectively. The variation between both the manual and digital datasets was quite small. MBE for the month of March and April were 0.19 mm and 0.15 mm, respectively and the correlation coefficients were very high ($R > 0.97$) for both datasets.



PLATE 2. Field Arrangements of Tensiometer, Runoff Meter and Pan Evaporimeter

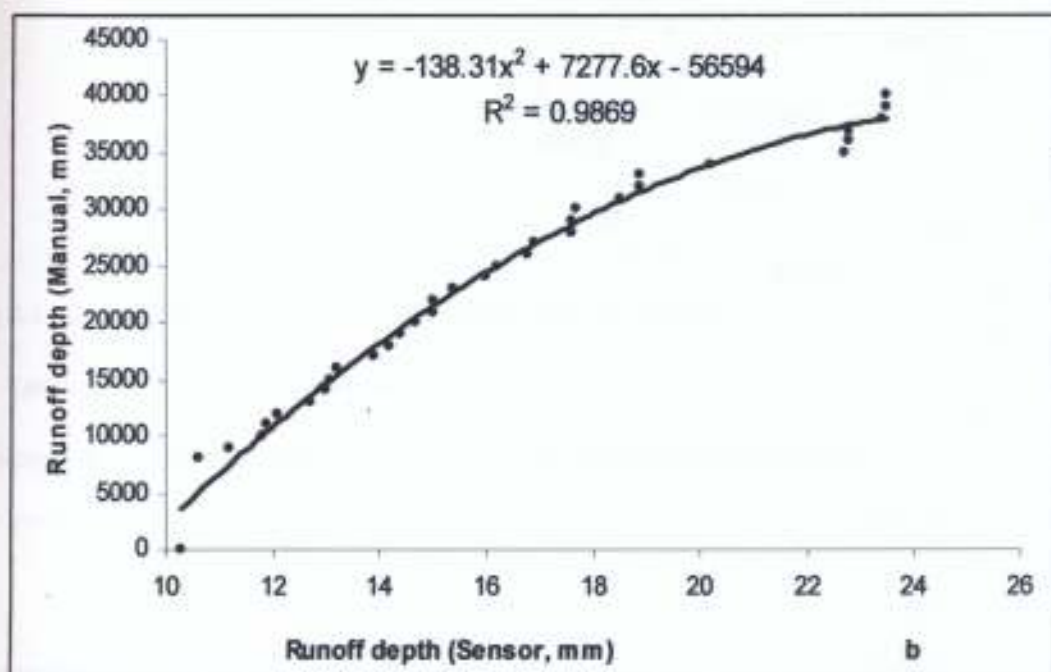
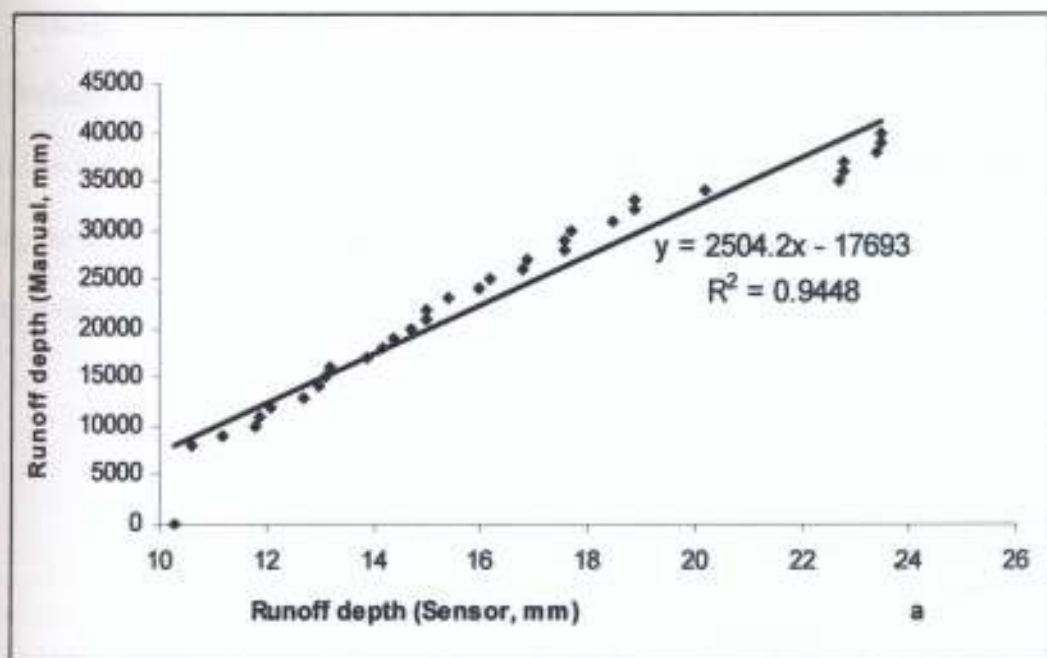


Figure 3.3: Calibration curves for digital sensor (a) Linear fitted (solid line) and (b) Quadratic fitted.

3.5.4 Drainage

Drainage was assumed negligible during dry season experiments, but Darcy law was used to estimate the drainage below the root zone from an earlier studies and following the method used by Hulugale and Lal (1978). A cross-section of the installed weighing lysimeter and its dimensions is shown in Figure 3.4.

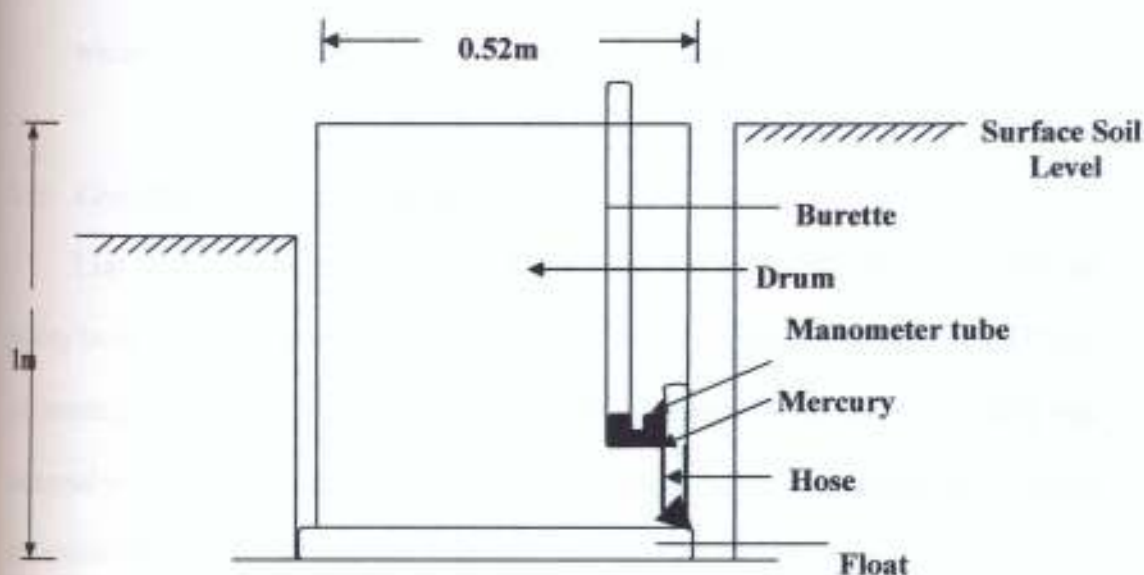


Figure 3.4. A cross-section of the installed hydraulic lysimeter

3.5.5 Estimation of Consumptive use

Consumptive use of the crop was estimated using the water balance equation:

$$ET = P + I \pm \Delta S \pm D \pm R \quad 3.1$$

where:

ET – consumptive use

P – precipitation i.e. rainfall

I – water applied by irrigation

ΔS – change in soil water storage

D – drainage

R – runoff

All terms are expressed in mm

Crop factor (K_c) was determined from the relationship below:

$$K_c = \frac{ET_{max}}{ET_p} \quad 3.2$$

where ET_{max} = Maximum Evapotranspiration (mm)

ET_p = Potential Evapotranspiration (mm)

3.5.6 Crop Biometric Measurements

Leaf area index (LAI), number of leaves and plant height were measured on weekly basis beginning from the 29 DOY of year to the maturity stage (i.e. 77 DOY). A representative plant was selected weekly for the measurement of LAI. Leaf area was measured with the aid of leaf area meter. Leaf area index according to Gong *et al.* (1995) was estimated from the relationship below:

$$\text{Leaf area index (LAI)} = \frac{\text{Area of leaf per plant}}{\text{Area of soil covered per plant}} \quad 3.3$$

3.5.7 Amaranthus Yield

Harvestable yields of *Amaranthus Cruentus* were determined on weekly interval starting from the 56 DOY to maturity. Fresh vegetables were harvested from representative plants in each of the treatment plots. The leaves stem and roots were carefully detached for ease of measurement of fresh biomass. The weight of the harvested fresh biomass was determined from an electronic weighing device that could measure up

to 0.01 level of accuracy. The weighted material was thereafter transferred into an oven and dried at 70°C until a constant weight is achieved to obtain dry matter yield.

3.5.7.1 ET – Yield Functions

The consumptive use of each treatment at various stages of the crop was estimated using the Water Balance Equation. Water production functions were established using the following expression:

$$ET = f(Y) \quad 3.4$$

$$\frac{ET_{\max}}{ET_{\min}} = f\left(\frac{Y_{\max}}{Y_{\min}}\right) \quad 3.5$$

$$\sum ET = f(Y^i) \quad 3.6$$

Where

Y is the yield (tha⁻¹)

i is the stage coefficient

ET_{max} is the maximum consumptive water use (mm/day)

ET_{min} is the minimum consumptive use of water (mm/day)

3.6 Data Analysis

Climatic, soil and crop data were subjected to statistical analysis to determine the mean, standard deviation, coefficient of variation, linear and non-linear regressions using SPSS, Solver, MS Excel and Sigma plot software packages.

3.7 DESIGN OF IRRIGATION SYSTEMS

3.7.1 NET WATER REQUIREMENT

Table 3.11 shows the soil moisture content at successive depths in the root zone before the start of experiment

Table 3.11: Soil Moisture (cm) in the Root Zone before Irrigation

Depth (cm)	Moisture stored (cm) at each layer of soil
0 – 10	0.79
10 – 20	0.70
20 – 30	0.83
30 – 40	0.84
40 – 50	0.48
50 – 60	0.88

Effective moisture content in the root zone is 4.88 cm/m depth of soil. The soil moisture content of the site at field capacity and permanent wilting point were determined to be 20.54 g/100g and 8.43 g/100g of soil respectively. The depth of root zone (DRZ) of *Amaranthus Cruentus* on average is 30 cm depth from soil surface and the Maximum allowable deficit for the crop is 50% (0.5).

$$\begin{aligned}
 \therefore \text{The design NWR} &= (\text{FC-PWP}) \times \text{BD} \times \text{DRZ} \times \text{MAD} & 3.7 \\
 &= (20.54 - 8.43) \times 1.27 \times 10 \times 0.3 \times 0.5 \\
 &= 23.07 \text{ mm} \\
 &= 2.31 \text{ cm}
 \end{aligned}$$

Irrigation frequency was obtained from the relationship:

$$\text{Irrigation Interval} = \frac{\text{Net Water Requirement}}{\text{Peak Consumption Use Rate}} \quad 3.8$$

Since the peak consumptive use rate from Penman-Monteith estimate is 4.05 mm/day, irrigation interval is therefore:

$$\frac{2.31}{4.05} = 0.57 \approx \text{twice per day at the peak of the dry season}$$

Phenological stages were determined by visual observation when more than 50% of the crop appears to have reached the same growth stage.

3.7.2 Design of Sprinkler System

Determination of precipitation under sprinkler system

Materials used include the followings:

- Measuring cylinder
- Stopwatch
- Catch can ($3 \times 10^{-3} \text{ m}^2$)s
- Micro-sprinkler
- Reservoir (0.04 m^3 Capacity)
- Scaffold (2m high)

Sixteen (16) catch cans were placed at an equidistance of 0.3cm on the vegetable beds. The distance of cans from micro-sprinkler which was placed at the centroid of the bed is shown in Table 3.12.

Table 3.12: Depth of water (mm) in catch cans from sprinkler

	0.87	0.66	0.66	0.86
	0.61	0.28	0.28	0.63
	0.60	0.24	0.29	0.65
	0.80	0.59	0.64	0.89

S - Sprinkler

After placing the catch cans in the predetermined positions, the control valves of the reservoirs were open to allow flow to the sprinkler heads which sprinkles water into the catch cans. The flow was allowed for one hour into the catch cans and recorded. Application rates (A) from sprinkler into the catch cans were also determined using the following relationship:

$$\text{Application rate (A)} = \frac{KQ}{a}$$

3.9

Where, A = Application rate mm/hr

Q = Sprinkler discharge, l/min

a = Wetted area of sprinkler; m² (surface area of can) ($3.12 \times 10^{-3} \text{ m}^2$)

K = Unit constant (K=60.0 for A in mm/hr, Q in l/min and a in m²)

The uniformity coefficient of the sprinkler system was also determined to ascertain the efficiency of the sprinkler irrigation system using the Christiansen's formula (Michael, 1998).

$$C_s = 100 \left[1 - \frac{\sum x}{mn} \right] \quad 3.10$$

Application rate for all the observation points and the coefficient of uniformity is shown in Table 3.13.

Table 3.13: Application rate at observation points

Catch cans	Flow rate ($\times 10^{-4}$)	Application rate (mm/hr)
A ₁	4.00	7.69 $\pm$ 1.44
A ₇	5.52	10.61 $\pm$ 1.48
A ₃	4.70	9.03 $\pm$ 0.10
A ₄	4.67	8.98 $\pm$ 0.15
B ₁	4.37	8.40 $\pm$ 0.73
B ₇	4.00	7.69 $\pm$ 1.44
B ₃	5.68	10.92 $\pm$ 1.79
B ₄	4.64	8.92 $\pm$ 0.21
C ₁	4.41	8.48 $\pm$ 0.65
C ₇	5.04	9.70 $\pm$ 0.57
C ₃	4.26	8.20 $\pm$ 0.93
C ₄	3.63	6.98 $\pm$ 2.15
D ₁	5.45	10.48 $\pm$ 1.35
D ₇	5.77	11.10 $\pm$ 1.97
D ₃	5.44	10.46 $\pm$ 1.33
D ₄	4.38	8.42 $\pm$ 0.71

$$\text{Mean of application rate} = \frac{146.06}{16} = 9.13$$

$$C_s = 100 \left[1 - \frac{17.00}{146.06} \right]$$

$$C_s = 100 [0.884] = 88.4\%$$

3.7.3 Design of the Drip Irrigation System

Emitter Selection and emitter uniformity coefficient

The selected emitter type is the point source emitter. This selection was made based on the crop to be irrigated (*Amaranthus Cruentus*). The point source emitter is equipped with an independent pressure compensating mechanism that ensures even distribution regardless of the difficult topographic situation and varying water pressure. The coefficient of variation for good point source emitter is <0.05 (James; 1993). The

coefficient of variation for the selected point source emitter is 0.03. The pressure at which the lateral would operate so that the emitter could deliver the specified amount of water was obtained from the manufacturers chart and the value was 0.96 m

The pressure variation in the lateral is normally kept within the range of the emission uniformity (ASAE, 1985). Emission uniformity of the drip system was estimated from the following relationship.

$$E_n = 100 \left(1.0 - \frac{1.27}{\sqrt{N_e}} C_v \right) \frac{Q_{\min}}{Q_{ave}} \quad 3.11$$

Where E_n = the design emission uniformity in percent;

N_e = number of point source emitters per emission point (1)

C_v = the manufacturers coefficient of variation for point source emitters

$Q_{\min}$ = the minimum emitter discharge rate in the system (l/h).

Q_{ave} = the average or design emitter discharge rate (l/h).

$$\begin{aligned} E_n &= 100 \left(1.0 - \frac{1.27}{\sqrt{1}} (0.03) \right) \frac{1.92}{1.96} \\ &= 0.9619 \times 0.979 \\ &= 0.94 = 94\% \end{aligned}$$

The emission uniformity coefficient is high. The system is efficient enough for irrigation.

The volume of water required per plant can therefore be estimated as follows:

$$\text{Volume of water / plant} = \frac{ET_p \times \text{area / crop}}{E_n} \quad 3.12$$

ET_p = Peak evapotranspiration of the month of February

Since area/crop was estimated to be = 0.12 m²

$$\therefore \text{Volume of water/plant} = \frac{3.85 \times 0.12}{0.94}$$

$$= 0.0005 \text{ m}^3/\text{day}$$

$$= 0.5 \text{ lit/day}$$

Design of Laterals

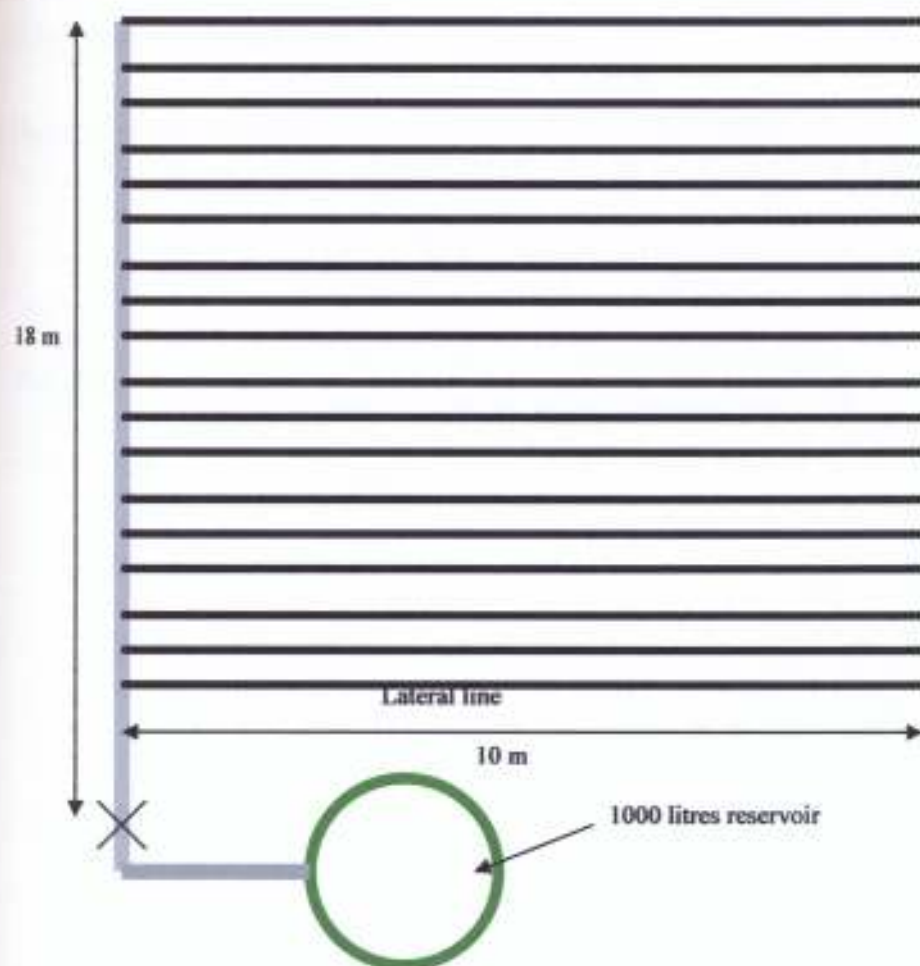


Figure. 3.5 Layout of drip irrigation system

Number of laterals = 18

Length of each lateral = 10 m

The slope of the lateral line = 0.01 downslope

There were ten (10) emitters spaced equally each lateral line.

The total number of emitters = 180

Amaranthus spacing = 20 cm x 20 cm apart

Reservoir capacity = 1000 litres

Time to completely discharge reservoir content (1000 litres) through emitters = 4 hrs

Discharge per emitter per hour = 1.389 l/hr = 0.0014 m³/s

The operating pressure head = 3 m

$$\begin{aligned}\text{where application rate (mm/hr)} &= \frac{\text{emitter discharge (l/hr)}}{\text{spacing between laterals (m)} \times \text{spacing on lateral (m)}} & 3.13 \\ &= \frac{1.389}{1 \times 1} = 1.389 \text{ mm/hr}\end{aligned}$$

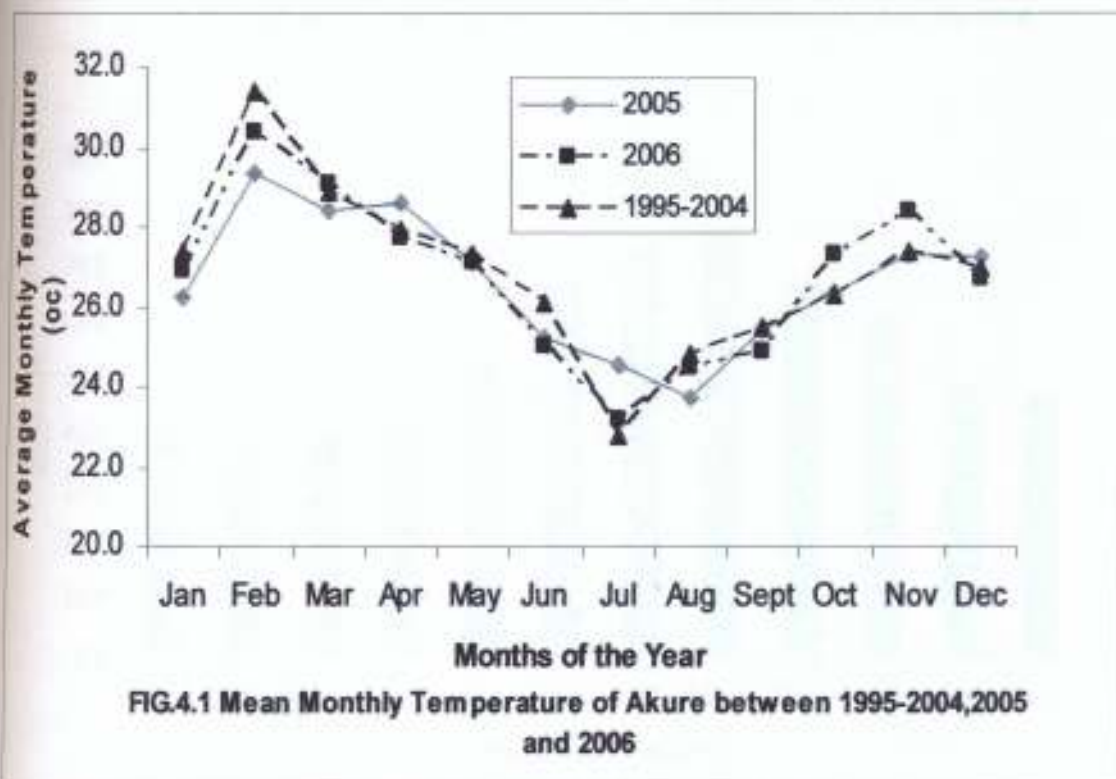
$$\begin{aligned}\text{Duration of irrigation} &= \frac{\text{litre / plant / day} \times \text{design interval (days)}}{\text{emitter discharge (l/hr)} \times \text{emitter per plant}} & 3.14 \\ &= \frac{0.5 \times 1}{1.389} = 0.36 \text{ hr} \\ &= 22 \text{ minutes}\end{aligned}$$

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1 Climate

Figure 4.1 shows the mean monthly temperature of the study area over ten years data analysis, and the 2005 and 2006 periods of experiment. The highest mean temperature of 29.3°C and lowest mean of 23°C occurred during 2005. Also, the highest mean air temperature of 30.4°C and the lowest minimum air temperature of 23°C were observed in 2006. The highest mean air temperature and the lowest mean air temperature were observed during the months of February and July respectively. An R^2 value of 0.07 was observed between minimum relative humidity and rainfall (Figure 4.2).



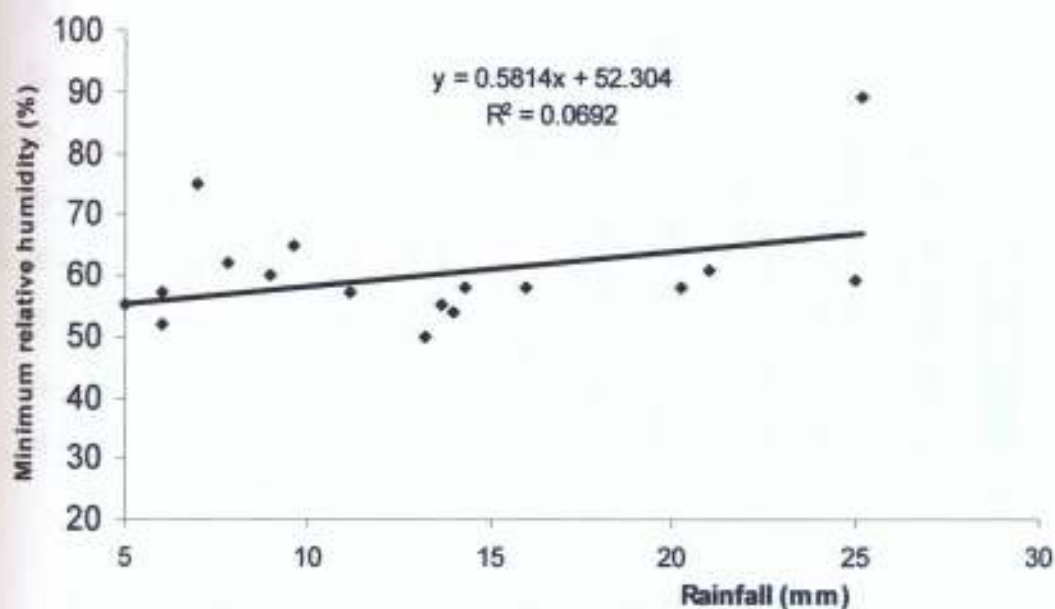


FIG. 4.2 Minimum Relative Humidity-Rainfall Relationship for 2006

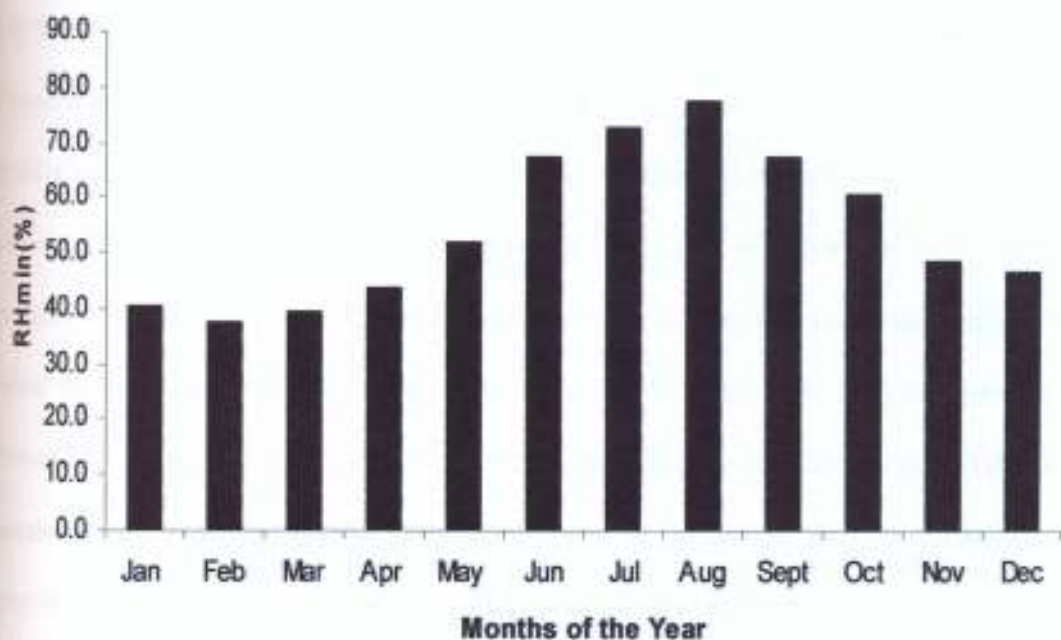


FIG. 4.3 Minimum Relative Humidity of site during 2005

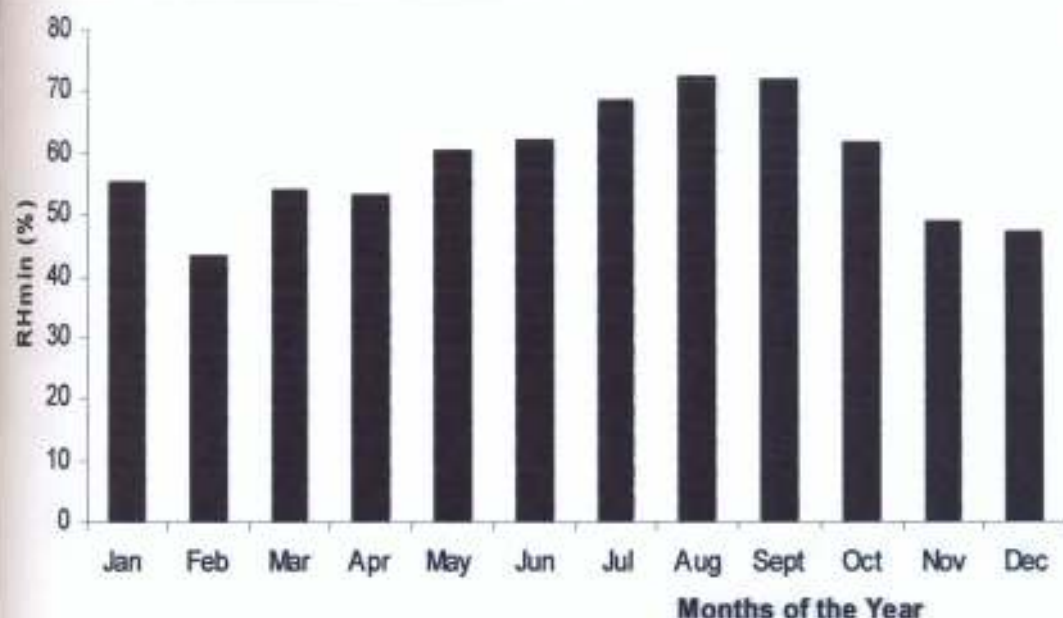


FIG. 4.4 Minimum Relative Humidity of site during 2006

Relative humidity in Akure is very high, more than 90% during the night and early morning falling to between 60% and 80% in the afternoon (Figures 4.3 and 4.4).

Minimum relative humidity of between 37 and 77% was observed on the site during the period of experiment while maximum relative humidity ranged between 93 and 100%.

Analysis of rainfall data showed a higher monthly average of rainfalls during 2006 when compared with storm events of 2005 (Figures 4.5 – 4.6). Rainfall was characterized by gradual rise from the month of January with a value of 10.2 mm to its peak in June with a value of 210.4 mm. A drop in rainfall occurrence was observed between July and August (commonly called August break). Thereafter, it rose to its second peak in the month of September and this marked the second modal rainfall after which the dry season begins. A sharp drop in the magnitude of rainfall was noticed in the month of August. Thereafter, it rises to its second peak in the month of October and then recedes to the minimum in November and December.

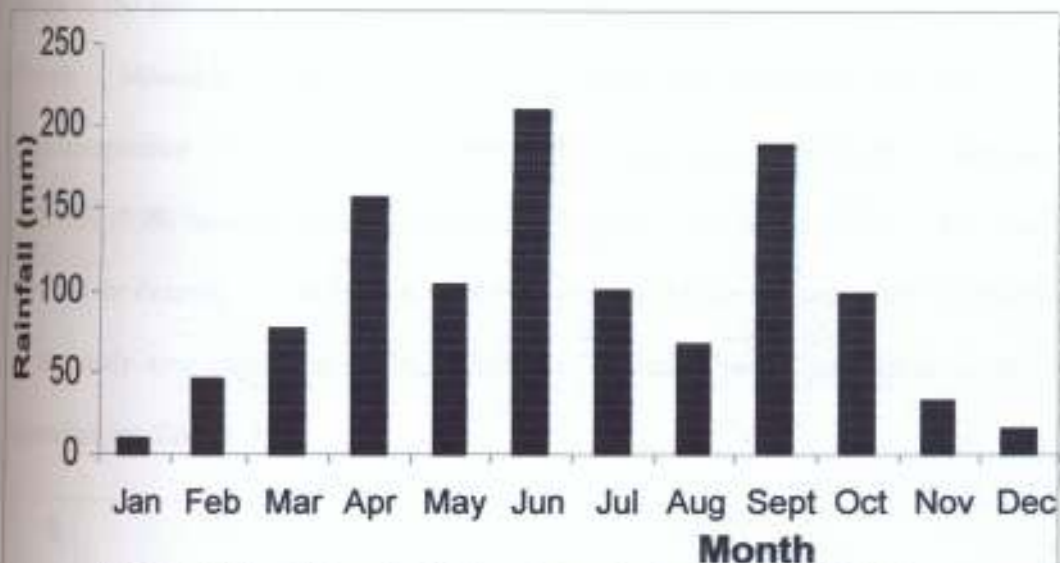


FIG.4.5 Monthly rainfall regime in the year 2005 at FUTA,Nigeria

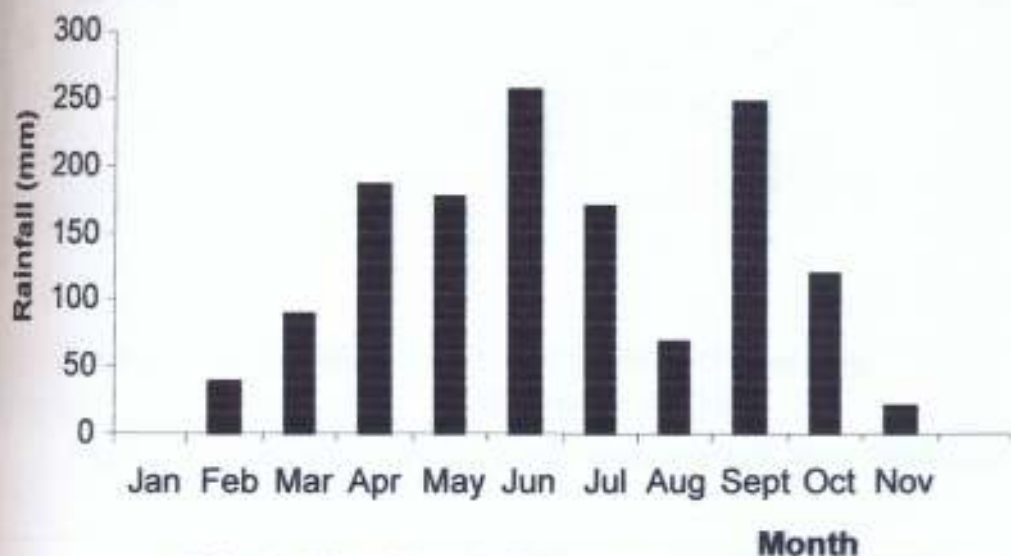
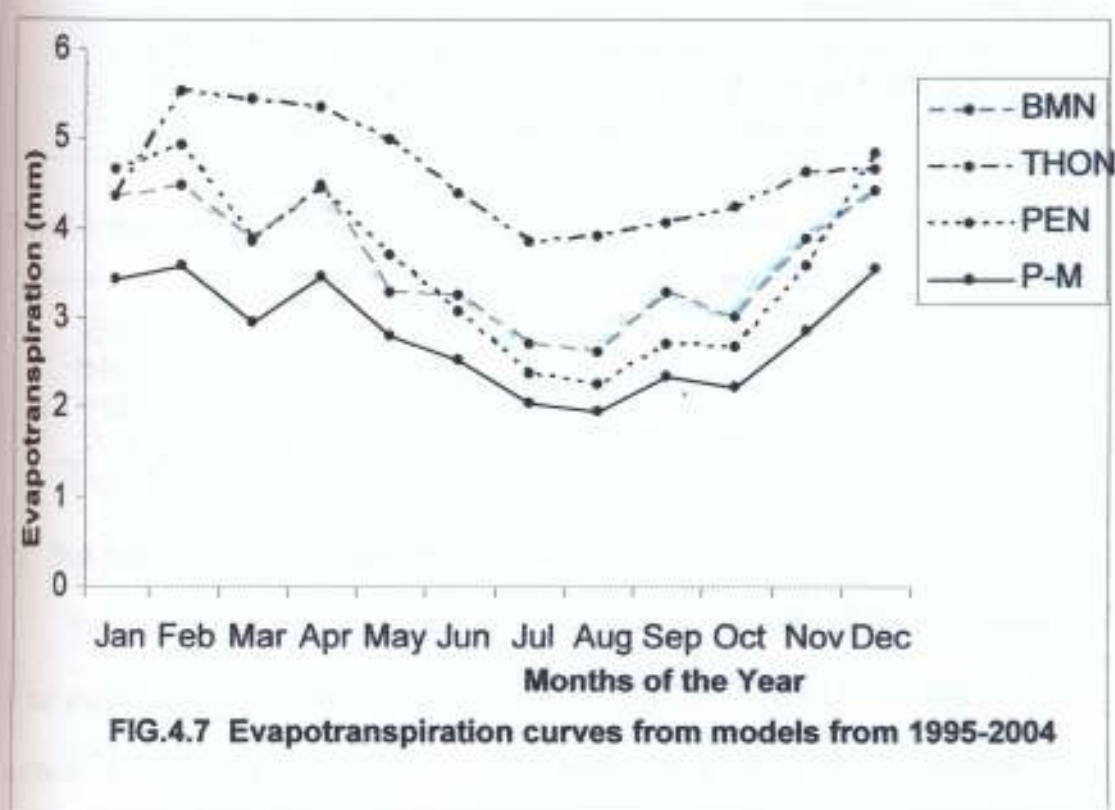


FIG.4.6 Monthly rainfall regime in the year 2006 at FUTA,Nigeria

Figure 4.7 shows the potential evapotranspiration for the five years duration as determined using the Blaney-Morin (B-M) model, Thonthwaite (THON), Penman (PEN)

and the modified FAO- Penman – Monteith (P-M) ET models (Brown et al., 2001). Similarly, the reference evapotranspiration for the study periods were estimated from Penman – Monteith model is presented in Figure 4.8. Statistical analyses of the evapotranspiration (ET) values from the models used showed a highest correlation coefficient (0.99) between the Penman and the Penman – Monteith models. This goes to show that the Penman – Monteith model is very reliable for the estimation of ET potential for the study area regardless of the number of climatic variables considered for its estimation (see Table 6.1).



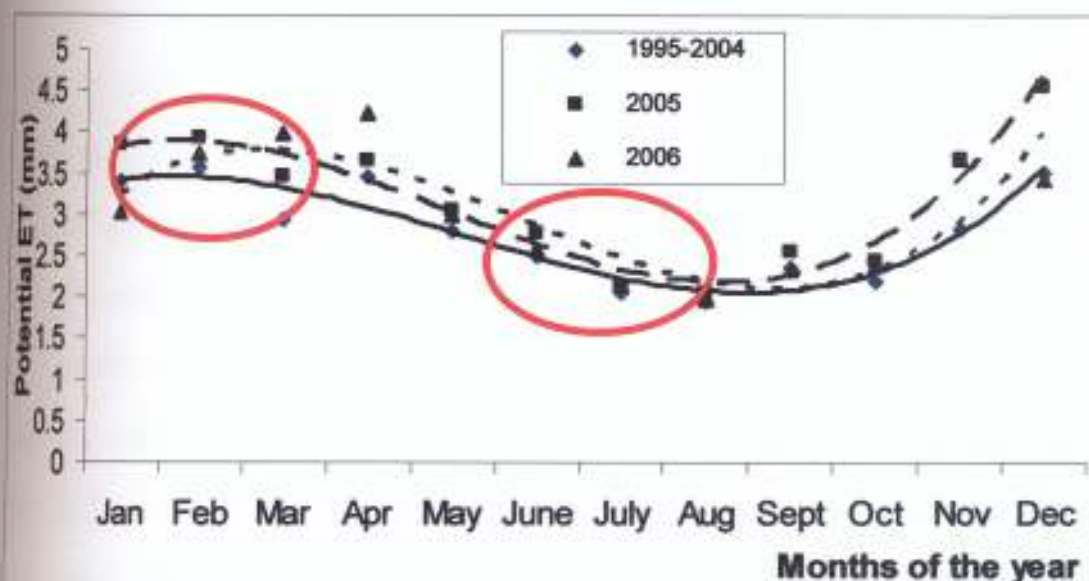


FIG. 4.8 Potential evapotranspiration of the study site between 1999-2004, and in 2005 and 2006 periods of experiment using the Penman monteith model

Table 4.1: Results of Correlation among Potential ET Models

	<i>BNM</i>	<i>THON</i>	<i>PEN</i>	<i>P-M</i>
<i>BNM</i>	1			
<i>THON</i>	0.63572	1		
<i>PEN</i>	0.949537	0.713326	1	
<i>P-M</i>	0.953711	0.70259	0.992994	1

Note: *BMN*, *THON*, *PEN* and *P-M* are as defined above

4.2 Soil Properties at the Experimental Site

Presented in Tables 4.2 and 4.3 are the descriptive statistics of the soil properties at the experimental site. The sprinkler irrigation site has a mean soil texture (USDA method) of sandy clay loam in the top soil which forms mainly the agricultural layer required for the cultivation of most vegetables. Minimum and maximum organic carbon content of 0.86% and 1.52% respectively were observed within the top 0.3m depth of soil. The top soil average carbon content falls within the range (0.6-1.2%) given by Young (1976) as desirable for tropical crop production. The high organic carbon content

may be due to the fact that the sampled points were not frequently cultivated and primary carbon production is high. The organic matter accumulation may also be due to continuous plant growth in and around the site of experiment. This is in agreement with the work done by Nelson *et al.*, (1994).

The soil pH varies from acidic to neutral on the surface soil (5.7-7.1). The mean of the pH falls within the slightly acidic range (6.4) and is below the average value of 6.5 which was considered ideal for good availability of plant nutrients in the mineral soils (Foth and Ellis, 1997). The bulk density of the experimental site ranges from 1.20 – 1.50 gcm^{-3} within the first 0.3 m depth of soil. This is below the critical value of 2.1 gcm^{-3} , beyond which plant growth is severely limited.

Table 4.2 Descriptive statistics of soil properties at the sprinkler irrigation plots

Plots	Sand (%)	Clay (%)	Silt (%)	Organic carbon	N (%)	P (mg/kg)	K (meq/100g)	Ca (meq/100g)	Mg (meq/100g)	Na (meq/100g)
1	60	28	12	1.50	0.20	9.55	0.58	4.20	4.10	0.20
2	62	26	12	1.48	0.16	10.15	0.61	8.00	5.00	0.21
3	63	26	11	1.36	0.18	6.29	0.52	2.90	2.00	0.19
4	64	22	14	1.52	0.14	7.82	0.49	2.95	3.10	0.24
5	62	24	14	1.46	0.21	7.90	0.52	3.60	2.50	0.23
6	63	26	11	1.28	0.19	8.42	0.54	4.00	4.10	0.22
7	64	24	12	1.33	0.15	9.23	0.47	6.20	4.00	0.20
8	60	27	13	1.43	0.13	10.05	0.50	5.40	3.80	0.18
9	63	25	12	1.36	0.14	10.12	0.48	5.30	3.40	0.22
10	61	24	15	1.51	0.17	9.67	0.58	3.00	2.60	0.19
11	62	24	14	1.37	0.18	9.04	0.60	6.10	2.50	0.24
12	65	25	10	1.44	0.13	8.56	0.55	4.80	2.20	0.23
13	69	23	8	0.86	0.12	9.15	0.61	8.10	3.10	0.31
14	66	24	10	0.90	0.13	10.18	0.59	7.60	3.60	0.25
15	61	25	14	0.96	0.16	8.77	0.46	6.30	4.30	0.26
16	64	25	11	1.15	0.18	8.74	0.52	5.70	4.70	0.24
17	65	23	12	1.17	0.14	8.39	0.53	6.00	4.40	0.18
18	64	24	12	1.26	0.15	9.48	0.49	6.10	3.80	0.20
Min	60	22	8	0.86	0.12	6.29	0.46	2.90	2.00	0.19
Max	69	28	15	1.52	0.21	10.18	0.61	8.10	5.0	0.31
Mean	63.2	24.	12.1	1.30	0.2	8.97	0.5	5.30	3.50	0.20
STD	224	1.4	1.76	0.22	0.03	1.13	0.05	1.74	0.95	0.04
Skewne	0.78	0.4	0.25	-1.84	-1.30	-2.71	-3.28	-0.04	-0.44	-1.33
Kurtosi	1.29	0.2	0.22	-0.02	-0.91	1.59	-1.29	-0.86	-101	1.68

The soils in the drip irrigation plot have a high sand content with mean values of about 70% in the topsoil. Like the sand content, the clay content, though high, does not change so much from one point to the other around the sampled points (21%), indicating similar soil textural classification within the 0 -30 cm soil depth. The soil has a texture of sandy clay loam. The carbon content gave mean value of 1.14%. Comparison of soil data

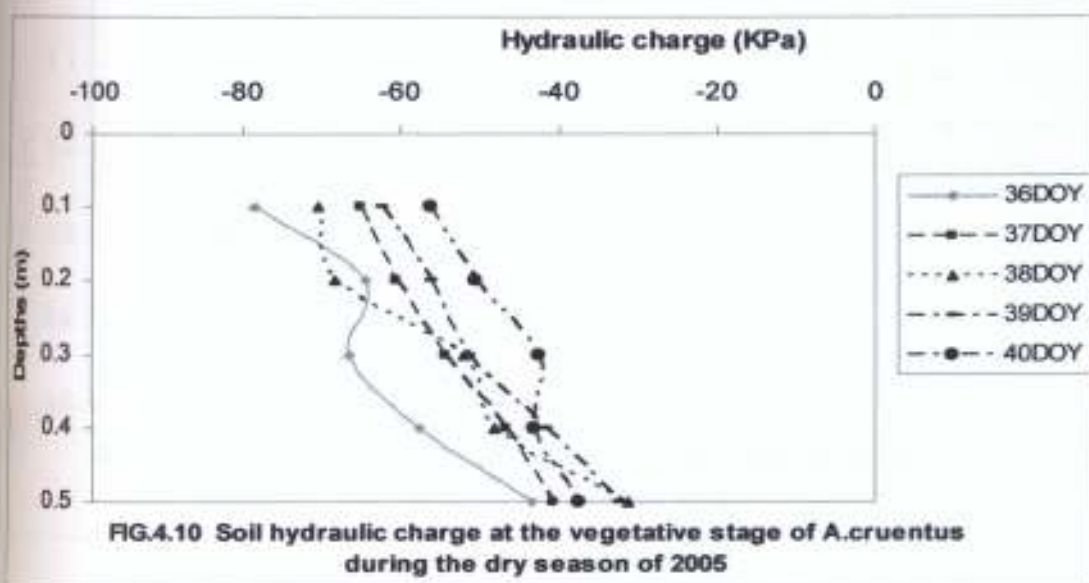
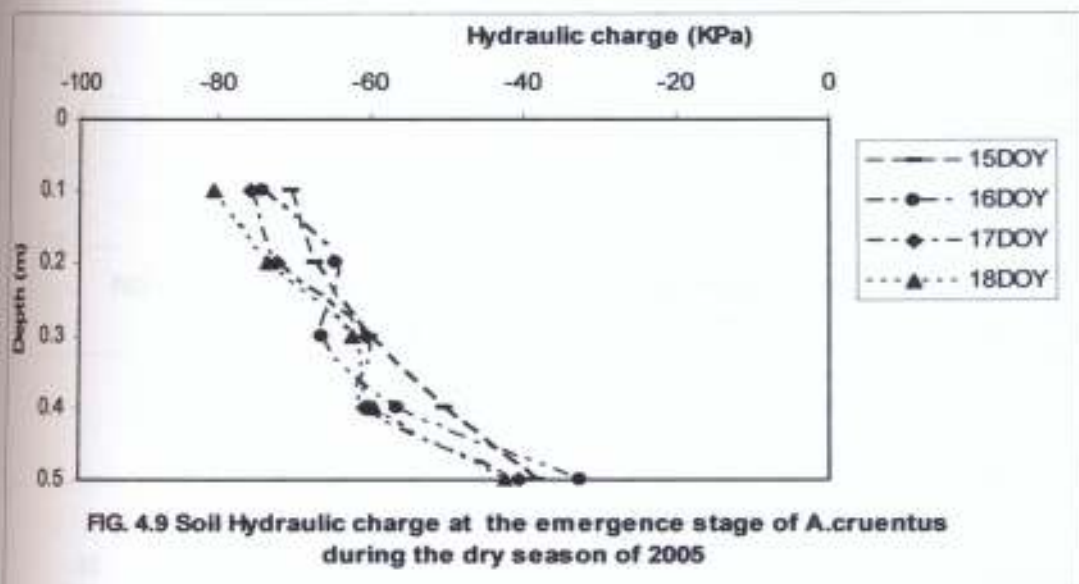
from the sprinkler and drip sites indicate that the soil at the two sites varies slightly irrespective of the topography of the area. The soils at the drip site have a comparatively higher sand content within the 0.3 m depth of soil. The mean organic carbon content at drip site is higher than the soils of the sprinkler site

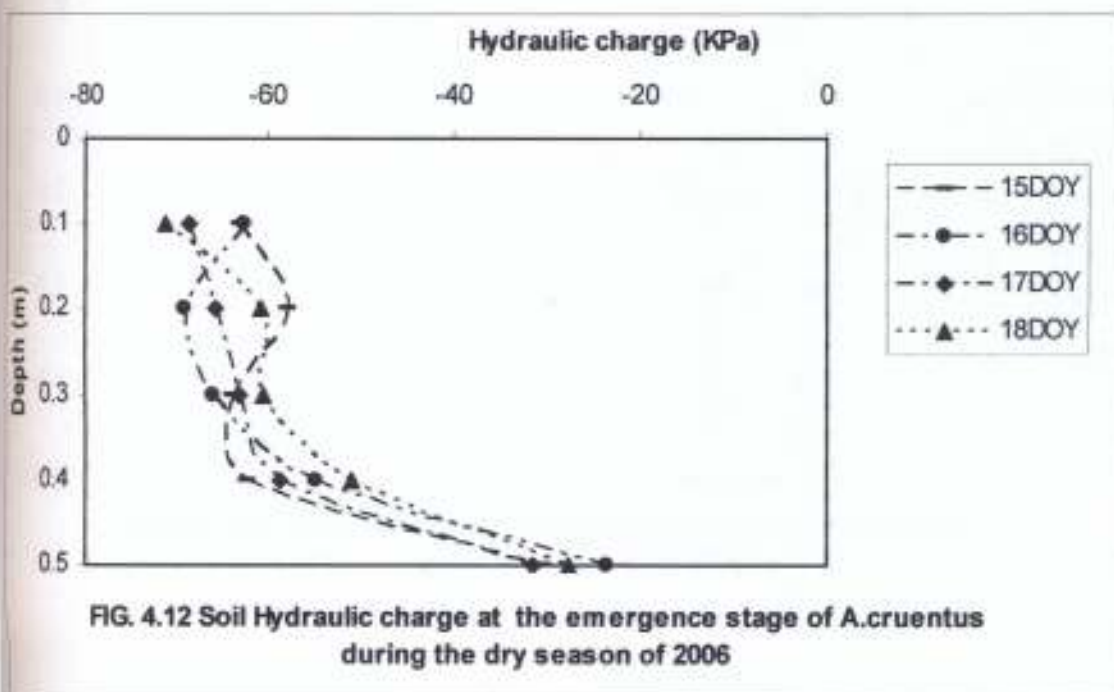
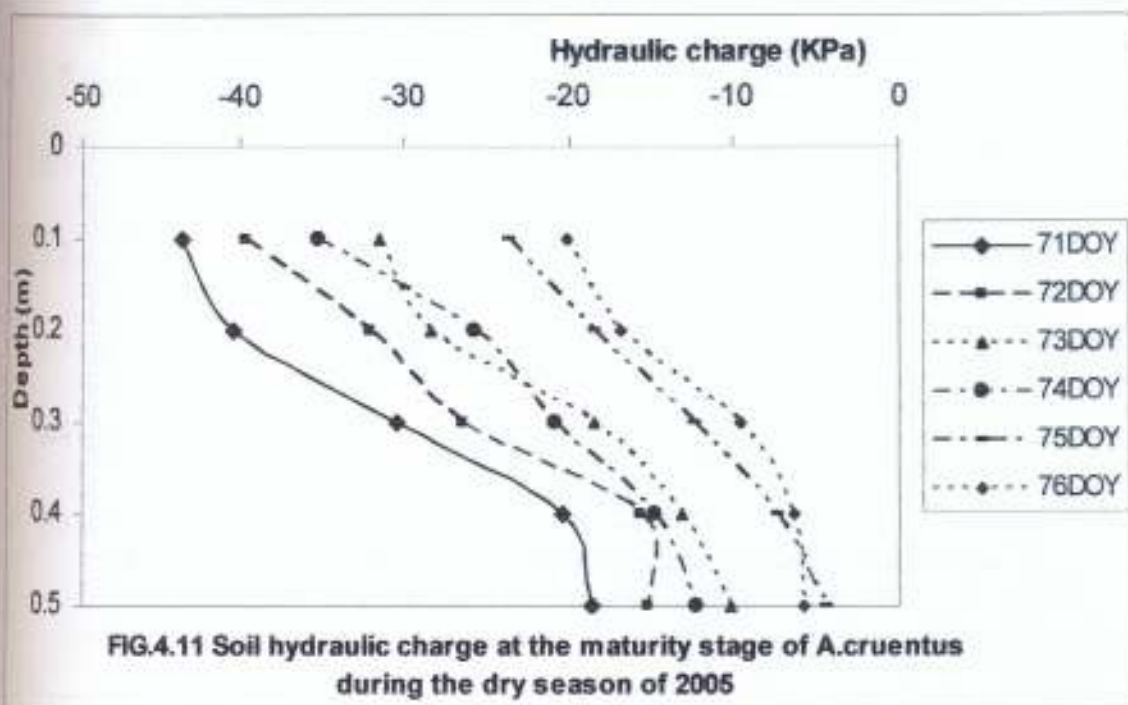
Table 4.3 Descriptive statistics of soil properties at the drip irrigation plots

Plots	Sand (%)	Clay (%)	Silt (%)	Organic carbon	N (%)	P (mg/kg)	K (meq/100g)	Ca (meq/100g)	Mg (meq/100g)	Na (meq/100g)
1	70	20	10	1.25	0.18	9.60	0.43	4.22	3.80	0.23
2	68	22	10	1.08	0.16	9.67	0.52	7.60	4.50	0.32
3	69	24	7	1.40	0.16	7.55	0.57	3.60	3.20	0.20
4	70	19	11	1.34	0.14	7.57	0.38	5.38	3.00	0.19
5	67	23	10	1.11	0.17	9.56	0.46	4.54	2.80	0.22
6	68	20	12	1.29	0.17	8.54	0.51	6.36	3.60	0.24
7	69	22	9	1.02	0.13	9.04	0.39	5.64	3.21	0.21
8	69	21	10	1.35	0.14	9.87	0.53	4.76	4.12	0.16
9	70	19	11	0.93	0.16	9.64	0.47	5.33	3.67	0.24
10	68	21	11	1.20	0.14	10.00	0.55	4.62	2.98	0.18
11	69	21	10	1.02	0.17	8.33	0.60	6.75	3.11	0.22
12	67	20	13	1.27	0.15	8.45	0.62	4.96	2.45	0.30
13	69	21	10	1.15	0.13	8.99	0.54	4.76	3.00	0.35
14	70	22	8	1.20	0.15	9.87	0.48	7.66	3.50	0.25
15	68	20	12	1.12	0.14	9.27	0.44	5.76	3.10	0.27
16	67	23	10	0.89	0.16	7.89	0.50	6.28	4.00	0.26
17	67	21	12	0.90	0.15	8.00	0.52	7.10	3.70	0.17
18	69	20	11	1.14	0.17	8.78	0.47	6.75	3.30	0.20
Min	67	19	7	0.89	0.13	7.55	0.38	3.60	2.45	0.16
Max	70	24	13	1.40	0.18	10.00	0.62	7.66	4.50	0.35
Mean	68.6	21.	10.4	1.14	0.2	8.92	0.50	5.70	3.40	0.20
STD	1.10	1.3	1.46	0.15	0.02	0.85	0.07	1.27	0.57	0.06
Skewness	-4.65	0.4	-	-0.17	-3.11	-3.33	-2.14	-0.70	-1.49	-0.19
Kurtosis	1.21	0.3	0.72	-0.86	-1.06	-1.21	-0.36	-0.93	-0.02	0.17

4.2.1 Soil Hydraulic Charge

The variations of the soil moisture tension for the period of experiment are presented in Figures 4.9 – 4.14. The soil moisture tension within 0.1m depth of soil was found to be highest when compared with other measured values, an indication that moisture tension decreases down the soil profile. Variations in soil moisture tension at the different soil profile were significant at 5% level.





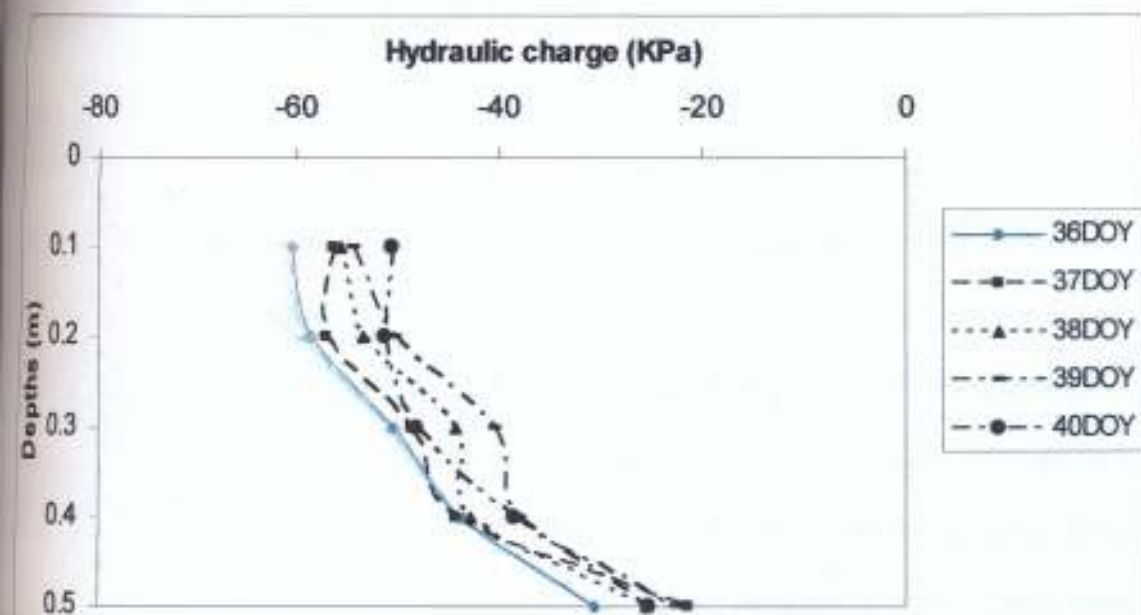


FIG.4.13 Soil hydraulic charge at the vegetative stage of *A.cruentus* during the dry season of 2006

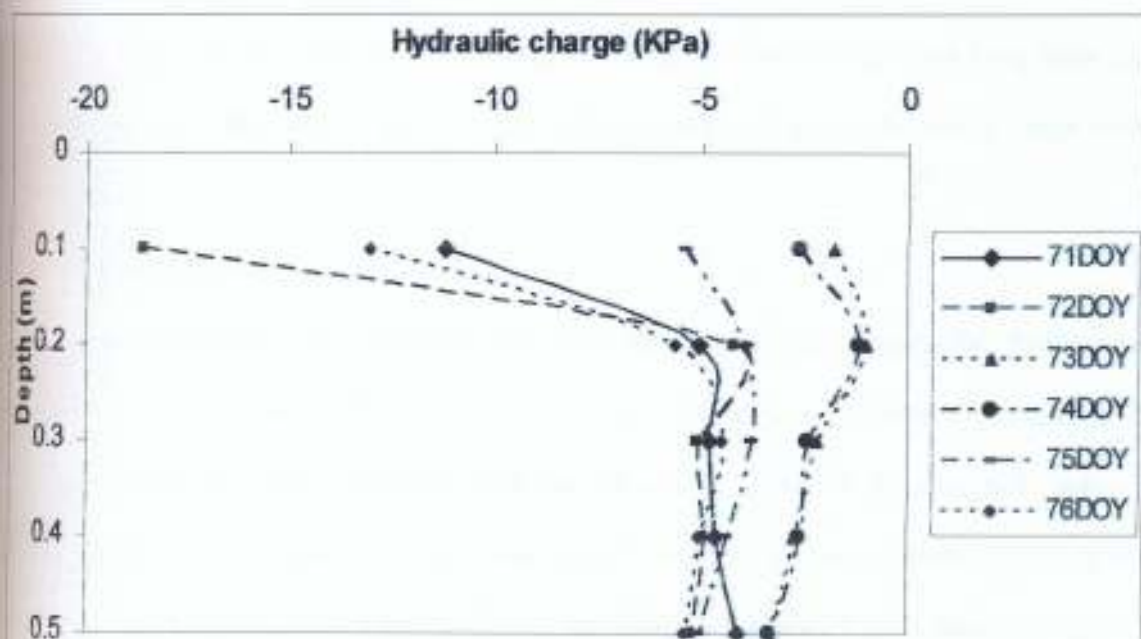


FIG.4.14 Soil hydraulic charge at the maturity stage of *A.cruentus* during the dry season of 2006

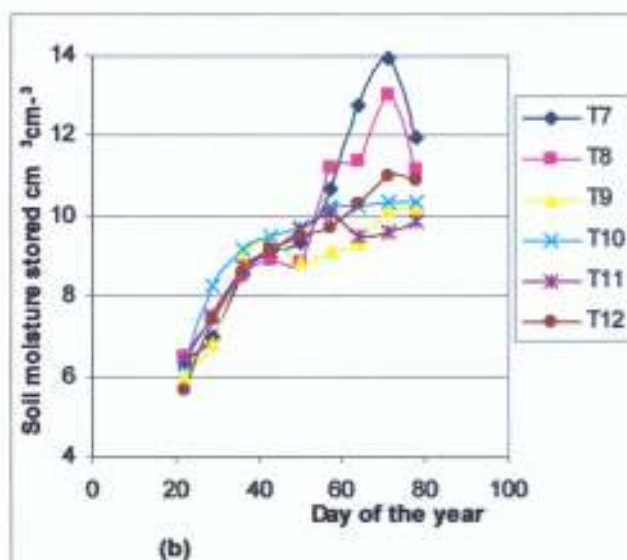
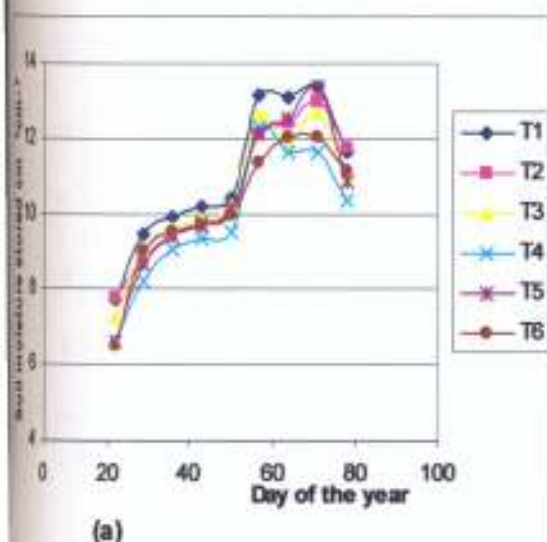
The moisture tension at the 0.1 m depth of soil during the dry season experiment of 2005 ranges between -80.6 and -42.6 KPa at depths 0.1 and 0.5 m respectively at crop emergence (18DOY). However, soil hydraulic charge reduced to -43.5 and -5.7 KPa at depths 0.1 and 0.5 m respectively at crop maturity (71 – 76DOY). This observation might have been occasioned by scanty rainfalls experienced during this period of the year. Soil hydraulic charge was found to be -70.9 and -27.6 KPa at depths 0.1 and 0.5 m respectively during the dry season experiment of 2006. Moisture depletion during the wet season experiment was not enough to warrant any irrigation as there were zero moisture tensions most especially at the root zone of the crop. Hence, water demands of crop were met purely by precipitations during this period. Low moisture tension value of 45 KPa was recorded at 0.1 m depth during crop maturity (148 and 163 DOY) in 2006. Zero moisture tension was mostly recorded at depths 0.4 and 0.5 m during the wet season experiments. The decreased soil moisture potential at the root zone of *Amaranthus* must have been caused by moisture accumulation due to soil cover by plant canopy and hence decreased direct evaporation from bare soil.

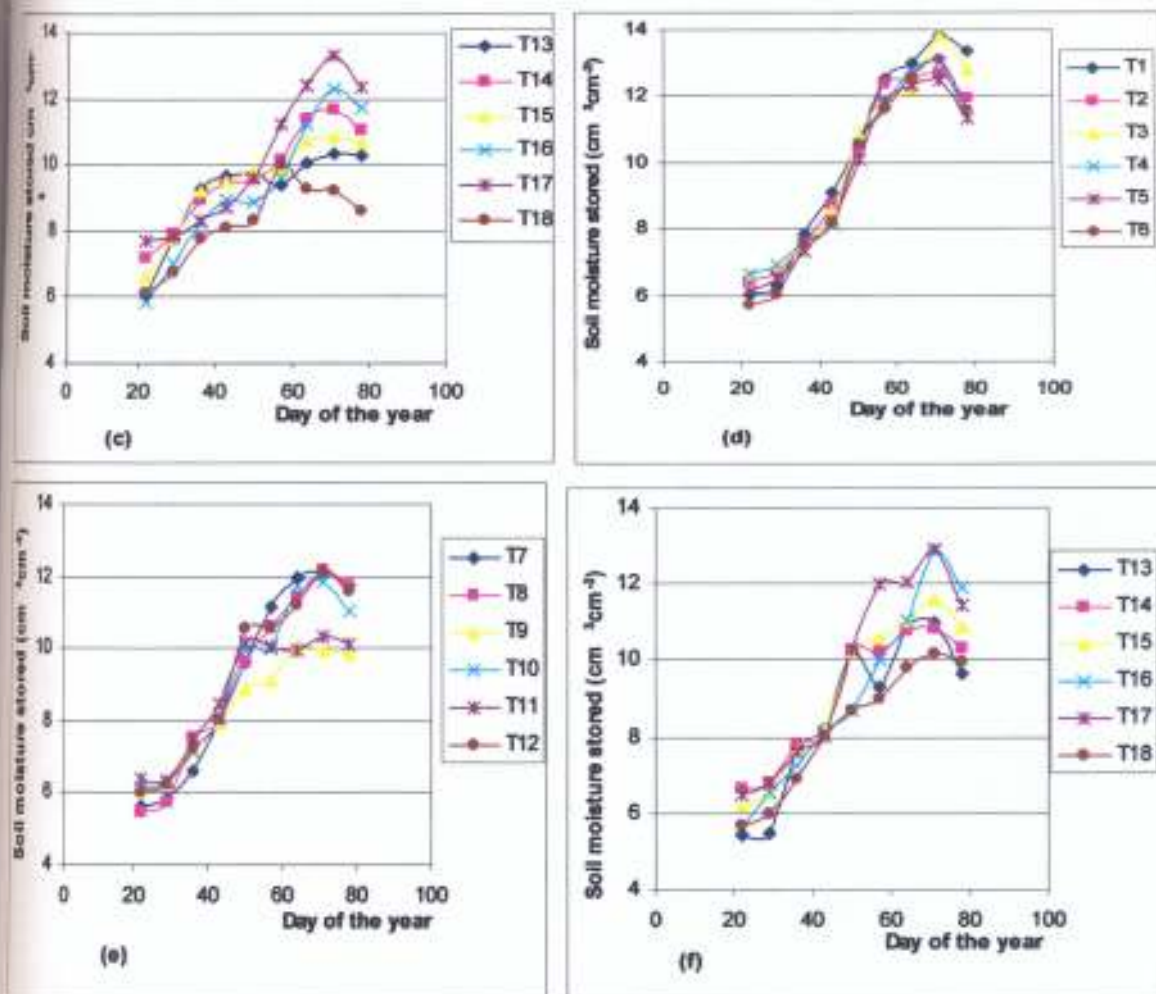
4.2.1 Moisture storage in the soil profile

The variations in the volumetric soil moisture content in the *Amaranthus* field up to a depth of 0.6 m are shown in Figures 4.15 a, b, c, and 4.16 d, e, f. The stored moisture in the soil profile was observed to increase down the soil profile. However, the moisture regime in the Treatment T1 was highest among all treatments in the sprinkler irrigation plots. The soil column refill in treatment T1 must have been facilitated by the daily application of irrigation water to the plot from the Mid-season (Flowering stage) to crop maturity. The sequence of moisture depletion and replenishment agrees with the findings of Allen *et al.*, (1999). As the crop reaches maturity, soil moisture storage for all the treatments took a down turn.

Defoliation of leaves around this time resulted into soil exposure to direct solar radiation and hence increased evaporation from bare soil surface.

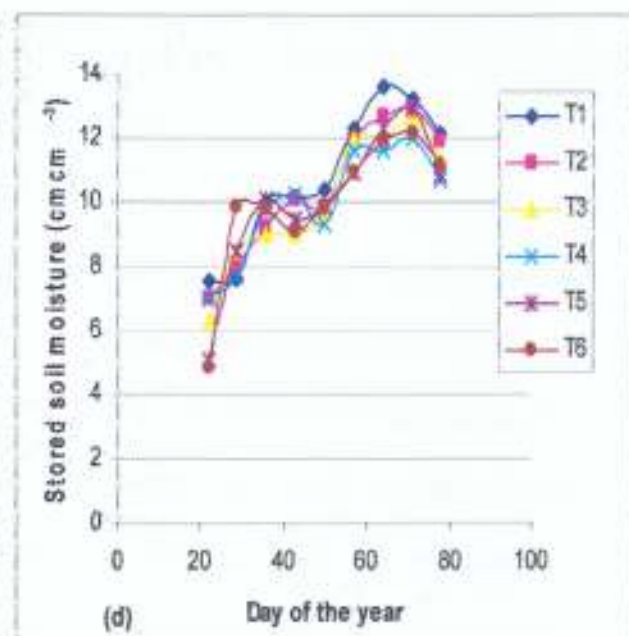
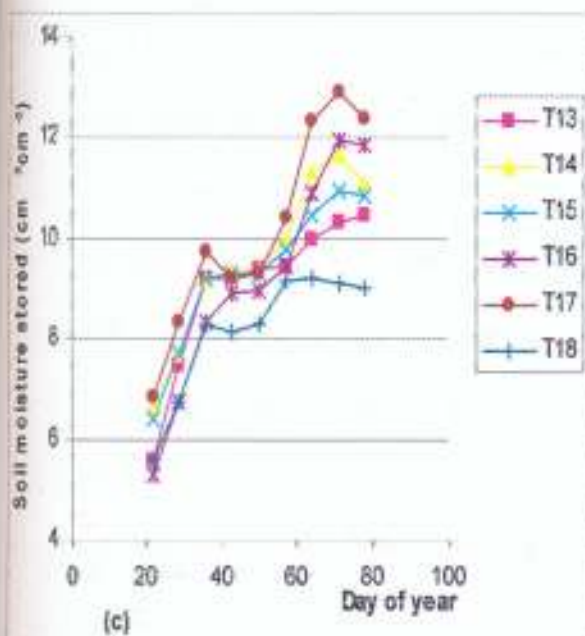
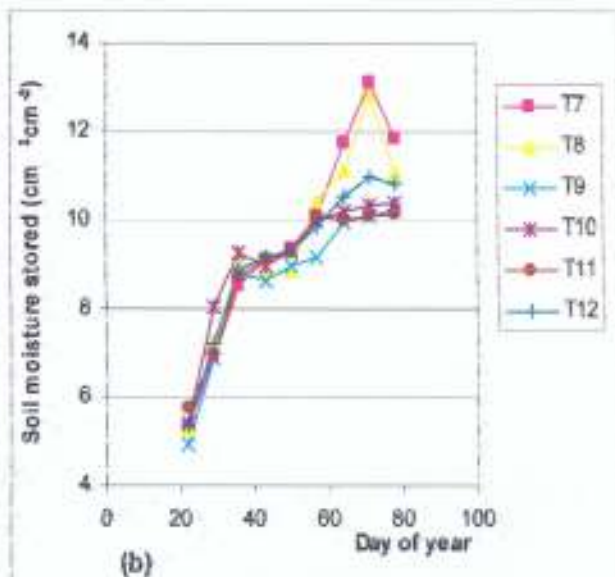
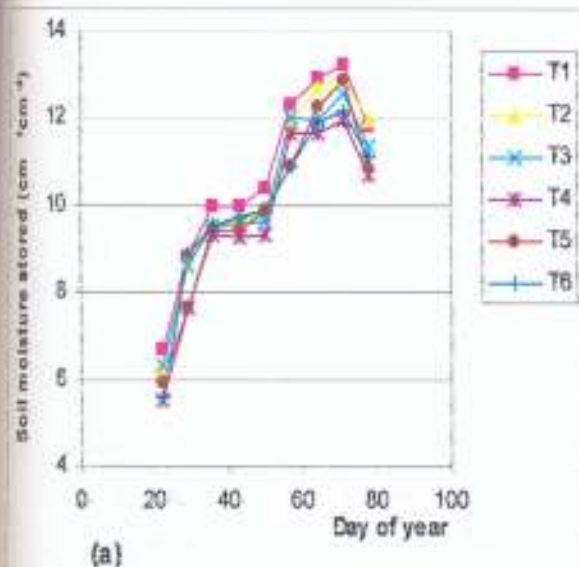
However, moisture stored in treatment T1 was highest (13.86 cm) at the 71DOY. This was so because gentle drips of water had enough time to accumulate around the root zone of crop, thus, permitting moisture build up at the topsoil. A general rise in stored soil moisture was observed within the first six (6) – seven (7) weeks after planting until it reaches its peak

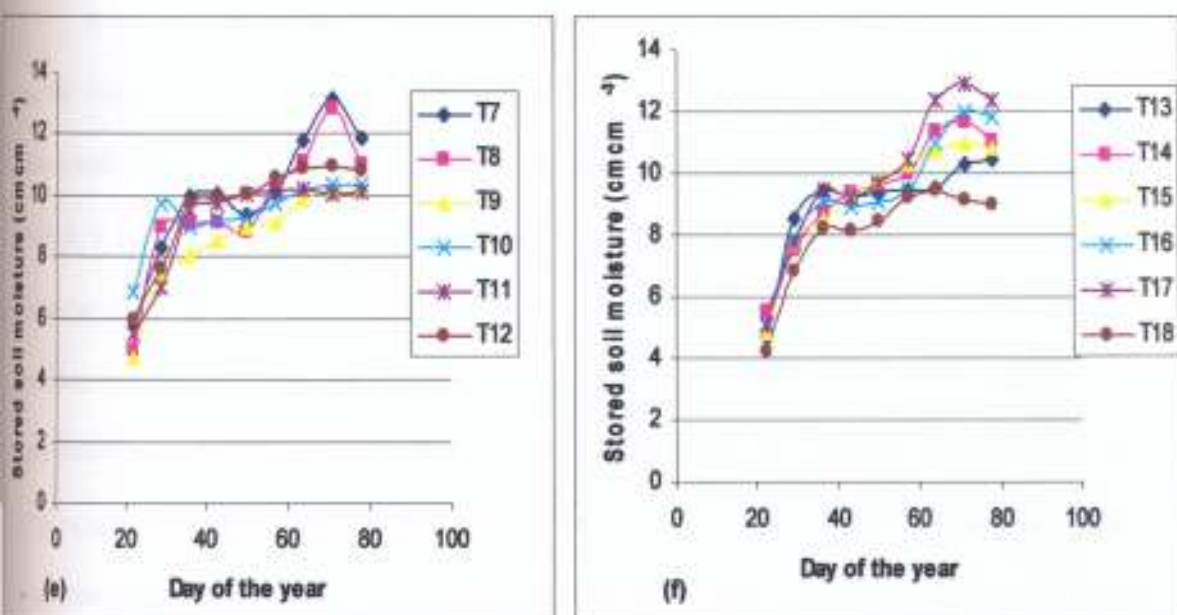




Figures. 4.15 a, b, c, and 4.16 d, e, f are stored soil moisture in sprinkler and drip irrigation treatment plots respectively during the dry season of 2005

Thereafter, it declined gradually due to reduction in leaf canopy that shaded the soil from direct solar radiation. The plot of stored soil moisture during the dry season of 2006 (Figure 4.17 a, b, c and 4.18 d, e, f) tends to rise with increase in days of irrigation and increase in soil depth. The differences of moisture stored for all the treatment plots were significant at 5% level. More water was stored in the drip treatment plot possibly due to direct application of water around the root zone depth of crop.



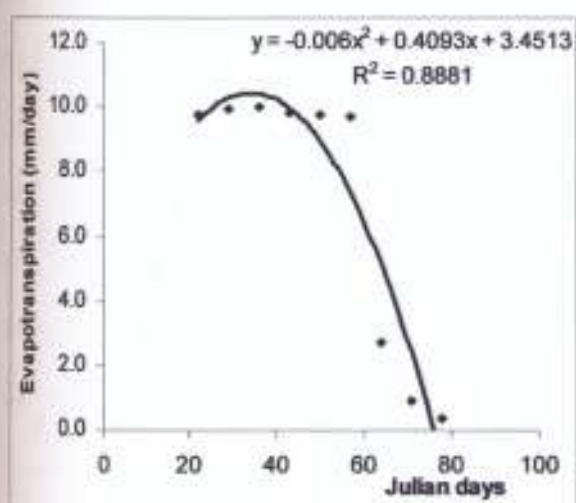


Figures 4.17 a, b, c, and 4.18 d, e, f are stored soil moisture in sprinkler and drip irrigation treatment plots respectively during the dry season of 2006

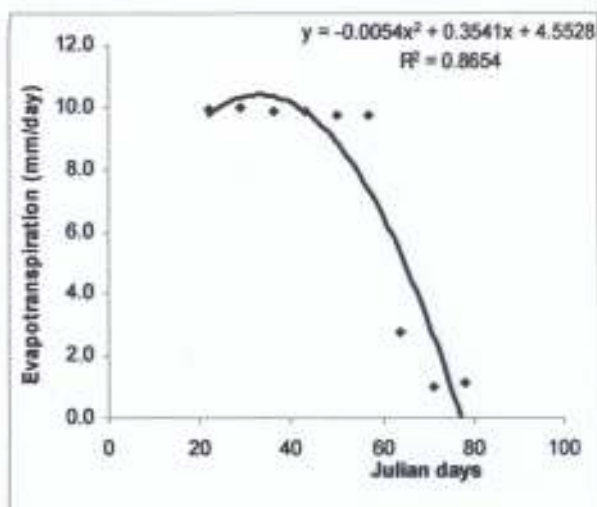
4.3 Crop Water Use

Figure 4.19 show the variations of mean crop water use estimates on drip irrigation plots on function of Julian day during the dry season experiment of 2005 and 2006. Water use of crop was highest on drip plots DT1 and DT2 with a value of 9.96 mm/day during the peak of the dry season in February (DOY 57-64). Consequently, low values were observed in March at the onset of rainfall. There were variations in the crop water use and this was largely due to the different irrigation schedules for all the treatment plots. Plots that received frequent irrigation have enough water to meet evapotranspiration needs i.e. evapotranspiration increases as the days between irrigation decreases because evapotranspiration is dependent on the length of time since wetting. This observation was confirmed by Hanks *et al.* (1971).

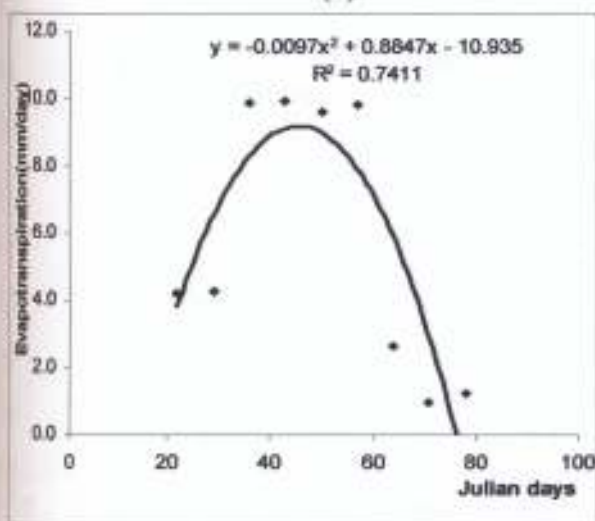
It was observed that some plants which were not frequently irrigated reached maturity earlier than normal and this must have been caused by some alterations in the physiological characteristics of the crop under study. Also, some abnormal curves observed for instance in Plot T11 occurred in a few of the treatment plots and this was largely caused by some irregular rainfalls and short supply of water when the crop needed it most. This must have resulted in moisture stress within the soil pores, and consequently altering the normal growth and development of the crop. Calder (1998) also noted was the fact that raindrop size, plant physiology, and radiation, but not soil water and crop size are the major factors that control evapotranspiration in wet tropical climate. Statistical analysis of the crop water use showed that the least value of variance (7.34) was observed in the month of January (22 DOY) and was highest in February (64DOY). Also, all the values of crop water use in January, February and March were significantly different at ($p = 0.05$).



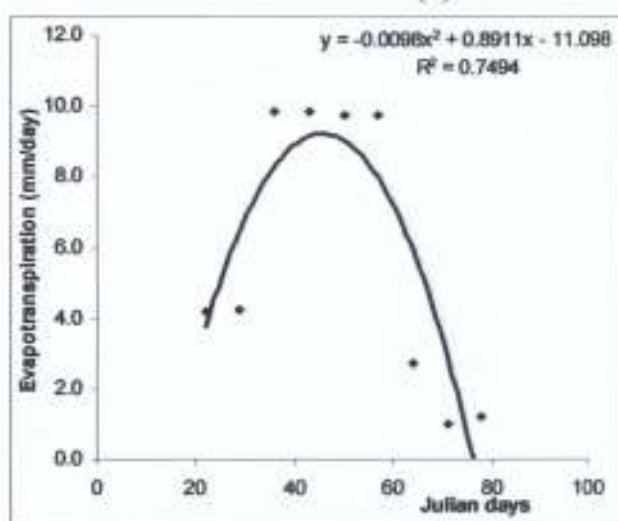
(a)



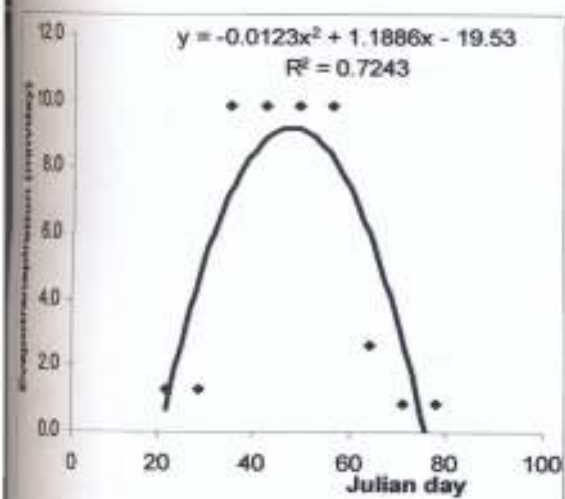
(b)



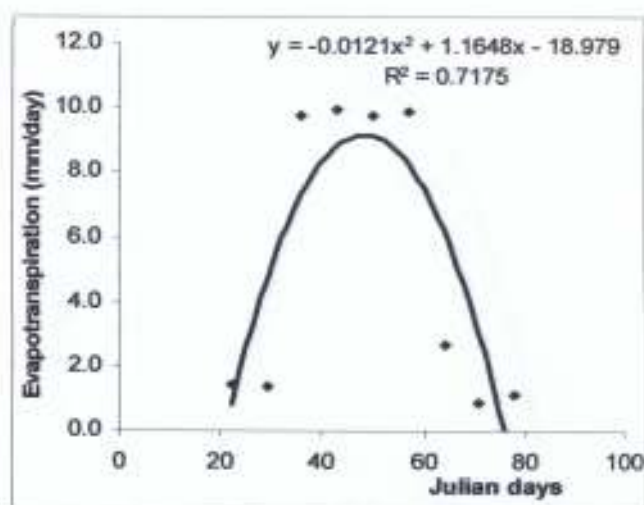
(c)



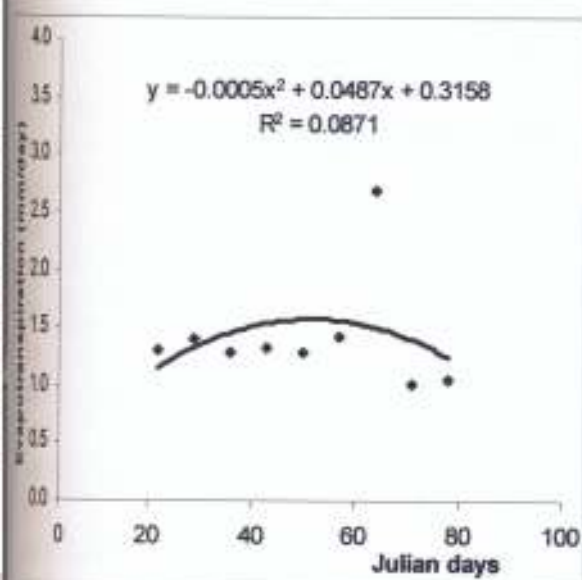
(d)



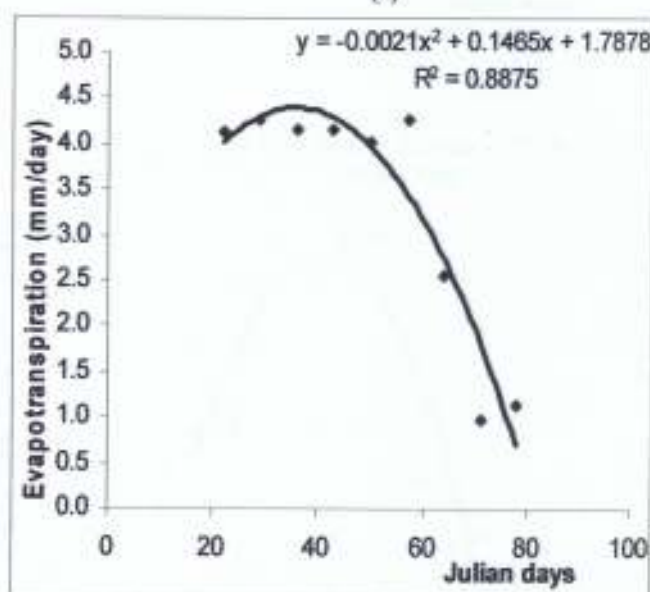
(e)



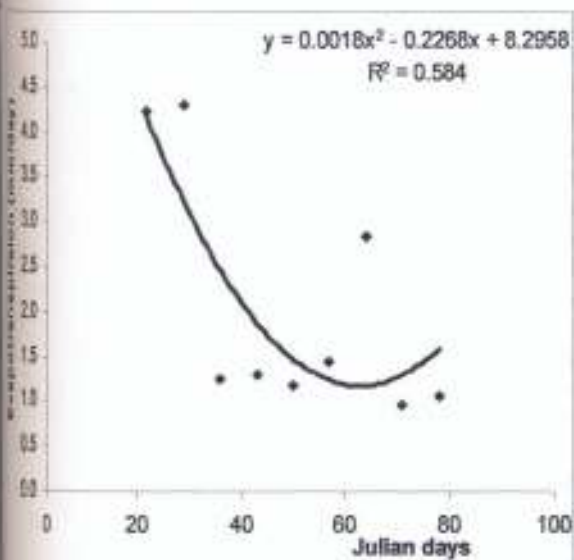
(f)



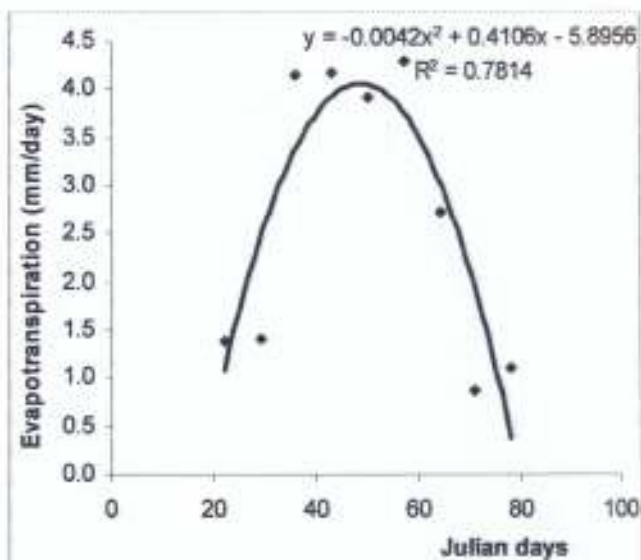
(g)



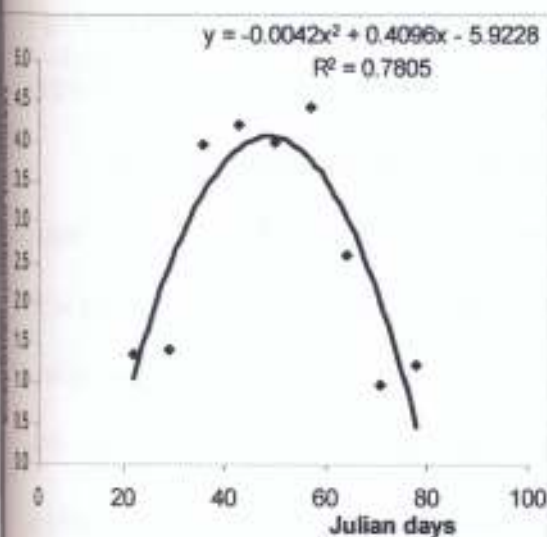
(h)



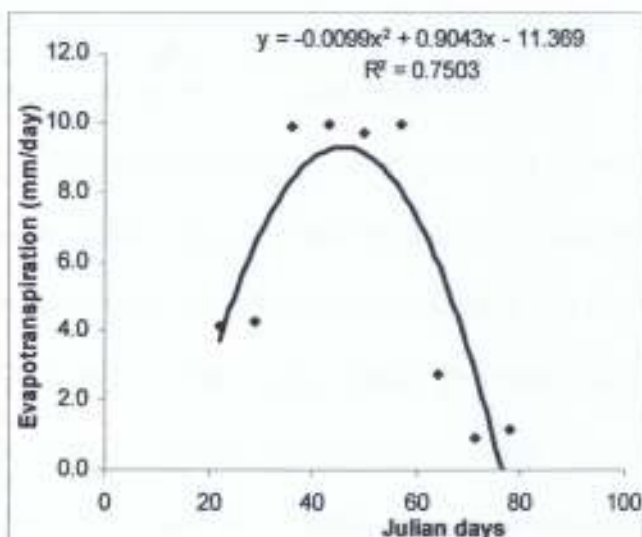
(i)



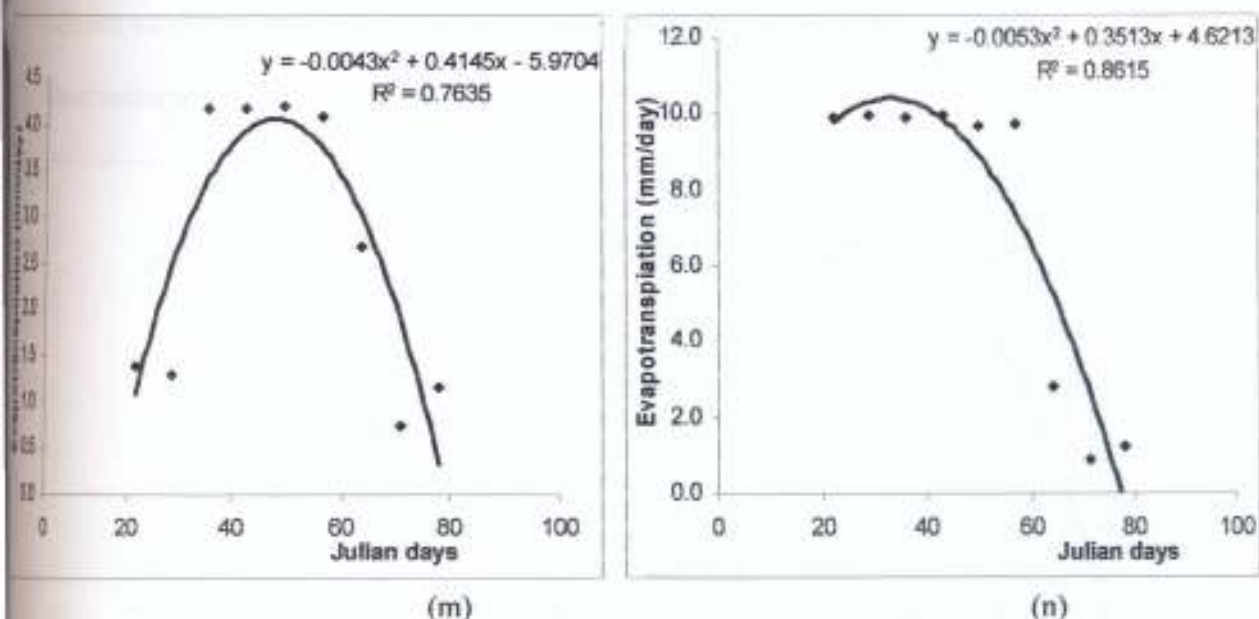
(j)



(k)



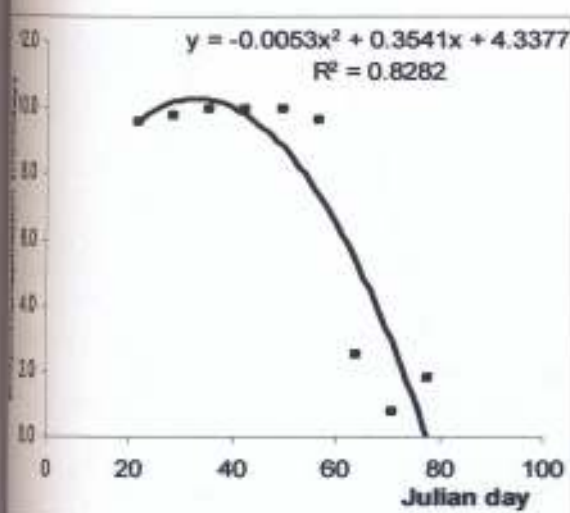
(l)



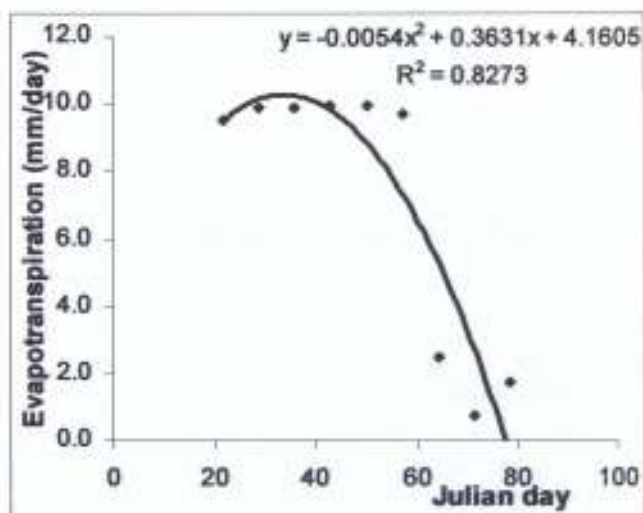
Figures. 4.19 Crop Evapotranspiration of *A. cruentus* grown under drip irrigation system in treatments (a) DT1 (b) DT2 (c) DT4 (d) DT5 (e) DT7 (f) DT8 (g) DT9 (h) DT10 (i) DT11 (j) DT12 (k) DT13 (l) DT15 (m) DT16 (n) DT17 during the dry season of 2005

Results of mean evapotranspiration on plots irrigated under sprinkler system are shown in Figure 4.20. The highest evapotranspiration value of 10.01 mm/day was obtained on sprinkler plot T8 at the 50 DOY. The coefficient of correlation between the crop evapotranspiration and the growth stages of *Amaranthus* (emergence to maturity) was highest in sprinkler irrigation plot T6 with value above 0.94. It was also noticed that some *Amaranthus* on sprinkler irrigation plots reached maturity earlier than normal and this must have been due to water stress at the sensitive stage of crop growth which falls between the vegetative and flowering stages of the crop (i.e. 50-57 DOY). This might have accounted for some abnormal curves of evapotranspiration that were observed on sprinkler plots. Evapotranspiration from both the drip and sprinkler plots were dependent mostly on rainfall amount and irrigation water applied. Evapotranspiration is generally higher during the dry season than during the wet season and this was so because of the high solar

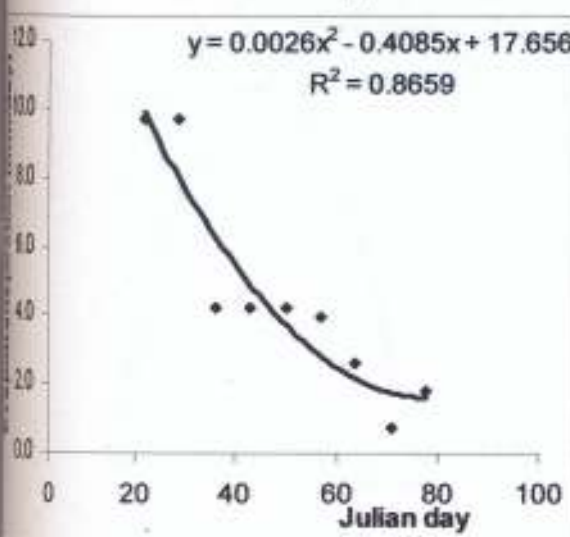
radiation which resulted to rapid loss of moisture both from soil and the crop surfaces and also transpiration in order to respond to evaporative demand.



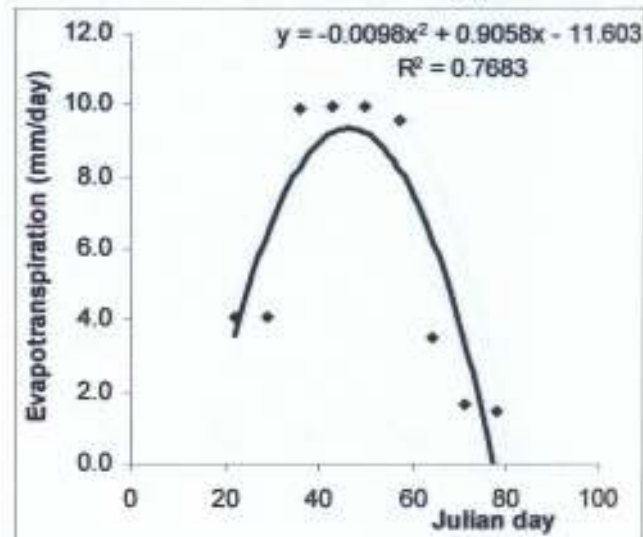
(a)



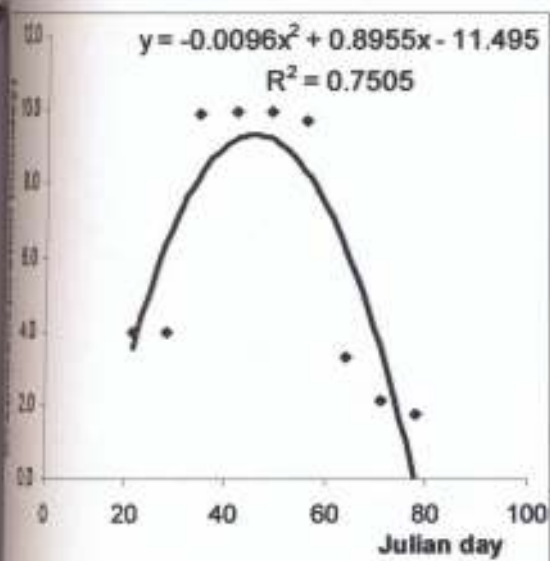
(b)



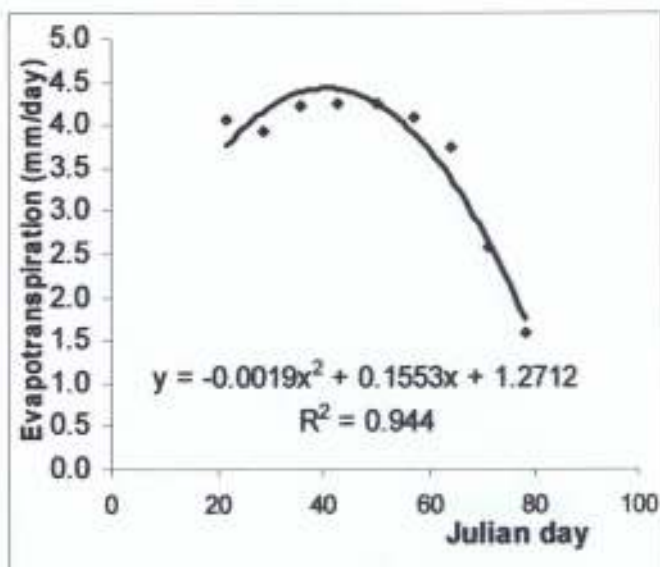
(c)



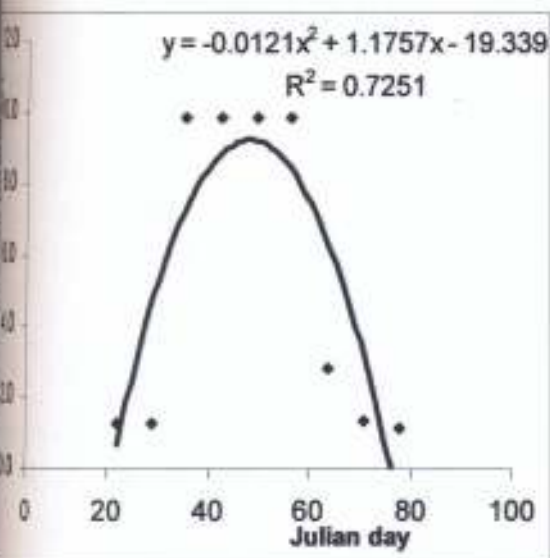
(d)



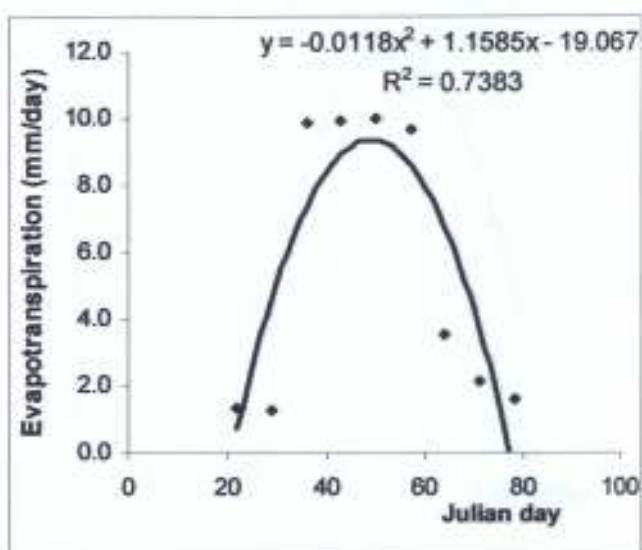
(e)



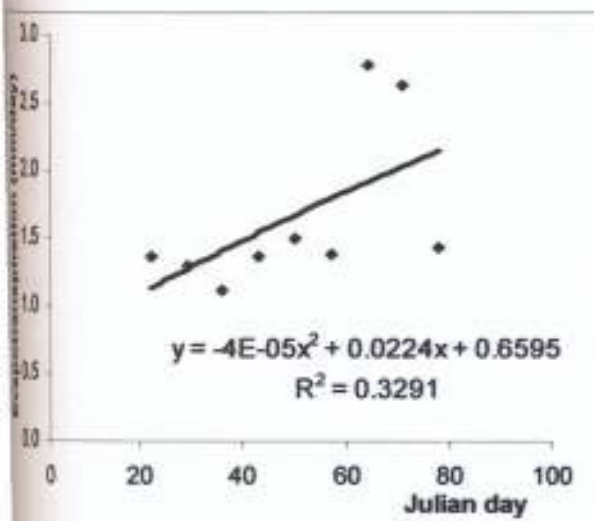
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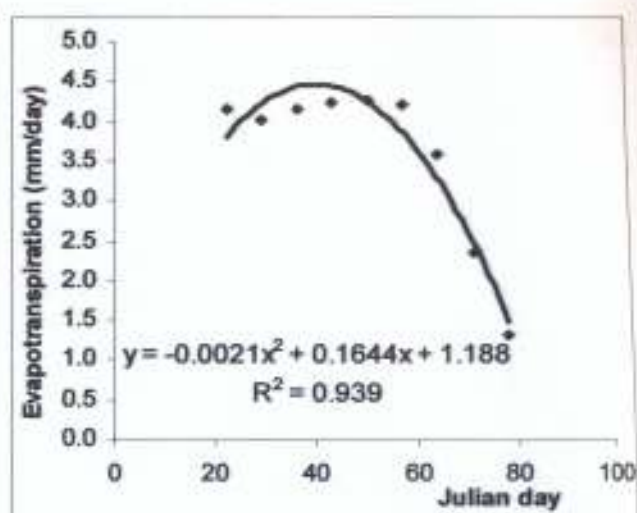
(g)



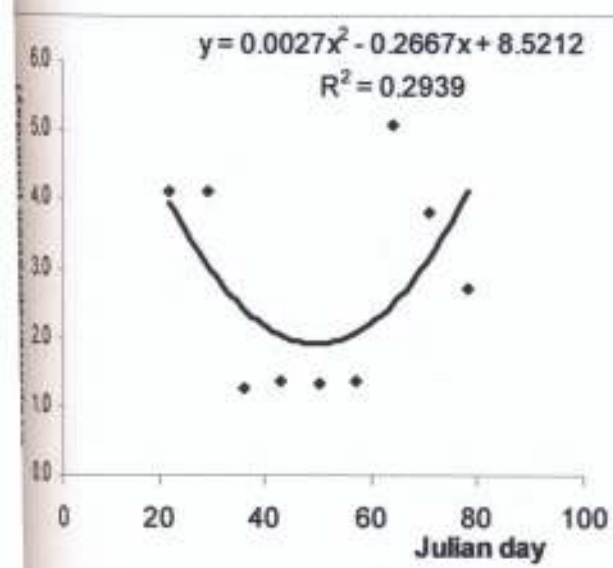
(h)



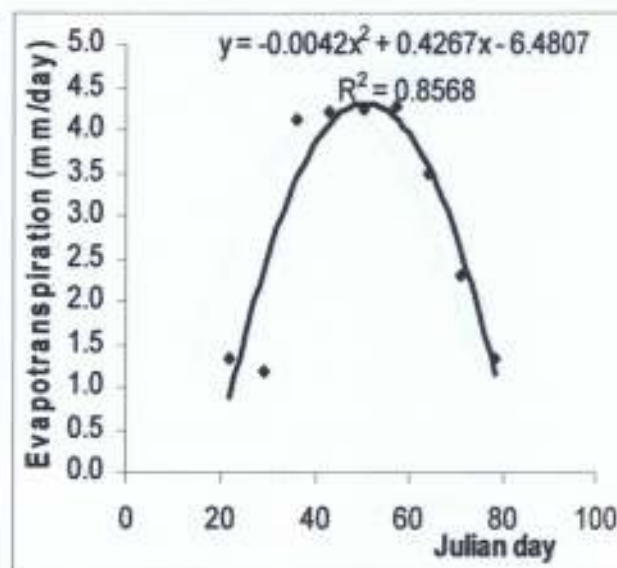
(i)



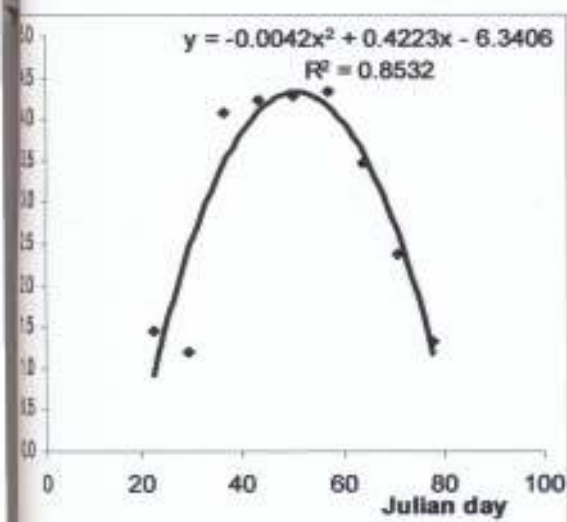
(j)



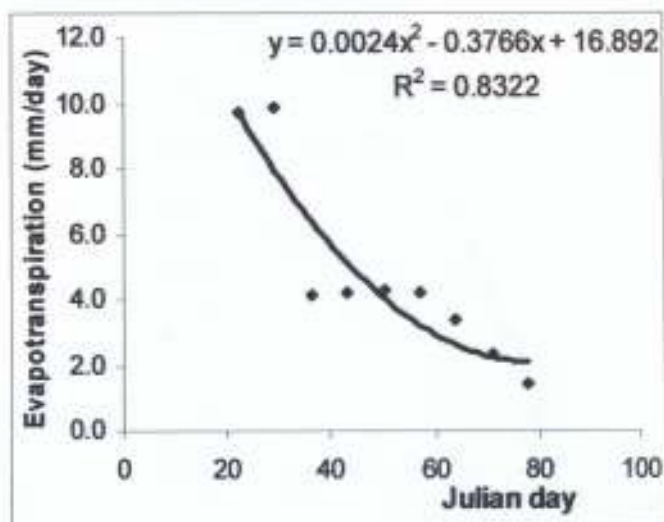
(k)



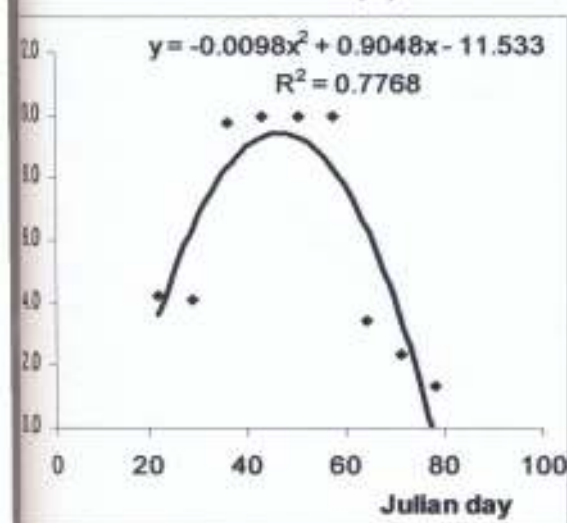
(l)



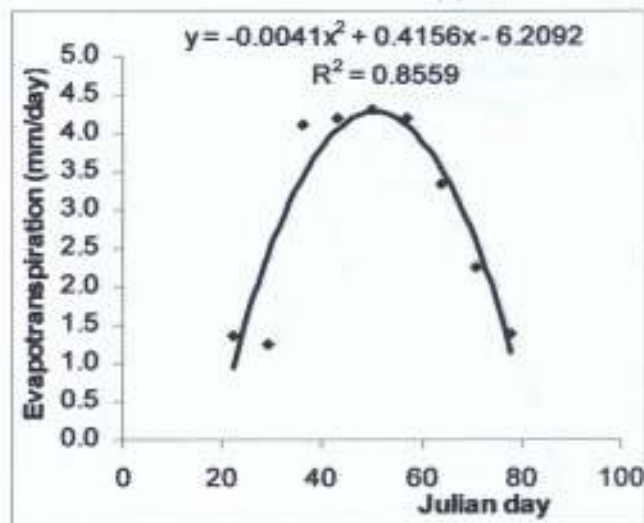
(m)



(n)

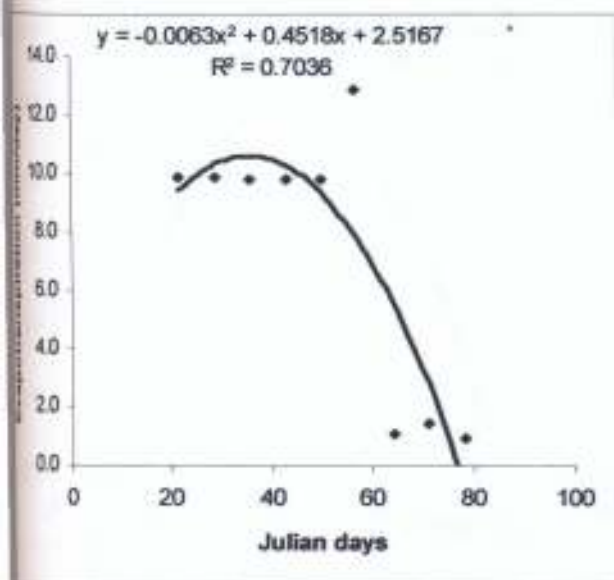


(o)

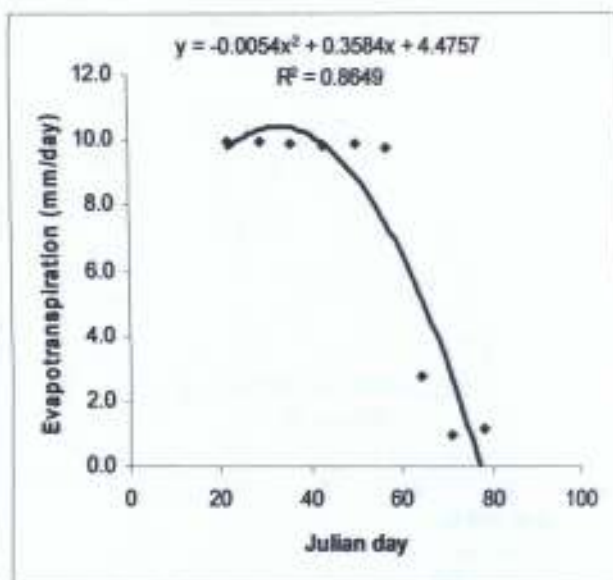


(p)

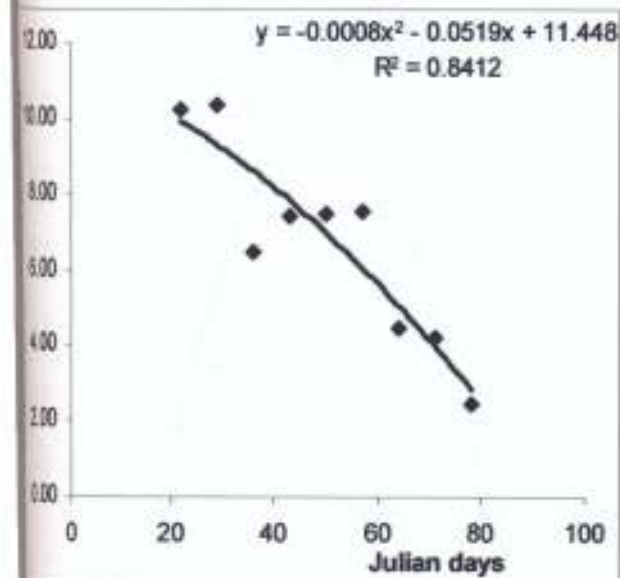
Figure 4.20 Crop Evapotranspiration of *A. cruentus* grown under sprinkler irrigation system in treatments (a) ST1 (b) ST2 (c) ST4 (d) ST5 (e) ST7 (f) ST8 (g) ST9 (h) ST10 (i) ST11(j) ST12 (k) ST13 (l) ST14 (m) ST15 (n) ST16 (o) ST17 (p) ST18 during the dry season of 2005



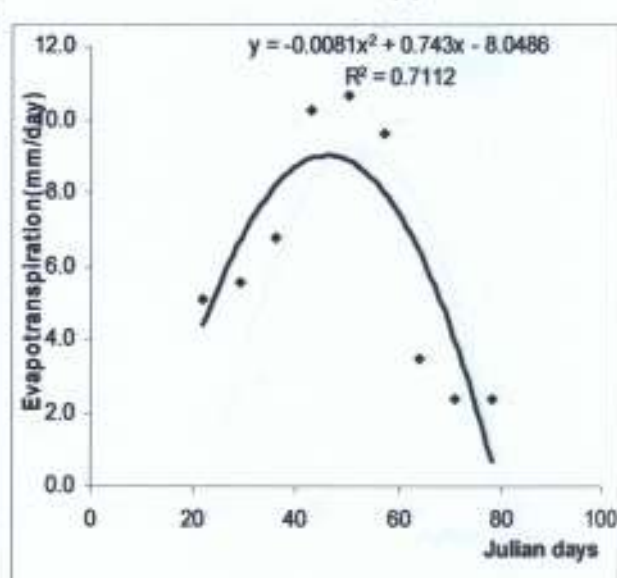
(a)



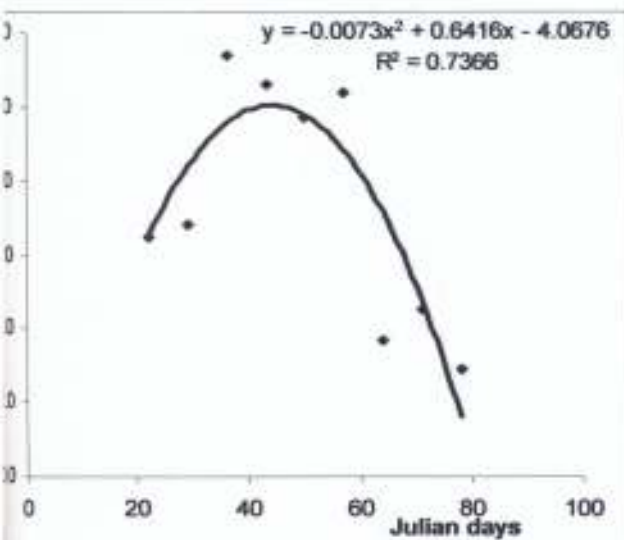
(b)



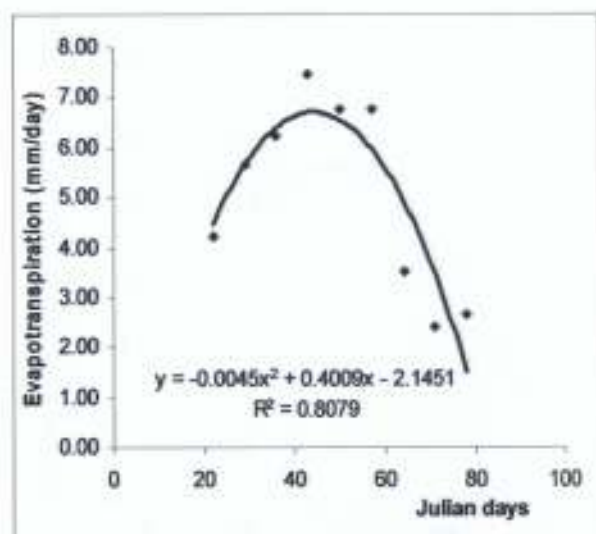
(c)



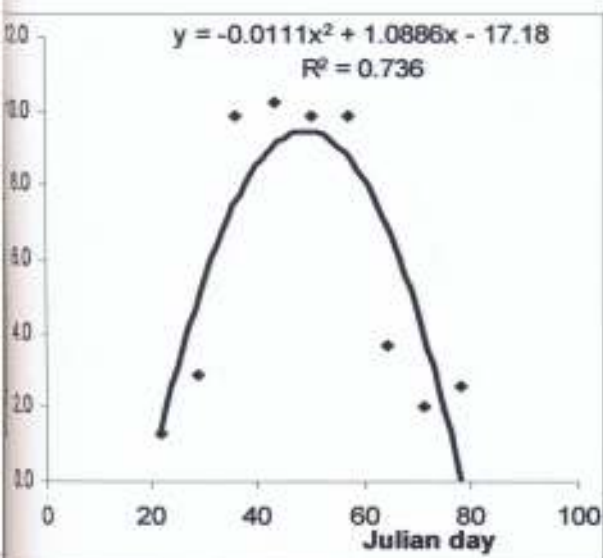
(d)



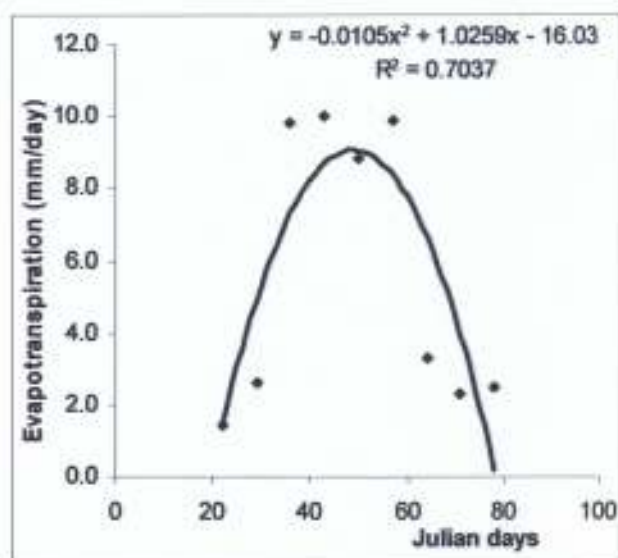
(e)



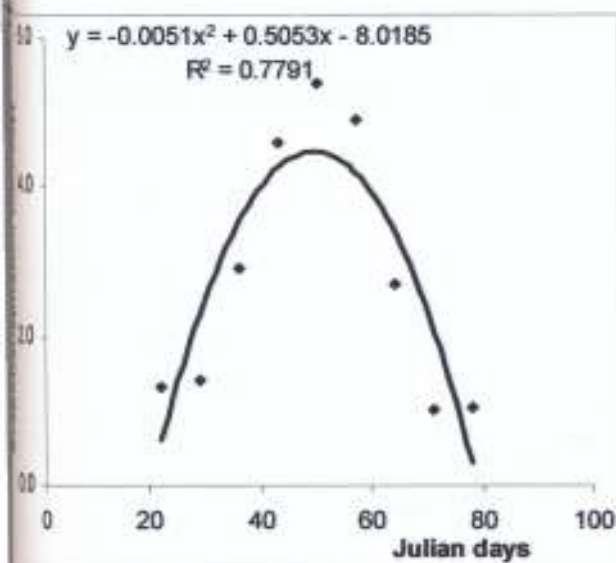
(f)



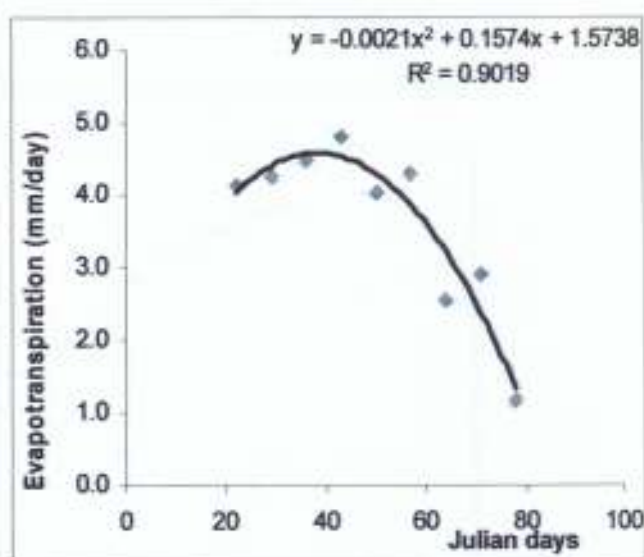
(g)



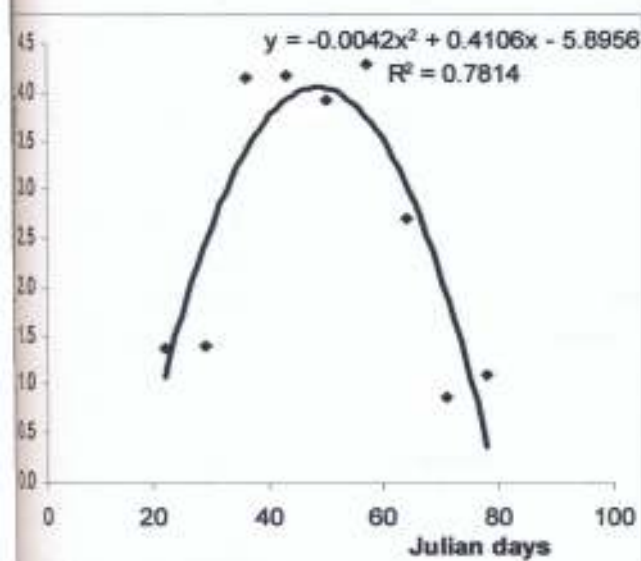
(h)



(i)



(j)

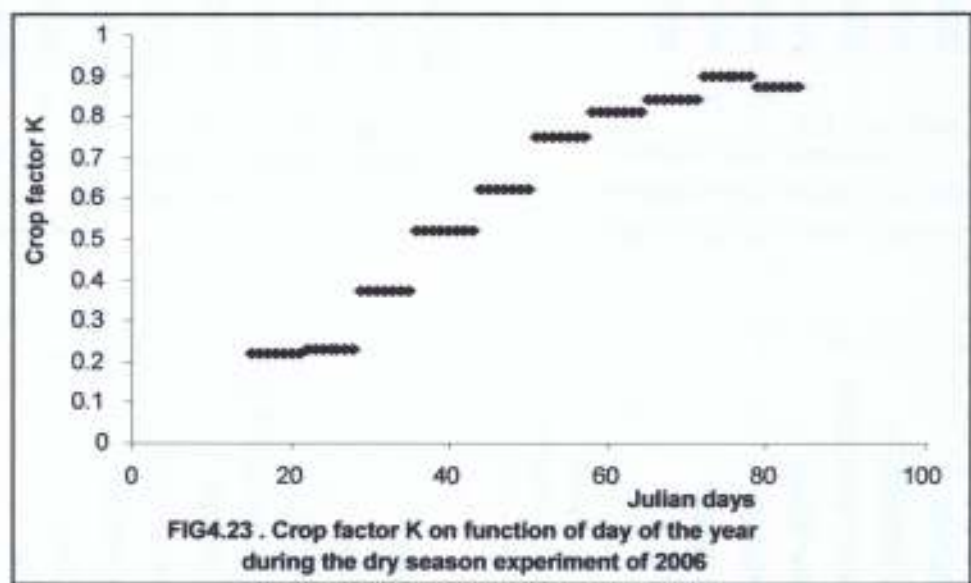
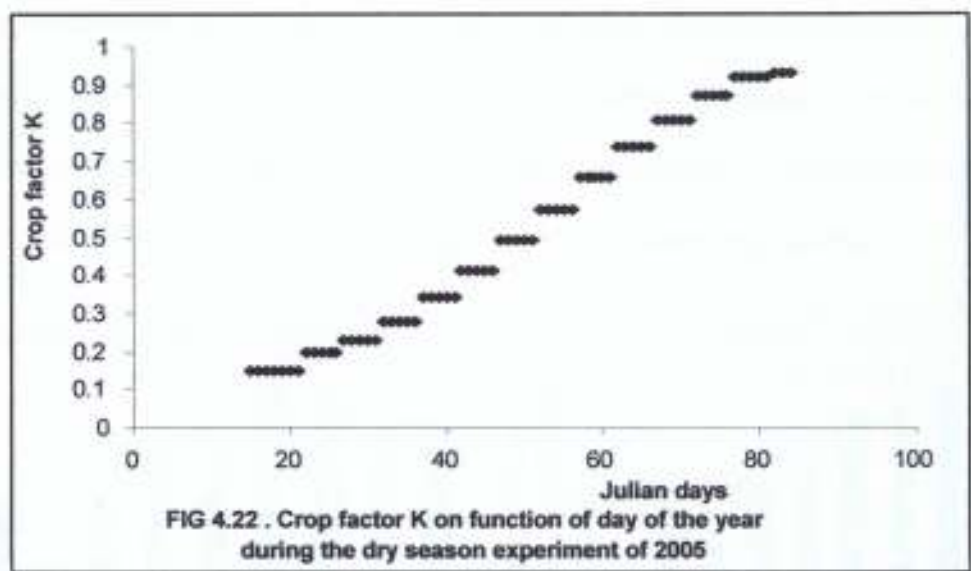


(k)

Figure 4.21 Crop Evapotranspiration of *A. cruentus* grown under drip irrigation system in treatments (a) DT1 (b) DT2 (c) DT4 (d) DT5 (e) DT7 (f) DT8 (g) DT9 (h) DT10 (i) DT11 (j) DT12 (k) DT13 during the dry season of 2006

The crop factor K_c of *A. cruentus* was plotted against days of the year as presented in Figure 6.22. The crop factor K_c appears to be constant at the earlier stage of crop growth but rose sharply during the productive stage of the crop. At late season when the crop reaches senescence, the crop

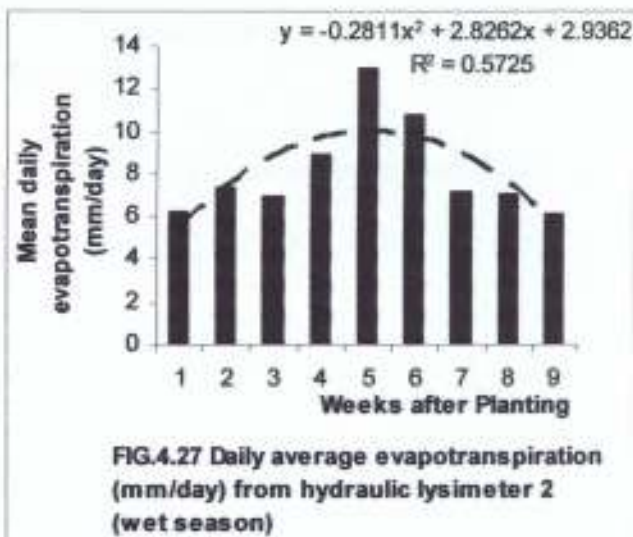
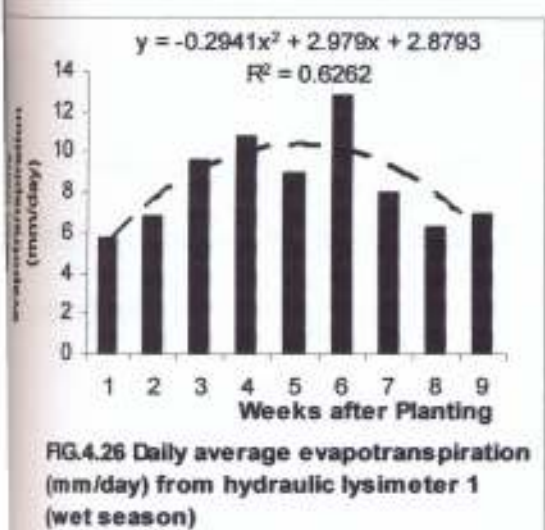
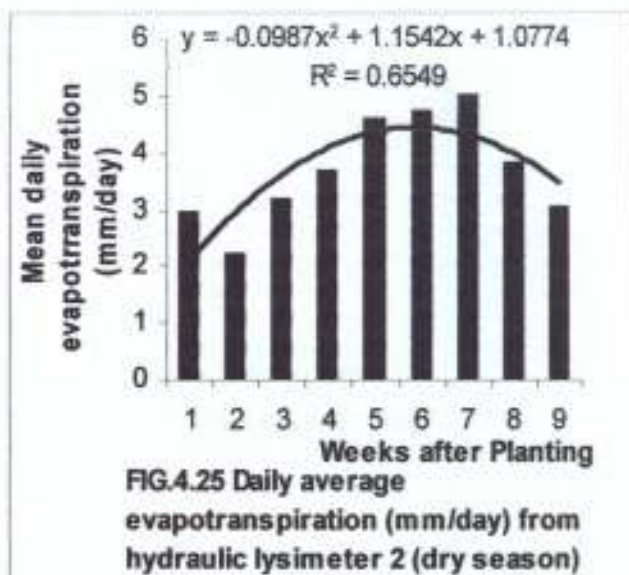
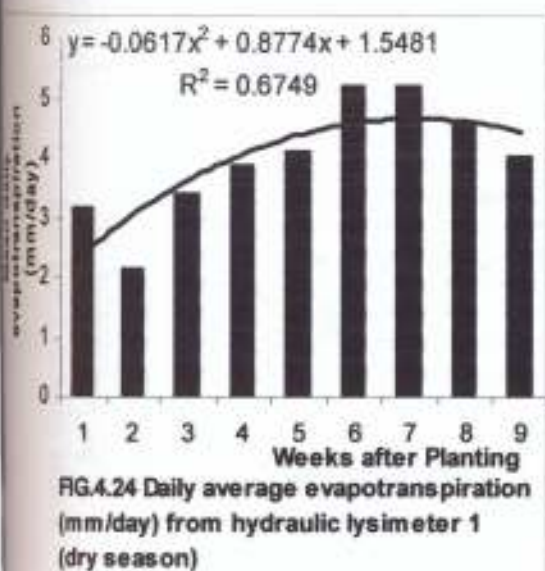
factor K_c appears constant again. The sharp rise observed at mid- season is an indication that the crop evapotranspires more at its vegetative stage than other stages of its development.



4.4 Direct Evapotranspiration from Lysimeter

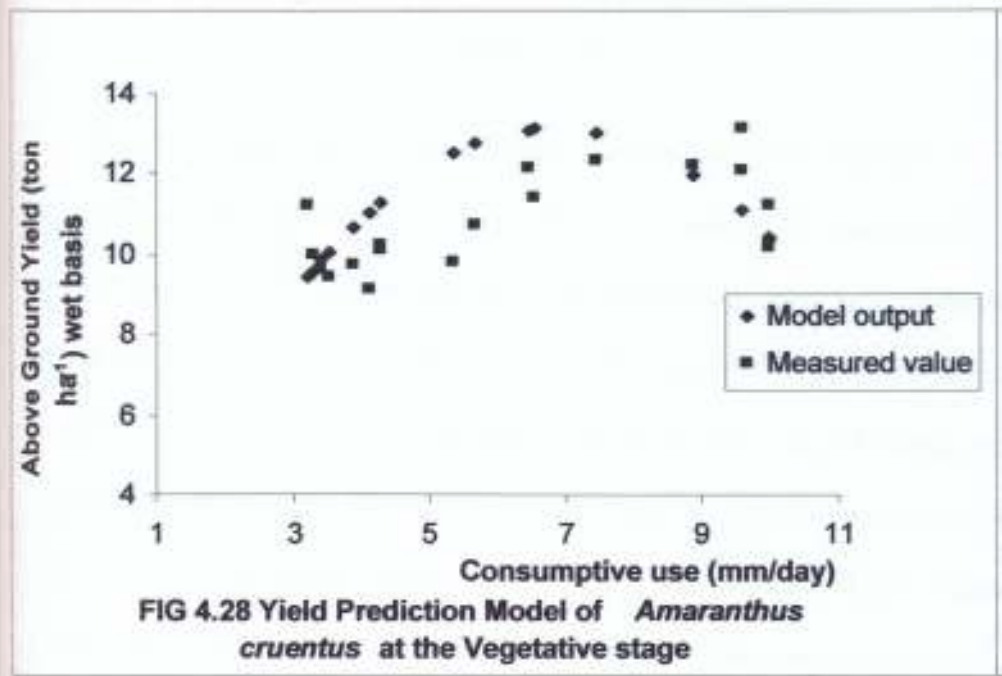
Direct evapotranspiration of Amaranth from installed hydraulic lysimeter is shown in Figures 4.24-.27. The consumptive use for the two lysimeter show similar trend i.e. ET increased

steadily to its peak around the 6th week after planting, during inflorescence formation and then declined during inflorescence maturation at the 8th week after planting. Amaranth inflorescence development implies the crop passed through a significant change in its physiological stage, which were accentuated in the pattern of water use. The correlation coefficient obtained from the dry season experiment was highest in lysimeter 1 with a value of 0.81. A polynomial correlation gave a lowest value of $R^2 = 0.72$ in lysimeter 2 during the wet season experiments.

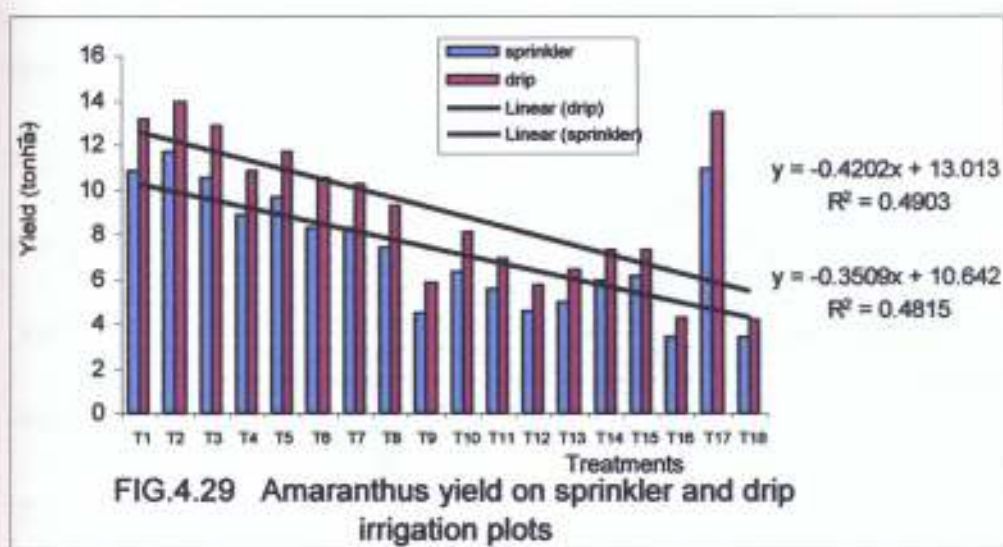


4.5 The Crop Yield Model

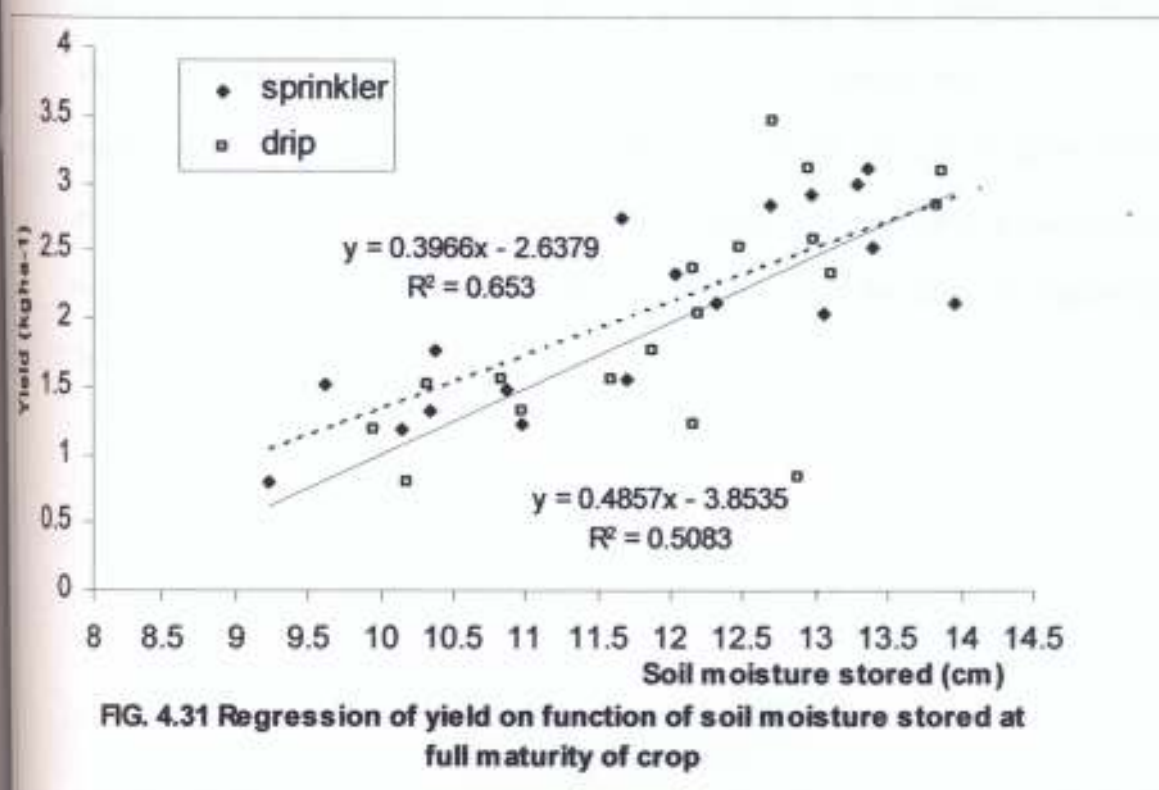
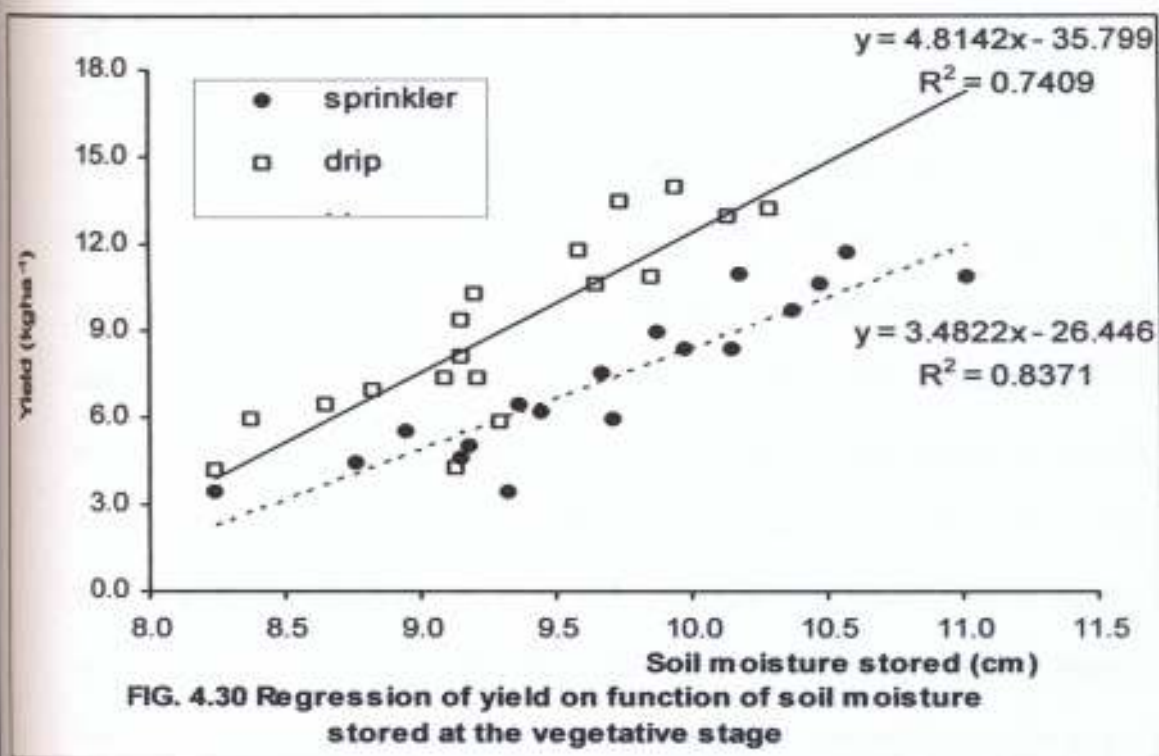
The crop yield model (Quadratic model) based on equation calibrated on *Amaranthus cruentus* showed good agreement with the field data. The result of the model is presented in Figure 4.28. The correlation coefficient (R^2) of the model output and the measured value of yield was significantly high (0.79). Parametric constants a and b from the model were -0.28 and 3.84 respectively.



Maximum crop yield was estimated as a function of the soil moisture availability. The highest and the lowest crop yield obtained in treatments DT2 and DT18 were 13.94 and 4.2 tonha⁻¹ respectively.



The yield variations on sprinkler and drip plots are shown in Figure 4.29. The highest and the lowest yield from the sprinkler plots were observed in treatments T2 and T18 with values 11.16 and 3.39 tonha⁻¹ respectively. The yield on drip plots were observed to be higher than what was obtained on sprinkler plots for all treatments. The control experiment though received the highest amount of water was found to be lower in yield when compared to the yield in treatment plot T2. Figure 4.30 and 4.31 show the linear regression model carried out on the yield of *Amaranthus cruentus* in response to soil moisture. It was observed that at the vegetative stage of the crop, the correlation coefficient between the yield and soil moisture was higher ($R^2 = 0.84$) on drip plots than on sprinkler plots (0.74). However, at full maturity/senescence, the R^2 value was reduced and this was due to yield reduction from both systems of irrigation and the leaf drops that accompanies maturity.



4.6 ET-Yield Model

Relationship “Yield – Evapotranspiration” for the dry season experiment of 2005 shows that *Amaranthus cruentus* differs in sensitivity to water deficit in the separate developmental stages (Figures 4.32 and 4.33). The relationship between yield and evapotranspiration was expressed by a linear equation in relative terms (Shalhevet, 1979 and reported by Varlev *et al.* (1994). Obviously, the relative relationship “yield – evapotranspiration” varied with variation in water supply to crop and also to variations in rainfall and air temperature. The coefficient of correlation between relative yield and relative evapotranspiration were significantly high, $R = 0.78$ and 0.74 for the drip and sprinkler irrigation systems respectively. This result shows that the yield of *Amaranthus cruentus* under the drip irrigation system have a higher correlation with the crop water use. It is therefore logical that dimensionless relationship would be universally applicable for different crops and soil conditions. It is evident from the models that experimental observations are quite satisfactory interpreted with the linear model. The relationships “yield – evapotranspiration” with linear equations gave a high precision within the range of $0.2 - 1.00$ of relative yields, which includes all economically important yield.

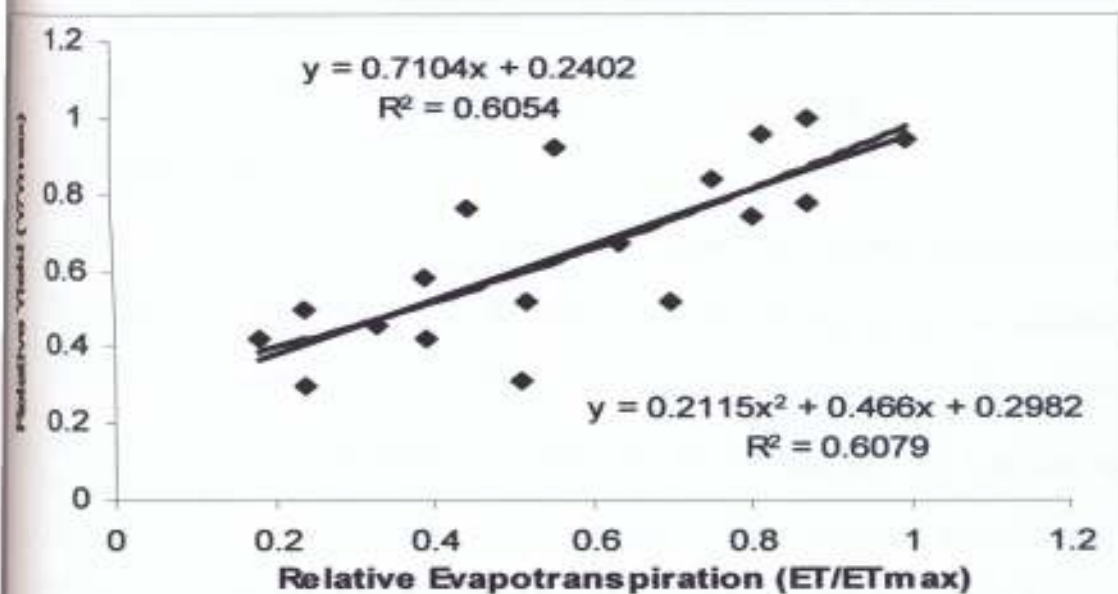


FIG.4.32 Relative yield against Relative evapotranspiration on drip plot during the dry season of 2005

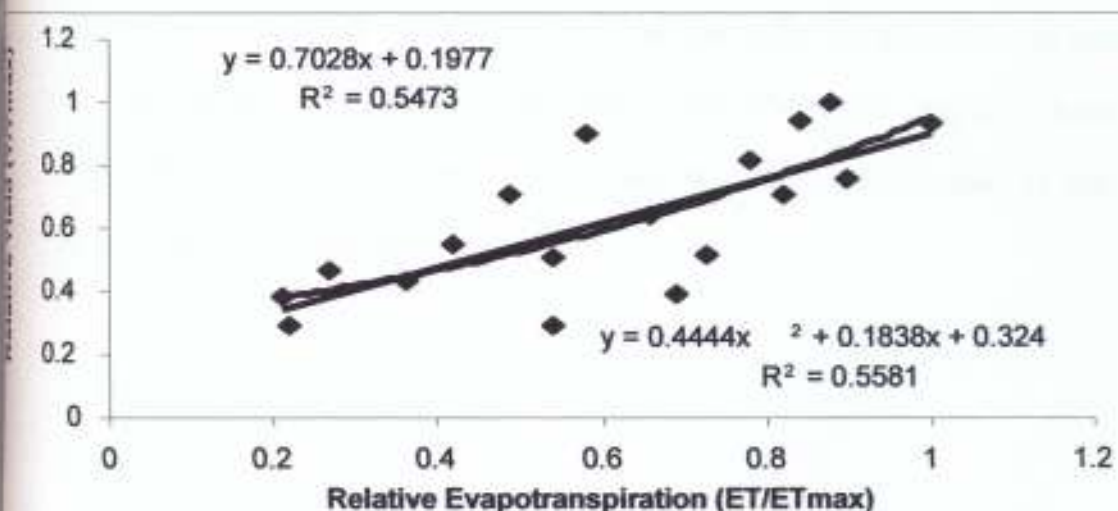
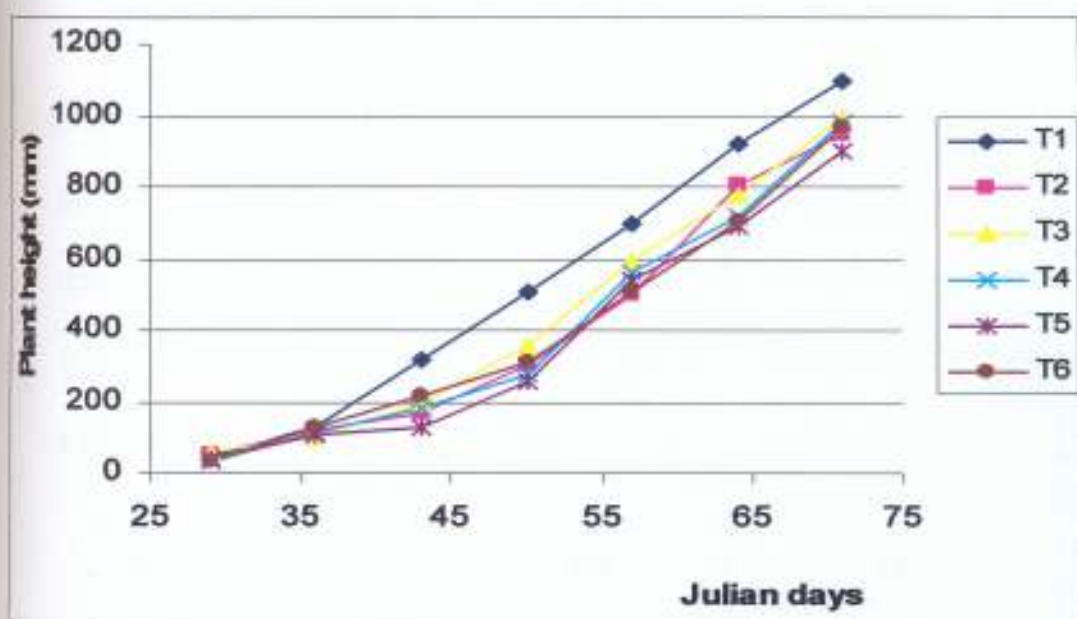


FIG. 4.33 Relative Yield against Relative Evapotranspiration on sprinkler plots during the dry season of 2005

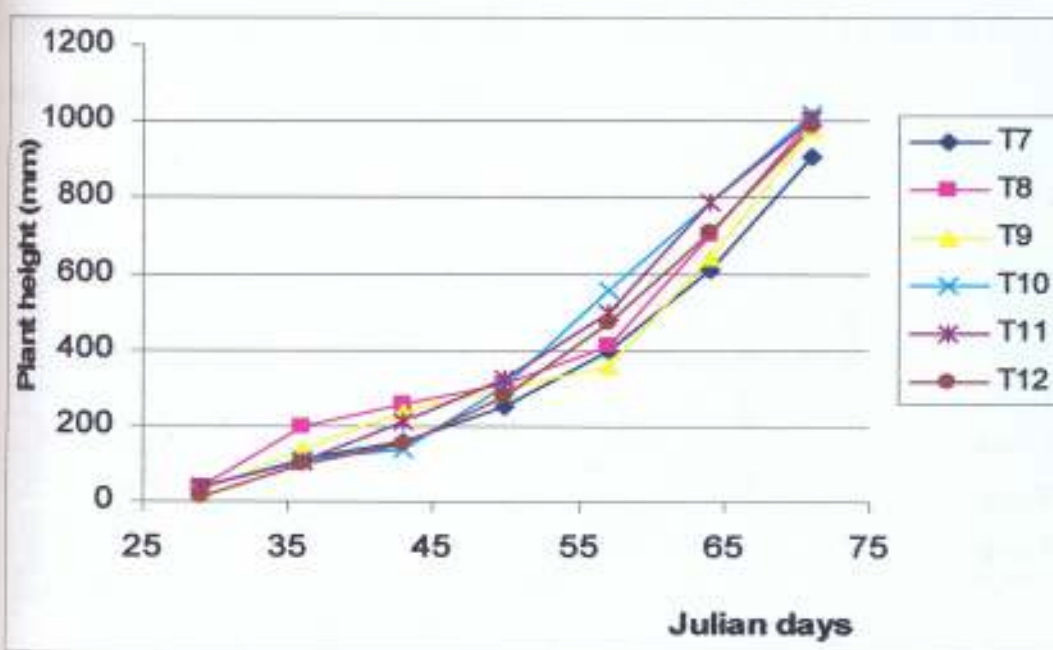
4.7 *AMARANTHUS* AGRONOMIC CHARACTERISTICS

4.7.1 Plant Height

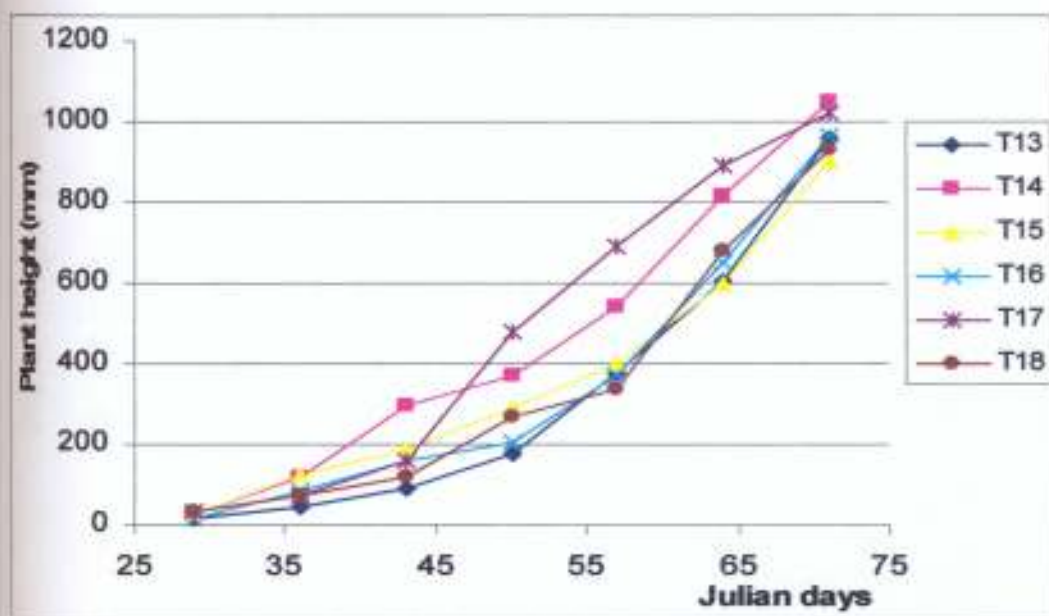
The results of plant height for all treatment plots under drip and sprinkler irrigation systems are presented in Figures 4.34 – 4.37. The highest plant height was recorded in treatment plot T1 for both irrigation methods. The sprinkler irrigation plot T1 increased in height from 49 – 110 cm during the dry season experiment of 2005. The plant height on drip treatment plot T1 also increased from 72 – 90.5 cm during the dry season of 2005. However, there were no significant difference in plant height on treatment plots T1 and T2 at 5% level. All other treatments on sprinkler and drip plots were significantly lower when compared with the plant height on treatment plots T1 and T2. *Amaranthus cruentus* growth during the rainy season experiments were considerably lower when compared with the height of crops grown under irrigation. The crop responded rapidly to soil moisture and emerged faster at the earlier stage of the crop during the rain-fed experiment. Growth was however slow and retarded at the vegetative and maturity stages of the crop during the rainy season experiment. This observation may have been caused by frequent rainfalls which sometimes resulted to soil saturation, and consequently lead to reduced aeration within the crop root zone.



(a)

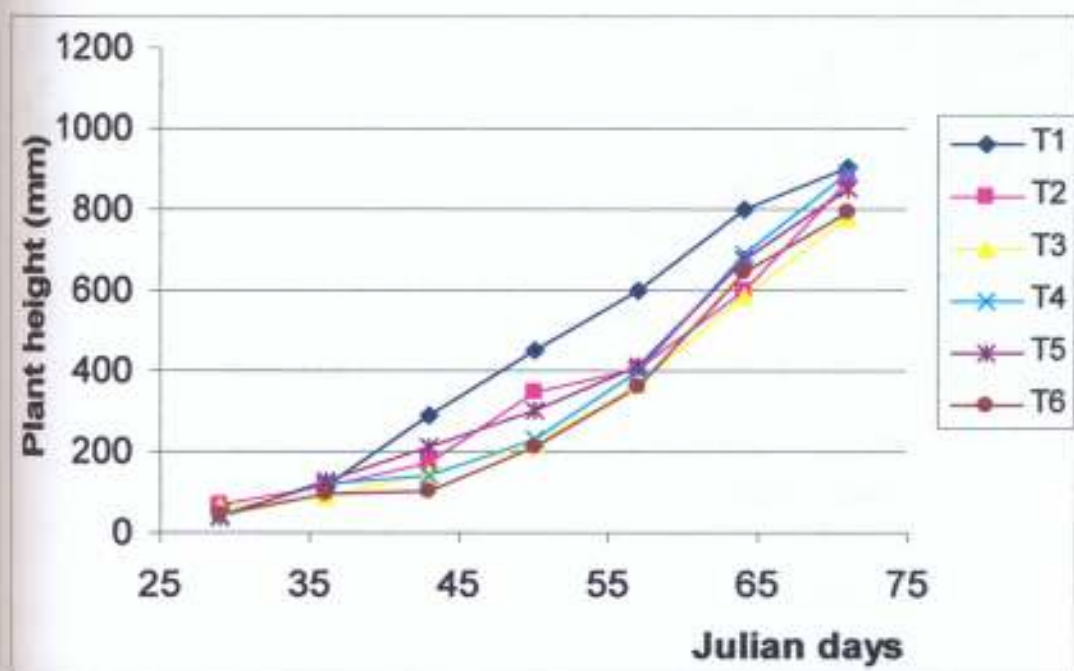


(b)

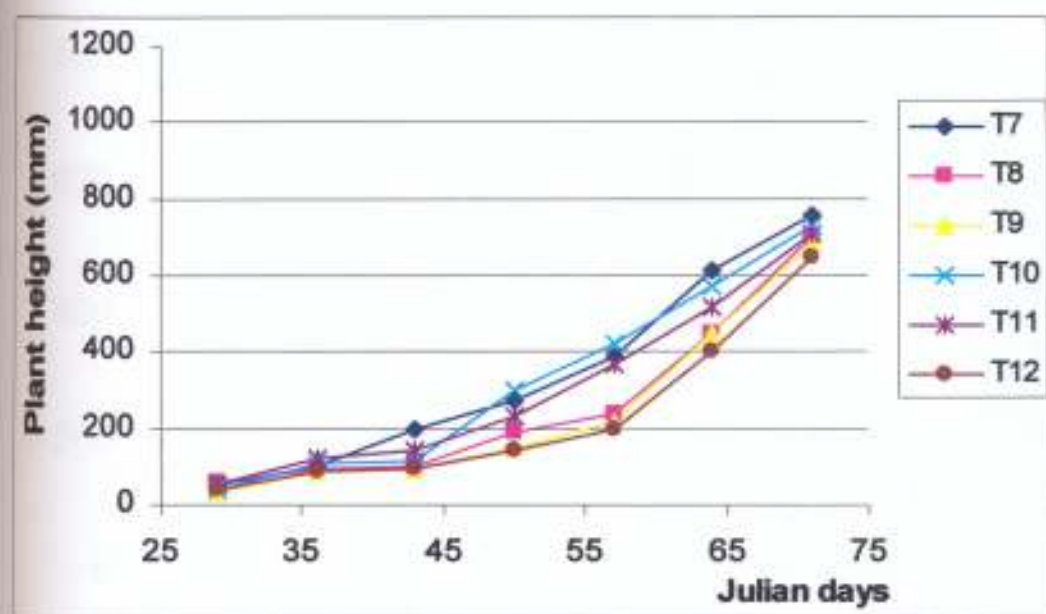


(c)

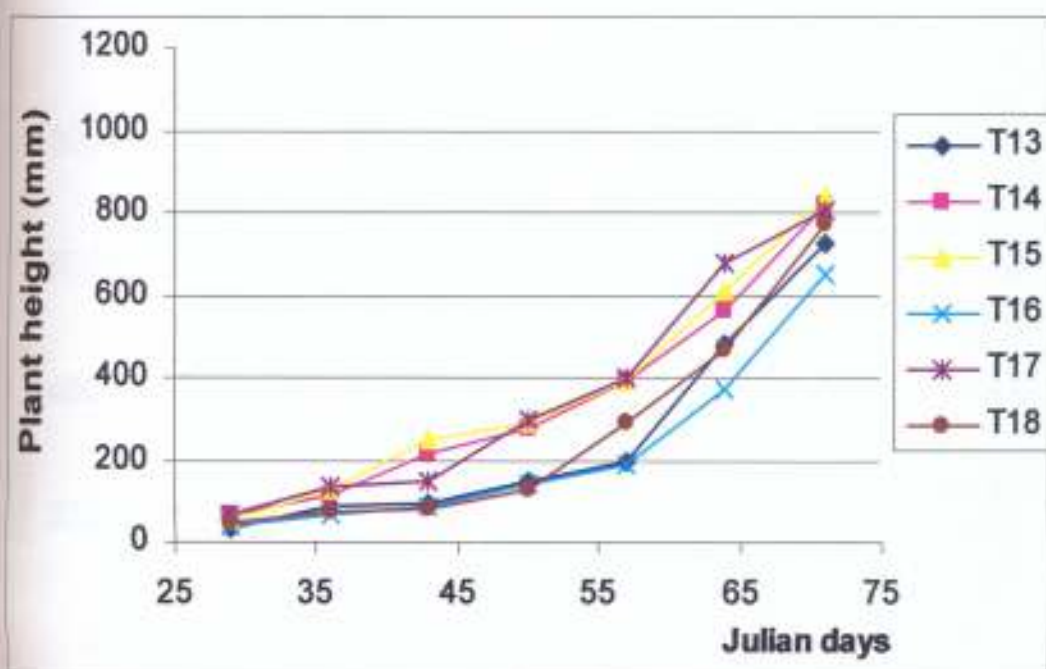
Figure. 4.34 Plant heights on treatment plots ST1 – ST6 (a), ST7 – ST12 (b), ST13 – ST18 (c) during the dry season experiment of 2005.



(a)

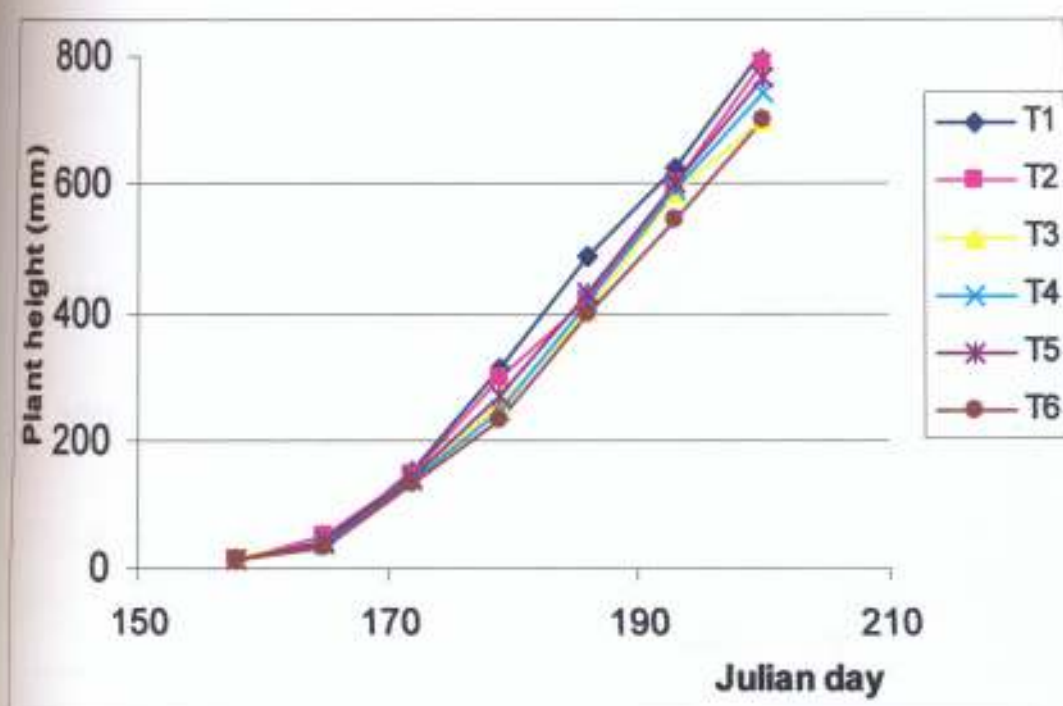


(b)

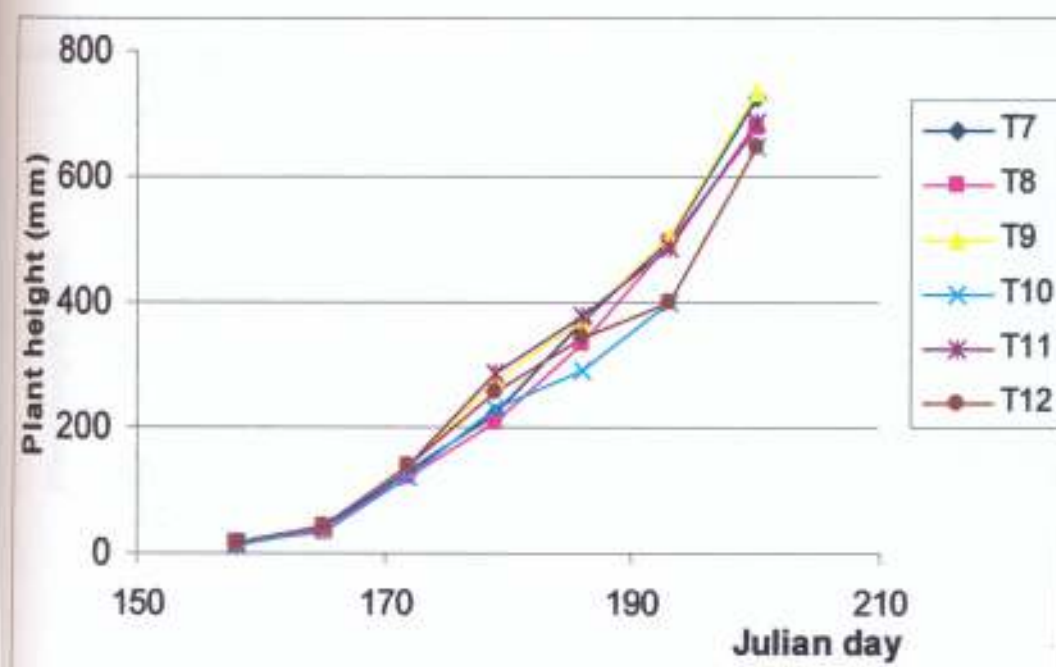


(c)

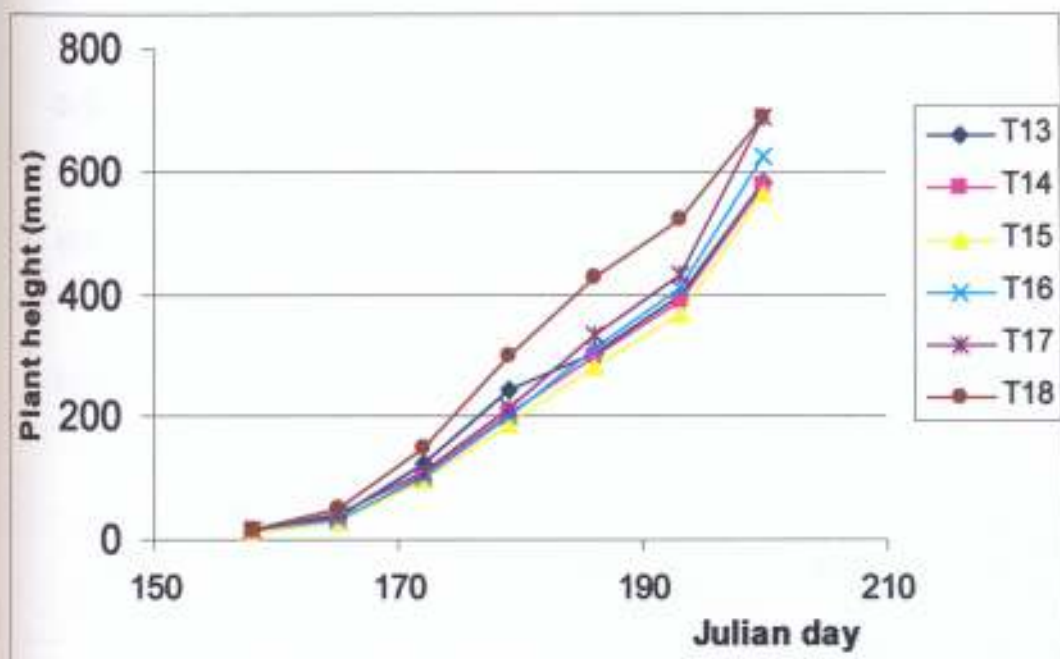
Figure.4.35 Plant heights on treatment plots DT1 – DT6 (a), DT7 – DT12 (b), DT13 – DT18 (c) during the dry season experiment of 2005.



(a)

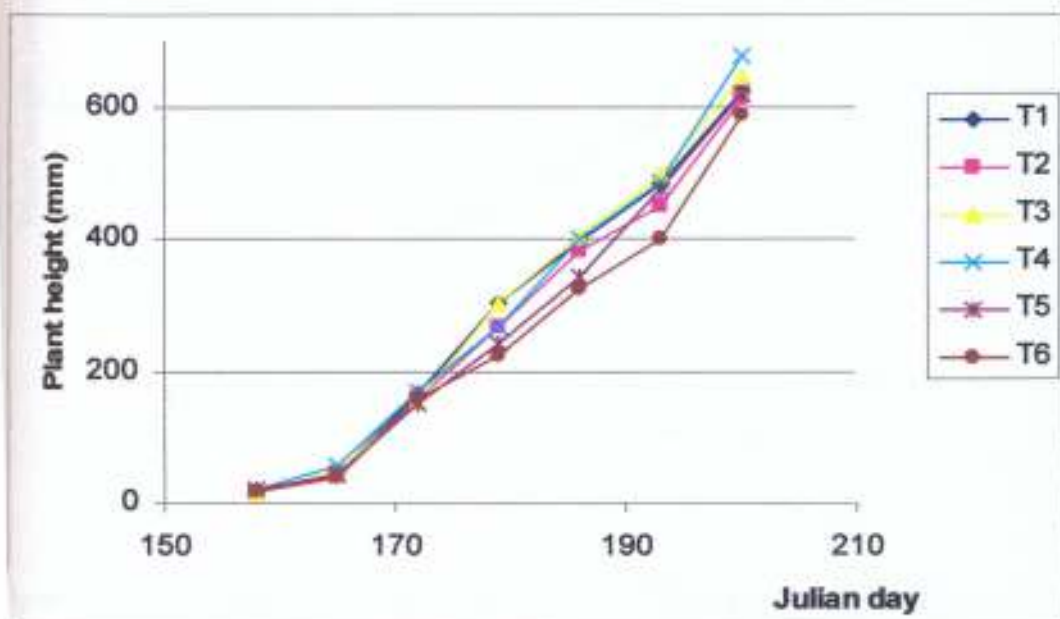


(b)

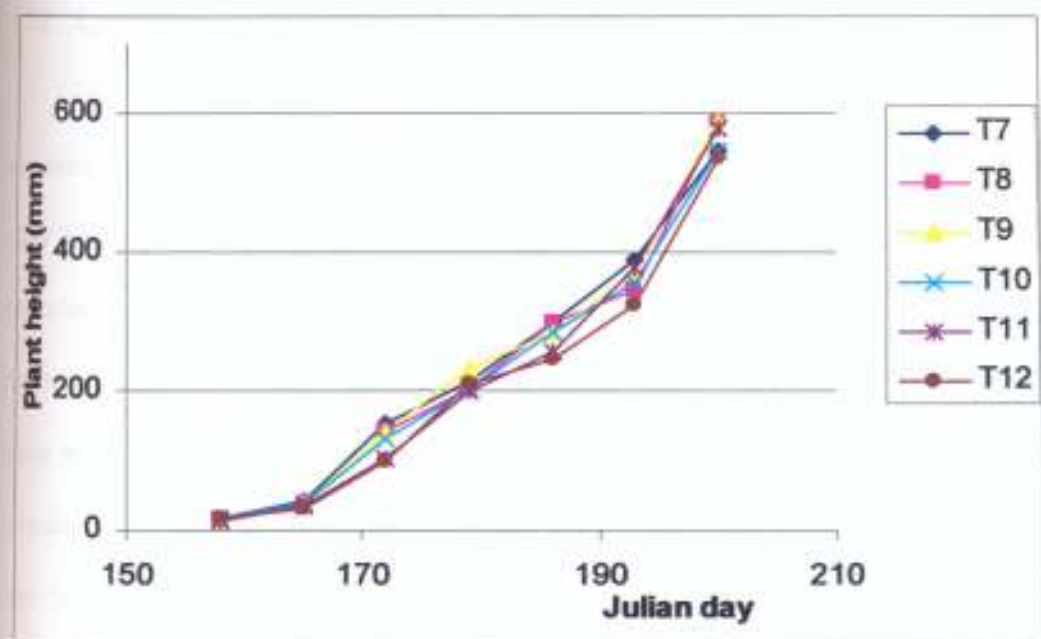


(c)

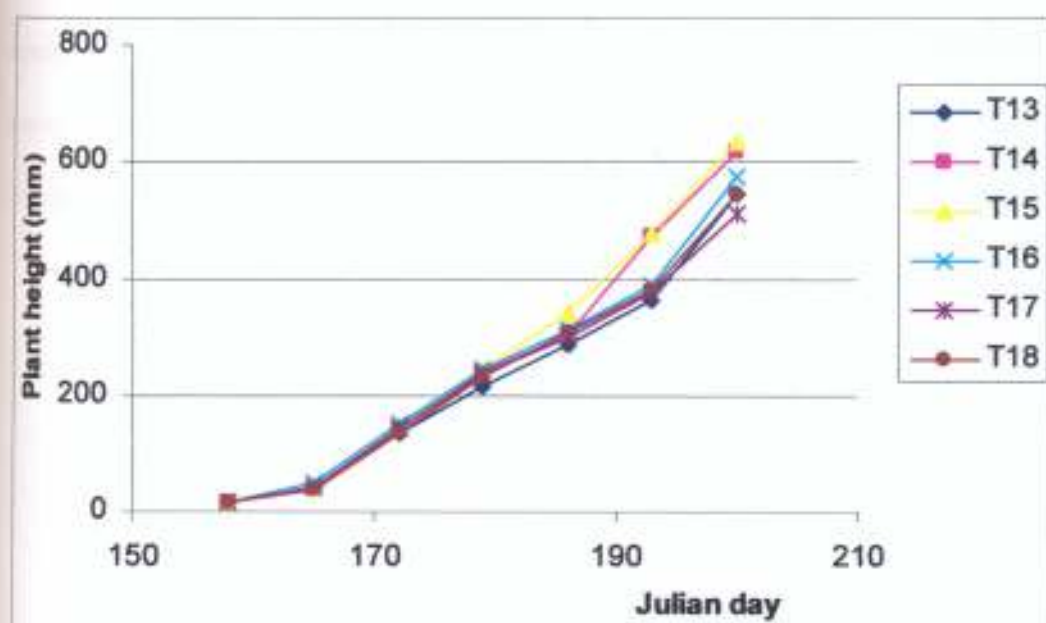
Figure. 4.36 Plant heights on treatment plots ST1 – ST6 (a), ST7 – ST12 (b), ST13 – ST18 (c) during the rainy season experiment of 2005.



(a)



(b)



(c)

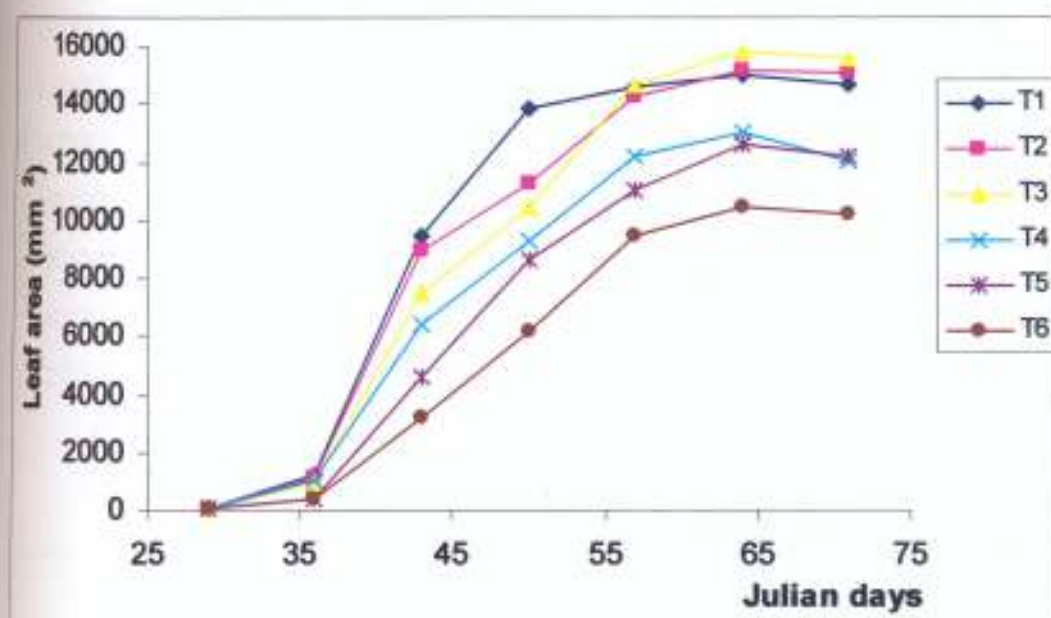
Figure. 4.37 Plant heights on treatment plots DT1 – DT6 (a), DT7 – DT12 (b), DT13 – DT18 (c) during the rainy season experiment of 2005.

4.7.2 Leaf Area

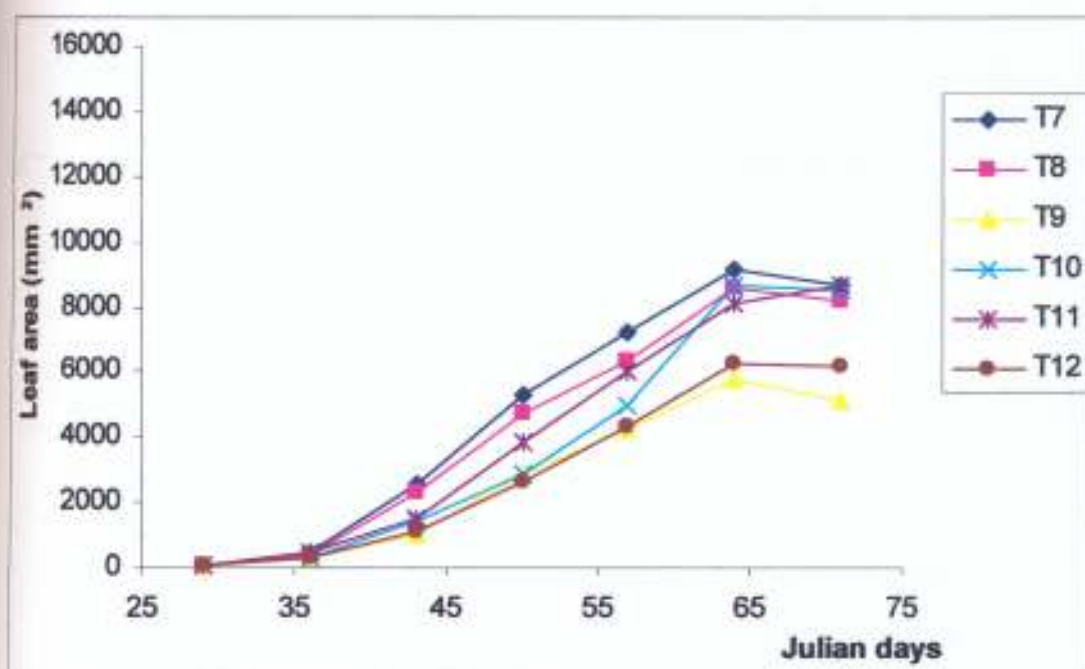
The result of leaf area on function of days of the year during 2005 and 2006 is presented in Figures 4.38 – 4.41. *Amaranthus* grown under irrigation produced luxuriant and wider leaves when compared with crop grown under rain-fed condition. The poor leaf formation of crops grown under rain-fed could be due to frequent rainfalls that resulted to pest and diseases infestation. Samples of *Amaranthus* grown under drip irrigation performed better in terms of leaf area formation when compared with samples grown under sprinkler irrigation system. This must have resulted from point application of water to the root zone of crop which brought about a better water use by the crop during anabolic and catabolic processes.

Generally, leaf area of *Amaranthus* during the second growing season (2006 experiments) was less comparatively with leaf area of crop samples that received same water treatment during the 2005 experiments. The reduced leaf area formation must have been caused by reduction in soil micro and major elements during the second year experiments.

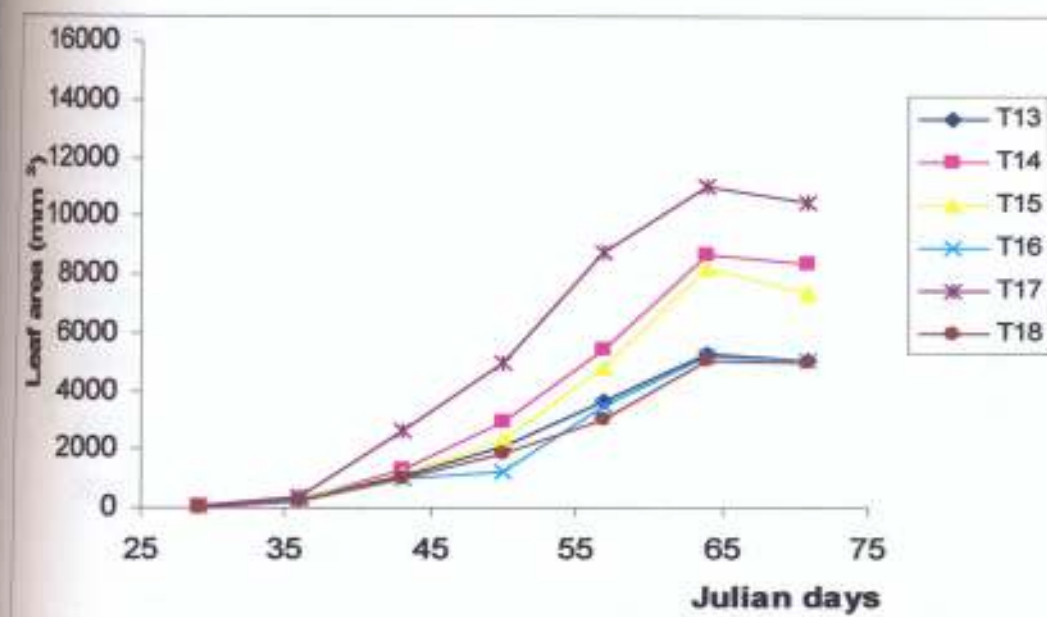




(a)

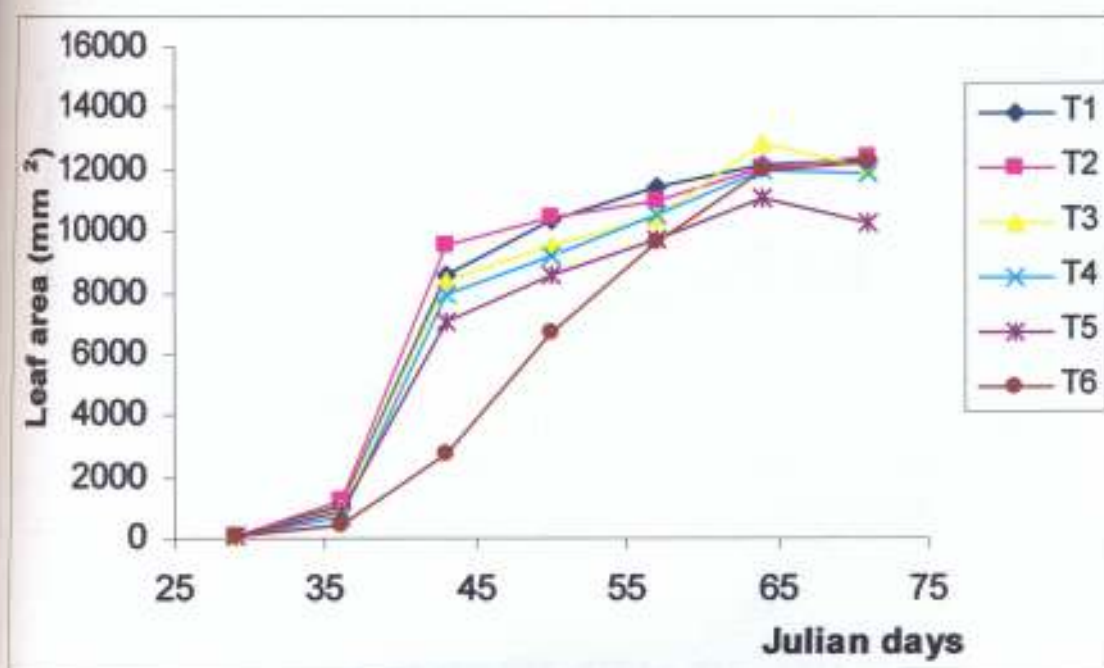


(b)

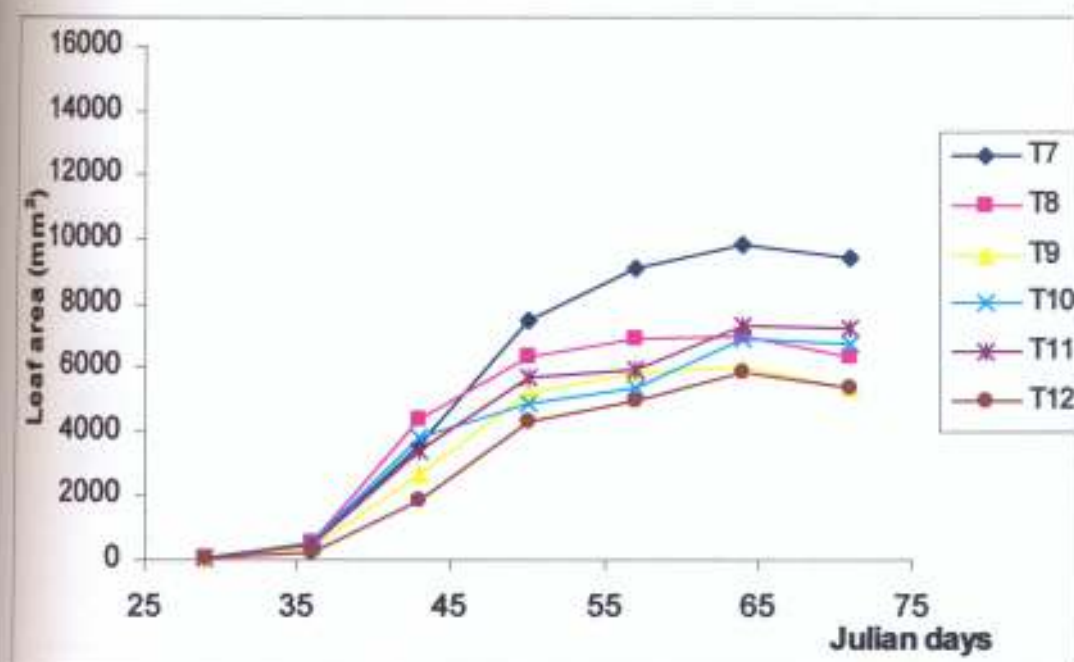


(c)

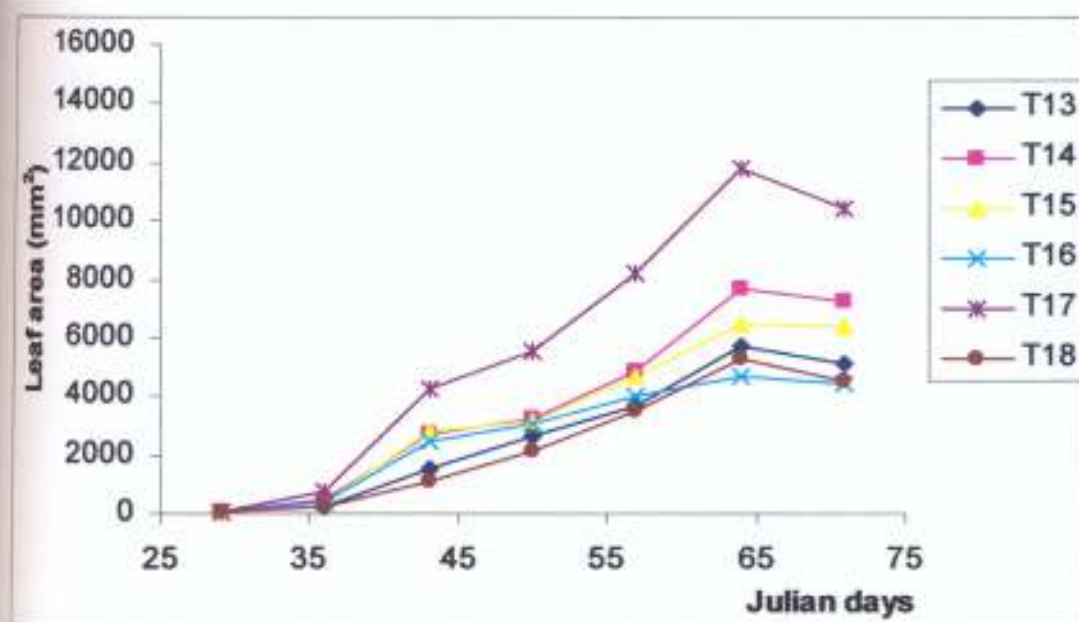
Figure.4.38 Leaf area of treatment plots DT1 –DT6 (a), DT7 – DT12 (b), DT13 – DT18 (c) during the dry season experiment of 2005.



(a)

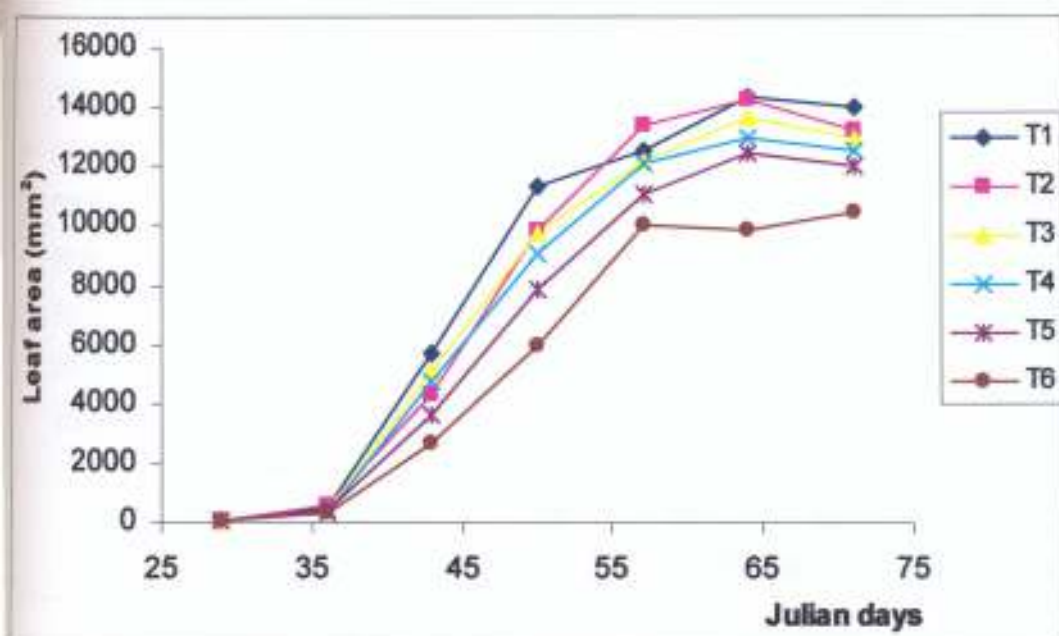


(b)

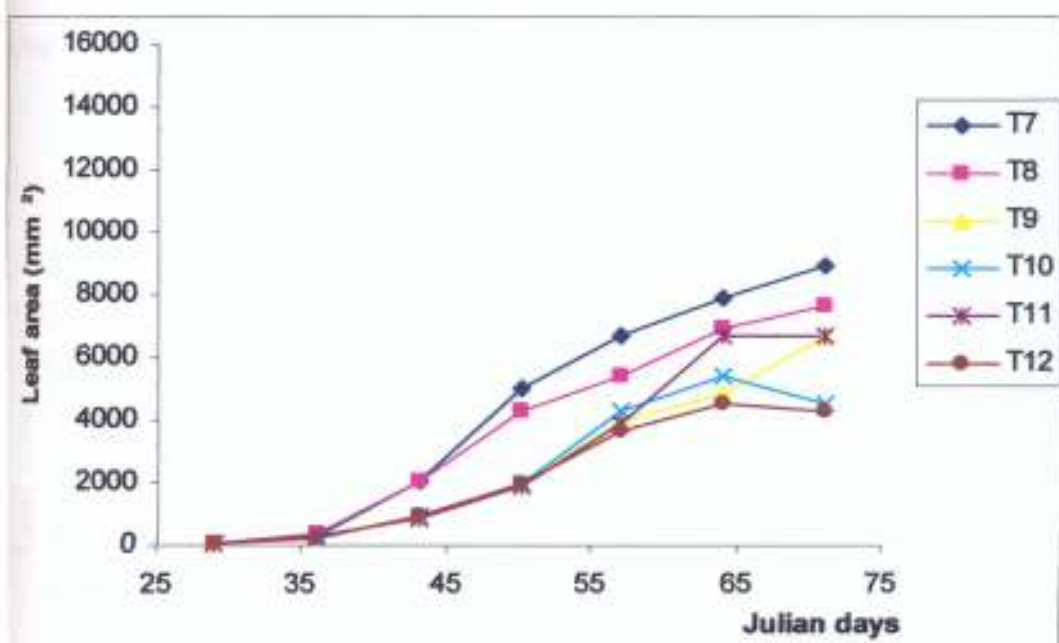


(c)

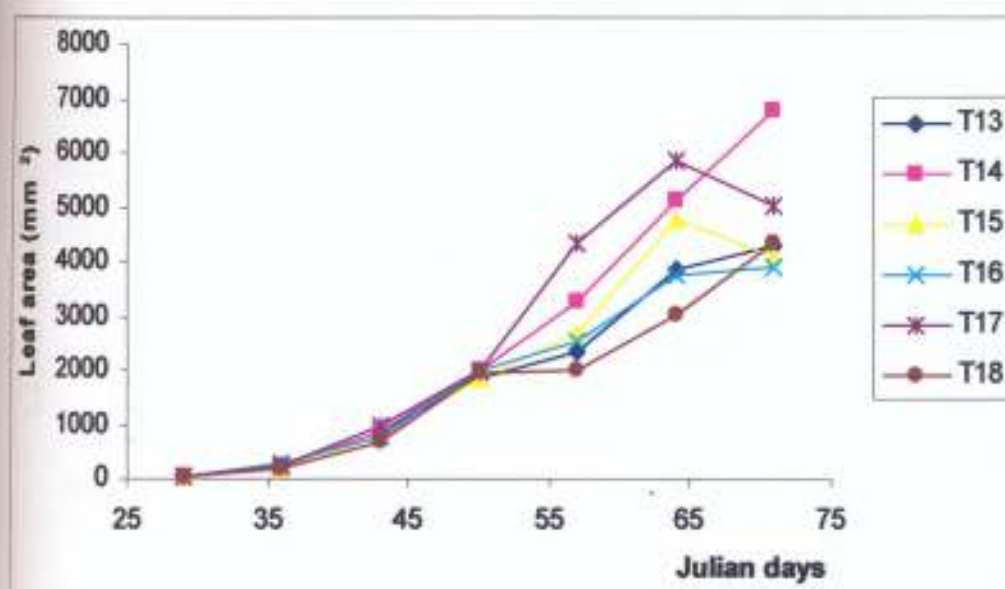
Figure.4.39 Leaf area of treatment plots ST1 –ST6 (a), ST7 – ST12 (b), ST13 – ST18 (c) during the dry season experiment of 2005.



(a)

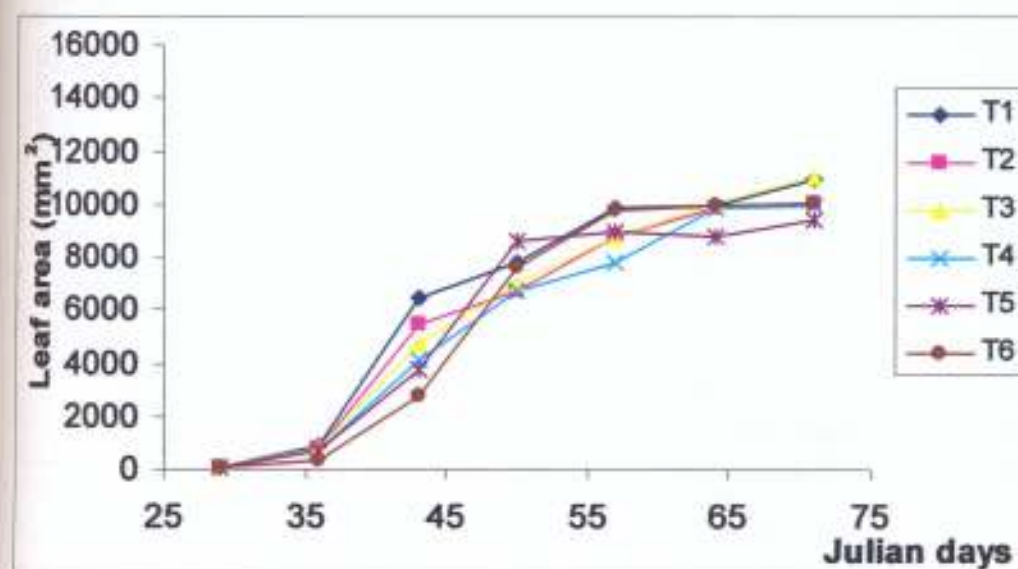


(b)

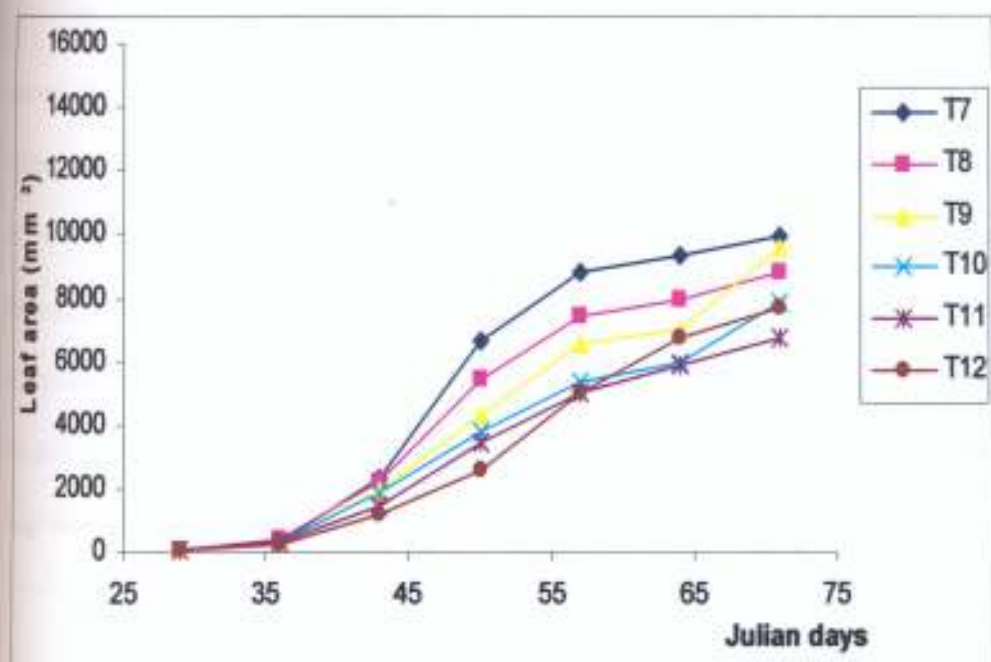


(c)

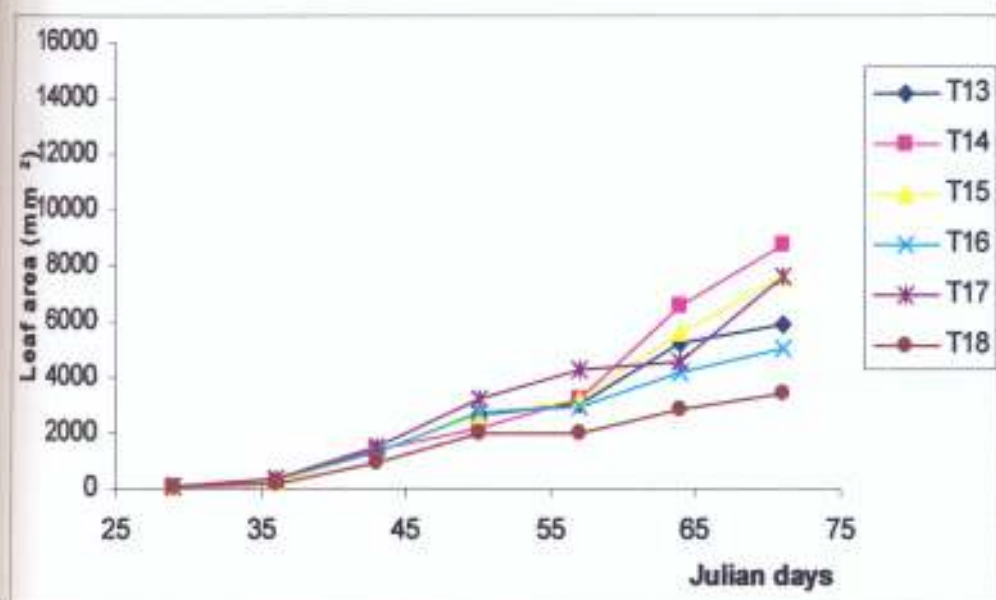
Figure 4.40 Leaf area of treatment plots DT1 –DT6 (a), DT7 –DT12 (b), DT13 – DT18 (c) during the rainy season experiment of 2005.



(a)



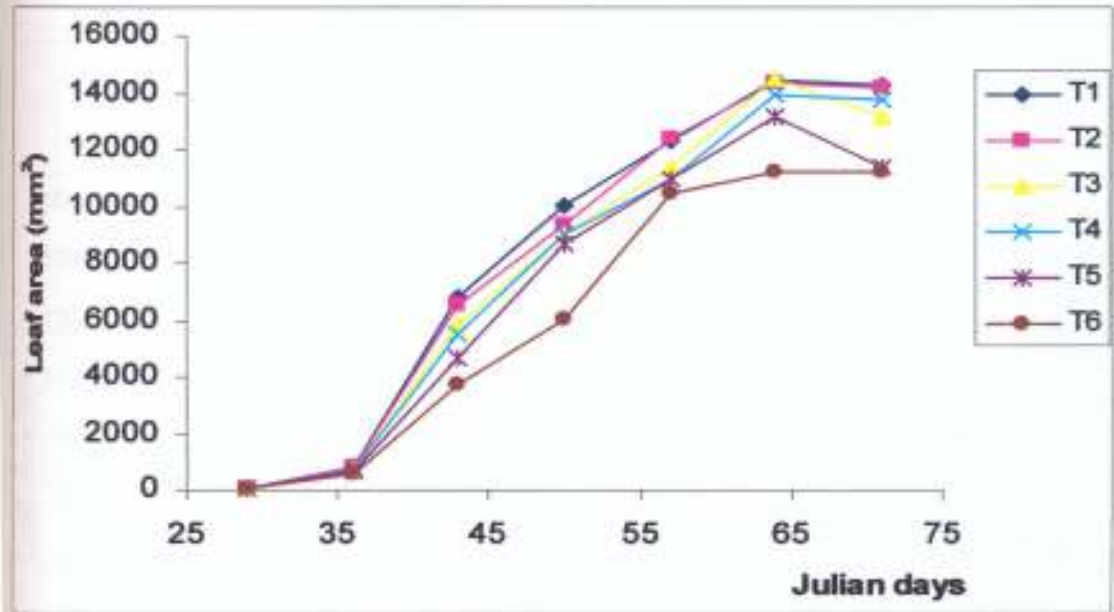
(b)



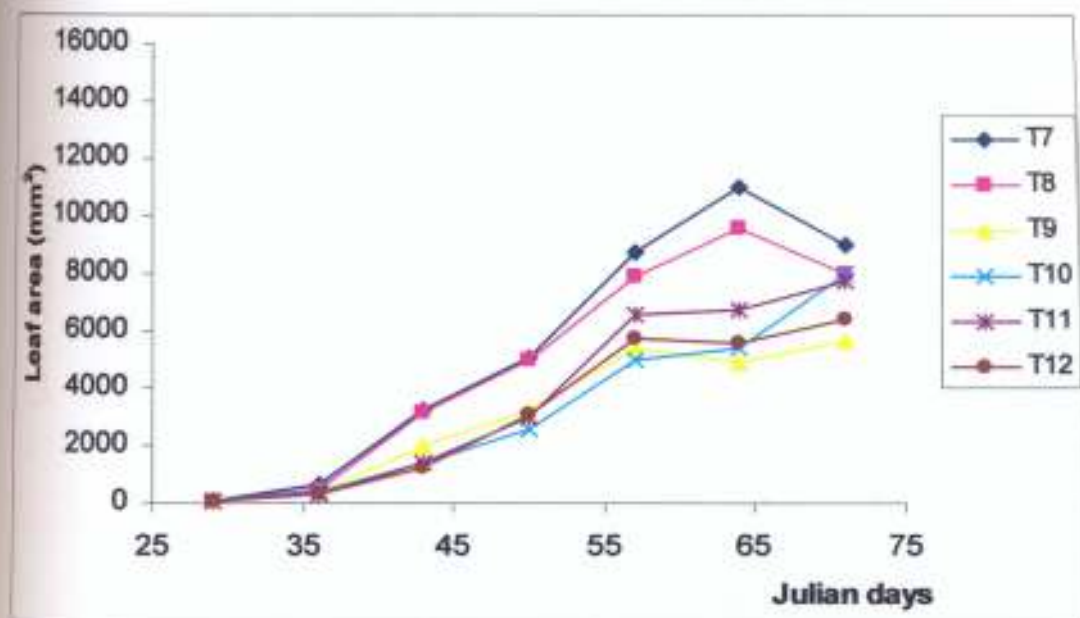
(c)

Figure.4.41 Leaf area of treatment plots ST1 –ST6 (a), ST7 – ST12 (b), ST13 – ST18 (c) during the rainy season experiment of 2005.

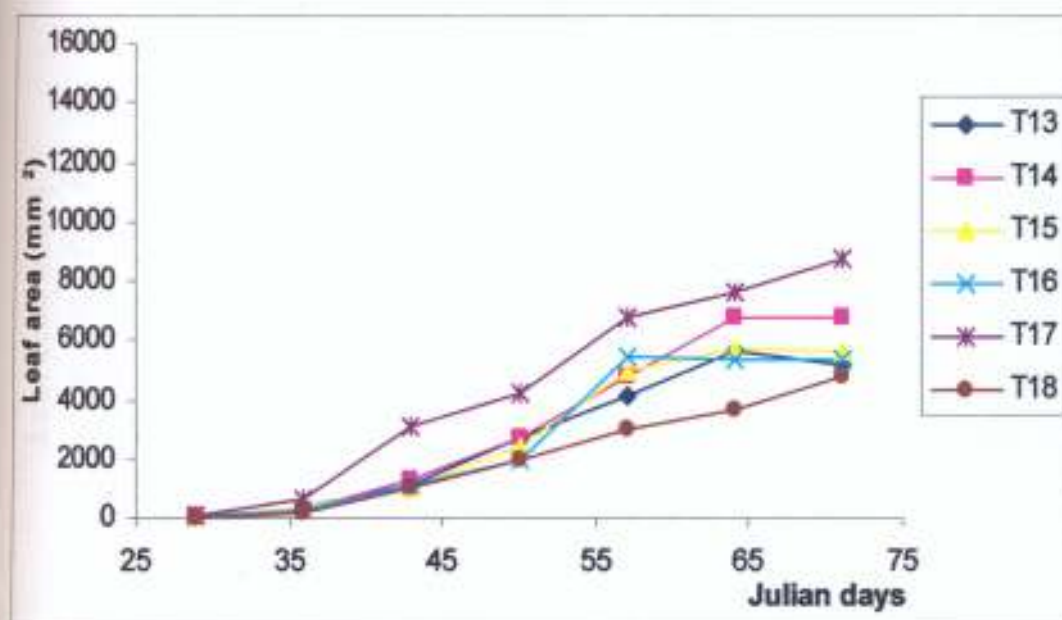
The leaf area obtained from field experimentation during the dry season of 2006 was essentially low than what was obtained during the dry season of 2005 (Figures 4.42 – 4.43) . The difference was not much notice at the emergence stage of this crop but became highly significant at 5% level starting from the 43DOY. The difference may be adduced to soil compaction and destruction of soil structure from the use of tractor and equipment during field preparation. The observed reduction may also be due to reduction in some essential macro and micro elements in the soil. Also, *Amaranthus*, during the second year experiment became vulnerable to pest such as bugs that attacked the leaves, thus, resulting to poor leave formation.



(a)

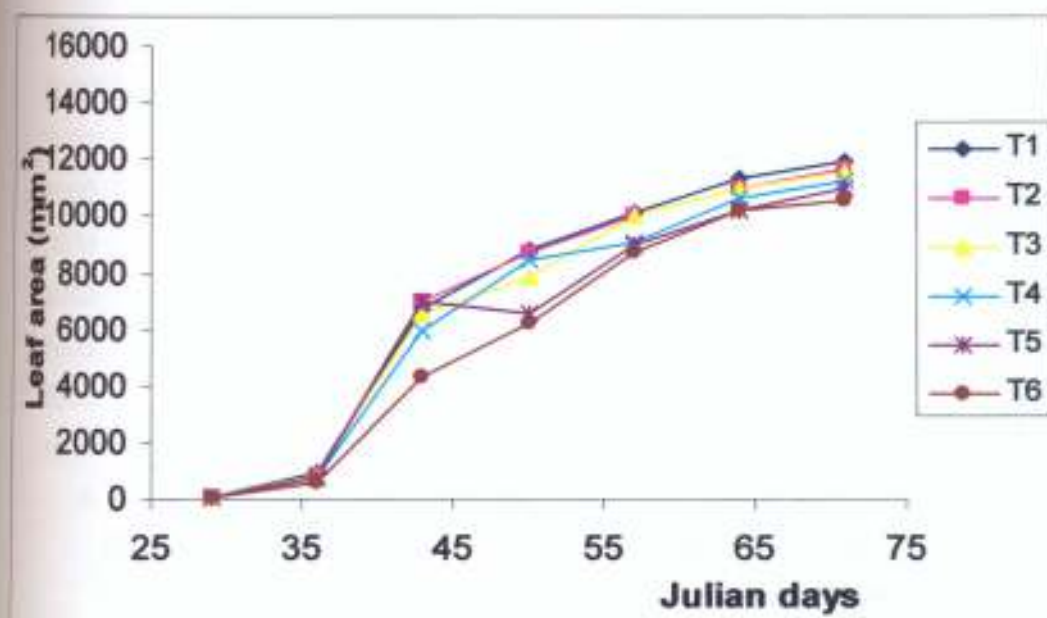


(b)

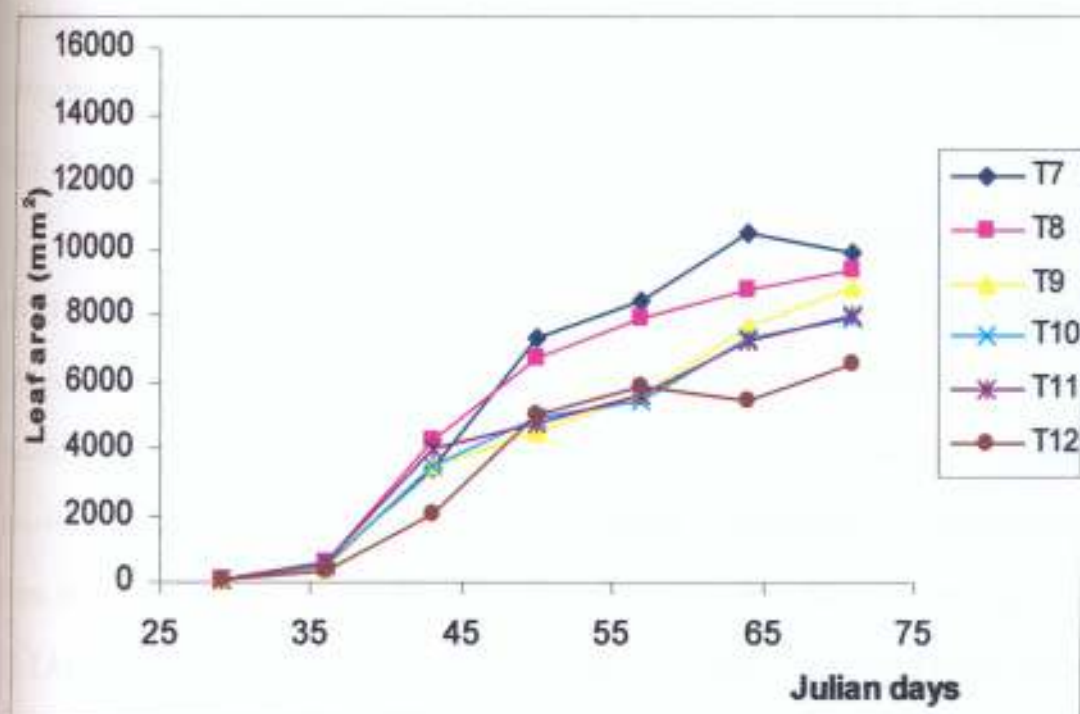


(c)

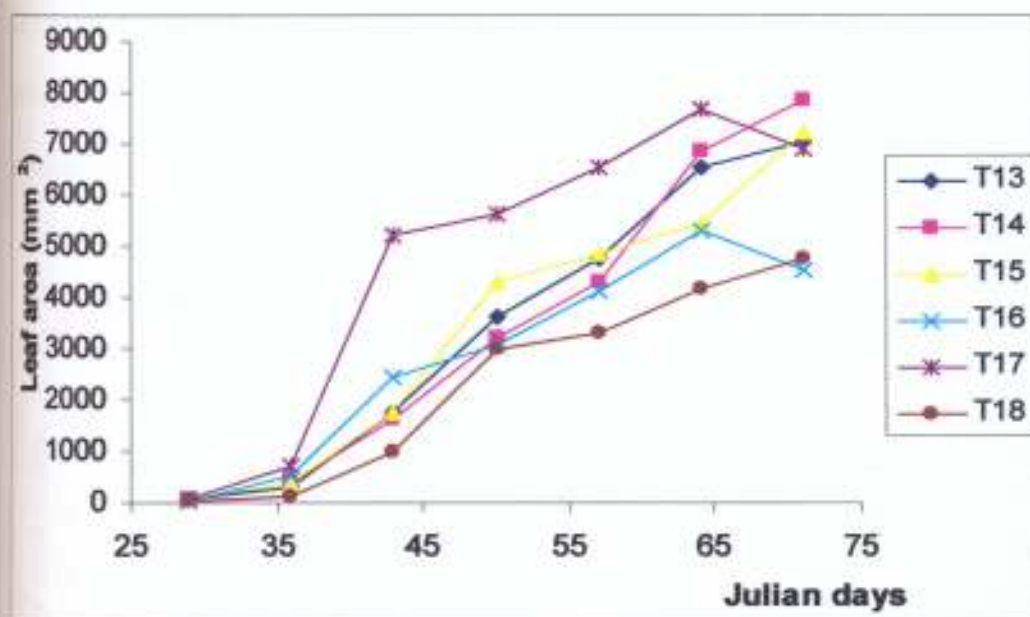
FIG.4.42 Leaf area of treatment plots DT1 –DT6 (a), DT7 – DT12 (b), DT13 – DT18 (c) during the dry season experiment of 2006.



(a)



(b)



(c)

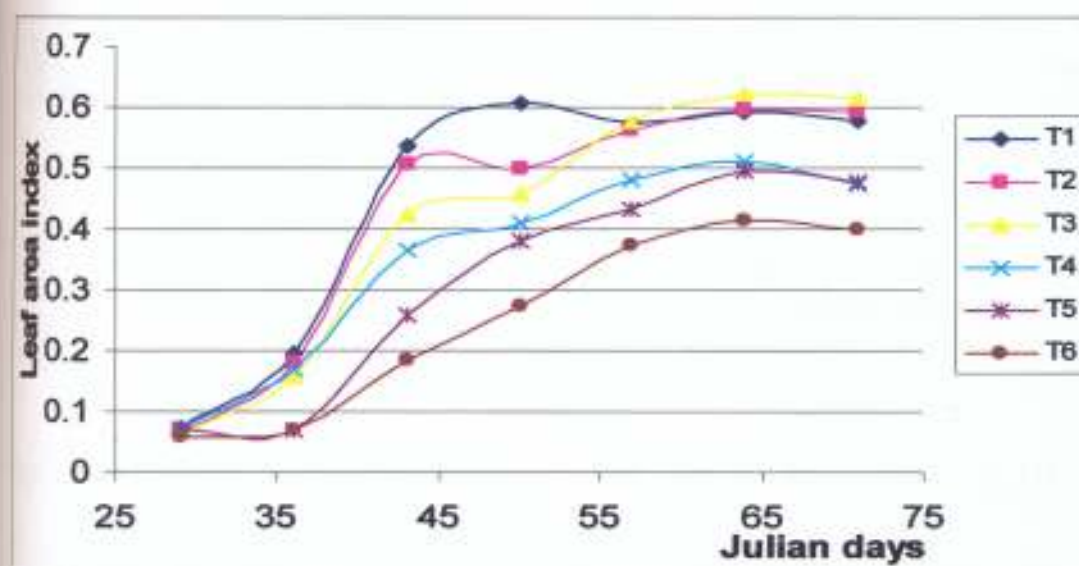
FIG.4.43 Leaf area of treatment plots ST1 –ST6 (a), ST7 – ST12 (b), ST13 – ST18 (c)

during the dry season experiment of 2006.

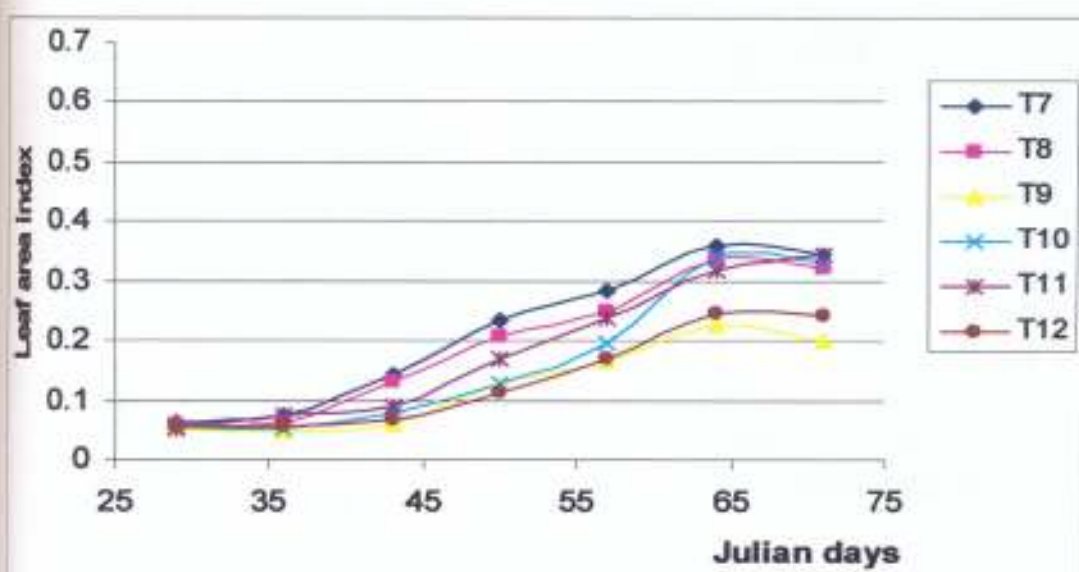
4.7.3 Leaf Area Index (LAI)

Leaf area index (LAI) of *Amaranthus cruentus* samples on all treatment plots for the dry and rainy season of 2005 and 2006 are presented in Figures 4.44 – 4.47. There were increase in LAI from emergence and reached its peak at maturity. However, the LAI reduced when the crop reached senescence. This was due to leaf droppings from sample plots when the crop reached full maturity. The values of LAI were found to be highest in treatment T1 (control experiment). These high values of LAI in treatment T1 were closely followed by observed LAI in treatment T2. LAI increased from 0.075 to 0.577 in treatment T1, while it developed from 0.067 to 0.594 in drip treatment plot T2 during the dry season experiment of 2005.. The difference in LAI between treatments T1 and T2 were not significant at 5% level both at flowering and maturity stages of the crop.. The limited water supply to *Amaranthus* in other treatments affected the

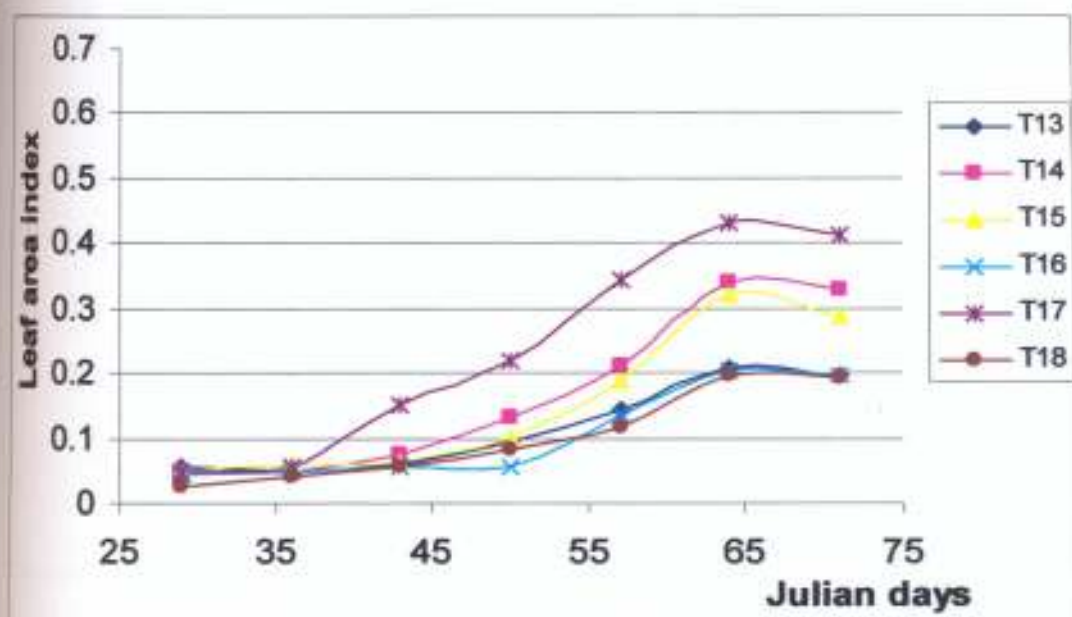
physiological development of the crop, the effect of which was highly pronounced during the maturity stage of the crop when the crop actually needed much more quantum of water for its evapotranspiration.



(a)

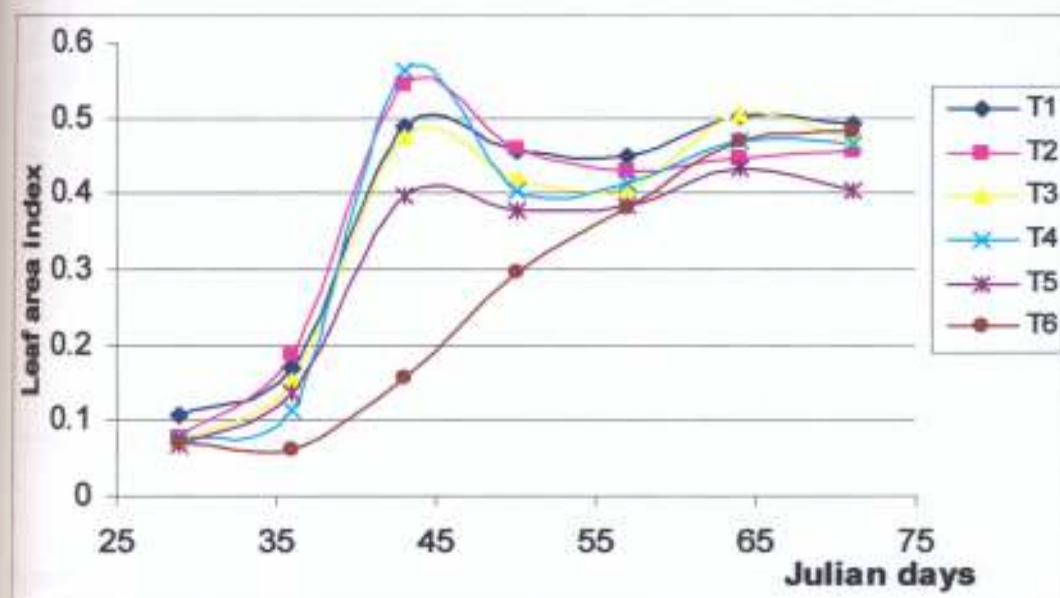


(b)

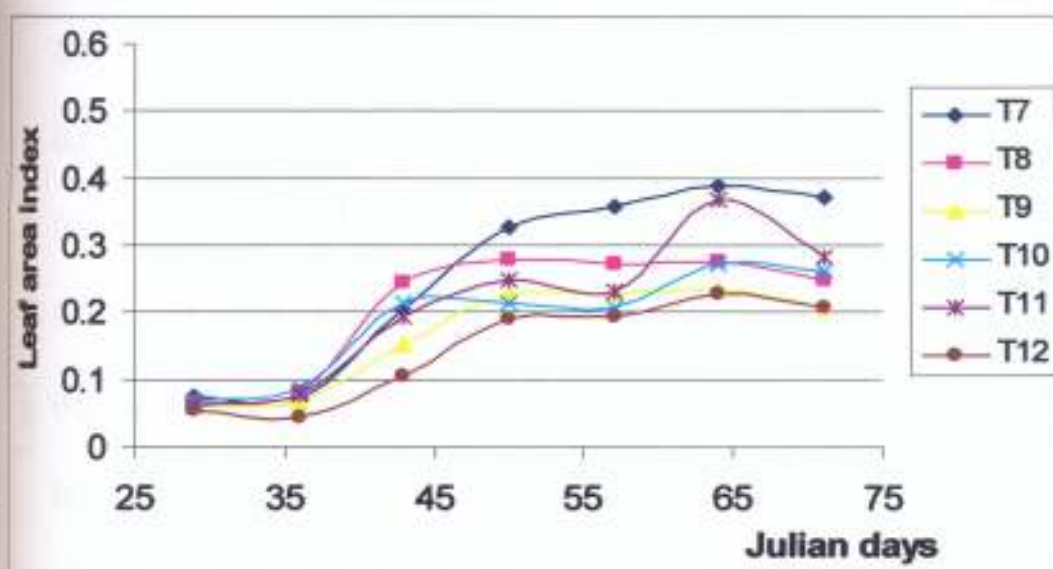


(c)

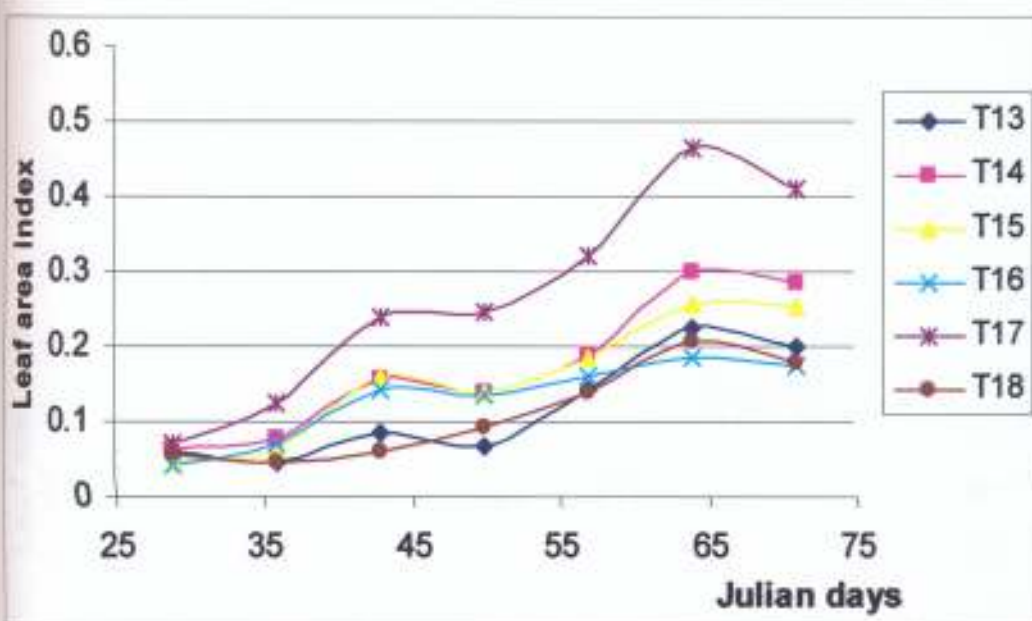
Figure.4.44 Leaf area index of treatment plots DT1 –DT6 (a), DT7 – DT12 (b), DT13 – DT18 (c) during the dry season experiment of 2005.



(a)

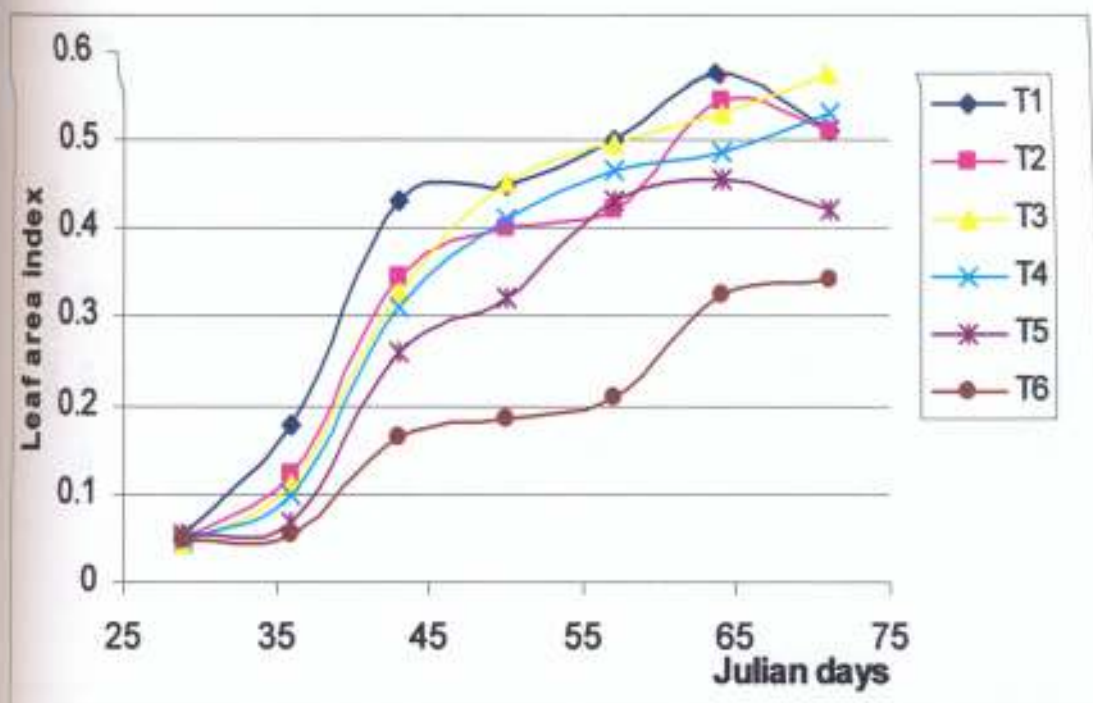


(b)

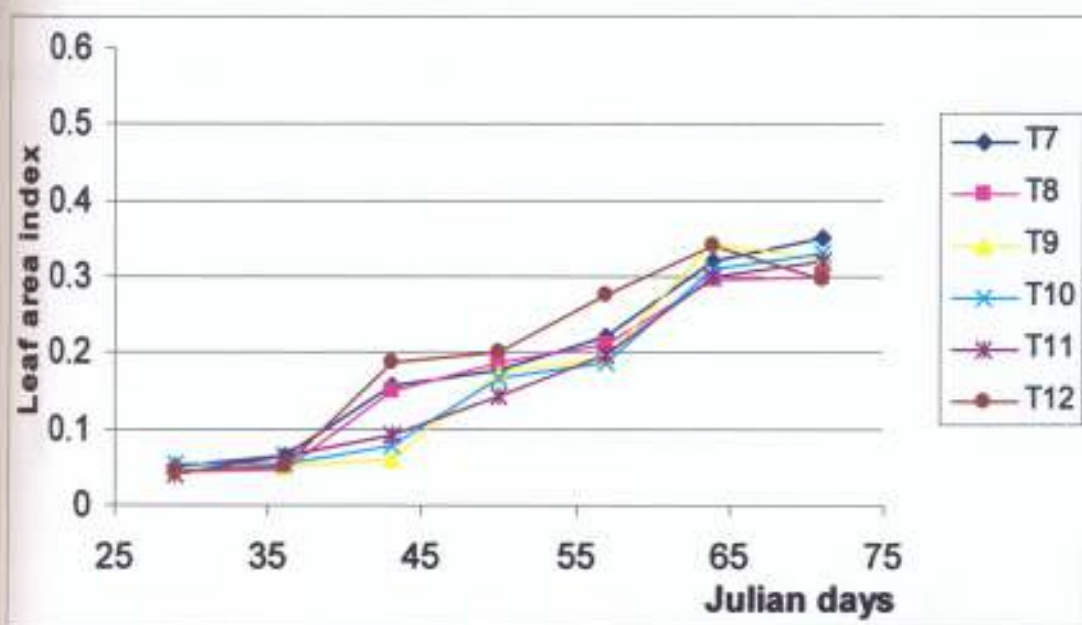


(c)

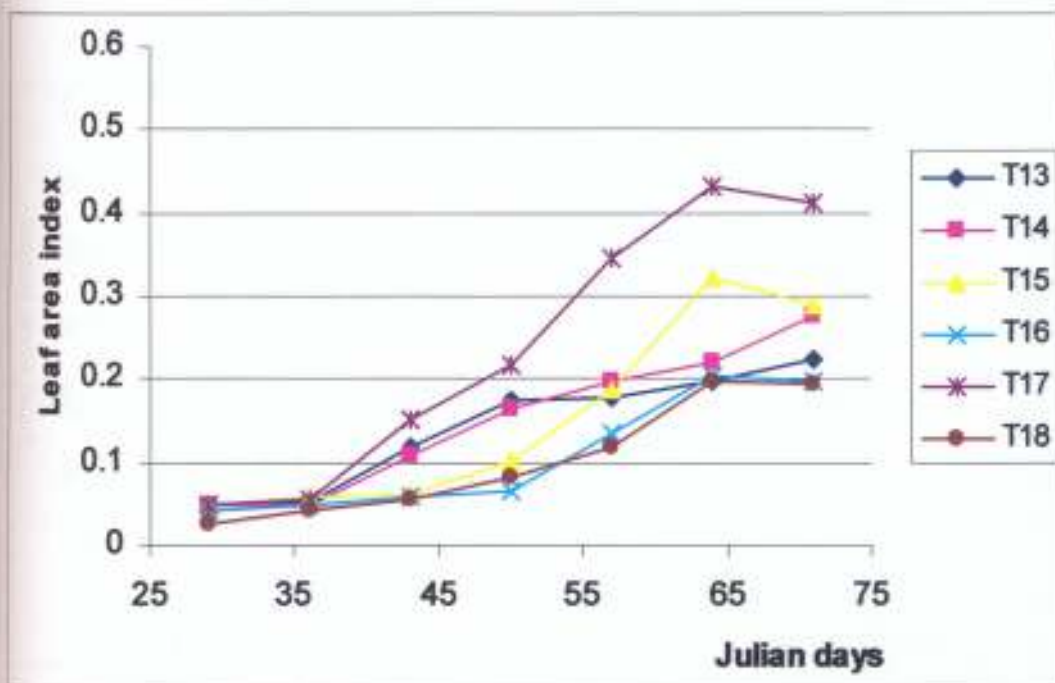
Figure.4.45 Leaf area index of treatment plots ST1 – ST6 (a), ST7 – ST12 (b), ST13 – ST18 (c) during the dry season experiment of 2005.



(a)

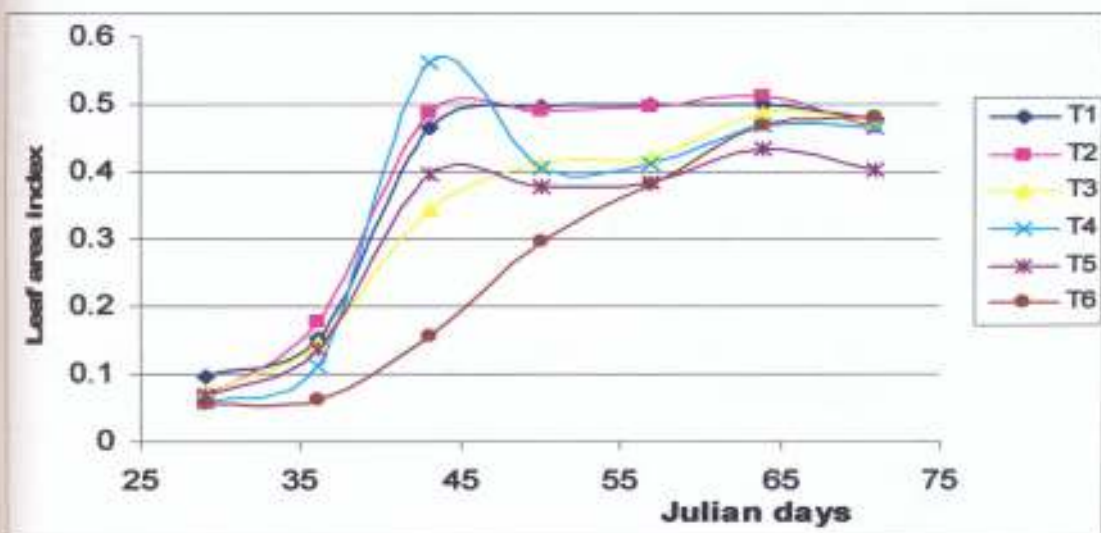


(b)

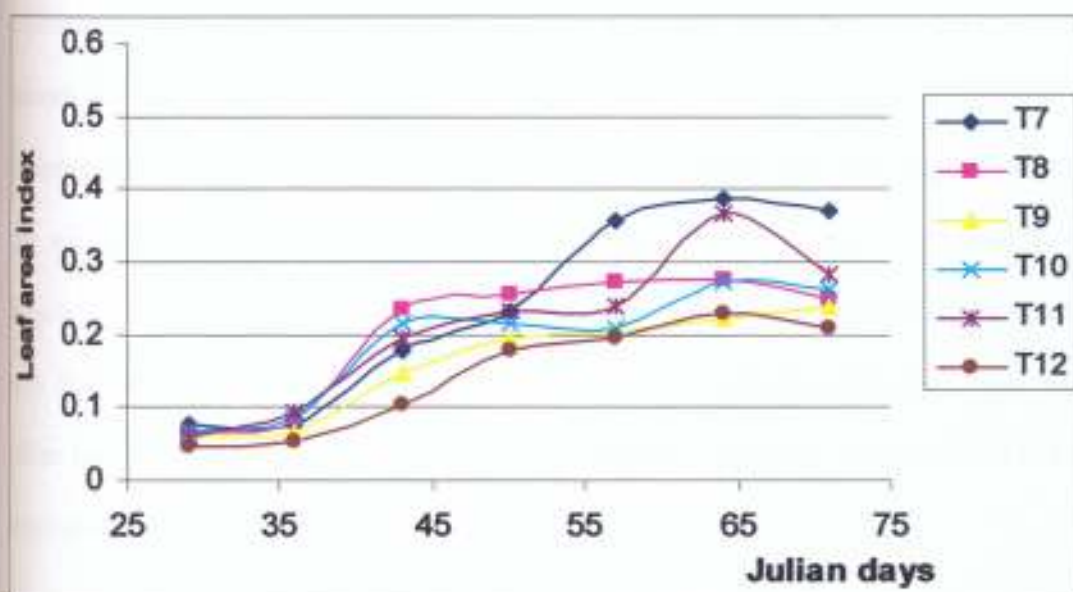


(c)

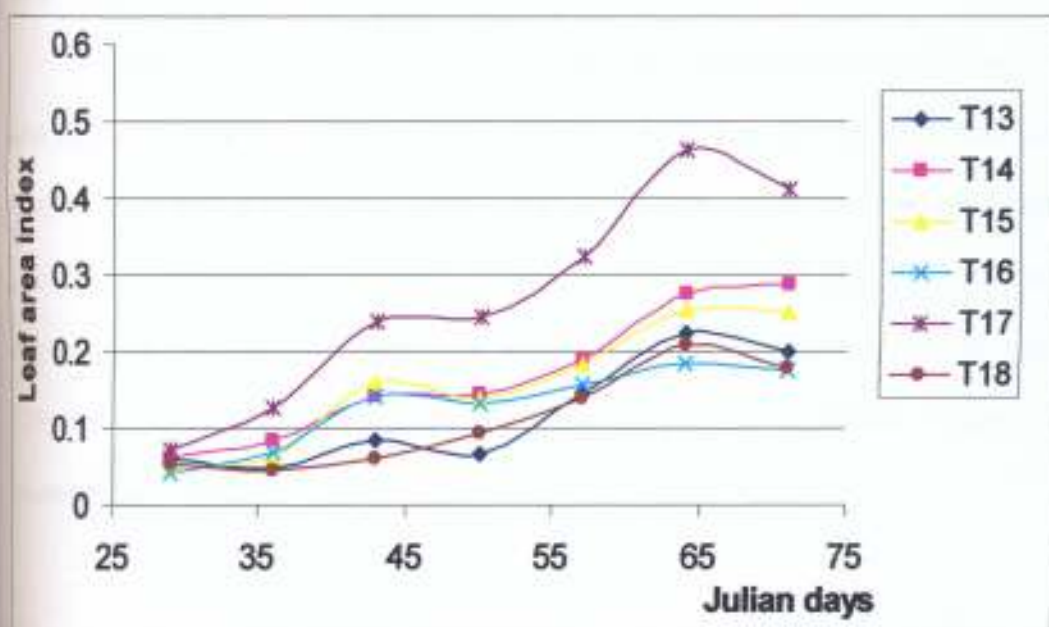
Figure 4.46 Leaf area index of treatment plots ST1 –ST6 (a), ST7 – ST12 (b), ST13 – ST18 (c) during the rainy season experiment of 2005.



(a)



(b)



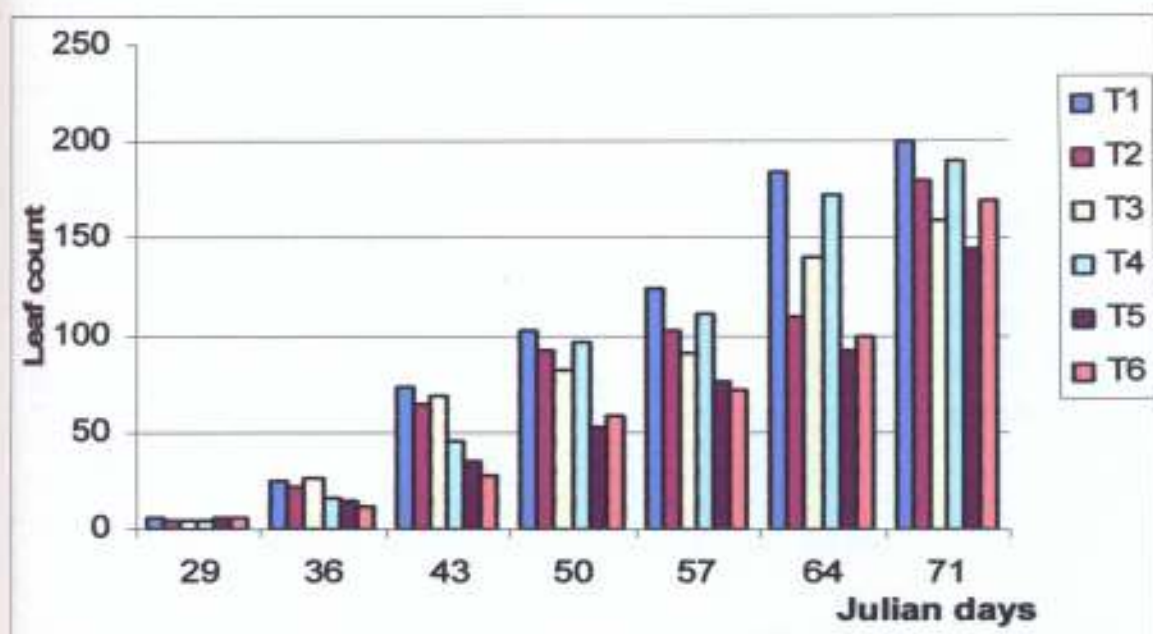
(c)

Figure.4.47 Leaf area index of treatment plots DT1 –DT6 (a), DT7 – DT12 (b), DT13 – DT18 (c) during the rainy season experiment of 2005.

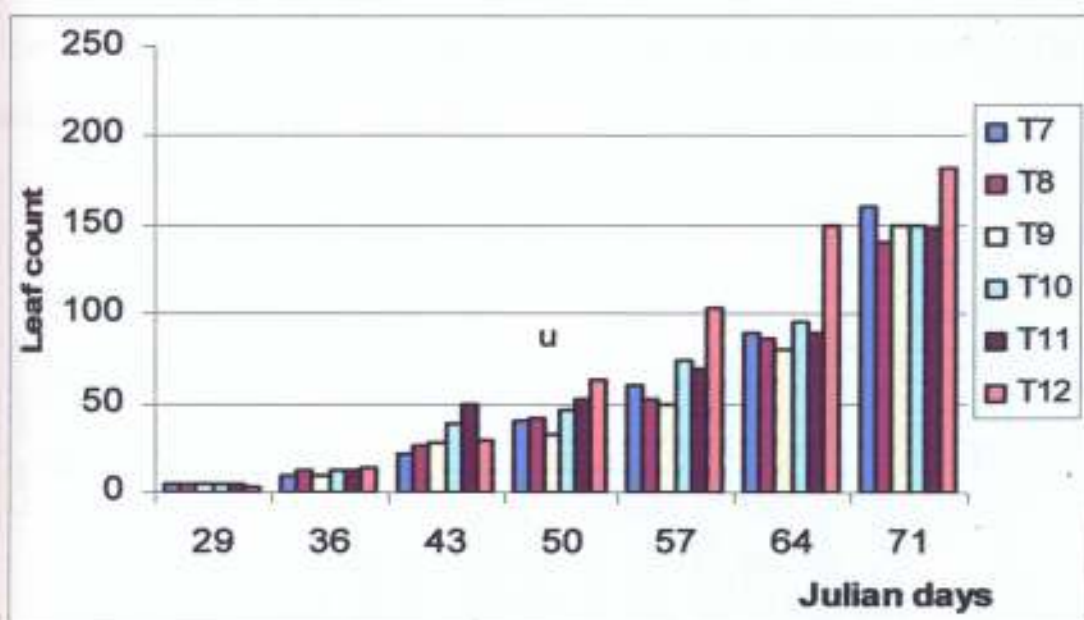
Furthermore, comparison of the first and second season data for the 2005 and 2006 experiments showed a reduction in LAI during the rainy season. LAI differences between dry seasons and the rainy season can be attributed to lower plant population during the dry season experiments. The higher LAI observed during the dry season was not only due to the thinning that was carried out but also to the selective application of water to the sample plots. This irrigation activity prevented to a reasonable level the growth of weeds that could easily compete with the crop. Consequently, *Amaranthus* samples on treatment plots were able to effectively utilize the water supplied to it, thus producing broad and luxuriant leaves during the dry season irrigation experiments.

4.7.4 Leaf Count

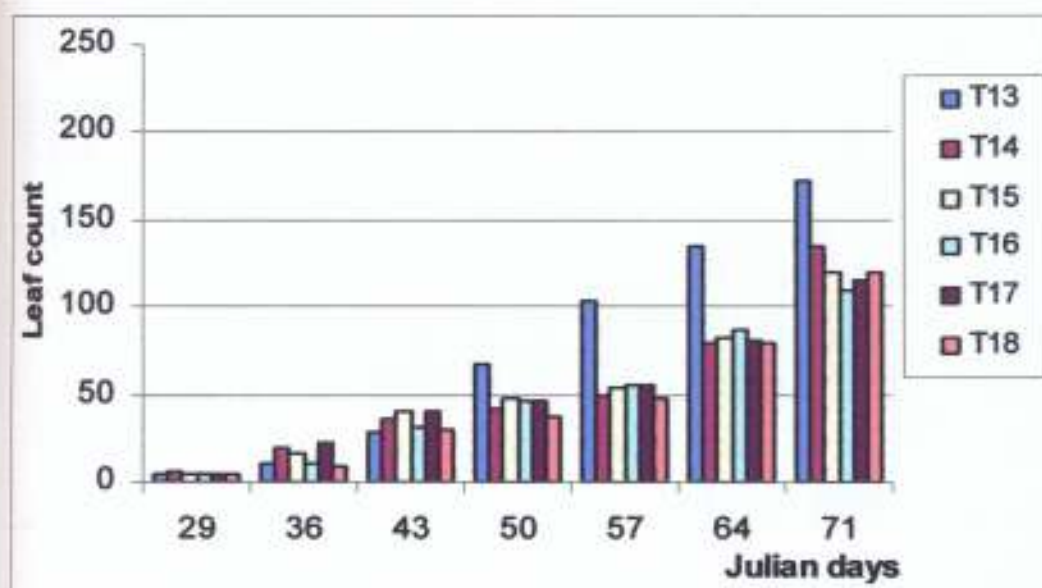
Treatment T1 which received irrigation water application on daily basis was observed to have the highest number of leaves (Figures 4.48 – 4.51). The treatment T1 was in a state of “water comfort” and hence performed better than samples on other treatment plots both on drip and sprinkler irrigation system. However, it was generally observed that leaf formation was higher in drip irrigation treatment plots than same treatment sample on sprinkler plots. Treatments T2, T3, and T17 were characterized by high leaf counts and there were no significant difference among the three treatments at ($P > 0.05$).



(a)

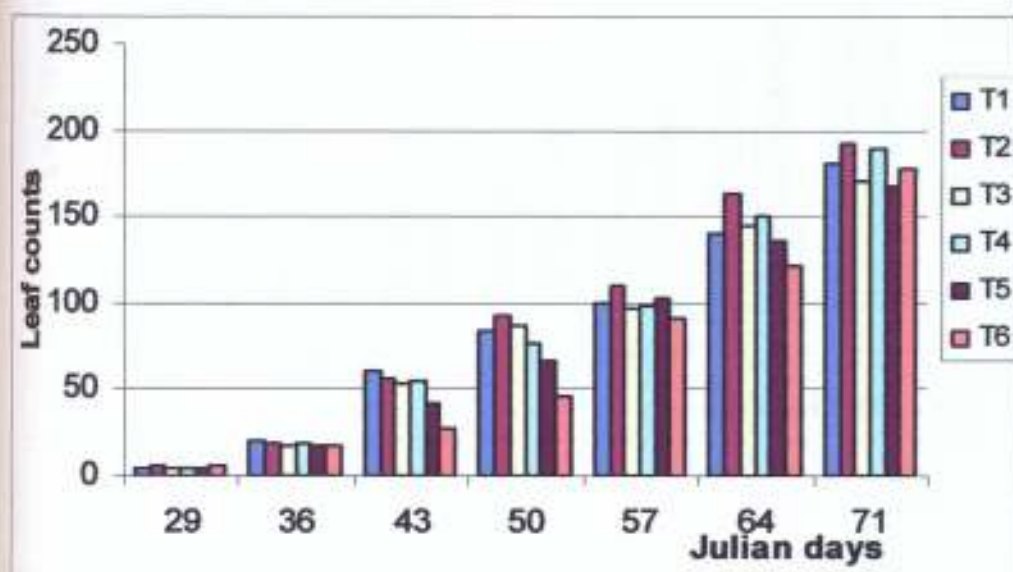


(b)

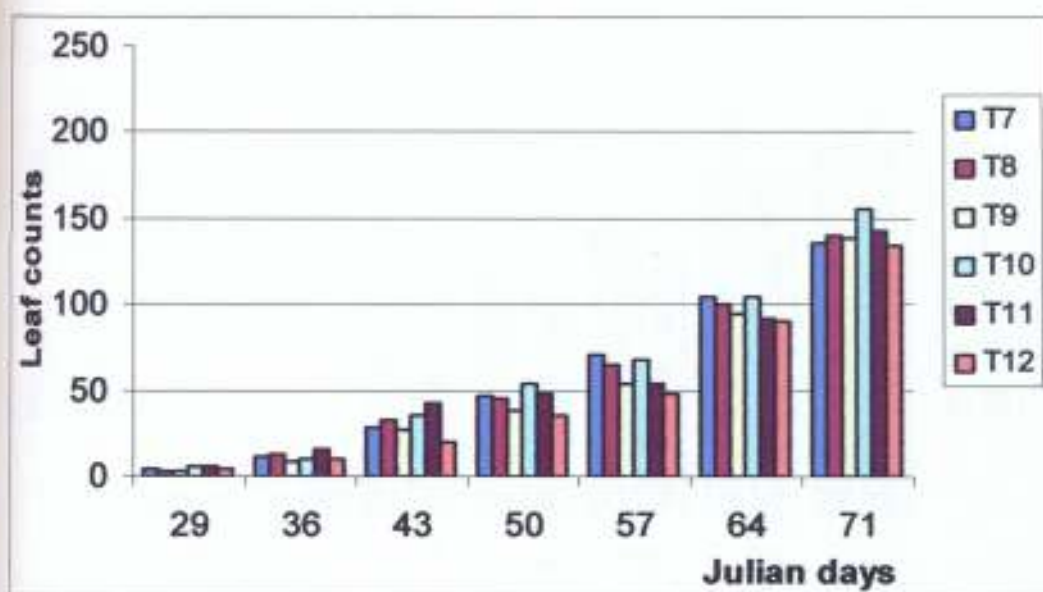


(c)

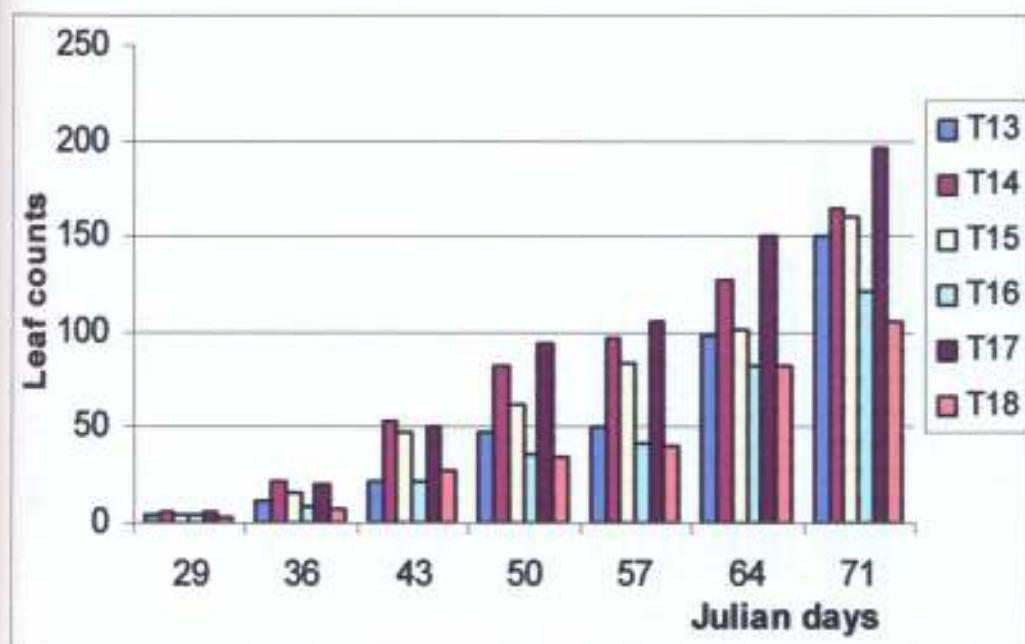
Figure 4.48 Leaf counts of treatment plots ST1 – ST6 (a), ST7 – ST12 (b), ST13 – ST18 (c) during the dry season experiment of 2005.



(a)

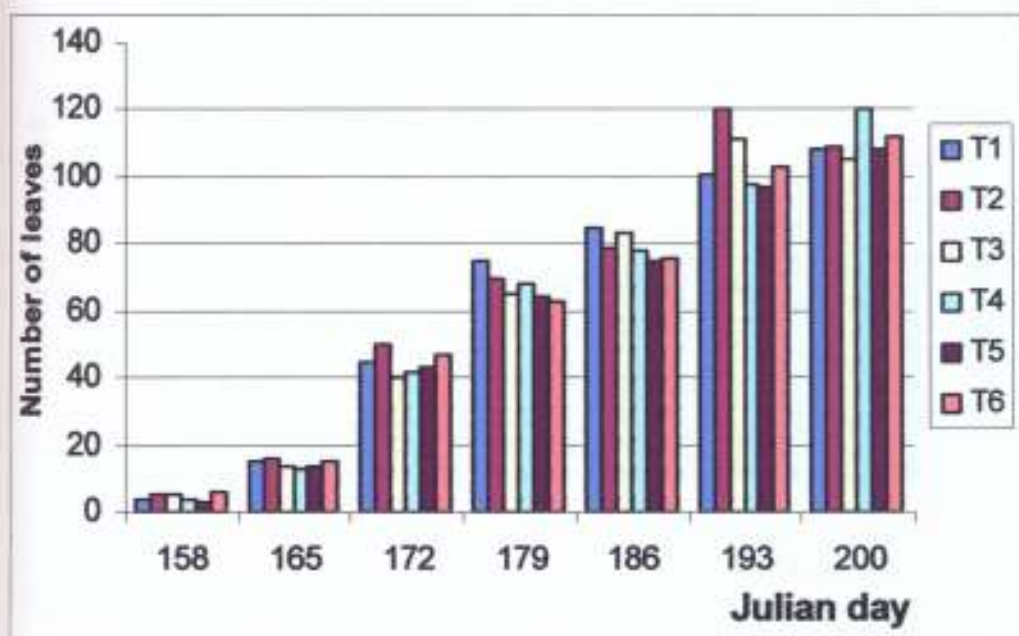


(b)

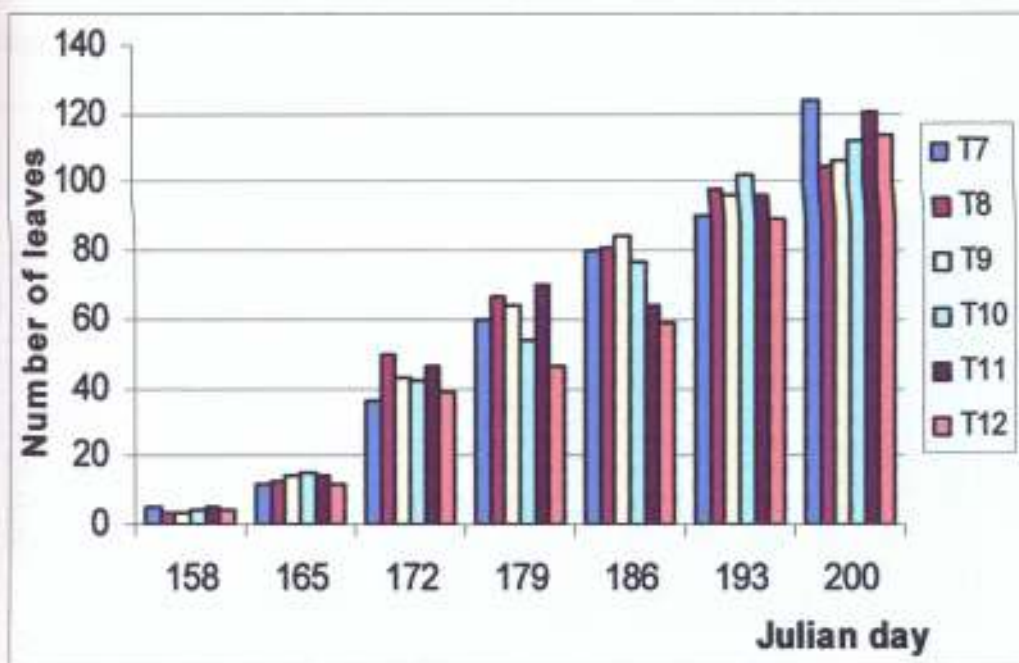


(c)

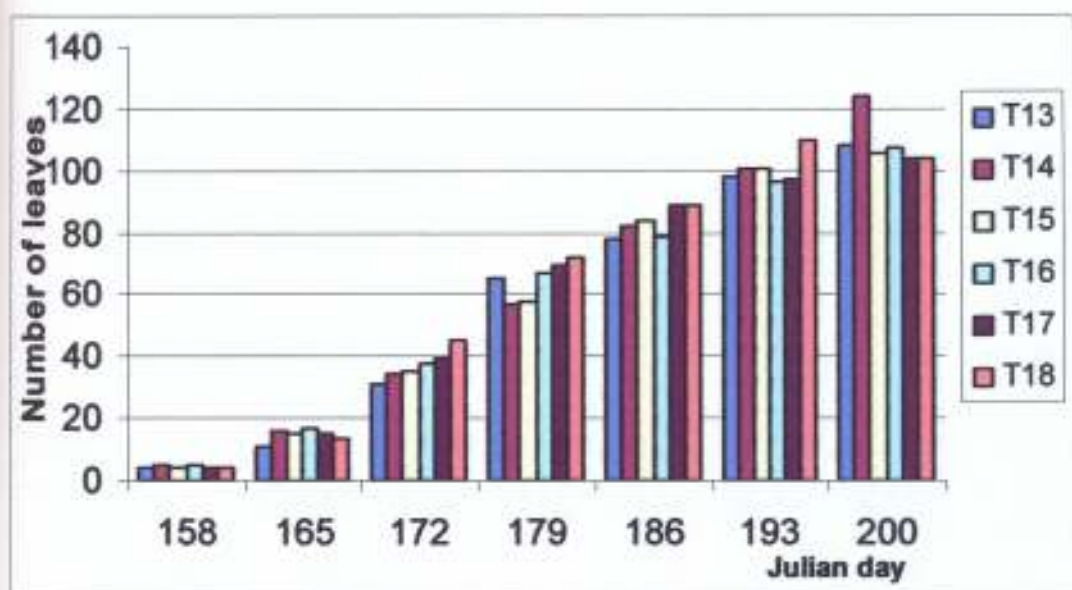
Figure.4.49 Leaf area index of treatment plots DT1 –DT6 (a), DT7 – DT12 (b), DT13 – DT18 (c) during the dry season experiment of 2005.



(a)

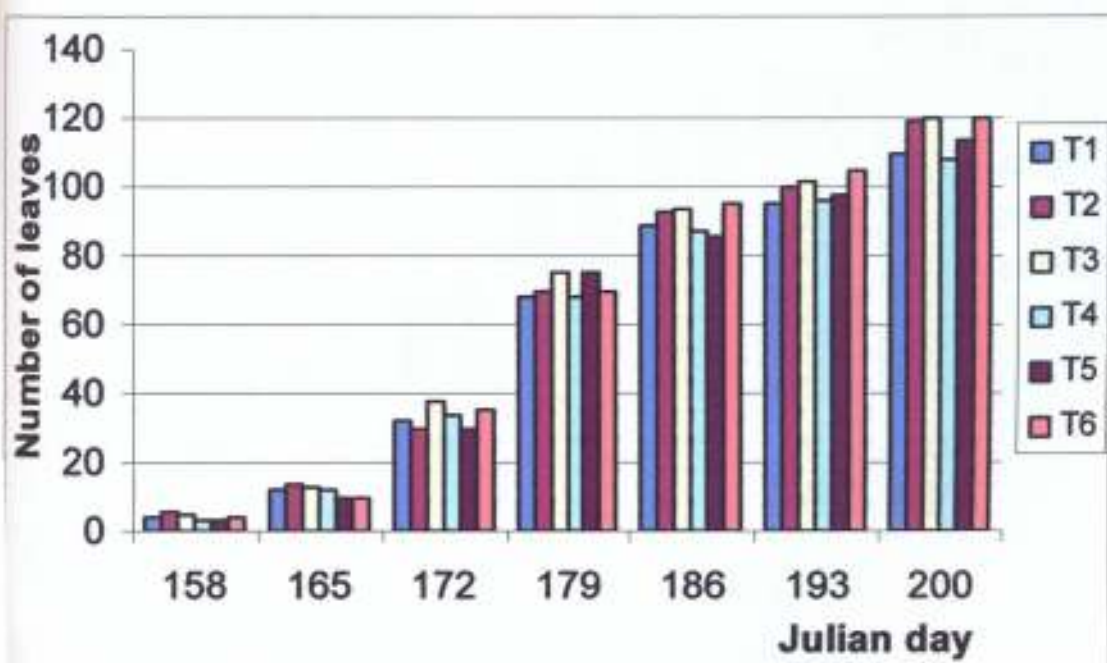


(b)

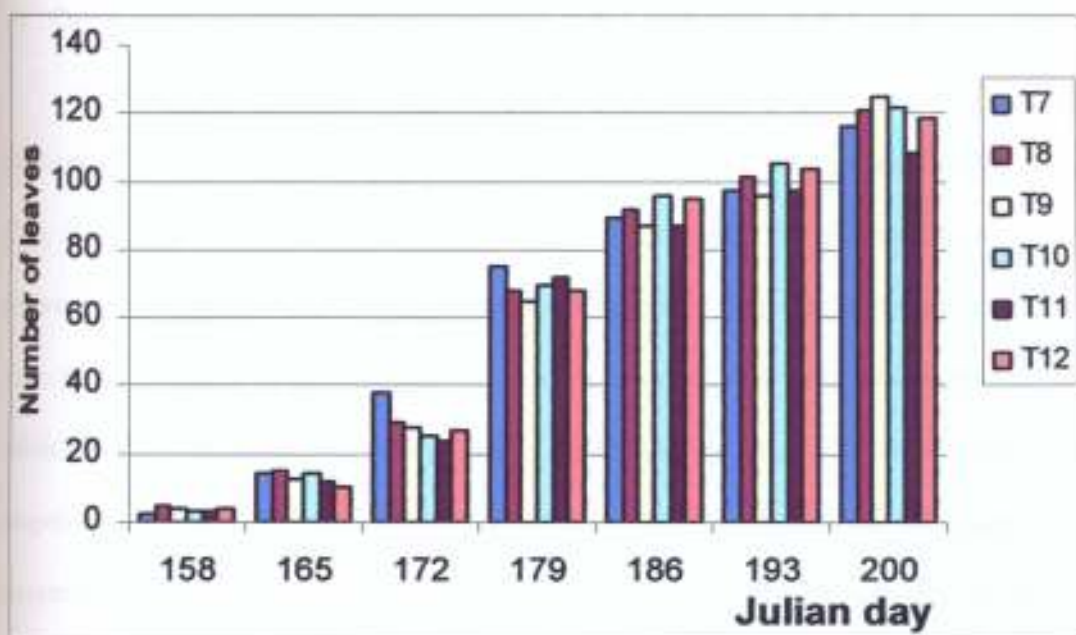


(c)

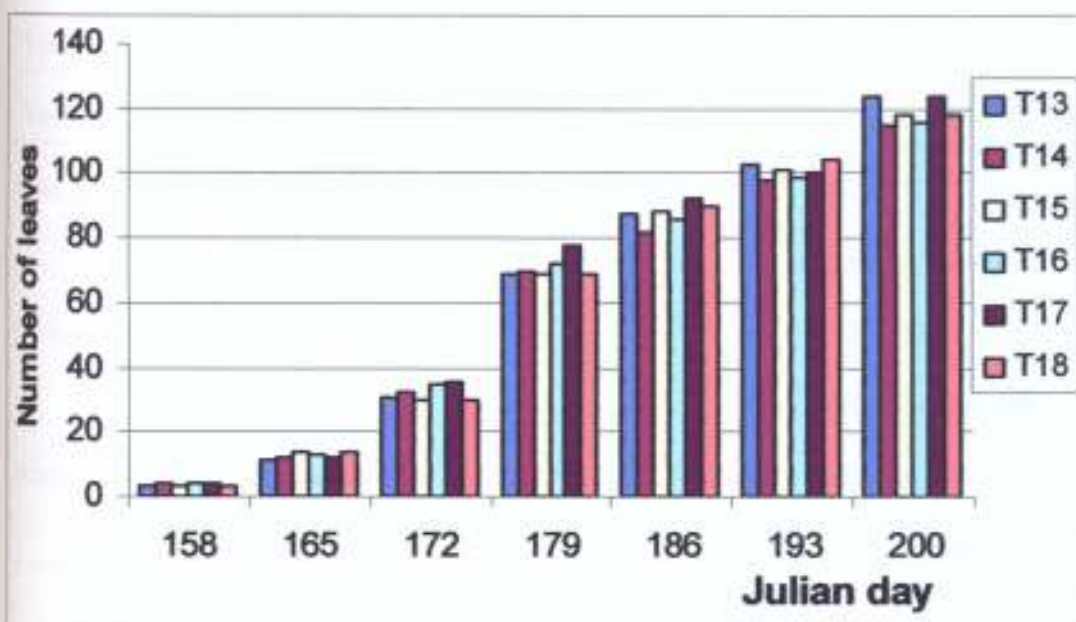
Figure.4.50 Leaf counts treatment plots DT1 –DT6 (a), DT7 – DT12 (b), DT13 – DT18 (c) during the rainy season experiment of 2005.



(a)



(b)



(c)

Figure.4.51 Leaf counts treatment plots ST1 –ST6 (a), ST7 –ST12 (b), ST13 –ST18 (c) during the rainy season experiment of 2005.

4.8 Calibration of the WaSim model

Calibration was performed on the first thirty days of the dry season experiment (January 15 – February 15). Three parameters (Growth and development, Evapotranspiration (ET), Root Zone depth) to be determined were calibrated by fitting the most sensitive observed variables and the corresponding model outputs. The results presented in Table 4.4 show that the values of the parameters agree reasonably well with the orders of magnitude published in literature. A fairly good agreement in the simulated and measured evapotranspiration was as a result of the scenario where evaporation and transpiration an inseparable natural phenomenon from soil surface becomes limited due to the canopy interception of solar radiation when the crop is well developed and completely covers the soil, and transpiration becomes the main process (Jensen *et al.*, 1990).

Table 4.4. Summary of the calibrated parameters of the model

Variable used for the calibration	Final calibrated value	Values found in literature
Root depth (mm)	13	10 – 15 (Myer, 1996)
Crop cover (mm)	27	25 – 30 (Henderson, 1999)
Actual Evapotranspiration (mm)	3.2	3.2 - 5.4 (Jensen, 1990)

4.8.1 Input parameters to the model

Table 4.5 shows a typical soil, climate and crop inputs into the model during the period of experiment (2005 and 2006). The input parameters are dependent on the treatments imposed as well as the result of actual measurements on fields.

Table 4.5 Input parameters to the model

<i>Parameters</i>	<i>Values</i>
<i>Soil</i>	
Field capacity (%)	20.5
Permanent wilting point (%)	8.4
Saturation paste (%)	39.8
<i>Drainage</i>	
Diameter (m)	0.54
Depth (m)	1
Spacing (m)	10
<i>Climate</i>	
Daily rainfall (mm)	_____
Daily evapotranspiration (mm)	_____
<i>Crop data</i>	
Planting date	15/Jan
Emergence date	29/Jan
20% cover	10/Feb
Full cover	15/Mar
Maturity	30/Mar
Harvest	30/Mar
Max. root date	25/Mar
Max. cover (%)	95
Mulch cover (%)	0
Planting depth (m)	0
Max. root depth (m)	0.3
<i>Irrigation</i>	
Timing: Irrigate at fixed depletion (% TAM)	50
Amount: Return to fixed deficit (mm)	0

Crop growth and the soil-water balance were simulated with WaSim for *A. cruentus* on a typical sandy-clay-loam soil of Akure. In preliminary simulation run of the model with weather, soil and management data of the experiment site, there was a good agreement between simulated and field determined growth and actual evapotranspiration of *A. cruentus*. The simulated results for 2005 and 2006 with parameters estimated using data obtained from the field shows that the water simulation model is capable of predicting the root development, crop cover, runoff, actual evapotranspiration, and root zone moisture deficit under different moisture stress levels (see figures 4.52–4.53). The output of WaSim model from the three irrigation plans is presented in Appendix C.

Figure 4.52 presents measured and simulated root depth. Statistical parameters were used to assess the model accuracy. The parameters are coefficient of determination (R^2), root mean square error (RMSE). Also, Figure shows the result of model validation using multiple regression analysis. The model simulated crop growth and crop cover well, the coefficient of determination $R^2 = 9.9$. The crop actual evapotranspiration was also well predicted by the model, the coefficient of correlation $R = 0.69$. The difference in root depth between the simulated and measured value is not significant at < 0.001 level. A calibration equation of the form:

$$Y = 1.39x - 0.01x^2 - 2.33 \quad 10$$

where y is the simulated root depth and x is the measured root depth was obtained from the validation process.

The simulated crop cover presented in Figure also show that the crop canopy increases with increase in calendar days until the crop reaches senescence, a point where leaf drop begins.

2D Graph 1

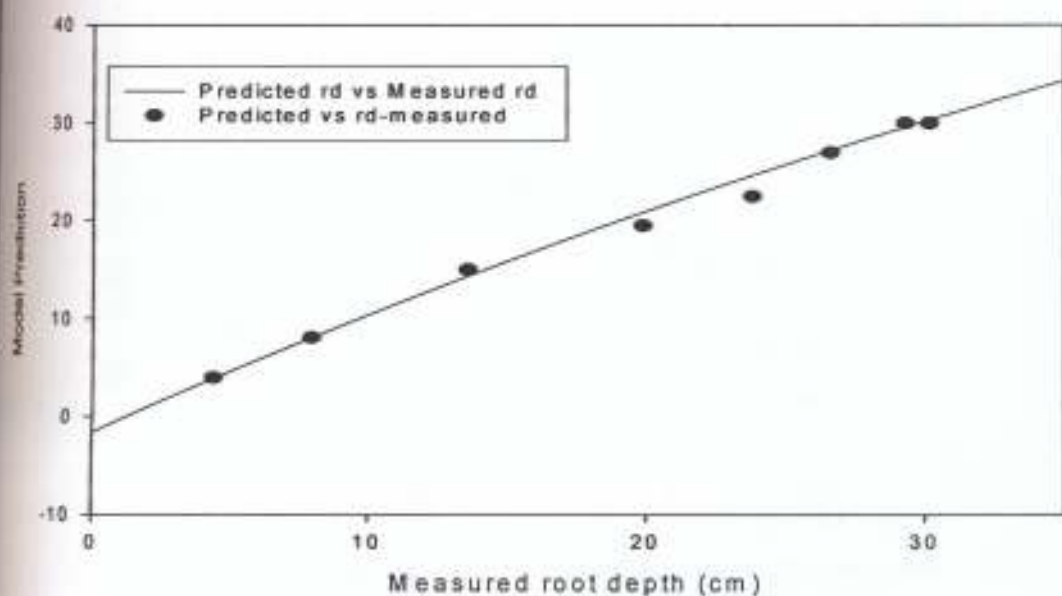


Figure.4.52 Multiple regression model between measure and simulated root depth

2D Graph 1
X Axis 2

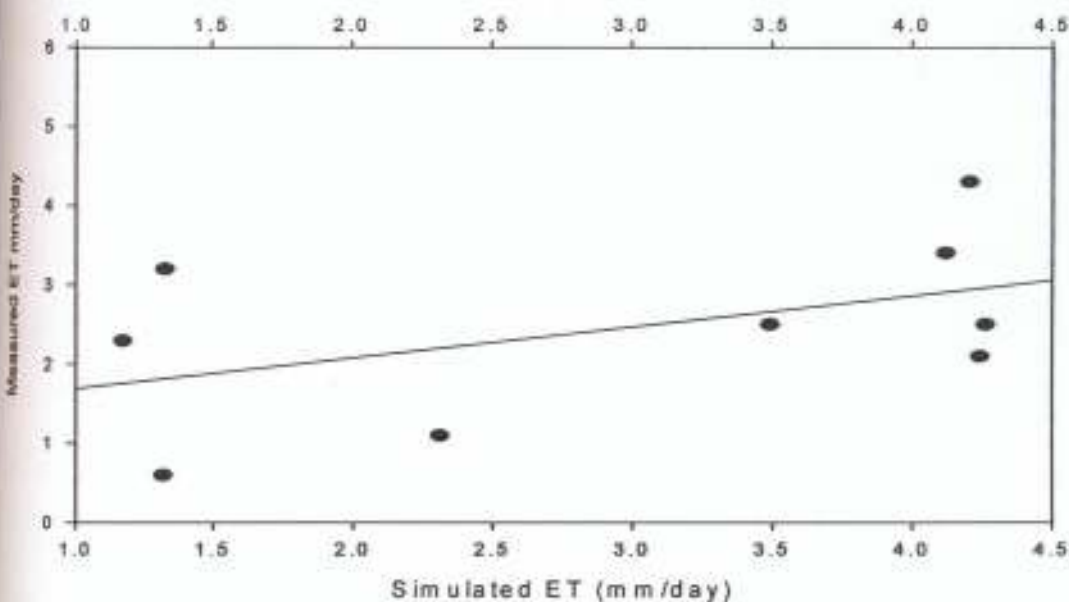


Figure.4.53 Simple linear regression model between measured and simulated crop ET

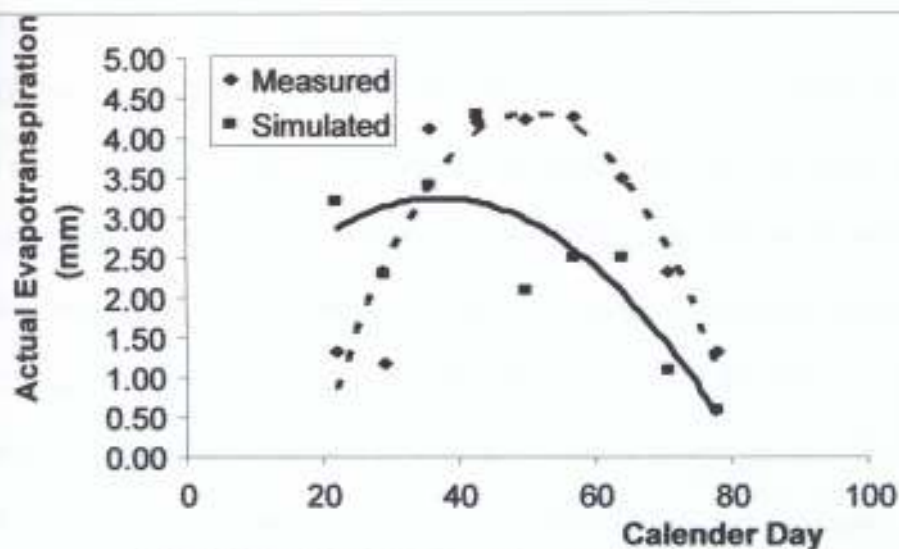


FIG 4.54 . Simulated and measured *A. cruentus* actual evapotranspiration during 2005

CHAPTER FIVE

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The study of soil-plant-atmosphere relationships is very important in hydro-ecological and climatological cycles. The available water within the soil profile dictated the ease with which plants extract moisture for its growth and yield and the atmosphere provides the energy with which plant soil moisture transport takes place from the soil reservoir through the plant and to the atmosphere as well. Therefore, a detailed knowledge of the irrigation water needs of crop, its temporal and spatial variability is essential for assessment of water resources and storage requirements, irrigation systems capacity and optimal allocation of water to crops. The study is highly desirable if all year round crop production is to be maintained. The research was aimed at quantifying the response of *Amaranthus cruentus* to water application via two irrigation systems (sprinkler and drip) and to calibrate and validate a soil water simulation model (WaSim) using soil, crop and climatic data obtained from field experimentation.

The study was carried out in two phases. The phase one involves a preliminary investigation of the climate soil and water resource of the study area to ascertain its potential for dryseason farming. The second phase involved field experimentations i.e design and establishment of irrigation system, planting of Amaranth seeds and assessment of the soil and crop agronomic parameters at the different phenological stages of the crop.

Measurements carried out during the period of experiment include the determination of soil physicochemical properties, soil bulk density, soil moisture content

using gravimetric method, soil hydraulic charge using tensiometers, surface runoff using a developed and calibrated runoff meter and deep drainage by means of installed hydraulic lysimeter. Other measurements include the leaf area index (LAI), plant height, leaf counts and *Amaranthus cruentus* yield. Weather parameters such as solar radiation, maximum and minimum temperature, maximum and minimum relative humidity e.t.c were collected from an automatic meteorological station located at about 200 m away from the site of experiment.

The results obtained from field experimentation were analyzed using appropriate statistical softwares.

Based on the results obtained, the following conclusions can be drawn:

- i. The mean soil texture (sandy clay loam) in the top soil of the study site forms mainly the agricultural layer required for the cultivation of most vegetables.
- ii. The minimum organic carbon content observed in the study site is suitable for the cultivation of tropical vegetables.
- iii. The pH of the soil of the study site falls within slightly acidic range and is considered ideal for good availability of plant nutrients in mineral soil.
- iv. Spatial variability analysis of the soil bulk density of the study site gave a range of values (1.20 – 1.50) gcm⁻³, beyond which plant growth is severely impeded.
- v. Automatic runoff meter for overland flow measurement has been developed
- vi. The soil hydraulic charge increases down the soil profile. The surface soil between 0.1 and 0.2 m depth lack moisture at the peak of the dry season and this affected the crop as some *Amaranthus* quickly reached maturity most especially at the vegetative

stage of the crop growth. However the crop was able to extract moisture from depth 0.3 m and below.

- vii. The pattern of soil water extraction differed significantly among treatments ($P < 0.05$). *Amaranthus cruentus* extracts water for its use depending on available moisture in the soil.
- viii. Moisture use by crop under the drip irrigation system was considerably higher when compared with the sprinkler system; because that the crop grown under drip system had enough time to accumulate moisture around the root zone of crop, thus permitting moisture build-up at the root zone of crop.
- ix. Prediction model between *Amaranthus* yield and consumptive use was established (R^2) of the model output and measured value of yield was significantly high (0.79) at $P < 0.05$.
- x. At the vegetative stage of *Amaranthus* growth, correlation between the yield and moisture stored in soil was higher ($R^2 = 0.9$) on drip plot than on sprinkler plot ($R^2 = 0.85$).
- xi. The relationship between yield and evapotranspiration expressed by a linear equation showed that yield-evapotranspiration varied with variation in water supply to crop and also to variations in rainfall and air temperature.
- xii. "Yield – Evapotranspiration" relationships with linear equation gave a high precision within the range 0.2 – 1.0. of relative yields which include all economically important yield.
- xiii. *Amaranthus* growth and development, evapotranspiration (ET) and rooting depth were calibrated by fitting the most sensitive variables to obtain the

corresponding, model output show that the measured parameters and the model predictions agree reasonably well.

- xiv. The agreement between simulated and measured evapotranspiration might be due largely to crop canopy which provide complete cover on the soil, thus, making transpiration the main process of water loss.
- xv. The WaSim model simulated crop growth and crop cover well, coefficient of determination R^2 being 0.99. The difference between simulated and measured root depth is not significant at <0.001 .

5.2 Recommendations for further studies

From the findings and results of this study, the following recommendations are suggested:

- i. Variations in water use and yield of *Amaranthus cruentus* was established in the study area; there is need to carry out similar studies in other climatic and pedological areas of the country;
- ii. Owing to cost implications meteorological data were obtained from nearby meteorological station (i.e. within 300m from experimental site); accuracy could be improved if automatic meteorological station could be permanently installed on the farm site;
- iii. There is need to constantly monitor soil nutrient status on long term basis (i.e before and after experiments); this will constitute be useful data for the experimental site;
- iv. Further studies should be carried out to ascertain the dynamic response of *Amaranthus cruentus* to water stress among different phenological stages. This will supplement the results on the response of the crop at the different

stages already established in this study. It will lead to better strategic planning of irrigation management of this crop.

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APPENDIX A

Table A1: Initial soil moisture content of sprinkler plots before the start of experiment (cm)

Treatments	0.10m	0.20m	0.30m	0.40m	0.50m	0.60m	STORED SOIL MOISTURE
ST1	0.79	0.7	0.83	0.84	0.84	0.88	4.88
ST2	0.59	0.66	0.7	0.77	0.85	0.85	4.42
ST3	0.72	0.79	0.75	0.87	0.98	1.37	5.48
ST4	0.8	0.75	0.84	0.86	0.91	0.96	5.12
ST5	0.76	0.71	0.7	0.8	0.77	0.85	4.59
ST6	0.62	0.62	0.68	0.93	0.94	1.15	4.94
ST7	0.58	0.84	0.83	0.89	0.88	1.22	5.24
ST8	0.55	0.89	1.06	1.07	1.15	1.16	5.88
ST9	0.55	0.67	0.81	1.06	1.24	1.25	5.58
ST10	0.72	0.73	0.77	0.98	1.06	1.07	5.33
ST11	0.51	0.66	0.85	0.83	1.02	1.29	5.16
ST12	0.54	0.62	0.79	1.01	0.89	1.14	4.99
ST13	0.71	0.89	0.92	1.05	1.29	1.36	6.22
ST14	0.61	0.66	0.76	0.97	1.1	1.18	5.28
ST15	0.82	0.92	1.07	1.17	1.24	1.29	6.51
ST16	0.59	0.74	0.88	0.99	1.02	1.11	5.33
ST17	0.58	0.66	0.8	0.89	1.11	1.17	5.21
ST18	0.59	0.76	1.06	1.05	1.17	1.23	5.86

Table A2: Initial soil moisture content (cm) on drip irrigation plot before the start of experiment during the dry season of 2005

Treatment	0.1m	0.2m	0.3m	0.4m	0.5m	0.6m	stored soil moisture
DT1	0.59	0.68	0.77	0.92	1.01	1.3	5.27
DT2	0.67	0.86	0.92	1.04	1.1	1.33	5.92
DT3	0.64	0.97	1.01	1.02	1.18	1.22	6.04
DT4	0.77	0.92	1.06	0.97	1.23	1.25	6.2
DT5	0.66	0.64	0.86	0.97	1.1	1.15	5.38
DT6	0.61	0.76	0.89	1.01	1.06	1.1	5.43
DT7	0.71	0.62	0.85	0.94	1.02	1.18	5.32
DT8	0.59	0.71	0.77	0.99	1.09	1.14	5.29
DT9	0.72	0.8	0.85	0.97	1.12	1.22	5.68
DT10	0.6	0.67	0.76	0.88	0.99	1.16	5.06
DT11	0.73	0.81	0.93	1.05	1.22	1.23	5.97
DT12	0.59	0.82	0.9	1.1	1.11	1.12	5.64
DT13	0.58	0.65	0.66	0.81	0.95	1.24	4.89
DT14	0.7	0.74	0.93	1.09	1.18	1.23	5.87
DT15	0.61	0.69	0.82	0.93	1.06	1.22	5.33
DT16	0.72	0.7	0.74	0.91	1.09	1.2	5.36
DT17	0.79	0.84	0.92	1.08	1.13	1.23	5.99
DT18	0.59	0.72	0.88	0.93	1.17	1.19	5.48

Table A3: Soil moisture content (cm) at 22DOY on sprinkler

irrigation plots							Soil moisture stored
Treatment	0.1	0.2	0.3	0.4	0.5	0.6	
ST1	0.92	1.18	1.3	1.38	1.42	1.56	7.76
ST2	0.92	0.99	1.31	1.4	1.51	1.69	7.82
ST3	0.93	0.92	1.23	1.3	1.38	1.52	7.28
ST4	0.83	0.89	1.18	1.19	1.19	1.36	6.64
ST5	0.85	1.02	1.07	1.14	1.22	1.31	6.61
ST6	0.72	0.98	1.08	1.17	1.25	1.32	6.52
ST7	0.7	1.01	1.02	1.13	1.23	1.26	6.35
ST8	0.67	1.01	1.17	1.18	1.21	1.27	6.51
ST9	0.74	0.79	0.96	1.09	1.11	1.28	5.97
ST10	0.77	0.88	0.92	1.07	1.23	1.43	6.3
ST11	0.72	0.81	1.01	1.2	1.27	1.4	6.41
ST12	0.62	0.74	0.88	1.1	1.11	1.23	5.68
ST13	0.76	0.82	0.93	1.08	1.1	1.4	6.09
ST14	0.78	1.06	1.17	1.25	1.42	1.55	7.23
ST15	0.76	0.83	1.14	1.27	1.27	1.35	6.62
ST16	0.65	0.79	0.9	1.11	1.17	1.23	5.85
ST17	0.9	1.07	1.28	1.42	1.51	1.54	7.72
ST18	0.76	0.83	0.85	1.1	1.2	1.37	6.11

Table A4: Soil moisture content (cm) at 22DOY on drip

irrigation plots							Stored soil moisture
Treatment	0.1	0.2	0.3	0.4	0.5	0.6	
DT1	0.71	0.8	0.97	1.02	1.04	1.5	6.04
DT2	0.77	0.88	1	1.07	1.18	1.57	6.47
DT3	0.8	1.03	1.11	1.16	1.23	1.35	6.68
DT4	0.78	0.99	1.1	1.13	1.15	1.51	6.66
DT5	0.74	0.85	1	1.11	1.13	1.29	6.12
DT6	0.65	0.77	0.91	1.01	1.07	1.31	5.72
DT7	0.75	0.8	0.88	0.97	1.01	1.24	5.65
DT8	0.63	0.76	0.86	0.97	1.11	1.15	5.48
DT9	0.73	0.83	1.01	1.11	1.16	1.23	6.07
DT10	0.74	0.85	1.01	1.06	1.23	1.3	6.19
DT11	0.78	0.87	1.04	1.14	1.26	1.3	6.39
DT12	0.64	0.85	1	1.13	1.17	1.23	6.02
DT13	0.62	0.72	0.78	0.98	1.06	1.26	5.42
DT14	0.79	0.86	0.98	1.16	1.27	1.61	6.67
DT15	0.74	0.85	0.97	1.09	1.19	1.35	6.19
DT16	0.76	0.77	0.88	0.94	1.12	1.18	5.65
DT17	0.86	0.91	1	1.13	1.24	1.35	6.49
DT18	0.62	0.74	0.9	0.98	1.18	1.24	5.66

Table A5: Soil moisture content (cm) at 29DOY on drip irrigation plots

Treatment							Soil moisture stored
	0.1	0.2	0.3	0.4	0.5	0.6	
DT1	0.74	0.88	0.98	1.07	1.13	1.5	6.3
DT2	0.83	0.9	1.03	1.13	1.27	1.57	6.73
DT3	0.84	1.12	1.13	1.2	1.27	1.37	6.93
DT4	0.8	1.03	1.13	1.15	1.23	1.58	6.92
DT5	0.81	0.88	1.01	1.14	1.23	1.42	6.49
DT6	0.78	0.86	0.92	1.02	1.07	1.38	6.03
DT7	0.77	0.87	0.9	1.01	1.04	1.26	5.85
DT8	0.67	0.77	0.88	1	1.17	1.25	5.74
DT9	0.74	0.84	1.05	1.14	1.24	1.27	6.28
DT10	0.75	0.88	1.02	1.08	1.27	1.31	6.31
DT11	0.79	0.9	1.06	1.15	1.19	1.25	6.34
DT12	0.71	0.88	1.01	1.17	1.22	1.25	6.24
DT13	0.64	0.8	0.83	1	1.07	1.15	5.49
DT14	0.78	0.87	1	1.2	1.35	1.62	6.82
DT15	0.81	0.9	1.01	1.15	1.24	1.42	6.53
DT16	0.88	0.92	1.06	1.2	1.22	1.29	6.57
DT17	0.92	1.03	1.06	1.18	1.29	1.31	6.79
DT18	0.67	0.81	1	1.06	1.15	1.32	6.01

Table A6: Soil moisture content (cm) at 29DOY on sprinkler irrigation plots

Treatment							Soil moisture stored
	0.1	0.2	0.3	0.4	0.5	0.6	
ST1	1.36	1.44	1.58	1.59	1.69	1.82	9.48
ST2	1.19	1.36	1.46	1.49	1.57	1.76	8.83
ST3	1.34	1.4	1.5	1.56	1.57	1.72	9.09
ST4	1.15	1.31	1.38	1.41	1.4	1.61	8.26
ST5	1.3	1.35	1.44	1.5	1.52	1.57	8.68
ST6	1.25	1.4	1.54	1.56	1.62	1.65	9.02
ST7	0.93	0.99	1.19	1.27	1.28	1.36	7.02
ST8	1.09	1.11	1.15	1.3	1.36	1.44	7.45
ST9	1.03	1.07	1.1	1.2	1.15	1.3	6.85
ST10	1.22	1.26	1.36	1.44	1.41	1.58	8.27
ST11	1.06	1.14	1.23	1.3	1.38	1.4	7.51
ST12	1.02	1.09	1.17	1.38	1.3	1.48	7.44
ST13	1.16	1.22	1.29	1.39	1.27	1.43	7.76
ST14	1.1	1.15	1.24	1.31	1.52	1.6	7.92
ST15	1.11	1.13	1.27	1.35	1.39	1.5	7.75
ST16	0.98	1.06	1.22	1.26	1.16	1.38	7.06
ST17	1.04	1.12	1.29	1.44	1.36	1.59	7.84
ST18	0.89	1.01	1.04	1.16	1.26	1.38	6.74

Table A7: Soil moisture content (cm) at 36DOY on sprinkler

irrigation plots							Soil moisture stored
Treatment	0.1	0.2	0.3	0.4	0.5	0.6	
ST1	1.42	1.48	1.59	1.73	1.8	1.91	9.93
ST2	1.34	1.43	1.59	1.62	1.68	1.82	9.48
ST3	1.38	1.48	1.58	1.63	1.73	1.88	9.68
ST4	1.24	1.38	1.49	1.55	1.61	1.82	9.09
ST5	1.37	1.43	1.57	1.63	1.67	1.73	9.4
ST6	1.25	1.44	1.6	1.67	1.75	1.8	9.51
ST7	1.17	1.29	1.44	1.51	1.54	1.61	8.56
ST8	1.19	1.33	1.38	1.49	1.55	1.6	8.54
ST9	1.3	1.37	1.48	1.53	1.61	1.7	8.99
ST10	1.28	1.41	1.54	1.57	1.68	1.73	9.21
ST11	1.25	1.2	1.49	1.53	1.6	1.67	8.74
ST12	1.26	1.34	1.39	1.48	1.53	1.62	8.62
ST13	1.3	1.42	1.51	1.56	1.71	1.77	9.27
ST14	1.24	1.37	1.51	1.58	1.49	1.73	8.92
ST15	1.15	1.24	1.57	1.64	1.73	1.88	9.21
ST16	1.06	1.22	1.33	1.49	1.54	1.65	8.29
ST17	1.17	1.24	1.3	1.49	1.5	1.65	8.35
ST18	1.11	1.16	1.18	1.3	1.43	1.58	7.76

Table A8: Soil moisture content (cm) at 36DOY on drip

irrigation plots							Stored soil moisture
Treatment	0.1	0.2	0.3	0.4	0.5	0.6	
DT1	1.06	1.17	1.25	1.28	1.5	1.61	7.87
DT2	1.03	1.11	1.15	1.19	1.44	1.65	7.57
DT3	1.01	1.17	1.24	1.26	1.37	1.51	7.56
DT4	0.92	1.12	1.23	1.3	1.41	1.69	7.67
DT5	1.06	1.09	1.14	1.23	1.29	1.54	7.35
DT6	1.05	1.16	1.23	1.27	1.37	1.47	7.55
DT7	0.75	0.98	1.09	1.2	1.25	1.36	6.63
DT8	1.06	1.18	1.24	1.29	1.35	1.38	7.55
DT9	0.97	1.05	1.14	1.29	1.34	1.44	7.23
DT10	0.1	1.07	1.18	1.24	1.32	1.37	7.18
DT11	1.05	1.16	1.19	1.29	1.37	1.45	7.51
DT12	1.07	1.09	1.17	1.25	1.29	1.35	7.22
DT13	1.03	1.13	1.32	1.37	1.4	1.42	7.67
DT14	0.99	1.18	1.24	1.3	1.48	1.64	7.83
DT15	1.05	1.14	1.17	1.28	1.36	1.65	7.65
DT16	1.08	1.07	1.17	1.25	1.29	1.43	7.29
DT17	1	1.16	1.23	1.29	1.42	1.54	7.64
DT18	0.95	1.02	1.14	1.18	1.24	1.38	6.91

Table A9: Soil moisture content (cm) at 43DOY on sprinkler irrigation

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Soil moisture stored
ST1	1.48	1.56	1.61	1.77	1.81	1.98	10.21
ST2	1.4	1.46	1.63	1.64	1.69	1.91	9.73
ST3	1.43	1.47	1.64	1.65	1.74	1.93	9.86
ST4	1.3	1.41	1.55	1.61	1.64	1.86	9.37
ST5	1.44	1.48	1.6	1.66	1.74	1.78	9.7
ST6	1.3	1.49	1.64	1.7	1.74	1.85	9.72
ST7	1.25	1.36	1.46	1.57	1.61	1.89	9.14
ST8	1.29	1.37	1.44	1.52	1.62	1.7	8.94
ST9	1.32	1.39	1.5	1.65	1.74	1.8	9.4
ST10	1.37	1.45	1.57	1.62	1.73	1.77	9.51
ST11	1.3	1.37	1.56	1.6	1.61	1.67	9.11
ST12	1.32	1.42	1.54	1.6	1.65	1.67	9.2
ST13	1.33	1.58	1.6	1.66	1.73	1.8	9.7
ST14	1.37	1.39	1.54	1.62	1.76	1.79	9.47
ST15	1.29	1.3	1.61	1.66	1.77	1.89	9.52
ST16	1.25	1.35	1.45	1.55	1.62	1.71	8.93
ST17	1.23	1.33	1.37	1.54	1.57	1.66	8.7
ST18	1.17	1.18	1.3	1.34	1.48	1.62	8.09

Table A10: Soil moisture content (cm) at 43DOY on drip irrigation plots

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Soil moisture stored
DT1	1.35	1.37	1.43	1.54	1.62	1.77	9.08
DT2	1.23	1.3	1.38	1.53	1.57	1.73	8.74
DT3	1.2	1.29	1.4	1.49	1.54	1.64	8.56
DT4	1.1	1.19	1.28	1.39	1.49	1.65	8.1
DT5	1.15	1.24	1.35	1.41	1.48	1.65	8.28
DT6	1.17	1.24	1.33	1.37	1.49	1.56	8.16
DT7	1.13	1.17	1.31	1.39	1.45	1.56	8.01
DT8	1.14	1.24	1.34	1.4	1.38	1.5	8
DT9	1.09	1.18	1.24	1.36	1.43	1.62	7.92
DT10	1.13	1.18	1.28	1.43	1.49	1.55	8.06
DT11	1.21	1.28	1.37	1.45	1.51	1.66	8.48
DT12	1.11	1.24	1.29	1.38	1.42	1.58	8.02
DT13	1.18	1.25	1.36	1.4	1.51	1.54	8.24
DT14	1.1	1.16	1.26	1.37	1.5	1.66	8.05
DT15	1.19	1.22	1.27	1.37	1.49	1.69	8.23
DT16	1.15	1.25	1.3	1.36	1.42	1.63	8.11
DT17	1.05	1.24	1.27	1.42	1.46	1.58	8.02
DT18	1.12	1.19	1.28	1.37	1.45	1.61	8.02

Table A11: Soil moisture content (cm) at 50DOY on sprinkler irrigation plots

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Stored soil moisture
ST1	1.55	1.61	1.64	1.7	1.86	2.08	10.44
ST2	1.48	1.49	1.7	1.6	1.77	2.02	10.06
ST3	1.52	1.51	1.68	1.72	1.78	2.06	10.27
ST4	1.45	1.32	1.6	1.58	1.66	1.9	9.51
ST5	1.49	1.51	1.68	1.79	1.77	1.88	10.12
ST6	1.4	1.53	1.6	1.73	1.8	1.92	9.98
ST7	1.26	1.39	1.61	1.66	1.62	1.81	9.35
ST8	1.37	1.37	1.3	1.53	1.62	1.65	8.84
ST9	1.22	1.32	1.37	1.48	1.69	1.78	8.86
ST10	1.41	1.48	1.58	1.67	1.76	1.8	9.7
ST11	1.42	1.5	1.6	1.64	1.73	1.77	9.66
ST12	1.38	1.53	1.61	1.67	1.64	1.7	9.53
ST13	1.36	1.51	1.67	1.64	1.74	1.83	9.75
ST14	1.39	1.4	1.62	1.66	1.72	1.77	9.56
ST15	1.4	1.43	1.61	1.77	1.74	1.89	9.84
ST16	1.2	1.34	1.47	1.58	1.64	1.65	8.88
ST17	1.36	1.47	1.55	1.61	1.72	1.88	9.59
ST18	1.18	1.2	1.34	1.4	1.53	1.68	8.33

Table A12: Soil moisture content (cm) at 50DOY on drip irrigation plots

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Soil moisture stored
DT1	1.52	1.62	1.67	1.74	1.9	2.19	10.64
DT2	1.5	1.53	1.73	1.73	1.8	2.14	10.43
DT3	1.6	1.64	1.74	1.77	1.86	2.19	10.8
DT4	1.55	1.51	1.72	1.79	1.87	2.13	10.57
DT5	1.4	1.56	1.63	1.73	1.86	1.93	10.11
DT6	1.48	1.62	1.66	1.8	2	1.98	10.54
DT7	1.29	1.42	1.64	1.69	1.71	1.89	9.64
DT8	1.49	1.44	1.51	1.63	1.72	1.84	9.63
DT9	1.24	1.34	1.4	1.49	1.7	1.77	8.94
DT10	1.53	1.56	1.63	1.7	1.72	1.8	9.94
DT11	1.5	1.53	1.68	1.77	1.78	1.91	10.17
DT12	1.44	1.67	1.68	1.81	1.9	2.06	10.56
DT13	1.39	1.6	1.76	1.77	1.79	1.95	10.26
DT14	1.44	1.58	1.71	1.8	1.87	1.89	10.29
DT15	1.49	1.59	1.63	1.74	1.86	1.92	10.23
DT16	1.27	1.37	1.4	1.41	1.51	1.71	8.67
DT17	1.42	1.52	1.64	1.68	1.87	2.13	10.26
DT18	1.27	1.3	1.37	1.42	1.64	1.7	8.7

Table A13: Soil moisture content (cm) at 57DOY on sprinkler irrigation plots

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Stored soil moisture
T1	1.81	1.93	2.19	2.26	2.37	2.6	13.16
T2	1.56	1.7	1.89	2.14	2.28	2.51	12.08
T3	1.7	1.91	2.08	2.17	2.28	2.54	12.68
T4	1.69	1.86	2	2.07	2.19	2.52	12.33
T5	1.68	1.9	2.02	2.08	2.14	2.31	12.13
T6	1.59	1.76	1.8	1.99	2.07	2.17	11.38
T7	1.42	1.66	1.77	1.8	1.93	2.12	10.7
T8	1.47	1.73	1.81	1.97	2.04	2.19	11.21
T9	1.28	1.41	1.48	1.57	1.68	1.7	9.12
T10	1.41	1.54	1.61	1.77	1.85	2.08	10.26
T11	1.29	1.48	1.72	1.77	1.88	1.96	10.1
T12	1.33	1.45	1.54	1.76	1.77	1.87	9.72
T13	1.3	1.4	1.54	1.67	1.74	1.77	9.42
T14	1.54	1.67	1.72	1.66	1.79	1.78	10.16
T15	1.41	1.6	1.65	1.64	1.74	1.79	9.83
T16	1.36	1.31	1.54	1.62	1.73	2.04	9.6
T17	1.43	1.53	2	2.02	2.06	2.21	11.25
T18	1.3	1.56	1.72	1.77	1.79	1.87	10.01

Table A14: Soil moisture content (cm) at 57DOY on drip irrigation plots

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Stored soil moisture
DT1	1.74	1.88	2	2.04	2.13	2.73	12.52
DT2	1.78	1.92	1.9	2.12	2.21	2.44	12.37
DT3	1.81	1.91	1.89	1.95	2.06	2.29	11.91
DT4	1.62	1.86	1.92	2.07	2.07	2.21	11.75
DT5	1.67	1.77	1.86	2	2.24	2.3	11.84
DT6	1.64	1.76	1.87	2.01	2.09	2.22	11.59
DT7	1.62	1.77	1.87	1.88	2	2.02	11.16
DT8	1.52	1.6	1.76	1.9	1.92	1.9	10.6
DT9	1.29	1.42	1.49	1.54	1.55	1.86	9.15
DT10	1.53	1.6	1.61	1.69	1.77	1.8	10
DT11	1.48	1.62	1.66	1.7	1.8	1.82	10.08
DT12	1.62	1.67	1.72	1.74	1.92	1.9	10.57
DT13	1.3	1.45	1.56	1.58	1.67	1.77	9.33
DT14	1.5	1.59	1.68	1.71	1.81	1.94	10.23
DT15	1.61	1.67	1.74	1.79	1.88	1.87	10.56
DT16	1.41	1.6	1.64	1.69	1.8	1.88	10.02
DT17	1.68	1.84	1.9	2	2.09	2.52	12.03
DT18	1.3	1.4	1.42	1.53	1.66	1.67	8.98

Table A15: Soil moisture content (cm) at 64DOY on sprinkler irrigation plots

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Stored soil moisture
ST1	1.86	1.94	2.09	2.19	2.34	2.7	13.12
ST2	1.74	1.9	2.01	2.07	2.2	2.54	12.46
ST3	1.62	1.78	1.89	2.04	2.16	2.42	11.91
ST4	1.67	1.77	1.87	2	2.03	2.33	11.67
ST5	1.79	1.93	1.95	2.1	2.31	2.44	12.52
ST6	1.77	1.84	1.8	2.05	2.22	2.36	12.04
ST7	2.06	1.92	1.9	2.1	2.3	2.51	12.79
ST8	1.74	1.86	1.95	1.92	2.06	1.84	11.37
ST9	1.41	1.48	1.54	1.61	1.57	1.75	9.36
ST10	1.58	1.5	1.68	1.75	1.86	1.91	10.28
ST11	1.4	1.47	1.55	1.67	1.72	1.68	9.49
ST12	1.54	1.56	1.74	1.81	1.87	1.8	10.32
ST13	1.52	1.6	1.67	1.66	1.82	1.78	10.05
ST14	1.67	1.74	1.8	1.92	2.06	2.24	11.43
ST15	1.57	1.61	1.74	1.88	1.94	2.02	10.76
ST16	1.74	1.76	1.8	1.91	1.99	2.03	11.23
ST17	1.76	1.88	2.06	2.14	2.19	2.41	12.44
ST18	1.32	1.48	1.54	1.61	1.67	1.68	9.3

Table A16: Soil moisture content (cm) at 64DOY on drip irrigation plots

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Stored soil moisture
DT1	1.92	2	2.06	2.13	2.2	2.7	13.01
DT2	1.88	1.94	1.99	2.05	2.14	2.54	12.54
DT3	1.73	1.9	2	2.06	2.21	2.31	12.21
DT4	1.8	2.05	1.94	2.19	2.26	2.5	12.74
DT5	1.74	1.88	1.98	2.08	2.16	2.5	12.34
DT6	1.72	1.93	2.05	2.19	2.16	2.52	12.57
DT7	1.64	1.8	1.92	2.06	2.18	2.37	11.97
DT8	1.62	1.72	1.83	1.92	2.06	2.3	11.45
DT9	1.51	1.53	1.58	1.73	1.81	1.88	10.04
DT10	1.63	1.74	1.8	2.04	2.13	2.41	11.75
DT11	1.51	1.52	1.59	1.74	1.8	1.82	9.98
DT12	1.58	1.8	1.9	2	1.93	2.02	11.23
DT13	1.51	1.7	1.86	1.89	1.93	1.98	10.87
DT14	1.53	1.67	1.77	1.86	1.94	2	10.77
DT15	1.66	1.73	1.8	1.86	1.91	2.06	11.02
DT16	1.61	1.76	1.79	1.92	1.93	2.03	11.04
DT17	1.67	1.88	1.99	2	2.07	2.47	12.08
DT18	1.5	1.52	1.6	1.69	1.7	1.81	9.82

Table A17: Soil moisture content (cm) at 71DOY on sprinkler irrigation plots

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Soil moisture stored
ST1	1.92	1.94	2.13	2.2	2.38	2.81	13.38
ST2	1.83	1.95	2.13	2.17	2.25	2.64	12.97
ST3	1.7	1.87	1.94	2.32	2.35	2.51	12.69
ST4	1.67	1.77	1.87	2	2.03	2.33	11.67
ST5	1.8	1.99	2.13	2.43	2.5	2.54	13.39
ST6	1.82	1.9	1.92	1.94	2.12	2.34	12.04
ST7	2.13	2.15	2.24	2.32	2.51	2.61	13.96
ST8	1.88	1.96	2.13	2.23	2.41	2.45	13.06
ST9	1.54	1.63	1.67	1.7	1.79	1.82	10.15
ST10	1.61	1.65	1.69	1.71	1.76	1.95	10.37
ST11	1.5	1.53	1.58	1.64	1.68	1.69	9.62
ST12	1.63	1.69	1.84	1.88	1.96	1.98	10.98
ST13	1.57	1.6	1.64	1.75	1.88	1.9	10.34
ST14	1.69	1.76	1.84	1.96	2.14	2.31	11.7
ST15	1.6	1.65	1.79	1.83	1.94	2.06	10.87
ST16	1.79	1.89	1.92	1.97	2.33	2.41	12.31
ST17	1.8	1.9	2.16	2.43	2.51	2.55	13.35
ST18	1.23	1.34	1.6	1.64	1.71	1.71	9.23

Table A18: Soil moisture content (cm) at 71DOY on drip irrigation plots

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Stored soil moisture
DT1	1.9	2.13	2.23	2.34	2.4	2.86	13.86
DT2	1.89	1.93	1.98	2.15	2.2	2.56	12.71
DT3	1.7	1.92	2.02	2.6	2.68	2.91	13.83
DT4	1.65	2.11	2.16	2.2	2.3	2.57	12.99
DT5	1.76	1.9	1.95	2.1	2.23	2.54	12.48
DT6	1.69	1.95	2.23	2.3	2.36	2.57	13.1
DT7	1.7	1.78	1.96	2.11	2.2	2.41	12.16
DT8	1.68	1.77	1.89	2.12	2.32	2.41	12.19
DT9	1.52	1.56	1.61	1.71	1.76	1.8	9.96
DT10	1.6	1.75	1.78	1.96	2.33	2.46	11.88
DT11	1.59	1.6	1.65	1.76	1.85	1.88	10.33
DT12	1.61	1.85	1.92	2.21	2.27	2.3	12.16
DT13	1.48	1.71	1.87	1.89	1.96	2.07	10.98
DT14	1.54	1.65	1.72	1.82	1.87	2.23	10.83
DT15	1.69	1.81	1.85	1.9	2.12	2.23	11.6
DT16	1.59	1.79	2.22	2.24	2.51	2.53	12.88
DT17	1.69	1.78	1.84	2.44	2.57	2.63	12.95
DT18	1.6	1.62	1.65	1.71	1.76	1.85	10.19

Table A19: Soil moisture content (cm) at 78DOY on sprinkler irrigation plots

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Soil moisture stored
ST1	1.82	1.85	1.9	1.95	2	2.15	11.67
ST2	1.71	1.75	1.92	1.95	2.12	2.33	11.78
ST3	1.52	1.58	1.77	1.92	2.02	2.13	10.94
ST4	1.42	1.53	1.7	1.85	1.89	2	10.39
ST5	1.61	1.65	1.74	1.89	1.94	2.05	10.88
ST6	1.74	1.79	1.82	1.87	1.93	1.98	11.13
ST7	1.78	1.9	1.91	2.08	2.1	2.21	11.98
ST8	1.65	1.68	1.71	1.89	2.06	2.15	11.14
ST9	1.64	1.67	1.7	1.7	1.75	1.76	10.22
ST10	1.61	1.64	1.71	1.74	1.8	1.87	10.37
ST11	1.6	1.61	1.63	1.67	1.68	1.71	9.9
ST12	1.67	1.72	1.8	1.85	1.92	1.95	10.91
ST13	1.6	1.62	1.65	1.7	1.82	1.89	10.28
ST14	1.62	1.7	1.75	1.82	1.96	2.22	11.07
ST15	1.62	1.64	1.74	1.78	1.92	1.96	10.66
ST16	1.78	1.85	1.9	1.92	2.13	2.19	11.77
ST17	1.79	1.86	2.02	2.04	2.31	2.35	12.37
ST18	1.11	1.21	1.45	1.52	1.64	1.69	8.62

Table A20: Soil moisture content (cm) at 78DOY on drip irrigation plots

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Soil moisture stored
DT1	1.85	2.11	2.2	2.28	2.3	2.63	13.37
DT2	1.74	1.82	1.89	2	2.16	2.35	11.96
DT3	1.68	1.78	1.95	2.41	2.45	2.53	12.8
DT4	1.65	1.75	1.84	1.9	2.03	2.18	11.35
DT5	1.65	1.72	1.83	1.9	2.01	2.22	11.33
DT6	1.54	1.67	1.89	1.96	2.08	2.45	11.59
DT7	1.64	1.72	1.85	2.1	2.15	2.31	11.77
DT8	1.56	1.7	1.75	2.05	2.3	2.38	11.74
DT9	1.45	1.55	1.61	1.71	1.72	1.78	9.82
DT10	1.62	1.7	1.75	1.8	1.96	2.23	11.06
DT11	1.54	1.57	1.6	1.7	1.79	1.92	10.12
DT12	1.59	1.75	1.84	2.04	2.16	2.23	11.61
DT13	1.35	1.45	1.56	1.62	1.71	1.95	9.64
DT14	1.44	1.56	1.76	1.8	1.82	1.96	10.34
DT15	1.56	1.74	1.8	1.84	1.92	2.02	10.88
DT16	1.48	1.66	1.89	1.97	2.4	2.53	11.93
DT17	1.33	1.78	1.8	1.96	2.15	2.45	11.47
DT18	1.54	1.59	1.6	1.71	1.72	1.79	9.95

Table A21: Soil moisture content (cm) at 157DOY on sprinkler
irrigation plots

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Soil moisture stored
DT1	1.91	1.99	2.12	2.19	2.4	2.59	13.2
DT2	1.86	1.94	2.02	2.21	2.26	2.44	12.73
DT3	1.93	2.08	2.15	2.2	2.28	2.38	13.02
DT4	1.88	1.97	2.03	2.15	2.22	2.46	12.71
DT5	1.78	1.9	2	2.1	2.33	2.6	12.71
DT6	1.95	2.02	2.07	2.15	2.29	2.72	13.2
DT7	1.9	1.98	2.02	2.12	2.18	2.5	12.7
DT8	1.97	2.07	2.12	2.19	2.32	2.44	13.11
DT9	1.79	1.92	2.02	2.11	2.27	2.31	12.42
DT10	1.83	1.9	2.07	2.2	2.39	2.48	12.87
DT11	1.75	1.88	1.93	2.17	2.28	2.4	12.41
DT12	1.79	1.87	1.98	2.07	2.16	2.19	12.06
DT13	1.91	1.94	2.05	2.12	2.26	2.43	12.71
DT14	1.92	2	2.06	2.19	2.27	2.31	12.75
DT15	1.79	1.87	1.97	2.02	2.17	2.28	12.1
DT16	1.96	2.01	2.12	2.23	2.34	2.57	13.23
DT17	1.87	1.93	2.02	2.1	2.2	2.46	12.58
DT18	1.88	1.96	2.06	2.21	2.3	2.51	12.92

Table A22: Soil moisture content (cm) at 157DOY on drip
irrigation plots

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Soil moisture stored
DT1	1.99	2.38	2.4	2.47	2.45	2.57	14.26
DT2	1.87	1.89	2.24	2.37	2.41	2.51	13.29
DT3	1.91	2.12	2.29	2.4	2.41	2.53	13.66
DT4	1.91	2.02	2.16	2.21	2.39	2.58	13.27
DT5	2.06	2.23	2.32	2.4	2.46	2.51	13.98
DT6	1.81	2	2.21	2.46	2.53	2.71	13.72
DT7	1.95	1.93	2.29	2.4	2.44	2.76	13.77
DT8	1.82	2.12	2.19	2.28	2.34	2.62	13.37
DT9	2.03	2.13	2.22	2.44	2.56	2.8	14.18
DT10	1.92	2.06	2.32	2.46	2.57	2.76	14.09
DT11	1.77	1.88	2.12	2.19	2.43	2.58	12.97
DT12	1.8	1.86	2.02	2.12	2.18	2.45	12.43
DT13	1.62	1.85	1.82	2.14	2.19	2.37	11.99
DT14	1.87	1.98	2.31	2.28	2.49	2.6	13.53
DT15	1.76	1.88	2.07	2.31	2.46	2.69	13.17
DT16	1.86	2	2.18	2.43	2.51	2.54	13.52
DT17	1.74	1.78	1.92	2.19	2.34	2.76	12.73
DT18	1.87	2.02	2.12	2.3	2.48	2.67	13.46

Table A23: Soil moisture content (cm) at 164DOY on sprinkler irrigation plots

Treatment							Soil moisture stored
	0.1	0.2	0.3	0.4	0.5	0.6	
ST1	1.62	1.81	1.92	2.07	2.31	2.57	12.3
ST2	1.66	1.74	1.83	2.13	2.26	2.51	12.13
ST3	1.64	1.79	1.93	2.26	2.37	2.69	12.68
ST4	1.73	2	2.06	2.13	2.34	2.67	12.93
ST5	1.68	1.78	1.99	2.19	2.37	2.43	12.44
ST6	1.78	1.8	1.93	2.08	2.19	2.56	12.34
ST7	1.6	1.77	1.81	1.99	2.3	2.44	11.91
ST8	1.7	1.86	1.9	2	2.26	2.4	12.12
ST9	1.8	2.06	2.14	2.23	2.31	2.51	13.05
ST10	1.79	1.93	2.02	2.14	2.2	2.53	12.61
ST11	1.73	1.88	2.03	2.15	2.32	2.6	12.71
ST12	1.79	1.99	2.11	2.28	2.44	2.74	13.35
ST13	1.81	1.98	2.12	2.32	2.49	2.69	13.41
ST14	1.7	1.83	1.91	2.2	2.41	2.63	12.68
ST15	1.64	1.79	1.94	2.12	2.32	2.44	12.25
ST16	1.66	1.85	1.94	2.18	2.32	2.58	12.53
ST17	1.79	1.94	2.04	2.25	2.36	2.5	12.88
ST18	1.73	1.89	1.93	2.17	2.47	2.7	12.89

Table A24: Soil moisture content (cm) at 164DOY on drip irrigation plots

Treatment							Soil moisture stored
	0.1	0.2	0.3	0.4	0.5	0.6	
DT1	1.81	1.99	2.05	2.15	2.37	2.63	13
DT2	1.73	1.82	2.02	2.08	2.42	2.71	12.78
DT3	1.94	2.13	2.14	2.19	2.5	2.76	13.66
DT4	1.88	2.04	2.16	2.24	2.39	2.65	13.36
DT5	1.92	2.13	2.19	2.32	2.63	2.81	14
DT6	1.73	1.88	2.12	2.36	2.64	2.87	13.6
DT7	1.88	2.01	2.29	2.49	2.56	2.66	13.89
DT8	1.88	2.04	2.24	2.5	2.67	2.81	14.14
DT9	1.93	2.02	2.14	2.34	2.68	2.89	14
DT10	1.7	1.9	1.99	2.28	2.63	2.88	13.38
DT11	1.83	2.12	2.2	2.37	2.51	2.74	13.77
DT12	1.9	2.04	2.21	2.47	2.69	2.89	14.2
DT13	1.87	2	2.12	2.4	2.6	2.77	13.76
DT14	1.88	1.94	2.19	2.43	2.78	2.86	14.06
DT15	1.91	2.06	2.16	2.41	2.64	2.81	13.99
DT16	1.72	1.89	1.99	2.26	2.49	2.75	13.1
DT17	1.81	1.92	2.06	2.27	2.5	2.89	13.45
DT18	1.93	2.07	2.24	2.37	2.69	2.91	14.21



Table A25: Soil moisture content (cm) at 171DOY on sprinkler irrigation plots

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Soil moisture stored
ST1	1.96	2.08	2.34	2.5	2.7	2.89	14.47
ST2	2.08	2.2	2.43	2.53	2.76	2.84	14.84
ST3	2.02	2.19	2.47	2.62	2.77	2.87	14.94
ST4	1.89	2.11	2.34	2.64	2.81	2.97	14.76
ST5	2	2.08	2.35	2.51	2.81	3	14.75
ST6	2.06	2.19	2.43	2.7	2.98	3.08	15.44
ST7	1.93	2.16	2.4	2.59	2.83	2.98	14.89
ST8	1.88	2.15	2.34	2.59	2.76	2.91	14.63
ST9	2	2.19	2.45	2.71	2.91	2.99	15.25
ST10	2.05	2.27	2.37	2.76	2.9	3	15.35
ST11	1.97	2.19	2.45	2.63	2.69	3.07	15
ST12	1.89	2.15	2.37	2.48	2.76	2.94	14.59
ST13	2.14	2.27	2.4	2.56	2.89	3.04	15.3
ST14	2.19	2.36	2.47	2.69	2.86	3.07	15.64
ST15	1.93	2.23	2.46	2.72	2.93	3.07	15.34
ST16	2.04	2.25	2.4	2.64	2.79	2.9	15.02
ST17	1.94	2.16	2.42	2.77	2.88	3.09	15.26
ST18	2.04	2.26	2.44	2.78	2.91	3.14	15.57

Table A26: Soil moisture content (cm) at 171DOY on drip irrigation plots

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Soil moisture stored
DT1	1.94	2.12	2.29	2.57	2.85	3.13	14.9
DT2	2.1	2.26	2.38	2.69	2.84	2.92	15.19
DT3	1.91	2.08	2.34	2.64	2.84	2.77	14.58
DT4	1.81	1.97	2.23	2.51	2.57	2.91	14
DT5	1.92	2.04	2.3	2.44	2.8	2.93	14.43
DT6	1.94	2.21	2.43	2.78	2.98	3.08	15.42
DT7	1.88	2.34	2.51	2.68	2.98	3.14	15.53
DT8	1.91	2.19	2.41	2.69	2.84	3.03	15.07
DT9	1.95	2.07	2.55	2.73	2.92	3	15.22
DT10	2.06	2.33	2.39	2.84	2.97	3.03	15.62
DT11	1.96	2.24	2.31	2.59	2.88	2.9	14.88
DT12	1.92	2.19	2.56	2.68	2.85	3.07	15.27
DT13	1.93	2.07	2.44	2.6	2.68	3.08	14.8
DT14	2.06	2.42	2.5	2.63	2.69	2.89	15.19
DT15	2.04	2.29	2.38	2.5	2.59	2.71	14.51
DT16	2.03	2.21	2.26	2.56	2.71	2.84	14.61
DT17	2.02	2.16	2.38	2.78	2.87	2.97	15.18
DT18	2.07	2.06	2.14	2.16	2.43	2.6	13.46

Table A27: Soil moisture content (cm) at 178 DOY on sprinkler irrigation plots

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Soil moisture stored
ST1	2.09	2.13	2.44	2.72	2.98	3.27	15.63
ST2	2.12	2.34	2.41	2.6	2.94	3.06	15.47
ST3	2.09	2.21	2.24	2.69	3.01	3.26	15.5
ST4	1.93	2.14	2.19	2.54	2.82	2.98	14.6
ST5	1.91	2.19	2.38	2.81	2.94	3.02	15.25
ST6	1.87	2.08	2.45	2.65	2.89	3.16	15.1
ST7	1.94	2.21	2.7	2.87	2.92	3.03	15.67
ST8	2.06	2.2	2.52	2.7	2.98	3.19	15.65
ST9	2.05	2.23	2.6	2.85	3.06	3.15	15.94
ST10	1.88	2.27	2.7	2.88	2.97	3.05	15.75
ST11	1.92	2.06	2.26	2.73	2.8	2.94	14.71
ST12	1.88	2.19	2.32	2.55	2.75	3.06	14.75
ST13	1.91	2.06	2.28	2.75	2.8	2.92	14.72
ST14	2.09	2.16	2.3	2.7	2.84	3.02	15.11
ST15	2.13	2.21	2.29	2.47	2.67	2.84	14.61
ST16	1.97	2.07	2.28	2.64	2.85	3.1	14.91
ST17	1.81	1.85	2.13	2.26	2.54	2.73	13.32
ST18	2.05	2.15	2.24	2.37	2.44	2.75	14

Table A28: Soil moisture content (cm) at 178 DOY on drip irrigation plots

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Soil moisture stored
ST1	1.94	2.1	2.57	2.82	3	3.3	15.73
ST2	2.13	2.26	2.48	2.62	2.87	3.18	15.54
ST3	1.94	2.26	2.48	2.68	3.05	3.27	15.68
ST4	2.04	2.17	2.37	2.62	2.94	3.08	15.22
ST5	1.99	2.15	2.46	2.76	2.89	3.09	15.34
ST6	1.86	2.16	2.5	2.59	3	3.14	15.25
ST7	2.01	2.22	2.75	2.54	2.92	3.04	15.48
ST8	2.12	2.34	2.53	2.76	3.02	3.16	15.93
ST9	2.03	2.12	2.39	2.51	3.08	3.12	15.25
ST10	1.9	2.28	2.5	2.78	3.04	3.14	15.64
ST11	1.99	2.16	2.57	2.88	2.9	3.02	15.52
ST12	2	2.09	2.51	2.71	3.04	3.07	15.42
ST13	1.99	2.19	2.41	2.55	2.93	3.05	15.12
ST14	2.14	2.24	2.41	2.78	2.87	3.09	15.53
ST15	2.02	2.37	2.39	2.57	2.89	3.01	15.25
ST16	1.9	2.22	2.34	2.67	2.88	3.05	15.06
ST17	1.91	2.12	2.28	2.51	2.69	4.88	16.39
ST18	2.03	2.16	2.36	2.47	2.63	2.93	14.58

Table A29: Soil moisture content (cm) at 185 DOY on sprinkler irrigation plots

Treatment							Soil moisture stored
	0.1	0.2	0.3	0.4	0.5	0.6	
ST1	2.19	1.93	2.13	2.57	2.73	2.92	14.47
ST2	1.98	2.07	2.22	2.5	2.62	2.89	14.28
ST3	2	2.14	2.17	2.37	2.68	2.93	14.29
ST4	1.89	1.91	2.15	2.28	2.56	2.89	13.68
ST5	1.81	2	2.12	2.29	2.51	2.81	13.54
ST6	1.9	1.96	2.19	2.41	2.5	2.77	13.73
ST7	1.91	2.05	2.27	2.34	2.56	2.85	13.98
ST8	1.99	2.17	2.4	2.55	2.91	2.91	14.93
ST9	1.9	2.09	2.24	2.49	2.75	2.89	14.36
ST10	1.79	1.98	2.13	2.28	2.51	2.63	13.32
ST11	1.95	2.01	2.08	2.31	2.5	2.75	13.6
ST12	1.81	2.01	2.05	2.29	2.55	2.82	13.53
ST13	1.87	1.9	2.02	2.16	2.5	2.71	13.16
ST14	1.94	2.08	2.25	2.43	2.61	2.81	14.12
ST15	1.98	2.03	2.09	2.37	2.56	2.72	13.75
ST16	1.78	2.05	2.16	2.3	2.63	2.73	13.65
ST17	1.74	1.88	2.03	2.28	2.48	2.64	13.05
ST18	1.82	1.91	2.09	2.3	2.56	2.69	13.37

Table A30: Soil moisture content (cm) at 185 DOY on drip irrigation plots

Treatment							Soil moisture stored
	0.1	0.2	0.3	0.4	0.5	0.6	
DT1	1.9	2.03	2.41	2.69	2.85	3.04	14.92
DT2	1.94	2.15	2.29	2.66	2.72	2.81	14.57
DT3	1.88	2.03	2.26	2.63	2.88	3.02	14.7
DT4	1.99	2.12	2.3	2.68	2.89	3.01	14.99
DT5	1.86	2.01	2.13	2.31	2.76	2.89	13.96
DT6	1.75	1.92	2.17	2.45	2.63	2.79	13.71
DT7	1.86	2.05	2.32	2.63	2.92	3.06	14.84
DT8	1.96	2.12	2.33	2.7	2.8	3	14.91
DT9	1.91	2.01	2.18	2.5	2.77	2.92	14.29
DT10	1.77	1.89	2.06	2.48	2.88	3.13	14.21
DT11	1.86	1.93	2.18	2.19	2.53	2.94	13.63
DT12	1.94	2.12	2.37	2.49	2.6	2.75	14.27
DT13	1.91	2.13	2.43	2.77	2.84	3.15	15.23
DT14	1.96	2.17	2.44	2.8	3.01	3.16	15.54
DT15	1.88	2.06	2.38	2.63	2.78	3.01	14.74
DT16	1.82	1.99	2.37	2.71	2.92	3.17	14.98
DT17	1.79	2.05	2.43	2.76	2.88	3.01	14.92
DT18	1.87	2.1	2.45	2.63	2.76	2.84	14.65

Table A31: Soil moisture content (cm) at 192 DOY on sprinkler irrigation

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Soil moisture stored
ST1	1.75	1.9	1.93	2.27	2.52	2.57	12.94
ST2	1.9	1.97	2.07	2.34	2.44	2.63	13.35
ST3	1.88	1.92	2.04	2.28	2.37	2.51	13
ST4	1.76	1.87	2.02	2.16	2.41	2.56	12.78
ST5	1.75	1.85	1.87	2.08	2.28	2.43	12.26
ST6	1.8	1.9	1.92	2.15	2.33	2.56	12.66
ST7	1.77	1.8	1.99	2.17	2.41	2.62	12.76
ST8	1.73	1.93	2.07	2.18	2.38	2.69	12.98
ST9	1.81	1.99	2.15	2.3	2.5	2.62	13.37
ST10	1.82	2.02	2.16	2.25	2.34	2.53	13.12
ST11	1.67	1.86	2.07	2.18	2.36	2.58	12.72
ST12	1.78	1.95	2.09	2.2	2.37	2.54	12.93
ST13	1.74	1.91	2.02	2.13	2.28	2.52	12.6
ST14	1.72	1.86	2.05	2.2	2.3	2.56	12.69
ST15	1.61	1.79	2.05	2.18	2.34	2.68	12.65
ST16	1.77	1.92	2.07	2.24	2.32	2.62	12.94
ST17	1.73	1.9	2.02	2.15	2.28	2.56	12.64
ST18	1.8	1.92	2.05	2.17	2.33	2.46	12.73

Table A32: Soil moisture content (cm) at 192 DOY on drip irrigation plots

Treatment	0.1	0.2	0.3	0.4	0.5	0.6	Soil moisture stored
DT1	1.86	2.01	2.03	2.16	2.41	2.5	12.97
DT2	1.88	1.93	2.06	2.28	2.33	2.56	13.04
DT3	1.77	1.88	2.02	2.33	2.44	2.68	13.12
DT4	1.77	1.87	1.99	2.25	2.41	2.57	12.86
DT5	1.79	1.93	2.05	2.36	2.44	2.58	13.15
DT6	1.73	1.9	2.04	2.34	2.49	2.68	13.18
DT7	1.78	2	2.13	2.24	2.44	2.75	13.34
DT8	1.77	1.9	2.02	2.19	2.32	2.6	12.8
DT9	1.79	1.93	2.03	2.3	2.43	2.81	13.29
DT10	1.74	1.91	2.01	2.3	2.4	2.7	13.06
DT11	1.72	1.9	2.05	2.33	2.44	2.84	13.28
DT12	1.91	1.94	2.07	2.43	2.51	2.7	13.56
DT13	1.82	1.92	2.05	2.37	2.43	2.75	13.34
DT14	1.77	1.86	1.98	2.19	2.37	2.82	12.99
DT15	1.88	1.93	2.05	2.2	2.38	2.51	12.95
DT16	1.9	1.95	2.06	2.17	2.33	2.63	13.04
DT17	1.72	1.86	1.99	2.24	2.31	2.68	12.8
DT18	1.73	1.82	1.96	2.17	2.31	2.51	12.5

APPENDIX B

Table B1. Change in soil moisture stored on sprinkler plot during the dry season of 2005

Dry of the Year	22	36	43	50	57	64	71	78	85
T1	2.88	1.72	0.45	0.28	0.23	2.72	-0.04	0.26	-1.71
T2	3.4	0.95	0.65	0.25	0.33	2.02	0.38	0.51	-1.19
T3	1.8	1.81	0.59	0.22	0.41	2.41	-0.77	0.78	-1.75
T4	1.52	1.62	0.83	0.28	0.14	2.82	-0.66	0	-1.28
T5	2.02	2.07	0.72	0.3	0.42	2.01	0.39	0.87	-2.51
T6	1.58	2.5	0.49	0.21	0.26	1.4	1.09	0	-0.91
T7	1.11	0.67	1.54	0.58	0.21	1.35	2.09	1.17	-1.98
T8	0.63	0.94	1.09	0.4	-0.1	2.37	0.16	1.69	-1.92
T9	0.39	0.88	2.14	0.41	-0.54	0.26	0.24	0.79	0.07
T10	0.97	1.97	0.94	0.3	0.19	0.56	0.02	0.42	0
T11	1.25	1.1	1.23	0.37	0.55	0.44	-0.61	0.13	0.28
T12	0.69	1.76	1.18	0.58	0.33	0.19	0.6	0.66	-0.07
T13	-0.13	1.67	1.51	0.43	0.05	-0.33	0.63	0.29	-0.06
T14	1.95	0.69	1	0.55	0.09	0.6	1.27	0.27	-0.63
T15	0.11	1.13	1.46	0.31	0.32	-0.01	0.93	0.11	-0.21
T16	0.52	1.21	1.23	0.64	-0.05	0.72	1.63	1.08	-0.54
T17	2.51	0.12	0.51	0.35	0.89	1.66	1.19	0.91	-0.98
T18	0.25	0.63	1.02	0.33	0.24	1.68	-0.71	-0.07	-0.61

Table B2. Change in soil moisture stored on drip plots during the dry season of 2005

	22	36	43	50	57	64	71	78	85
T1	0.77	0.26	1.57	1.21	1.56	1.88	0.49	0.85	-0.49
T2	0.55	0.26	0.84	1.17	1.69	1.94	0.17	0.17	-0.75
T3	0.64	0.25	0.63	1	2.24	1.11	0.3	1.62	-1.03
T4	0.46	0.26	0.75	0.43	2.47	1.18	0.99	0.25	-1.64
T5	0.74	0.37	0.86	0.93	1.83	1.73	0.5	0.14	-1.15
T6	0.29	0.31	1.52	0.61	2.38	1.05	0.98	0.53	-1.51
T7	0.33	0.2	0.78	1.38	1.63	1.52	0.81	0.19	-0.39
T8	0.19	0.26	1.81	0.45	1.63	0.97	0.85	0.74	-0.45
T9	0.39	0.21	0.95	0.69	1.02	0.21	0.89	-0.08	-0.14
T10	1.13	0.12	0.87	0.88	1.88	0.06	1.75	0.13	-0.82
T11	0.42	-0.05	1.17	0.97	1.69	-0.09	-0.1	0.35	-0.21
T12	0.38	0.22	0.98	0.8	2.54	0.01	0.66	0.93	-0.55
T13	0.53	0.07	2.18	0.57	2.02	-0.93	1.54	0.11	-1.34
T14	0.8	0.15	1.01	0.22	2.24	-0.06	0.54	0.06	-0.49
T15	0.86	0.34	1.12	0.58	2	0.33	0.46	0.58	-0.72
T16	0.29	0.92	0.72	0.82	0.56	1.35	1.02	1.84	-0.95
T17	0.5	0.3	0.85	0.38	2.24	1.77	0.05	0.87	-1.48
T18	0.18	0.35	0.9	1.11	0.68	0.28	0.84	0.37	-0.24

APPENDIX C

Table C1: Statistical analysis of crop water use

SUMMARY

Groups	Count	Sum	Average	Variance
9.921429	17	62.95714	3.703361	7.325026
9.962857	17	63.48286	3.734286	7.44828
9.88	17	101.5457	5.973277	12.22444
9.832857	17	102.5586	6.032857	12.2359
9.758571	17	99.92857	5.878151	12.03472
9.722857	17	102.6071	6.035714	11.70556
12.79	17	150.1914	8.83479	12.26501
5.261429	17	82.91429	4.877311	9.851462
5.421429	17	86.52	5.089412	10.03616

Table C2 ANOVA of Crop Water use

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	321.5116	8	40.18895	3.802308	0.000445	2.003251
Within Groups	1522.025	144	10.56962			
Total	1843.537	152				

Table C3. Optimization of Crop Water use

A	B	RSME	1.3525816
-0.280555	3.839899		Error Sum
			32.9305856
Measured Value	input	Model Output	Error
13.16	9.56	11.06850299	4.37435973
12.08	9.56	11.06850299	1.0231262
12.23	8.87	11.98670645	0.05919175
12.33	7.45	13.03574366	0.49807412
12.13	6.45	13.09555916	0.9323045
11.38	6.55	13.11482756	3.00962667
10.7	5.66	12.74608058	4.18644575
11.21	3.21	9.343520901	3.14988304
9.12	4.11	11.0428177	3.697243358
10.26	4.27	11.28103747	1.04251752
10.1	4.29	11.30980443	1.4362677
9.72	3.89	10.69182079	0.94443566
9.42	3.54	10.07743942	0.43222659
10.16	9.98	10.3788018	0.04787423
9.83	5.33	12.49640273	7.10970352
9.6	3.43	9.870152051	0.07298213
11.25	9.96	10.4138815	0.69908135
10.01	3.28	9.576545808	0.18788254

Table C4. Correlation between Measured values, Input and Model output

	Measured value	Input	Model output
Measured value	1		
Input	0.88054924	1	
Model Output	0.791844837	0.924155	1

Table C5. Summary statistics of yield under drip irrigation system

Groups	Count	Sum	Average	Variance
1.53	17	23.63	1.39	0.123563
2.85	17	29.8	1.752941	0.506547
3.09	17	32.99	1.940588	0.625293
2.98	17	33.38	1.963529	0.515687
2.69	17	29.45	1.732353	0.413357

Table C6. ANOVA of Harvestable yield from different treatments

Source of Variation	SS	df	MS	F	P-value	Fcrit
Between Groups	3.598318	4	0.899579	2.059056	0.093956	2.485883
Within Groups	34.95114	80	0.436889			
Total	38.54946	84				

Table C7: Statistics of soil hydraulic charge

Groups	Count	Sum	Average	Variance
63	69	3253.9	47.15797	570.8389
58	69	2624.5	38.03623	637.0668
63.8	69	2393.6	34.68986	579.0886
62.2	69	2082.6	30.18261	475.1897
30.6	69	1265.3	18.33768	160.2706

Table C8. ANOVA of Soil Hydraulic Charge

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	30999.68	4	7749.921	15.99601	5.19E-12	2.39821
Within Groups	164726.9	340	484.4909			
Total	195726.6	344				

Table C9: Statistics of plant height on sprinkler plots in 2005

Groups	Count	Sum	Average	Variance
T1	7	3725	532.1429	157490.8
T2	7	2907	415.2857	123148.9
T3	7	3104	443.4286	129321.3
T4	7	2866	409.4286	123994
T5	7	2673	381.8571	109240.8
T6	7	2882	411.7143	112740.6
T7	7	2477	353.8571	96144.14
T8	7	2926	418	109130.3
T9	7	2685	383.5714	106108
T10	7	2967	423.8571	141238.5
T11	7	2974	424.8571	130478.5
T12	7	2713	387.5714	127391.3
T13	7	2279	325.5714	122155.6
T14	7	3228	461.1429	137011.8
T15	7	2537	362.4286	92682.95
T16	7	2452	350.2857	117833.6
T17	7	3356.7	479.5286	162049.9
T18	7	2452	350.2857	113075.6

Table C10: ANOVA of Plant Height on plots irrigated under sprinkler system

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	317985	17	18705	0.152263	0.999965	1.718165
Within Groups	13267418	1108	122846.5			
Total	13585403	125				

Table C11: Statistics of plant height during wet season 2005

Groups	Count	Sum	Average	Variance
T1	7	2039.4	291.3429	51445.05
T2	7	1940.1	277.1571	48185.94
T3	7	2068.6	295.5143	55485.78
T4	7	2082.2	297.4571	57179.5
T5	7	1899.5	271.3571	49852.15
T6	7	1751.1	250.1571	41785.34
T7	7	1661.4	237.3429	35815.56
T8	7	1638	234	39255.65
T9	7	1673.6	239.0857	40253.66
T10	7	1583.1	226.1571	35205.73
T11	7	1562.4	223.2	40831.56
T12	7	1461.4	208.7714	33497.34
T13	7	1607.9	229.7	35099.23
T14	7	1844.8	263.5429	49666.58
T15	7	1909.7	272.8143	52241.66
T16	7	1741.9	248.8429	38842
T17	7	1634.9	233.5571	32329.63
T18	7	1659.6	237.0857	36594

Table C12. ANOVA of Plant Height during wet season

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	85585.74	18	4754.763	0.109613	0.999998	1.701041
Within Groups	4641398	107	43377.55			
Total	4726984	125				

Table C13. Summary statistics of Number of leaves on plots irrigated under sprinkler system

Groups	Count	Sum	Average	Variance
6	17	81	4.764706	0.691176
25	17	250	14.70588	2734559
73	17	641	37.70588	167.8456
103	17	946	55.64706	354.3676
124	17	1224	72	486.25
184	17	1751	103	812
200	17	2547	149.8235	599.1544

Table C14. ANOVA of Number of leaves on plots irrigated under sprinkler system

Source of Variation	SS	df	MS	F	P-Value	Fcrit
Between Groups	265799.2	6	44499.87	126.6924	1.53E-47	2.180563
Within Groups	39162.47	112	349.6649			
Total	304961.7	118				

APPENDIX D

Select Soil Type

Soil Type

Sandy Loam

Soil Types

Soil Type	Saturation	Field Capacity	Permanen...	Last Edited	Comments
Sandy	0.475	0.368	0.272	7/1/1999 18:13...	
Loam	0.464	0.321	0.197	7/1/1999 18:26...	
Silt	0.463	0.279	0.117	9/24/1999 5:18...	
Sandy Silt	0.437	0.168	0.055	9/8/2000 3:485...	
Silt	0.437	0.115	0.033	7/11/1999 5:40...	
Sandy Clay	0.43	0.311	0.239	7/1/1999 18:28...	
Sandy Clay Loam	0.398	0.265	0.084	3/9/2007 12:48...	
Sandy Loam	0.453	0.245	0.095	9/11/2000 2:00...	
Loam	0.501	0.324	0.133	7/1/1999 18:25...	

Define Row

Delete Record

Close

Notes	
1	Sandy Clay Loam
2	Drainage
3	C:\Documents and Settings\J. T. FASH\Desktop
4	Amaranthus cruentus
5	IRRIG PLAN 1
6	Not Used
7	Not Used
8	Not Used
9	Not Used
10	Not Used
11	15-Jan-2005 - 26-Mar-2005

Select Drainage Scenario

Drainage Scenario

Drainage Scenarios

	Diameter (in)	Depth (in)	Spacing (in)	Last Edited:	Comments
1	0.54	1	10	3-9-2007 12:50...	
2	0.15	2	50	7-7-1999 5:07:5...	

Define New

Delete Record

Close

Scenario	
1	Sandy Clay Loam
2	Drainage
3	C:\Documents and Settings\J. T. FASB\Desktop
4	Amaranthus cruentus
5	IRRIG PLAN 1
6	Not Used
7	Not Used
8	Not Used
9	Not Used
10	15-Jan-2005 - 26-Mar-2005



Select Climate Data

File View Help

Open File: C:\Documents and Settings\J. T. FASH\Desktop\J08150

Select New
Climate File

Title Name Description

Start Date

Finish Date

Close



Station	
1	Sandy Clay Loam
2	Drainage
3	C:\Documents and Settings\J. T. FASH\Desktop
4	Amaraethus cuneatus
5	RRG PLAN 1
6	Not Used
7	Not Used
8	Not Used
9	Not Used
10	Not Used
Notes	15-Jan-2005 - 26-Mar-2005

Crop Data Entry Form

000

Amaranthus creentes

Crop Number: 1

15 Jan 2005

Last Edited: 3/13/2007 3:52:40

Crop Interval

15 Jan 2005



Crop Year 1

Crop Year 2

Day 14 (28 Jan)	←		→
Day 24 (07 Feb)	←		→
Day 57 (12 Mar)	←		→
Day 79 (25 Mar)	←		→
Day 71 (26 Mar)	←		→
Day 64 (27 Mar)	←		→

Canopy 95 ← →

Stem 8 ← →

Leaf Area Index 1 ← →

Interception

Adjust for Interception

Depth 0.00 ← →

Depth 0.15 ← →

Transpiration Factors

p-Fraction 0.50 ← →

Yield Response 1.00 ← →

Salinity Threshold (dS/m) 1.70 ← →

Slope (°/dS/m) 12.00 ← →

Reduce ET due to excess water

Depth 0 ← →

Depth 1.00 ← →

Plot Crop Development

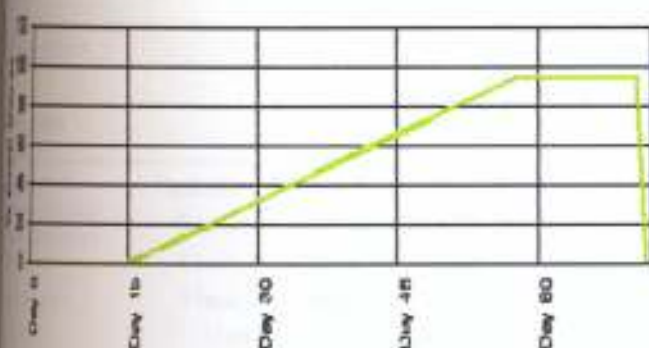
Save As New Record

Confirm

Location	C:\Documents and Settings\J. L. FASH\Desktop
Plot ID	Amaranthus creentes
Crop ID	ISSRG PLAN 1
Plot ID	Not Used
Crop ID	Not Used
Plot ID	Not Used
Crop ID	Not Used
Plot ID	Not Used
Crop ID	Not Used
Location	15 Jan 2005 - 26 Mar 2005

Crop Development

Crop Cover and Root Development



Crop Growth Cycle

OK

Plot Crop Development

Save As New Record

Confirm

File	U:\Documents and Settings\J. L. FASH\Desktop
Plot	Amaranthus cruentus
Watering	IRRIG PLAN 1
Plot 1	Not Used
Plot 2	Not Used
Plot 3	Not Used
Plot 4	Not Used
Plot 5	Not Used
Start Date	15 Jun 2005 - 26 Mar 2005

Selected Crop Type for Crop Number: 1

Crop Type for Crop Number: 1

Clear Crop

Location: Amman, Jordan

Plot Crop
Development

Select
Irrigation

Plot Crop Types

Crop	Planting Date	Harvest	Last Edited	Comments
Amaranthus cruentus	15 January	26 March	3/13/2007 4:03...	
Wheat	1 January	31 December	11/22/1999 11:0...	
Wheat grass	1 January	31 December	11/8/1999 10:27...	
Wheat	1 April	31 August	11/19/1999 3:30...	

Define View

Delete Record

Close

Location	
Soil	Sandy Clay Loam
Drainage	Drainage
Path	C:\Documents and Settings\J. T. FASH\Desktop
Crop	Amaranthus cruentus
Plot (1)	IRRIG PLAN 1
Plot (2)	Not Used
Plot (3)	Not Used
Plot (4)	Not Used
Plot (5)	Not Used
Period	15-Jan-2005 - 26-Mar-2005

Irrigation Data Entry Form

000

Irrigation Plan Name: IRRIG PLAN 1

Last

Edited: 3/13/2007 3:57:10

Plot:

☐ No Irrigation
 ☐ Rainfall Interception
 ☐ Water Salinity Flow Rate
 ☐ Controlled Drainage

Crop Name: Amaranthus cruentus

Crop Number:

1

Plot Crop Development

Harvest Date: 15 Jan

Harvest

25 Mar

Duration (days)

71

Irrigation Schedule

Irrigation Method

 50

 0

Irrigation Start Date: 15 Jan

Finish Date: 25 Mar, Day 70



Location	C:\Documents and Settings\J. L. FASMA\Desktop
Crop	Amaranthus cruentus
Plan	IRRIG PLAN 1
Method	Not Used
Method	Not Used
Method	Not Used
Method	Not Used
Method	Not Used
Dates	15-Jan-2005 - 26-Mar-2005

vWin

Initial Conditions

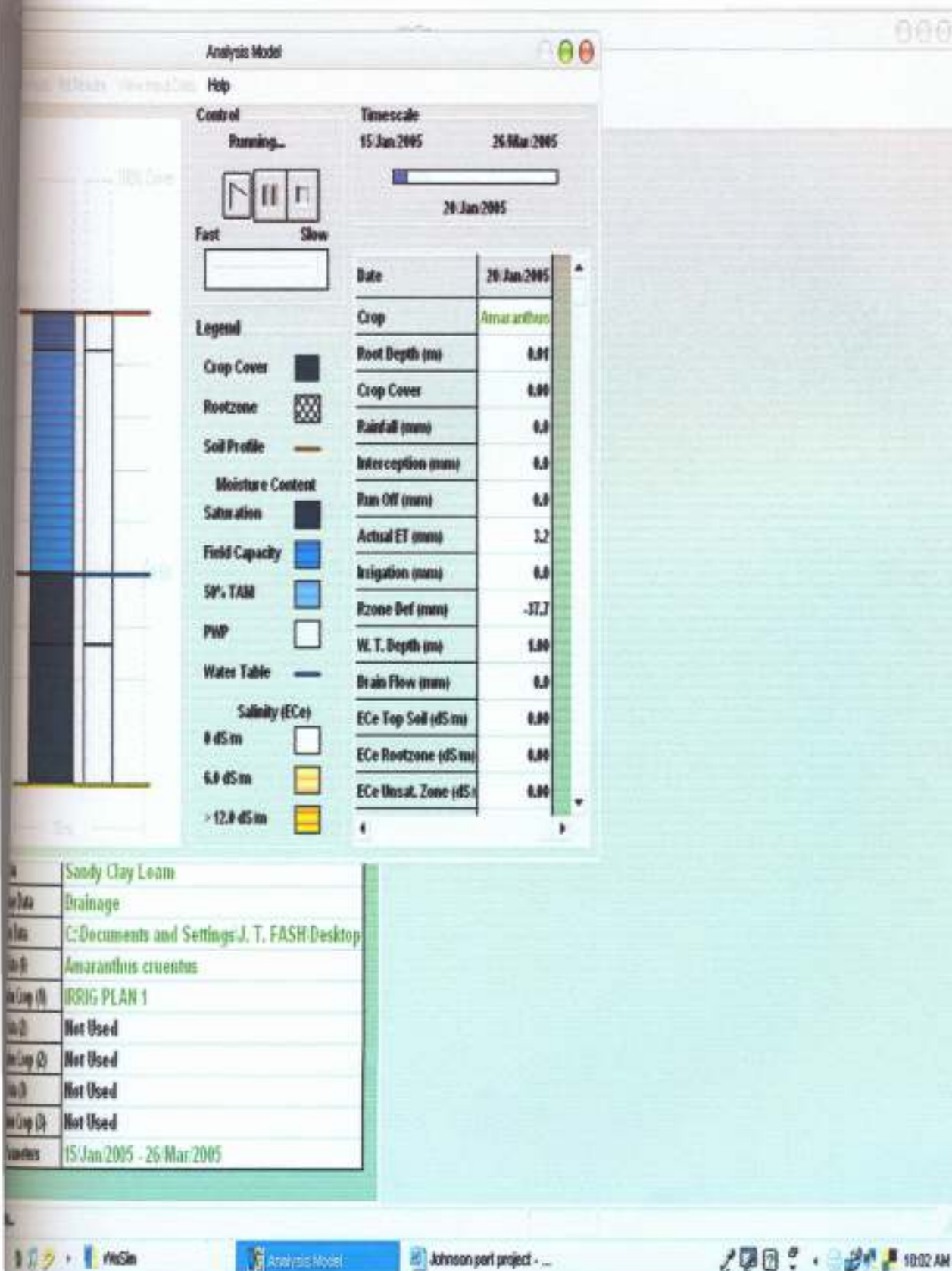
Dates	Water Content	Salinity
To Location		
All dates in Climate File 01 Dec 1995 30 Dec 1995		
Selected Dates from 15 Jan 2005 to 26 Mar 2005		
Summary Results		
Annually at 01 Apr		

Cancel
Close

Soil Status	
Soil	Sandy Clay Loam
Soil Data	Drainage
Soil Data	C:\Documents and Settings\J. T. FASH\Desktop
Soil (1)	Amaranthus cruentus
Soil Crop (1)	IRRIG PLAN 1
Soil (2)	Not Used
Soil Crop (2)	Not Used
Soil (3)	Not Used
Soil Crop (3)	Not Used
Parameters	15 Jan 2005 - 26 Mar 2005

IRRIGATION PLAN 1

WaSim model run for irrigation plan 1



Analysis Model

Help

Control

Running...

Timescale

15 Jan 2005

26 Mar 2005

20 Jan 2005

Fast

Slow

Legend

Crop Cover



Rootzone



Soil Profile



Moisture Content

Saturation



Field Capacity



SP's TMR



PWP



Water Table



Salinity (ECe)

0 dS/m



6.0 dS/m



> 12.0 dS/m



Date

20 Jan 2005

Crop

Amaranthus

Root Depth (mm)

0.01

Crop Cover

0.00

Rainfall (mm)

0.0

Interception (mm)

0.0

Run Off (mm)

0.0

Actual ET (mm)

3.2

Irrigation (mm)

0.0

Rzone Def (mm)

-37.7

W.T. Depth (m)

1.00

Brain Flow (mm)

0.0

ECe Top Soil (dS/m)

0.00

ECe Rootzone (dS/m)

0.00

ECe Unsat. Zone (dS/m)

0.00

Sandy Clay Loam

Drainage

C:\Documents and Settings\J. T. FASH\Desktop

Amaranthus cruentus

IRRIG PLAN 1

Not Used

Not Used

Not Used

Not Used

15 Jan 2005 - 26 Mar 2005

Analysis Model

Johnson port project

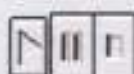
10:02 AM

Analysis Model

Help

Control

Running...



Fast

Slow

Legend

Crop Cover



Rootzone



Soil Profile



Moisture Content

Saturation



Field Capacity



50% TSM



PWP



Water Table



Salinity (ECe)

0 dS/m



6.0 dS/m



> 12.0 dS/m



Timescale

15 Jan 2005

26 Mar 2005

28 Jan 2005

Date

28 Jan 2005

Crop

Amaranthus

Root Depth (m)

0.04

Crop Cover

0.00

Rainfall (mm)

0.0

Interception (mm)

0.0

Run Off (mm)

0.0

Actual ET (mm)

3.3

Irrigation (mm)

0.0

Rzone Def (mm)

-33.1

W. T. Depth (m)

1.00

Drain Flow (mm)

0.1

ECe Top Soil (dS/m)

0.00

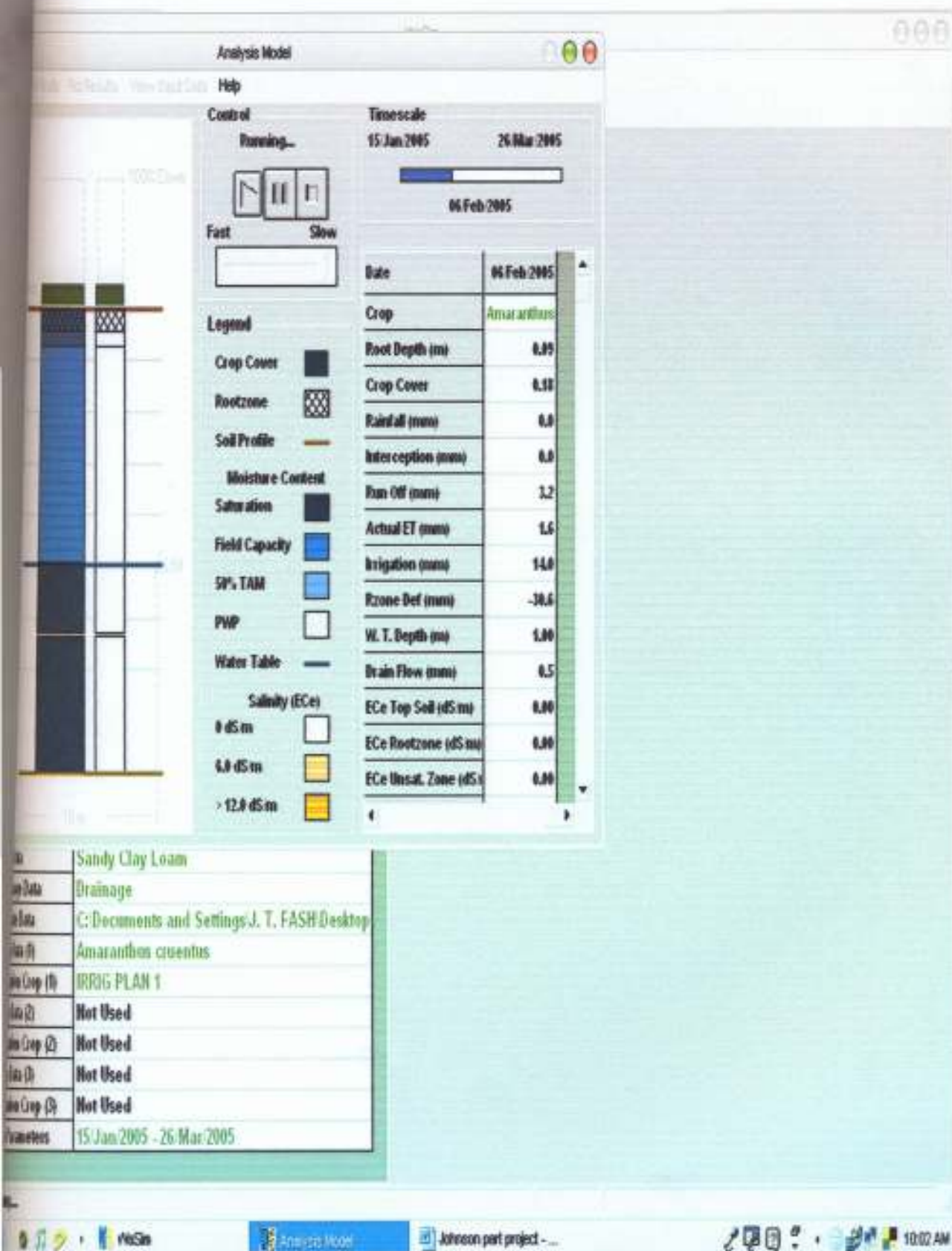
ECe Rootzone (dS/m)

0.00

ECe Unsat. Zone (dS/m)

0.00

Soil	Sandy Clay Loam
Soil Data	Drainage
Soil Data	C:\Documents and Settings\J. T. FASH\Desktop
Soil (1)	Amaranthus cruentus
Soil Crop (1)	IRRIG PLAN 1
Soil (2)	Not Used
Soil Crop (2)	Not Used
Soil (3)	Not Used
Soil Crop (3)	Not Used
Parameters	15 Jan 2005 - 26 Mar 2005



Analysis Model

Help

Control

Running...



Fast

Slow

Legend

Crop Cover



Rootzone



Soil Profile



Moisture Content

Saturation



Field Capacity



SP% TSM



PWP



Water Table



Salinity (ECe)

0 dS/m



6.0 dS/m



> 12.0 dS/m



Timescale

15 Jan 2005

26 Mar 2005



12 Feb 2005

Date	12 Feb 2005
Crop	Amaranthus
Root Depth (m)	0.14
Crop Cover	0.31
Rainfall (mm)	0.0
Interception (mm)	0.0
Run Off (mm)	1.5
Actual ET (mm)	1.3
Irrigation (mm)	14.0
Rzone Def (mm)	-21.6
W. T. Depth (m)	0.99
Drain Flow (mm)	0.3
ECe Top Soil (dS/m)	0.00
ECe Rootzone (dS/m)	0.00
ECe Unsat. Zone (dS/m)	0.00

Soil	Sandy Clay Loam
Map Data	Drainage
Map Data	C:\Documents and Settings\J. T. FASH\Desktop
Map Data (1)	Amaranthus cruentus
Map Crop (1)	IRRIG PLAN 1
Map Crop (2)	Not Used
Map Crop (3)	Not Used
Map Crop (4)	Not Used
Parameters	15 Jan 2005 - 26 Mar 2005

Analysis Model

Help

Control

Running...



Fast

Slow

Legend

Crop Cover



Rootzone



Soil Profile



Moisture Content

Saturation



Field Capacity



50% TAW



PWP



Water Table



Salinity (ECe)

0 dS/m



6.0 dS/m



> 12.0 dS/m



Timescale

15 Jan 2005

26 Mar 2005

10 Feb 2005

Date 10 Feb 2005

Crop Amaranthus

Root Depth (m) 0.30

Crop Cover 0.45

Rainfall (mm) 0.0

Interception (mm) 0.0

Run Off (mm) 1.5

Actual ET (mm) 1.0

Irrigation (mm) 14.0

Rzone Def (mm) -26.3

W. T. Depth (m) 0.30

Drain Flow (mm) 1.1

ECe Top Soil (dS/m) 0.00

ECe Rootzone (dS/m) 0.00

ECe Unsat. Zone (dS/m) 0.00

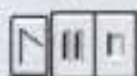
Soil	Sandy Clay Loam
Map Data	Drainage
Map Data	C:\Documents and Settings\J. T. FASH\Desktop
Map Data (1)	Amaranthus cruentus
Map Crop (1)	IRRIG PLAN 1
Map Crop (2)	Not Used
Map Crop (2)	Not Used
Map Crop (3)	Not Used
Map Crop (3)	Not Used
Parameters	15 Jan 2005 - 26 Mar 2005

Analysis Model

Help

Control

Running...



Fast

Slow

Legend

Crop Cover



Rootzone



Soil Profile



Moisture Content

Saturation



Field Capacity



50% TBM



PWP



Water Table



Salinity (ECe)

0 dS/m



6.0 dS/m



> 12.0 dS/m



Timescale

15 Jan 2005

26 Mar 2005



24 Feb 2005

Date 24 Feb 2005

Crop Amaranthus

Root Depth (m) 0.23

Crop Cover 0.59

Rainfall (mm) 0.0

Interception (mm) 0.0

Run Off (mm) 2.7

Actual ET (mm) 2.0

Irrigation (mm) 14.0

Rzone Def (mm) -14.6

W. T. Depth (m) 0.99

Drain Flow (mm) 1.4

ECe Top Soil (dS/m) 0.00

ECe Rootzone (dS/m) 0.00

ECe Unsat. Zone (dS/m) 0.00

Soil	Sandy Clay Loam
Drainage	Drainage
Location	C:\Documents and Settings\J. T. FASH\Desktop
Crop	Amaranthus cruentus
Irrig Plan	IRRIG PLAN 1
Water	Not Used
Fertilizer	Not Used
Pesticide	Not Used
Harvest	Not Used
Simulation	15 Jan 2005 - 26 Mar 2005

Analysis Model

Help

Control

Running...

Timescale

15 Jan 2005

26 Mar 2005

01 Mar 2005

Fast

Slow

Legend

Crop Cover

Rootzone

Soil Profile

Moisture Content

Saturation

Field Capacity

SP% TAM

PNP

Water Table

Salinity (ECe)

0 dS/m

6.0 dS/m

> 12.0 dS/m

Date 01 Mar 2005

Crop Amaranthus

Root Depth (m) 0.27

Crop Cover 0.70

Rainfall (mm) 0.1

Interception (mm) 0.0

Run Off (mm) 0.0

Actual ET (mm) 0.6

Irrigation (mm) 0.0

Rzone Def (mm) -25.6

W. T. Depth (m) 0.95

Drain Flow (mm) 2.2

ECe Top Soil (dS/m) 0.00

ECe Rootzone (dS/m) 0.00

ECe Unsat. Zone (dS/m) 0.00

Soil	Sandy Clay Loam
Soil Data	Drainage
Soil Data	C:\Documents and Settings\J. T. FASH\Desktop
Soil (1)	Amaranthus creentus
Soil Crop (1)	IRRIG PLAN 1
Soil (2)	Not Used
Soil Crop (2)	Not Used
Soil (3)	Not Used
Soil Crop (3)	Not Used
Parameters	15 Jan 2005 - 26 Mar 2005

Analysis Model

Help

Control

Running...

Timescale

15 Jan 2005

26 Mar 2005

07 Mar 2005

Fast

Slow

Legend

Crop Cover



Rootzone



Soil Profile



Moisture Content

Saturation



Field Capacity



SPH TAM



PWP



Water Table



Salinity (ECe)

0 dS/m



6.0 dS/m



> 12.0 dS/m



Date	07 Mar 2005
Crop	Amaranthus
Root Depth (mm)	0.30
Crop Cover	0.04
Rainfall (mm)	0.0
Interception (mm)	0.0
Pan Off (mm)	0.0
Actual ET (mm)	0.2
Irrigation (mm)	0.0
Rzone Def (mm)	-21.0
W. T. Depth (m)	0.99
Drain Flow (mm)	1.2
ECe Top Soil (dS/m)	0.00
ECe Rootzone (dS/m)	0.00
ECe Unsat. Zone (dS/m)	0.00

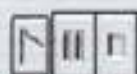
Soil	Sandy Clay Loam
Soil Data	Drainage
Soil Data	C:\Documents and Settings\J. T. FASH\Desktop
Soil (1)	Amaranthus crentus
Soil Crop (1)	IRRIG PLAN 1
Soil (2)	Not Used
Soil Crop (2)	Not Used
Soil (3)	Not Used
Soil Crop (3)	Not Used
Parameters	15 Jan 2005 - 26 Mar 2005

Analysis Model

Help

Control

Running...



Fast

Slow

Legend

Crop Cover



Rootzone



Soil Profile



Moisture Content

Saturation



Field Capacity



50% TAW



PHP



Water Table



Salinity (ECe)

0 dS/m



0.9 dS/m



> 12.0 dS/m



Timescale

15 Jan 2005

26 Mar 2005

13 Mar 2005

Date 13 Mar 2005

Crop Amaranthus

Root Depth (m) 0.33

Crop Cover 0.95

Rainfall (mm) 0.0

Interception (mm) 0.0

Run Off (mm) 0.0

Actual ET (mm) 0.1

Irrigation (mm) 0.0

Rzone Def (mm) -38.0

W. T. Depth (m) 0.99

Drain Flow (mm) 1.6

ECe Top Soil (dS/m) 0.00

ECe Rootzone (dS/m) 0.00

ECe Unsat. Zone (dS/m) 0.00

Soil	Sandy Clay Loam
Map Data	Drainage
Map Data	C:\Documents and Settings\J. T. FASH\Desktop
Map (1)	Amaranthus crinitus
Map Crop (1)	IRRIG PLAN 1
Map (2)	Not Used
Map Crop (2)	Not Used
Map (3)	Not Used
Map Crop (3)	Not Used
Parameters	15 Jan 2005 - 26 Mar 2005

Analysis Model

Help

Control

Running...

Timescale

15 Jan 2005

26 Mar 2005

19 Mar 2005

Fast

Slow

Legend

Crop Cover

Rootzone

Soil Profile

Moisture Content

Saturation

Field Capacity

50% TAM

PHP

Water Table

Salinity (ECe)

0 dS/m

6.0 dS/m

> 12.0 dS/m

Date

19 Mar 2005

Crop

Amaranthus

Root Depth (m)

0.35

Crop Cover

0.95

Rainfall (mm)

1.1

Interception (mm)

0.0

Run Off (mm)

0.0

Actual ET (mm)

0.2

Irrigation (mm)

0.0

Rzone Def (mm)

-35.4

W. T. Depth (m)

0.99

Drain Flow (mm)

1.5

ECe Top Soil (dS/m)

0.00

ECe Rootzone (dS/m)

0.00

ECe Uns. Zone (dS/m)

0.00

Data	Sandy Clay Loam
age Data	Drainage
ie Data	C:\Documents and Settings\J. T. FASH\Desktop
y Data (1)	Amaranthus cruentus
ion Crop (1)	IRRIG PLAN 1
y Data (2)	Not Used
ion Crop (2)	Not Used
y Data (3)	Not Used
ion Crop (3)	Not Used
Parameters	15 Jan 2005 - 26 Mar 2005

Analysis Model

Help

Control

Panning...



Fast

Slow

Legend

Crop Cover



Rootzone



Soil Profile



Moisture Content

Saturation



Field Capacity



SP% TAM



PHP



Water Table



Salinity (ECe)

0 dS/m



6.0 dS/m



> 12.0 dS/m



Timescale

15 Jan 2005

26 Mar 2005

25 Mar 2005

Date 25 Mar 2005

Crop Amaranthus

Root Depth (m) 0.35

Crop Cover 0.95

Rainfall (mm) 0.0

Interception (mm) 0.0

Run Off (mm) 0.0

Actual ET (mm) 0.2

Irrigation (mm) 0.0

Rzone Def (mm) -39.4

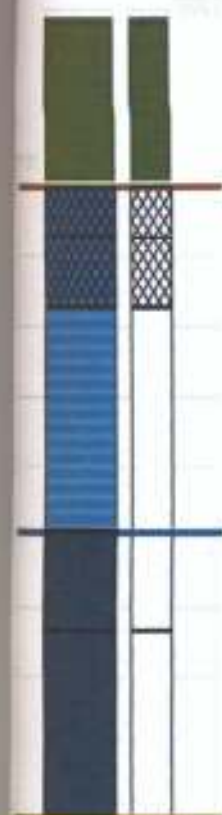
W. T. Depth (m) 0.99

Drain Flow (mm) 2.2

ECe Top Soil (dS/m) 0.00

ECe Rootzone (dS/m) 0.00

ECe Unsat. Zone (dS/m) 0.00



Soil	Sandy Clay Loam
Map Data	Drainage
Map Data	C:\Documents and Settings\J. T. FASH\Desktop
Map (1)	Amaranthus cruentus
Map Crop (1)	IRRIG PLAN 1
Map (2)	Not Used
Map Crop (2)	Not Used
Map (3)	Not Used
Map Crop (3)	Not Used
Parameters	15 Jan 2005 - 26 Mar 2005

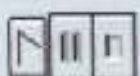
IRRIGATION PLAN 2
WaSim model run for irrigation plan 2

Analysis Model

Help

Control

Running...



Fast

Slow

Legend

Crop Cover



Rootzone



Soil Profile



Moisture Content

Saturation



Field Capacity



SP% TAM



PWP



Water Table



Salinity (ECe)

0 dS/m



6.0 dS/m



> 12.0 dS/m



Timescale

15 Jan 2005

26 Mar 2005



20 Jan 2005

Date

20 Jan 2005

Crop

Amaranthus

Root Depth (m)

0.01

Crop Cover

0.00

Rainfall (mm)

0.0

Interception (mm)

0.0

Run Off (mm)

0.0

Actual ET (mm)

1.2

Irrigation (mm)

0.0

Rzone Def (mm)

-25.4

W. T. Depth (m)

1.00

Drain Flow (mm)

0.0

ECe Top Soil (dS/m)

0.00

ECe Rootzone (dS/m)

0.00

ECe Unsat. Zone (dS/m)

0.00

Data	Sandy Clay Loam
Usage Data	Drainage
File Data	C:\Documents and Settings\J. T. FASH\Desktop
File Data (1)	Amaranthus cruentus
File Data (2)	PLAN 2
File Data (3)	Not Used
File Data (4)	Not Used
File Data (5)	Not Used
File Data (6)	Not Used
Parameters	15 Jan 2005 - 26 Mar 2005

Analysis Model

Help

Control

Running...



Fast

Slow

Legend

Crop Cover



Rootzone



Soil Profile



Moisture Content

Saturation



Field Capacity



SP's TSM



PWP



Water Table



Salinity (ECe)

0 dS/m



6.0 dS/m



> 12.0 dS/m



Timescale

15 Jan 2005

30 Mar 2005

31 Jan 2005

Date	31 Jan 2005
Crop	Amaranthus
Root Depth (m)	0.05
Crop Cover	0.03
Rainfall (mm)	0.0
Interception (mm)	0.0
Run Off (mm)	2.1
Actual ET (mm)	3.7
Irrigation (mm)	14.0
Rzone Def (mm)	-32.6
W. T. Depth (m)	1.00
Drain Flow (mm)	0.0
ECe Top Soil (dS/m)	0.00
ECe Rootzone (dS/m)	0.00
ECe Unsat. Zone (dS/m)	0.00

Data	Sandy Clay Loam
Input Data	Drainage
Input Data	C:\Documents and Settings\J. T. FASH\Desktop
Input Data (1)	Amaranthus cruentus
Input Data (2)	IRRIG PLAN 2
Input Data (3)	Not Used
Input Data (4)	Not Used
Input Data (5)	Not Used
Input Data (6)	Not Used
Parameters	15 Jan 2005 - 30 Mar 2005

Analysis Model

Help

Control

Running...



Legend

- Crop Cover
- Rootzone
- Soil Profile
- Moisture Content
- Saturation
- Field Capacity
- SP's TBM
- PWP
- Water Table
- Salinity (ECe)
- 0 dS/m
- 4.0 dS/m
- > 12.0 dS/m

Timescale

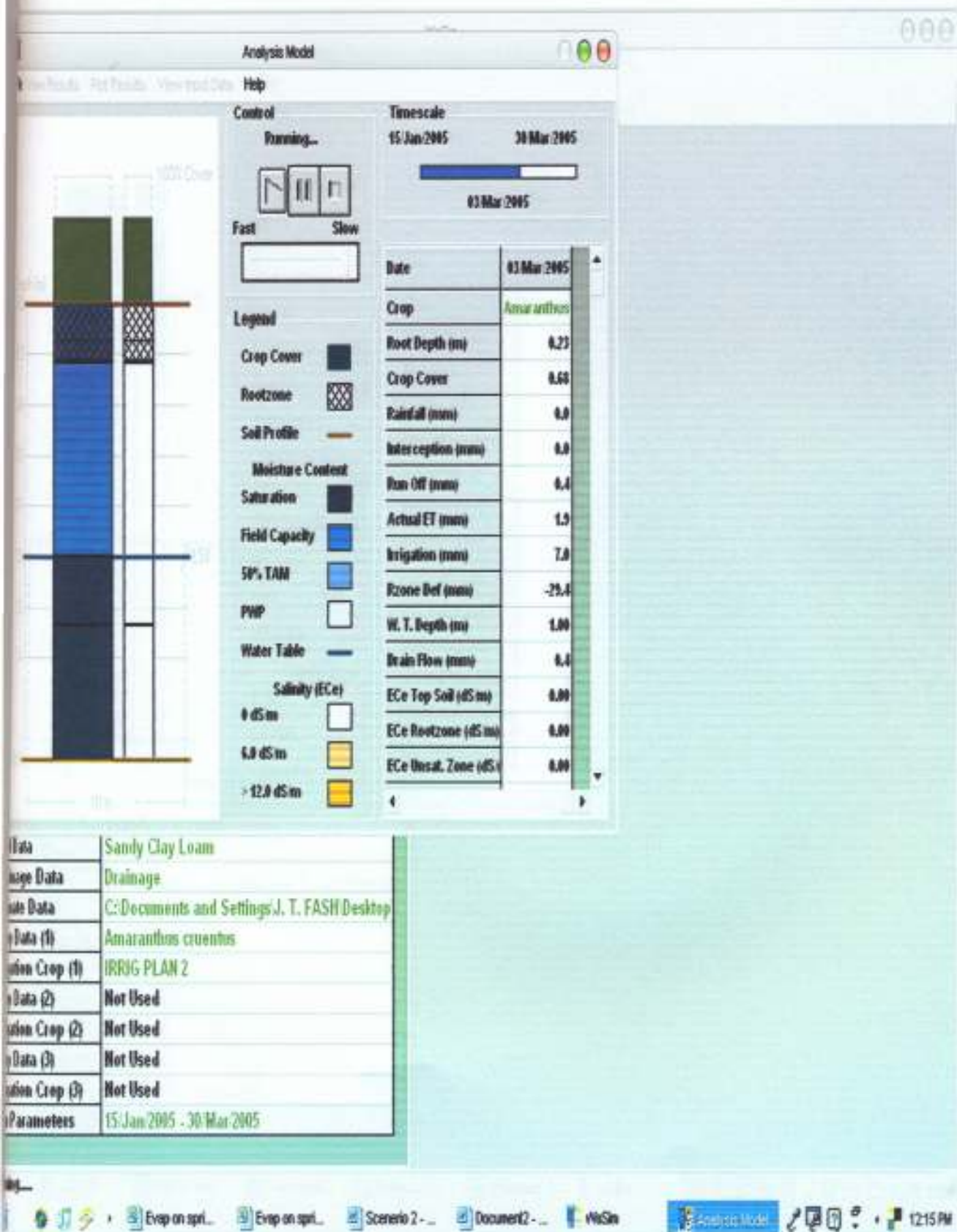
15 Jan 2005

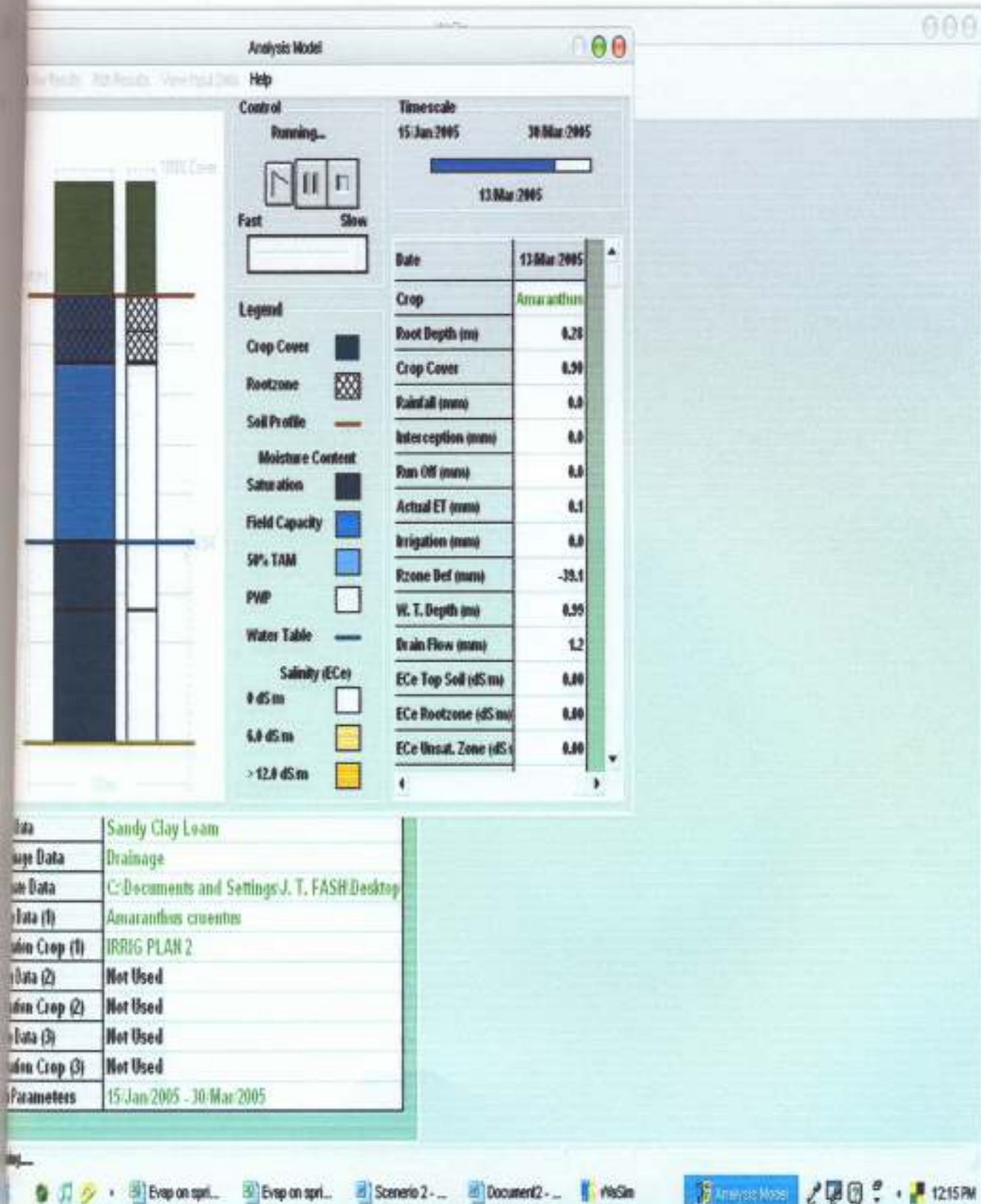
30 Mar 2005

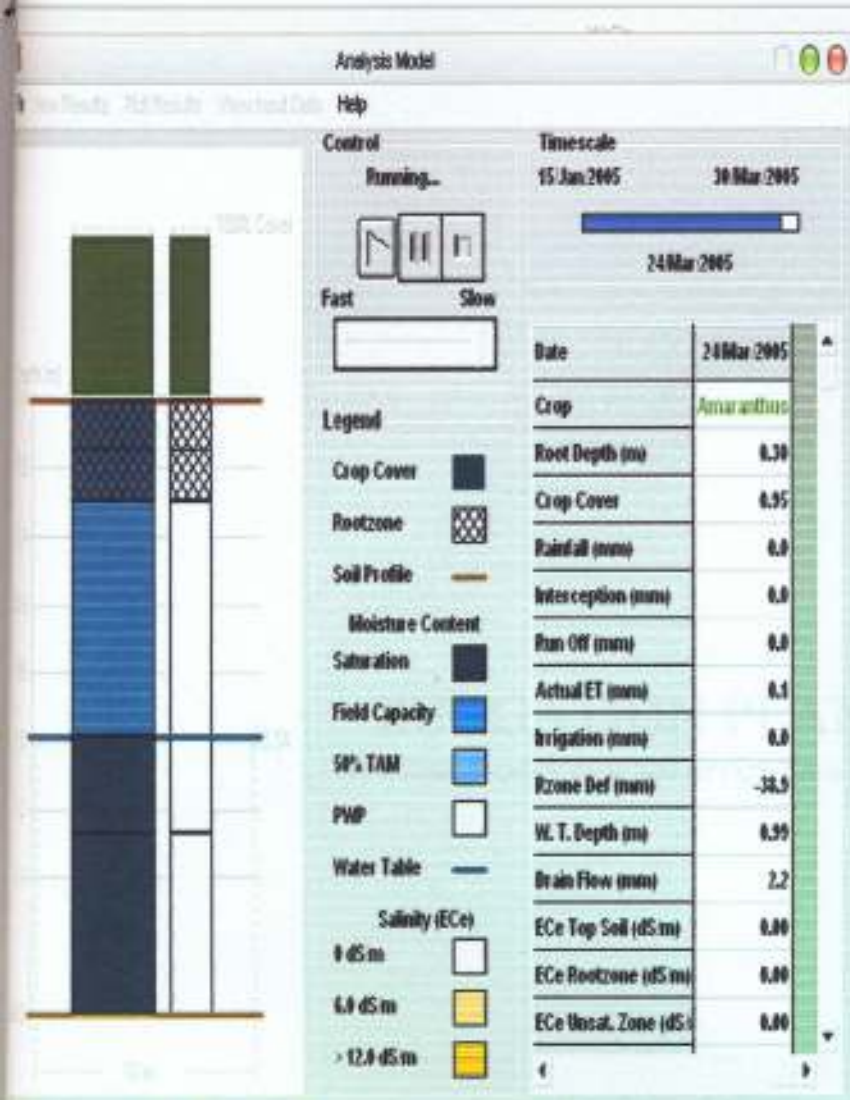
20 Feb 2005

Date	20 Feb 2005
Crop	Amaranthus
Root Depth (m)	0.17
Crop Cover	0.43
Rainfall (mm)	0.0
Interception (mm)	0.0
Run Off (mm)	0.0
Actual ET (mm)	0.0
Irrigation (mm)	0.0
Rzone Def (mm)	-3.2
W.T. Depth (m)	1.00
Drain Flow (mm)	0.2
ECe Top Soil (dS/m)	0.00
ECe Rootzone (dS/m)	0.00
ECe Unsat. Zone (dS/m)	0.00

Data	Sandy Clay Loam
Image Data	Drainage
State Data	C:\Documents and Settings\J. T. FASH\Desktop
Crop Data (1)	Amaranthus cruentus
System Crop (1)	IRRIG PLAN 2
System Crop (2)	Not Used
System Crop (3)	Not Used
System Crop (4)	Not Used
Parameters	15 Jan 2005 - 30 Mar 2005

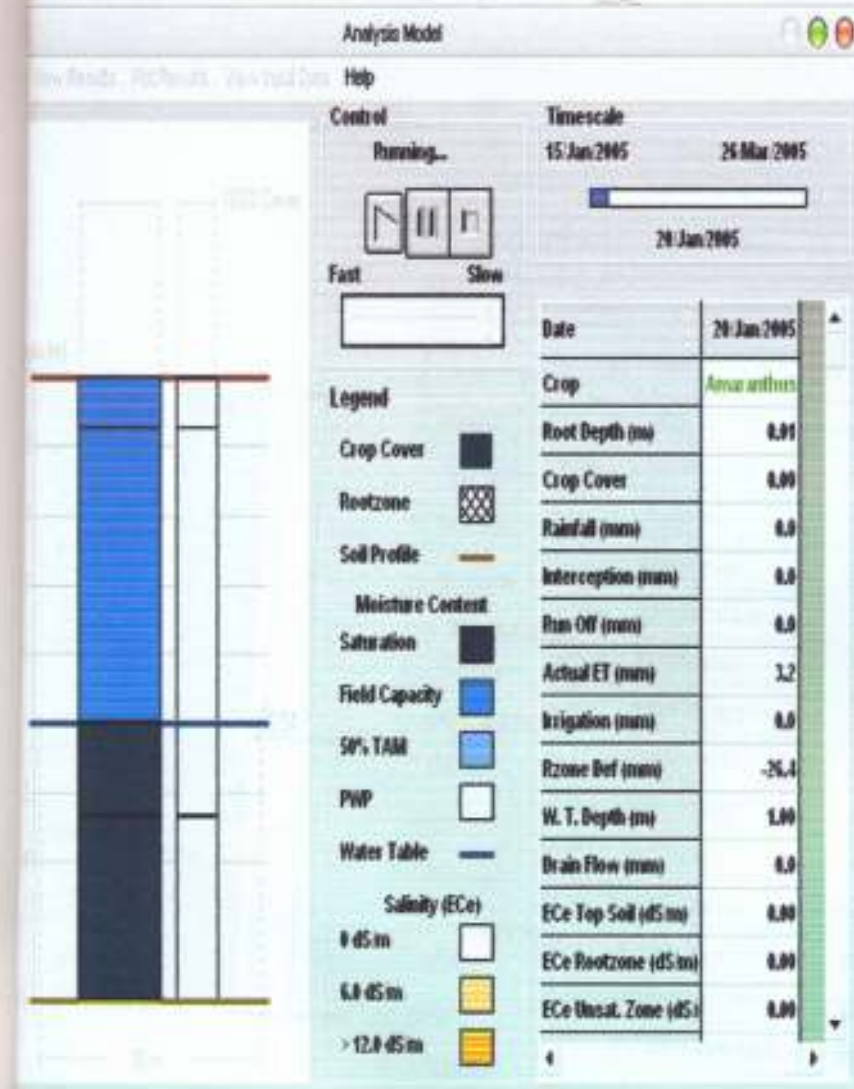




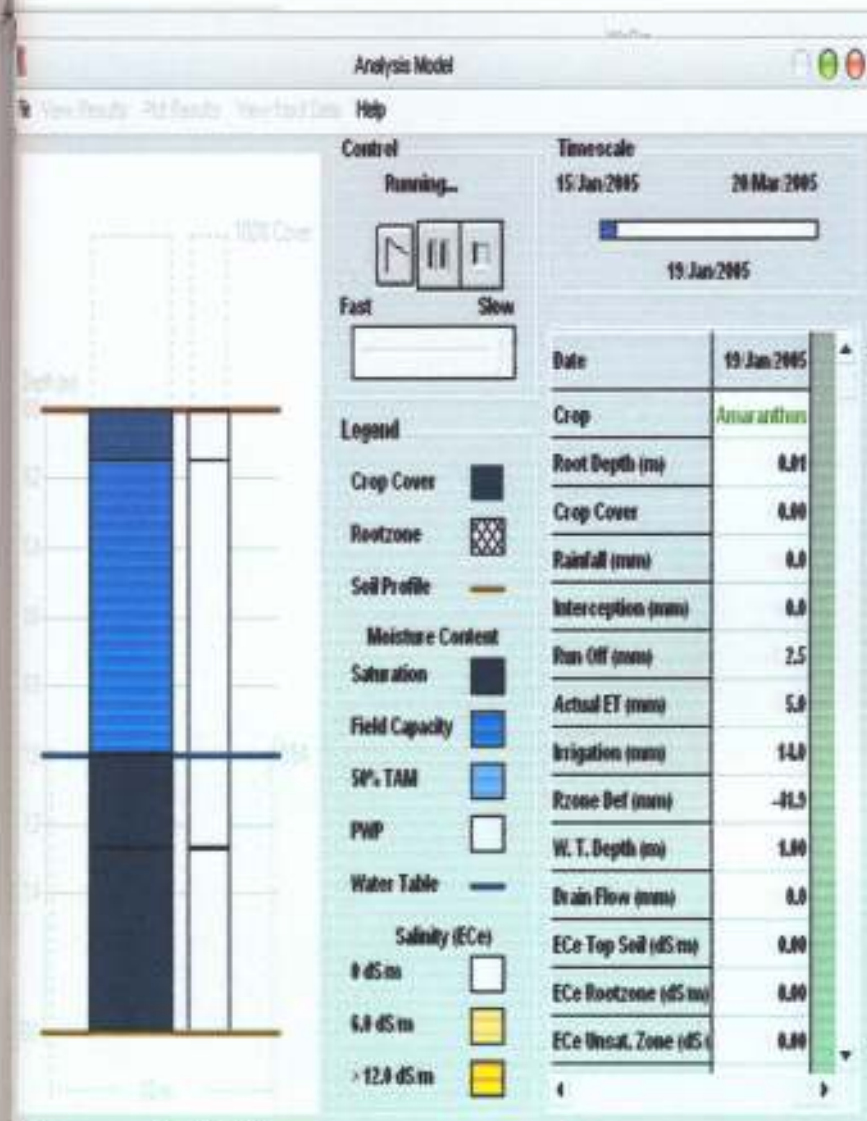


Data	Sandy Clay Loam
Image Data	Drainage
Input Data	C:\Documents and Settings\J. T. FASH\Desktop
Input Data (1)	Amaranthus cruentus
Input Data (2)	IRRIG PLAN 2
Input Data (3)	Not Used
Input Data (4)	Not Used
Input Data (5)	Not Used
Input Data (6)	Not Used
Parameters	15 Jan 2005 - 30 Mar 2005

IRRIGATION PLAN 3
WaSim model run for irrigation plan 3



Data	Sandy Clay Loam
age Data	Drainage
ate Data	C:\Documents and Settings\J. T. FASH\Desktop
Data (1)	Amaranthus cruentus
ion Crop (1)	PLAN 2
Data (2)	Not Used
ion Crop (2)	Not Used
Data (3)	Not Used
ion Crop (3)	Not Used
Parameters	15 Jan 2005 - 26 Mar 2005



soil Data	Sandy Clay Loam
Image Data	Drainage
Base Data	C:\Documents and Settings\J. T. FASH\Desktop
Crop Data (1)	Amaranthus cruentus
Irrigation Crop (1)	IRRIG PLAN 3
Crop Data (2)	Not Used
Irrigation Crop (2)	Not Used
Crop Data (3)	Not Used
Irrigation Crop (3)	Not Used
Simulation Parameters	15 Jan 2005 - 20 Mar 2005

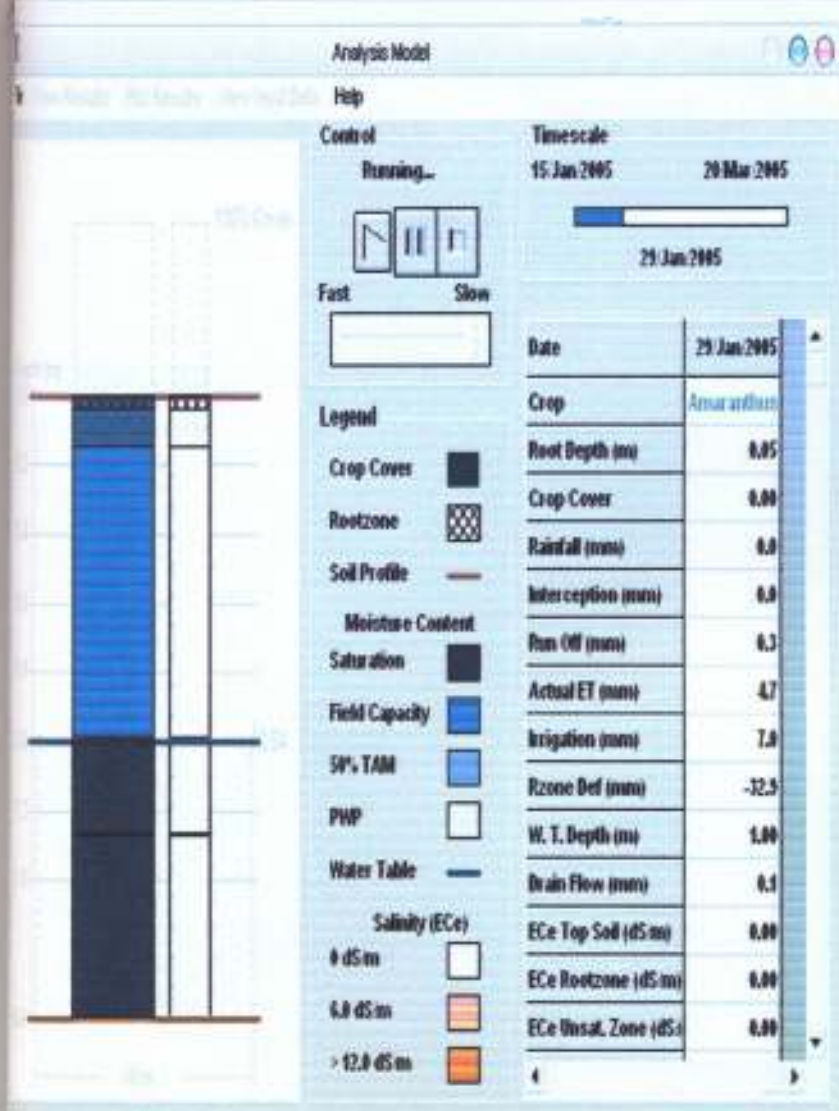
Running...

McSim

Analysis Model

Johnson part project - ...

10:43 AM



Data	Sandy Clay Loam
Image Data	Drainage
Location Data	C:\Documents and Settings\J. T. FASH\Desktop
Crop Data (1)	Amaranthus cruentus
Irrigation Crop (1)	IRRIG PLAN 3
Crop Data (2)	Not Used
Irrigation Crop (2)	Not Used
Crop Data (3)	Not Used
Irrigation Crop (3)	Not Used
Parameters	15 Jan 2005 - 20 Mar 2005

Analysis Model

Help

Control

Running...



Fast

Slow

Legend

Crop Cover



Rootzone



Soil Profile



Moisture Content

Saturation



Field Capacity



50% TAM



PWP



Water Table



Salinity (ECe)

0 dS/m



6.0 dS/m



> 12.0 dS/m



Timescale

15 Jan 2005

20 Mar 2005



20 Feb 2005

Date

20 Feb 2005

Crop

Amaranthus

Root Depth (m)

0.20

Crop Cover

0.01

Rainfall (mm)

0.0

Interception (mm)

0.0

Run Off (mm)

0.0

Actual ET (mm)

1.5

Irrigation (mm)

-0.0

Rzone Def (mm)

-0.5

W. T. Depth (m)

1.00

Drain Flow (mm)

0.2

ECe Top Soil (dS/m)

0.00

ECe Rootzone (dS/m)

0.00

ECe Unsat. Zone (dS/m)

0.00

Soil Data	Sandy Clay Loam
Irrigation Data	Drainage
Location Data	C:\Documents and Settings\J. T. FASH\Desktop
Crop Data (1)	Amaranthus cruentus
Irrigation Crop (1)	IRRIG PLAN 3
Crop Data (2)	Not Used
Irrigation Crop (2)	Not Used
Crop Data (3)	Not Used
Irrigation Crop (3)	Not Used
Simulation Parameters	15 Jan 2005 - 20 Mar 2005

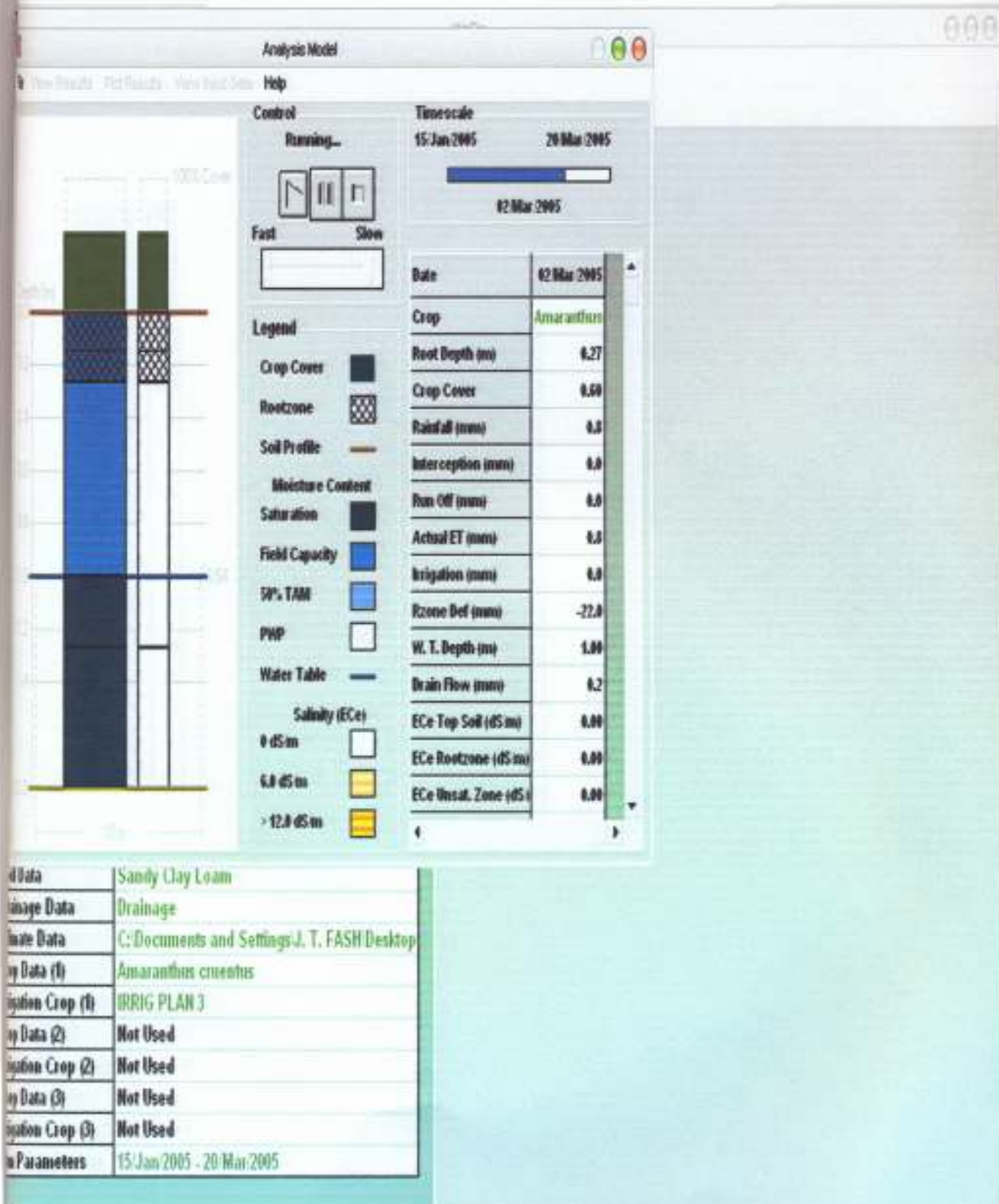
Running...

Analysis Model

Analysis Model

Johnson part project -

10:40 AM

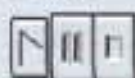


Analysis Model

Help

Control

Running...



Fast

Slow

Legend

Crop Cover



Rootzone



Soil Profile



Moisture Content

Saturation



Field Capacity



SP% TBM



PWP



Water Table



Salinity (ECe)

0 dS/m



6.0 dS/m



> 12.0 dS/m



Timescale

15 Jan 2005

20 Mar 2005



13 Mar 2005

Date	13 Mar 2005
Crop	Amaranthus
Root Depth (m)	0.21
Crop Cover	0.01
Rainfall (mm)	0.0
Interception (mm)	0.0
Run Off (mm)	0.0
Actual ET (mm)	0.2
Irrigation (mm)	0.0
Rzone Def (mm)	-14.0
W. T. Depth (m)	1.00
Drain Flow (mm)	0.0
ECe Top Soil (dS/m)	0.00
ECe Rootzone (dS/m)	0.00
ECe Unsat. Zone (dS/m)	0.00

Soil Data	Sandy Clay Loam
Drainage Data	Drainage
Climate Data	C:\Documents and Settings\J. T. FASH\Desktop
Crop Data (1)	Amaranthus cruentus
Irrigation Crop (1)	IRRIG PLAN 1
Crop Data (2)	Not Used
Irrigation Crop (2)	Not Used
Crop Data (3)	Not Used
Irrigation Crop (3)	Not Used
Run Parameters	15 Jan 2005 - 20 Mar 2005

Running...

Analysis Model

Johnson port project -