ASSESSING THE EFFECTIVENESS OF LOCALLY MADE CLAY POT AS AN IRRIGATION DEVICE

BY

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A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN
IRRIGATION ENGINEERING AND MANAGEMENT OF SOKOINE
UNIVERSITY OF AGRICULTURE. MOROGORO, TANZANIA.

ABSTRACT

Among traditional irrigation systems, pitcher irrigation is one of the most efficient. Water seeps out of a buried pitcher due to the pressure head gradient across the wall of the pitcher directly into the root zone of the irrigated crop. The pressure gradient results from a positive pressure head inside the pitcher and negative pressure head at the outer surface of the pitcher which is in contact with soil. Pitcher irrigation is a cost effective traditional technique, which is easy for small scale farmers to comprehend with. This study considered the effectiveness of locally made pitchers as a micro-irrigation device using beans and amaranths crops. The experimental design was 2 x 3 factorial arrangements of treatments in a split plot design. The main-plots were two different initial soil moisture contents i.e. soil moisture content at field capacity (31 %, vol.) and 26 % (vol.). The sub-plots were three different plant densities i.e. 4 plants/pot, 6 plants/pot and 8 plants/pot and were replicated three times giving a total of 18 combination treatments. A positive relationship was found between seepage rate and actual evapotranspiration for all pitchers ($R^2 = 0.37$) showing a sign of auto-regulative capabilities. Under beans, the pitchers were not effective in water saving in all the combination treatments because of high water loss through deep percolation because of poor pot characterization. However under amaranths the pitchers were effective in optimizing the water applied. The water applied was not statistically different ($P < 0.05$) for all the treatments. These results show that clay pots had low application efficiency. However the pots can still be used on amaranths, with a plant density of 16 plants/pot and at initial soil moisture content of 26 % (volume).

DECLARATION

I, Mahatsindry Randzato Solo do hereby declare to the senate of Sokoine University of Agriculture that this dissertation is my own original work and that has neither been submitted nor concurrently being submitted for degree award in any other Institution.

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ACKNOWLEDGEMENTS

Above all things I want to thank GOD for guiding me to this academic level, without whom I would be lost in the wilderness.

I am indebted to my supervisors Prof. N. I. Kihupi and Prof. A. K. P. R. Tarimo for their guidance throughout the study period of my research work. Their devotion to work, specifically in support of my research undertaking albeit my academic weakness, is unparalleled. I can never thank them enough only God knows how.

This study would not have been possible for me without the assistance of my family: my Father Mr. Isidore, Mother Madam Vololoniaina, my Brothers Tefy, Hasina, and Christian, and to my sister Tina. They are my source of inspirations and encouragements, to all of those people, I can only say thank you.

I would like to express my gratitude to ICART/SADC for the financial support in terms of scholarship which enabled me to embark on a study career I had longed for irrigation engineering. Coming from a humble background, this is like a dream come true. Iwill always treasure the opportunity availed to me by my sponsors.

Many people have contributed in one way or another to the successful completion of my dissertation research work. It is not possible to mention everyone by name, but the following played a big role towards that end: Ms. Matema, Mr. Nyireinda, Mr. Njaka, Mr. Xavier, all the staff of the soil science laboratory, Dr. Msogoya, Dr.

Mwatawala and Dr. Kusolwa (Crop science department, SUA), Mr. January and Mr. Macha (SUA horticultural unit). To all of them I say thank you.

DEDICATION

To almighty God, who has directed me since I was born and to my family, without their support I would not have accomplished any of this. To all of them I say thank you.

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LIST OF ABREVIATIONS AND SYMBOLS

AET	Actual evapotranspiration
a	Initial soil moisture content at field capacity
b	Initial soil moisture content at 26 % (by volume)
B_k	Resistance block reading at a temperature at k°C
cm	Centimeter
cc	Cubic centimeter
CV	Coefficient of variation
DP	Deep percolation
e	Exponential
Ea	Application efficiency
ETc	Crop evapotranspiration
ET_0	Reference evapotranspiration
FC	Soil water at field capacity
GC	Ground cover
Grav	Calculated soil moisture content from the tensiometer calibration equation
HI	Harvest index
Ii	Irrigation interval
IRR	Amount of water applied through irrigation
IWUE	Irrigation water use efficiency
PWUE	Physiological water use efficiency
Kc	Crop coefficient

Kp	Pan coefficient
Kr	Ground cover factor
LAI	Leaf area index
LA	Leaf area
L	Leaf width
lsd	Least square difference
Max	Maximum
Min	Minimum
NPK	Nitrogen, phosphate, potassium
P	Soil moisture depletion factor
Ψ	Soil matric potential
PWP	Soil water content at permanent wilting point
ρ_b	Soil bulk density
RAM	Readily available soil moisture
RD	Root zone depth
RETC	Retention curve
RH	Relative humidity
RDm	Maximum root zone depth
RWS	Relative water supply
R 1	Time to flowering
R 4	Time when the 50% of flower appeared
SCL	Sandy clay loam
SUA	Sokoine University of Agriculture
SWC	Soil water content within root zone depth

SWC_O	Soil water content in the passive root zone
UNEP	United Nation Environment Program
UCW	Uniformity coefficient of Wilcox and Swailes
θm	Soil water content by weight
θv	Soil water content by volume
TAM	Total available soil moisture for plant
Var	Variety
ΔSW	Soil water variation
ΔRD	Incremental rooting depth
WUE	Water use efficiency
y'	Normalized resistance block reading
Y	Calculated soil moisture content by weight from the resistance block
Y	Yield in kilograms
θ_s	Saturated soil moisture content (%)
θ_r	Residual soil moisture content (%)
4a	4 plants/pot in the main plot a
6a	6 plants/pot in the main plot a
8a	8 plants/pot in the main plot a
4b	4 plants/pot in the main plot b
6b	6 plants/pot in the main plot b
8b	8 plants/pot in the main plot b

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Clay pot irrigation or pitcher irrigation is a technique that was used by the Chinese some 2000 years ago. Pitcher irrigation entails burying an unglazed, porous clay pot next to a plant. Water poured into the pot seeps slowly into the soil, feeding the plant's roots with a steady supply of moisture. When a pot, filled with water and covered by a lid (wooden or clay), is buried in the soil, the water oozes out of the clay pot due to hydraulic head and moisture gradient differences between the pot surface and the surrounding soil until it is in equilibrium with the surrounding area. It acts more like the ceramic cup of a tensiometer. The rate of seepage of water from pitcher depends on the type of plant, soil, the pot characteristics and climatic conditions around the pot. The movement of water is as a result of the water uptake by the crops and continues as long as the plants take it up and evaporation from the soil takes place. When the surrounding area becomes saturated, water will tend to move back to fill up the pot. The system is therefore self-regulating (Stein, 1998).

Syial and Skaggs (2009) and Daka (1991) affirmed that clay pot as an irrigation device is cheap, less complicated and can be made available in most rural areas. Budi *et al.* (2006) determined the use of the pitcher irrigation technique in the fertigation system, while Daka (1991) found that the application efficiency is as high as and sometimes higher than the conventional trickler irrigation techniques when used in different plants.

There are many irrigation methods suitable for small scale farmers to increase the irrigated land and yield. However, the technologies developed in most cases are at variance with the farmers' level of comprehension. It is important that such technologies are developed and tested for the end users i.e. the farmer, taking into consideration the social and economical intricacies typical of a rural setting in a developing country. The last few decades have witnessed water scarcity in many places around the world making it a rather expensive resource. The competition among the different users in various sectors requires efficient use of that resource. In agriculture, the effect of this scarcity is palpable especially when the reliability of the rainfall is questionable and the only solution is to irrigate. This calls for better management of water to alleviate the problem of competition.

Morogoro with a mean annual rainfall of around 800 mm is not immune to the problems of water scarcity. The land has high agricultural potential but for it to be exploited, judicial use of water is necessary. The concept of irrigation as an activity for maximization of profit has to change in the light of unfavourable trends in water availability especially in tropical African countries. Optimization of profit should instead be the goal as this ensures high water use efficiency which is important under the current circumstances. Water saving irrigation techniques should therefore be sought targeting those with appropriate technologies to match the educational level of the farmers. Such techniques should aim at minimizing the deep percolation loss component of root zone water balance as well as unwanted surface runoff losses. Deep percolation, surface runoff, as well as evaporation constitute the major components of the water balance. Loss of water through the plant or transpiration which along with evaporation constitutes evapotranspiration is a "necessary evil" as the process has to be sustained for plant survival. So out of the three major components of the water balance evapotranspiration cannot be minimized to any great extent without seriously affecting crop production. Pitcher irrigation appears to be one of those techniques which take all the concerns raised above into consideration.

Increasing the cultivated land may not be achieved without the use of irrigation. In sub-Saharan Africa where small scale farmers make up the majority of farmers, introduction of simple and cost effective irrigation systems such as pitcher micro-irrigation would seem to be more appropriate. This method is not new, but site-specific. Therefore there is a need to explore scientifically the applicability of the pitcher irrigation technique by evaluating the locally made clay pots in terms of their hydraulic characteristics and ability to maintain crop growth.

1.2 Objectives

1.2.1 Main objective

The overall objective of this study was to assess the effectiveness of locally made buried clay pots as a micro irrigation device.

1.2.2 Specific Objectives:

i. To characterize the clay pots produced at Magadu village.

ii. To determine the performance of the clay pots under beans and amaranths crops.

iii. To evaluate the water balance under pitcher irrigation for different plant densities under beans and amaranths crops.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Introduction

In its simplest form, pitcher irrigation entails burying an unglazed porous clay pot next to plants. Water poured into the pot seeps slowly into the soil, feeding the plant roots with a steady supply of moisture. It is one of the most efficient and least costly irrigation systems, ideal for small scale farmers trying to eke a living out of dry marginal land. In fact, it is even recorded in Chinese texts dating back more than 2000 years (Syial and Skaggs, 2009).

2.2 Water Saving Aspect of the Pitcher Irrigation

To compare pitcher irrigation to flood or sprinkler irrigation one must take into account the differences in scales. Pitcher irrigation is used on small-scale projects, while flood and sprinkler systems are for more extensive fields. However, among the sub-surface irrigation systems, pitcher irrigation is far more efficient in water utilization (Padma *et al*, 2007). Pitcher irrigation uses water more efficiently than other systems since it delivers water directly to the plant root zone, instead of spreading all over the field. With pitcher irrigation, deep percolation losses are negligible. The rate of water loss can be controlled from site to site by the amount of water put in each pitcher and competition from weeds is reduced under pitcher irrigation because of the limited wetted area. A study in India found that weed dry biomass was only 62 kg ha^{-1}under pitcher irrigation compared to 465 kg ha^{-1} under basin irrigation (Bainbridge, 2001). Daka (1991) found that water saving from pitcher irrigation was up to 70% compared to the conventional watering can. Crop water requirements in a pitcher irrigated field can be even less than that for a drip irrigated system (of the same scale) due to the very low saturated hydraulic conductivity of the pitchers, as well as reduced evaporation losses (UNEP, 2006). Compared to other irrigation techniques, clay pot irrigation has higher crop water use efficiency. It may use as little as 10% of the water used in conventional surface irrigation. In India the WUE of melon under pitcher irrigation was 1250 kg.ha^{-1}.mm^{-1}which was far much higher than that under flood irrigation system which was 126.9 kg.ha^{-1}.mm^{-1} (Bainbridge, 2001). An increase of dry matter production was observed in maize by using a pitcher with high water application rate (Stein, 1998). However, higher water application rates result in an increase of crop production but also in an increase of losses like those through deep percolation or reduced yield in the vicinity of the pitcher wall (Stein, 1998).

2.3 Mechanisms of Pitcher Irrigation

The wetting front produced by a pitcher is similar to that produced by sub-surface drip sources (Batchelor*et al.*, 1996). The water seeps out of the pot due to pressure gradient between the inner and the outer parts of the pitcher i.e. from an area of positive to one of negative potential till equilibrium is established (Majed*et al.*, 2006). The refilling time of the pots is done when 60% to 70% of the volume of water in the pot has been utilized (Majed*et al.*, 2006), Daka (1991) proposed 50% of the seepage volume or if the tensiometer reading indicates -20 kPa to -40 kPa. The seepage rate is ideally about 15% per day of the total volume inside the pot (Syial and Skaggs, 2009). This level of porosity allows water to seep out slowly. The refilling time is a function of the seepage rate of the pitcher (Daka, 1991). Majed*et al.* (2006) found that the seepage rate of pitcher irrigation is a function of the pressure head in the pitcher and evaporation. Seepage rate increases linearly with an increase in temperature and change of relative humidity (RH). At a temperature of 18°C and RH 66 % and at a temperature equal to 30°C with a RH equal to 49 % for a pitcher of capacity 7.5 to 8 L, seepage rate ranged from 0.344 to 0.908 l/day, and from 0.473 to 0.969 l/day, respectively (Padma *et al.*, 2007). The pitcher has an ability to control the seepage rate according to soil moisture content and crop water requirement: by reducing the seepage rate when the soil is at field capacity and increasing the seepage rate when the soil moisture has depleted due to evapotranspiration. The ETc can increase the seepage rate of pitcher up to 200 % of its value under atmospheric conditions (Stein, 1998). For pitchers with a volume of 5.0 L, the average seepage rates of pitchers at ETo values of 1 and 16 mm/day were 0.125 L/day and 1.020 L/day, respectively (Majed*et al.*, 2006). This particular ability is qualified by Stein (1998), as "reaction capability", a property, which is determined by the following three main interaction components: the hydraulic conductivity of the pitcher material, the size of the surface area and the wall thickness of the pitcher.

Optimization of the system with reference to its seepage rates and "reaction capabilities" can be conducted by using the interaction diagram shown in Fig. 1. This interaction diagram only allows a qualitative assessment of the interplay of the pitcher properties. A quantitative assessment is not possible. With reference to the soil-pitcher interaction it also has to be taken into consideration that the interaction is not a constant one. The increasing root growth around pitchers reduces the interaction potentiality over time. Hence the seepage rates and "reaction capabilities" decrease with the length of the crop growth period irrigated under pitcher irrigation system. Under practical irrigation conditions, both the seepage rate and "reaction capability" should be taken as being much lower than is potentially possible (Stein, 1998).

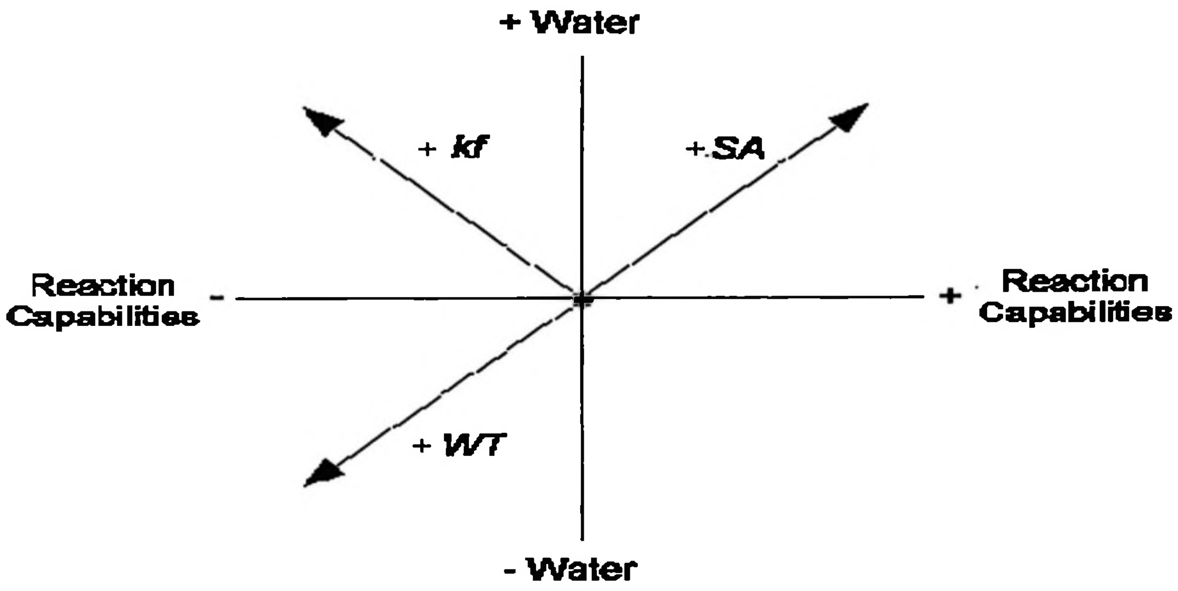


Figure 1: **Interaction diagram of seepage rates showing the relationship between the hydraulic conductivity, wall thickness and surface (source: Stein, 1998).**

Legend:

-water	=	decrease in seepage rate
+water	=	increase in seepage rate
+reaction capability	=	increase in reaction capability
-reaction capability	=	decrease in reaction capability
+WT	=	wall thickness
+kf	=	saturated hydraulic conductivity
+SA	=	surface area

Based on HYDRUS 2D/3D software, Siyal and Skaggs (2009) designed a sub-surface irrigation system and assessed the geometry of the wetting front of a buried clay pipe under bare soil. They found that the wetting front forms a series of circles and that the value of the soil moisture content varies according to the pressure head depending on the soil texture. The study revealed that the geometry of the wetting front does not affect the evaporation loss. Budi *et al.* (2006) reported that the wetting front of the pitcher irrigation system is about 20 to 25 cm from the wall of the pot and has a shape of a standing oval ball, with a vertical height of 70 cm from the soil surface, that is for a pot size of 2.3 L. On the other hand for a pot size of 11 L the horizontal distance is 30 cm from the rim of the pot and the vertical distance is 50 cm from the soil surface (Syial*et al.*, 2009).

2.4 Characteristics of Pitcher

Porous clay pots are characterized by the following parameters: saturated hydraulic conductivity, wall thickness, and the surface area which affects the seepagerate of the pot. Pitchers have self-regulative capability in conditions where seepage is controlled by the soil water pressure head, which is, in turn, a function of the soil water content, matric potential and ETc around the pitcher (Majed and Atoum, 2004; Majed*et al.*, 2009).

2.5 Economical Aspect of Pitcher Irrigation

The pitcher irrigation technique creates business opportunities for the potter and small scale industry in the rural areas because the pots are locally made(Daka, 2001). By using pitcher irrigation, the farmer can save time and/or labour because the irrigation interval is less frequent than using a watering can. It can increase also the area that can be cultivated by enabling the farmer to plant into the marginal land due to drought or saline lands (Bainbridge, 1999; Budi *et al.*, 2006). Compared to the other irrigation systems i.e. drip and sprinkler systems, pitcher irrigation is cheap and easily adaptable to small scale farmers because, it costs US$ 0.25 per pot and is affordable by the majority of end users. Finally, pitcher irrigation is sustainable because pots are made available from readily and locally available materials which are in abundance (Daka, 1991; Syial and Skaggs, 2009).

2. 6 Disadvantages of Pitcher Irrigation

i The pots may need to be moved if the soil is to be tilled. During installation or removal, they must be handled with care to avoid breakage during installation or removal (UNEP, 2006).

ii The buried clay pots may clog up over time, especially if left dry for a long time. If this happens, they need to be removed from the soil and scrubbed, or soaked, or re-fired to clean out the pores (UNEP, 2006).

iii The clay mixture, firing time and temperature and choice of clay need to be right to be sure that the pot is porous enough for this method (UNEP, 2006).

iv If silty muddy water is used, it will block the tiny holes in the clay pot and stop it from working as well.

v The system doesn't work very well with some types of clay soils, but incorporating and and/or organic matter in the soil can help to make it work (UNEP, 2006).

vi The number of plants planted around each pitcher needs to be adjusted according to the pot's volume (Stein, 1998).

vii Clay pots are less robust compared to clay pipe, and are more labour intensive because pots have to be filled individually and it is difficult to use pitcher irrigation when the plant water requirement is high (batchelor*et al.*, 1996).

2.7 Considerations in Clay Pot Production

Stein (1998) found that, besides the material composition, the method of production and firing process had a substantial influence on the permeability of the pitcher material. Porous clay pots once made are burnt in a kiln at temperatures less than 1200°C; with a porosity of about 10 to 15% at this temperature. A melted piece of copper metal is placed inside the kiln to indicate attainment of the optimum temperature. Normally copper melts at 1083°C. Both over baking and the nature of the material used make the pot impermeable (Daka, 1991). Daka (1991) reported that the use of a combination of sand and clay in ratios of 1:4 enhances the saturated hydraulic conductivity of the pot. Soil type, crop type and weed competition are key considerations which should be taken into account when designing a pitcher irrigation system (Bainbridge, 2001). The size of the pot will depend on the desired pot refilling time and on the type of the plant i.e. perennial or annual. For perennials, it is advisable to use a pot which has a capacity of 10 to 20 litres, while 2-5 litres capacity pitchers could suffice for vegetables (UNEP, 2006).

2.8 Irrigation Performance Indicators

The process of performance assessment hinges around the capacity of the managers of an organization to answer two simple questions (Marinus, 1997):

i. *"Am I doing things correctly"?* which asks whether the intended level of service (that has been set and agreed upon) is being achieved. This is the basis for good operational performance.

ii. *"Am I doing the right thing"?* a question that aims at finding out whether the wider objectives are being fulfilled, and fulfilled efficiently. The latter is part of the process of assessment of strategic performance. Quantifying the performance of irrigation systems, both on drawing board as design and management criterion and in the field as an operation criterion is necessary because in design and management of irrigation system efficient use of water is now often a major goal as well as the crop production. Of interest also is the uniformity of application, which reflects the need for equal treatment of plants in various portions of the field (Burt *et al.,* 1997).

2.8.1 Irrigation adequacy and irrigation uniformity

Irrigation uniformity deals with the issue of how uniformly the water is distributed to the crop. A non-uniform water distribution may deprive portions of the crop with water, but also can over irrigate portions of the field leading to water logging, salt accumulation and leaching. There are many factors which affect the uniformity of micro –irrigation systems such as: manufacturer's variation, grouping of emitters, temperature, and spacing. The manufacturer's variation can be considered as the indicator of uniformity, which can be measured by the statistical "coefficient of variation" of the emitter flow. For an emitter flow variations ranging from 10% to 20% the uniformity coefficients range between 90% and 80% (I-Pai, 1996).The uniformity coefficient of Wilcox and Swailes (UCW) is expressed by Equation (1) (Karmeli *et al.*, 1985):

$UCW = 100 - CV$ ....(1)

Where:

UCW = uniformity coefficient of Wilcox and Swailes (%)

CV = statistical coefficient of variation (%)

Adequacy of irrigation is an important performance indicator in any type of irrigation application system. It is measured by the relative water supply (RWS). RWS is the ratio of the water input and the water output. The output includes the potential evapotranspiration and the deep percolation (David *et al.*, 1998). If the RWS shows a value less than one then the water supply is less than that required. If RWS value is ranged from 1 to 1.15 then the water supply is adequate, and if RWS has a value of >1.15 then there is an oversupply. Though, for the sake of maximizing returns on water, RWS equal to 0.8 is an indicator of deficit irrigation practice (Rowshon*et al.*, 2006).

2.8.2 Water productivity

Water productivity is defined as the amount of production (mass or monetary value) divided by the amount of irrigation water either supplied to the project as irrigation or irrigation plus rain, or the amount of water depleted by the project usually in terms of evapotranspiration (Clemmens and Molden, 2007).

With mounting water shortages and water quality concerns, there is growing interest in measures to increase the water productivity commonly expressed by the water use efficiency (WUE). WUE is a good indicator for assessing performance of irrigation systems and management practices, WUE can be used to compare different irrigation systems, evaluating the existing performance and exploring options for water savings (Kihupi, 2009).

systems, evaluating the existing performance and exploring options for water savings (Kihupi, 2009).

The water use efficiency (WUE) is expressed as the amount of water used per unit yield or the yield per unit water used. The yield can be the net biomass or the grain yield. The WUE can be calculated as follows (van Lier *et al.*, 1999):

$$WUE = \frac{Y}{WU} \qquad (2)$$

Where:

WUE = water use efficiency

Y = Dry matter or grain yield

WU = Total evapotranspiration /seasonal irrigation water use

WUE values reported in literature vary according to whether authors express the denominator as the amount of water applied (the sum of rainfall and irrigation) or as the amount of water transpired (unproductive soil evaporation is not taken into account) thus the WUE can be broken down to (Sam and Dirk, 2009):

$$IWUE = \frac{Y}{irrigation\ depth\ applied} \qquad (3)$$

Or

$$PWUE = \frac{Y}{\sum_{i=1}^{n} ET_c} \qquad (4)$$

Where:

$IWUE$ = irrigation water use efficiency

$PWUE$ = Physiological water use efficiency

ET_c = Crop evapotranspiration

n = Length of growing season in days

2.8.3 Field application efficiency

This can be expressed as the inverse equation of the relative water supply (RWS) i.e. the ratio of the water needed to eliminate any unnecessary stress, over the volume of water input, as shown in Equation 5 (Burt *et al.*, 1997):

$$E_a = \frac{\textit{crop water requirement}}{\textit{water delivered to field}} \quad \text{.......} \quad (5)$$

Where:

E_a = Field application efficiency

Gross irrigation requirement, is the quantity of water, regardless of its source, required by a crop or diversified pattern of crops during a given period of time for a normal growth under field conditions. It includes losses due to evaporation from soil surface and plant transpiration through the plant system, plus water loss during the irrigation application, as well as the water needed for special operations or processes such as land preparation, transplanting, frost protection and leaching (Musa, 2003).

If $E_a < 1$, it can be concluded that there is an over irrigation in the field, because the water delivered into the field is higher than that required.

$E_a = 1$, it can be concluded that the application is 100% efficient, the water input is exactly the same as that required

$E_a > 1$, there is under irrigation, the input does not meet the required water.

2.9 Water Balance

At the heart of any consideration of irrigation performance is the irrigation water balance and the determination of the fate of various fractions of the total water applied; how much gets to the crop and how it is distributed among the plants, how much of the remainder is recoverable, how much enters the ground water surface drainage and so forth. Any water supply outside of irrigation affects the crop water needs for irrigation and is part of the overall water balance (Burt *et al.*, 1997).

The soil water balance in the crop root zone considers that the maximum root depth of the crop grown in the field is a soil reservoir. The reservoir is divided into two layers: an active soil layer in which the roots are present and from which both moisture extraction and drainage occur, and the passive soil layer from which only drainage occurs. During the initial period of crop growth, these two zones exist separately with their relative depth. When roots attain maximum depth the entire root zone is occupied by the active layer. The daily soil water balance in the active root zone is given by the Equation 6 and illustrated by Fig.2 (Panigrahi and Sudhindra, 2002).

$$SWC_iRD_i = SWC_{i-1}RD_{i-1} + IRR_i + \Delta RD_iSWCo_{i-1} - DP_i - AET_i \text{ ....(6)}$$

Where:

SWC_i = soil water content in the active root zone (mm.cm^{-1})

$SWCo_{i-1}$ = the soil water content out of the passive root zone (mm.cm^{1})

RD = root depth (cm)

ΔRD = incremental rooting depth (cm)

DP = deep percolation out of active root zone depth (mm)

AET = actual evapotranspiration (mm)

IRR = irrigation water (mm)

i = time index, taken as the day of measurement

2.10 Crop Growth Parameters

Leaf area index (LAI), ground cover (GC %), and dry matter (DM), are related to the plant water uptake (Gerson*et al.*, 2001). LAI is defined as the area of leaves per area of ground surface averaged over a large area with units of $m^2.m^{-2}$. Only one side of the 'green,' healthy leaves that are active in vapour transfer, is considered. For all crops, full cover conditions can generally be assumed to occur when the LAI exceeds 3 (Allen *et al.*, 1998; Richard and Pereira, 2009).

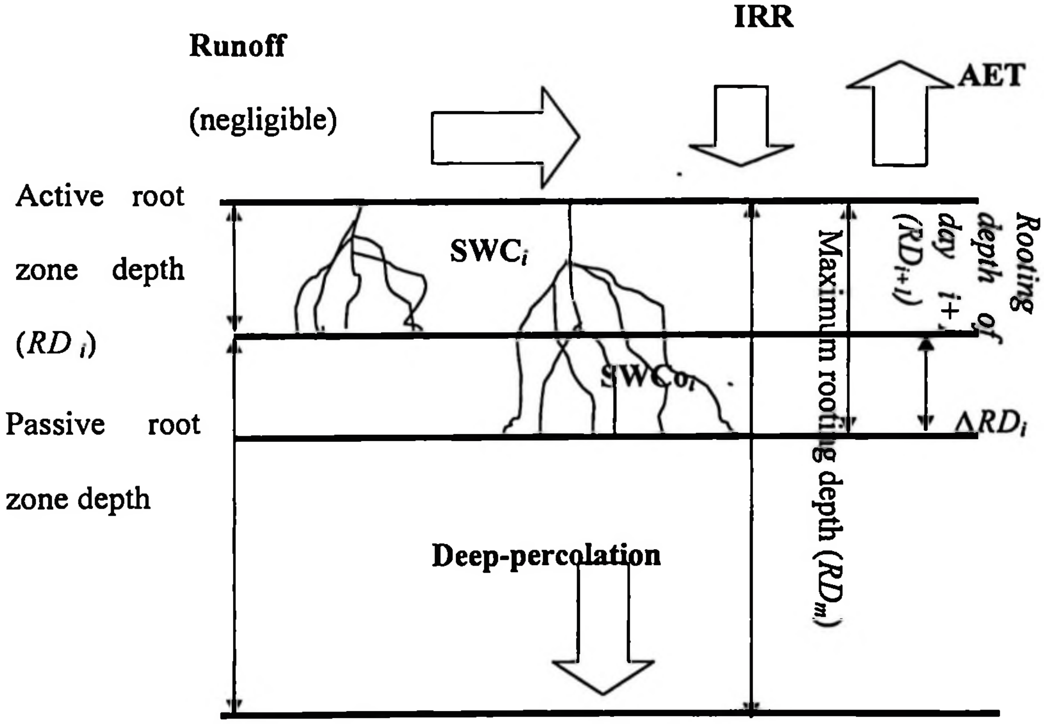


Figure 2: Schematic diagram illustrating the water balance components (Source: Sudhindra and Panigrahi, 2002).

There are several equations that are used to determine the leaf area for beans, De Jesus *et al.* (2001) proposed the following model based on the maximum width of the leaves, which can be applied to all bean varieties and cultivars.

$LA = 2.1371L^{1.9642} - 2.7013$...(7)

Where:

LA = leaf area (cm^2),

L = maximum leaf width (cm).

And the LAI is expressed as follows:

$$LAI = \frac{k \times n \times LA}{Soil\ surface} \qquad (8)$$

Where:

k = number of leaves/plant

n = number of plants/unit area

Soil surface = soil surface area (cm^2)

The dry biomass is the weight of plant parts when dried to constant weight in an oven at 80°C, usually for 24 h. Drought stress significantly decreases plant total dry mass and affects the growth of plant organs differently. Thus, the proportions of the various components are related to total biomass as follows (Liu and Stutzel, 2003):

$$root\ dry\ mass\ ratio = \frac{dry\ root\ biomass}{total\ biomass} \qquad (9)$$

$$leaf\ dry\ mass\ ratio = \frac{dry\ leaf\ biomass}{total\ biomass} \qquad (10)$$

$$stem\ dry\ biomass\ ratio = \frac{dry\ stem\ biomass}{total\ biomass} \qquad (11)$$

Harvest index (HI) is the ratio between the usable biomass and the total biomass (Liu and Stützel, 2003).

Borg and Grimes (1986) proposed a model shown in Equation 12 for the estimation of root growth on any day (t), for annual crops.

$$RD_t = RD_m \left[0.5+0.5\sin\left(3.03\left(\frac{t}{t_m}\right)-1.47\right)\right] \qquad (12)$$

Where:

RD_i = rooting depth at day i (cm);

RD_m = maximum rooting depth (cm);

t_m = duration of the full development of the root (days).

t = time at the date of the measurement (days)

RD_m and t_m are genetically related.

2.11 Soil Moisture

The soil acts as a reservoir of water. The water may be from precipitation and/or from the irrigation. On the other hand, when the soil moisture content is high the infiltration rate is low while in granular soils, the infiltration rate is higher than in massive soils. The ability of soil to store water is highly dependent on the volume of the pore space of the soil. The soil moisture content is mostly expressed as depth of water (mm), and determined by the gravimetric method. Ideally the soil moisture is expressed on volume basis and is converted to equivalent depth.

2.11.1 Soil moisture measurement

The methods of soil moisture measurement can be grouped into two viz direct methods and indirect methods. In one hand the direct methods measure the energy (tension) of soil to hold the water. The higher the tension the more difficult is to extract the water. These methods indicate the plant water availability not the quantity of water in the soil thus: it is directing us when to irrigate rather than how much to irrigate. Thus to determine the amount of water available in the soil, calibration with the gravimetric method is required. The following devices are used to measure the soil tension: tensiometers and porous blocks. On the another hand the quantitative methods provide directly to the user the amount of soil water per unit volume or mass of soil usually expressed in terms of water content as percentage by volume or mass and is converted to equivalent depth.

2.11.1.1 Tensiometers

Tensiometers measure soil water suction. They provide an indication of how hard it is for the plant to get water from the soil. The manometer shows suction level up to -70 kPa (maximum reading provided in the manometers for most of the tensiometers) or pF 2.7. When soil is drier than pF 3.0 the soil surrounding the porous cup will suck all water out of the tube. Tensiometers are widely available, but fail to read the soil water suction at approximately -85 kPa or more (Leo, 2010). Mike (2000) found that the upper limit of soil moisture for which tensiometers can give an accurate reading is 50% of the moisture content at field capacity, while the lower limit is a function of soil texture i.e. under sandy soil, tensiometers can give an accurate reading if soil moisture is equal to or less than 40% of field capacity moisture content. Under clay soil, tensiometers lose their effectiveness when soil moisture reaches 75% of field capacity moisture content. Tensiometers are used mostly for intensive cultures (Leo, 2010).

2.11.1.2 Porous blocks

A porous block in contact with moist soil equilibrates with the soil water. Changes in the water content of the block (and hence the soil) cause various properties of the block to change. The two most commonly measured properties are electrical resistance and thermal conductivity. Embedded pairs of stainless wires or wire grids are used to measure the electrical resistance of gypsum (Plaster of Paris), nylon or fibreglass blocks. Gypsum blocks are most common, since nylon and fibre glass are extremely sensitive to the concentration of dissolved solids in the soil water solution.

Because gypsum blocks are most accurate at soil potentials less than -100kPa, they are often used with tensiometers to obtain the entire range of soil water availability. Calibration curves relating electrical resistance of the block to soil water potential and the characteristic curve of the soil are used to infer soil water content.

A particularly serious problem is that the calibration curve is not valid when the sensor is used in different soils (Whalley *et al.*, 2001). Most of the dielectric sensors are affected by the soil salinity, hysteresis and temperature, thus to calibrate the resistance block, temperature effects should not be ignored, in order to minimize the error in the estimation of soil water content (Clinton *et al.*, 2007; Keyhani, 2001). The gypsum wets quickly but dries slowly and disintegrates in one growing season. However they are cheap and have a wide range of reading (Leo, 2010). At near field capacity, gypsum block readings are less accurate. The use of plaster of Paris ensures that the electrodes are surrounded by calcium saturated water, which buffers the sensor's calibration against changes in the electrical conductivity of the soil water (Whalley *et al.*, 2001).

2.11.1.3 Gravimetric

Gravimetric method requires oven drying of a known mass of soil at 105°C and determining the weight loss. This method is time consuming and destructive to the sampled soil, meaning that it cannot be used for repetitive measurements at the same location. However, it is indispensable as a standard method for calibration and evaluation purposes (Leo, 2010).

2.11.2 Soil moisture retention curve

The soil moisture retention curve represents the relationship between the soil pressure head and the soil water content. It highlights the drying and wetting soil water retention function. Several empirical models have been developed to represent that relationship. Among of those models is the one proposed by van Genuchten (1980) and it is expressed as follows:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{1}{1+(\alpha h)^n}\right)^m \quad \text{...}(13)$$

Where:

θ = soil moisture content

θ_s = saturated soil moisture content (%)

θ_r = residual soil moisture content (%)

h = pressure head (cm)

n, m and α are curve shape parameters, and m is expressed by the

Equation 14 (van Genuchten, 1980):

$$m = 1 - \frac{1}{n} \quad \text{..}(14)$$

Turgut and Sabit (2008) stated that α and n curve shape parameters are sensitive to variability of soil properties such as soil bulk density and contents of organic matter and sand, silt, and clay fractions. The range of parameter α for Gleysols is from 0.012 to 0.6557 and is larger than for Phaeozems which is from 0.004 to 0.1336.The value of parameter is more variable for Phaeozems and ranges from 1.089 to 1.6381, while under Gleysols, the differences in *n* are small and ranges from 1.17 to 3.4 (Porebska*et al.*, 2006).

2.12 Crop evapotranspiration

Crop evapotranspiration (ETc) is normally used for planning of irrigation projects and/or future needs of water if agricultural development is to take place. In an operating irrigation system, the actual evapotranspiration might not necessarily be the potential evapotranspiration under water stress conditions (Musa, 2003). The amount of water to be evaporated into the atmosphere is a function of the soil moisture condition at the soil surface. When the soil moisture is readily available, the evaporation from the soil is dictated by the atmospheric demand and when the soil moisture is depleted below the readily available level, the amount of water to be evaporated is a function of the soil moisture. In the case of transpiration, it is a function of the soil moisture within the root zone and the ability of the plant to take up the water. There are a number of equations suggested to estimate the actual evapotranspiration (AET) among which is the equation proposed by Panigrahi and Sudhindra (2002).

If: $PWP<SWC_i< (1-p)(FC-PWP)$ the AET_i can be calculated as follows:

$$AET_i = \frac{SWC_i-PWP}{(1-p)(FC-PWP)} ET_C \quad \text{....(15)}$$

If: $(SWC_i-PWP) \geq (1-p)\ (FC-PWP)$, then

$$AET_i = ETc_i \quad \text{....(16)}$$

Where:

AET_i = actual evapotranspiration at day i

p = soil water depletion factor,

ETc_i = crop potential evapotranspiration (mm) determined from class A evaporation pan,

FC = soil water content at field capacity (mm)

PWP = soil water content at permanent wilting point (mm)

SWC = soil water content within the root zone depth (mm).

i = time index, taken as the day of measurement

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of the Study Area

3.1.1 Location

The study was conducted at the horticulture unit of Sokoine University of Agriculture (SUA) in Morogoro, Tanzania, located at latitude 6°51′S, longitude 37°39′E and at an altitude of 525 m above mean sea level (Chibuye, 2001).

3.1.2 Climate

The climate of the area is between sub humid and semi-arid (Chibuye, 2001) with an annual average rainfall of 834 mm. Morogoro is characterized by a bimodal rainfall regime. The short rainy season is from October to December and the long rainy season is from March to May. The maximum temperature is observed in March and September, the lowest in June. The average temperature is 24°C, while the mean maximum temperature and minimum temperatures are 30°C and 18°C respectively.

3.1.3 Geology

The geology of the study area belongs to the Usagaran system of the Mozambican belt with Precambrian gneiss. The predominant rocks are metamorphic horneblende, pyroxene granulites (Chibuye, 2001).

3.1.4 Soils

The main soils of the horticulture unit consist of alluvial soil formed from deposits of the nearby Kikundi stream. These deposits range from about 2 m to around 20 m thick and increase from the East to the West as well as from the South to the North.

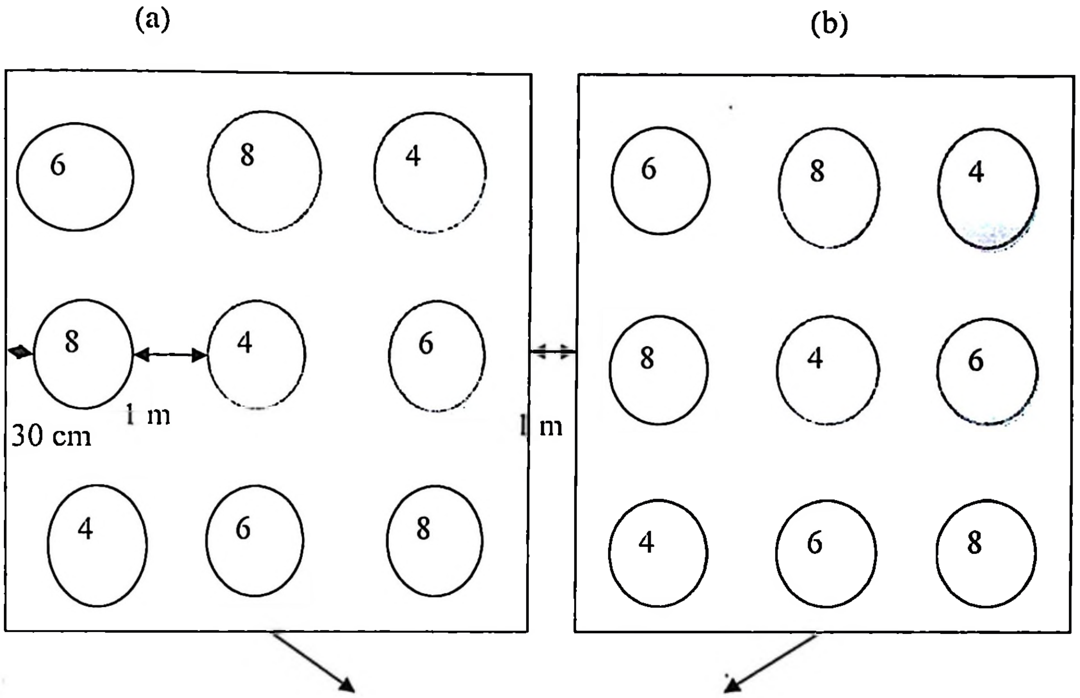
The south-eastern part consists of highly weathered reddish soils which originated from the nearby Uluguru Mountains (Chibuye, 2001).

3.1.5 Hydrology

The main sources of water for the unit are the seasonal Kikundi stream, and three shallow wells sunk within the unit. The Kikundi stream has a minimum discharge ranging between 17 to 19 l/s while the maximum flow for a 10 year return period is estimated at 11327 l/s. The shallow wells have a mean discharge of 7.3 l/s, 6.5 l/s, and 6.8 l/s respectively (Chibuye, 2001).

3.2 Field Experimental Design

The experimental design was a 2 x 3 factorial arrangement of treatments in a split plot design. The main-plots were the initial soil moisture content (soil moisture content at field capacity and soil moisture content at 26 % by volume). The sub-plots were the three plant densities (4 plants/pot, 6 plants/pot and 8 plants/pot). The study had a total of 18 sub-plots (9 in each whole plot and these were randomly assigned) (Figure 3). The total area of study plot was 18 m^2, 9 m^2 for each main plot and the distance separating each sub-plot within the main plot was 1 m. To prevent surface run-off from coming into the study area, a 0.5 m depth cut-off drain was dug around the entire experimental field to drain off the water. In addition, to prevent sub-surface flow coming into the experimental field a metal sheet was placed around to a depth of 0.5 m. Further, the experimental field was protected from rain water by covering with a plastic sheet.



Main plots bound by a 0.5 m depth metal sheet

a = treatment where initial soil moisture content is at field capacity

b = treatment where initial soil moisture content is at 26 % (volume)

Figure 3: Schematic representation of the experimental layout

In Fig. 3, the circles within the main plots represent sub-plot treatments, and the number indicated inside the circle represents the number of plants which were planted around the clay pot. The coloured circles represent the plots where the soil moisture content was monitored during the study period.

3.3 Calibration of the Tensiometers and the Porous Blocks

Before using the tensiometers and resistance blocks in the field a calibration analysis was conducted. The porous blocks were calibrated according to the method proposed by Keyhani (2001). Soil samples were taken from the experimental field at three different depths (30 cm, 60 cm and 90 cm). Composite samples based on depth were analysed for textural classification. During the calibration process, 686.6 g of oven dry soil was put into a 2000 cc beaker in which one tensiometer and 8 porous blocks were embedded. The soil was wetted up to saturation and an initial weight taken. Initial readings were also taken for the tensiometer and porous blocks. The calibration was conducted by using 3 soil samples and readings were taken once every day at 8:00 am. These comprised of tensiometric readings, gypsum block resistance data from a data logger (model 5610A soil moisture meter) and soil moisture depletion from weight differences between the current weight (container with respective components) and initial weight (previous total weight). The calibration process took one month, and during this period the relative humidity in the chamber was maintained at 45% while the temperature used was regulated on a 3-day cycle every 24 hours i.e. at 24°C, 28°C and 30°C according to Keyhani (2001).

Calibration was done using regression analysis as suggested by Keyhani (2001). However, before the regression analysis was conducted, a descriptive statistical analysis was conducted for each gypsum block reading throughout the calibration period. From the analysis, gypsum blocks which had coefficients of variation greater than 20 % were not used in the regression analysis and were discarded, because they could not provide consistent readings. The aim of carrying out the calibration process was (i) to facilitate choosing gypsum blocks which could be used in the field. (ii) to enable development of equations which could be used along with data collected from the field. The regression equations were developed from the gypsum blocks and tensiometers which recorded the widest range of readings (from -9kPa to -80kPa).

To calibrate the tensiometers, soil moisture retention curve was constructed by plotting the soil moisture content against the pressure head then fitting the van

Genuchten (1980) and models, by using the RETC (van Genuchten*et al.*, 1991)computer program.

The equations obtained from the calibration analysis were validated by plotting the observed soil moisture content with the calculated soil moisture content obtained from each equation for each instrument. The two data sets were obtained from one soil sample. The instruments provide reliable data firstly, if the relationship between the observed data and the calculated data is linear and secondly if the slope between the observed and calculated soil moisture content is equal to 1 and with an intercept equal to zero.

3.4 Soil Analysis

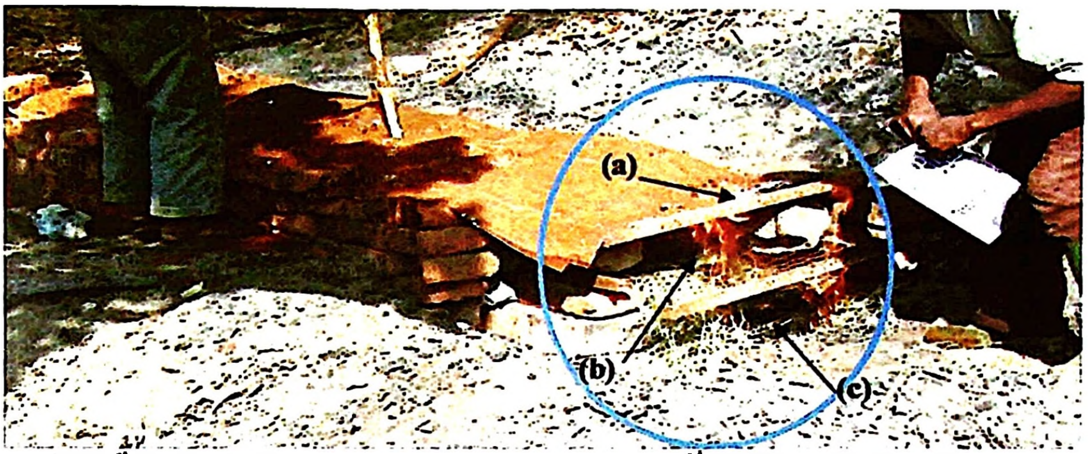
Prior to the experimental set up, two pits were dug in the study area where soil samples were taken. Samples were taken at 30 cm and 60 cm depths. The parameters analyzed from the samples were particle density, particle size distribution, organic matter content and bulk density. Soil texture analysis was done using the hydrometer method as suggested by David (1994).

3.5 Installation of Soil Moisture Sensors

The resistance blocks and tensiometers were soaked overnight in water prior to field installation. Three holes around the pot, at a distance of 15 cm from the rim of the pot were augered to the appropriate depth for each soil moisture sensor (tensiometer and/or gypsum block) i.e. 30 cm and 60 cm. Either a tensiometer or a resistance block (the tensiometers were used as replacement of the defected gypsum block) was put in each of the holes. In order to increase the contact between the soil and the tensiometers and/or resistance blocks, slurry made from the soil taken from the bottom of each hole was dropped into the hole. The wire leads from each of the gypsum blocks were connected to the resistance meter (model 5610A soil moisture meter) via a PVC guide tube. Holes were backfilled gently. The resistance block sensors were placed in the field 4 days before planting, in order to allow the sensors to be in equilibrium with the surrounding area.

3.6 Pot Fabrication

Clay pots were locally moulded by the potters at Magadu village. They were not given any specifications as to the clay-sand ratio. The kiln used had no facility for adjusting the temperature though the temperature could be measured at a particular point in time. As such, the first batch of clay pots of thirty pieces, were burnt at 800°C and the second batch of 25 pieces were burnt at 600°C. To avoid the non-uniformity of porosity among the pots, only the pots that were burnt at 800°C were used in the field. The temperature was measured by using a digital millimetre (MASTECH MY-62) which is able to read a temperature up to 2000°C. The kiln was specially designed in such a way that the temperature could reach 1200°C. The kiln was designed in the form of tunnel with three shelves; the first shelf was at the bottom where the firewood was placed, while the second shelf in the middle was reserved for the pots and the charcoal was put on the top shelf. The tunnel was covered with old newspapers before covering the whole kiln with slurry (Fig. 4). According to Bainbridge (1998), the clay pots when burnt at 800°C have a porosity of about 15%, while those burnt below 700°C, have an undefined porosity.



(a) :1st shelf where the charcoals were placed, (b):2nd shelf where the pots were burnt, (c): 3rd shelf where the fire wood were placed.

Figure 4: Kiln with its component parts

3.7 Agronomic Practices

The bean crop (*Phaseolus vulgarisvar SUA 90*) was sown on 7th November 2009. The sowing depth was approximately 2 cm below the soil surface. Each bean seed was sown separately around a pot at a distance of 10 to 15 cm away from the wall of the pot and at a seed rate of 12, 18 and 24 bean seeds around each pot for the 4, 6 and 8 planting densities respectively. When the plants reached three leaves, they were thinned to 4, 6 and 8 plants per pot respectively as per design (Fig. 5). Every 10 days, a fungicide LINKOMIL at a rate of 5 mL and an insecticide (KARATE) at a rate of 10 g/10 L of water were applied. Inorganic and organic fertilizers were applied to the crop around each pot. NPK was applied at a rate of 13 g and farm yard manure at a rate of 500 g i.e. 7.07 t/ha as recommended (SUA, 2007). Due to adverse soil temperatures which went up to 35°C during the experimental period, and the stem blight attack, the bean crop did not grow up to physiological maturity thus the only data obtained from that crop was the actual evapotranspiration, LAI, plant height, and all the components of the water balance. In order to have all the necessary data

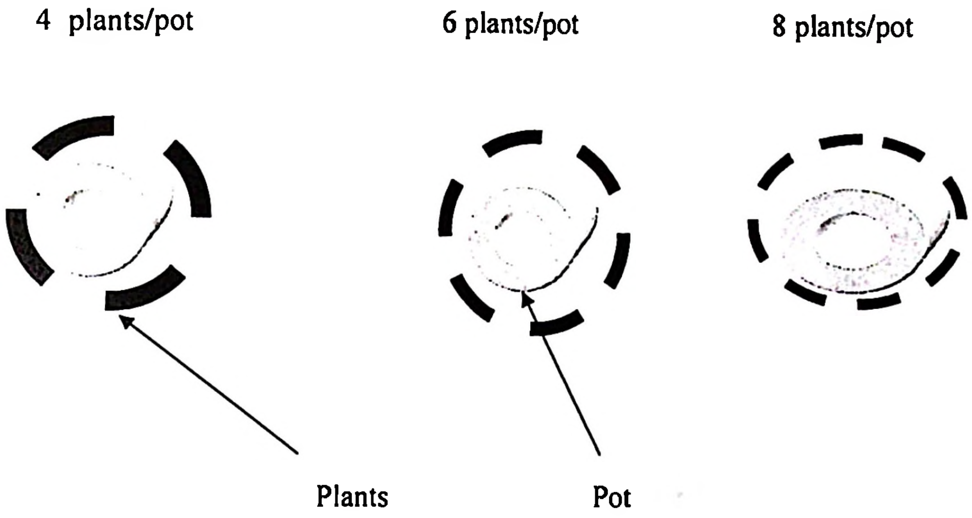


Figure 5: **Plant configuration around the pots**

needed for the study, amaranths (*Amaranthushypochandricus*) was planted from which only biomass yield was taken and used in the data analysis. Since amaranths are consumed as a vegetable and not as grain, biomass was determined exactly 21 days (standard duration of harvesting amaranths) after planting which is the standard duration for harvesting amaranths (as vegetables). The amaranths were however thinned to 16 plants/pot, 24 plants/pot and 36 plants/pot and were fertilized with poultry manure only at a rate of 100 g around each pot i.e. 12 t/ha (Kolawole and Sarah, 2009).

3.8 Data Collection

3.8.1 Climatic data

Ten-year (1988-1997) climatic data for wind speed at 2 m height, relative humidity and mean temperature obtained from Morogoro meteorological station were used in the study. These climatic parameters were used to adjust the pan and crop coefficients Kp and Kc, respectively.

3.8.2 Soil moisture measurement

Soil moisture was measured using either tensiometers or porous blocks at three different depths i.e. 0.3 m and0.6 m respectively. Soil temperature readings were also taken at the same depths because calibration of porous blocks is temperature dependent. Changes in the growth of roots over the growing period were determined by using Equation 12. The rooting depth was physically measured (from excavated plants) after 35 days of the first planting (due to attack of stem blight), after 48 days of the second planting and during the three leaves stages (i.e. after 12 days of planting). The data were used to validate the model. This is needed to calculate the soil moisture content within the root zone. The simulated rooting depth was used along with data collected from moisture measurements in order to determine the available soil moisture for the plants within the root zone and deep percolation losses. The total available soil moisture content (TAM), readily available soil moisture (RAM) and the irrigation water requirement were calculated.

3.8.3 Crop evapotranspiration

The class A evaporation pan was placed 5 m away from the experimental plot. The Kc values used were those proposed by Allen *et al.* (1998). The Kc values were adjusted according to the climatic data that was obtained from the Morogoro meteorological station.

Ground cover and LAI were determined only for beans. In order to calculate the LAI using Equation 8, the number of leaves for all the plants for each of the treatments were counted and for each leaf of each plant the maximum width was measured using a tape. This data was collected on weekly basis. For each treatment a wetted area of 706.95 cm^2 was considered. That area is based on the assumption that the wetting front from the pitcher irrigation forms concentric circles with a maximum radius of 25 cm, from the wall of the pot, but at such a distance the water is only made available by the pot at a depth of 30 cm (Budi *et al.*, 2006). So a radius of 15 cm was arbitrarily taken, which corresponds to a surface area as indicated above. Readings from the class A evaporation pan were taken on a daily basis for estimation of the reference crop evapotranspiration. The Kr values were determined on a weekly basis based on the equation given by Decroix (1973) (Equation 17) and in order to get daily values of Kr a regression equation was derived from the weekly values of LAI and GC. The ground cover (GC) was obtained by solving Equation (18) (Gerson *et al.*, 2000). This enabled the computation of ETc on daily basis. The crop coefficient curve was constructed according to Allen *et al.* (1998).

$K_r = 0.1 + GC \text{ or } 1 \text{ whichever is the smallest}$ .... (17)

$LAI = -0.297 + 4.8 \times 10^{-2}(GC\%) - 7.54 \times 10^{-5}(GC\%^2)$ ....(18)

3.8.4 Irrigation scheduling

The pots were calibrated volumetrically by marking the respective volumes on the inside walls using indelible ink. Water depleted from the pots was considered to constitute irrigation water of the previous day(s). Water was replenished in the pots when depletion reached 50% of the total volume of the respective pots, or when the tensiometer registered between 30 kPa and 40 kPa or when plants started to show he signs of stress. The observed irrigation interval was compared to the irrigation t of interval obtained by Equation 19. e the

$Ii = \frac{RAM}{ET_c}$ .... and the

sture. The

Where:

Ii = irrigation interval (days)

ETc = crop evapotranspiration ($mm.day^{-1}$)

The Ii was calculated for each plant density and the total allowable depletion used was 45%.

3.8.5 Biomass measurement

Fresh biomass was taken by uprooting the amaranths; leaves and roots were cut off from the stem for each plant of each treatment. Thereafter it was oven dried at 70°C, for 48 hours, and then the dry biomass was weighed to determine the leaf dry mass ratio (Equation10), stem dry mass ratio (Equation 11), harvest index and root dry mass ratio (Equation 9).

3.8.6 Calculation of the irrigation performance indicators

The adequacy of irrigation supply during the growing period was evaluated as the temporal average of the ratio of amount of water delivered to amount of water required (David *et al.*, 1998). In addition to this indicator application efficiency, (Equation 6) was also determined, which is the ratio of the crop water demand to the water applied. The amount of water applied was measured by using a measuring cylinder and the amount of water required by crop was set to ETc replenishment.

The uniformity coefficient of Wilcox and Swailes (UCW) was used to determine the application uniformity of the irrigation system, and it is based on the amount of cumulative daily seepage rate for each treatment during the study period because the seepage rate of the pots was a function of the moisture gradient of the inner and the outer part of the pot thus a function of plant density and initial soil moisture. The uniformity of the seepage rate was rated according to the value of UCW as proposed by Pitts (1997).

Table 1: Range of UCW for rating of the irrigation uniformity

Rating	UCW (%) (Pitts, 1997)
Excellent	> 90
Good	80-90
Fair	70-80
Poor	< 70

(Source: Oswald, 2002)

3.8.7 Calculation of the water productivity and land productivity

Water productivity was calculated as the physical productivity, defined as the biomass yield divided by the quantity of water depleted using Equation 2. The land productivity was calculated as the physical product over the cropped area.

3.9 Data Analysis

3.9.1 Water balance

The monitored water balance components were the soil moisture content within and outside the root zone denoted as SWC_i and SWC_{oi} respectively which were monitored on daily basis using either gypsum blocks and thermometers or tensiometers; the irrigation water denoted as IRR measured using a measuring cylinder, the actual evapotranspiration calculated from Equations 14 or 15 and the deep percolation calculated from Equation 6.

3.9.2 Field application efficiency and crop water use efficiency

The crop irrigation water use efficiency (IWUE) was only determined for the amaranths because the beans did not reach the harvest stage. The bean plants had been infected with stem blight, and stressed by severe temperature before the pod formation. On the other hand, the field application efficiency was determined only for the beans because the crop water requirement of the amaranths had not been determined due to inadequate data to perform a regression analysis. An analysis of variance (ANOVA) for the respective variables was conducted using the statistical package GENSTAT version 3 and excel.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results and discussion of the findings from the study which focused on the applicability of the clay pot as an irrigation device. More specifically the study looked at the performance of the clay pot irrigation in terms of soil moisture, irrigation efficiency, irrigation uniformity, irrigation adequacy, crop water use efficiency and biomass production using beans and amaranths as test crops. Calibration of moisture sensing instruments such as tensiometers and porous blocks was also given due consideration taking into account the fact that accuracy of data is dependent on the authenticity of the instruments used. A part from those results, soil analysis, clay pots properties and irrigation water requirements were also covered in this chapter.

4.2 Soil Analysis

Results of soil analysis for particle size, bulk density and particle density are presented in Table 1.Results show that the soil is sandy clay loam. A statistical analysis of the physical properties of soil from the different samples indicated that there was no significant difference in texture at the two different depths at the 5% level. These results suggest that only one calibration equation can be used to determine the soil moisture content for the three different depths (GLOBE, 2005).

Table 2: Physical properties of soil in the study area

Soil Depth	Bulk density ($g.cm^{-3}$)*	Particle density ($g.cm^{-3}$)*	Clay (%)	Silt (%)	Sand (%)	Soil texture	Organic Matter (%)
30 cm	1.425a	2.60f	23b	11d	66e	SCL	3.2
60 cm	1.468a	2.67f	26b	10d	65e	SCL	2.5
LSD	0.1558	0.12	6.365	5.81	9.72		

*The numbers followed by the same letter are not statistically different at 5% level of significance

4.3 Calibration of Soil Moisture Sensing Instruments

4.3.1 Calibration of the porous blocks

The porous block was calibrated by plotting the electrical resistance against the respective moisture content on weight basis at a temperature of 30°C. The resulting plot is a power relation as shown in Fig. 6 and supported by the findings of Keyhani (2001).

The Equation 20 representing the relationship between soil moisture content and electrical resistance is given as:

$$y = 5.599x^{0.386} \quad \text{……………………………………………………………………(20)}$$

R^2 = 0.95

Where:

x = block reading at 24°C.

y = soil moisture content (weight, %)

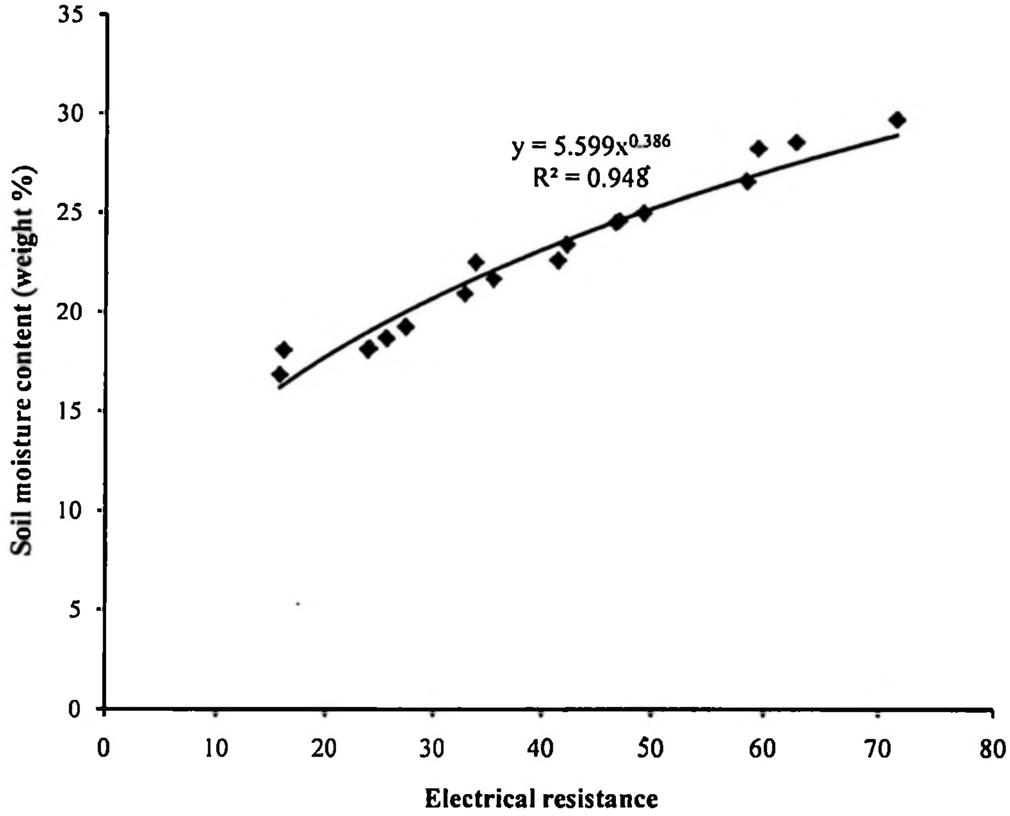


Figure 6: **Soil moisture content against electrical resistance at 30°C**

To eliminate the effect of the temperature, a normalized resistance deviation y', was needed and it is expressed by Equation 21 (Keyhani, 2001).

$$y' = \frac{B_k - x}{x} \qquad \text{(21)}$$

Where:

y' = is the normalized resistance deviation

B_k = is the block reading at k°C

x = block reading at 30°C

The regression analysis showed that the normalized resistance deviation (dependent variable) has a linear relationship with the soil temperature (T) and the block reading at a soil temperature k°C (B_k) as expressed by Equation 22:

$$y' = -0.79 + 0.025T + 0.004B_k \text{ ....}(22)$$

R^2=0.66

By substituting the right hand side of Equation 21 for y' in Equation 22 and solving for B_{30} Equation 23 is obtained:

$$x = \frac{B_k}{0.21+0.025T+0.004B_k} \text{ ....}(23)$$

Substituting the right hand side of Equation 23 for x in Equation 20 the final equation for soil moisture content is obtained as:

$$y = 5.59\left(\frac{B_k}{0.21+0.025B_k+0.004T}\right)^{0.386} \text{ ....}(24)$$

y = soil moisture content (% by weight)

B_k = block reading at soil temperature T°C

T = soil temperature (°C)

This equation was used for inferring soil moisture content from the electrical resistance readings obtained by the gypsum blocks at different soil temperatures.

There was good agreement between observed and calculated soil moisture content (Fig. 7). The slope of the linear least squares fit of observed vs calculated data did not differ significantly from the expected slope of 1.0 at 5 % level. The intercept of the linear least squares line (-0.012) is also negligible and not significantly different from 0 at 5 % level. This shows that the calibration equation from the resistance block can provide reliable data.

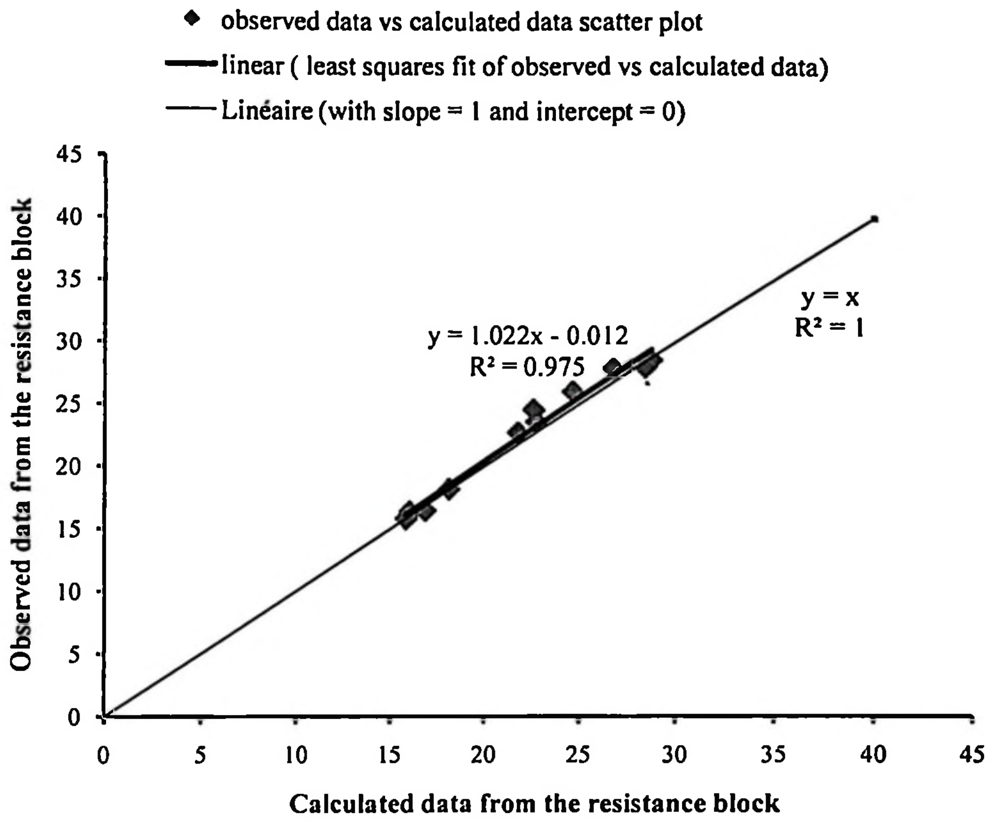


Figure 7: **Comparison between the observed data and the calculated data from the resistance block calibration equation.**

4.3.2 Calibration of the tensiometers

Fig. 8 shows the soil moisture characteristic curve within the measurable range of a tensiometer. A regression equation was derived from the observed data (Equation 23) the inverse of which (Equation 24) was used to determine the soil moisture content from the tensiometer readings.

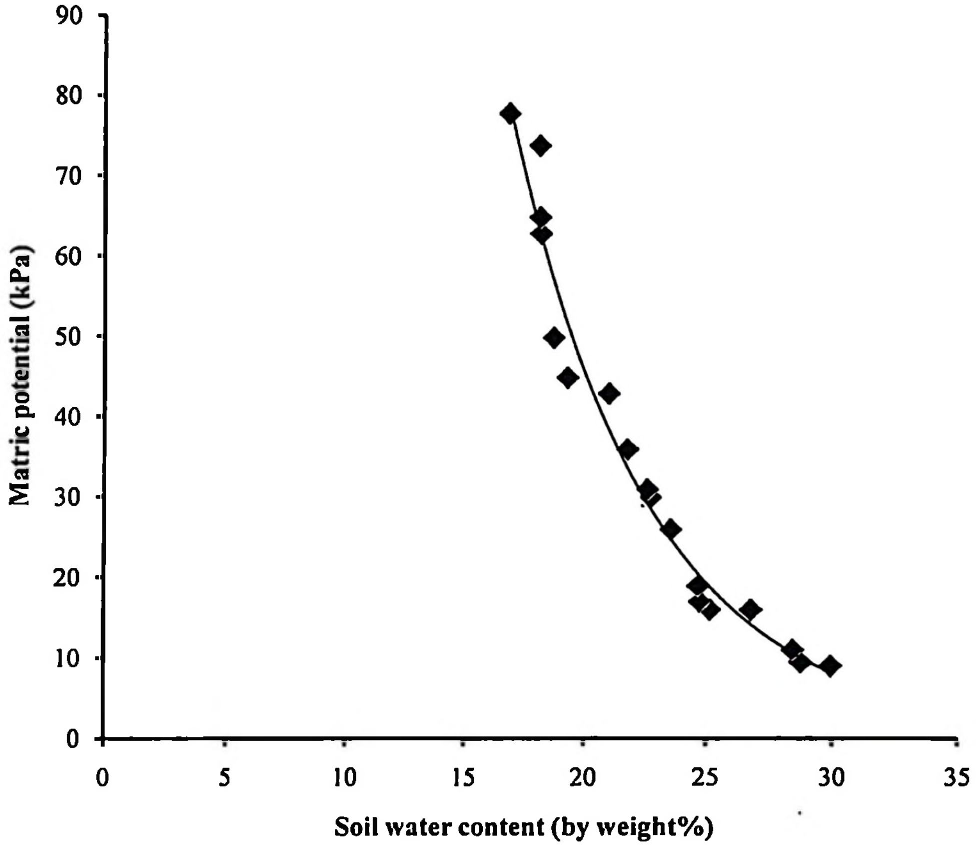


Figure 8: **Soil moisture characteristics curve**

Van Genuchten's model (van Genuchten, 1980) was fitted to measured data (Fig. 9) (the fitted model was obtained from the RETC software). The model appeared to fit the data reasonably well ($R^2 = 0.965$). The optimized values for α, θr, θs, n, and m are 0.15, 0.04, 0.34, 3.34, and 0.32 respectively (Equation 25).

$$\frac{\theta - 0.04}{0.34 - 0.04} = \left[\frac{1}{1 + (0.15 \times h)^{3.34}}\right]^{0.32}, R^2 = 0.965 \ldots\ldots (25)$$

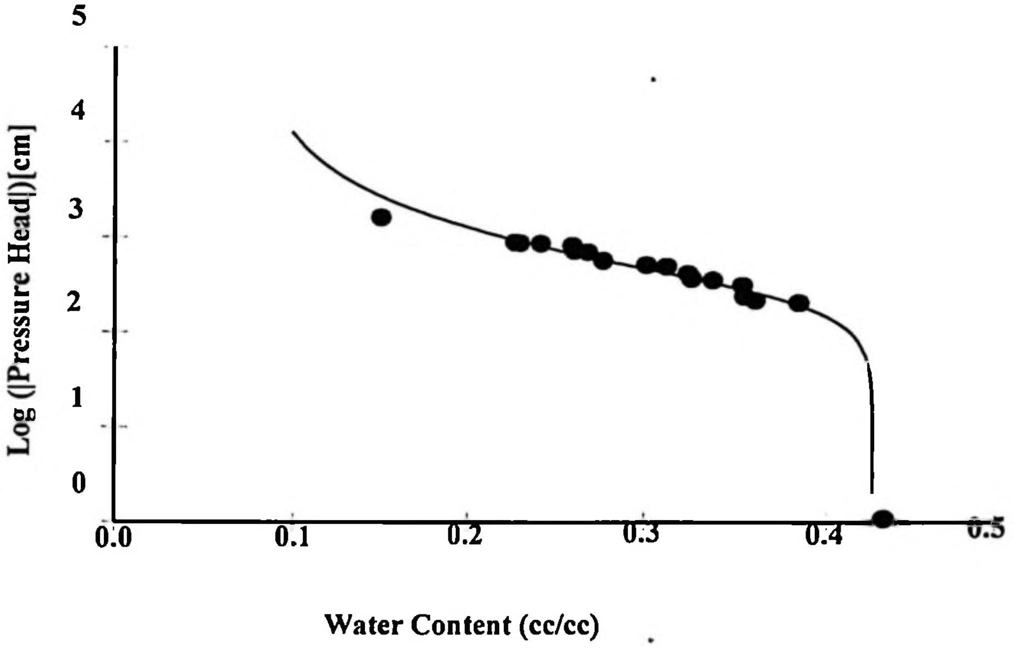


Figure 9: **Soil moisture retention curve based on van Genuchten model**

ψ = $1456e^{-0.12(grav)}$ ....(26)

R^2 = 0.979

Where:

ψ = the matric potential (kPa)

grav = soil moisture content (%, by weight)

Equation 24 was inversed to get the final equation which transforms the tensiometric readings into soil moisture content, as shown below:

$grav$ = $-5.66 \times ln(\psi) + 41$ ....(27)

R^2 = 0.979

Where:

grav = soil moisture content (%, weight)

ln = natural logarithm

ψ = matric potential (kPa)

There was good agreement between observed and calculated soil moisture content (Fig. 10). The slope of the linear least squares fit of observed vs calculated data (0.976) did not differ significantly from the expected slope of 1.0 at 5 % level. The intercept of the linear least squares line was 0, thus the derived equation can be used to provide reliable soil moisture content data from tensiometric readings.

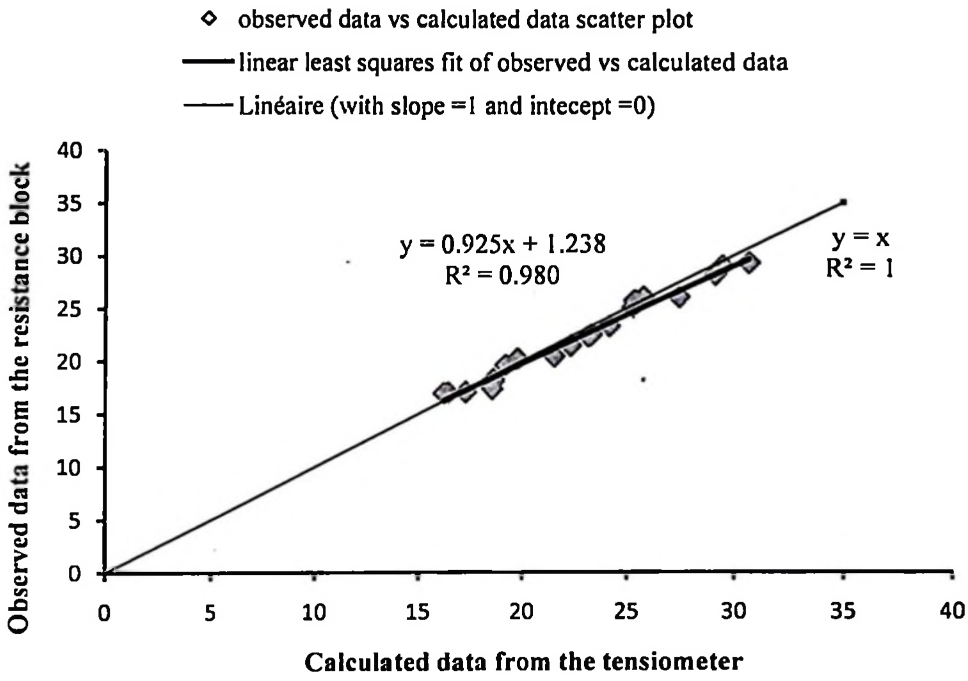


Figure 10: **Comparison between the observed data and calculated data from the tensiometer calibration equation**

4.4 Physical Properties of Clay Pots

4.4.1 Seepage rate

The seepage rate of the clay pots was not significantly different ($P < 0.05$) under the various treatments (Table 3) i.e. the plant density and the initial soil moisture. This could be attributed to the weak relationship between the AET and the seepage rate ($R^2 = 0.37$) (Figure 10). Even though the correlation between the seepage rate and the AET was weak, the trend was positive (Figure 10) which indicates that the pots had the ability to control water supply to plants. In other words the pots can auto regulate water supply to plants (Majede*t al.*, 2009). Further, the difference between the two initial soil moisture contents (26% and 31% by volume) was not large enough to make the difference of the seepage rate in the main block.

The daily seepage rate of the pots in the field was 0.68 l/day which was far much higher than that suggested by Syial and Skaggs (2009) which is supposed to be 15 % of the pot's volume per day i.e. 0.282 l/day for the size of pots used in this study. The higher seepage rate experienced in this study could be as a result of higher saturated hydraulic conductivity and higher porosity.

4.4.2 Capacity

Pots used during the study had a capacity of 1.88 L which was slightly lower than the recommended size i.e. 2.0 L. However the volume of the pots was more or less the same with a CV of 12.5 %.

Table 3: Effect of various treatments on the seepage rate of the pitchers

Treatments	Seepage* rate (l/day)
4a	0.65a
6a	0.8a
8a	0.49a
4b	0.74a
6b	0.73a
8b	0.66a
lsd	*0.39*

*The number followed by the same letter is not statistically different at 5 % level of significance.

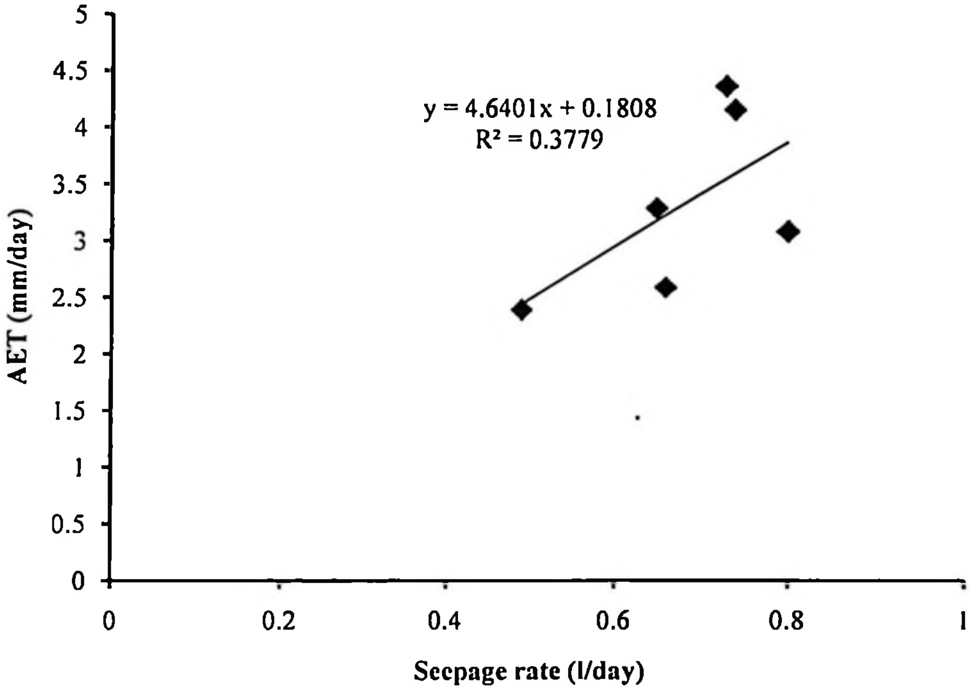


Figure 11: **Correlation between seepage rate and the AET**

4.5 Irrigation Water Requirement

4.5.1 Irrigation frequency

Irrigation frequency was based on the criterion for refilling the pots and thus was variable depending on the evaporative demand of the atmosphere as well as crop characteristics. In practical terms the irrigation frequency was one day. Results indicated that the plant density had no significant effect on the irrigation interval. This may be attributed to the small difference of the planting densities used during this study.

During the study period, the observed irrigation frequency was far much higher than that calculated (Table 4) which may be attributed to the high seepage rate of the pots, which was not pre-determined.

Table 4: **Comparison between observed irrigation interval and the calculated irrigation interval**

Treatments	ETc (mm)	Gross water requirement(mm)	Calculated Ii (day)	Observed Ii (day)*
4a	3	16.45	5	1a
6a	4.09	16.45	4	1a
8a	4.3	16.45	4	1a
4b	2.54	16.45	6	1a
6b	3.26	16.45	5	1a
8b	3.44	16.45	5	1a
lsd				*0.052*

* The numbers followed by the same letter are not statistically different at 5%level of significance

4.5.2 Crop ground cover and LAI

Under localized irrigation system the crop water requirements are lower than those under sprinkler and surface irrigation by a crop ground cover factor (Kr).The ground cover (GC %) (Different from the ground cover factor) was a function of the plant density and the initial soil moisture content (Figures 10 and 11). GC (%) delayed to reach the peak (100 %) under lower plant density and under lower initial soil moisture content. The GC (%) peaked 20, 22, 25, 31, 31 and 39 days after sowing for treatments 8a, 6a, 4a, 8b, 6b and 4b respectively. This shows that, the GC(%) increases with the plant density and with the initial soil moisture content due to the fact that under lower initial soil moisture content the plants grow slowly compare to that under higher initial soil moisture content. Results from Figures 12 and 13 show that, the plants emerged 19 and 10 days after sowing for initial soil moisture content at 26 % (volume) and at field capacity respectively.

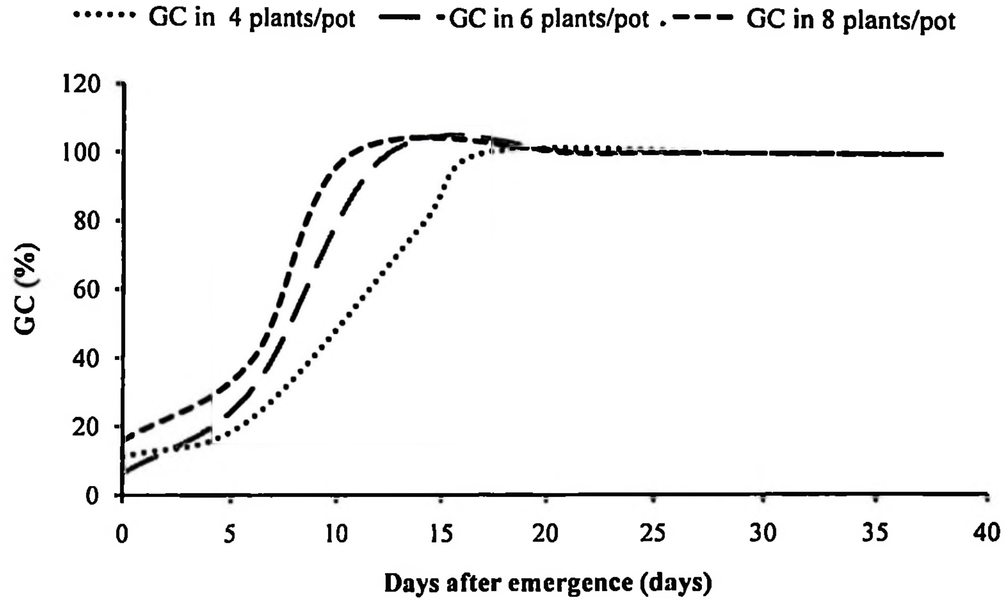


Figure 12: Trend of GC under various treatments for initial soil moisture at Field Capacity

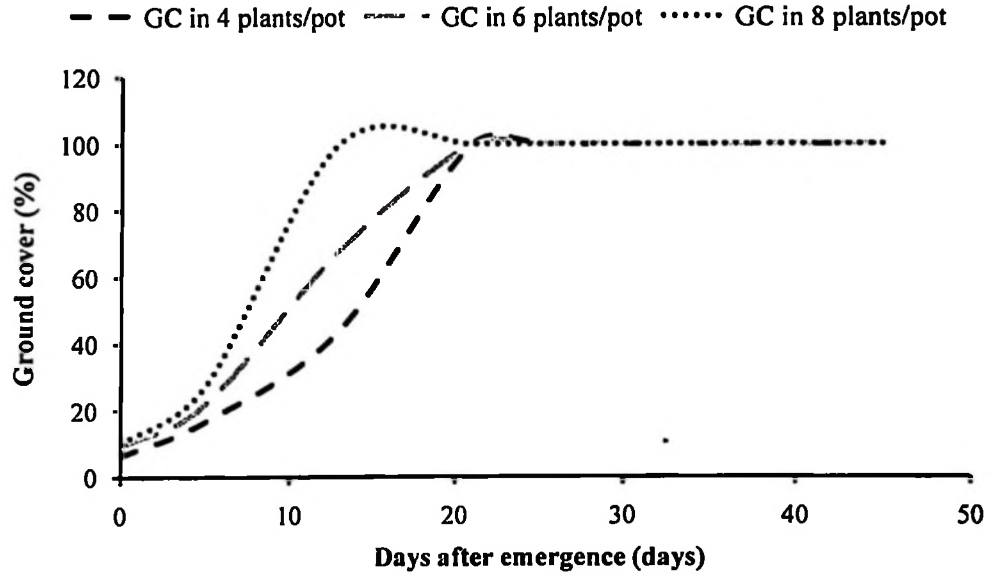


Figure 13: Trend of GC under various treatments for initial soil moisture at 26 %

4.5.3 Comparison of ETc and irrigation applied

Throughout the study period, in all the treatments, beans were over irrigated. This was because the water supply from the pots was higher than that required for a crop of beans based on climatic conditions. The high water application was as a result of the high seepage rate of the pots. The water applied through irrigation was not significantly influenced by the initial soil moisture and the plant density ($P < 0.05$) (Table 5). The average daily water application through irrigation was 9.64 mm which is far much higher than the ETc under different plant densities. This is also shown in Figure 14 where the excess amount of water applied is well above the ETc amount. The total water loss through deep percolation throughout the study period was amounted 115, 26.4, 26.5, 184.4, 102.5 and 186.6 mm for treatments 4a, 6a, 8a, 4b, 6b and 8b respectively.

Table 5: Mean daily water application for various treatments

Combination treatment	*Mean daily IRR (mm)
4a	9.26a
6a	11.44a
8a	6.98a
4b	10.48a
6b	10.36a
8b	9.36a
lsd	*5.547*

*the numbers followed by the same letter are not statistically different at 5% level of significance

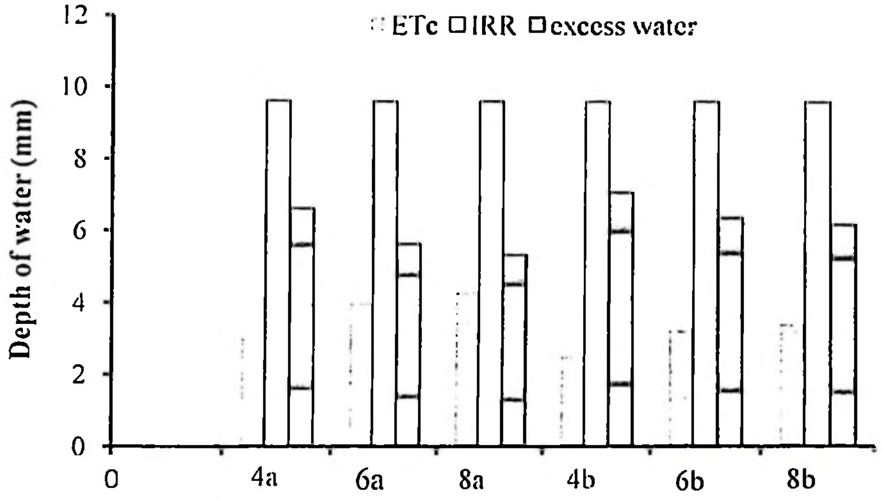


Figure 14: **Comparison of mean daily water application, Etc and excess water applied for various treatments**

4.6 Soil Moisture Status

4.6.1 Crop root development

Root growth trend was derived from Equation 12 as proposed by Borg and Grimes (1986) and is illustrated in Fig.15. This was used to compute the soil moisture content within the root zone. The model was cross checked by using the actual measurements from excavated plants during the initial infestation of stem blight which was 35 days after the first planting for the first attempt and 48 days after the second planting for which the respective rooting depths were 31 cm and 44 cm. At three leaves stage (12 days after sowing), the observed root length after excavation was 6 cm. The simulated root growth and the observed root length were in good agreement (Fig. 15).

The simulated root length of the beans was also compared with the data of Maghembe (1999) who did studies on the same variety of beans i.e.

Phaseolusvulgarisvar SUA 90. For the three different development stages, i.e. days to first flowering, days to 50 % flowering and days to maturity, results compared favourably with the simulated root growth.

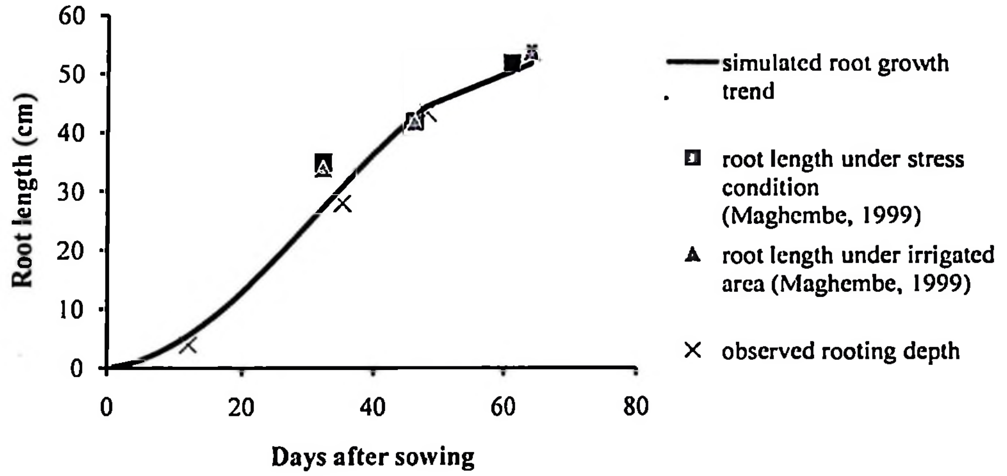


Figure 15: **Trend of root growth for beans**

4.6.2 Soil moisture content within the root zone

Soil moisture content was measured either by tensiometers or porous blocks and thermometer. Plants were constantly irrigated. The mean daily soil water depth within the root zone over the growing period was 58.45 mm, 58.56 mm, 55.4 mm, 54.95 mm 61.06 mm and 59.1 mm for treatments 4a, 6a, 8a, 4b, 6b and 8b, respectively. These values were higher than the critical soil water depth (readily available water depth for plant) but less than the soil water depth at FC i.e. 25.06 mm and 62.32 mm respectively. This means that none of the plants during the study period were subjected to water stress. However, there was a period of over-irrigation starting from the 26th day after sowing, 33rdday after sowing and 32nd day after sowing for treatments 4a, 6b and 8b, respectively (Fig. 16,17, 19, 20 and 21), it is important to note that the excess of water i.e. the amount of water which is above the

FC water content is not available for the plants. Under-irrigation was observed under treatment 8a towards the end of the growth period (Fig. 16).

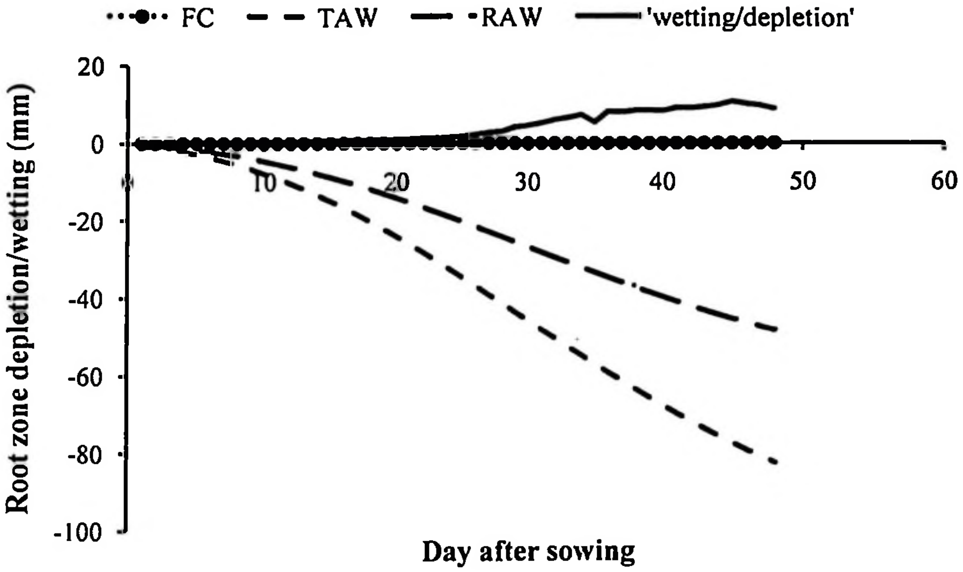


Figure 16: **Soil moisture status under 4a treatment**

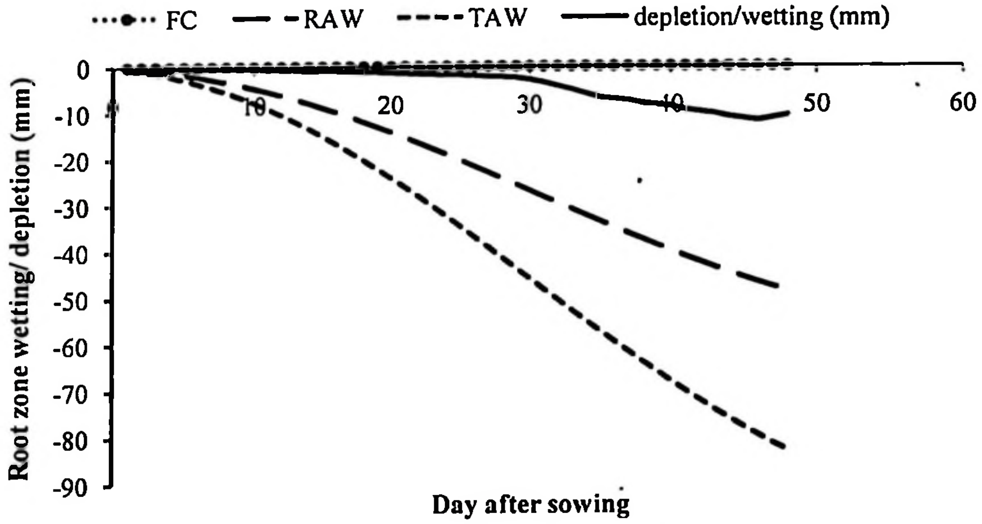


Figure 17: **Soil moisture status under treatment 6a**

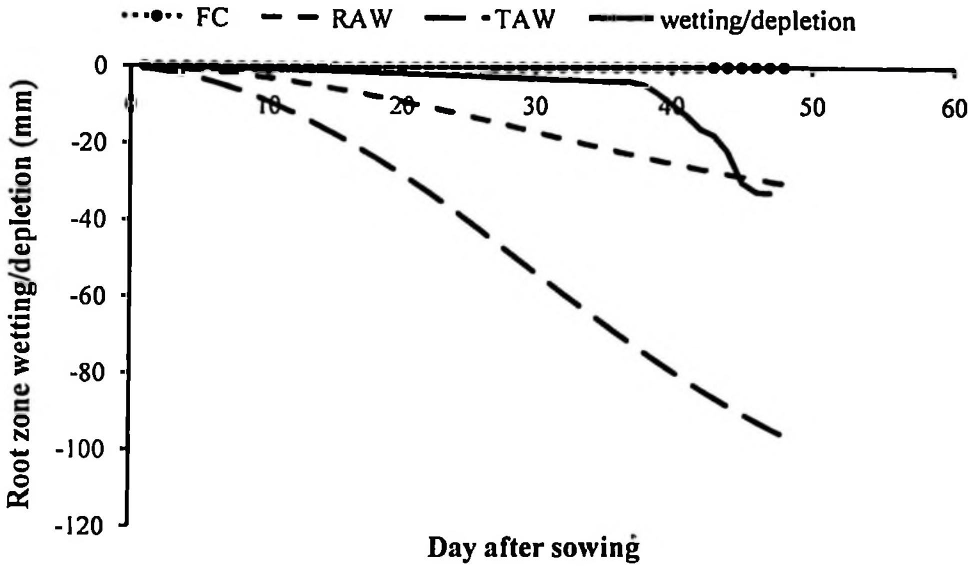


Figure 18: Soil moistures status under treatment 8a

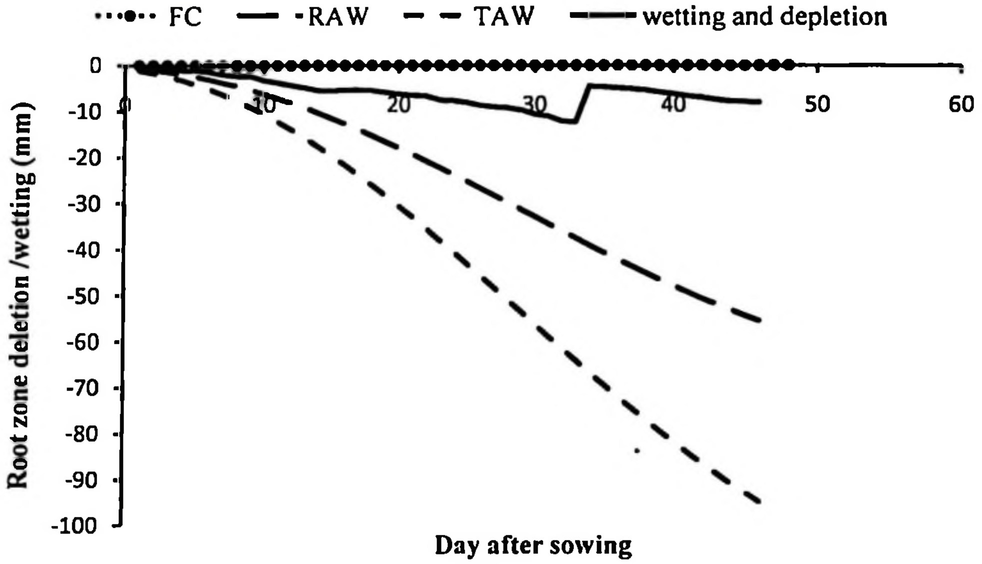


Figure 19: Soil moisture status under treatment 4b

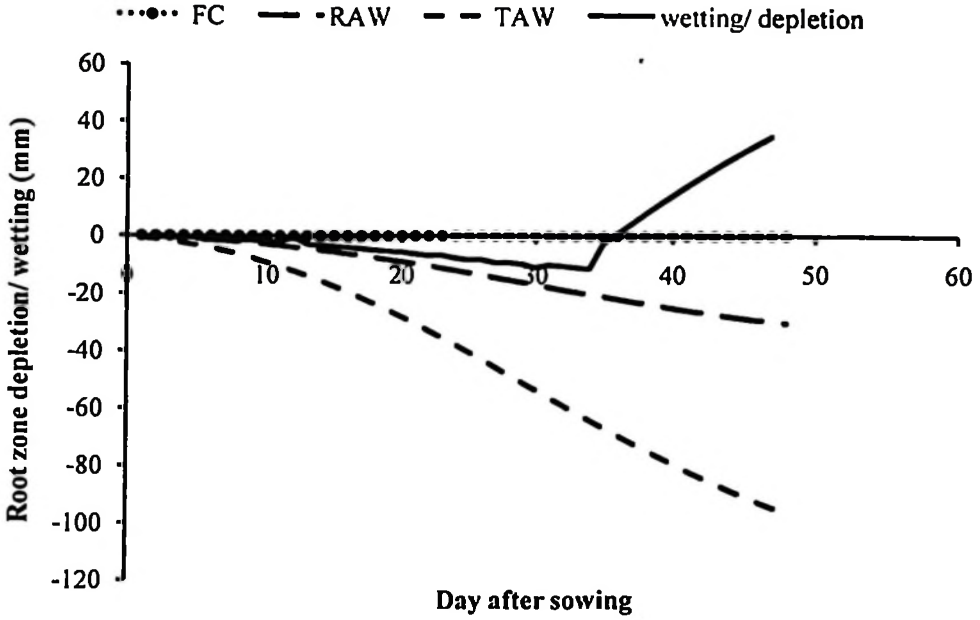


Figure 20: Soil moisture status under treatment 6b

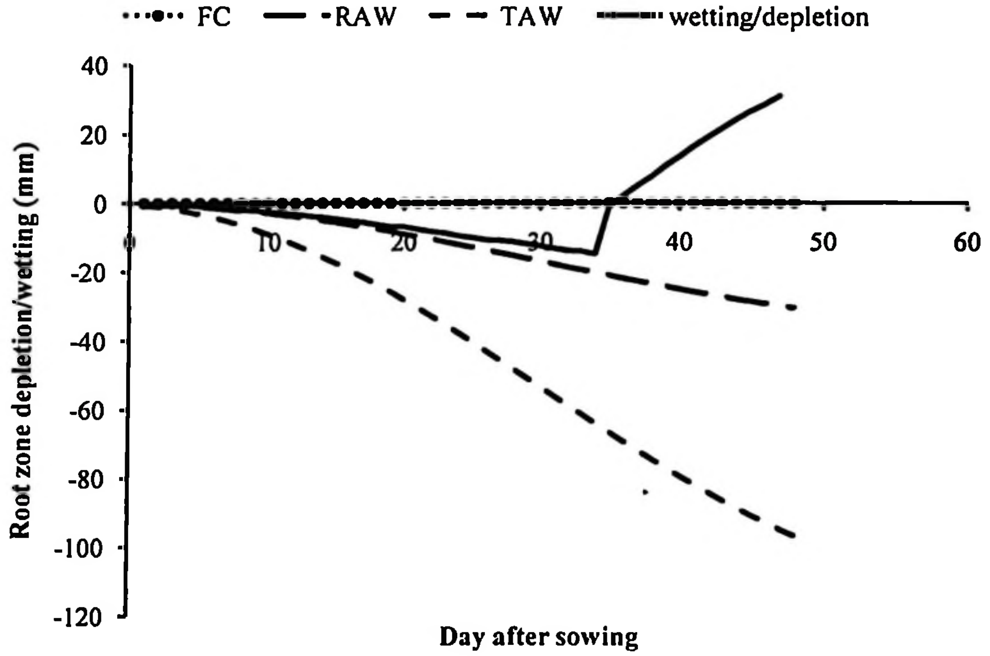


Figure 21: Soil moisture status under treatment 8b

4.7 Soil Water Balance

4.7.1 Actual evapotranspiration

The available soil moisture was sufficient for crop consumption throughout the entire growth period without undue water stress. Since the crop evapotranspiraton is a function of the ground cover, AET increased with the plant density per pot and initial soil moisture. The mean daily AET amounted to 3 mm/day, 4 mm/day, 4.3mm/day, 2.54 mm/day, 3.26 mm/day and 3.44 mm/day for the respective treatments 4a, 6a, 8a, 4b, 6b and 8b, respectively.

4.7.2 Soil water storage in the root zone

The change in storage within the root zone was calculated by the difference of the soil moisture content within the root zone of the day before the day of measurement with the soil moisture content within the root zone during the day of the measurement. The mean daily change in soil water storage within the root zone in treatments 4a, 6a, 8a, 4b, 6b and 8b amounted to 2.83 mm, 2.76 mm, 2.48 mm, 0.05 mm, 2.74 and 2.47 mm respectively. Compared to the AET these amounts were low. This was because of the soil textural properties i.e. the soil texture was sandy clay loam (SCL) which has low water holding capacity i.e.150 $mm.m^{-1}$ (Savva and Franken, 2002). Besides, as the amount of the water applied through irrigation increased, the amount of water stored within the root zone decreased ($R^2 = 0.889$) and during the study, over-irrigation was observed in all the treatments consequently a lower soil water storage within the rooting depth was found.

The soil water uptake by the plant roots did not affect the amount of water stored within the root zone ($R^2= 0.291$), because the amount of the AET was too small compared to the other components (DP and IRR) of the water balance. Consequently the effect of that parameter was not observed (Fig. 22).

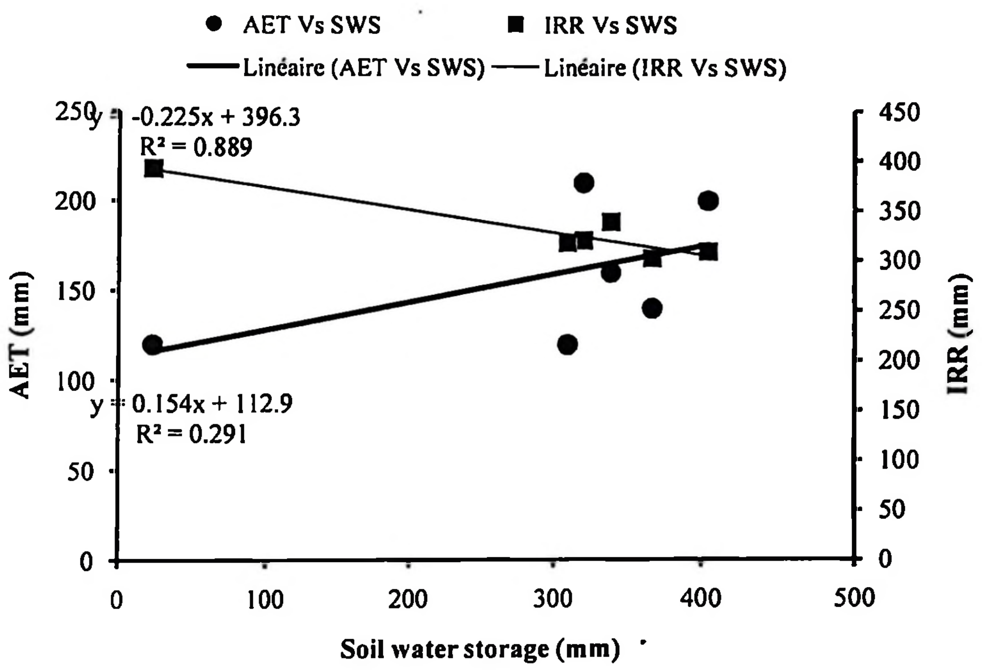


Figure 22: **Correlation between actual evapotranspiration, amount of irrigation water and the soil moisture variation**

4.7.3 Deep percolation

During the entire growth period the total amount of water loss through deep percolation was 115 mm, 26.4 mm, 26.5 mm, 184.4 mm, 102.5 mm and 186.6 mm for the 4a, 6a, 8a, 4b, 6b and 8b treatments respectively (Table 6). There was weak linear relationship between the water loss through deep percolation and the water applied, though the relationship is positive (Fig.24).Based on the ratio of the amount of water loss through deep percolation with the water input (water from irrigation only) the deep percolation was 32.5%, 6 %, 6.3 %, 50.03 %, 26.4 % and 32.5 % for the 4a, 6a, 8a, 4b, 6b and 8b treatments respectively. The water loss due to deep percolation was high because of over irrigation. This is in agreement with Stein (1998) who observed that higher water application rates under pitcher irrigation can cause an increase of water losses through deep percolation. Further, the soil at the study site was a sandy clay loam with an organic matter content of 2.5% - 3.2% and therefore had lower water holding capacity but higher drainage rate. The soil water content showed a weak correlation with the water loss through deep percolation ($R^2 = 0.22$) (Fig. 23).

Table 6: Mean values of DP, IRR, SWC and AET per treatment

Treatment	DP (mm)	IRR (mm)	SWC (mm)	AET (mm)	DP %
4a	115	302.3	693.78	144.13	32.5
6a	26.5	310.2	919.46	196.71	6.9
8a	26.4	320.2	919.46	206.82	6.3
4b	184.4	337.4	696.72	122	50.03
6b	102.5	338.8	835.88	156.72	26.4
8b	186.6	392	919.46	116.85	32.5

4.8 Comparison of the Water Supply with the Water Required

The irrigation water requirement calculations were based on irrigation efficiency of 90% as suggested by Karmeli *et al.* (1985) for sub surface drip irrigation system. Based on the 90% efficiency, the gross application depth was 24 mm for treatments 4a and 4b at an irrigation interval of 5 and 6 days respectively, while for the rest of the treatments, the gross application depth was 18 mm, at 4 days irrigation interval for the treatments 6a and 8a on other hand the irrigation interval is 5 days for 6b and 8b treatments (Fig. 25).

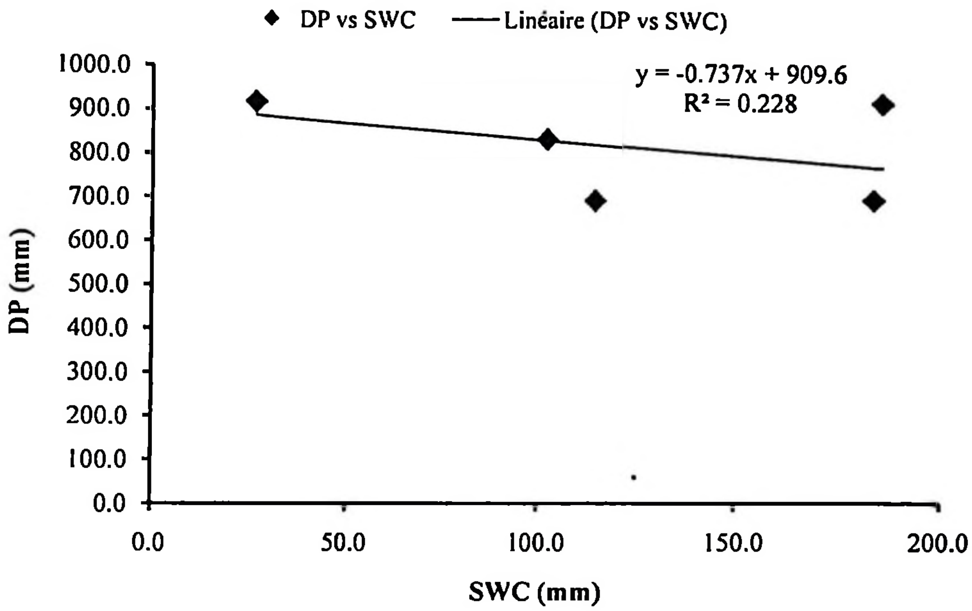


Figure 23: Correlation between the DP and SWC

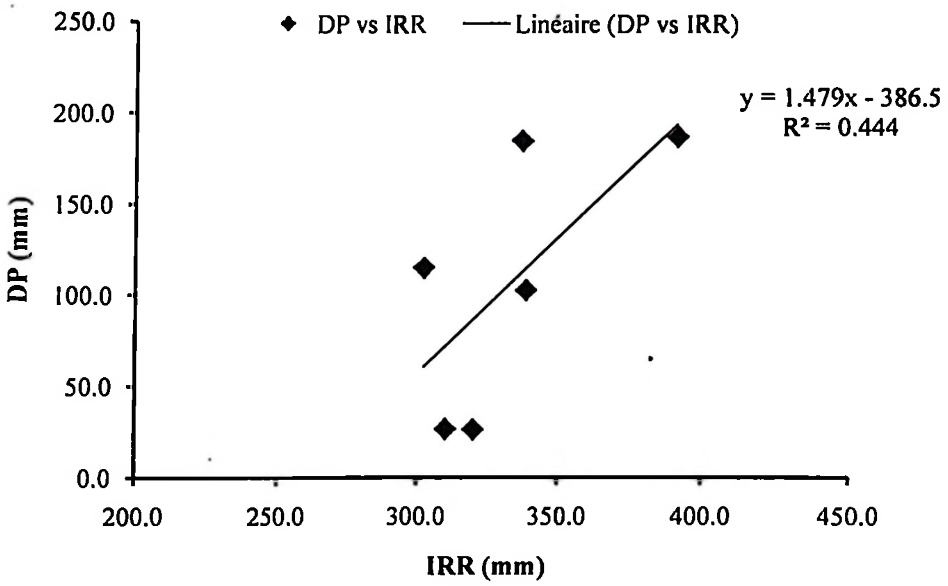


Figure 24: Correlation between the DP and IRR

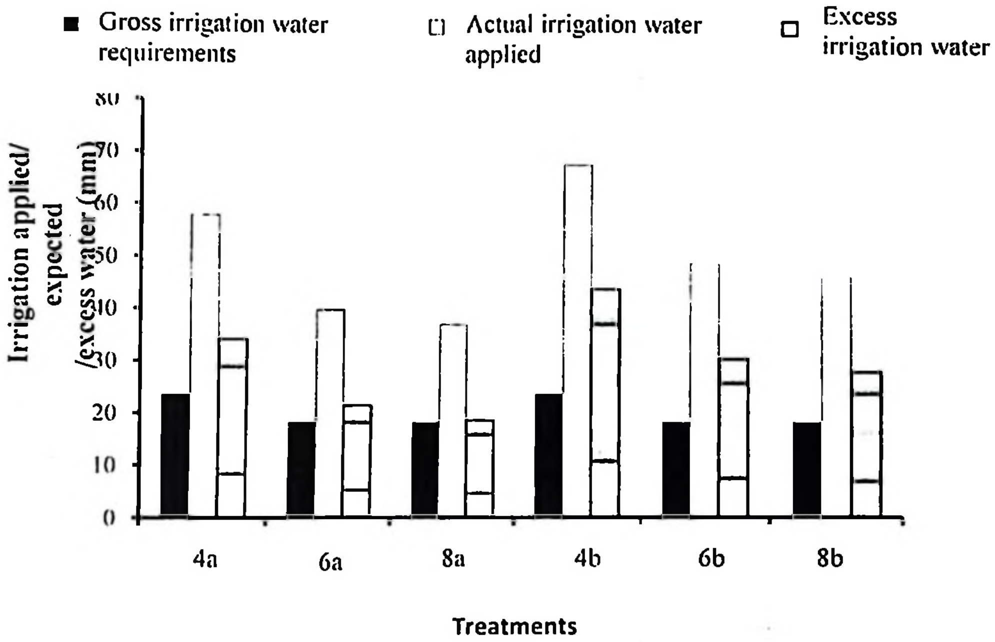


Figure 25: **Comparison of the irrigation requirement with the observed of irrigation applied**

The excess of the irrigation water applied increased with a decrease in initial soil moisture content, and decreased with an increase in the plant density, because the water loss increases as the water applied increases (Fig. 25). This is as a result of the positive relationship between the AET and the seepage rate, which indicates that, the seepage rate of the pots is control by the difference between the pressure head between the inner and the outer pot (Majed *et al.*, 2009; Stein, 1998).

4.9 Effect of the Water Supply on the Plant Growth

4.9.1 Leaf area index

The total leaf area index increased with plant density as well as with initial soil moisture content (Fig.26 and 27). There was a linear correlation between LAI and the mean AET (R^2 = 0.79) (Fig. 28). This was because the plants did not suffer from water stress thus the leaf expansion was mainly due to the characteristics of the plants (Usman *et al.*, 2010).

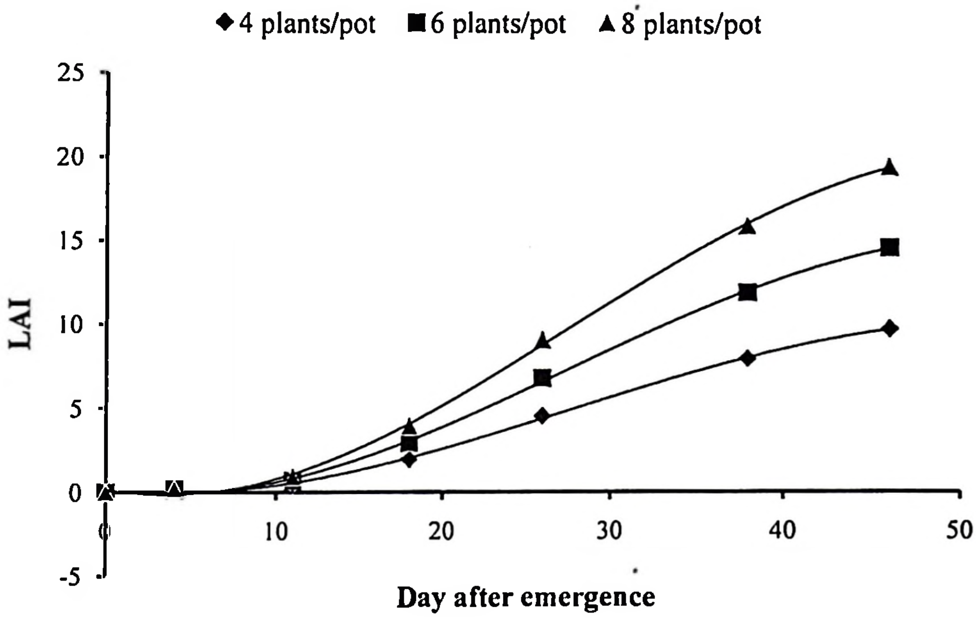


Figure 26: LAI for various treatments with initial soil moisture at 26 % (volume)

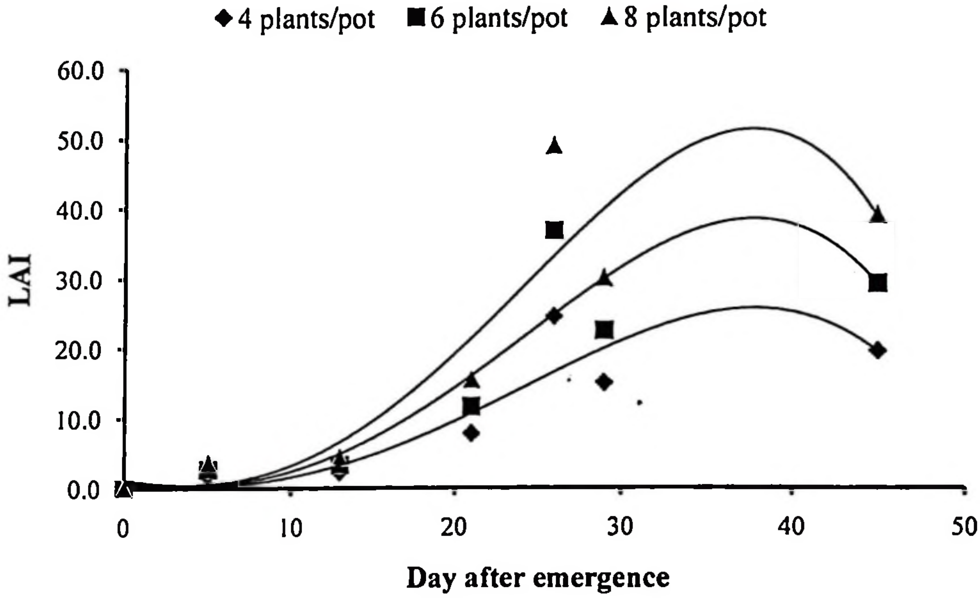


Figure 27: LAI for various treatments with initial soil moisture at FC

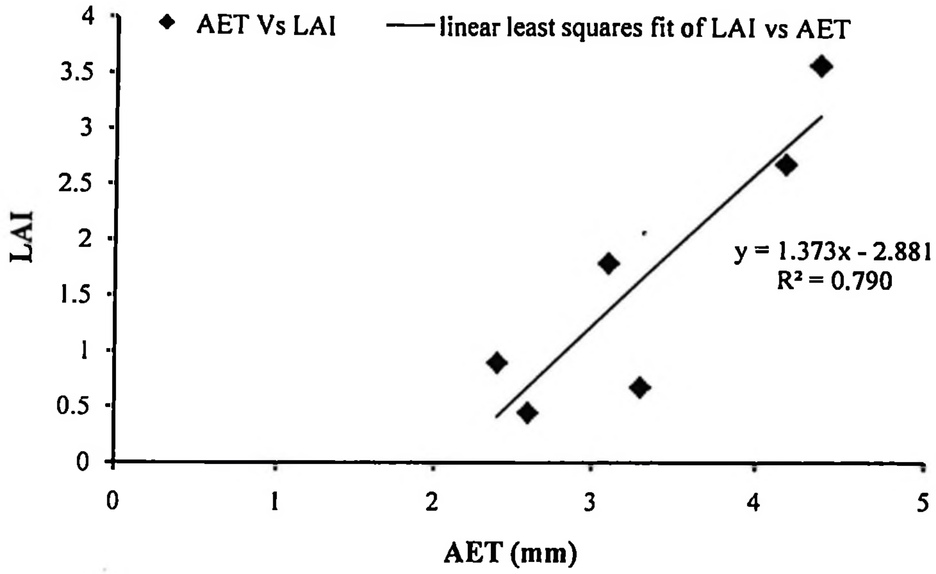


Figure 28: **Correlation between LAI and AET**

Table 7: **LAI pattern over time under various treatments**

Treatment	Equations	R^2
4a	$LAI = -6.10^{-7}t^4+0.028t^2 - 0.186t+0.172$	0.99
6a	$LAI = -4.10^{-7}t^4+0.021t^2-0.139t+0.129$	0.99
8a	$LAI = -3.10^{-7}t^4 + 0.014t^2-0.093t +0.086$	0.99
4b	$LAI = -6.10^{-5}t^4 + 0.002t^3 + 0.041t^2-0.393t +1.255$	0.82
6b	$LAI = -4.10^{-5}t^4+0.001t^3+0.031t^2-0.295t+0.941$	0.82
8b	$LAI = -3.10^{-5}t^4 +0.001t^3+0.021t^2-0.196t+0.627$	0.82

Compared to the study by Maghembe (1999), the values of total LAI found in this study were very high. This is because the plant densities which were used during the study were very high. Maghembe (1999) had used 333333 plants ha^{-1}.On the other hand, the lowest plant density used in the present study was 565810 plants.ha^{-1}(observed in 4 plants/pot) Budi *et al.* (2006) and Tsegay (2009) suggested that the planting density around each pot is 4 plants/pot, for a pot of 2 L capacity.

The comparison was done under two stages of development i.e. first day of flowering (R1) and days to 50% flowering (R4) and the data were taken from a non-water stressed condition (Table 8).

Table 8: LAI comparison

Development stage	days	LAI		
		(Maghembe., 1999)	observed	
			Main plot a	Main plot b
R1	31	14.8	43.771	31.209
R4	46	20	99.181	70.284
R1	31	10.8	31.854	23.182
R4	46	15	72.279	52.207
R1	31	7.2	21.885	21.877
R4	46	10	50.76	52.522

4.9.2 Plant height

Plants from treatments 4a, 6a, and 8a had the same height and were higher than those from treatments 4b, 6b and 8b. This could be attributed to the difference in the dates of emergence which were 18th and 26th of November respectively i.e. 10 days and 19 days after sowing. The difference in the days to emergence was a result of the difference in the initial soil moisture content in the main plots i.e. main plot a and main plot b (Fig. 29).

The beans in this study were shorter than those reported by Maghembe (1999) i.e. after 31 and 32 days after sowing under stress and under well irrigated conditions respectively. This suggests that the plants in this study were highly stressed of nutrients, light and space as a result of higher plant density per pot, compared to those studied by Maghembe (1999). This could have affected plant growth by reducing cell turgor (Theodore, 1973).

4.10 Irrigation Performance

4.10.1 Irrigation uniformity

The seepage rate (through the wall of the clay pot) was significantly different at 5% level among the pots with a mean UCW of 67.7%. According to Pitts (1997), a coefficient of uniformity of 67.7 %, is rated as poor. The lack of uniformity in materials and production of the pots as discussed in Section 4.4.1 also cannot be ruled out.

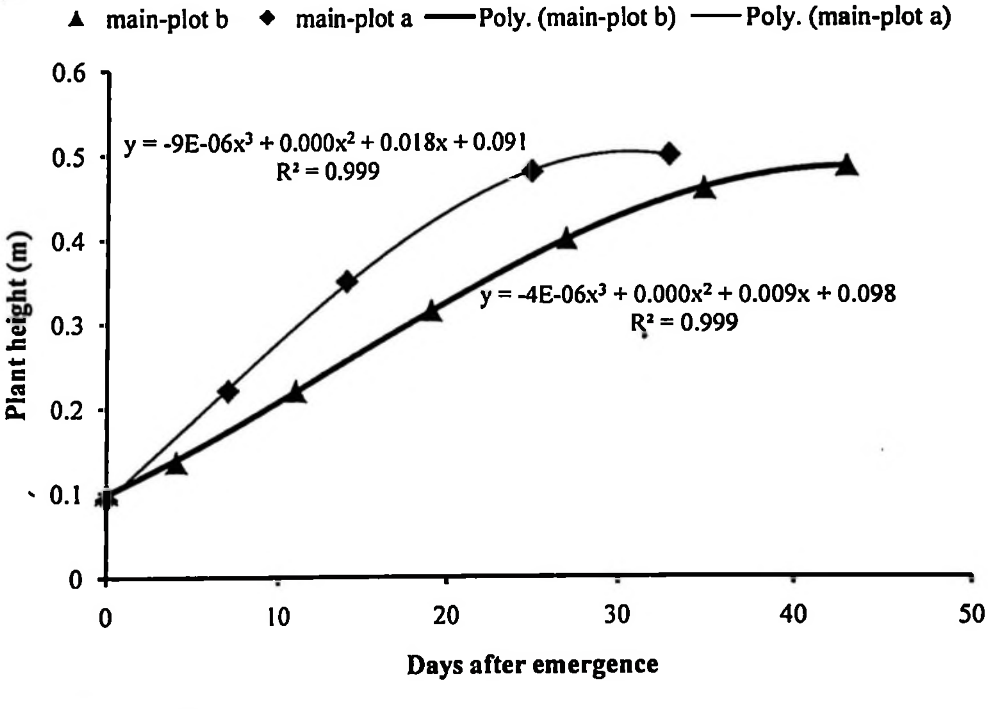


Figure 29: Plant height trend in the main plot a and main plot b

Table 9: Irrigation uniformity under different treatments

Treatment	(IRR)† *l*	SD (*l*)	CV (%)	UCW (%)	Rating (Pitts1997*)
6a	526.06a	132.96	25.27	74.73	fair
4b	482a	176.56	36.63	63.37	poor
6b	476.66a	180.84	37.94	62.06	poor
8b	429.81a	51.35	11.95	88.05	good
4a	425.76a	43.32	10.17	89.83	good
8a	320.97a	193.22	60.20	39.80	poor
lsd	*255.14*				

*Source: Oswald (2002)

†The numbers followed by the same letter are not statistically different at 5 % level of Significance

4.10.2 Application efficiency and irrigation adequacy

The Application efficiency and relative water supply were calculated from the water balance component i.e. the ratio between the water input and the water output and the water output and the water input for the RWS and Ea respectively, in which the water input comprised IRR. On the other hand the water output included the AET, DP. The soil is a reservoir of water for the plant implying that it contributes into the water balance either as input of water or as an output. If the IRR replenishes the soil water loss (i.e. $\Delta SW = SWC_i{*}RD_i - SWC_{i-1}{*}RD_{i-1} > 0$), then, the amount of water for replenishment is considered as an output. In the opposite case the soil water contributes into the water balance as an input when there is a decrease of the soil water during the growth period of the crop the decrease can be due to either deep percolation, or crop evapotransiration or both. For these cases, the soil water content decreases (i.e. $\Delta SW = SWC_i{*}RD_i - SWC_{i-1}{*}RD_{i-1} < 0$).

Table 10: **Water balance components, application efficiency and irrigation adequacy under different treatments**

Treatment	AET (mm)	IRR (mm)	DP (mm)	ΔSW* (mm)	ETc (mm)	RWS	E_a
4a	144.1	302.3	157.1	34.3	144.4	0.9	0.5
6a	196.7	309.0	120.7	45.4	196.7	0.9	0.6
8a	206.8	320.2	26.7	45.4	206.8	1.1	0.6
4b	122.0	318.0	165.6	-0.2	122.0	1.1	0.4
6b	156.7	338.9	102.0	41.3	156.7	1.1	0.5
8b	116.7	392.0	186.6	45.4	165.7	1.0	0.4

*($\Delta SW = SWC_i * RD_i - SWC_{i-1} * RD_{i-1} = IRR_i - DP_i - AET_i + \Delta RDi * SWC_{oi-1}$)

For all the treatments the water supply was adequate i.e. 1<RWS<1.15 (Rowshon *et al.*, 2006) except for treatments 6a and 4a where there was a deficit of water supply through irrigation which resulted in a high water application efficiency for the same treatment (E_a = 0.6). Besides in all the treatments, the field applied water was not efficient (E_a< 1) because the water loss through deep percolation was higher than that expected i.e., around 10 % of the water applied (based on the standard Ea = 90 % for sub surface irrigation). This may be attributed to the over irrigation (Stein, 1998) and soil water holding capacity. The over irrigation was caused by the irrigation scheduling which was based on the seepage rate of the pot. The seepage rate of the pots was resulting in a high water application and high irrigation frequency hence the over irrigation.

4.11 Water Productivity

The stem biomass ratio, the leaves biomass ratio, the harvest index (HI), total biomass and yield per unit area were not significantly different among the treatments

($P < 0.05$). This may be attributed to the difference in plant density. At lower plant density treatment, plants grow vigorously resulting in the increase of stem girth, plant height, leaf number and leaf surface area per plant. While under higher plant density, stem girth, plant height, leaf number and leaf surface area per plant are much reduced because of inter-plant competition for water, space, light, moisture and nutrients (Kolawole and Sarah, 2009).IWUE was not significantly different among the treatments, because the amaranth is drought tolerant plant. The plants express various responses and develop a wide diversity of drought tolerance mechanisms from both morphological and physiological aspects (Blum, 1996).

The physiological basis of drought resistance in amaranths genotypes have previously been reported by Liu and Stützel (2002a, b), who showed that vegetable amaranth exhibits a high capacity of osmotic adjustment (1.08–1.24MPa), which ensures that the plants continue to function in severe drought conditions (Liu and Stützel, 2002a). Besides, the difference among the initial soil moisture content and water applied for each treatment were not significantly different as such the biomass production among the treatments and thus the IWUE was not significantly different (Table 11).

Table 11: Summary of the yield performance of amaranths and under different treatments

Treatment	Total biomass (kg)*	HI (kg)*	Yield (kg/ha)*	IRR (mm) *	IWUE (kg/ha/ mm)*	Root (g)*	Leaf (g)*	Stem (g)*
16a	0.145a	0.7b	2047.1c	8.1d	2673e	7f	12g	12h
24a	0.13a	0.78b	1852.6c	9.17d	2046e	8.8f	12g	12h
32a	0.145a	0.75b	2055.1c	6.41d	3225e	10.5f	12g	12h
16b	0.133a	0.78b	1876.7c	7.07d	2707e	6.4f	7g	7.6h
24b	0.11a	0.77b	1607.7c	8.21d	2017e	3.9f	8.57g	9.3h
32b	0.1a	0.73b	1535.9c	9.05d	1746e	6f	12.1g	13.2h
Lsd	*0.084*	*0.1*	*1199.2*	*2.46*	*1960.3*	*10*	*37.36*	*40.55*

*the numbers followed by the same letter are not statistically different at 5% level of significance

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

i. The results obtained showed clearly, that the clay pot which is available in Morogoro can be used as an irrigation device. It has a field application efficiency ranging from 40% to 60%.However this is lower than the standard field application efficiency for subsurface irrigation which is 90%.

ii. The pots used in this study had a high seepage rate (0.68 l/day) leading to over irrigation and high water losses through deep percolation. This resulted into low field application efficiency.

iii. To reduce the refilling frequency of the pots during the plant growth period a pot of a larger sized should be used.

iv. The study on beans showed that the initial soil moisture content as well as the plant density did not affect the amount of water applied. No significance differences at the 5%level were found in the water applied.

v. The water productivity in all the treatments in this study was not significantly different under different treatments at the 5% level.

vi. 16 plants /pot was the best suited plant density for amaranths and initial soil moisture content of 26 % (vol.) was the best for saving water.

vii. Results showed that the amaranths' biomass and the water applied were19227.3 kg/ha and8mm/day respectively for all treatments.

5.2 Recommendations

The following recommendations can be drawn:

i. There is a need for a research to find out how to improve the rate and uniformity of seepage from the clay pots.

ii. To avoid any plant stress caused by the plant competition for space, nutrients and light, using the recommended plant density for each plant is advisable and further study should focus on the pots layout.

iii. To avoid over irrigation the standard method for irrigation scheduling in subsurface irrigation could be a better option to help reduce the water loss through deep percolation thus improving the application efficiency

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APPENDICES

Appendix 1: Data climatic, Kc and Kp adjustment

a Kpadjustement

Item	November	December
RH mean	50.27	50.73
Wind speed (m/day)	137.8	118.9
Wind speed (m/s)	9.9E-07	8.5E-07
Kp	0.65	0.65

b Kc value for plant beans (Allen *et al.*, 1998)

There was no Kc adjustment because:

(i) The plants were frequently irrigated and soil was almost constantly wet, so K_{cini} did not need any adjustment.

(ii) The RH mean was 50% and the wind speed was near zero m/s so the K_{cmid} had not to be changed

(iii) By using the equation proposed by Allen et al. (1998) the indicated Kc end should adjusted as follows:

$$K_{c\,end} = K_{c\,end(tab)} + [0.04 \times (U_2 - 2) \times 0.004(RH_{min} - 45)] \times \left(\frac{h}{3}\right)^{0.3}$$

Where:

K_{cend} = adjusted Kc end value

$K_{cend(tab)}$ = tabulated Kc end

U_2 = wind speed at 2mhigh above the ground (m.s-1)

RH_{min} = minimum relative humidity (%)

h = plant height (m)

$$K_{cend} = 0.35 + [0.04(9.9 \times 10^{-7} - 2)] \times 0.004(50. - 45)\left(\frac{0.5}{3}\right)^{0.3} = 0.349$$

	Value
Kcini	0.4
Kc mid	1.15
Kc end	0.35

Appendix 2: Calibration analysis

2.1 Resistance blocks

Soil oven dry weight: 686.6 g

Table a: Mean value of resistance block at different soil temperature and their corresponding soil moisture content (weight %)

Soil moisture content % (weight)	Resistance block reading at different temperature		
	30 °C	28 °C	24 °C
29.93	138.4	74.39	71.44
28.75	87.00	80	62.66
28.43	83.95	76.50	59.33
26.77	69.33	65.65	58.33
25.14	60.79	56.90	49.12
24.73	58.66	54.73	46.92
24.66	56.33	53.08	46.62
23.55	53.00	49.36	42.13
22.74	43.66	42.87	41.33
22.60	40.49	38.20	33.66
21.77	35.95	35.74	35.33
21.02	34.64	33.98	32.66
19.31	31.38	30	27.21
18.73	29.28	28	25.44
18.19	26.40	22.33	23.85
18.15	26.17	20.66	23.73
18.12	26.01	16	16.00
16.85	19.26	15.66	15.66
16.05	15	11.64	8.00
15.83	14	11.17	5.5

Table b: **Normalized value of the resistance block reading and the regression analysis**

Y	Bk	T
0.39	83.95	30
0.42	69.33	30
0.19	60.79	30
0.24	58.66	30
0.25	56.33	30
0.21	53.00	30
0.26	43.66	30
0.06	40.49	30
0.20	35.95	30
0.02	34.64	30
0.06	31.38	30
0.15	29.28	30
0.15	26.40	30
0.28	76.50	28
0.29	65.65	28
0.13	56.90	28
0.16	54.73	28
0.17	53.08	28
0.14	49.36	28
0.17	42.87	28
0.04	38.20	28
0.13	35.74	28
0.01	33.98	28
0.04	30	28
0.10	28	28
0.10	22.33	28

Regression analysis for the normalized resistance blocks

Regression equation

Y= -0.79+0.02(T)+0.004(Bk)

R^2 = 0.664
adjR^2= 0.63
PRE R^2= 0.577

ANOVA

Source	SS	Df	MS	F	P
Regression	0.18		0.09	22.75	0
T	0.026	1	0.026	6.61	0.17
Bk	0.15	1	0.15	38.89	0
Error	0.09	23	0.004		0
Total	0.276	25			

Table statistics for the regression analysis

Column	Coefficient	Sdt error	t (coef =0)	p	CL (+/-95%)
Intercept	-0.79	0.36	-2.18	0.032	0.74
T	0.025	0.01	2.01	0.0556ns	0.025
Bk	0.004	7.8E-4	6.23	0	0.0016

Df of two tailed t test =23

if p=<0.05 then the coefficient is significantly different from 0

2.2 Tensiometers calibration

Table D: data summary for the calibration analysis of the tensiometers

Soil oven dry weight: 686.6 g

Total weight	Equipment Weight	Soil weight g	Soil water depletion G	Soil water depletion %	Tensiom reading kPa	Soil m content %
1345.8	459.6				9	
1351.7	459.6	892.1	8.1	8.910891	9	29.93009
1343.6	459.6	884	8.1	8.910891	9.5	28.75036
1341.4	459.6	881.8	2.2	2.420242	11	28.42994
1330	459.6	870.4	11.4	12.54125	16	26.76959
1318.8	459.6	859.2	11.2	12.32123	16	25.13836
1316	459.6	856.4	2.8	3.080308	17	24.73056
1315.5	459.6	855.9	0.5	0.550055	19	24.65773
1307.9	459.6	848.3	7.6	8.360836	26	23.55083
1302.3	459.6	842.7	5.6	6.160616	30	22.73522
1301.4	459.6	841.8	0.9	0.990099	31	22.60414
1295.7	459.6	836.1	5.7	6.270627	36	21.77396
1290.5	459.6	830.9	5.2	5.720572	43	21.0166
1278.8	459.6	819.2	11.7	12.87129	45	19.31255
1274.8	459.6	815.2	4	4.40044	50	18.72997
1271.1	459.6	811.5	3.7	4.070407	63	18.19109
1270.8	459.6	811.2	0.3	0.330033	65	18.14739
1270.6	459.6	811	0.2	0.220022	74	18.11826
1261.9	459.6	802.3	8.7	9.570957	78	16.85115
1256.4	459.6	796.8	5.5	6.050605	79	16.0501
1254.9	459.6	795.3	1.5	1.650165	80	15.83163

Regression analysis

regression equation

$y = 29.35 \times e^{(-0.0076)} \times x$

$R^2=0.94$

ANOVA

Source	SS	Df	MS	F	P
Regression	0.71	1	0.71	328.47	0
X	0.71	1	0.71	328.47	0
Error	0.039	18	0.002		
Total	0.75	19			

Table C:of statistics for the Regression Coefficients

Column	Coef	Sdt Error	t (Coef=0)	P	CL (+/-95%)
Intercept	3.37	0.019	171.17	0	0.004
X	-0.0076	4.20E-04	-18.12	0	8.80E-04

degree of freedom for two-tailed t tests = 18

if p=< 0.05, the coefficient is significantly different from 0

Appendix 3: LAI and ground cover

a LAI and GC in main plot a (soil moisture starting at field capacity)

Leaf number

		Leaf number		
Date	DAS	4 plants/pot	6 plants/pot	8 plants/pot
15-Nov	0	8	12	16
19-Nov	4	20	30	40
26-Nov	11	32	48	64
3-Dec	18	92	138	184
10-Dec	26	144	216	288
17-Dec	38	240	360	480
24-Dec	46	216	324	432

LA, LAI and GC (%)

	LA			LAI		
Date	4 plants	6 plants	8 plants	4 plants	6 plants	8 plants
15-Nov	16.6	24.9	33.2	0.0	0.0	0.0
19-Nov	1275.2	1912.8	2550.4	1.8	2.7	3.6
26-Nov	1568.9	2353.3	3137.7	2.2	3.3	4.4
3-Dec	5476.4	8214.6	10952.8	7.8	11.6	15.5
10-Dec	10579.6	15869.5	21159.3	15.0	22.5	29.9
17-Dec	17284.1	25926.2	34568.3	24.5	36.7	48.9
24-Dec	13735.8	20603.7	27471.6	19.4	29.2	38.9

	GC		
DAS	4 plants	6 plants	8 plants
0	6.7	7.0	7.2
5	47.3	70.4	95.8
13	57.7	87.6	100.0
21	Xxx	100.0	xxx
29	Xxx	xxx	xxx
26	Xxx	xxx	xxx
45	Xxx	xxx	xxx

b LAI and GC in main plot b (soil moisture content at 26 % (volume))

Leaf number

	Leaf number		
Date	4 plants/pot	6 plants/pot	8 plants/pot
12-Nov	8	12	16
26-Nov	16	24	32
3-Dec	56	84	112
10-Dec	92	138	184
17-Dec	128	192	256

LA, LAI and GC (%)

	LA			LAI		
Date	4 plants/pot	6 plants/pot	8 plants/pot	4 plants/pot	6 plants/pot	8 plants/pot
12-Nov	78.4	117.6	156.8	0.1	0.2	0.2
26-Nov	320.4	480.6	640.8	0.5	0.7	0.9
3-Dec	1381.9	2072.8	2763.8	2.0	2.9	3.9
10-Dec	3203.9	4805.8	6407.7	4.5	6.8	9.1
17-Dec	5610.7	8416.1	11221.5	7.9	11.9	15.9
24-Dec	6859.4	10289.0	13718.7	9.7	14.6	19.4

	GC		
Date	4 plants/pot	6 plants/pot	8 plants/pot
12-Nov	5.5	6.7	7.9
26-Nov	16.1	21.2	26.4
3-Dec	52.3	68.3	73.8
10-Dec	90.5	100	100
17-Dec	Xx	xx	xx
24-Dec	Xx	xx	xx

Appendix 4: Root growth parameters and plant height

a Root growth

Table a: Data Maghembe (1999)

	Root length (cm)		
Day	Wet	Day	Dry
32	35	32	34
46	42	46	42
61	52	64	54

Mean RDm = 52 cm and mean tm = 64 days

Table b: Data obtained from the previous observation

Days	Observed rooting depth			Mean
12	4	8	6	6
35	28	31	33	30.7
48	43.5	44	44.5	45

Table C: Simulated trend of root growth (Pahigrani and Sudhindra, 2002)

Date	Days	Rooting depth (cm)
7-Nov	1	0.3
8-Nov	2	0.5
9-Nov	3	0.8
10-Nov	4	1.1
11-Nov	5	1.5
12-Nov	6	1.9
13-Nov	7	2.4
14-Nov	8	2.9
15-Nov	9	3.5
16-Nov	10	4.2
17-Nov	11	4.9

Table C **continued**

Date	Days	Rooting depth (cm)
19-Nov	13	6.4
20-Nov	14	7.2
21-Nov	15	8.1
22-Nov	16	9.0
23-Nov	17	10.0
24-Nov	18	10.9
25-Nov	19	12.0
26-Nov	20	13.0
27-Nov	21	14.1
28-Nov	22	15.2
29-Nov	23	16.3
30-Nov	24	17.5
1-Dec	25	18.7
2-Dec	26	19.8
3-Dec	27	21.0
4-Dec	28	22.3
5-Dec	29	23.5
6-Dec	30	24.7
7-Dec	31	25.9
8-Dec	32	27.2
9-Dec	33	28.4
10-Dec	34	29.6
11-Dec	35	30.8
12-Dec	36	32.0
13-Dec	37	33.2
14-Dec	38	34.4
15-Dec	39	35.6
16-Dec	40	36.7
17-Dec	41	37.8
18-Dec	42	38.9
19-Dec	43	39.9
20-Dec	44	41.0
21-Dec	45	42.0
22-Dec	46	42.9
23-Dec	47	43.8
24-Dec	48	44.7

Table D: **Plant height**

Main plot b		Main plot a	
Days after emergence	Plant height (m)	Days after emergence	Plant height (m)
0	0.1	0	
4	0.14	7	0.1
11	0.2	14	0.2
19	0.31	25	0.35
27	0.4	33	0.5
35	0.5	41	0.5
43	0.5		

Appendix 5: ANOVA
IRR

ANOVA

Source of variance	DF	SS	MS	V.R	F.
Sub-plot	2	22.95	11.47	1.18	0.3
Main plot	1	3.16	3.16	0.33	0.5
Sub-plot*main-plot	2	9.2	4.6	0.47	0.63
Residual	12	9.7	9.72		
Total	17	151.9			

Grand mean: 9.64 mm

Total IRR

Source of variation	DF	SS	MS	F	P
Main effects					
Treatments	5	74744.5	14948.9	0.72	0.61
Error	12	246824.1	20.56.64		
Total	17	321568.6			

Grand mean: 443.54 mm

Irrigation frequency

Source of variation	DF	SS	MS	F	P
Sub-plot	2	8.5E-4	4.2E-4	0.49	0.61
Main-plot	1	0.019	0.019	23.09	0.0004***
Sub-plot*main-plot	2	8.5E-4	4.2E-4	0.49	0.618
Error	12	0.01	8.5E-4		
Total	17	0.03			

Lsd: 0.52 /day

Plant/pot	4	6	8
A	1.31	1.31	1.31
B	1.23	1.24	1.26

Amaranths performance

Stem biomass

SOV	DF	SS	MS	F	P
Sub-plot	2	0.01	0.0064	1.81	0.205
Main-plot	1	2.3	2.3E-5	0.006	0.9
Sub-plot*main plot	2	0.003	0.0019	0.54	0.54
Error	12	0.004			
Total	17	0.059			

Root biomass

SOV	DF	SS	MS	F	P
Sub-plot	2	0.013	0.0067	1.19	0.33
Main-plot	1	5.60E-04	5.6E-6	9.9E-4	9.7E-1
Sub-plot*main-plot	2	0.0016	8.2E-4	0.14	0.86
Error	12	0.068	0.005		
Total	17	0.08			

Leaves biomass

SOV	DF	SS	MS	F	P
Sub-plot	2	0.005	0.002	0.66	0.53
Main-plot	1	6.E-6	6E-6	0.0001	0.9
Sub-plot*main-plot	2	0.01	0.005	1.23	0.32
Error	12	0.04	0.004		
Total	17	0.065			

HI

SOV	SS	MS	F	P
Sub-plot	2	0.01	0.006	0.33
Main-plot	1	5.6E-6	5.6E-6	0.9
Sub-plot*main plot	2	0.001	8.2E-4	0.81
Error	12	0.06	0.005	
Total	17	0.08		

Total biomass

SOV	DF	SS	MS	F	P
Sub-plot	2	1797.2	898.6	0.39	0.68
Main-plot	1	347.6	347.6	0.15	0.7
Sub-plot*main plot	2	896.9	448.4	0.19	0.8
Error	12	27567	2296.9		
Total	17	30605.6			

Yield per unit area

SOV	DF	SS	MS	F	P
Sub-plot	2	36036632.8	18018316	0.39	0.68
Main-plot	1	6969875.7	6969876	1.5	0.7
Sub-plot*main-plot	2	17984585.5	8992293	1.9	0.82
Error	12	552690345	46057529		
Total	17	613681439			

IWUE

SOV	DF	SS	MS	F	P
Sub-plot	2	0.014	0.0073	0.61	0.5
Main-plot	1	0.004	0.0041	0.34	0.5
Sub-plot*main-plot	2	0.001	0.008	0.72	0.5
Error	12	0.14	0.0012		
Total	17				

SPE