EVALUATION OF WATER USE EFFICIENCY IN UPLAND RICE (Oryza sativa L.) UNDER DEFICIT IRRIGATION

BY

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DECLARATION

I, Mbita Nakapite, hereby declare that all the work presented in this dissertation is my own and has not previously been submitted for a degree at this or any other university.

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APPROVAL

This dissertation of Mbita Nakapite is approved as fulfilling part of the requirements for the award of Master of Science degree in Integrated Soil Fertility Management (ISFM) from the University of Zambia.

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DEDICATION

I dedicate my degree to my two children, Kalima and Nataizya, for the time I spend away from them in pursuit of my career. I also owe a big thank you to my husband and my father for their whole-hearted support and encouragement in all my endeavours.

ABSTRACT

In the light of increasing pressure on limited fresh water resources, the growing world population and increasing greenhouse gas emission, maximizing crop water use becomes an important topic. Considerable research is being done on deficit irrigation. However, there is limited published work elaborating the water use efficiency of upland rice grown under deficit irrigation in Sub-Saharan Africa (SSA). In this study, the growth of upland rice (*Oryza sativa* L.) was evaluated under deficit irrigation in the greenhouse at the University of Zambia. The aim of the study was to evaluate the effect of deficit irrigation on the growth and water use of upland rice. The study was arranged as a Randomized Complete Block Design (RCBD) with four levels of irrigation water regimes in four replications. NERICA 4 rice, a recommended upland variety grown in Zambia, was used in this study. The irrigation water regimes based on irrigation intervals were: one day (I_1), two days (I_2), three days (I_3), and four days (I_4). The irrigation treatments were exerted at the start of the reproductive stage till harvest. Observations made on growth parameters were namely: tiller number, plant height, the number of panicles, aboveground biomass, 1000 grain weight, grain yield, and harvest index (HI). Other parameters included crop consumptive water use (ET_c), crop coefficient (K_c), crop response factor (K_y) and water use efficiency (WUE). Irrigation interval significantly affected ($p<0.001$) plant height, panicle length, aboveground biomass, grain yield, 1000 grain weight and harvest index (HI). These parameters increased with increased frequency of water application. I_4 had the lowest actual seasonal consumptive water use (ET_a) of 750.1 mm while I_1 and I_2 were not significantly different with 967.3 mm and 997.1 mm, respectively. The potential maximum yield (Y_m) was estimated as the sum of the average and the standard deviation of grain yield in the control (I_1) treatment. Yield reduction from Y_m ranged from 7.1% for I_1 to 81.7% for I_4 while evapotranspiration deficit ranged from 3.66% for I_2 to 28.68% for I_4. Treatment I_2 had a smaller relative ET reduction (3.66%) than I_1 (10.14%) but bigger relative yield reduction (41.0% and 7.1%, respectively), even though their seasonal ET were not significantly different ($P>0.05$). At reproductive stage, the average ET_c value for I_1 was significantly ($P<0.001$) higher than the one for I_2 by 51.8 mm. This lower consumptive water use accounted for the higher yield reduction under treatment I_2 as rice is highly sensitive to moisture stress at reproductive stage. Irrigation intervals also had highly significant ($P<0.001$) effect on ET_c and K_c at both reproductive and maturity stages. Both ET_c and K_c reduced with an increase in the irrigation interval from 341.8mm to 170.8mm and from 2.63 to 1.32, respectively, during the reproductive stage. The average ET_c values at maturity stage were 316.4 mm, 374.1 mm, 320.3 mm and 268.0 mm while K_c values were 1.94, 2.30, 1.97 and 1.64 in order of widening irrigation interval. In conclusion, under the conditions of this study, both biomass and grain WUE will increase with increase in irrigation interval and depth of water applied. The results of this study did not show an optimum WUE.

Key words: NERICA, Evapotranspiration, Water balance, Yield reduction, Evapotranspiration deficit, Water stress.

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ACRONYMS OF ABBREVIATIONS

ABA	Abscisic Acid
ANOVA	Analysis of Variance
CV	Coefficient of Variation
^{o}C	Degrees Celcius
Ca_2	Calcium
$CaCo_3$	Calcium Carbonate
CO_2	Carbon Dioxide
^{o}E	Degrees East
ETa	Actual Evapotranspiration
ETc	Crop Evapotranspiration (Crop Water Requirement)
ETm	Maximum Evapotranspiration
ETo	Reference Evapotranspiration
FAO	Food and Agricultural Organisation
Fe	Iron
H_2O	Water
HI	Harvest Index
I	Irrigation
LSD	Least Significant Difference
M	Molar
Mg	Magnesium
N	Nitrogen
Na	Sodium

K	Potassium
Kc	Crop Coefficient
Ky	Yield response factor
MPa	Megapascal
MT	Metric Ton
NERICA	New Rice for Africa
P	Phosphorus
pH	Soil Reaction
PI	Panicle Initiation
Q	Discharge
RCBD	Randomised Complete Block Design
^{o} S	Degrees South
ΔS	Change in storage
S	Sulphur
SADC	Southern African Development Community
T	Temperature
USDA	United States Department of Agriculture
WARDA	West Africa Rice Development Association
WUE_b	Biomass Water Use Efficiency
WUE_g	Grain Water Use Efficiency
Y	Total Grain Yield
Ya	Actual Yield
Ym	Maximum Yield
ZARI	Zambia Agricultural Research Institute

CHAPTER ONE: INTRODUCTION

1.1. Background

The growing world population is accompanied by a steady increase in the demand for rice (*Oryza sativa* L.). It is a staple food for over half the world's population, and rice has the second largest cereal production after maize with over 745 million tonnes recorded in 2013 (FAO Stat, 2015). In sub-Saharan Africa, rice is the fourth most important cereal after sorghum, maize, and millet with respect to production (Rodenburg *et al*., 2006). The United Nations General Assembly recognized the growing importance of rice when it declared the Year 2004 as the “International Year of Rice (IYR),” under the theme “Rice is Life.” Most countries in Africa are unable to produce enough rice to meet national demand (Norman and Kebe, 2006). According to Nozaka (2015), for example, Zambia is unable to attain self-sufficiency in rice production for more than half a decade.

This scenario is not peculiar to Zambia, consumption of rice in sub-Saharan Africa continues to outpace production. This imbalance has economic implications because rice is steadily becoming a staple food in the African diet (Kueneman, 2006). Thus much needed foreign currency is lost to meet importation of huge quantities of rice into the continent. Rice import costs for central and southern Africa are estimated at US$30 989 million, against exports worth US$ 785 million (Norman and Kebe, 2006). Zambia’s ever increasing annual rice deficit was estimated at 15,500 MT (Nozaka, 2015).

1.2. Aerobic Rice Systems

As stated above, water for rice production is diminishing while the world population and demand for rice continue to increase steadily. This mismatch necessitates the development of irrigated rice systems that require less water than traditionally flooded rice ecosystems (Bouman *at el.,* 2005). The development of aerobic rice systems, i.e. growing rice under non-flooded and non-saturated soil conditions using supplemental irrigation is in its infancy. Thus, more research is needed to develop sustainable management systems and high-yielding varieties (Bouman *et al*., 2007).

Identification of promising varieties and the quantification of their yield potential, water use, and water productivity should be done in the early stages of developing such systems (Bouman *et al*., 2005).

1.3. Deficit Irrigation

In the context of improving water use efficiency (WUE) or water productivity, studies are being conducted on deficit irrigation, the world over. Deficit irrigation involves applying water below maximum crop-water requirement (evapotranspiration), allowing mild moisture stress with minimal effects on yield (Fereres and Soriano, 2007; FAO, 2002). The imposed water stress results in partial stomatal closure and reduced CO_2 assimilation. This has the advantage of reducing transpiration with marginal biomass production decrease. This may have little effect on yield if the reduction in biomass production occurs at a particular growth stage and the crop can recover and compensate in subsequent growth stages (Smith *et al*., 2002).

These stages are, for instance: flowering and boll formation in cotton; during the vegetative phase in groundnuts and soybeans; for wheat, it is the flowering and grain filling stages; and the vegetative and yielding stages of sugar beet and sunflower. For rice, the most sensitive stage to water stress is the reproductive stage. Deficit irrigation can be applied either at pre-determined growth stages or throughout the growing season for crops like maize, cotton, wheat, potato and sunflower (Gupta and O'Toole. 1986; Kirda, 2002; Nautiyal *et al.*, 2002). In the recent studies, the performance of rice under deficit irrigation has shown promising results (Soundharajan and Sudheer. 2009; Sarkar *et al*., 2012; El Baroudy *et al*., 2014).

1.4. New Rice for Africa

To develop rice varieties that were high yielding but tolerant to African drought conditions, NERICA rice - short for “New Rice for Africa”- was developed. Plant breeders developed it at the Africa Rice Center (formerly known as the West Africa Rice Development Association - WARDA). NERICA is a cross between *Oryza sativa*, a high yielding Asian rice, and *Oryza glaberrima.*, a stress tolerant African rice. Since its development in the 1990’s, several African countries have adopted appropriate varieties for their environmental conditions from the released 18 NERICA varieties (WARDA, 2001; Kueneman, 2006; Rodenburg *at el*, 2006). NERICA 4 outperformed the other 17 varieties in trials carried out by the Zambia Agricultural Research Institute (ZARI) and was adopted in Zambia (Mr. Malumbe, personal consultation).

Since the drought tolerance of species, varieties and crop stages varies considerably, deficit irrigation requires precise knowledge of crop response to this water saving strategy (FAO, 2002). NERICA 4 was used in this study. It was an appropriate variety for an aerobic production study since it is an upland variety and hence its breed for such conditions. It was grown under deficit irrigation effected at reproduction (the most sensitive stage to moisture stress for rice) in the form of irrigation intervals. The effect of such treatments on the yield and water use efficiency of upland rice was then determined.

1.5. Statement of the Problem

The most common rice farming methods such as irrigated lowland, rainfed lowland, and deep water/floating rice farming involve excessive use of water (Nguyen, 1990). Rice production uses 24 to 30% of the world's fresh water or about 34 to 43% of the world's irrigation water (Bouman et al., 2006). However, poor distribution of rainfall, excessive withdrawal of ground water, demographic pressure, and increased use of irrigation water pose a challenge to rice production systems. This highlights the need to research on technologies that give more agricultural produce, particularly rice, with less water. Deficit irrigation has the potential to achieve that.

1.6. Objectives

1.6.1. Main Objective

To evaluate the performance of upland rice (NERICA-4) under deficit irrigation.

1.6.2. Specific Objectives

To assess the effect of irrigation intervals on rice growth parameters; and

To determine the optimum water use efficiency (WUE) for upland rice.

1.7. Hypothesis

Deficit irrigation will effectively improve water use efficiency of upland rice with minimal reduction in yield.

1.8. Justification of the Study

Agriculture is the main user of water on the globe, with rice using a third of the world's fresh water through irrigated agriculture. But this is not sustainable in the advent of the water scarcity being experienced by the entire globe. The dwindling water resources are projected to culminate in a serious reduction in and competition for fresh water. According to Jury and Vaux (2005), the water supplies in most parts of the world are currently not enough to meet all of the industrial, environmental, urban and agricultural demands. They further stated that forecast indicates that in the next two decades, there will be a significant reallocation of water resources from the agricultural sector to other sectors in response to market forces. This means in future, the human race will have to sustain itself on less water per person than it is today. Water will become the most limiting resource in food production. This entails finding ways of producing enough food, rice inclusive, with less agricultural water. The solution to this predicament starts with making irrigated agriculture a more efficient user of water (Jury and Vaux, 2005). Studies have shown that deficit irrigation is an effective water saving technique for some varieties of rice (Venkatesan *et al*., 2005; Sikuku *et al*., 2010).

1.9. Organisation of Dissertation

The first chapter of the dissertation introduces the background of the study. It also shows the importance of carrying out more research on aerobic rice systems, states the problem of the study, and gives the objectives. It concludes by providing justification for the study. The second chapter looks at the importance of rice, its production status, growth stages and crop water requirements. It further gives an overview of the irrigation statistics for Zambia, irrigation methods and deficit irrigation as a water saving strategy. It also explains how rice responds to water stress. The third chapter gives a description of where and how the study was conducted, including the materials and methods used. The fourth chapter discusses the results obtained at the end of the study with the aid of figures, tables and references to other studies. The fifth and final chapter concludes the study findings in the light of the set objectives and gives recommendation for future studies on the subject.

CHAPTER TWO: LITERATURE REVIEW

2.1. Rice

Rice is an important source of carbohydrates, proteins, fats and some vitamins. Worldwide, rice provides 27 and 20% of dietary energy and protein supply, respectively. In developing countries its nutrient supply accounts for 27 - 50% carbohydrates, 20 - 50% protein, 3 - 27% fat and adequate levels of B vitamin in the diet of humans. It also contains small amounts of vitamin A, C, and D. Due to its high cost of production, rice is mainly grown as a food commodity. However, its nutritious bran is used as an animal feed supplement, especially on farms. Rice bran has the highest content of dietary fiber, most of the B vitamin, and minerals like P, Ca, K, Zn, and Fe (Kueneman, 2006; Calpe, 2006).

By 1981, upland rice was being cultivated in Asia, Latin America, and Africa, mainly by small-scale subsistence farmers in very poor regions of the world (De Datta, 1981). Recent worldwide statistics indicate that a cultivated area of about 79 million ha is planted with irrigated lowland rice, with an average yield of 5 MT/ha; 54 million ha is under rainfed lowland rice with average yields of 2.3 MT/ha; 14 million ha is planted with rainfed upland rice with an average yield of 1.0 MT/ha; and 11 million ha of flood-prone areas have an average yield of 1.5 MT/ha (Bouman *et al*., 2007). It is estimated that 80,000 ha in China and 250,000 ha in Brazil are planted with aerobic rice varieties (Nguyen, 1990).

The development of NERICA rice has led to an increase in the adoption of upland rice farming in Africa. Characteristics of the NERICA varieties include tolerance to diseases, pests and soil acidity. They are high yielding and have good weed competitiveness. NERICA rice also has the advantage of maturing at 100 days, which is about 15 days earlier than most other rice varieties. This makes NERICA rice ideal for the short rainy season in drought-prone areas of sub-Saharan Africa. Furthermore, NERICA rice varieties fair favorably with regard to taste, aroma and cooking characteristics when compared with most of the imported rice in Africa (Kueneman, 2006; Rodenburg at el, 2006; Norman and Kebe, 2006).

2.2. Rice Production in Zambia

Though produced mainly by small-scale farmers in Zambia, rice has been growing in importance as a food crop in SSA and Zambia in particular (Nozaka, 2015; Rodenburg et al., 2006; Kueneman, 2006). National rice production output for Zambia is estimated at 50, 000 MT from approximately 36, 000 ha planted with rice. The national average expected yield stands at 1.21 MT/ha, which is only half of the continental average yield per hectare (Nozaka, 2015).

In Zambia NERICA 4 has a potential yield of 2.5 to 3 tonnes/ha and 125 days to maturity. However, farmers have only been able to achieve grain yield of 1.2 to 1.4 tonnes/ha due to poor agronomic practice such as late planting, fertilizer application and weeding (Malumbe, 2015 personal communication).

2.3. Rice Growth Stages

Rice growth has four growth stages of (i) seedling/initial, (ii) vegetative/crop development, (iii) reproductive/midseason and (iv) ripening/maturity or late season (Tyagi et al., 2000; Bhandari. and Kayastha, 2012). However, the seedling stage is normally included in the vegetative stage (Yoshida, 1981).

2.3.1. Initial or Seedling Stage

This growth stage runs from germination to the start of tillering. The optimum temperature range for rice germination is 18-40^{o}C, with temperatures below 16^{o}C and above 45^{o}C being unsuitable (De Datta, 1981). Imbibition of water by the seed marks the beginning of germination. Carbohydrates start getting converted into sugars, and the embryo gets activated. The radicle and the coleoptile develop inside the embryo and continue to grow and elongate until they push out of the hull. Their appearance marks the completion of germination. The radicle develops seminal roots while the secondary roots and the first four leaves develop from the coleoptile before the start of tillering (Moldenhauer, 2013; Louisiana State University, 1999).

2.3.2. Vegetative or Crop Development Stage

The second stage is from start of tillering to the initiation of panicle primordia. Characteristics of this vegetative stage include the emergence of leaves at regular intervals, active tillering and gradual increase in plant height. The main stem (culm) starts putting tillers at 5^{th} – 6^{th} leaf stage. It was observed to start when the main culm was at the fourth leaf stage in this study. The vegetative or crop development stage is said to be the primary determinant of the growth duration of cultivars (Yoshida, 1981; Moldenhauer, 2013).

The actual initiation of panicle primordial is hard to pin point. The agronomic panicle initiation stage, when the panicle has grown to about 1 mm long (observed with the aid of a magnifying glass) occurs about 7–10 days after the actual initiation (Yoshida, 1981). Maximum tiller production occurs at the end of the vegetative stage (De Datta, 1981).

2.3.3. Reproductive or Mid-Season Stage

The reproductive growth stage starts with panicle initiation (PI) and encompasses booting, heading, and flowering. Cultivar and weather conditions influence the onset of the reproductive stage. This growth stage proceeds with a decline in tiller number and significant culm elongation. The boot is the sheath of the flag leaf inside which the panicle and its parts grow and develop, this causes the swelling of the flag leaf sheath. Continuous elongation of the main stem’s uppermost internode gradually forces the panicle out of the sheath. The stem is considered to have headed when the tip of the panicle is exposed, in a process called panicle exertion. It takes about 23 - 25 days for rice to go from panicle initiation to heading, regardless of variety. Further, due to variation in panicle exertion among tillers and plants, it takes 10 - 14 days for a crop to complete heading. Environmental stress, such as temperature and moisture stress, during the development of reproductive organs, may lead to a reduction in grain yield (De Datta, 1981; Yoshida, 1981; Moldenhauer, 2013; Louisiana State University, 1999).

The events that occur between the opening and closing of the spikelet (floret) characterized through flowering or anthesis. Heading starts upon panicle exertion or on the following day. Branches of the panicle flower as they emerge from the boot, starting with the upper branches and ending with the lower branches. Pollination occurs within the 1 to 2½ hours between the opening and closing of the spikelet. The entire panicle typically completes flowering within 4 to 7 days. In tropical environments, anthesis usually occurs between 8 and 13 hours, and fertilization ends 5 - 6 hours later (Yoshida, 1981; Moldenhauer, 2013).

2.3.4. Ripening / Maturity stage

The grain filling and ripening or maturation phase include all the processes that follow complete fertilization up to full maturation of the rice crop. Grain formation is due to an accumulation of carbohydrates in the pistils of the florets. Thus, the florets on the main stem become immature grains of rice. Translocation of photosynthates from the three to four uppermost leaves and the stem is the primary source of the carbohydrates stored in the form of starch in the grain. This translocation results in increased grain size and weight, eventually causing the panicle to bend over. Leaf senescence and changes in grain-color from green to gold or straw color at maturity are a sign of the ripening phase. At maturity, carbohydrates are no longer translocated to the panicle and moisture loss is the primary process occurring to the grain. Physiological maturity happens when grain filling ceases, and the grain on the main stem gets to 25 to 30% moisture content (Yoshida, 1981; Moldenhauer, 2013; Louisiana State University, 1999).

2.4. Crop Water Requirements

Crop water requirements refer to the depth of water needed to meet the water loss through evaporation and transpiration of a disease-free plant growing under optimal conditions and completely covering the ground surface (Doorenbos and Pruitt, 1977). Factors that influence the crop's water needs include the weather parameters, plant characteristics, management and environmental factors. The crop water requirements are related to reference evapotranspiration (ET_o) through the crop coefficient K_c (Brouwer and Heibloem, 1986) which expresses the evaporating power of the atmosphere dependent only on weather parameters. Several methods for estimating ET_o are available. These include the Blaney-Criddle method, Pan Evaporation method, Turc method, Radiation method, Penman method and the FAO Penman-Monteith, the latter being a modification of the original Penman method

(Doorenbos and Pruitt, 1977; Finkel, 1982; Allen et al., 1998). According to the FAO (Allen et al., 1998), Penman-Monteith equation has become the standard for estimating reference evapotranspiration.

Most crops have broader leaves than grass and different growth cycle lengths. Thus, the crop coefficient (K_c) is used to relate ETo to crop water needs or crop water requirements ET_c (Phocaides, 2007).

$$ETc = Kc * ETo \qquad \textbf{Equation 1}$$

where: ET_c = Crop water requirement, ET_o = Reference evapotranspiration K_c = Crop coefficient

The value of K_c changes by the crop stage, leaf area, and the prevailing weather conditions. Therefore, it tends to be specific and should be determined. Standard values of crop coefficients are available in tables (Doorenbos and Kassam, 1979).

Crops respond differently to water stress occurring throughout the growth cycle or just during particular growth stages. Doorenbos and Kassam (1979) presented an equation which relates evapotranspiration deficit to the resulting yield loss using a yield response factor (k_y). It is crop specific and tends to vary with growth stage over the growing season. The bigger the k_y value, the more sensitive the crop to water deficit and hence a larger proportion of yield reduction in response to reduced water use. A k_y value of 1 means that the reduced water use, and yield reduction are directly proportional. The k_y values for most crops have been derived and are available in literature (Steduto et al., 2012).

Yoshida (1981) indicated 180–300 mm monthly crop water requirement during the growth cycle or a total of 1,240 mm as the average crop water requirement for irrigated rice. For upland rice, Oikeh et al. (2008) recommended planting when the soil receives at least 14 – 20 mm of rainfall during a consecutive five-day period during the growing season. The crop water requirements of rice are different for each of the four growth stages. The seedling stage for rice has low water requirement, and excess water would damage the radicles from lack of oxygen supply. Rice has a high-water requirement during most of the reproductive growth stage and is susceptible to moisture stress at this stage (De Datta, 1981). The most sensitive period is from panicle initiation to flowering stage. The booting stage, on the other hand, is sensitive to excessive water which might lead to a decrease in calm strength and increase the occurrence of lodging. The ripening stage also has a low water requirement (De Datta, 1981).

2.5. Irrigation Statistics - Zambia

Zambia has a total land surface of 752 610 km^2 (75.26 million ha), of which 16.35 million ha is estimated to be a cultivable area with an irrigation potential of 523, 000 ha (FAO, 2015). The country receives between 750 mm and 1, 400 mm of rainfall in different parts. Though this amount of rainfall is adequate for most crops, rain-fed agriculture is greatly affected by annual variations that occur from year to year (Mendes et al., 2014). Variations in rainfall distribution within the season also affect production of most rain-fed crops.

There has been a steady increase in land under irrigation in Zambia. The Aquastat report (FAO, 2015) showed that in 2002, 55 387 hectares were under irrigation. Out of this irrigated land: 32,189 hectares were under surface irrigation; 17,570 hectares were under the sprinkler, and 5,628 hectares were under drip irrigation. The need to promote appropriate irrigation technologies in Zambia is a top priority.

If the country is to increase its annual crop production through irrigation, it is critical to invest in research on efficient irrigation technologies and in managing water resources efficiently. Interest in irrigation should be placed on small scale farmers as these farmers are the main contributors to annual crop production in Zambia (Ngona and Dube, 2013). The Crop Forecast Survey of 2011/2012 showed that smallholder farmers dominated the production of maize, millet, sorghum, groundnuts, seed cotton, rice, sunflower and mixed beans, which is under non-irrigated crop production. Their percent production ranged from 93 % for sorghum to 100% for rice, with percent production of the other crops listed above falling in between. The same survey showed that large-scale farmers only dominated the production of tobacco (74%), wheat (100%) and soybeans (93%).

Zambia lies within the African savannah, alongside countries like Angola, Kenya, Lesotho, Malawi, Mozambique, Swaziland, Tanzania, and Zimbabwe. This region has experienced declining crop yields and recurrent crop failures due to water stress associated with dry spells and drought during critical crop growth stages. However, Mati (2007) observed that the main problem in crop production is the inappropriate management of the water resource. Most small scale or peasant farmers in the Southern African Development Community (SADC) region and Zambia in particular, practice poor crop husbandry associated with late planting, use recycled seeds, poor weed and pest control practices, and poor soil fertility management. It is also important to select early maturing varieties that have high water productivity. However, most small-scale farmers pay no attention. Further, only a few small-scale farmers practice soil moisture retention techniques aimed at improving yield. Since the same small-scale farmers are the major producer of rice in the region, particularly in Zambia, it is important to assess water management techniques that can help improve crop production.

2.6. Irrigation Methods

The three main methods of irrigation are sprinkler, drip, and surface or flood irrigation. Surface irrigation methods apply water by gravity flow to the surface of the field, wetting it either partially or completely. Surface irrigation can further be sub-divided into three types - furrow, border, and basin irrigation. The water is fed into small channels in furrow irrigation and strips of land in border irrigation, while basin irrigation involves flooding the entire field (Brouwer et al., 1988; Savva and Frenken, 2002). Surface irrigation methods are characterized by low irrigation efficiency (<60%), relatively low initial costs and are labor intensive.

Sprinkler irrigation mimics natural rainfall by applying irrigation water to crops in the form of a spray through pressurized systems (Mati, 2007). Pumps normally provide the pressure required to operate this system. The water conveyance and distribution to the sprinkler heads is by either surface or buried pipelines, or by both. This pressurized pipe network delivers the water to a system of nozzles which then sprays the water onto the land (Savva and Frenken, 2002; USDA, 1997). The advantages of sprinkler irrigation over surface irrigation methods are that it has a higher efficiency (≤80%), lower labor requirement, and it is suitable for light and frequent irrigation. Good water distribution enables sprinklers to wet the entire field evenly. The nutrient pool for plant roots widens, unlike drip systems which give localized wetting (Brouwer, 1989; Savva and Frenken, 2002; USDA, 1983). The disadvantages of sprinkler irrigation include its high initial cost and inconvenience for cultural operations in the field (USDA, 1997). According to Savva and Frenken, (2002), sprinkler irrigation is not suitable for crops that are sensitive to prolonged contact with water and crops requiring ponding of water at some stage of their life. This method is susceptible to water loss through wind drift, relatively high energy demanding and requires good water quality especially sodium and chloride levels in irrigation water.

Drip irrigation on the other hand is a localized system which applies water to the root zone in small volumes and at low pressure. Though drip irrigation is the least common of the three methods, its history dates to ancient times. Ancient civilizations practiced drip irrigation in the form of buried perforated (unglazed) clay pots (pitchers) which captured rain water or were manually filled with water. The pots then gradually leaked into the root zone of nearby vegetation (Bainbridge, 2006). However, drip irrigation as we know it today, with plastic tubing or drip lines, was pioneered by, among others, Netafim in the 1960's (Netafim, 2013).

Drip irrigation is under promotion, and more farmers are adopting the technology. A drip irrigation system comprises a source of water, pump, control head, main pipe, sub-main, manifold, and laterals or drip lines, in sequence. Laterals have water emitters or drippers on them which are of various types - micro-jet, long path, short path, tortuous, vortex or sprayers, compensating, flushing, simple orifice, and a small pipe.

Drip irrigation has been gaining popularity because of its advantages over sprinkler or flood irrigation. These include its good conveyance and uniformity of application which give drip the highest efficiency of 90%, as compared to the sprinkler, 75% and surface irrigation 60% (Brouwer, 1989). Drip irrigation has low labor operating requirements and can result in a yield increase of 10% - 45 % compared to surface irrigation methods and an improvement in crop quality (Phocaides, 2007).

Because a low volume of water is applied to the root zone at a time through drip irrigation, only a small area around the base of each plant is wetted. Thus water losses through direct soil surface evaporation are reduced; runoff and erosion are also reduced or eliminated. There is also reduced weed growth between crop rows since this area is kept dry (FAO, 2002). Thus, drip irrigation saves resources such as labor, fertilizer, water, and soil. Fertilizer can also be applied using drip through a process called fertigation or nutrition. Application of just the right amount of nutrients as and when required by the plant without wetting the leaves is ensured under fertigation.

However, drip has its disadvantages. The high initial cost of setting up a drip system is probably the major reason for its low adoption rates among small scale farmers. Thus, farmers may be tempted to buy cheap low-quality components which can deteriorate when exposed to weathering and the ultraviolet rays of the sun. In fact, whether they are of poor or good quality, the small plastic components of drip systems are fragile and hence easily damaged by equipment, animals, or humans during operations (FAO, 2002). It is worth noting that, despite the preceding disadvantages of plastic components; plastic is the preferred material to metal as they are less costly. Emitters also tend to clog due to insufficient filtration of impurities in the irrigation water, algal growth, or precipitation of $CaCO_3$ and Fe. Drip also requires skilled workforce for maintenance of the system. Moreover, drip irrigation requires frequent application of water, unlike sprinkler, and has both advantages and disadvantages. The disadvantage is that, unless it is automated (which is expensive), the system is more labor intensive than sprinkler irrigation. The advantage of drip is that soil moisture remains close to field capacity during irrigation, eliminating any possibility of moisture stress.

2.7. Deficit Irrigation

Deficit irrigation is the practice of supplying the crop with less water than its maximum requirement (Fereres and Soriano, 2007; FAO, 2002). Observations have shown higher yields under deficit irrigation when the same amount of water as under full irrigation was applied (Zhang, 2003). The water saved under the system can be used to increase the area under irrigation. Therefore, any potential loss in yield due to moisture stress may be compensated for in this way, resulting in higher water productivity.

Studies have shown that, depending on the crop's or growth stage's sensitivity to stress, deficit irrigation can result in yield reductions that are proportionately less than the reduction in irrigation water applied. In such cases, it is possible for crop WUE to increase despite the reduction in crop yield (Kirda, 2002). Models for deficit irrigation strategies have been developed to account for yield loss due to water stress (Heeren et al., 2011*)* and depict the technological adjustment of farmers (Severini et al., 2008).

Deficit irrigation has been proven to be an effective water saving strategy for most crops. However, a study conducted in Tunisia (Amami et al., 2001) showed that deficit irrigation could be problematic for some crops e.g. wheat. Thus, it requires both good irrigation scheduling decisions and appropriate evaluation of the economic impacts at farm level (Amami et al., 2001). Some soybeans cultivars also show a significant decrease in yields under deficit irrigation (Comlekcioglu and Simsek, 2011).

Though rice is mainly suitable for flooded growing conditions, research has shown that some deficit irrigation strategies can work for rice production (Soundharajan and Sudheer. 2009; Sarkar et al., 2012; El Baroudy et al., 2014). There is still need for further studies on deficit irrigation applied to rice production. Different combinations of climatic conditions, soil characteristics and cultivar characteristics may need different deficit irrigation strategies.

2.8. Rice Response to Water Stress

Water stress in plants is influenced by many factors, making it difficult to predict and mitigate with a high level of accuracy. According to Gupta and O'toole (1986), when the ratio of actual evapotranspiration (ET_a) to potential evapotranspiration (ET_o) falls below 1.0 then the crop is under water stress or in a drought condition. Some crops are more sensitive to water stress than others. Therefore, yield response to water stress differs between and within crop species (Comlekcioglu and Simsek, 2011).

Rice is extremely sensitive to water or moisture stress as it evolved from a semi-aquatic ancestor. The most sensitive stage to water stress is during the reproductive stage. When panicle water potential is low (e.g. -1.8 MPa) spikelets scheduled to pollinate on that day do not open to shed pollens, leading to spikelet sterility. Thus the harvest index (HI) is reduced (Steduto et al., 2012).Moisture stress induces the production of abscisic acid (ABA) by plant roots. This hormone is then transported to plant leaves where it induces stomatal closure. Plant leaf stomata allow the diffusion of CO_2 into the leaf for photosynthesis and the diffusion of H_2O out of the leaf during transpiration. The opening and closing of stomata are one of the important factors controlling plant water loss by transpiration and yield production by photosynthesis. The regulation of gas exchange in leaf stomata is by pairs of guard cells that surround each stomatal pore. Abscisic acid induces stomatal closure by reducing the turgor of these guard cells during periods of water deficit (Zhang, 2011). Water loss is reduced through reduced transpiration but also the rate of photosynthesis is lowered, hence reducing yield production. Studies have shown that full stomatal opening in previously water-stressed plants occurs only several days after rewatering (Finkel, 1982). The effects of water stress on photosynthesis can be expected to last several days after the end of water stress. By maintaining soil moisture near field capacity, drip irrigation prevents the adverse effects of moisture stress on yield and its quality.

CHAPTER THREE: MATERIALS AND METHODS

3.1. Description of Study Area and Location

The pot experiment was set up in a screen house located at the University of Zambia in Lusaka (latitude 15.43 ^{o} S, longitude 28.33^{o} E, and 1263 m altitude). The location has an aridity index of 0.57 and annual potential evapotranspiration of 1508 mm and. It lies in Region II of the Zambian agro-ecological regions, which receives 800 to 1,000 mm of rainfall per year. There was no artificial control of light, CO_2 concentration and temperature. During the study, the temperature ranged from 11-55 ^{o} C and the average relative humidity was 82% respectively.

3.2. Experimental Site and Design

The experimental design was a Randomised Complete Block Design (RCBD) with four (4) levels of irrigation as treatment in four (4) replications. All the treatments received the same depth of water per irrigation event except for the irrigation intervals. The treatments were I_1, I_2, I_3, and I_4 corresponding to irrigation intervals (i) daily, (ii) 2 days, (ii) 3 days and four days, respectively.

3.2.1. Pot Experiment Setup

The experimental setup had plastic containers (10 L capacity) with a height of 290 cm and a radius of 24 cm. Perforated plastic tubes were installed at the base of the pots covered with fine sand to allow collection of drainage water during the experiment The containers were then filled with soil material collected from surface soil (0- 20cm depth) which was thoroughly mixed before packing in the containers. A loamy soil collected within the university premises was used because of its good water holding capacity, as rice does not perform well in coarse soils. Drainage water was collected using bottles installed at the drainage outlet tubes (Figure 1).

Figure 1: Arrangement of drainage water collection bottles

3.2.2. Soil Analysis

A soil sample was also collected, from the bulk soil that was to be put in the pots, for soil characterization to determine the soil's physical and chemical properties. Chemical analysis was done for some major nutrient elements: N, P, K, Ca, Mg, and S. Soil organic matter, Na content and soil reaction (pH) were also determined. The Kjeldahl Method was used to determine the total nitrogen content of the soil (Bremner and Mulvaney, 1982). The Bray 1 Method was used for P analysis since the soil was slightly acidic. Exchangeable cations, Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}, were determined using the Ammonium Acetate Method (Thomas, 1982). The Walkley – Black Wet Combustion Method was used to determine soil organic matter (Bashour and Sayegh, 2007), while soil reaction (pH) was determined in 0.01M CaCl using a 1:2.5 soil to solution ratio, a standard method used to measure pH in Zambia.

Physical properties determined included bulk density, gravimetric water content, field capacity, permanent wilting point, available water holding capacity and particle size distribution of the soil. The Core Method (Blake, 1965) was used to measure the bulk density of the soil while particle size distribution was done using the Hydrometer Method (Day, 1965).

3.3. Evaporation and Evapotranspiration

3.3.1. Measurement of Evaporation

The evaporation rate is controlled by the availability of energy at the water surface, and the ease with which water vapour can mix into the atmosphere. To measure open water evaporation in the greenhouse, four empty plastic pots (10 litre capacity) were regularly filled with water and loss in water was monitored by recording the height of water in the pot. The height of water was used to estimate the open water evaporation occurring in the greenhouse during the experiment. The estimated evaporation was calibrated with the pan evaporation obtained from the weather station within 500 m from the greenhouse structures.

3.3.2. Measurement of Crop Evapotranspiration

The evapotranspiration was estimated from water balance approach. The pots were each weighed using a hanging scale before irrigation and every five days to determine the change in weight attributed to drainage and crop evapotranspiration (weight gain by crop biomass in five days was assumed to be negligible). The depth of water loss was calculated by dividing the volume of water loss by the surface area of the pots. The calculation of the water balance was done at daily scale for the pots at which the fluxes and storage changes were measured. The water balance equation for the pots under greenhouse conditions was solved for actual evapotranspiration (ET) from the following water balance equation (Equation 2):

$$ET = I - Q - \Delta S$$ **Equation 2**

where: ET = actual crop evapotranspiration (mm); I = the irrigation (mm); Q = discharge or drainage below the pot (mm); ΔS = change in water storage in the pot (mm).

3.3.3. Weather Data

The evaporative demand of the atmosphere in the green house was also estimated from the limited data measured within the greenhouse. Ambient temperature was recorded with minimum and maximum thermometers while the wet and dry bulb thermometer readings were recorded to estimate the humidity in the greenhouse (Figure 2). Readings on both thermometers were taken twice daily at 08:30 and at 15:00. The reference evapotranspiration (ET_o) in the greenhouse was estimated using the Hargreaves equation (HG) as it needs only temperature and radiation data (**Equation 3**). The HG for calculating reference evapotranspiration (Hargreaves and Samani (1985) is one of the most suitable approach that has been used when the availability of weather data is limited. This method requires only measurements of maximum and minimum temperatures, with extra-terrestrial radiation calculated as a function of latitude and day of the year (Itenfisu et al., 2003). The HG is as shown in the following equation:

$$ET_o = C_H(T_{max} - T_{min})^{E_H} * (T_{mean} + 17.8) * R_a \qquad \textbf{Equation 3}$$

where: ET_o = Computed reference evapotranspiration (mm day^{-1}); Ra = Extra - terrestrial radiation (mm day^{-1}); T_{max}, T_{min}, and T_{mean} = maximum, minimum, and mean air temperatures (°C); and Values of constants C_H and E_H are 0.0023 and 0.5 respectively.

Figure 2: Location of thermometers in the greenhouse

3.4. Crop Management

For crop management, the soil in the pots was irrigated to field capacity at planting. Three seeds were drilled into the soil at five planting stations in each pot at approximately 5 cm apart. After emergence the seedlings were thinned to 1 plant per station to give rise to 5 plants per pot (Figure 3). The basal dressing was applied at a rate of 300 kg/ha Compound ‘D’ fertilizer (10:20:10) was applied at seeding. Later top dressing fertilizer (Urea 35% N) was applied as a split application at 30 and 45 days after planting with Urea at a rate of 100 kg/ha. The pots were kept weed-free throughout the experiment by manually removing weeds. The soil in the pot was irrigated to field capacity throughout the vegetative stage of growth on a daily basis.

Figure 3: More than one seedling per station before thining

Irrigation water treatments were exerted (on Day 43 after planting) after initiation of panicle primordia, which was the beginning of the reproductive stage. A fixed amount of irrigation water was scheduled and applied at four intervals (I_1=daily, I_2= every two days, I_3 = every three days and I_4 = every four days). Specified irrigation schedules per plot were applied to each treatment. Irrigation water was regularly measured with transparent graduated cylinders to ascertain the accuracy of the irrigation system at regular intervals.

3.4.1. Irrigation Scheduling

The crop season length (100 days) of NERICA 4 variety considered in the trial was divided into four growth stages (initial, development, mid-season and late season) each with specific duration in days. Reference evapotranspiration (ET_o) was calculated using the FAO Penman Monteith equation from historical weather data from UNZA Meteorological Station (located within 500 m away from the site) (Allen et al.,, 1998). The crop coefficient (K_c) was determined (Allen et al., 1998) for each growth stage (Table 1). The estimation was made from growth stages curve with an assumption that the humidity and wind speed were medium. With reference evapotranspiration (ET_o) and crop coefficient known, crop evapotranspiration (ET_c) was calculated using equation (1).

Table 1: Crop Coefficients (k_c) and Evapotranspiration Values for Rice Growth Stages

	Crop Development Stages				**Growing Period**
	Initial	Crop Development	Midseason	Late Season	
Growth stage(days)	20	25	30	35	110
K_c	1.13	1.13	1.2	1.0	1.11
ET_o (mm/day)	3.88	4.07	4.33	4.16	4.11
ET_c (mm/day)	4.36	4.58	5.20	4.16	4.75

The K_c values for rice at each growth stage are given in Table 1: with corresponding values of ET_c calculated (**Equation 1**) for the location of the experiment. The ET_o values used were determined using New_LocClim software while the K_c values were obtained from Doorenbos and Kassam (1979). The decadal irrigation schedule for the season is given in Table 2 below.

Table 2: Decadal Irrigation schedule for the entire season (mm)

Irrigation interval / Decade	I_1*	I_2	I_3	I_4
1	59	59	59	59
2	117	117	117	117
3	205	205	205	205
4	448	382	352	352
5	728	536	462	440
6	1065	727	580	528
7	1367	881	719	639
8	1749	1080	888	727
9	2043	1241	991	815
10	2293	1366	1094	866

* I_1 = one day, I_2 = two days, I_3 = three days, and I_4 = four days.

3.5. Measurement of Plant Growth Parameters

In this study, biometric observations included number of tillers per plant and plant height. The number of tillers per plant were counted and recorded once a week during the initial and vegetative stages. The height of the main stem of each rice plant was measured every two weeks starting on the 28th day after planting. Measurements were taken, using a measuring tape, from the base of the plant to the collar of the highest leaf.

The yield attributing characteristics observed were panicle length and number of panicles per plant. The number of heads or panicles per plant was counted weekly during the reproductive stage and at harvesting. Panicle length was measured using a meter rule.

Total dry above ground biomass was also weighed at harvest time. Further, 100 grains from each treatment and replication were weighed to determine the 1000 grain weight after harvesting. All the grain harvested from each treatment and replication was weighed separately and the harvest index was determined.

3.5.1. Water Use Efficiency (WUE)

The WUE was calculated using the following equations (**Equation 4** and **Equation 5**)

$$WUEg = Y/ETc$$ **Equation 4**

where: WUE_g= water use efficiency (g/plant/mm); Y = total grain yield (g/plant); ET_c = seasonal crop evapotranspiration (mm).

$$WUEb = B/ETc$$ **Equation 5**

where: WUE_b= water use efficiency (g/plant/mm); B = total above ground biomass (g/plant); ET_c = seasonal crop evapotranspiration (mm).

3.5.2. Yield Response Factor (k_y)

The effect of the proposed deficit irrigation on the yield of upland rice was calculated using a water production function (Doorenbos and Kassam, 1979):

$$\left(1-\frac{Y_a}{Y_m}\right) = K_y * \left(1-\frac{ET_a}{ET_m}\right)$$ **Equation 6**

$$K_y = \frac{\left(1-\frac{Y_a}{Y_m}\right)}{\left(1-\frac{ET_a}{ET_m}\right)}$$ **Equation 7**

where: Y_m = maximum yield; Y_a = actual yield; ET_m= maximum evapotranspiration; ET_a = actual evapotranspiration; and K_y = yield response factor.

The yield response factor K_y represents the effect of the evapotranspiration deficit 1-ET_a/ET_m on yield losses 1-Y_a/Y_m (Steduto et al., 2012). In this study, the Y_m and ET_m values used in calculating k_y were determined from the treatment with daily water application. The potential maximum yield (Y_m) was estimated as the sum of the average and the standard deviation of grain yield in rice under daily irrigation. The ET_m was estimated in the same way.

3.6. Statistical Analysis

The data collected was subjected to analysis of variance (ANOVA) using Genstat in order to determine if the treatment effects were significant. The treatment means were separated using the least significant difference (LSD) test at 5% level of significance. In-built graphics within R Software were used to illustrate statistical differences.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1. Characterisation of the Soil and Weather

Selected chemical and hydraulic properties of the soil are presented in Table 3 and **Error! Reference source not found.**. The soil used was a sandy clay loam with a soil reaction of 5.81 (pH) and had organic matter content of 2.38%. Soil texture is an important for upland rice production as it influences nutrient and water holding capacity of the soil (Gupta and O'toole, 1986). According to Oikeh et al. (2008) a clayey soil and high organic matter content are good for rice production, while deep sandy soils are unsuitable for rice production (Louisiana State University, 1999)

Table 3: Pre-Planting Soil Characterisation

Soil Property	Value
Soil reaction (pH)	5.81±0.23
Total N (%)	0.031±0.01
Plant available P (mg/kg)	3.68±0.9
Exchangeable cations (cmol(+)/kg)	
K^{+}	0.25±0.01
Mg^{2+}	11.11±0.65
Ca^{2+}	15.10.51±.196
Na^{+}	±1.53
Organic matter (%)	2.38±0.59

4.2. Yield Components

Results on yield components of upland rice are presented in Figure 4. The average number of tillers varied from 5.61 to 6.43 with an average of 5.9 per station while the heads per plant varied from 4.19 to 4.6 with an average of 4.4 (Figure 4). Irrigation interval did not significantly affect ($p>0.05$) the number of tillers and heads per plant. Sikuku et al. (2010), however, observed significant effect of water deficit (effected in the form of irrigation intervals) on the yield of some NERICA rice varieties. In that study, increase in water deficit significantly ($p<0.05$) reduced tillering.

Table 4: Hydraulic Properties of the Soil

Soil Property	**Value**
Sand (%)	55.3
Silt (%)	19.1
Clay (%)	25.6
Bulk Density* (g/cm^3)	1.21
Θ_{fc} (0.1bar) cm^3/cm^3	0.33
Θ_{wp} cm^3/cm^3	0.17
Θ_s cm^3/cm^3	0.49
Ks (mm/day)	484.1
n_e	0.20
τ	0.75

* Of the soil in the pots

τ = drainage characteristic (tau), n_e = effective porosity; Θ_s = saturation moisture content; Θ_{fc} = moisture content at field capacity; Θ_{wp} = moisture content at wilting point; Ks = saturated hydraulic conductivity

The difference in observations between the two studies could have resulted from the difference in the crop stage at which treatments were enforced. In the other study, water treatments were started at 21 days, during the vegetative stage. In the current study, water treatments were enforced at the beginning of the reproductive stage. Most tillers are formed during vegetative growth and maximum tiller production is complete by the time reproductive growth begins (De Datta, 1981). Hence the in insignificant differences in the number of tillers per plant between water treatments in this study.

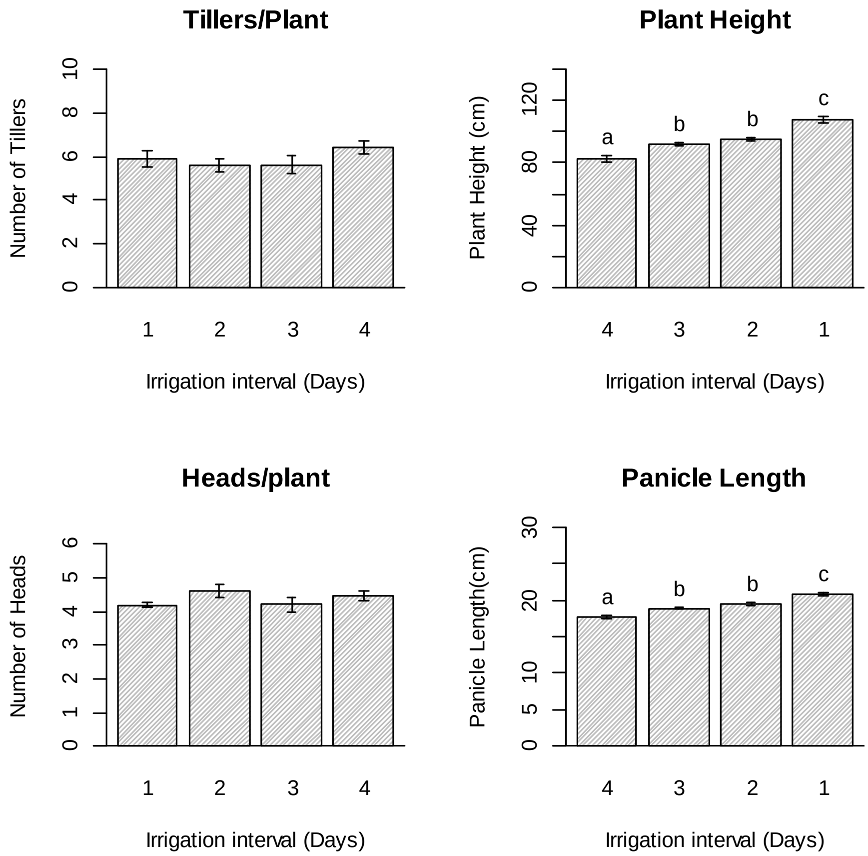

Figure 4**:** Effect of Irrigation Interval on number of tillers, plant height, heads and panicle length**.**

In their genetic characterisation study, Fukuta et al. (2012) reported that 17 NERICA varieties (including NERICA 4) had the smallest panicle number (or number of heads) per plant as compared to the other 31 varieties analyzed in the study. However, the number of heads per plant reported in that study (8.1) is still higher than the one observed in this study (4.4). This could have been due to differences in environmental factors such as temperature. High temperatures have the potential to improve yield, but very high temperature have a negative effect on reproduction (Louisiana State University, 1999). De Datta (1981) stated that climatic conditions during tillering strongly affect the number of heads. He indicated 25-31^{o}C as the optimum temperature for tillering with the critical limits being 9-15^{o}C on the low end and 33^{o}C on the high end. The average minimum and maximum temperature during the vegetative stage were 20.8^{o}C and 40^{o}C, respectively.

The plant heights were 82.56 cm for treatment I_4, 91.7 cm for I_3, 94.9 cm for I_2 and 107.5 cm for I_1. Then the panicle lengths were 17.66 cm, 18.91 cm, 19.45 cm and 20.8 cm respectively (Figure 4). There were highly significant ($P<0.001$) increases in both plant height and panicle length with increased frequency of watering. This means that higher frequency of watering gave the plant more available water required for plant growth. Similar results have been obtained in other studies on NERICA 4 (Akinbile and Sangodoyin, 2011; Sikuku et al., 2010). However, it can be observed in Figure 4 that the effects of treatments I_2 and I_3 were not significantly different ($P>0.05$).

The total above ground biomass, stover, grain yield, 1000 grain weight and HI were as indicated in Table 5. Total above ground biomass and grain yield per plant both showed a highly significant increase ($P<0.001$) with an increase in the frequency of irrigation. Water is an important component of photosynthesis, the process by which plants produce sugars which go into biomass and grain production.

Table 5: Effect of Irrigation Interval on Total Biomass, Stover, Grain Yield, 1000 Grain Weight and HI of NERICA 4 rice

Treatment (Irrigation interval (days)	**Total Biomass (g/plant)**	**Stover (g/plant)**	**Grain Yield (g/plant)**	**1000 Grain Weight (g)**	**HI (%)**
1	20.35^{d}	7.056	13.295^{d}	26.48^{c}	65.53^{c}
2	15.98^{c}	7.533	8.445^{c}	24.22^{b}	53.45^{b}
3	12.30^{b}	5.953	6.347^{b}	23.78^{ab}	50.74^{b}
4	8.97^{a}	6.349	2.621^{a}	22.16^{a}	27.96^{a}
Mean	14.40^{***}	6.72^{ns}	7.68^{***}	24.16^{***}	49.4^{***}
LSD	1.118	1.278	1.376	1.832	10.83
CV (%)	11	26.8	25.3	10.7	31
Fpr	< 0.001	0.072	< 0.001	< 0.001	< 0.001

*1000 grain weight determined at 10.5% moisture content

Biomass weight ranged from 8.97 g/plant to 20.35 g/plant; under field conditions, total biomass weight of NERICA varieties can go up to 48.1 g/plant (Fukuta et al., 2012). In this study, rice grain yield increased from 2.62 g/plant under four days irrigation interval to 13.30 g/plant under daily irrigation. This shows how sensitive rice yield is to moisture stress. Rice yields as high as 28.52 g/plant have been reported for other varieties under field conditions (Ranawake, 2013).

Stover was determined as the total above ground biomass less grain yield. Irrigation interval had no significant effect ($P>0.05$) on stover per plant. This means that the observed differences in above ground biomass between treatments were due to differences in grain yield. Treatments I_2 and I_3 had the highest and lowest values of 7.53 and 5.95, respectively. The average stover per plant was 6.72 g (Table 5

Irrigation interval had a highly significant effect ($P<0.001$) on grain weight and harvest index. Grain weight increased from 22.16 g/1000 grains under four days irrigation interval to 26.48 g/1000 grains under daily irrigation. The effect of three days irrigation interval was neither significantly different from that of four days irrigation interval nor that of two days irrigation interval. Environmental factors that affect the rate and duration of ripening, e.g. light, temperature, determine whether the grain weight will be as characteristic of the cultivar or lower (Moldenhauer et al., 2013).

The average HI determined in this study was 49.4%. This was within the range of the HI for NERICA 4 determined in other studies (Hussain et al., 2014; Bekere et al., 2014). The highest average HI was recorded in daily irrigation treatment I_1 (Table 5), and the reductions in HI for treatments I_2, $I_{3,}$ and I_4 as compared to I_1 were 18.43%, 22.57%, and 57.33%, respectively.

4.3. Soil Water Balance

The actual seasonal crop water requirement (ETa) was very significantly different ($P<0.05$) and ranged from 750.1 mm for treatment I_4 to 997.1 mm for treatment I_1 (Figure 5). This means evapotranspiration increased with increase in the frequency of watering. At each irrigation event, the soil was brought to saturation. Thus the higher the frequency of watering, the longer the soil was at, or close to, field capacity. The crop absorbs water with less energy expenditure when the soil is near field capacity (0.1 bar pressure) than when it gets dryer, and the soil holds the water with greater tension. The same goes for evaporation. This explains the trend observed in seasonal evapotranspiration.

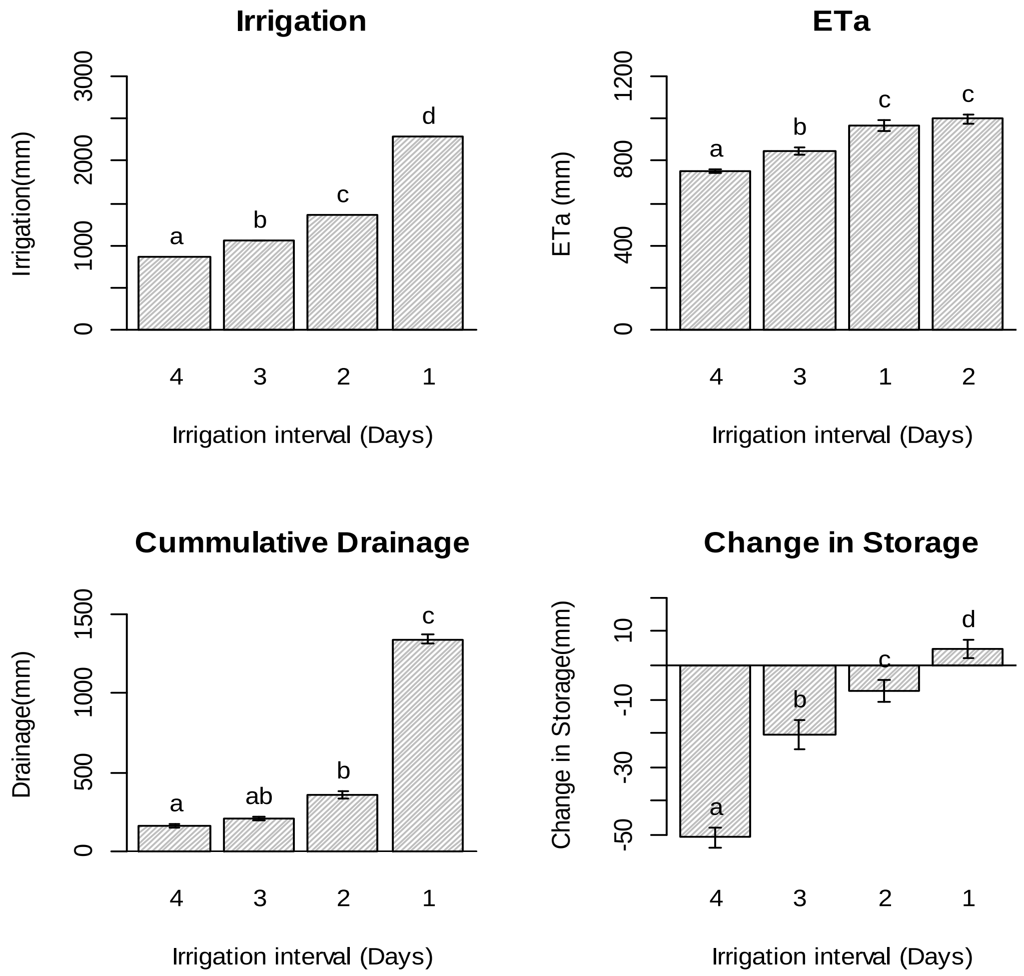

Figure 5: Effect of Irrigation Interval on ETa, drainage, and soil water storage

The 997.1 crop water requirement was higher than that estimated by Oikeh et al. (2008) for upland rice but within the range of the 1,240 mm estimated by Yoshida (1981) for irrigated rice. It can be observed from the Figure 5 that effects of daily irrigation and two days irrigation interval on ET_a were not significantly different ($P>0.05$). Thus an irrigation interval of two days, with 1366 mm total irrigation water, was optimal under the conditions that prevailed in this study. Excess above this irrigation depth only increased drainage and storage.

Drainage and seasonal water storage also revealed highly significant differences ($P<0.05$) in the treatments. Treatments I_3 and I_4 had the lowest drainage and were not significantly different ($P<0.05$) in this regard. However, all treatments had significantly different ($P<0.05$) effect on change in storage. Treatment I_1 was the only one to give an increase in storage of 4.88 mm. The rest of the treatments, I_2, I_3 and I_4, resulted in decreases in the storage of 7.47 mm, 20.58mm and 50.84 mm, respectively.

4.4. Water Use Efficiency

The effect of irrigation interval on biomass and grain water use efficiency (WUE_b and WUE_g) was highly significant ($P<0.001$) as can be seen in Figure 6. The values of WUE_b were 21.1, 16.1, 14.5 and 12.0 mg/plant/mm, in order of increasing irrigation interval and volume of water applied. Other studies have reported similar trends (Akinbile, 2010). The WUE_g also had a similar trend, the values being 13.9, 8.6, 7.6 and 3.6 mg/plant/mm. In the case of WUE_g, however, two days and three days irrigation intervals were not significantly different ($P>0.05$). This means that under the conditions of this study, two days and three days irrigation interval gave the same additional grain yield per additional millimetre of water applied.

The reduction, with respect to the daily irrigation treatment I_1, in WUE_b and WUE_g for treatments I_2, I_3 and I_4 were 23.70% and 38.13%, 31.28% and 45.32%, and 43.13% and 74.10% respectively. Oikeh et al. (2008) recommended that upland rice planting should be timed such that the crop receives at least 14–20 mm of rainfall every five days. That would amount to 440 mm crop water requirement. This would have resulted in severe moisture stress and yield loss under the atmospheric conditions of this study. Treatment I_4 was irrigated once every four days and received a total irrigation depth of 866 mm. This resulted in WUE_b and WUE_g reduction of 43.13% and 74.10% as compared to daily irrigation.

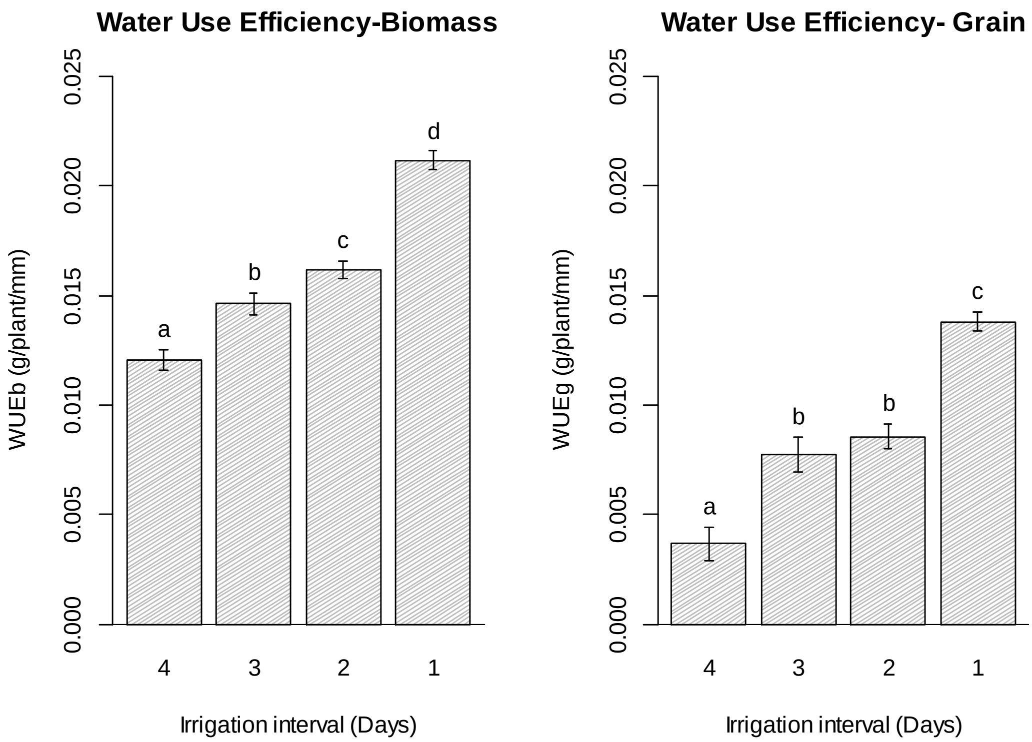

Figure 6: Biomass and Grain WUE as affected by Irrigation Interval

4.5. Yield Response to Stress

Yield response to stress is an analysis of yield reduction $1\text{-}Y_a/Y_m$ incurred as a result of evapotranspiration deficit $1\text{-}ET_a/ET_m$ (**Equation 6**). In this study, yield reduction ranged from 0.071 for I_1 to 0.817 for I_4 while evapotranspiration deficit ranged from 0.037 for I_2 to 0.287 for I_4 (Figure 7). This means that, when NERICA 4 is exposed to environmental conditions similar to those prevalent in this study and irrigated daily to satisfy a consumptive water use of 967.3 mm, the average yield loss would be 7.1%. This yield loss would be as a result of 10.14% reduction in ET. However, if it is irrigated every four days to satisfy a consumptive water use of 750.1 mm, the yield loss would be as high as 81.7%, resulting from 28.68% reduction in ET.

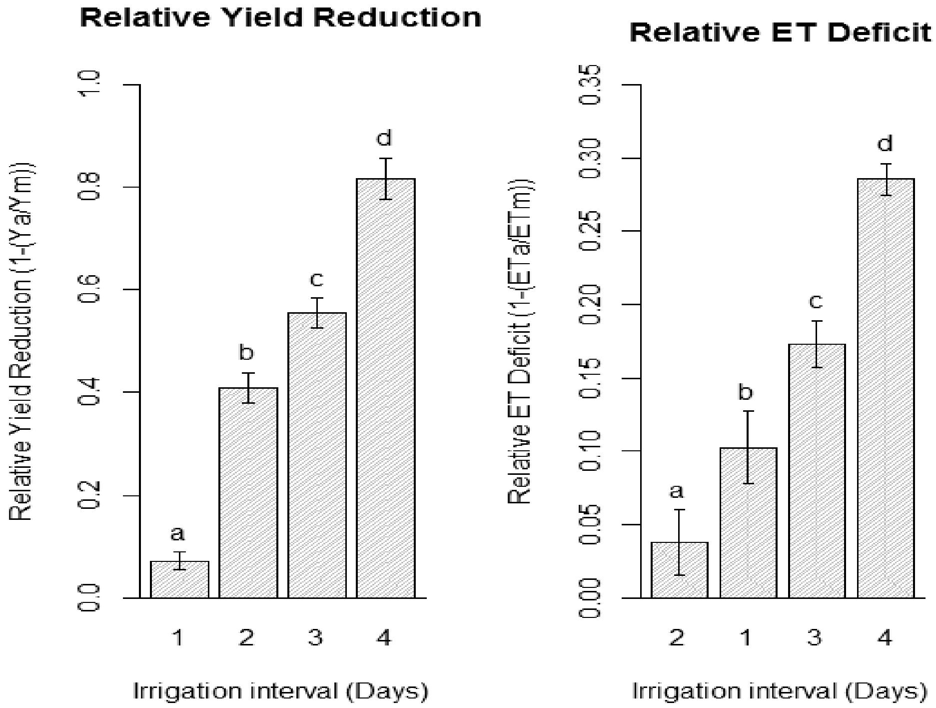

Figure 7: Effect of Irrigation Interval on relative ET deficit and relative yield reduction

Treatment I_2 had a smaller relative ET reduction (3.66%) than I_1 (10.14%) but bigger relative yield reduction (41.0% and 7.1%, respectively), even though their seasonal ET (Figure 5) were not significantly different ($P>0.05$). This was due to differences in irrigation interval which meant that their water demands were satisfied to different degrees during reproductive and maturity stages. These are the only stages in which the two treatments had significantly different ET values (irrigation treatments were effected at the beginning of the reproductive stage). At reproductive stage, the average ET_c value for I_1 was higher than the one for I_2 by 51.8 mm. This higher consumptive water use accounted for the lower yield reduction in treatment I_1. Rice, like other cereals, is highly sensitive to moisture stress at reproductive stage i.e. during the formation of reproductive organs and flowering (De Datta, 1981).

The crop yield response factor ky being a ratio of relative yield reduction to relative evapotranspiration deficit means that the greater its value, the greater the yield loss per unit ET_c deficit. Irrigation had a highly significant effect ($P<0.001$) on k_y. Results of this study showed that yield k_y, and hence yield loss, increased with increase in irrigation interval (Figure 8). The higher the k_y value (or the steeper the slope), the higher the yield loss per unit reduction in ET as a result of water deficits (Steduto *et al*, 2012)

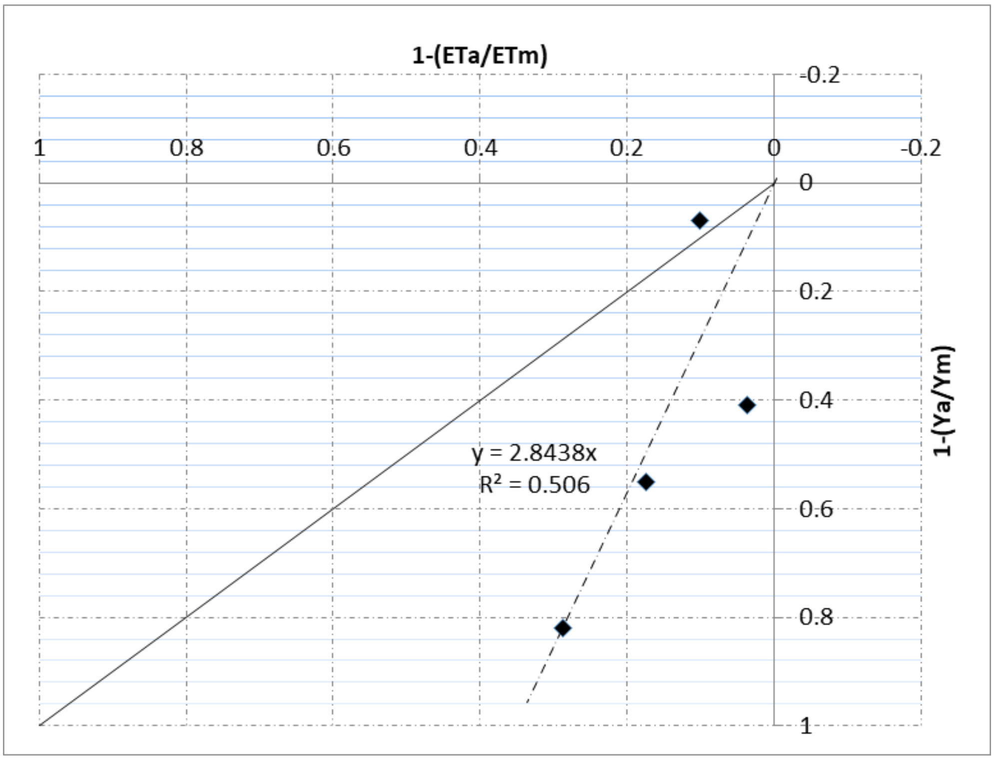

Figure 8: Effect of Irrigation Interval on relative ET deficit and relative yield reduction of NERICA.

According to Doorebos and Kassam (1979), a crop's sensitivity to moisture stress or deficit irrigation can be determined from the k_y value of its total growing period. They stated that ky values < 0.85 mean low sensitivity, 0.85 - 1.0 mean medium-low sensitivity, 1.0 - 1.15 0 mean medium-high sensitivity and >1.15 mean high sensitivity to moisture stress. The average k_y for upland rice in this study was 2.84, showing that rice has very high sensitivity to moistures stress.

Moisture stress, resulting from long irrigation intervals, had a negative effect on crop development (Figure 9). Rice under daily irrigation booted and flowered earliest.

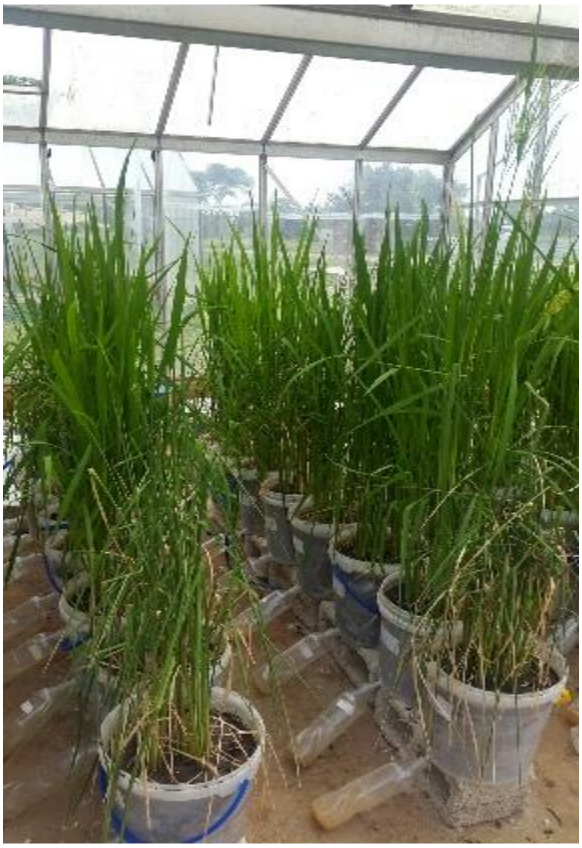

Figure 9: Signs stress in some treatments and differences in development.

4.6. Crop Coefficients

The crop evapotranspiration ranges were 38.28 mm to 40 mm for the initial stage and 214.00 mm to 229.30 mm for the vegetative stage. The crop coefficients ranged from 0.42 to 0.44 in the initial stage and 1.46 to 1.56 in the vegetative stage. The crop evapotranspiration and coefficients of rice in the initial and vegetative stages (before treatments started) were not significantly different ($P>0.05$), as shown in Table 6. The average ET_c values were 39.01 mm and 221.9 mm for the initial and vegetative stages, respectively. The average K_c for the initial stage was 0.43. Akinbilel and Sangodoyin (2010) estimated the K_c value for upland rice (NERICA) to be 0.9. The average K_c value of 1.48 for the vegetative or crop development stage was within the range reported by other researchers (Tyagi et al., 2000; Doorenbos and Kassam, 1979)

Table 6: Effect of Irrigation Interval on ET_c and K_c for the Initial and Vegetative Stages

Treatment (Irrigation interval (days)	Initial Stage ET_c (mm)	Initial Stage K_c	Vegetative Stage ET_c (mm)	Vegetative Stage K_c
1	39.01	0.43	217.7	1.48
2	39.71	0.44	229.3	1.56
3	40.00	0.44	214.0	1.46
4	38.28	0.43	226.5	1.54
Mean	39.01^{ns}	0.44^{ns}	221.9^{ns}	1.51^{ns}
LSD	2.41	0.02672	16.08	0.1093
cv (%)	8.70	8.7	10.2	10.2
Fpr	0.491	0.491	0.196	0.196

The ET_c values at maturity stage were 316.4 mm, 374.1 mm, 320.3 mm and 268.0 mm while K_c values were 1.94, 2.30, 1.97 and 1.64 in order of widening irrigation interval (Figure 10). The differences in crop evapotranspiration and crop coefficient among the irrigation treatments were highly significant ($P<0.05$) at both reproductive and maturity stages. Both ET_c and K_c reduced with an increase in the irrigation interval from 341.8mm to 170.8mm and from 2.63 to 1.32, respectively, during the reproductive stage. This is because less water was available for consumptive crop use as the irrigation intervals widened. Tyagi et al. (2000) estimated the K_c for rice during reproductive stage at 1.14.

Treatment I_4 had the lowest ET_c at both reproductive and maturity stages. The plants were unable to complete physiological processes to the full due to water stress, resulting in low yield and yield components. Treatment I_1 on the other hand had the highest ET_c at reproductive stage but the second lowest at maturity stage. The plants under I_1 had sufficient water during the reproductive stage, but at physiological maturity, the plants did not need a lot of water anymore hence the reduction in ET_c. Treatments I_2 and I_3 were in between these two cases.

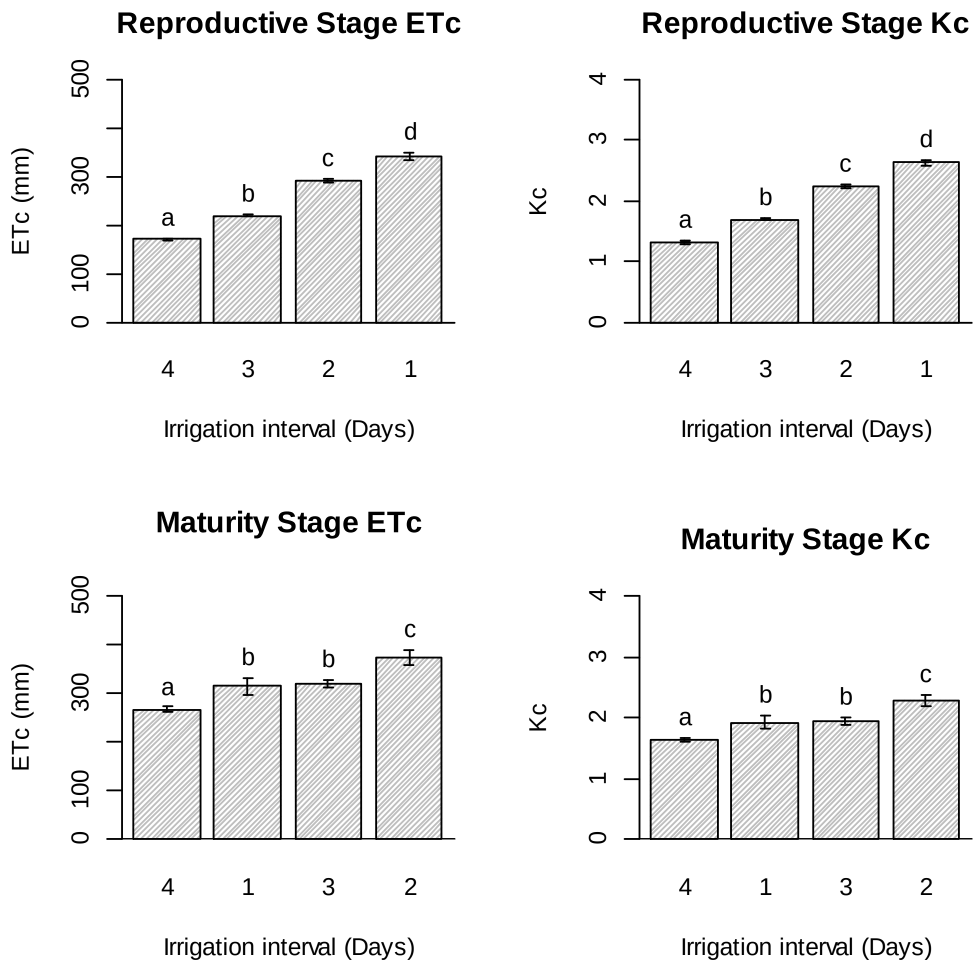

Figure 10: Effect of Irrigation Interval on ET_c and K_c for the maturity and reproductive stages.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

5.1. Conclusion

In this study, increase in the frequency of irrigation significantly improved plant growth and most components of yield such as grain yield, grain weight and harvest index. In general, both biomass and grain WUE significantly increased with increase in irrigation interval and depth of water applied. Though two days and three days irrigation intervals have no significant effect on WUE_g, the results of this study did not show an optimum WUE.

However, seasonal water balance indicated that, under the conditions of this study, the optimal irrigation for upland rice was a two days irrigation interval. Excess above that irrigation depth only resulted in more drainage and an increase in seasonal water storage.

Ultimately, the results of this study showed that, though rice performs best with high irrigation depth, it can be grown and deficit irrigation. Though this may result in reduction in some yield components

5.2. Recommendations

A field study should be conducted to confirm: (a) the optimal ET_c observed in this study and (b) the yield components obtainable under field conditions under the said ET_c.

Another study should look at how upland rice can perform in Zambia when levels of deficit irrigation are applied at vegetative and maturity stages only, and compare water saving with yield loss for each treatment

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APPENDIX

YEILD COMPONENTS

Appendix 1: ANOVA of Biomass per Plant

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	13.184	4.395	1.76	
Rep.*Units* stratum					
Water	3	1148.680	382.893	153.68	<.001
Residual	57	142.018	2.492		
Total	63	1303.883			

Appendix 2: ANOVA of Stover per Plant

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	45.515	15.172	4.66	
Rep.*Units* stratum					
Water	3	23.980	7.993	2.45	0.072
Residual	57	185.643	3.257		
Total	63	255.138			

Appendix 3: ANOVA of Grain per Plant

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	12.260	4.087	1.08	
Rep.*Units* stratum					
Water	3	951.667	317.222	83.96	<.001
Residual	57	215.372	3.778		
Total	63	1179.299			

Appendix 4: ANOVA of 1000 Grain Weight

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	13.715	4.572	0.68	
Rep.*Units* stratum					
Water	3	152.081	50.694	7.57	<.001
Residual	57	381.830	6.699		
Total	63	547.626			

Appendix 5: ANOVA of HI

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	1654.5	551.5	2.36	
Rep.*Units* stratum					
Water	3	11809.9	3936.6	16.82	<.001
Residual	57	13344.3	234.1		
Total	63	26808.7			

Appendix 6: ANOVA of Number of Heads per Plant

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	2.7219	0.9073	2.41	
Rep.*Units* stratum					
Water	3	1.9369	0.6456	1.72	0.174
Residual	57	21.4356	0.3761		
Total	63	26.0944			

Appendix 7: ANOVA of Number of Tillers per Plant

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	10.152	3.384	1.77	
Rep.*Units* stratum					
Water	3	6.943	2.314	1.21	0.315
Residual	57	109.142	1.915		
Total	63	126.237			

WATER BALANCE

Appendix 8: ANOVA of Drainage

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	57632	19211	3.40	
Rep.*Units* stratum					
Water	3	14709610	4903203	868.36	<.001
Residual	57	321851	5647		
Total	63	15089093			

Appendix 9: ANOVA of Change in Storage

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	753.0	251.0	1.38	
Rep.*Units* stratum					
Water	3	27494.9	9165.0	50.42	<.001
Residual	57	10361.8	181.8		
Total	63	38609.7			

Appendix 10: ANOVA of ETc

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	59871	19957	4.53	
Rep.*Units* stratum					
Water	3	621059	207020	47.03	<.001
Residual	57	250900	4402		
Total	63	931831			

WATER USE EFFIECIENCY

Appendix 11: ANOVA of Biomass Water Use Efficiency

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	3.882E-06	1.294E-06	0.40	
Rep.*Units* stratum					
Water	3	7.109E-04	2.370E-04	73.48	<.001
Residual	57	1.838E-04	3.225E-06		
Total	63	8.985E-04			

Appendix 12: ANOVA of Grain Water Use Efficiency

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	4.209E-05	1.403E-05	2.08	
Rep.*Units* stratum					
Water	3	8.540E-04	2.847E-04	42.29	<.001
Residual	57	3.837E-04	6.732E-06		
Total	63	1.280E-03			

YIELD RESPONSE TO STRESS

Appendix 13: ANOVA of Relative ET Deficit

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	0.064050	0.021350	4.26	
Rep.*Units* stratum					
Water	3	0.552084	0.184028	36.73	<.001
Residual	57	0.285598	0.005010		
Total	63	0.901732			

Appendix 14: ANOVA of Relative Yield Reduction

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	0.05990	0.01997	1.08	
Rep.*Units* stratum					
Water	3	4.64980	1.54993	83.96	<.001
Residual	57	1.05230	0.01846		
Total	63	5.76200			

CROP COEFFICIENTS

Appendix 15: ANOVA of ETc at Initial Stage

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	39.54	13.18	1.14	
Rep.*Units* stratum					
Water	3	28.24	9.41	0.82	0.491
Residual	57	657.78	11.54		
Total	63	725.56			

Appendix 16: ANOVA of ETc at Vegetative Stage

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	11902.4	3967.5	7.69	
Rep.*Units* stratum					
Water	3	2497.2	832.4	1.61	0.196
Residual	57	29421.3	516.2		
Total	63	43820.8			

Appendix 17: ANOVA of Kc at Initial Stage

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	0.004882	0.001627	1.14	
Rep.*Units* stratum					
Water	3	0.003486	0.001162	0.82	0.491
Residual	57	0.081207	0.001425		
Total	63	0.089575			

Appendix 18: ANOVA of Kc at Vegetative Stage

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	0.55006	0.18335	7.69	
Rep.*Units* stratum					
Water	3	0.11540	0.03847	1.61	0.196
Residual	57	1.35968	0.02385		
Total	63	2.02514			

Appendix 19: ANOVA of ETc at Reproductive Stage

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	319.4	106.5	0.36	
Rep.*Units* stratum					
Water	3	273008.0	91002.7	305.84	<.001
Residual	57	16960.1	297.5		
Total	63	290287.5			

Appendix 20: ANOVA of ETc at Maturity

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	26633.	8878.	4.14	
Rep.*Units* stratum					
Water	3	90269.	30090.	14.02	<.001
Residual	57	122360.	2147.		
Total	63	239262.			

Appendix 21: ANOVA of Kc at Reproductive Stage

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	0.01895	0.00632	0.36	
Rep.*Units* stratum					
Water	3	16.20414	5.40138	305.84	<.001
Residual	57	1.00665	0.01766		
Total	63	17.22975			

Appendix 22: ANOVA of Kc at Reproductive Stage

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	1.00241	0.33414	4.14	
Rep.*Units* stratum					
Water	3	3.39755	1.13252	14.02	<.001
Residual	57	4.60537	0.08080		
Total	63	9.00532			