YIELD RESPONSE OF DIFFERENT LOCAL AND HYBRID PADDY VARIETIES TO DIFFERENT PONDING DEPTHS

BY

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ABSTRACT

The combined increase in demand for food and scarcity of water worldwide highlights the need for prudent use of water resources. Agriculture, particularly, paddy production, faces two major challenges: (i) to save water; (ii) to increase productivity. One way to deal with this situation is using water saving regimes at field scale. This study therefore was aimed at evaluating some of the water-saving cultural practices in paddy production under Tanzanian conditions. Four different ponding levels (5 cm, 3 cm, 0 cm and the control based on ETc replenishment) represented the main plots while the paddy rice varieties were randomly assigned as sub-plots in each of the main plots. The experiment was designed as 4 x 4 factorial arrangement of treatments in a split- plot design replicated three times (three blocks). Yield, water productivity and seepage and percolation were assessed for each sub-treatment. Results showed no significant difference ($p< 0.05$) in yield of the varieties as a result of ponding depths and no significant interaction between ponding depth and variety. However, the variety effect on yield was significant. On the other hand, there was significant interaction between ponding depth and variety in terms of water productivity. About 10% of the water applied to whole plot treatments with ponding depths 3 cm and 5 cm was consumptively used. The whole plot treatments based on ETc replenishment resulted in the highest water productivity for all the varieties. Variety TXD88 yielded highest at all ponding levels while the 0 cm ponding level had the least seepage and percolation losses amounting to 78% of water applied. This shows that traditional cultural practices requiring inundation over a long period and using large amounts of water can be

dispensed with at minimal loss in yield but at significantly higher levels of water productivity.

DECLARATION

I Emmanuel Mabvuto Nyirenda do hereby declare to the senate of Sokoine University of Agriculture that this dissertation is my own original work and that it has never been submitted for a degree award in any other University.

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DEDICATION

I wish to give special dedication to my mother who though with little formal education; had the conviction that I needed to go to school than to herd cattle, even if it meant me not getting married because of not having cattle to pay dowry. She said and I quote "If these animals (cattle) came in this village so that my children should not go to school, then we should sell them off. My children should go to school. I have never seen anybody failing to get married because they did not have cattle". I pray that God should allow her to live more days.

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LIST OF ABBREVIATIONS AND ACRONYMS

AIT	Asian Institute of Technology
ASA	American Society of Agronomy
ANOVA	Analysis of Variance
ASNS	Alternate Submergence non Submergence
AWD	Alternate Wetting and Drying
AWDI	Alternate Wetting and Drying Irrigation
CA	Comprehensive Assessment
CGIAR	Consultative Group on International Agricultural Research
CRRWS	Cumulative Rice Relative Water Supply
CS	Continuously submergence
E	Evaporation
EM31	Electromagnetic 31
ER	Effective Rainfall
ET	Evapotranspiration
ETc	Crop Evapotranspiration
ETo	Reference Crop Evapotranspiration

ET rice	Crop Evapotranspiration of Rice
FAO	Food and Agriculture Organization
FI	Flush Irrigation
FMIS	Farmer Managed Irrigation Scheme
HYV	High Yielding Varieties
IFPRI	International Food Policy Research Institute
IIMI	International Irrigation Management Institute
IRC	International Rice Commission
IR	Irrigation Requirement
IRRI	International Rice Research Institute
IR rice	Irrigation Water Requirement of Rice
IUE	Irrigation Use Efficiency
IWMI	International Water Management Institute
JICA	Japanese International Co-operation Agency
Kc	Crop factor or crop coefficient
K_p	Coefficient for class A evaporation pan
LR	Nursery and land preparation requirement
MWRM-Cambodia	Ministry of water resources and management of Cambodia

NGO	Non Governmental Organization
NR	Nursery requirement
P	Percolation
Pe	Effective Precipitation
RIS	Relative Irrigation Supply
RRWS	Rice Relative Water Supply
RWS	Relative Water Supply
SADC-ICART	Southern Africa Development Community- Implementation & Coordination of Agricultural Research & Training
SGVP	Standardized Gross Value of Production
SP	Seepage and Percolation
SSC	Saturated Soil Culture
T	Transpiration
UNDP	United Nations Development Programme
USA	United States of America
WP_{I+R}	Water Productivity (Irrigation+ Rainfall)
WP_{ET}	Water Productivity (evapotranspiration)
WRI	Water Resources Institute

WSI	Water Saving Irrigation
$WSmax_j$	Maximum standing water depth
WS_j	Present standing water depth

CHAPTER ONE

1.0 INTRODUCTION

1.1 Global Outlook on Water Availability

More than 97 percent of the world's water resources are in the oceans and seas and are too salty for most production uses. Two-thirds of the remainder is locked up in ice caps, glaciers, permafrost, swamps and deep aquifers. Every year, about 108 000 billion m^3 precipitates on to the earth's surface. About 60 percent of this (61 000 billion m^3) evaporates directly back into the atmosphere, leaving an annual water resource of 47 000 billion m^3 (Barker *et al.*, 2000). If this amount were distributed evenly across the world's population, there would be approximately 9000 m^3 per person per year. However, water availability varies across continents, with North and South America being better watered than Africa, Asia and Europe (Barker *et al.*, 2000). Furthermore, much of Africa and Asia's potential supply is lost through runoff caused by heavy seasonal rains. It is estimated that only 9000 billion m^3 to 14 000 billion m^3, or about a quarter of the annual water resource, may ultimately be controllable. At present, an estimated 3400 billion m^3 to 3700 billion m^3 of water is utilized in the world (Seckler, 1993; Postel *et al.*, 1996; WRI, 1994).

Agriculture is the largest consumer of water, using on average 72 percent of the total worldwide and about 87 percent in developing countries. With the growing demand of water for non-agricultural uses (domestic, municipal, industrial and environmental), the proportion available for agriculture is projected to decline to 62 percent worldwide and 73 percent in developing countries by 2025. In developing countries, the growth in water demand for industrial and municipal uses, in absolute terms, is expected to exceed the growth in water demand for agriculture between 1995 and 2020 (Rosegrant *et al*, 1997).

In agriculture, the principle source of water withdrawal is irrigation. About 60 percent of irrigated cropland is in Asia, and approximately 50 percent of the irrigated area is devoted to rice production. A shift in the future allocation of water among competing uses is inevitable. The global trend will reduce the share of water for agricultural use. The growth in irrigated area has slowed in the past decade and is projected to increase at an annual rate of less than 1 percent between 1995 and 2020 (Rosegrant *et al*, 1997).

Major changes in practices, policies and institutions are required to ensure that limited water resources are appropriately managed to increase the productivity of water in irrigated agriculture. If these steps are not taken, rice will be the crop most affected, as it depends most heavily on irrigation. The increase in water needed to meet the demand for food is a major concern given the growing water scarcity and related environmental problems in many parts of the world. Already 1.4 billion people live in places where water is physically scarce (Mahoo *et al.*, 2007). Another 1.5 billion people live in places where water is available in nature but infrastructure to access it is lacking. It's probable that if today's food production and consumption and environmental trends continue, crises will occur in many parts of the world (Mahoo *et al.*, 2007) The challenges become even greater when we include newly emerging issues such as climate change and its implications for water variability and scarcity, and the demand for agricultural produce for bio-energy and industry. Improvements of water productivity and agricultural productivity in general, are therefore urgent and necessary.

1.2 Implications of Water Scarcity on Agricultural Sustainability

Decreasing availability of good quality fresh water (Postel, 1997) and population growth necessitate more efficient use of water in irrigated paddy production systems. The high water demand of irrigated lowland paddy mainly arises from the traditional requirement of maintaining a permanent layer of water on the field. The permanent water layer causes evaporation, seepage and percolation loses to be higher than in non-flooded fields. In Asia, irrigated agriculture accounts for 90% of total diverted freshwater, and more than 50% of this water is used to irrigate rice alone (Barker *et al.*, 1999). Reducing water input in rice production can have a high societal and environmental impact if the water saved can be diverted to areas where competition is high. A reduction of 10% in water used in irrigated rice worldwide would free 150 000 million m^3 corresponding to about 25% of the total fresh water used globally for non agricultural purposes (Klemm, 1999). Until recently, this amount of water used in lowland paddy production has been taken for granted, but now the global "water crisis" caused by among other factors climate change threatens the sustainability of irrigated rice production. The available amount of water for irrigation is becoming scarce (Gleick, 1993; Postel, 1997). The reasons for this are diverse and location specific, but include decreasing quality (chemical pollution, salinization), decreasing resources (e.g., falling groundwater tables, silting of reservoirs), and increased competition from other sectors such as urban and industrial uses. The urban and industrial demands are likely going to receive priority over irrigation hence it is essential to develop and adopt strategies and practices that will use water more efficiently in irrigated paddy production. This is particularly true in parts of Africa, where demand for rice is increasing and water is less abundant than in Asia i.e. 9 percent renewable water resources compared to 28 percent of global fresh water resources for Asia (Shiklomanov and Rodda, 2003). Various water-saving technologies exist or are being developed to help farmers cope with water scarcity in irrigated environments (Tuong and Bouman, 2005; Humphreys *et al.*, 2005). These technologies increase the productivity of water (rainfall and irrigation) mainly by reducing unproductive seepage and percolation losses and to a lesser extent by reducing evaporation. Achieving high water productivity in paddy irrigated systems will thus provide part of the solution to the limited water availability more so for the Sub-Saharan African region. So far, the discussion on reducing water demand has centered on how to produce more food with less water.

The world faces growing scarcity of and competition for water. By far the largest consumer of water is irrigated agriculture. Within agriculture, rice is the dominant irrigated crop, accounting for approximately 30 percent of the irrigated area (Barker *et al.*, 2000). But water is becoming increasingly scarce. By 2025, the per capita available water resources in Asia are expected to decline by 15–54 percent compared with 1990 (Guerra *et al.*, 1998). Agriculture's share of water will decline at an even faster rate because of the increasing competition for available water from urban and industrial sectors. This study therefore aims at looking at means of saving water by studying the response of different local and hybrid rice varieties to four different ponding depths. The assumption is that water saving technologies could be adopted by farmers at field level which could eventually benefit the society at large.

1.3 Objectives of Study

The overall objective of the study was to evaluate the yield response of four rice varieties to different ponding depths.

The specific objectives included to:-

i) Determine the water productivity of rice varieties at different ponding depths.

ii) Evaluate the differences in vertical saturated hydraulic conductivity reduction as a result of differences in hydrostatic pressure due to ponding depth.

iii) Evaluate the optimum ponding depth of local and hybrid rice varieties.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Water Saving in Rice Cultivation

The term "water saving" has different meanings to different people. Real water saving occurs when losses that cannot be recaptured are reduced or eliminated, however the magnitude of any water saving can vary considerably depending on the spatial and temporal scales of interest (Seckler, 1996; Loeve *et al.*, 2002). Despite this complexity, the ultimate objectives of "water saving" are clear – to minimize unsustainable over exploitation of surface and groundwater resources and increase the amount of water available for non-agricultural purposes (urban, environmental, and recreational). Humphreys *et al.* (2004) thus concluded that water saving in Rice systems has the dual goals of using less water than is currently being used, while increasing production.

For a farmer, "water saving" is likely to mean using less irrigation water to grow a crop, ideally with the same or higher yield (or ultimately profit), thus increasing irrigation water productivity (g grain/kg irrigation water or $/kg irrigation water). However, saving irrigation water does not necessarily mean that total water use (from rain and soil water as well as irrigation) is reduced at the field scale – i.e. that water is really "saved". While saving irrigation water per se has many benefits such as reducing costs to the farmer (e.g. pumping, water charges), increasing both yield and total water productivity (g grain/kg water from rain + irrigation + soil water) are required to meet the increasing demand for food, and to produce it from less water (Humphreys *et al.*, 2004). Saving water in cropping systems is ultimately about reducing non-beneficial losses that is losses that can't be economically recaptured elsewhere in the system. These non-beneficial losses are evaporation from the soil and irrigation water (as opposed to transpiration), and surface and deep drainage into waters too contaminated for reuse (e.g. saline groundwaters, the sea or into locations from which it is too difficult to recapture e.g. aquifers with low transmissivity) (Humphreys *et al.*, 2004).

Saving irrigation water for one crop in one field does not necessarily mean a net saving in irrigation or total water over time. For example, within a field, it may be possible to reduce the amount of irrigation and force a crop such as wheat to use more of the stored soil water while maintaining the yield. However, this may also mean that a larger amount of irrigation water is required to refill the soil profile for the next crop, with no net irrigation or total water savings over the cropping system. Humphreys *et al.* (2004) suggested that in evaluating strategies for saving water it is important to consider the cropping system over time rather than individual crops in isolation. Issues of scale are also extremely important (Molden, 1997). For example, if deep and surface drainage can be captured and reused elsewhere at the spatial scale of interest, a reduction in drainage is not a water saving. Evaluation of the impact of irrigation water saving technologies at the field and farm scales on the availability of water at larger scales is complex and requires the use of approaches that integrate the effects over space and time, such as the 3-dimensional surface-groundwater interaction models developed by Khan *et al.* (2002a, 2002b; 2003b) for the Rechna Doab basin in Pakistan and the lower Murrumbidgee basin in Australia.

Water can also be saved by using varieties of shorter duration; however, this may come at the expense of yield. For the Australian situation, Reinke *et al.* (1994) argued that reducing duration could save up to 10% of irrigation water, whereas Williams *et al.* (1999) concluded that reduced duration will always reduce yield potential and hence water productivity. While there is some evidence for the latter argument, varieties with higher yield potential and shorter duration have been developed (Reinke *et al.*, 2004). Short duration varieties also facilitate increased water use efficiency of the farming system. For example, early maturity allows earlier harvest, increasing the chance of timely establishment of a winter crop after rice and making more efficient use of stored soil water and winter rainfall instead of losing it as deep and surface drainage or transpiration by weeds (Humphreys *et al.*, 2004).

2.2 Water Saving and Productivity

Rice has always been grown in lowland areas under flooded conditions. Rice grown under traditional practices in the Asian tropics and subtropics requires between 700 mm and 1500 mm of water for a cropping season depending on soil texture (Bhuiyan, 1992). The water requirement consists of: (1) 150 – 250 mm for land preparation; (2) about 50 mm for growing rice seedlings in the nursery before transplanting; and (3) 500 – 1200 mm (5 – 12 mm per day for 100 days) to meet the crop evapotranspiration (ET) demand and unavoidable seepage and percolation in maintaining a saturated root zone during the crop growth period (Guerra *et al.,* 1998). Studies conducted on the manipulation of depth and interval of irrigation to save water use have demonstrated that continuous submergence is not essential for obtaining high rice yields (Guerra *et al.*, 1998). Hatta (1967). Tabbal *et al.* (1992), and Singh *et al.* (1996) reported that maintaining a very thin water layer, at saturated soil condition, or alternate wetting and drying can reduce water applied to the field by about 40–70 percent compared with the traditional practice of continuous shallow submergence, without a significant yield loss. The actual amount of water used by farmers for land preparation and during the crop growth period is much higher than the actual field requirement because of seepage and percolation losses.

Paddy farmers often store water in their fields as a back-up safety measure against unreliability in water supply. Also, there is often field-to-field irrigation. This leads to a high amount of surface runoff, seepage and percolation accounting for about 50–80 percent of the total water input to the field (Sharma, 1989). Alternate wetting and drying irrigation (AWDI) is one method that can increase the productivity of water at the field level by reducing seepage and percolation during the crop-growth period. There are different forms of AWDI practiced in different parts of the world. In general, the lighter the texture of the soil, the greater the possible reduction in water requirements (Van der Hoek *et al.*, 2003). The duration of the dry period after the disappearance of ponded water depends on the depth of the water table. The shallower the water table, the longer the interval between irrigation events can be (Mishra *et al.*, 1990; 1997). Water saving as discussed in this study refers to water saved locally in paddy fields. Whether the water saved locally will result in water savings at the level of the irrigation system or river basin depends on what happens to the drainage water, i.e. the amount of water that is delivered to the field but not used by the crop for evapotranspiration (ET). Drainage water may flow to saline areas or to the oceans, where the water is effectively lost to further beneficial uses. In this case, reducing drainage can result in real water savings. On the other hand, in paddy irrigation systems, field to field irrigation is practiced as such recycling occurs. Because of recycling and reuse, one person's drainage may be another person's water supply (Seckler, 1996). In this case, reducing drainage from rice fields is not a real water saving. So, the quantity of water saved through alternate wetting and drying irrigation depends on the location of the paddy field relative to other paddy fields and what happens to the drainage water.

2.3 Water Saving Practices in paddy rice cultivation

Paddy cultivation uses large quantities of water usually under ponded conditions. Paddy fields with artificially controlled hydrological conditions namely irrigation, cover about half of the whole paddy field area in the world and produce three fourths of the total world rice production. Paddy rice culture is sustainable at high productivity because of special cultivation systems, as practiced in Japan. In wet paddies, the surface soil is ponded, and seepage through the root zone removes salts and other toxic constituents (Yoshisuke, 2001). Furthermore, rice yields have been increasing with advances in the science and technology of rice cultivation. Excellent rice varieties, standardized fertilizers, pesticide applications and improved water management have all assured high and stable crop productivity. In addition, labour savings in paddy rice cultivation is an important characteristic. By ponding water, weed control is minimized, whereas this feature of cultivation is one of the most laborious tasks in upland fields. Because of land leveling, agricultural machinery can easily be introduced and efficiently worked. Another labour saving option is the use of rice plant seedling planting machines (Maruyama and Tanji, 1997). Water saving practices in rice paddy cultivation are conducted at field level and project level. Field level practices are soil puddling to decrease percolation, intermittent irrigation, accurate water consumption measurement, water level controller installation and cyclic use of irrigation water. For the project level, practices include introduction of the pipeline water delivering system, optimal system control by the computer and the utilization of information on weather and crop growing conditions.

2.4 Water Management to Reduce Hydrostatic Pressure

Reducing seepage and percolation flows through reduced hydrostatic pressure can be achieved by changed water management (Bouman *et al.*, 1994). Instead of keeping the rice-field continuously flooded with 5–10 cm of water, the floodwater depth can be decreased; the soil can be kept around saturation (saturated soil culture (SSC)) or alternate wetting and drying (AWD) regimes can be imposed. Soil saturation is mostly achieved by irrigating to about 1 cm water depth a day or so after disappearance of standing water. In AWD, irrigation water is applied to obtain 2–5 cm floodwater depth after a number of days (ranging from 2 to 7) have elapsed since the disappearance of ponded water. Wei Zhang and Si-tu Song (1989) reported yield increase under AWD. However, other studies carried out showed that these were exceptions rather than the rule (Bouman and Tuong, 2001; Tabbal *et al.*, 2002b). In most cases, SSC and AWD decreased yield. The level of yield decrease depended largely on the water-table depth, the evaporative demand and the drying period in between irrigation events (in the case of AWD) (Bouman and Tuong, 2001). Mostly, however, relative reductions in water input are larger than relative losses in yield, and therefore water productivities in respect of total water input increased. In some cases, AWD even doubled the water productivity compared with conventional flooded irrigation, but with yield reductions of up to 30% (Tabbal *et al.*, 1992).

2.5 Water Management Strategies to Reduce Water Input in Lowland Rice Production

Large reductions in water input can potentially be realized by reducing the unproductive seepage and percolation flows during crop growth and idle periods (Bouman and Tuong, 2001). There are basically two ways to do so: (1) increasing the resistance to water flow in the soil and (2) decreasing the hydrostatic pressure (depth) of the ponded water. The resistance to water flow can be increased by changing the soil physical properties. Cabangon and Tuong (2000) have shown the beneficial effects of additional shallow soil tillage before land preparation to close cracks that cause rapid bypass flow at land soaking. Thorough puddling results in a good compacted plow soil that impedes vertical water flow (De Datta, 1981). Soil compaction using heavy machinery can decrease soil permeability in certain coarse-textured soil types (Harnpichitvitaya *et al.*, 2001). Finally, researchers have even experimented with introducing physical barriers underneath rice soils such as bitumen layers and plastic sheets (Garrity *et al.*, 1992). However effective, though, most of these soil improvements are expensive and beyond the financial means of farmers. Reducing S&P flows through reduced hydrostatic pressure can be achieved by water management. Instead of keeping the rice field continuously flooded with

5 –10 cm of water, the floodwater depth can be decreased, the soil can be kept around saturation (SSC), or AWD regimes can be imposed. Under these management practices, the hydrology of the soil changes from anaerobic under flooded and SSC regimes to alternately anaerobic and aerobic under AWD. Ultimately, rice could be grown under completely aerobic conditions and continuous S&P eliminated completely.

2.6 Reducing Seepage and Percolation Losses in Rice Fields

Percolation or deep drainage loss is the vertical movement of water below the root zone where it cannot be recovered by crops, whereas seepage is lateral flow through bunds. Seepage and percolation losses at the field scale may be recaptured at a higher system scale, however recapture often comes at a cost in terms of energy for pumping, purchase of irrigation water and labour, construction of drainage systems, and greenhouse gas emissions associated with the production or use of energy. Seepage and percolation losses can be reduced by measures such as reducing ponding depth, AWD irrigation for rice, laser leveling and raised beds. Puddling is also used to reduce percolation rate during the rice cropping period, but whether the total input of water is actually reduced and whether water is really saved are highly questionable.

Soil type has a large influence on irrigation water requirement due to much higher percolation losses on coarser textured soils. This is particularly true for rice grown under ponded or saturated conditions for most of the season. Seasonal percolation losses of 57-83% of the total input water were reported in the North West Indo Gangeti Plains (NW IGP), with highest losses (up to 1500 mm) on sandy and sandy loam soils, and lowest losses on loams and clay loams (up to 890 mm) (Prihar and Sandhu, 1987 as cited by Hira and Khera, 2000). As rice is a shallow-rooted crop, with the majority of roots in the top 20 cm, some of the water percolating beyond the root zone of rice is likely recaptured during the wheat phase, when roots can extract water up to depths of around 200 cm (Prihar *et al.*, 1976; Prihar *et al.*, 1978a; Gajri and Prihar, 1985; Humphreys *et al.*, 2004). Therefore, percolation losses from rice in many studies probably over estimate the actual drainage losses below the root zone in Rice-Wheat systems. Nonetheless, deep drainage losses below the root zone of the rice system can still be very large. For example, assuming that after rice harvest the plant available water content of the profile in sandy loam and clay loam soils to a depth of 200 cm is 300 and 500 mm, respectively, and that this water is used by a subsequent wheat crop, then the deep drainage losses below the root zone of the Rice –Wheat system in the studies of Tripathi, (1996) would range from 390 mm to 1,200 mm. Much of the Rice – Wheat area of the NW -IGP is located on sandy loam to clay loam soils with infiltration rates up to 20 mm/day (Bhatti and Kijne, 1992; Velayutham *et al.*, 1999).

In addition to the problem of high irrigation water requirement, excessive percolation from channels and fields on permeable soils has led to high water tables and problems of salinisation in substantial areas where groundwater quality is poor, such as in much of the Rice-Wheat area in Pakistan (especially in Sindh province) (Aslam, 1998) and problems of water logging in south west Punjab, India (Hira and Khera, 2000). In such regions the groundwater may not be suitable for reuse, for example in most areas of Sindh, and reducing percolation losses is real water saving. In contrast to the NW IGP, annual deep drainage from Australian rice fields is around 200 mm as farmers are tightly regulated to reduce percolation losses and thus water table rise and secondary salinisation (Humphreys *et al.*, 1994). Rice culture is restricted to soils with at least 2-3 m of continuous medium to heavy clay (i.e. > 45% clay) in the top 3.5 m, and irrigation water use must not exceed a target set at the end of each rice season based on actual net evaporative demand. In addition, the total area of rice that is permitted on each farm each year is restricted, and rice area and water use are closely monitored by the farmer-owned irrigation companies. "Rice environmental policy" is defined and implemented by the irrigation companies as part of their overall Land and Water Management Plans. There is considerable variation in percolation rates across soil types and within fields (Van der Lely and Talsma, 1978; Beecher *et al.*, 2002) and small highly permeable areas can make a large impact on total percolation losses (Tuong *et al.*, 1994; Humphreys *et al.*, 1998). Therefore there has been widespread adoption of recently developed electromagnetic (EM31) survey technology for rapidly, accurately and inexpensively identifying soil variability and assessing suitability from texture, or more accurately from soil sodicity, for rice fields, irrigation channels, drains and water storages (Beecher *et al.*, 2002). Most rice in Asia is transplanted into puddled soils. Puddling is done for a range of reasons including weed control, ease of field leveling and transplanting, and to reduce percolation losses.

The relative importance ascribed to each of the above reasons varies. For example, Tabbal *et al.* (2002) considered that puddling in central Luzon, Philippines, is done primarily for weed control, whereas Kukal and Aggarwal (2003) and Gajri *et al.* (1992) placed more emphasis on its role in reducing percolation losses in North West India, where soils are highly permeable. Thorough puddling results in a good compacted plough soil that impedes vertical water flow (De Datta, 1981). Puddling is not essential for rice growth and yield, with many studies (but not all e.g. Singh *et al.*, 2001) reporting similar yields for transplanted or direct seeded rice with and without puddling (e.g. Aggarwal *et al.*, 1995; Humphreys *et al.*, 1996; Kukal and Aggarwal 2003). The high yielding rice cultural systems of Australia and California, (USA) are not puddled.

Although it is widely recognized that puddling reduces percolation, there are surprisingly few reports of quantitative field comparisons of percolation losses in puddled and non-puddled soils. These indicate that the effect of puddling on percolation rate ranges from little to reductions from 30 to 13 mm/day on flooded sandy loam soils and from 17 to 3 mm/day on flooded clay soils (Wickham and Singh, 1977; Sharma and De Datta, 1985; Humphreys *et al.*, 1992, 1996; Kukal and Aggarwal, 2002).

Despite reducing percolation losses during the rice cropping period, puddling does not necessarily reduce the total water input for rice (Tuong *et al.*, 1996; Guera *et al.*, 1998; Tabbal *et al.*, 2002). However, there are only a few reports on comparisons of total water use or percolation losses in puddled and non-puddled systems that include the whole period from pre-irrigation to harvest, and that use the same water management after planting. An exception was the study of Singh *et al.* (2001) which compared water use and yield of water seeded rice with and without puddling on a sandy loam at Delhi, with water depth maintained at 5 cm in both treatments. Averaged over three years there was irrigation water saving of only 75 mm with puddling out of a total irrigation water application of 1537 mm. Thus, even on this highly permeable soil, the irrigation water saving with puddling was relatively small in comparison with the total water use. Puddling for rice induces high bulk density, high soil strength and low permeability in sub-surface layers (Sharma and De Datta, 1986; Aggarwal *et al.*, 1995; Kukal and Aggarwal, 2003), which can restrict root development and water and nutrient use from the soil profile for other crops like wheat after rice (Sur *et al.*, 1981; Gajri *et al.*, 1992). However the impact of puddling for rice on the performance of wheat after rice is variable across sites and years (Sharma *et al.*, 2002). Sharma *et al.* (2003) noted that the few negative yield trends for wheat in long term experiments (Ladha *et al.*, 2003) were mostly observed in medium- to fine-textured soils, which undergo more radical changes in soil physical properties during puddling, while yield trends were positive on the coarse-texture soils of Punjab and Haryana.

2.7 Irrigation Water Requirements of Rice

Paddy rice, growing with "its feet in the water", is an exception in terms of calculation of irrigation water requirements. Not only does the crop water requirement (ET crop) need to be supplied by irrigation or rainfall, but also water is needed for: (i) Nursery and land preparation before transplanting or land preparation for direct sowing and (ii) Seepage and deep percolation during the entire growing season except when draining. Therefore, the seasonal irrigation requirements for rice can be estimated by the following equation (MWRM, 2003):

$$\text{IR rice} = \text{ETc rice} + \text{NR} + \text{LR} + \text{S\&P} - \text{Pe} \quad \ldots\ldots (1)$$

Where,

IR rice = Irrigation water requirements of rice

ETc rice = Crop water requirements of rice

NR = Nursery requirement

LR = Land preparation requirement

S&P = Seepage and percolation

Pe = Effective rainfall

Water required for nursery and land preparation (or for land preparation only in case of direct sowing) is added to the field before transplanting or sowing within a short time (usually a month) by 2-3 applications. The total requirement is therefore added during the first month of the rice cultivation. The amount of water required for nursery and/or land preparation depends on the field condition (soil type, initial soil moisture contents, etc.) and varies between 200 to 300 mm.

Once rice is transplanted (or direct sown), the irrigation requirements are estimated using the following formula (MWRM, 2003):

IR rice = ET rice + SP – Pe ....(2)

The percolation and seepage losses depend on the type of soil. They will be low in very heavy, well-puddled clay soils and high in the case of sandy soils. The percolation and seepage losses vary between 1-8 mm/day (MWRM, 2003). Percolation rate can also be estimated in the field using the infiltrometer. The water balance in the paddy field is shown in Fig. 1.

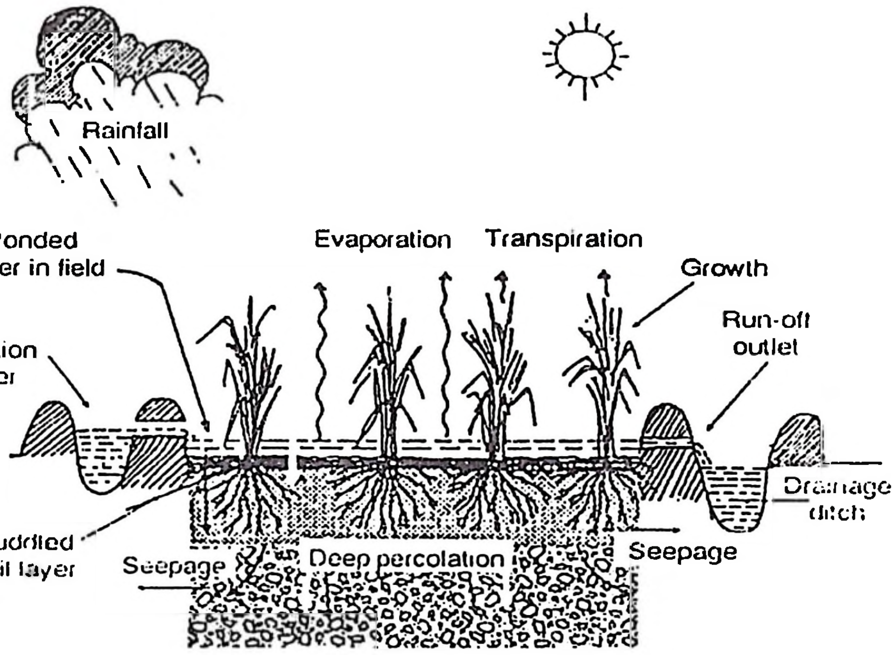

Figure 1: Water balance in the paddy field

(Source: MWRM, (2003)

2.8 Paddy Field Condition for Rice Cultivation

In paddy fields, there are necessary conditions for rice growing besides water, like allowable temperature, adequate daylight hours, abundant sunshine and suitable soil. While these conditions are natural, water is controllable except in the flood prone areas. Average water requirement of rice growth under stable water supply is 220 to 280g of water per g of matter which is almost equivalent to other plants with the same C3 photosynthetic pathway as rice (Yoshisuke, 2001). However rice has some sensitivity to water stress and some tolerance to excess water. There is therefore need to maintain adequate water supply in paddy fields by irrigation and this helps in the following (Tanaka. 1978):

a) Stabilization of water supply to rice plants.
b) Increased supplies of Nitrogen and Phosphorus and control of organic matter dynamics.
c) Supply of inorganic mineral salts contained in irrigation water.
d) Weed control.
e) Prevention of damages by blight and harmful animals. insects and other living things.
f) Maintaining temperature.

2.9 Rice Growing Calendar and Water Management

Fig.2 shows the typical growth stages of transplanted rice and associated management practices. Rice is sown in nursery beds, germinates in 5-7 days. and divides into several stalks in 25 – 30 days. At that time the seedlings are transplanted into wet paddies which had been prepared. About 30 days after transplanting, the stalks begin tillering reaching a maximum number of tillers. After 70-80 days of transplanting young ears form a process referred as heading. About 40-50 days after heading rice can then be harvested. Thus the growth of rice plants can be divided into ten growth stages as shown in Fig 2. A number of water management practices are carried out in accordance with these agronomic practices and growth stages of rice. In order to establish the seedling transplants and to eliminate excess water seepage, soil puddling has to be done before transplanting. Because of potentially large losses from percolation, this is a very important practice for saving water needed in paddy rice culture.

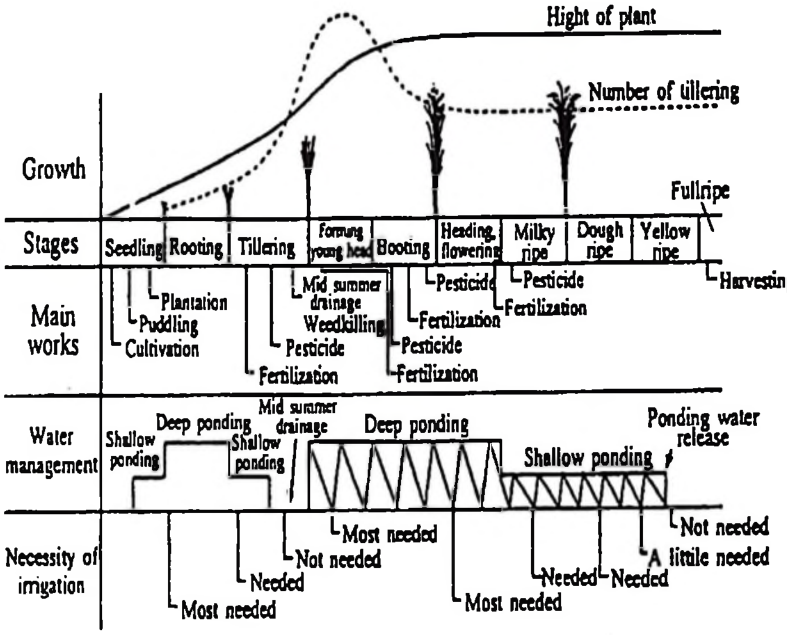

Figure 2: Rice growth stages

source: (Maruyama and Tanji, (1997)

2.9.1 Water Balance in Paddy Fields

Yoshisuke (2001) suggested that the typical water balance equation of a paddy field can be expressed as follows:

$$R + Qi = ET + P + Qo + \Delta S \quad \text{..} \quad (3)$$

Where R is precipitation, Qi is the irrigation water. ET is the evapotranspiration, P is the percolation. Qo is the surface runoff and ΔS the change in storage. When the budget includes the rice and the soil rhizosphere, the storage S includes both ponded water and water content in the soil profile.

ET consists of evaporation (E) from the water or ground surface, and transpiration (T) from rice plants. Percolation (P) is a balance of seepage away from the budget domain and groundwater intrusion from outside of the domain. Usually P is positive since some water is ponded on the field surface. Surface runoff Qo includes runoff of excess rainfall which cannot be stored in the plot and spillage or drainage of water which has been applied or stored. In hydrological practice, the elements of water budget, i.e. the terms of Eq (3) are usually expressed in units of water depth per day. Fig.1 is a schematic representation of the elements in the water balance equation of a plot serviced by an irrigation canal and a drainage canal. Water balance is greatly influenced by the terms on the right- hand side of equation (3) because farmers usually irrigate in accordance with the water consumption and requirements of their plots. Although the consumptive elements on the right hand and the water supply on the left hand side are inseparably related, water application normally follows the fluctuation of water consumption (Yoshisuke, 2001).

2.9.2 Water Management for Rice

Numerous studies on irrigation water savings when changing from continuously flooded rice to saturated soil culture or alternate wetting and drying, have been done and indications are that yields decrease as soil water content declines below saturation

(Sandhu *et al.*, 1980; Heenan and Thompson, 1984; Thompson, 1985; Xu 1999; Bouman and Tuong, 2001; Bouman *et al.*, 2002). However, many studies throughout India and China have shown that continuous ponding is not necessary to maintain rice yields at economically acceptable levels (Sandhu *et al.*, 1980; Prihar and Sandhu, 1987 cited by Hira and Khera, 2000; Xu, 1999; Belder *et al.*, 2004; Tuong *et al.*, 2004). Results from NW India consistently showed substantial irrigation water savings (24 – 40 % or up to 650 mm) with no or small yield loss, and even a yield increase on a sodic soil, in changing from continuous submergence to irrigating 1 to 3 days after the floodwater has disappeared (Sandhu *et al.*, 1980; Sharma, 1999). Sandhu *et al.* (1982) also showed that about 60 mm of irrigation water can be saved, while maintaining yield, by cutting off irrigation 1 week earlier (about 2 weeks before harvest) on a sandy loam. Therefore the recommended practice in Punjab, India is to irrigate 2 days after the water has disappeared and to cease irrigating about two weeks before harvest. Sharma (1989) found no effect on rice yield and water saving of 843 mm (23%) by allowing the soil to dry to -10 kPa at 10 cm depth prior to flooding for periods of 1-3 weeks. Hira *et al.* (2002) compared the recommended practice with irrigation at soil matric potentials of -8 to -16 kPa at 15-20 cm depth. The number of irrigations was highest with the recommended practice of (29 irrigations and 50 mm per irrigation) declining to 18 irrigations when matric potential reached –16 kPa, irrigation water saving of 550 mm with no effect on yield. Much of the irrigation water saving with reduced water depth in Asia is probably due to reduced percolation losses, and therefore may not be a real saving. Kukal and Aggarwal, (2002) showed that percolation rate declined rapidly from about 15 to 5-10 mm/day as water depth declined from 100 to 60 mm on a puddled sandy loam, and from 35 to less than 20 mm/day as the water depth declined from 100 to around 20 mm without puddling.

Bouman and Tuong (2001) concluded that the most promising option to save irrigation water and increase input (irrigation plus rain) water productivity without too much effect on yield was by reducing the ponded water depth from 5-10 cm to the level of soil saturation. In practice this means shallow flooding and frequent irrigation to re-flood the field once the floodwater disappears, and requires timely and accurate water delivery to fields. Bouman and Tuong (2001) suggested that most Asian farmers in public irrigation systems have little incentive to reduce water input to their fields since irrigation water is mostly charged on an area basis, and irrigation systems would need to be able to supply water on demand. They considered that farmers operating pumps would be likely to benefit most from this water saving technique. However, while the cost of electricity for pumping is subsidized, and where power supply is unreliable and only available for short periods, as in NW India. then farmers will continue to apply deep water to their fields as insurance. In Australia, ponding water for 2-3 hours (sufficient time to saturate the root zone) every 7 days throughout the season reduced irrigation water use by 60%, but yields were very low (1-2 t ha^{-1} compared with 9 t ha^{-1} for conventional management) and grain quality was unacceptable (Heenan and Thompson 1984; Heenan and Thompson, 1985).

2.9.3 Water Use Efficiency and Water Productivity

Water use efficiency in crop production can be defined in many ways such as:

a) Amount of water (evapo) transpired per amount of irrigation water applied (IUE, m^3 / m^3)

b) Amount of yield (or biomass) per amount of water use (WP, kg / m^3).

The first definition can be interpreted as irrigation use efficiency (IUE), and the second definition reflects the water productivity. Irrigation use efficiency can be computed for various scales such as a field or a whole basin (Barker *et al.*, 1999). A low IUE can be regarded as inefficient use of irrigation water. Recently, Seckler, (1996) argued that losses on field scale may be used for evapotranspiration downstream and IUE is best computed for the basin level. Effective water management then consists of reducing water flows to sinks such as saline aquifers and seas, and upgrade water use from low to higher valued use. Other reports offer a wide range of management options to reduce irrigation water losses (Guerra *et al.*, 1998; Tuong, 1999 and Hamdy *et al.*, 2003). Water productivity (WP) is the amount of grain yield obtained per unit water. Depending on the type of water flows considered, water productivity can be defined as grain yield per unit water evapotranspired (WP_{ET}) or grain yield per unit total water input (irrigation plus rainfall) (WP_{IP}). At field level, WP_{ET} values under typical lowland conditions range from 0.4 to 1.6 g kg^{-1} and WP_{IP} values from 0.2 to 1.1 g kg^{-1} (Tuong,1999; Bouman and Tuong, 2001). The wide range of WP_{ET} reflects the large variation in rice yield as well as in ET caused by differences in environmental conditions under which rice is grown such as season (vapour pressure deficit), crop management (crop nutrition and protection), and genotypic variation (photosynthetic efficiency and stomatal conductance) (Turner, 1997).

Compared with other C_3 photosynthetic pathway crops, such as wheat, rice has only slightly lower WP_{ET} values. However, the WP_{IP} of rice is somewhat less than half that of wheat. The relatively low WP_{IP} of rice is largely due to the high unproductive outflows of S&P and E. Increasing water productivity at the field level can be accomplished by (i) increasing the yield per unit cumulative ET, (ii) reducing the unproductive water outflows and depletions (S&P, E); or (iii) making more effective use of rainfall (Bouman and Tuong, 2001). The last strategy being important from the economic and environmental points of view, where the water that needs to be provided through irrigation can be offset by that supplied or replaced entirely by rainfall. Two sets of terminologies have to be used to describe water conservation and water productivity. The water use efficiency index measures water conservation and is defined as productivity (P) per unit of water supplied. The water supply includes both diverted water plus rainfall. Water productivity is defined as productivity per unit of water consumed. Water consumed is essentially evapotranspiration, which includes evaporation from soil and transpiration through plants. The water use efficiency index is related to water productivity by the following equation.

$$\left(\frac{p}{s\text{ water supplied}}\right)=\left(\frac{p}{s\text{ water consumed}}\right)\text{x}\left(\frac{s\text{ water consumed}}{s\text{ water holding capacity}}\right)\text{x}\left(\frac{s\text{ water holding capacity}}{s\text{ water supplied}}\right)\;\ldots\ldots\ldots\ldots(4)$$

Where P is the productivity per unit of water supplied and S is the uptake factor.

Or in other words, water use efficiency index = water productivity x water uptake factor x water management factor. The water use efficiency index can be increased by three factors as indicated above. The first factor is water productivity. It can be increased by increasing P or reducing water consumed, or by both. Manipulation of this term is in the realm of plant scientists and bio-technologists. The second factor is the water uptake factor, which is in the realm of soil scientists. Given a particular type of plant, the issue is how to manipulate the soil and its structure so that it can hold sufficient water and supply adequate water so that productivity can be increased. The third is the water management factor wherein the manager operates the system in such a way that he is able to supply water just sufficient to be accommodated within the root zone and meet the crop water requirement in a timely fashion. AWDI is one method of managing the water so that water will not be wasted but it will aid the root growth, facilitate higher nutrient uptake, and increase land and water productivity.

2.9.4 Comparative indicators for irrigation system performance

Comparative performance indicators (output per cropped area, output per unit command, output per unit irrigation supply, output per unit water consumed, relative water supply, relative irrigation supply, Gross return on investment (%) and financial self-sufficiency) make it possible to see how well irrigated agriculture is performing at the system, basin or national scale. As a tool for measuring the relative performance of irrigation systems or tracking the performance of individual systems the International water management institute (IWMI) comparative performance indicators help:

a) Policy makers and planners to evaluate how productively land and water resources are being used for agriculture, and to make more informed strategic decisions regarding irrigation and food production.

b) Irrigation managers to identify long-term trends in performance, to set reasonable overall objectives and to measure progress.

c) Researchers to compare irrigation systems and identify factors that lead to better performance.

d) Donor agencies, governments and NGOs to assess the impact of interventions in the irrigation sector and to design more effective interventions.

Performance assessment has been prioritized as the most critical element to improve irrigation management (Abernethy and Pearce, 1987). Without monitoring and controlling water supply in lowland rice production, it is difficult to improve irrigation management. Traditionally rice is grown under continuous submergence or intermittent or variable ponding conditions depending on the farmer's choice and also water resources. De Datta and Williams (1968) reported that continuous submergence with 5-7 cm of water is probably the best for irrigated rice considering all factors and extreme deep water resulted in poor growth and yield. The overall irrigation efficiency of rice-based systems is less than 50% and is lower in the wet than in the dry season (Guerra *et al.*, 1998). It is also known that poor distribution of irrigation supply with respect to time and space is a prime issue for improving the water management as well as over all irrigation performance.

2.9.5 Irrigation Supply and Demand

The simplest indicator of water delivery performance is how tightly adequate water is delivered to the fields. The two most crucial factors in irrigation planning, design and operation are the available water supply and the water demand. Levin (1982) introduced a performance indicator, which is simply the ratio of irrigation supply and demand called relative water supply (RWS). It was stated then that practically no rice can be grown when RWS < 0.8 and upland crops could be substituted. Nihal (1992) and Sakthvadivel *et al.* (1993) described the methodology using cumulative relative water supply (CRWS) in conjunction with RWS for monitoring and assessing of irrigation water delivery performance. They described the application and weakness of the concept of RWS to assess water delivery performance of rice irrigation schemes. The RWS is useful for analysis and interpretation of irrigation delivery performance for different time intervals though the quantifying of the upper bound value of RWS is a difficult task due to the many variables that influence performance of irrigated agriculture, including infrastructure design, management, climate conditions, price and availability of inputs and social-economic settings. The demands of rice irrigation water are completely different as compared to upland crops. The irrigation delivery system must be flexible in order to respond to fluctuations in weather conditions. All the performance indicators have their own strengths and weaknesses. New performance indicators such as rice relative water supply (RRWS) and cumulative rice relative water supply (CRRWS) to assess the irrigation delivery performance of the rice- based irrigation system as the season advances have been proposed. The new indicators are oriented towards aspects that characterize the irrigation water delivery performance for the irrigation managers rather than indicator like crop yield that is also affected by other factors. The RRWS and CRRWS relate water supply to demand, and give some indication as to the condition of water abundance or scarcity, and how closely supply and demand are matched. In Malaysia, Rowshon *et al.* (2003) found that these new indicators were useful for irrigation managers to characterize the periodic irrigation delivery performance and delivering the right amount of water for the upcoming period depending on availability of water resources simultaneously as the season advances.

2.9.6 Relative water supply

The two most crucial factors in irrigation planning, design and operation are the available water supply and the water demand. The ratio of supply to demand constitutes an important concept called relative water supply (RWS), as originally described by Small, *et al* (1974) and Levine (1982). This ratio is actually the inverse of the traditional concept of "engineering efficiency" as used by irrigation engineers (Bos and Nugteren, 1990). The relative water supply relates the water made available for crops, including surface water, groundwater pumped and rainfall, to the amount crops need. When the crop is rice, the water 'lost' to seepage and deep percolation through the soil is considered when calculating crop demand. This indicator provides information about the relative abundance or scarcity of water. It is useful for analysis of adequacy for different time intervals- annual, seasonal, monthly or special periods such as land preparation. According to kloezen and Garces-restrepo (1998), RWS can be used both as a measure of adequacy and seasonal timeliness.

Sakthivadivel *et al.* (1999) outlined that during land preparation of rice fields, RWS values equal to 1 indicate that irrigation water supply meets irrigation requirement.

RWS values greater than 1 imply that the entire irrigated area is devoted to rice while RWS values less than 1 indicate a rapid decline of the cropped area. For a RWS of 2.5 or more a system with minimal operational control at main system distribution level would be adequate to ensure that water will not be a limiting factor in crop production. Relative water supply is given by the following equation:-

$$RWSj = \left(\frac{IRj + ERj}{ETj + SPj} \right) \qquad \text{...(5)}$$

Where RWS_j is the relative water supply in the j-th week (cm), IR_j is the irrigation water requirements in the j-th week (cm), ER_j is the effective rainfall received during the j-th week (cm), ET_j is the evapotranspiration during the j-th week (cm) and SP_j is the seepage and deep percolation during the j-th week (cm).

2.9.7 Relative Irrigation Supply

The relative irrigation supply indicates how well irrigation supply and demand are matched. A value over 1 suggests too much water is being supplied, possibly causing water logging and negatively impacting yields; a value less than one indicates that crops aren't getting enough water. Relative irrigation supply focuses on supply of irrigation water alone, in contrast to RWS, which also includes rainfall (IWMI, 2000).

$$\textbf{Relative Irrigation Supply} = \frac{\textbf{Irrigation Supply}}{\textbf{Irrigation demand}} \qquad \text{......................(6)}$$

Irrigation supply includes only surface diversions and pumped groundwater. The demands for rice irrigation water are completely different as compared to upland crops. In rice cultivation, the irrigation delivery systems must be flexible in order to respond to fluctuations in weather conditions. Weed control is an especially crucial issue in the rice fields as well as for conducting the agricultural practices during crop growth periods. To replenish the field water level up to the maximum standing water depth ($WSmax_j$), water is added into the paddy fields to meet the difference between the maximum standing water depth ($WSmax_j$) and the present standing water depth (WS_j). The RWS concept gives incorrectly higher values than the new indicators for not considering the depleted water ($WSmax_j - WS_j$). Similar findings were reported by Rowshon *et al.* (2003) who found that they experienced difficulties in monitoring irrigation water delivery performance as the seasons advanced for the Kerian rice irrigation scheme in Malaysia.

2.9.8 Rice relative Water Supply

The RRWS is defined as the ratio of the total supply as irrigation requirement (IR_j) and effective rainfall (ER_j) to the total demand as the sum of the difference between maximum standing water depth and the present standing water depth ($WSmax_j$-WS_j) for a particular irrigation period; evapotranspiration (ET_j) and seepage-percolation (SP_j) in the service areas for the duration being considered. It can distinctly characterize the oversupply for $RRWS_j > 1.0$ and undersupply for $RRWS_j < 1.0$ for any given period as the season advances. The value of $RRWS_j = 1.0$ indicates irrigation supply perfectly matched with the field water demand. The RRWS for crop growth period is mathematically expressed as follws:

$$RRWSj = \frac{IRj + ERj}{(\mathrm{WSmax} - \mathrm{WSj}) + ETj + SPj} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

The oversupply and undersupply is identified for any given irrigation period with the actual RRWS values compared with the RRWS=1.0 in a particular period. Irrigation supply is gradually increased with the amount of depleted standing water until it reaches the maximum level in the field. A value of RWS =0.8 may not represent a problem rather it may provide an indication that farmers could be practicing deficit irrigation with a short water supply to maximize returns on water (Molden *el al.*, 1998). This remark can be adopted for operating irrigation system even at RRWS = 0.5 for a particular period to overcome water shortage and store more rainfall, if WSmaxj is retained.

2.9.9 Cumulative Rice Relative Water Supply (CRRWS)

The CRRWS is defined as the accumulated value of RRWS which is the ratio of supply to the demand commuted over short intervals of time starting from a particular time of the season. The advantage of CRRWS is that it gives the integrated value, which is maintained within the operational range between upper and lower bound values of RRWS and incorporates a component of depleted standing water (WSmax_j – WS_j) in calculating its values and therefore is especially useful for evaluating delivery in rice based systems. In addition, CRRWS also overcomes the weakness of RWS and CRWS of showing false oversupply. Mathematically it is represented as:

$$\mathrm{CRRWS} = \sum_{j=1}^{n}\left(\frac{IRj + ERj}{(\mathrm{WSmaxj} - WSj) + ETj + SPj}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

A plot of CRRWS values provides useful management inferences simpler to interpret than that for CRWS. The values of CRRWS for daily, weekly or any other interval of cropping season with time can be plotted along the x- axis and CRRWS values along the y-axis. This curve carries with it the curve designated as CRRWS=1.0. If computed CRRWS line follows the CRRWS =1.0, it means that irrigation deliveries are properly matched with the field water demand for that particular irrigation period. An increasing slope of the actual CRRWS curve compared to CRRWS =1 means that irrigation supply can be slightly curtailed in the next period. On the other hand if the slope is downwards, supply has to be increased.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of the Study Area

3.1.1 Location

The study was conducted at Mkindo farmer - managed irrigation scheme located in Mvomero District in Tanzania (Fig.3). It is located between latitude 6 ^{0} 16' and 6^0 18' South and longitude 37^0 32'and 37^0 36' East and its altitude ranges from 345 to 365 meters above sea level and is about 85 km from Morogoro town (JICA,1996). The scheme that covers an area of 40 ha was developed in 1982/83 with assistance from the Netherlands Government as a pilot project. It is part of a larger programme to develop a nearby Mgongola village irrigation scheme (600 ha) for paddy production (FAO / UNDP, 1990; JICA, 1996). The scheme area lies between Mkindo river in the north and Mgongola river in the south. It forms part of the extensive Mkata flood plain, which drains into the Wami river and its tributaries. In this pilot scheme, double cropping in a year is being practiced under full irrigation conditions. The design and construction of the diversion weir, main canal and the system's water control structures was carried out by the donor agency and the Tanzanian government staff. Mkindo river which is perennial is the source of the irrigation water for the scheme. It flows eastwards and joins Wami river downstream of the Mgongolo area. Also the Dizingwi stream, which is a tributary of Mkindo river, floods the irrigation scheme during the rainy season. The scheme was developed in two phases. The main canal, which is about 2 km long, feeds secondary canal-1(Sc1) and secondary canal-2 (Sc2). The two secondary canals command a total area of 19 ha for phase I scheme. It also, feeds the secondary canal-3 (Sc3), which commands a total area of 21 ha for phase-II scheme. On the way to the phase-II scheme, the Sc3 crosses the Dizingwi river through an inverted siphon structure and through a pipe culvert for a trunk road (Morogoro- Turian). The Dizingwi river flows eastwards along the downstream border of the phase-I fields and joins the Mkindo river. It serves as a natural drain of the Mkindo scheme.

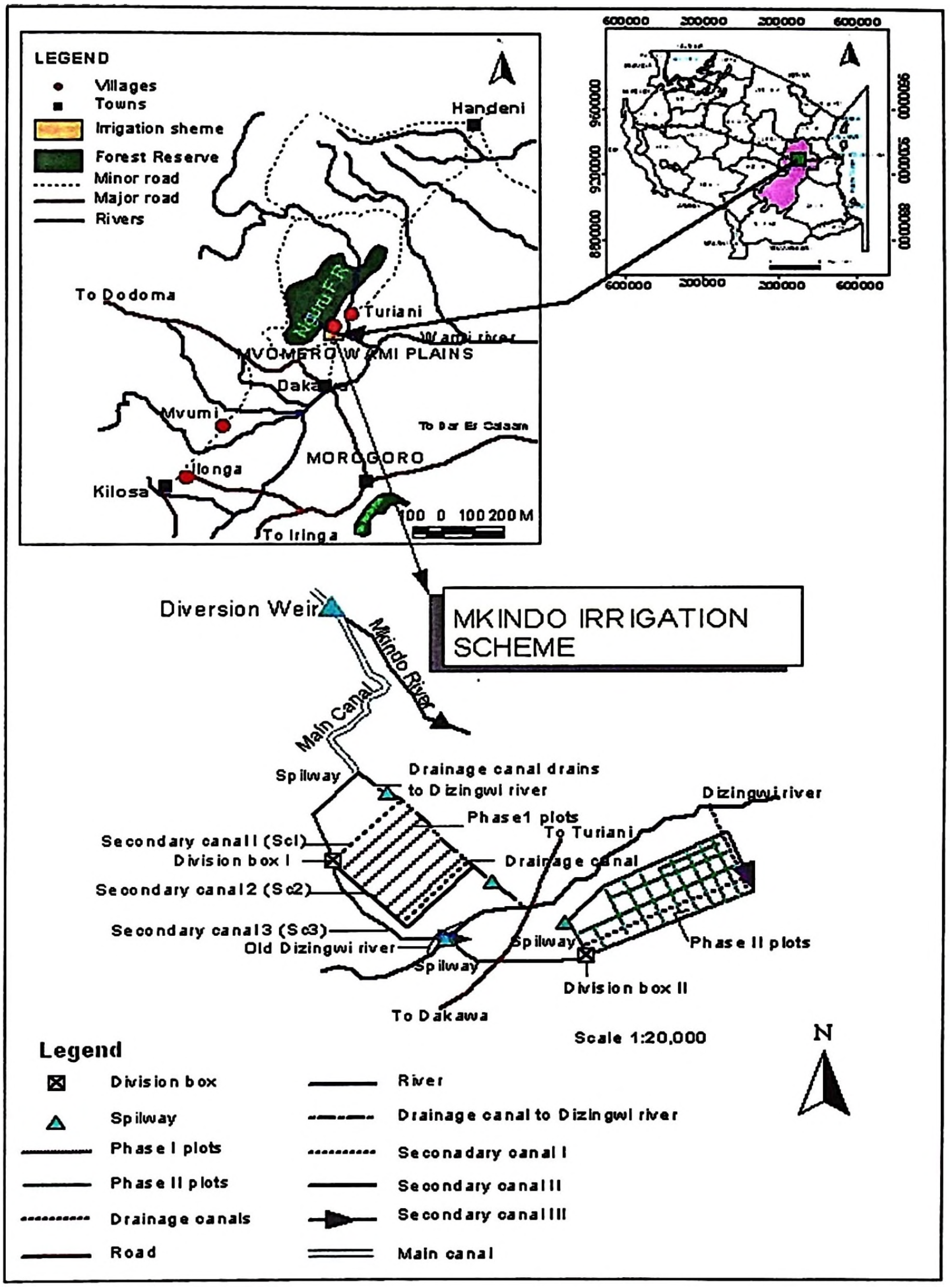

Figure 3: Location map of the study area. Insert shows the relative location within Tanzania. Source : (JICA, 1996).

3.1.2 Climate

Mkindo area is situated in the transition zone between climates with a unimodal rainfall pattern in the south and a bi-modal pattern in the north. Local conditions such as the presence of mountain complexes also influence the rainfall pattern. Mkindo's location at the foot hills of the Nguru mountains and on the wind ward side from the south-east. The Irrigation scheme experiences three distinct seasons that is a dry season starting from June to September, a short rainy season from October to February and a long rainy season from March to May. The average annual rainfall is 1200 mm with a peak rainy season in April. The average annual temperature is 24.4 °C with a minimum of 15.1 °C in July and a maximum of 32.1 °C in February. The minimum relative humidity is 67.5% in May. The mean annual sunshine duration is 7 hours per day. Annual evaporation rates vary from 3.1 mm/day in May to 6.7 mm/day in February. This makes the total annual values for evaporation to be more than 2160 mm which is much higher than the annual rainfall received in the area and therefore the need for irrigation (JICA, 1996).

3.1.3 Hydrology

The hydrological conditions of the Mkindo area are strongly influenced by the Nguru Mountains, the Dizingwi stream, lateral subsurface flow of groundwater and differences in topography. In the western block of the area, the water table lies between 1.5 m to 2 m during the dry season and much higher in the wet season (0.3 m to 0.5 m below the surface) (JICA, 1996). The watertable in the area is particularly influenced by seepage and lateral subsurface flow of water (interflows) from the higher ground.

Runoff from higher ground plays a minor role and the land is unlikely to be flooded for more than a few hours during and after heavy rains (JICA, 1996).The eastern block receives most water from the Dizingwi stream. During heavy rains, the river inundates the land and the water remains standing in the back swamps where internal drainage is slow (heavy clay soils). This area remains very wet during the rainy season with ponded water and water table close to the surface (0.2 m to 0.3 m). The Mkindo river is the main river draining the area. Estimated monthly mean discharge of the Mkindo river for twenty years shows that the river has a maximum flow of 1.9 m^3/sec in September (JICA, 1996).

3.1.4 Soils

The soils have relatively high inherent fertility, fine texture (clay to clay loam) and medium soil texture in the deep soil profile. The soil is mainly alluvial having been fossied by periodic floods. The drainage ability of these soils is poor mainly due to high ground water level. Most of the soil in the scheme is acidic with a pH ranging from 5.6 to 6.9 (JICA, 1996).The land in the scheme is intensively utilized for paddy cultivation with two crops per calendar year. One crop under rainfed conditions and another under irrigation.

3.1.5 Climatic data collection

Mkindo area does not have a meteorological station within its vicinity. The nearest station is the Morogoro meteorological station located approximately 85 km. Daily maximum and minimum temperature, humidity, sunshine hours, wind speed and rainfall data collected from Morogoro meteorological station over a ten year period

(1987-1996) were used in the Penman-Montheith equation to calculate reference evapotranspiration (ETo) as presented by Allen *et al.*, (1998). This was in turn used to calculate crop evapotranspiration (ETc) and net Irrigation requirement for the control treatment as shown in Appendix A. Morogoro station was chosen as relevant to represent the weather conditions in the study area. A rain gauge was installed at the study site during the study period. The collected rainfall data accounted for part of the water applied when calculating the water productivity (irrigation + rainfall) (Fig. 4). An evaporation pan was installed at the experimental site. The data on evaporation was used along with data from the drainage lysimeters to determine amount of transpiration taking place. This data was summed with that for seepage and percolation to calculate the total water losses in the different ponding levels.

Figure 4: Rain-gauge installed at the experimental site about five weeks after transplanting.

3.1.6 Experimental layout and agronomic practices

The experimental design was a factorial arrangement of treatments in a split plot design. There were three blocks representing the three replications and in each block, each ponding level representing a whole plot (ETc, 0 cm, 3 cm and 5 cm) was represented once in a 12 m^2 size bed with a spacing of 1m in between the whole plots. For each ponding level or whole plot, all the four rice varieties (subplots) were represented in a 2 m^2 sized bed with a 0.2 m space separating the different varieties within the whole plot. There was no genetic interference as a result of this spacing since rice is self pollinating. There were a total of 48 individual treatment combinations (3 blocks x 4 ponding depths x 4 varieties) (Fig. 7). All the four rice varieties were first sown in nursery beds and managed for one month on the nursery. Thereafter, the seedlings were transplanted on the same day. For the first two weeks, the small transplanted seedlings were not subjected to the different ponding levels to allow them to overcome the transplanting shock.

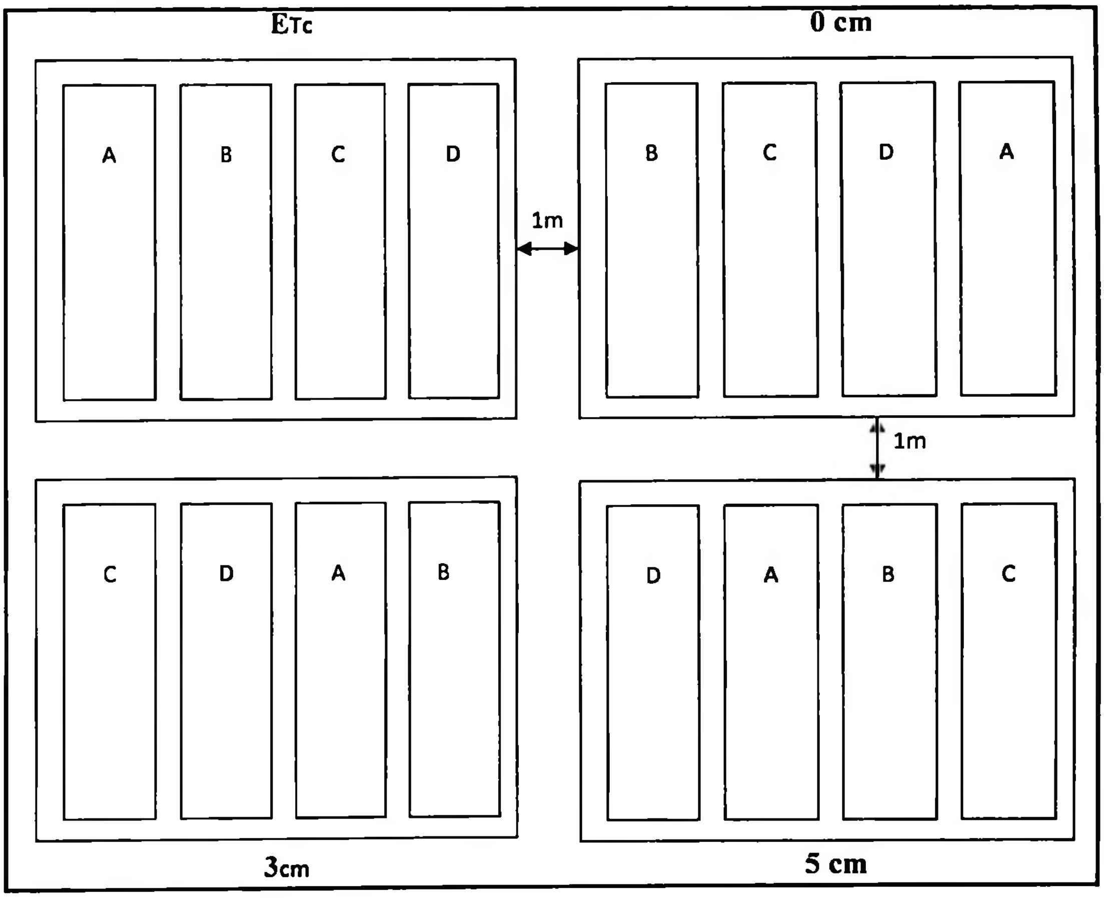

Figure 5: Schematic layout of subplots and whole plots for one of the blocks

i) Capital letters A, B, C and D are subplots representing the different paddy varieties each with an area of 2 m^2 spaced at 0.2 m.

ii) ETc, 0 cm, 3 cm and 5 cm are whole plots representing the different ponding depths each with an area of 12 m^2 (which includes space between subplots and space for the subplots).

Other than the different ponding levels, all the agronomic practices were the same in all the subplots. First Fertilizer application was done in the third week after transplanting at a rate of 46 kg nitrogen per hactare while the second application was done at 7 weeks after transplanting at the same rate of 46 kg nitrogen per hectare two days after draining the plots that had initially been flooded. The plots were flooded again to their respective levels after one week. In this study 0 cm ponding level refers to 1 cm depth of ponding water and ETc ponding level was the control treatment combination for the study and refers to water application based on daily climatic weather conditions and the amount of water in this treatment combination was applied on a daily basis and there was no permanent ponding. In the data analysis though, amount of water from rainfall was taken into account in the ETc ponding level. Weeding was carried out continuously during the entire growing season as the weeds appeared. All the plots were drained off for 10 days as from 6 weeks after transplanting to allow for sufficient supply of oxygen to the root zone of rice and removal of substances such as sulfides and organic acids. Second Fertilizer application was done during the draining period in the 7th week.

3.1.7 Evaluating differences in hydrostatic pressure due to ponding using the drainage lysimeters

Four pairs of drainage lysimeters were installed at the study site. Each pair represented one of the ponding levels. For each pair, one drum was opened on both sides to allow for free drainage flow while the other one was opened on one side only. Both were filled with disturbed soil to the same level, and planted with rice and managed till harvest. On a daily basis, the amount of water applied to maintain a specific ponding level was noted and at the end of the study summed up. The ponding depths were maintained in each pair for the entire period of the study. The difference between the amount of water added to maintain the ponding level to the drums opened on both sides and the ones opened on one side is the seepage and percolation loss. The amount of seepage and percolation was determined for the different ponding levels representing the four treatments. The drums only opened on one side lost water by evaporation and transpiration while the ones opened on both sides lost water by seepage and percolation besides the loss by evaporation and transpiration. The amount of seepage and percolation was determined by calculating the difference in the amount of water utilized in a particular pair of drums for each ponding level (Fig. 6).

Figure 6: Three pairs of drums planted with rice being used as lysimeters

Water productivity is defined as the amount of yield (or biomass) per unit water used. Water productivity of the different rice varieties at different ponding depths was determined by dividing the total yield from each sub plot by the total amount of water that was utilized from each sub plot over the study period. The optimum ponding depth was determined by considering the overall performance of the four varieties in terms of yield versus the amount of water used over the entire study period for each ponding level. The optimum ponding depth was taken as the ponding depth that had the highest water productivity.

3.1.8 Measurement of depth to water table

Three piezometer pipes were installed at the study site. One piezometer in each block. On a weekly basis the depth to watertable was measured. The depth to watertable ranged from 0.15 m to 0.30 m during the experimental period. Appendix E.

Figure 7: Picture showing the siting for one of the piezometer pipes, drainage lysimeter and a raingauge within the experimental site

Figure 8: The Four paddy rice seed varieties sown in different nursery beds

3.1.9 Nursery bed preparation

Before sowing, seeds were first soaked in water for 24 hours after which the seeds were removed from the water and allowed to germinate within about three to four days. After the seeds had germinated, they were taken and sown into the nursery beds. Agricultural practices on the nursery included application of fertilizer, weeding and irrigation while cultural practices included preventing mouse from eating the young seedlings. Seedlings were transplanted after four weeks into the respective plots.

Figure 9: The paddy rice seedlings a week before transplanting

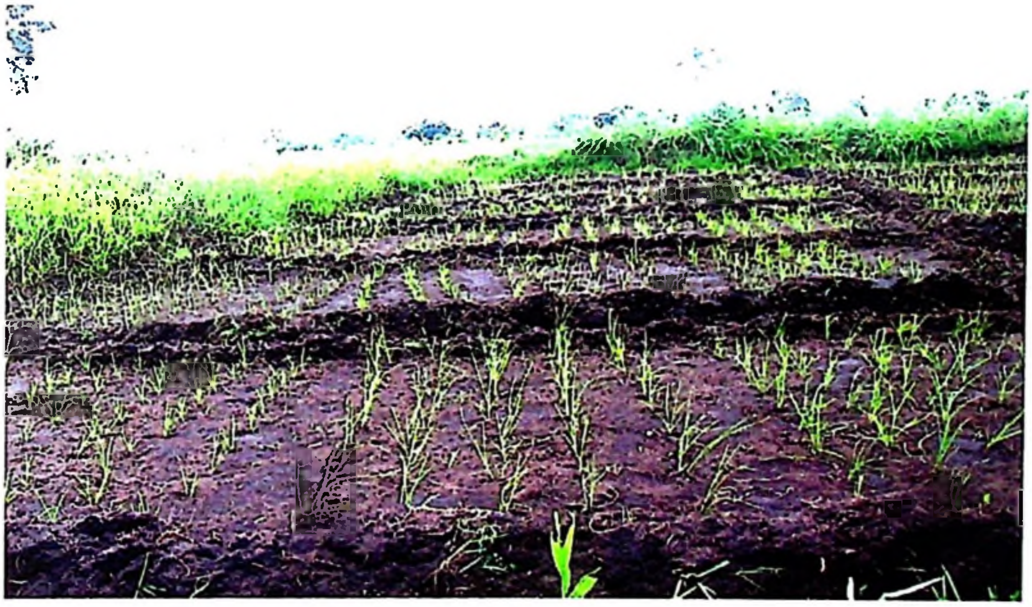

Figure 10: Transplanted paddy rice first week after transplanting before administering any ponding

Figure 11: One of the five cm ponding treatments, rice at tillering stage

3.1.10 Crop yield

The paddy rice was harvested separately for each of the (varieties) within the treatment plots and weighed just after harvesting and then allowed to dry for four days until the moisture content reached 14%. The weight at 14% was taken as the final yield because at this moisture content, rice can be stored. The moisture content was determined using a moisture meter.

3.1.11 Data analysis

A statistical computer programme constat was used to analyse variance (ANOVA) so as to test the amount of variation attributed to treatments by checking the unexplained residual variation. The error mean square was used to measure the variation among treatment plots. The least significance difference was used to separate means. In conformity with the experimental design described, the statistical analysis model adopted was the 4x4 factorial arrangements of treatments in a split plot design with three blocks as replications. The observations are described by the statistical model:

$$Y_{ijk} = \mu + \beta_i + \alpha_j + \omega_{ij} + \gamma_k + (\alpha\gamma)_{jk} + \varepsilon_{ijk} \quad \ldots\ldots(10)$$

For $i = 1, 2 \ldots a$

$j = 1, 2 \ldots b$

$k = 1, 2 \ldots n$

where :

Y_{ijk} is the response

μ is the general effect

β_i is the replication / block effect

α_j is the main factor effect

ω_{ij} is the main plot random error effect

γ_k is the sub plot factor effect

$(\alpha\gamma)_{jk}$ is the interaction effect

ε_{ijk} is the subplot random error effect

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents results of the yield response of one local paddy variety and three hybrid paddy varieties as influenced by different water ponding depths. The data obtained was used to evaluate three performance indicators namely:

i) Water productivity of the different paddy varieties.

ii) Differences in seepage and percolation rate as influenced by differences in hydrostatic pressure.

iii) The optimum water ponding treatment that resulted in the highest water saving.

4.2 Grain yield as influenced by paddy variety

The grain yield of paddy was affected by variety as is shown in Fig. 12.

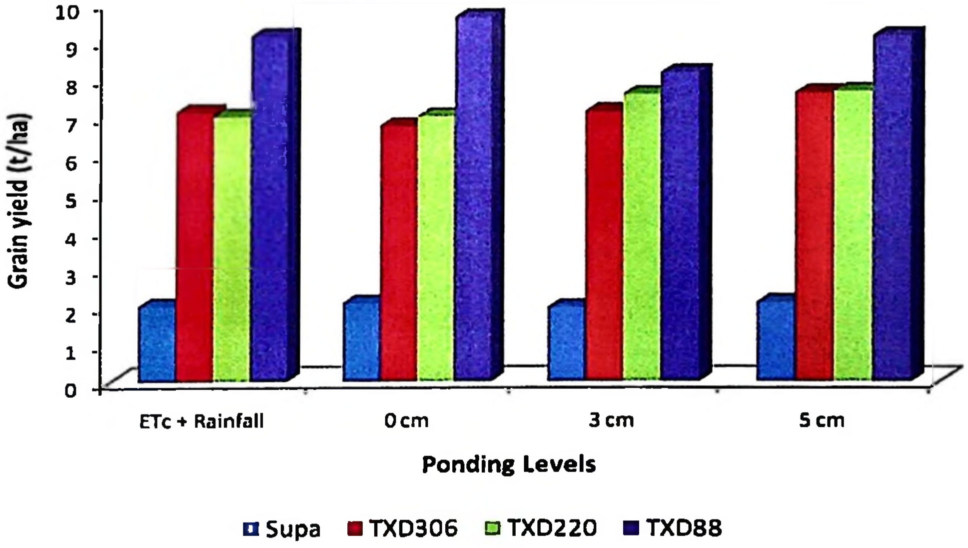

Figure 12: Grain weight for each paddy rice variety for each ponding level

Table 1: Grain weight produced by each variety at each ponding level

Ponding Levels	**Yield of varieties in tonnes per hectare**			
	Supa	TXD306	TXD220	TXD88
ETc + Rainfall	2(Ca)	7.12(Bb)	7(Bb)	9.12(Ab)
0 cm	2.08(Ea)	6.75(Dc)	7(Cb)	9.61(Ba)
3cm	1.96(Fa)	7.12(Eb)	7.58(Da)	8.15(Cc)
5cm	2.1(Fa)	7.62(Ea)	7.66(Ea)	9.12(Db)

Note: The capital letters represent significant difference across varieties and the lower case letters significant differences across ponding levels but within varieties at 5 % probability level.

The grain yield for each variety at each ponding level is given in Table 1. Statistical analysis of the data showed significant difference in yield as a result of varietal differences. TXD88 variety had the highest crop yield at all ponding levels with the maximum yield at the zero ponding level. This describes the influence of the difference in variety on crop yield. Supa variety had the lowest crop yield at all ponding levels with the highest yield at the 5 cm ponding level. Further, the results showed no interaction effect between ponding and variety at the 5% level. The 5 cm ponding level had the highest yield / ha for all varieties. Except for TXD 88 variety, the 5 cm ponding level had the highest yield / ha for all varieties.

Table 2: Differences in yield of varieties from lowest to highest

Variety	Supa	TXD306	TXD220	TXD88
Yield in tonnes/ha	2.1	7.62	7.66	9.61
% difference between lowest and highest	0	72.4	72.5	78.1

There was a 78.1% yield difference between the highest variety yielder TXD88 and the lowest variety yielder Supa, 72.4% between varieties TXD306 and Supa and 72.5% between varieties TXD220 and Supa respectively (Table 2). Based on Table 1 and 2 it can be concluded that in terms of yield of the four rice varieties, TXD88 is the best variety. This underpins the importance of choosing high yielding paddy varieties. In terms of water savings, any agronomic practices that increases the harvest index such as site-specific nutrient management, good weed management and proper land leveling; can result in more crop yield per unit water transpired by the crop and increase rice yield significantly without affecting ET. This may result in increased water productivity (Moody, 1993; Tuong *et al.*, 2000; Hill *et al.*, 2001). High yielding varieties like TXD88 would for the same amount of water produce more food and this is very important for a growing population in the sub region and the world at large. By producing more food with less water, more water will be made available for other natural and human uses (Molden and Rijsberman, 2001). Reducing water input in rice production can have a high societal and environmental impact if the water saved can be diverted to areas where competition is high (Klemm, 1999).

4.3 Influence of ponding levels on crop yield

The crop yield for each variety at each ponding level is shown in Table 1. Statistical analysis of the data showed no significant difference in crop yield of the different paddy varieties as a result of differences in ponding levels at the 5% level. This means that the yield of paddy was not affected by the different ponding levels. These findings are consistent with the findings of Guerra *et al.* (1998); Hatta (1967); Tabbal *et al.* (1992); Pirmoradian *et al.* (2004); Wu (1999); Li and Barker (2004) and Singh *et al* (1996). Their findings were that continuous submergence was not essential for obtaining high paddy yields and that a substantial amount of water was saved while yield was not affected as long as a saturation soil condition was maintained. Studies in India and China produced similar results (Sandhu *et al.*, 1980; Prihar and Sandhu 1987 as cited in Hira and Khera, 2000; Chaudhary, 1997; Xu, 1999; Belder *et al.*, 2004; Tuong *et al.*, 2004). Since in this particular study, yield of the paddy varieties was not influenced by the different ponding treatments, it means therefore that adopting minimum ponding depth to save water at field level is a practical water saving strategy.

Further the statistical analysis showed that there was no interaction effect between the ponding level and variety grain yield. This is probably due to the contribution of ground water because the water table in the study area was between 0.15 m - 0.3 m deep for most of the study period taking into account the fact that the effective rooting depth for rice is 0.4 m. Under different circumstances however, results might be different. Cabangon *et al.* (2004) and Belder *et al.* (2005a) observed that groundwater table depths were shallow (between 0- 0.30 m) in various water-saving field experiments in typical lowland paddy areas of China and Philippines. They found that under these conditions, the soil remained close to saturation and that the paddy benefited from direct water uptake from the shallow groundwater and from capillary rise. Yields under saturated non- saturated (SNS) or alternate wetting and drying (AWD) conditions in these fields were at par with yields under continuously flooded conditions. On the basis of water productivity and yield of the four varieties, the optimum ponding level that resulted in the highest yield is the 0 cm ponding level. It resulted in minimal losses by seepage and percolation compared with the 3 cm and 5 cm levels (Table 4). The water losses resulting from the different treatment combination increased in the following order ETc < 0 cm < 3 cm < 5 cm.

Table 3: Seepage and percolation rates under different ponding levels

Ponding depth	**ETc**	**0 cm**	**3cm**	**5cm**
Seepage & percolation in mm per day	0	2.5	5.95	9.4

4.4 Contribution of rainfall to the amount of water applied

Figure 13 shows the weekly amount of rainfall received and the weekly calculated evapo-transpiration for the study period. During the study period, a total of 300 mm rainfall was received. The amount of rainfall received translates to 53.6% of the crop consumptive use for the period. Of this amount, there was a contribution of 148.8 mm of rain to the amount of water applied to TXD88 and TXD306 varieties because of their short growing period and a contribution of 300 mm to the amount of water applied to Supa and TXD 220 varieties. There were five weeks in which the rainfall received was higher than ETc (Fig. 13). This explains why the WP_{I+R} values were lower compared to

WP_I as indicated in Tables 5 and 6. On the basis of the amount of rainfall that was received during the study period, it is plausible to conclude that there was a significant contribution of rainfall to the amount of water applied and therefore this affected the results for the ETc ponding level (Table 4 and Fig. 13). This means that the yield based on the ETc replenishment could have been influenced by rainfall. The other three ponding levels were not affected because the rainfall received did not result in ponding levels higher than the respective treatments as such only positively contributed to the amount of water applied.

Table 4: Total weekly rainfall and evapo-transpiration data in mm during study period

Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Rainfall	**6**	**0**	**6**	**22**	**31**	**3**	**40**	**40**	**0**	**43**	**62**	**28**	**19**	**0**	**0**	**0**	**0**	**0**
ETc	**40**	**45**	**45**	**48**	**46**	**40**	**33**	**31**	**33**	**33**	**23**	**21**	**21**	**21**	**20**	**20**	**18**	**21**

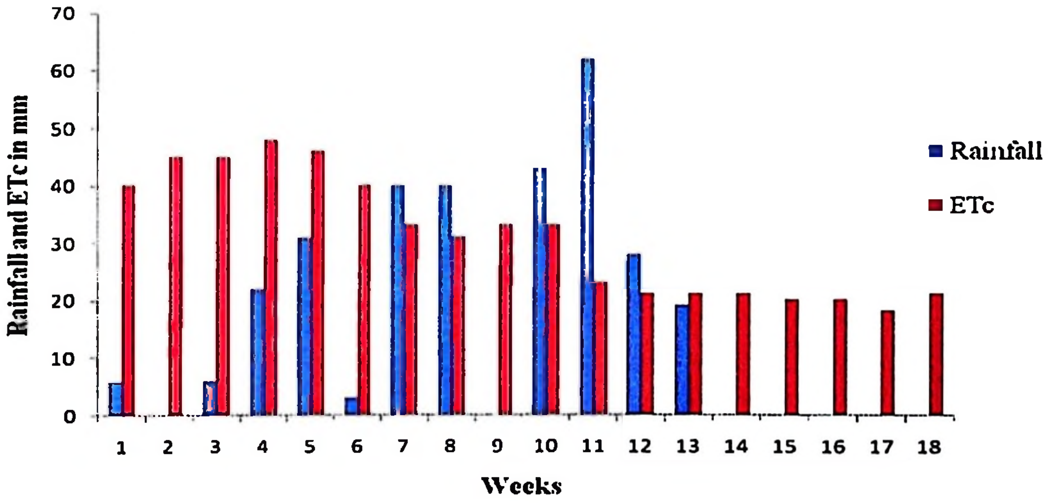

Figure 13: Plot of rainfall and ETc values for the study period

4.5 The effect of differences in hydrostatic pressure on seepage and percolation

Under flooded paddy cultivation conditions, water is required to match outflows (seepage, S, and percolation, P) to the surroundings and depletions to the atmosphere (evaporation, E, and transpiration, T). Seepage and percolation rates are a function of soil type, topography and ground water table conditions. Where the soils are heavy and watertable is close to the surface, seepage and percolation losses are as low as 1 mm/day or less and where the soils are light and the watertable is deep, the losses may be as high as 10 mm/day or more (Brouwer,1986). Because they are difficult to separate in the field, S and P are taken together as one term, i.e. S&P. Typical S&P rates for paddy-fields during the crop growth period vary from 1-5 mm per day in heavy clay soils to 25-30 mm per day in sandy and sandy loam soils (Wickham and Singh, 1977; Jha *et al.*, 1981).

Table 5: Soil textural classes for different depths within the study area

Depth (m)	Soil texture
0 – 0.3	Sandy clay
0.3 – 0.6	Sandy clay loam
0.6 – 0.9	Sandy loam
Composite sample	Sandy clay loam

The results of soil textural analysis are presented in Table 5. The composite sample indicated that the soils in the study area were sandy clay loam. Prihar and Sandhu, (1987) carried out studies in sandy and sandy loam soils and reported that seepage and percolation losses were as high as 57% - 83% of the water applied. Other studies on seepage and percolation carried out in the Indo- Gangetic Plains of India found that losses were as high as 1500 mm in sandy soils and 890 mm in loam soils for a single cropping season of paddy. Similar studies conducted in Japan in a loamy soil puddled paddy field surrounded by bunds under continuous submergence revealed that 60% - 70% of the total crop water requirement was lost through deep percolation and only a small portion 30% - 40% was utilized consumptively (Koga, 1992). The results in this study showed a linear relationship between the depth of ponding and the amount of seepage and percolation. The higher the ponding depth, the higher was the seepage and percolation rate for the same soil type, cultivation and agronomic practices. The results in Figure 14 and Table 6 demonstrate that it is possible to completely eliminate or reduce seepage and percolation losses if irrigation application is only up to field capacity or just slightly below saturation and therefore save water and increase the crop water productivity. Tabbal *et al.* (2002) reported reduced water inputs and increased water productivity of rice grown under just-saturated soil conditions compared with traditional flooded rice. It has been suggested that rice could be grown aerobically under irrigated conditions just like upland crops, such as wheat or maize (Bouman, 2001).

As indicated in Tables 3 and 6, the seepage and percolation rate in this study was found to be a function of depth of ponding. It was highest at 5 cm and lowest at 0 cm and there was no seepage and percolation from the ETc ponding level.

Table 6: Seepage and percolation water % at different ponding levels over the entire study period

Ponding level	Seepage and percolation (%)	Water consumptively used (%)
ETc	0.0	100
0 cm	78.27	21.73
3 cm	89.7	10.3
5 cm	93.7	6.3

About 94% of the water applied was lost as seepage and percolation in the 5 cm ponding depth, while 89.7%, 78.2% and 0% in the 3 cm, 0 cm and ETc ponding levels respectively over the entire study period Table 6. From these results it can be concluded that only about 10% of the total amount applied was used to meet the consumptive use for the crop in the 3 cm and 5 cm ponding levels. Fields at Mkindo Irrigation scheme are irrigated by field to field irrigation system and the slope of the land in the scheme area is in the west- east direction. This could have influenced the depth of water table during the study period and consequently the rate of seepage and percolation.

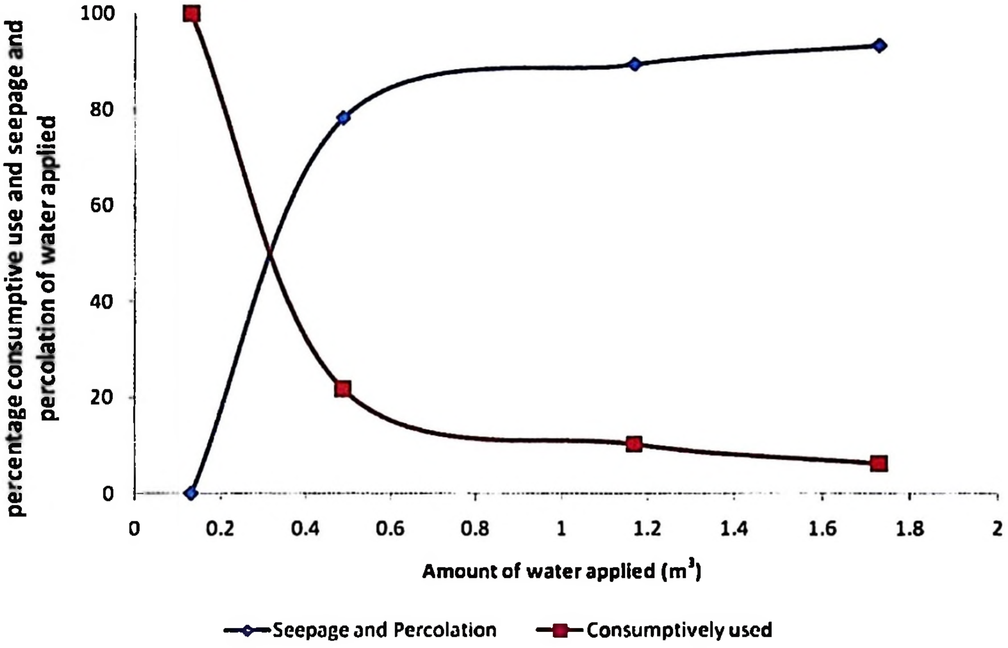

Figure14: Trend of consumptively used water and that lost due to seepage and percolation

As the ponding depth is increased, the amount of water used for irrigation increases as a result of increased seepage and percolation losses. Although the amount of water consumptively used remains the same, in percentage terms of water applied, the consumptive use decreases as amount of water applied is increased (Fig. 14). It can thus be concluded that there is no benefit for increasing the depth of ponding in paddy cultivation as it encourages unproductive losses. Consumptive use is 100% of water applied when seepage and percolation is zero and decreases to about 6% of water applied when seepage and percolation is about 94% of water applied at the 5 cm ponding level. Since depth of ponding and hence increase in water applied does not contribute to yield increase, it means that, the optimum ponding level is the one that had the minimum seepage and percolation loss which is the Zero ponding treatment. At this application, the amount of water applied is just slightly above the ETc replenishment value and therefore the most efficient in terms water utilization.

4.6 Water productivity

Water productivity (WP) expresses the output/input relation or 'crop per drop' (Kijne *et al.*, 2003). Water productivity can be computed as grain yield divided by total water input (WP_{I+R}) as shown in Table 7 or by evapotranspiration (WP_{ET}) as shown in Table 8. Water productivity is dependent on several factors, including crop genetic material, water management practices, agronomic practices and the economic and policy incentives to produce (Molden *et al.*, 2001). In this study, WP_{I+R} values of the four paddy varieties were lower than water productivity irrigation (WP_I) because of the contribution of rainfall to amount of water applied.

Table 7: Water productivity values (Irrigation + Rainfall) for the different paddy varieties at different ponding treatments (kg /m^3)

Variety	Water Productivity in kg /m^3			
	Ponding depths (cm)			
	ETc	0 cm	3 cm	5 cm
Supa	0.124(Dd)	0.065(Cc)	0.037(Bb)	0.036(Aa)
TXD220	0.314(Ee)	0.237(Dd)	0.146(Cb)	0.139(Ba)
TXD306	0.522(Ff)	0.371(Ee)	0.193(Db)	0.196(Ca)
TXD88	0.671(Gg)	0.529(Ff)	0.221(Ec)	0.234(Db)

Note: The capital letters represent significant differences across ponding levels while the lower case letters represent significant difference across variety at 5% level.

Table 8: Water Productivity (Irrigation) for the different paddy varieties at different ponding treatments (kg /m^3)

Variety	Water Productivity in kg/ m^3			
	Ponding depth			
	ETc	0 cm	3 cm	5 cm
Supa	0.253(Dd)	0.125(Ee)	0.052(Df)	0.049(Ff)
TXD306	1.154(Cc)	0.626(Dd)	0.241(Ce)	0.242(Ee)
TXD220	0.958(Bb)	0.494(Cc)	0.204(Cd)	0.192(Ed)
TXD88	1.483(Aa)	0.936(Bb)	0.276(Cc)	0.294(Dc)

Note: The capital letters represent significant difference across varieties while the lower case letters represent significant difference for the same variety but across ponding treatments at 5% level.

Variety TXD88 gave the highest WP_I and WP_{I+R} at all ponding treatments followed by TXD306, TXD220 and Supa variety had the lowest. The ETc ponding level had the highest water productivity for all varieties despite the contribution of rain to this treatment followed by the zero ponding level. The ETc ponding level had the highest water productivity (WP_{ET}) because ponded water was absent which reduced the seepage and percolation losses. The performance of these varieties in relation to water use could only have been affected by ground water contribution because of the high watertable as alluded to earlier. The difference in water productivity between the 3 cm ponding level and 5 cm ponding level was found to be small because the difference in the hydrostatic pressure was equally small. This indicates that the water productivity is directly related to the amount of water losses at field level. The paddy varieties in this study did not increase their yield as the ponding depth increased as such there was an inverse relationship between an increase in ponding depth and the resulting water productivity. The results obtained from this study are consistent with those reported by

Tuong (1999) though with different varieties as indicated in Table 9. It was observed that high yielding varieties are more water efficient than lower yielding varieties for the same amount of water applied and for the same soil conditions.

Table 9: Water productivity values for rice from different areas (Source: Tuong, 1999)

WP_{ET} g/kg	WP_{IR} g/kg	Source of data used in calculating water Productivity	Location
	0.05-0.25	Bhatti and Kijne(1992), rainwater not included	Pakistan
1.39- 1.61	0.29-0.39	Bhuiyan *et al* (1995), wet seeded rice	Philippines
1.1		Sandhu *et al* (1980)	India
0.88 - 0.95	0.33-0.58	Kitamura (1990), dry season	Malaysia
0.89		Mishra *et al* (1990)	India
0.4 – 0.5		Khepar *et al* 1997	India
	0.2 - 0.4	Bouman and Tuong (2001); 24 data sets	India
	0.3 – 1.1	Bouman and Tuong (2001); 16 data sets	Philippines

Similar results for lowland paddy have been reported elsewhere (Bouman and Tuong, 2001). The wide range of WP_{ET} reflects the large variation in paddy yield as well as in ET caused by differences in environmental conditions under which rice is grown such as season (vapour pressure deficit), crop management (crop nutrition and protection), and genotypic variation (photosynthetic efficiency and stomatal conductance) (Turner, 1997). Tabbal *et al.* (2002) suggested that the aerobic condition in rice could be maintained by using flush irrigation (FI) or sprinklers so that ponding occurs for only short periods of time just after irrigation or rain and therefore save water. The potential of water saving irrigation to reduce water inputs and its effect on yield and water productivity depend on soil type, groundwater table depth and climate (Bouman and Tuong, 2001).

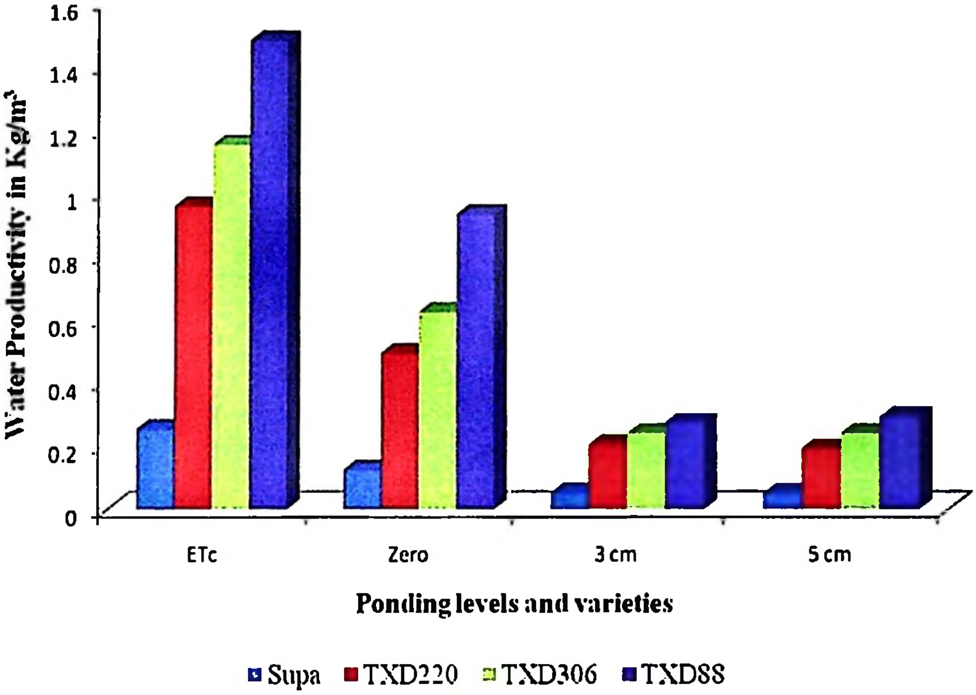

Figure15: Water productivity (irrigation)

Figures 15 and 16 show that as the ponding depth increases, it results in reduced water productivity. The calculated water productivity irrigation for the ETc treatment however included rainfall because there was no control over the rainfall. The results from this study emphasize the importance of saving water at field scale by reducing the water losses (seepage and percolation and evaporation) and the need to optimally utilize the rainfall contribution in order to produce more grain per drop of water and therefore achieve food security and sustain the environment which is of paramount importance in the world where water resources are getting scarce and the population is increasing.

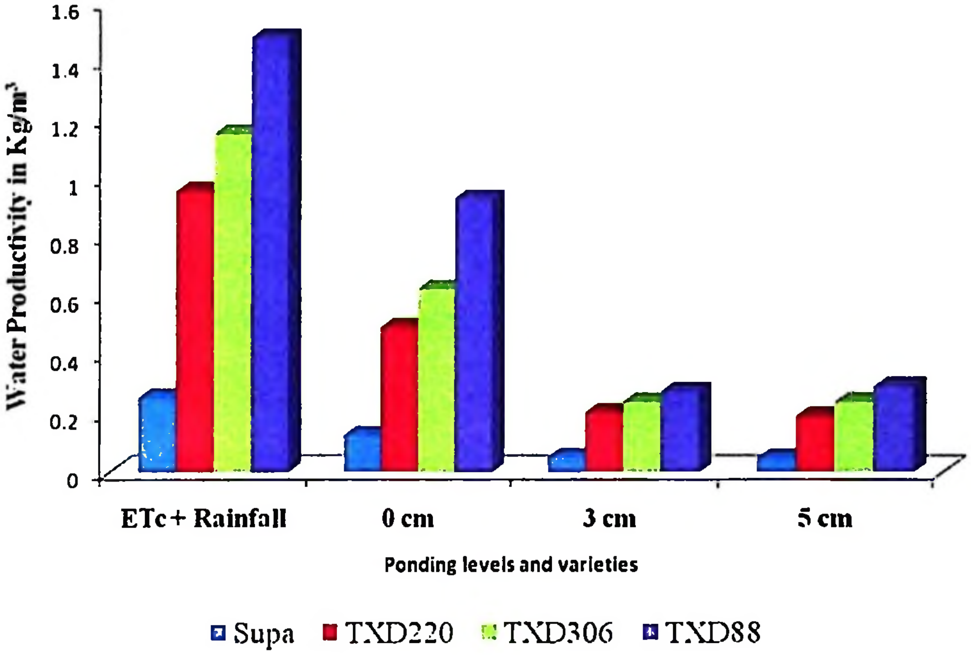

Figure 16: The water productivity (irrigation + rainfall)

4.7 Effect of length of growing period on water productivity

Irrigation water can also be saved by using varieties of shorter duration; however, this may come at the expense of yield. Reinke *et al.* (1994) argued that reducing duration could save up to 10% of irrigation water, whereas Williams *et al.* (1999) reported that reduced duration will always reduce yield potential and hence water productivity. While there is some evidence for the latter argument, varieties with higher yielding potential and shorter duration have been developed (Reinke *et al.*, 2004). Short duration varieties also facilitate increased water use efficiency of the farming system. For example, early maturity allows early harvest, therefore increasing the chance of timely establishment of a second crop after rice and making more efficient use of stored soil water instead of losing it as deep and surface drainage or transpiration by weeds. Of the four varieties that were used in this experiment, varieties TXD88 and TXD306 were short duration varieties i.e. they took 90 days after transplanting while TXD220 needed 105 days after transplanting and finally Supa variety took 120 days after transplanting. Because of the longer growing period for Supa and TXD220 varieties, the amount of water used was high and the resulting WP for the different ponding levels was lower compared to that for varieties TXD88 and TXD306 which have a short growing period (Fig. 17). TXD88 besides being high yielding is also a short maturing variety as such had the highest water productivity followed by TXD306 which has the same length of the growing period as TXD88 but does not yield as high as TXD88. Varieties TXD306 and TXD220 have the same yield levels but TXD220 had lower water productivity than TXD306 partly because of the longer growing period. Supa variety had both a longer growing period and very low yield levels as such had the lowest water productivity. Thus the longer the growing period, the higher the amount of water used and the lower the water productivity for the same yield levels resulting in less water being saved. On the other hand the shorter the growing period, the less will be the water utilized and therefore the higher the water productivity and the more the amount of water saved. This means that high water productivity at field level can be achieved by several factors as single entities or through a combination of factors. These are use of high yielding varieties, use of short growing period varieties, reduced ponding depth of water and agricultural practices such as puddling.

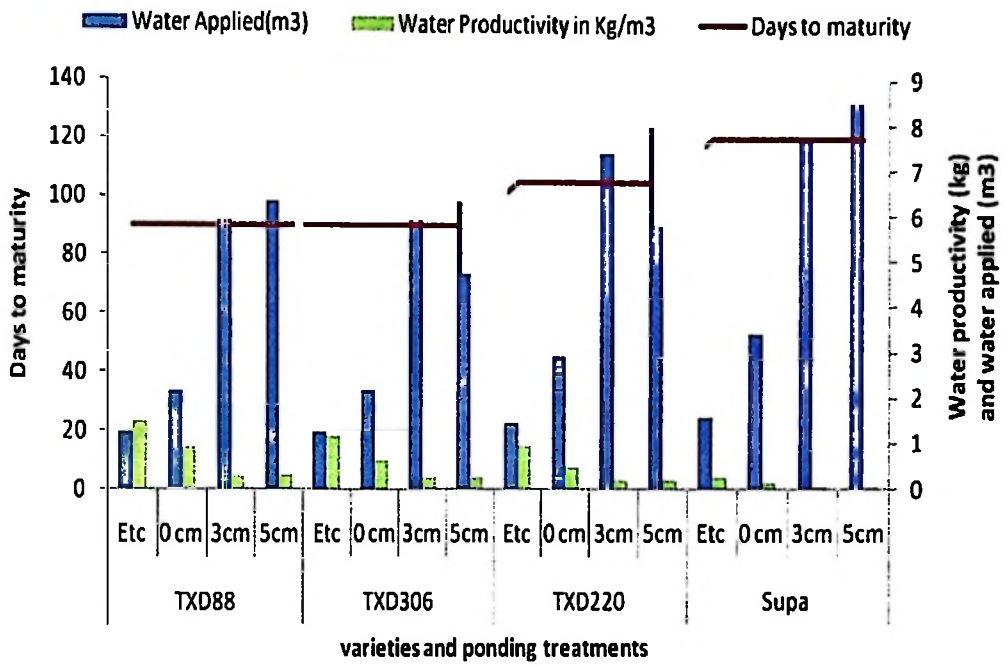

Figure 17: Cumulative amount of water applied, water productivity and days to maturity versus ponding levels for respective varieties

From Fig.17, it can be observed that the cumulative amount of water applied was a function of the number of days from transplanting to maturity and the depth of ponding. In so far as the ponding levels are concerned, as the depth of ponding increased, the amount of water applied also increased but the water productivity reduced with increase in ponding depth. Bennet (2003), identified short duration of crop growth and increase in harvest index as some of the factors that could increase production without increasing transpiration and therefore increase water productivity.

4.8 Characterizing the irrigation water delivery performance

4.8.1 For the Etc Ponding level

Various indicators are used for evaluating the performance of different aspects of an irrigation system. Performance assessment has been prioritized as the most critical element to improve irrigation management (Abernethy and Pearce, 1987). The importance of controlled water supply and monitoring is indispensable for the sustainability of lowland rice production. In this study the following indicators were used to characterize the irrigation water supply: Rice relative water supply (RRWS), Relative water supply (RWS), Cumulative rice relative water supply (CRRWS) and Cumulative relative water supply (CRWS). In the case of RWS, a value of 1.0 represents the lower bound while a value of 1.15 represents the upper bound (Nihal, 1992). In the case of CRWS which gives an integrated value, which is maintained within the operational range between upper and lower bound values of RWS, in an event that there is no rain, then RWS would have to be increased according to operational range (Nihal, 1992). As for RRWS, it distinctly characterizes oversupply for $RRWS_J > 1.0$ and undersupply for $RRWS_J < 1.0$ for any given period as the cropping season advances. A value of $RRWS_J = 1.0$ is indicative of the fact that supply is perfectly matched with field water demand. On the other hand, CRRWS gives the integrated value which should be maintained within the operational range between the upper and lower bound values of RRWS.

Table 10: Values for RRWS and RWS for the ETc ponding level

Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
RRWS	1	1	1	1	1	1	1.22	1.31	1	1.33	2.74	1.34	2.02	1	1	1	1	1
RWS	1	1	1	1	1	1	1.22	1.31	1	1.33	2.74	1.34	2.02	1	1	1	1	1

The weekly RRWS and RWS values for the ETc treatment were computed (Table 10) and plots made with upper and lower limits values of 1.15 and 1.0 respectively as indicated in Fig.18 and 19. The irrigation delivery can be characterized as having perfectly met the demand in 13 weeks out of 18 weeks, from weeks 1to 9 and after week 14 to week 18. There was an oversupply during weeks 7 and 8 and between weeks 10 and 14 which can be attributed to the 232 mm rainfall that was received during that period as indicated in Fig.14. The values for RRWS and RWS were found to be the same throughout the entire 18 weeks. This is because unlike the other three ponding levels, in this combination treatment there was no standing water as such in calculating RRWS, only ET and S&P were considered in the denominator of the equation which is exactly the same when calculating RWS. The highest value of 2.74 occurred in week 11 for both the RRWS and RWS which was the week when the highest rainfall far above ETc (Fig. 14) was recorded and the smallest value was 1.0 (Table 9).

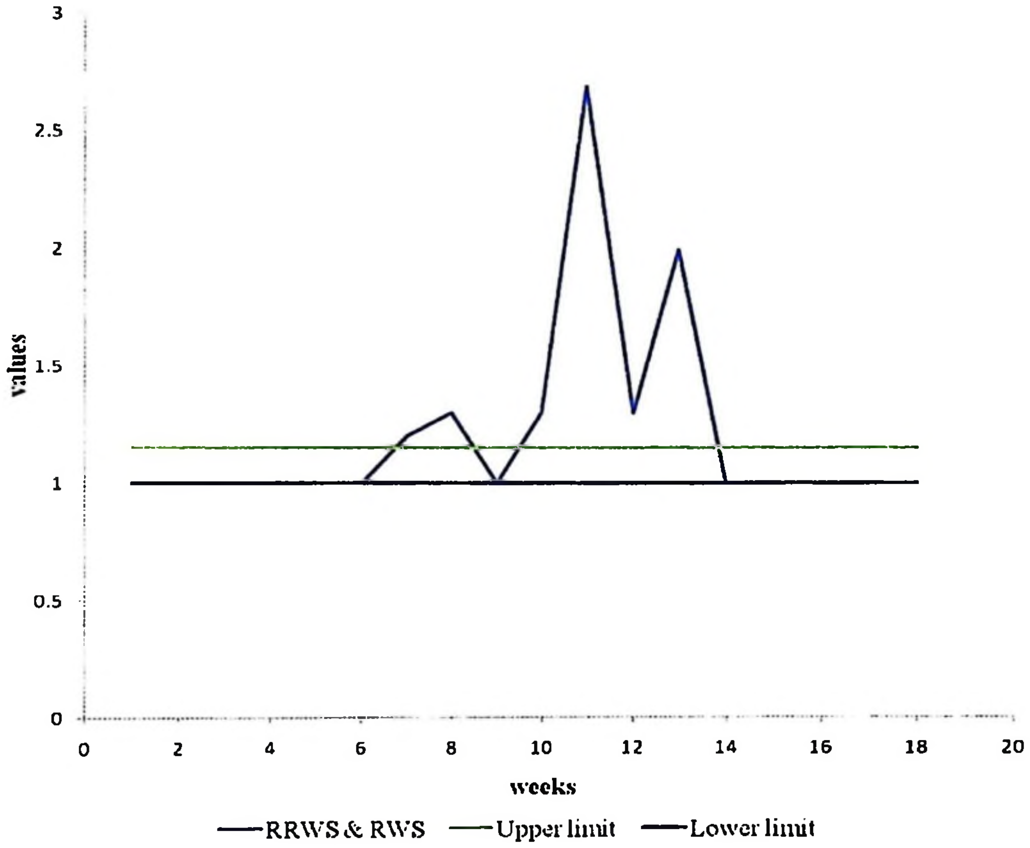

Figure 18: RWS & RRWS, upper and lower limits for ETc combination treatment

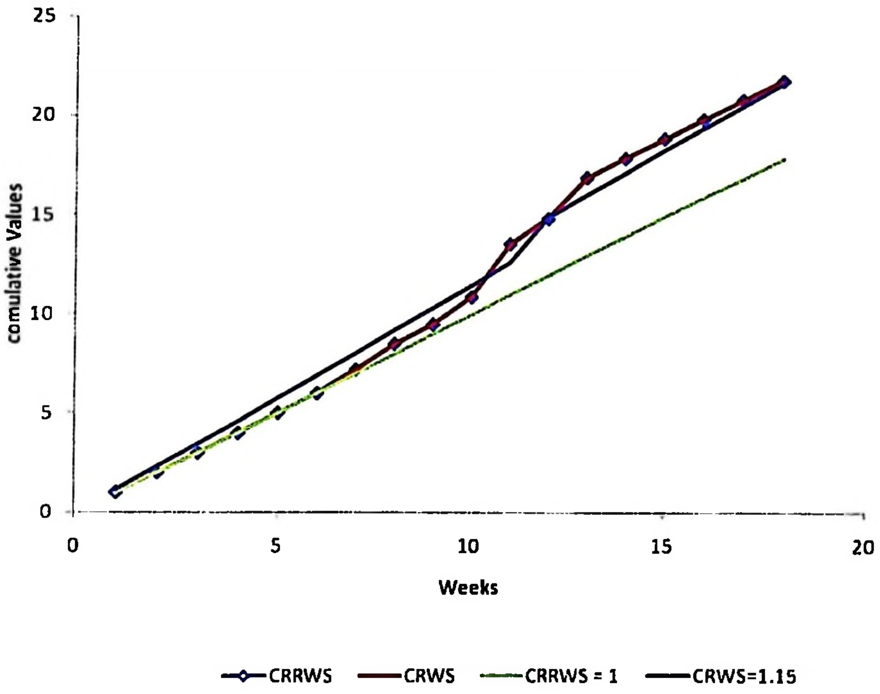

Figure 19: Plot of CRWS and CRRWS for the ETc combination treatment

The CRWS and CRRWS cumulative values were plotted for the entire study period along with curves designated CRRWS = 1 and CRWS = 1.15. During the study period, the graph obtained for CRRWS was higher than the CRRWS = 1 while the graph for CRWS did not exceed the upper bound line for CRWS = 1.15.It is thus plausible to conclude that in this treatment the water supply adequately met the demand with an oversupply between the 10th to 14th week. This is observed in Fig. 19 where there is an increasing slope of CRRWS line with respect to the CRRWS = 1 line.

4.8.2 For the 0 cm ponding level

The RWS values were greater than the RRWS values for the entire period except during weeks 7 and 8. This could be attributed to the fact that during this period, the study area was drained as such there was no ponding and therefore minimal seepage and percolation. The minimum value for RWS was 0.8 and the highest 1.6 while in the case of RRWS, the minimum value was 0.7 with the highest being 1.5. In both threshold values, the oversupply occurred during the 10 th and 13th weeks because of the contribution from the rains (Fig. 14). There was under supply between weeks one to Four and from week 14 to week 18. Over supply also occurred between the 7th and 8 th weeks.

According to (Molden *et al.* 1998) a RWS value of 0.8 may not represent a problem rather it may provide an indication that farmers are practicing deficit irrigation with a short water supply to maximize returns. Molden *et al.* (1998) further suggested that it was also possible to operate irrigation systems at RRWS = 0.5 for a particular period to overcome water shortage and store more rainfall. The values for RWS were found to be greater than the values for RRWS (Fig.20). This is consistent with what Rowshon *et al.* (2003) observed, that the RWS concept gives incorrectly higher values than RRWS and CRRWS because of not considering periods when there is depletion. A plot of CRRWS, CRWS and CRRWS = 1 and CRWS = 1.15 (Fig. 22) indicates that the computed CRRWS line was less than the CRRWS =1 line. This therefore means that the irrigation delivery was not entirely matched with the field demand during the entire study period and water supply needed to be increased. In terms of RRWS values, there was an oversupply in 6 (six) weeks out of 18 (eighteen) weeks (Fig. 21).

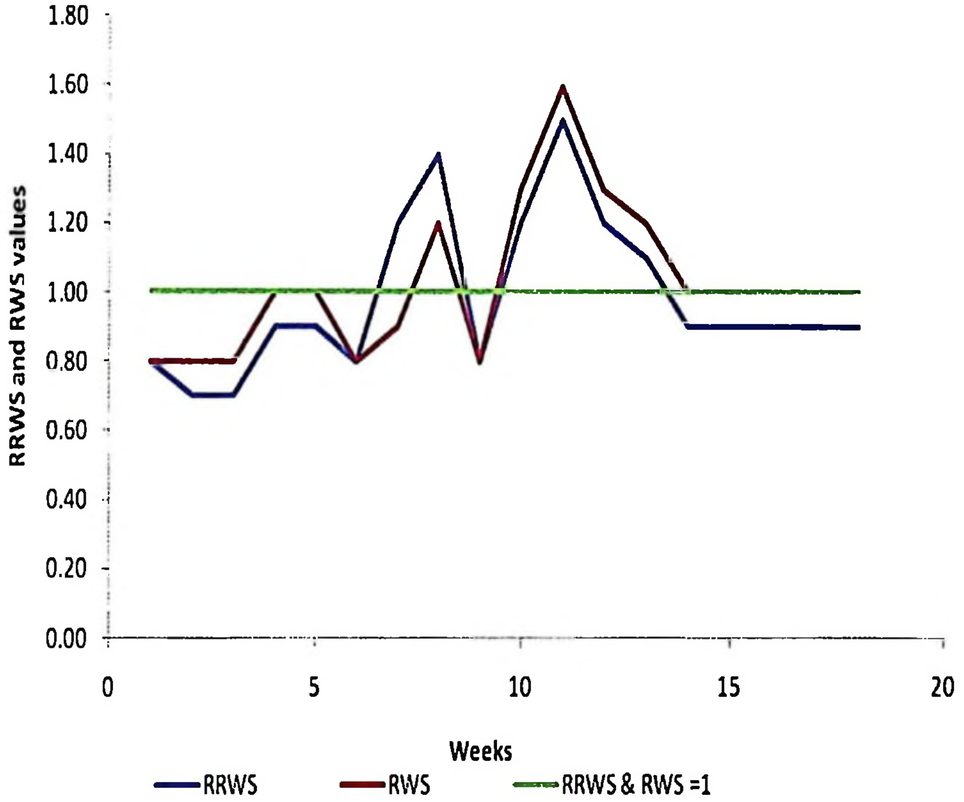

Figure 20: RRWS & RWS, RWS and RRWS for 0 cm ponding level

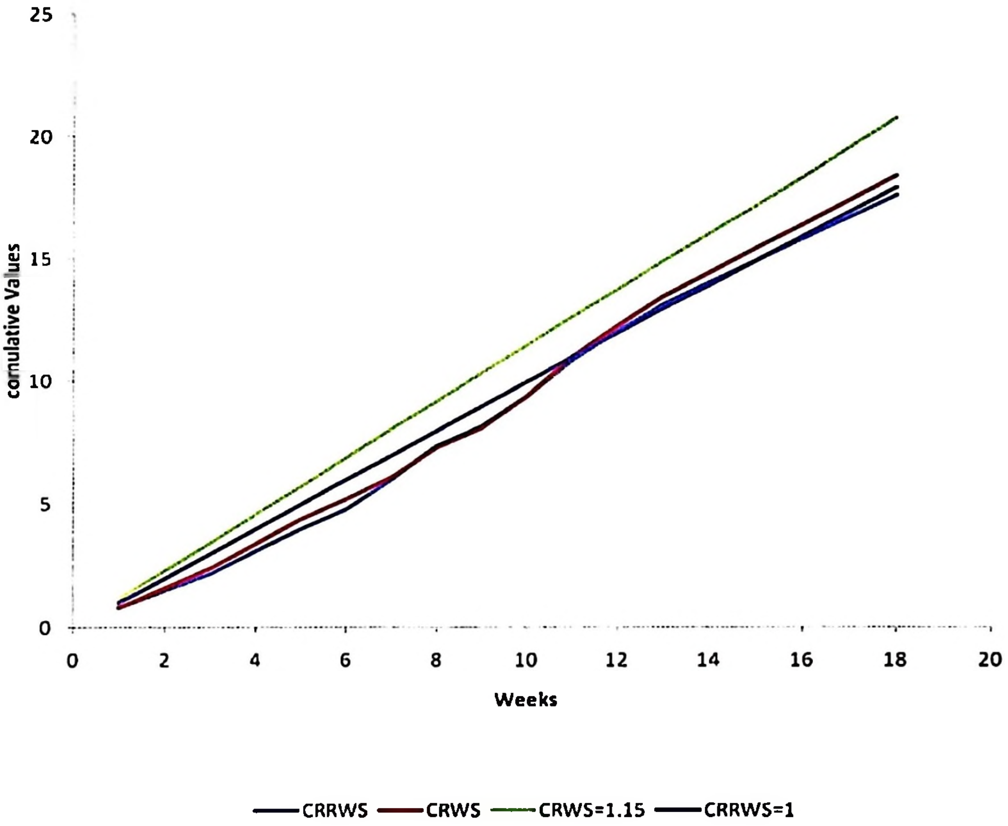

Figure 21: CRRWS & CRWS, CRRWS = 1 and CRWS =1.15 for the 0 cm ponding level.

4.8.3 For the 3 cm ponding level

In this combination treatment the values for RWS were greater than the values for RRWS throughout the study period. RWS values showed oversupply between weeks 7 and 8 and 10 and 14 but matched supply from week 1 to 6 and from week 13 to 18. The RRWS values showed undersupply throughout except in week 11 where there was matched supply. This can be attributed to the high rainfall of 62 mm that was received during that week (Fig. 14). The values for RRWS ranged from 0.6 to 1.0 while the values for RWS ranged from 1 to 1.2 (Fig.24). The plot for RRWS values showed undersupply (Fig. 23) for the entire period. The plot for CRRWS, CRWS, CRRWS = 1 and CRWS = 1.15 (Fig. 24) showed that the CRRWS was lower than the CRRWS=1 line indicative of the fact that water supply needed to be increased during the period to meet the water demand. Both the CRRWS and CRWS lines were lower than the upper bound values for CRRWS=1 and CRWS = 1.15 lines respectively (Fig. 24). The value for RRWS of 0.6 occurred in week 7 when water was deliberately withdrawn in order to allow for drainage.

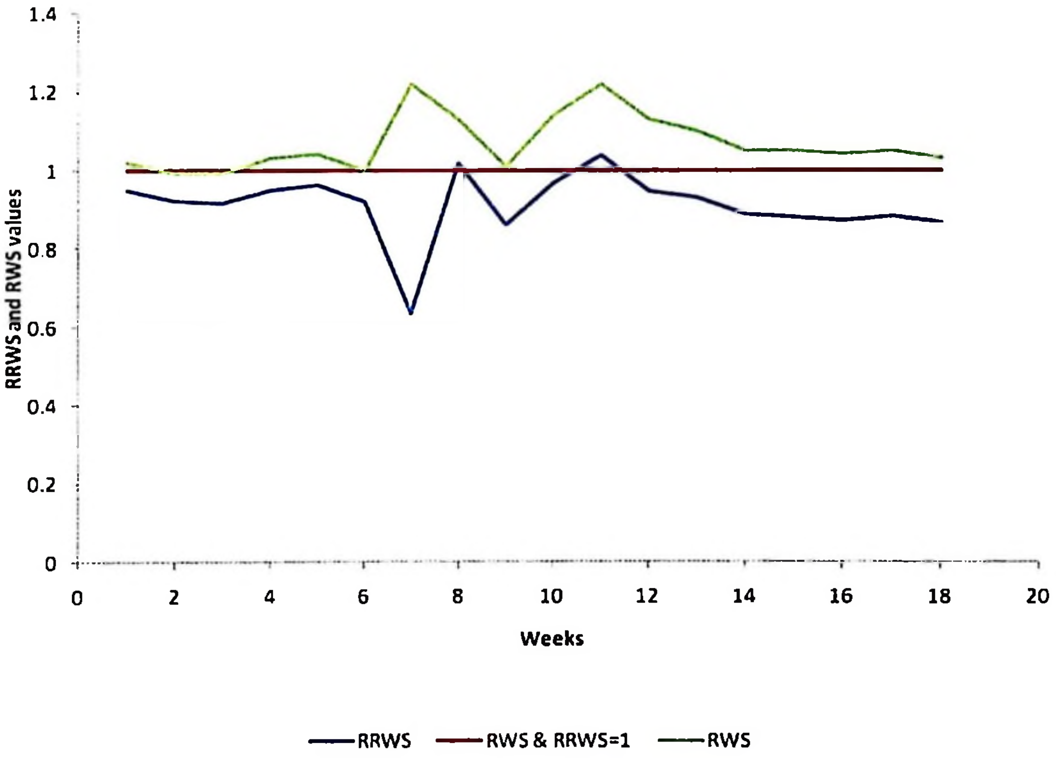

Figure 22: RRWS & RWS=1.0, RWS and RRWS for the 3 cm ponding level

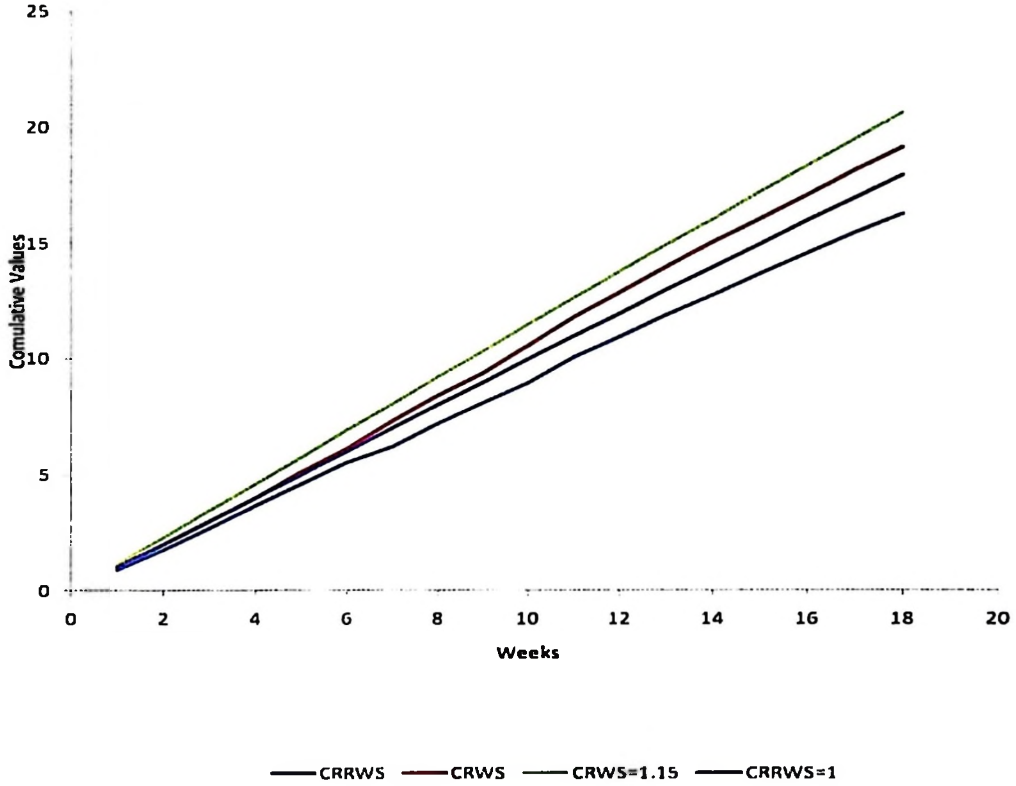

Figure 23: CRRWS & CRWS, CRRWS= 1.0 and CRWS= 1.15 for the 3 cm ponding level.

4.8.4 For the 5 cm ponding level

In this ponding treatment RWS values showed a matched supply to demand in weeks 1 to 6 , 9 and weeks 14 to 18 and an oversupply between weeks 7 and 8, 10 to13. The values for RWS were greater than the values for RRWS throughout the study period (Fig. 25). All the RRWS values were less than 1 with the smallest value being 0.5 for week 7 characterizing an undersupply situation as shown in Fig. 25. This also agrees with the plot of values for CRRWS which were less than the plot for CRRWS = 1 during the entire period thus indicating the need for increase in the water supply to meet the demand.

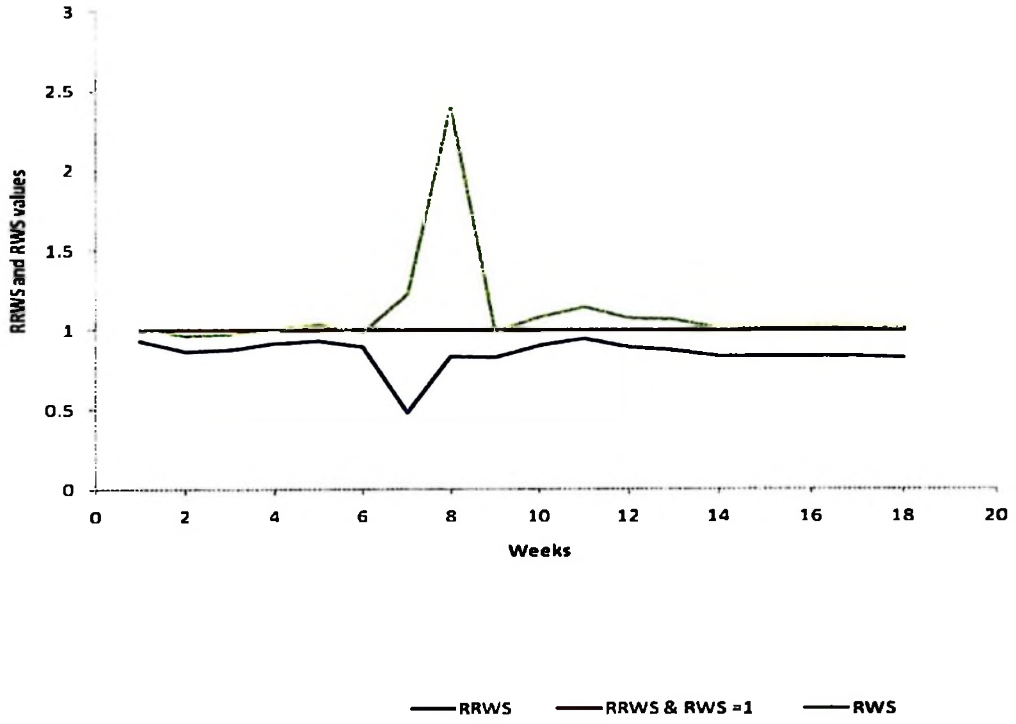

Figure 24: RRWS & RWS = 1, RRWS and RWS graphs for the 5 cm ponding level

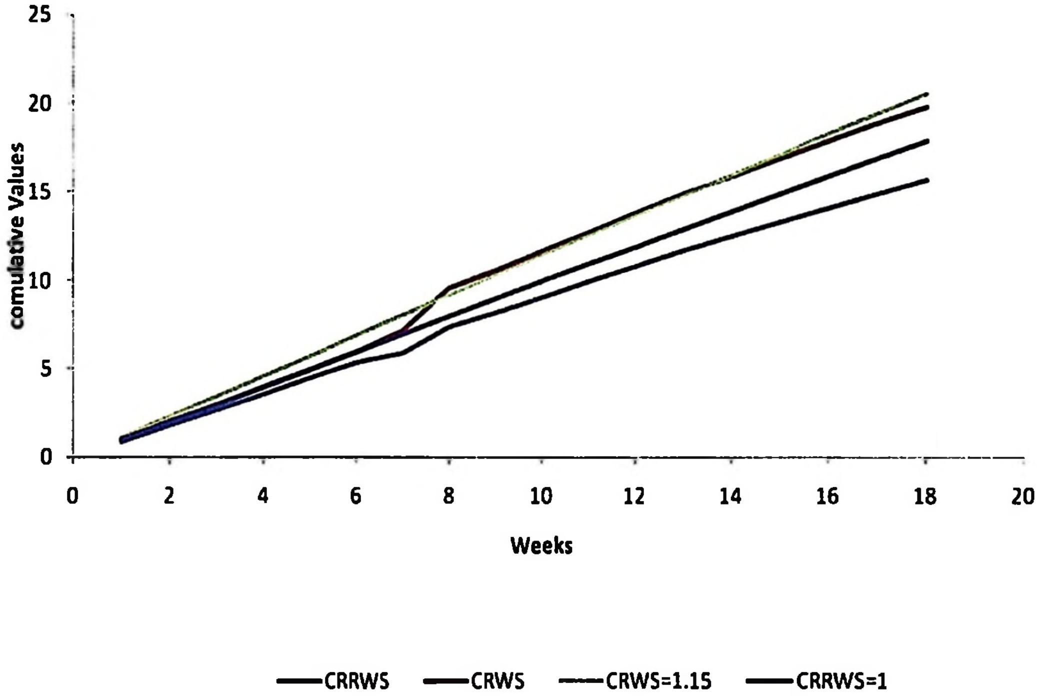

Figure 25: CRRWS & CRWS, CRRWS = 1 and CRWS = 1.15 for the 5 cm ponding level

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions can be made:

1. Different ponding depths had no influence on the yield of the rice varieties that were used for the experiment consequently significant amounts of water can be saved by adopting water saving technologies at field scale.
2. Variety TXD88 was the best variety of the four in terms of both yield level and water productivity. It yielded highest at all ponding levels with the highest yield in the 0 cm ponding level.
3. The optimum ponding depth was the 0 cm ponding level. It resulted in minimal water losses while at the same time ensuring optimum yield levels for all paddy varieties.
4. Water saving and high water productivity at field level were achieved by several factors as single factors or through a combination of factors. These are use of high yielding varieties e.g. TXD88, use of short maturing varieties like TXD88 and TXD306, reduced ponding depth of water like zero ponding depth and agricultural practices such as puddling.
5. From this study, it can be concluded that the water delivery performance can be said to have been good for the ETc treatment and unmatched for the 0 cm, 3 cm and 5 cm ponding levels.

5.2 Recommendations

1. It is recommended that further studies be conducted to address the contribution of groundwater and rainfall.

2. It is further recommended that farmers be sensitized on the use of water saving technologies for rice production.

3. The experiment should be carried out purely under irrigation setting (dry season) to avoid rainfall interference.

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APPENDICES

Appendix A Meteorological data obtained from Morogoro station

Appendix A1 : Mean Monthly Weather Summary

Station : Morogoro Month : October (1988-1997)

Day	Temperature in Degrees o C			3PM	Sun shine	Radiation	Wind	Evapo ration	Rain fall	Temp mean
	Max	Min	3pm Dp	RH	Hours	MJ/day	MI/day	mm	mm	o C
1	30.73	18.54	16.15	43.70	7.63	17.35	117.80	6.50	0.00	24.64
2	30.47	18.02	15.91	44.70	6.56	17.00	105.79	5.87	0.00	24.25
3	30.65	18.05	15.88	43.40	8.00	17.63	111.11	5.71	0.05	24.35
4	30.93	18.10	15.04	40.60	8.36	18.31	110.06	6.29	0.00	24.52
5	31.05	17.69	15.58	42.00	7.10	16.21	107.51	5.94	0.57	24.37
6	30.92	18.45	16.37	47.10	7.74	17.38	100.00	5.70	3.55	24.69
7	30.64	19.64	16.68	48.30	6.79	15.93	98.22	5.09	4.59	25.14
8	30.79	18.99	16.43	46.90	7.40	16.76	104.13	6.31	2.88	24.89
9	30.16	18.07	16.86	49.00	5.83	16.59	94.04	4.66	0.42	24.12
10	31.12	17.92	16.15	42.80	8.63	19.66	97.97	6.06	0.13	24.52
11	30.88	18.35	16.31	43.80	6.44	17.59	104.73	6.72	0.39	24.62
12	31.72	19.01	16.51	43.00	8.86	19.78	101.62	6.77	5.38	25.37
13	31.04	18.64	16.14	42.80	7.87	17.42	103.83	6.67	2.84	24.84
14	31.10	18.86	16.63	45.50	7.73	18.01	104.91	5.92	2.65	24.98
15	31.42	18.20	17.18	44.21	7.41	16.45	101.50	6.02	1.34	24.81
16	31.20	18.38	16.04	41.00	7.95	20.17	98.55	6.24	1.66	24.79
17	31.09	18.54	15.99	43.90	8.20	17.85	105.06	6.26	1.29	24.82
18	30.66	18.72	16.76	49.60	6.38	17.28	97.84	6.61	3.23	24.69
19	31.83	19.01	17.05	44.10	7.93	18.38	105.73	5.84	3.12	25.42
20	30.97	18.64	16.81	46.20	7.84	17.52	102.64	4.41	0.49	24.81
21	30.82	19.18	17.59	52.60	6.88	17.04	101.27	6.06	6.67	25
22	31.39	18.95	17.18	48.40	8.06	19.32	108.51	5.78	1.36	25.17

23	31.56	19.19	17.10	45.22	8.31	17.27	96.59	6.00	2.55	25.38
24	31.18	19.11	18.11	44.07	8.68	18.42	121.12	5.54	0.66	25.15
25	31.43	19.51	17.67	47.00	8.29	18.38	100.65	6.23	5.59	25.47
26	31.59	19.16	16.65	45.80	9.06	18.85	118.63	6.69	0.00	25.38
27	31.85	19.11	17.05	43.40	9.23	20.67	106.29	6.25	0.00	25.48
28	31.81	18.80	17.17	43.70	8.58	18.36	115.16	6.17	1.31	25.31
29	31.27	19.77	18.73	55.60	6.93	16.69	109.60	6.66	6.46	25.52
30	31.48	19.95	17.61	51.60	7.99	18.69	117.07	6.20	2.79	25.72
31	31.69	19.81	17.33	46.30	8.32	19.15	118.96	6.48	2.62	25.75

Mean Monthly Weather Summary

Station : Morogoro Month : November (1988-1997)

Day	Temperature in Degrees o C			3PM	Sun shine	Radiation	Wind	Evapo ration	Rain fall	Temp mean
	Max	Min	3pm Dp	RH	Hours	MJ/day	MI/day	mm	mm	o C
1	31.69	19.42	17.20	46.20	7.30	17.66	99.36	5.96	1.90	25.56
2	31.50	19.36	17.20	48.60	8.95	18.56	108.97	6.64	1.44	25.43
3	31.32	19.60	17.37	50.80	7.81	17.24	108.03	5.89	0.77	25.46
4	31.32	19.31	17.01	48.90	7.48	17.98	109.67	6.14	1.34	25.32
5	31.60	19.22	17.12	45.00	7.57	18.81	104.65	6.28	3.33	25.41
6	31.82	18.88	17.44	48.80	8.93	19.02	100.10	6.41	3.17	25.35
7	31.57	18.89	17.84	51.80	8.36	19.14	97.92	5.74	0.16	25.23
8	32.03	19.79	16.76	46.40	8.08	18.87	95.44	5.71	0.88	25.91
9	30.67	19.46	18.07	53.80	7.05	15.66	104.50	5.14	0.38	25.07
10	31.24	19.03	17.85	54.20	9.05	17.82	95.74	6.01	2.24	25.14
11	31.21	19.47	18.04	50.30	8.04	18.72	97.87	5.90	0.70	25.34
12	32.13	19.57	17.96	49.30	8.65	19.38	112.44	6.43	5.24	25.85
13	32.04	19.38	17.70	52.60	9.09	19.30	117.48	6.82	2.64	25.71
14	31.80	19.96	18.19	54.00	8.44	17.91	129.47	5.66	2.09	25.88
15	32.07	19.55	17.95	51.30	9.83	20.10	138.93	6.91	0.02	25.81
16	32.25	20.11	17.48	45.00	8.40	21.02	121.72	6.96	2.53	26.18
17	32.42	19.98	17.46	45.30	8.50	19.79	127.94	6.99	1.79	26.2
18	31.40	19.62	17.76	51.60	8.25	18.94	109.12	6.84	7.39	25.51
19	31.43	20.03	19.14	55.30	8.17	17.39	123.76	6.14	3.39	25.73
20	30.96	20.29	18.53	52.70	8.36	16.88	106.44	5.40	6.27	25.63
21	29.64	20.14	19.20	63.70	5.90	16.04	96.76	5.57	4.79	24.89
22	31.30	19.64	18.93	52.90	7.98	19.67	124.71	6.18	0.89	25.47
23	31.95	20.02	18.66	51.60	8.86	19.85	117.37	5.44	1.37	25.99
24	31.96	20.59	18.87	52.80	8.74	21.00	148.81	7.44	0.93	26.28

25	31.91	20.51	17.33	47.10	8.05	19.39	140.77	7.08	2.92	26.21
26	32.37	20.44	17.44	44.10	10.01	20.48	147.31	7.43	0.11	26.41
27	32.06	20.35	18.63	51.20	9.13	21.19	158.58	7.33	1.80	26.21
28	32.18	20.42	18.64	52.20	8.89	19.55	155.48	7.44	0.04	26.3
29	32.10	20.43	18.72	50.90	8.19	19.34	129.86	5.92	3.47	26.27
30	31.83	20.14	18.45	53.60	8.60	18.79	139.76	6.83	1.34	25.99

Mean Monthly Weather Summary

Station : Morogoro Month : December (1988-1997)

Day	Temperature in Degrees o C			3PM	Sun shine	Radiation	Wind	Evapo ration	Rain fall	Temp mean
	Max	Min	3pm Dp	RH	Hours	MJ/day	MI/day	mm	mm	o C
1	32.41	20.24	16.87	43.60	9.54	20.50	142.37	7.32	5.27	25.32
2	32.19	20.67	17.91	46.50	8.37	18.14	144.14	6.72	0.80	26.43
3	32.32	20.64	17.75	46.67	8.30	19.49	119.52	6.62	0.93	26.48
4	32.46	20.23	16.93	44.60	8.53	20.12	139.11	6.75	0.72	26.34
5	32.44	20.67	17.56	44.90	8.77	20.03	120.12	6.08	0.19	26.55
6	32.43	20.59	17.80	44.50	7.41	19.27	149.34	5.73	0.53	26.51
7	32.10	21.41	18.50	53.60	7.26	18.22	127.29	6.62	4.57	26.75
8	32.25	21.22	17.81	48.50	7.70	19.16	122.17	6.15	1.10	26.73
9	32.04	21.20	18.97	52.80	7.31	18.88	132.00	6.85	0.80	26.62
10	32.12	20.93	17.99	50.00	9.24	19.30	153.70	6.64	10.01	26.52
11	31.95	20.73	18.19	49.90	8.39	18.16	154.83	7.18	1.36	26.34
12	31.61	21.00	18.47	49.90	9.79	19.12	155.60	6.73	2.57	26.30
13	32.33	20.71	18.30	48.50	9.00	19.52	129.50	6.79	1.96	26.52
14	32.08	20.91	18.05	50.40	7.84	18.86	127.58	6.74	2.54	26.49
15	32.11	20.85	18.54	49.10	8.09	19.49	114.80	6.38	0.58	26.48
16	32.16	21.06	19.27	54.00	7.07	18.35	110.11	6.03	4.23	26.61
17	31.45	21.15	19.93	53.50	7.51	18.38	128.04	6.11	6.31	26.30
18	31.82	21.07	19.37	56.30	6.49	18.00	134.88	5.85	10.17	26.44
19	31.97	21.09	19.24	50.00	7.40	19.43	137.38	6.61	4.60	26.53
20	31.82	21.10	18.31	51.70	7.03	18.43	124.20	6.28	1.42	26.46
21	32.62	21.09	18.13	46.60	8.00	19.69	154.63	7.30	4.15	26.85
22	30.69	21.38	19.34	54.80	5.70	36.58	130.66	6.69	4.95	26.00
23	31.46	20.69	18.64	50.00	6.11	17.50	142.80	6.76	11.17	26.07
24	31.68	20.97	19.16	53.10	6.70	18.60	151.16	5.24	1.95	26.32

25	32.05	21.32	19.74	51.10	7.91	20.09	144.10	6.56	3.72	26.68
26	31.52	21.56	19.40	54.00	6.84	18.20	136.31	6.26	9.98	26.54
27	31.39	21.61	20.13	55.10	5.89	17.46	130.19	4.75	10.64	26.50
28	31.40	21.55	19.76	53.70	7.71	18.23	144.32	6.13	0.26	26.47
29	31.25	22.20	19.52	55.00	8.31	18.85	169.82	6.35	0.35	26.72
30	31.83	21.11	19.11	44.15	9.20	27.08	164.79	7.89	1.30	26.47
31	32.29	21.52	18.86	51.90	7.98	18.62	138.63	6.81	2.70	26.90

Mean Monthly Weather Summary

Station : Morogoro Month : January (1988-1997)

Day	Temperature in Degrees o C			3PM	Sun shine	Radiation	Wind	Evapo ration	Rain fall	Temp mean
	Max	Min	3pm Dp	RH	Hours	MJ/day	MI/day	mm	mm	o C
1	32.58	21.54	18.55	46.30	8.97	19.90	142.13	7.22	4.97	27.06
2	31.52	21.26	18.58	52.30	6.55	16.56	133.04	7.00	0.70	26.39
3	31.86	21.62	24.23	52.50	7.56	23.53	144.19	6.86	4.34	26.74
4	32.05	21.46	19.61	53.60	7.43	17.57	171.49	6.69	7.23	26.75
5	31.96	21.76	19.14	48.50	8.69	20.82	162.75	7.56	4.12	26.86
6	31.90	21.29	18.63	48.00	7.30	19.51	154.06	8.13	2.18	26.59
7	31.04	21.31	18.93	49.30	8.48	18.73	130.71	7.64	9.01	26.17
8	31.75	20.49	19.26	53.30	7.24	18.24	105.53	5.58	0.75	26.12
9	32.51	20.87	20.16	50.60	8.84	20.50	129.94	6.28	5.67	26.69
10	31.70	19.88	19.63	53.00	8.20	17.79	143.49	6.48	2.03	25.79
11	31.98	21.60	20.19	52.40	8.25	19.03	152.02	5.90	0.26	26.79
12	31.29	22.76	19.59	55.30	7.95	16.41	121.97	6.97	3.23	27.03
13	31.48	21.57	19.18	50.70	8.40	17.58	146.37	7.12	4.16	26.52
14	31.55	21.33	18.72	49.10	8.91	18.95	149.25	6.81	3.63	26.44
15	31.23	21.30	19.44	51.70	8.44	18.39	114.09	5.61	4.73	26.26
16	31.22	21.18	19.83	54.00	7.51	17.36	108.63	4.76	1.28	26.20
17	32.28	21.32	20.17	52.90	8.18	17.41	127.74	6.72	1.97	26.80
18	31.71	21.79	19.20	49.00	8.63	18.80	137.51	7.34	1.12	26.75
19	32.27	21.64	19.33	47.30	9.31	19.92	155.73	6.50	1.56	26.95
20	32.18	21.74	19.03	49.80	8.59	19.76	143.47	6.05	3.34	26.36
21	32.12	21.72	18.46	50.10	8.90	18.25	138.90	6.71	7.13	26.31
22	31.80	20.82	19.32	51.30	7.74	17.50	117.90	4.78	0.07	26.57
23	31.72	21.42	19.29	53.20	8.27	18.57	139.32	7.06	0.60	26.95
24	32.79	21.12	19.28	45.78	9.11	20.18	124.25	6.66	0.12	26.89

25	32.49	21.29	19.08	45.05	7.59	19.79	129.38	6.53	2.62	26.97
26	32.67	21.28	20.00	52.20	9.09	20.21	142.20	6.71	1.77	26.74
27	32.21	21.27	19.00	49.90	8.86	18.40	135.96	5.99	0.04	26.73
28	32.52	20.95	19.62	48.30	8.69	19.31	125.19	6.23	3.53	26.86
29	32.52	21.21	19.50	49.60	6.68	18.94	124.75	5.85	1.53	27.17
30	32.61	21.73	19.29	51.80	6.63	18.27	119.72	5.88	2.05	27.31
31	32.93	21.70	19.66	51.50	6.72	18.28	119.01	6.06	3.60	27.25

Mean Monthly Weather Summary

Station : Morogoro Month : February (1988-1997)

Day	Temperature in Degrees o C			3PM	Sun shine	Radiation	Wind	Evapo ration	Rain fall	Temp mean
	Max	Min	3pm Dp	RH	Hours	MJ/day	MI/day	mm	mm	o C
1	32.54	21.21	19.12	46.95	7.72	19.68	130.28	6.53	14.11	26.87
2	32.15	21.74	19.37	52.20	7.20	18.84	130.22	5.76	0.13	26.94
3	32.91	21.08	18.05	44.40	9.51	21.34	121.52	6.79	0.00	26.99
4	33.02	21.57	19.44	47.30	8.71	20.40	133.36	6.80	0.78	27.29
5	32.71	21.45	18.92	47.70	6.27	18.62	106.67	6.99	1.89	27.08
6	32.78	21.52	19.39	46.90	8.29	19.74	138.56	6.14	0.06	27.15
7	33.07	21.46	19.07	46.40	8.20	20.51	110.19	6.54	1.89	27.26
8	33.34	21.65	19.63	54.70	6.84	18.74	106.93	7.44	5.82	27.49
9	32.66	21.24	19.80	49.20	7.39	18.71	104.92	8.07	1.42	26.95
10	32.69	21.26	20.03	54.70	6.63	17.69	98.38	5.89	12.11	26.37
11	31.44	21.21	18.53	51.40	6.81	17.51	119.42	5.86	5.05	26.32
12	32.20	21.43	19.44	49.40	7.23	19.72	112.37	7.25	0.44	26.86
13	32.52	21.20	20.15	50.60	7.34	19.24	118.31	6.69	3.79	27.06
14	32.89	21.24	20.12	50.50	7.20	19.11	116.49	7.30	1.78	27.15
15	32.79	21.52	20.56	52.20	7.87	19.28	136.15	6.98	0.19	27.36
16	32.99	21.74	19.80	49.20	8.07	19.92	134.45	7.96	4.67	26.10
17	30.89	21.31	20.11	57.00	5.07	15.90	114.65	6.10	0.65	26.69
18	32.17	21.21	20.00	52.20	7.00	19.21	102.90	7.10	9.27	26.76
19	32.46	21.07	19.42	49.50	7.67	21.80	113.43	5.69	7.74	26.63
20	31.95	21.31	19.87	54.90	6.20	16.95	118.57	5.71	0.49	26.73
21	32.13	21.33	19.80	49.70	6.94	19.50	136.44	6.75	3.90	26.71
22	32.25	21.17	19.24	48.70	6.40	19.07	114.83	6.63	0.00	27.08
23	32.74	21.42	19.53	51.40	7.00	18.92	102.56	6.25	4.41	26.86
24	32.85	20.87	24.15	47.80	8.98	23.45	103.81	7.27	4.73	26.65

25	32.32	20.99	19.55	51.90	5.14	17.27	105.02	7.11	11.53	26.61
26	32.66	20.57	20.25	52.80	7.48	21.47	111.55	6.81	1.11	26.89
27	32.55	21.23	20.62	54.60	6.30	18.67	113.85	5.74	1.25	26.97
28	32.36	21.58	19.43	49.44	10.52	20.76	118.96	5.45	1.45	26.97
29	34.12	22.47	19.63	48.66	10.03	22.28	174.00	8.75	0.00	28.29

Mean Monthly Weather Summary

Station : Morogoro Month : March (1988-1997)

Day	Temperature in Degrees o C			3PM	Sun shine	Radiation	Wind	Evapo ration	Rain fall	Temp mean
	Max	Min	3pm Dp	RH	Hours	MJ/day	Ml/day	mm	mm	o C
1	32.16	21.85	19.52	55.70	7.04	18.30	130.33	6.66	6.40	27.00
2	32.61	20.84	19.83	52.10	7.59	18.30	113.99	5.21	1.22	26.72
3	32.04	21.46	19.58	53.80	7.00	17.24	105.64	6.03	4.49	26.75
4	31.89	20.56	19.90	53.70	6.88	17.29	119.11	5.73	5.54	26.22
5	31.96	21.51	23.37	48.89	9.09	18.16	114.36	7.17	4.25	26.73
6	31.39	20.92	20.36	55.10	6.14	18.27	113.61	5.64	1.01	26.15
7	32.53	21.49	20.16	51.30	8.77	18.90	119.20	6.94	6.45	27.01
8	32.46	21.19	19.46	44.45	9.63	28.34	126.70	5.98	0.48	26.82
9	32.39	21.00	19.22	51.90	8.13	19.61	91.58	5.52	1.41	26.58
10	32.64	20.52	19.60	53.10	8.28	19.23	104.86	6.61	4.59	26.53
11	32.40	20.66	19.29	50.10	8.48	18.95	98.43	5.04	1.53	26.49
12	32.01	20.98	19.27	58.30	6.82	16.64	95.36	6.87	4.93	26.50
13	31.94	21.06	20.59	57.40	7.39	17.93	87.03	4.64	2.93	26.61
14	31.94	21.28	20.44	59.60	7.31	17.18	88.41	5.27	2.06	26.90
15	32.58	21.23	20.16	57.60	7.31	17.83	76.95	5.24	2.63	26.82
16	32.29	21.36	20.09	57.10	8.52	18.37	95.96	5.23	1.92	26.06
17	30.70	21.42	20.41	59.40	7.54	27.61	65.36	5.86	9.09	25.89
18	30.71	21.08	20.62	62.50	5.36	16.22	84.36	5.34	10.38	25.63
19	30.40	20.87	20.55	63.10	4.49	15.03	87.32	4.62	2.85	25.95
20	30.84	21.07	20.94	61.80	6.64	17.79	67.10	4.49	8.56	26.10
21	30.91	21.29	20.41	57.80	6.98	16.88	68.26	4.60	1.00	25.86
22	30.53	21.20	20.97	63.10	5.99	17.06	78.28	5.35	8.26	26.03
23	31.09	20.98	21.26	62.80	5.67	16.67	67.44	4.34	4.99	25.72

24	30.40	21.05	21.56	69.70	5.92	15.86	60.49	4.42	0.66	25.96
25	30.74	21.19	21.20	67.10	6.28	16.57	63.06	9.63	13.91	25.85
26	30.37	21.34	21.27	65.80	5.08	15.52	60.04	3.82	10.69	25.50
27	30.02	20.98	21.45	65.30	4.89	23.18	52.94	4.59	5.81	25.49
28	30.16	20.83	20.95	64.70	5.54	16.47	47.78	4.15	4.13	25.71
29	30.44	20.98	21.00	62.10	5.54	16.50	71.03	3.83	5.57	25.84
30	30.73	20.95	21.26	62.50	6.71	17.63	64.54	5.60	6.74	26.16
31	31.20	21.13	21.36	60.80	7.66	18.23	79.59	4.90	5.15	26.16

Appendix B: Calculated amount of water applied to the ETc based treatment per day

CROP WATER REQUIREMENTS Etc
Month : November

Date	Mean ETo	Crop Coeff Kc	Daily ETc in mm	Area in m^2	Amount of Water per day in litres
1	4.71	1.05	4.95	12	59.5
2	4.9	1.05	5.15	12	61.8
3	4.69	1.05	4.92	12	49.2
4	4.83	1.05	5.07	12	59.0
5	4.9	1.05	5.15	12	59.5
6	4.85	1.05	5.09	12	61.1
7	4.76	1.05	5.00	12	60.0
8	4.95	1.05	5.20	12	62.4
9	4.23	1.05	4.44	12	53.3
10	4.52	1.05	4.75	12	57.0
11	4.67	1.05	4.90	12	58.8
12	5.07	1.05	5.32	12	63.8
13	5.12	1.05	5.38	12	64.6
14	4.99	1.05	5.24	12	62.9
15	5.42	1.05	5.69	12	68.3
16	5.52	1.05	5.80	12	69.6
17	5.45	1.05	5.72	12	68.6
18	4.89	1.05	5.13	12	61.6
19	4.65	1.05	4.88	12	58.6
20	4.46	1.05	4.68	12	56.2
21	3.97	1.05	4.17	12	50.0
22	4.94	1.05	5.19	12	62.3
23	5.09	1.05	5.34	12	64.1
24	5.55	1.05	5.83	12	69.9
25	5.51	1.05	5.79	12	69.5
26	5.78	1.05	6.07	12	72.8
27	5.7	1.05	5.99	12	71.9
28	5.49	1.05	5.76	12	69.1
29	5.2	1.05	5.46	12	65.5
30	5.18	1.05	5.44	12	65.3

CROP WATER REQUIREMENTS Etc

Month : December

Date	Mean ETo	Crop Coeff Kc	Daily ETc in mm	Area in m^2	Amount of Water per day in litres
1	5.81	1.2	6.97	12	83.6
2	5.35	1.2	6.42	12	77.0
3	5.31	1.2	6.37	12	76.4
4	5.72	1.2	6.86	12	82.3
5	5.43	1.2	6.52	12	78.2
6	5.61	1.2	6.73	12	80.7
7	5.14	1.2	6.17	12	74.0
8	5.32	1.2	6.38	12	76.6
9	5.17	1.2	6.20	12	74.4
10	5.6	1.2	6.72	12	80.6
11	5.37	1.2	6.44	12	77.3
12	5.41	1.2	6.49	12	77.9
13	5.35	1.2	6.42	12	77.0
14	5.25	1.2	6.30	12	75.6
15	5.13	1.2	6.16	12	73.9
16	4.85	1.2	5.82	12	69.8
17	4.8	1.2	5.76	12	69.1
18	4.96	1.2	5.95	12	71.4
19	5.23	1.2	6.28	12	75.4
20	5.09	1.2	6.11	12	73.3
21	5.75	1.2	6.90	12	82.8
22	7.3	1.2	8.76	12	105.1
23	4.98	1.2	5.98	12	71.8
24	5.18	1.2	6.22	12	74.6
25	5.32	1.2	6.38	12	76.6
26	4.99	1.2	5.99	12	71.9
27	4.68	1.2	5.62	12	67.4
28	4.97	1.2	5.96	12	71.5
29	5.35	1.2	6.42	12	77.0
30	6.47	1.2	7.76	12	93.1
31	5.3	1.2	6.36	12	76.3

CROP WATER REQUIREMENTS Etc

Month : January

Date	Mean ETo	Crop Coeff Kc	Daily ETc in mm	**Area in m^2**	**Amount of Water per day in litres**
1	5.62	0.9	5.06	12	60.7
2	4.85	0.9	4.37	12	52.4
3	4.91	0.9	4.42	12	53.0
4	5.26	0.9	4.73	12	56.8
5	5.73	0.9	5.16	12	61.9
6	5.51	0.9	4.96	12	59.5
7	4.99	0.9	4.49	12	53.9
8	4.69	0.9	4.22	12	50.6
9	5.24	0.9	4.72	12	56.6
10	4.81	0.9	4.33	12	52.0
11	5.18	0.9	4.66	12	55.9
12	4.67	0.9	4.20	12	50.4
13	5.03	0.9	4.53	12	54.4
14	5.31	0.9	4.78	12	57.4
15	4.75	0.9	4.28	12	51.4
16	4.48	0.9	4.03	12	48.4
17	4.79	0.9	4.31	12	43.1
18	5.18	0.9	4.66	12	55.9
19	5.57	0.9	5.01	12	60.1
20	5.48	0.9	4.93	12	59.1
21	5.31	0.9	4.78	12	57.4
22	4.72	0.9	4.25	12	51.0
23	5.11	0.9	4.60	12	55.2
24	5.36	0.9	4.82	12	57.8
25	5.35	0.9	4.82	12	57.8
26	5.4	0.9	4.86	12	58.3
27	5.19	0.9	4.67	12	56.0
28	5.13	0.9	4.62	12	55.4
29	5.12	0.9	4.61	12	55.3
30	5.07	0.9	4.56	12	54.7
31	5.06	0.9	4.55	12	54.6

CROP WATER REQUIREMENTS ETc

Month : February

Date	Mean ETo	Crop Coeff Kc	Daily ETc in mm	Area in m^2	Amount of Water per day in litres
1	5.35	0.6	3.21	12	38.4
2	5.17	0.6	3.10	12	37.2
3	5.7	0.6	3.42	12	34.2
4	5.55	0.6	3.33	12	41.0
5	5.03	0.6	3.02	12	36.2
6	5.47	0.6	3.28	12	39.4
7	5.38	0.6	3.23	12	38.8
8	5.07	0.6	3.04	12	36.5
9	4.89	0.6	2.93	12	35.2
10	4.65	0.6	2.79	12	33.5
11	4.84	0.6	2.90	12	34.8
12	5.1	0.6	3.06	12	36.7
13	5.01	0.6	3.01	12	36.1
14	5.05	0.6	3.03	12	36.4
15	5.18	0.6	3.11	12	37.3
16	5.45	0.6	3.27	12	39.2
17	4.25	0.6	2.55	12	30.6
18	4.84	0.6	2.90	12	34.8
19	5.42	0.6	3.25	12	39.0
20	4.64	0.6	2.78	12	32.4
21	5.2	0.6	3.12	12	37.4
22	5.04	0.6	3.02	12	36.2
23	4.96	0.6	2.98	12	35.8
24	4.98	0.6	2.99	12	35.9
25	4.64	0.6	2.78	12	33.4
26	5.23	0.6	3.14	12	37.7
27	4.83	0.6	2.90	12	34.8
28	5.35	0.6	3.21	12	38.5
29	6.51	0.6	3.91	12	46.9

CROP WATER REQUIREMENTS ETc

Month : March

Date	Mean ETo	Crop Coeff Kc	Daily ETc	Area in m^2	Amount of Water per day in litres
1	5.06	0.6	3.04	12	36.5
2	4.84	0.6	2.90	12	34.8
3	4.61	0.6	2.77	12	33.2
4	4.59	0.6	2.75	12	33.0
5	4.19	0.6	2.51	12	30.1
6	4.56	0.6	2.74	12	32.9
7	4.97	0.6	2.98	12	35.8
8	6.42	0.6	3.85	12	46.2
9	4.87	0.6	2.92	12	35.0
10	4.9	0.6	2.94	12	35.3
11	4.81	0.6	2.89	12	35.7
12	4.42	0.6	2.65	12	31.8
13	4.37	0.6	2.62	12	31.4
14	4.3	0.6	2.58	12	31.0
15	4.4	0.6	2.64	12	31.7
16	4.64	0.6	2.78	12	33.4
17	5.57	0.6	3.34	12	40.0
18	3.93	0.6	2.36	12	28.3
19	3.72	0.6	2.23	12	26.8
20	4.03	0.6	2.42	12	29.3
21	3.97	0.6	2.38	12	28.6
22	3.96	0.6	2.38	12	28.6
23	3.85	0.6	2.31	12	27.7
24	3.58	0.6	2.15	12	25.8
25	3.79	0.6	2.27	12	27.2
26	3.57	0.6	2.14	12	25.7
27	4.67	0.6	2.80	12	33.6
28	3.61	0.6	2.17	12	26.0
29	3.8	0.6	2.28	12	27.4
30	3.94	0.6	2.36	12	28.3
31	4.18	0.6	2.51	12	30.1

Appendix C: Analysis of variance

```
HOMOGENEITY OF VARIANCES - RAW DATA
Data Column: 4) Yield
Broken Down By:
3) Variety
2) Ponding
1) Block
Keep If:
A resulting probability of P<=0.05 indicates the variances may be not
homogeneous and you may wish to transform the data before doing an ANOVA.
AOV Filename: SP.AOV - Split Plot
Y Column: 4) Yield
Subplot Factor: 3) Variety
Main Plot Factor: 2) Ponding
Blocks: 1) Block
Keep If:
Rows of data with missing values removed: 0
Rows which remain: 48
Source          df Type III SS   MS         F       P
------------------------ -------- ----------- ---------   --------- --
Main plots
Blocks          2 0.031136167 0.0155681   0.4036148 .6848 ns
Ponding          3 0.044376417 0.0147921   0.3834978 .7690 ns
Main Plot Error    6 0.231429833 0.0385716<-
```

```
Variety          3 13.09880358 4.3662679   185.97956 .0000 ***

Variety * Ponding   9 0.187072583 0.0207858   0.8853652 .5517   ns

Error           24 0.563451333 0.0234771<-

------------------------ -------- ----------- ---------   --------- --

Total           47 14.15626992

Model            23 13.59281858 0.5909921   25.173089 .0000 ***

R^2 = SSmodel/SStotal = 0.96019775431

Root MSerror = sqrt(MSerror) = 0.1532225143

Mean Y = 1.27504166667

Coefficient of Variation = (Root MSerror) / abs (Mean Y) * 100% = 12.017059%

Compare Means

Factor: 3) Variety

Test: LSD

Significance Level: 0.05

Variance: 0.02347713889

Degrees of Freedom: 24

Keep If:

n Means = 4

LSD 0.05 = 0.12910269488

Rank Mean Name        Mean      n Non-significant ranges

----- --------- ------------- ------- --------------------------------

 1 txd88           1.801      12 a

 2 txd220          1.4625      12 b

 3 txd306    1.43083333333      12 b
```

```
 4 supa     0.40583333333     12 c
compare Means
Factor: 2) Ponding
Test: LSD
Significance Level: 0.05
Variance: 0.03857163889
Degrees of Freedom: 6
Keep If:
n Means = 4
LSD 0.05 = 0.19618994493
Rank Mean Name        Mean      n Non-significant ranges
----- --------- ------------- ------- ---------------------------------
1 fv      1.32391666667     12 a
2 ze            1.273     12 a
3 et      1.26183333333     12 a
4 th      1.24141666667     12 a
Compare Means
Factor: 1) Block
Test: LSD
Significance Level: 0.05
Variance: 0.03857163889
Degrees of Freedom: 6
Keep If:
n Means = 3
```

```
LSD 0.05 = 0.16990547628

Rank Mean Name        Mean      n Non-significant ranges

----- --------- ------------- ------- ---------------------------------

1 1            1.30775     16 a

2 3            1.27175     16 a

3 2           1.245625     16 a
```

Appendix D-1: Pan Coefficients (Kp) for class A pan for different pan sitting and environment and different levels of mean relative humidity and wind speed (source: Doorenbos and Prutt, 1984).

Class A Pan Wind Speed (m/ sec)	Case A Pan placed in short green cropped area			
	Fetch distance(m) Distance of green crop	Mean Relative Humidity		
		Low< 40	Medium40-70	High >70
Light < 2	1	0.55	0.65	0.75
	10	0.65	0.75	0.85
	100	0.70	0.80	0.85
	1000	0.75	0.85	0.85
Moderate 2-5	1	0.50	0.60	0.65
	10	0.60	0.70	0.75
	100	0.65	0.75	0.80
	1000	0.70	0.80	0.80
Strong 5-8	1	0.45	0.50	0.60
	10	0.55	0.60	0.65
	100	0.60	0.65	0.70
	1000	0.65	0.70	0.75
Very Strong > 8	1	0.40	0.45	0.50
	10	0.45	0.55	0.60
	100	0.50	0.60	0.65
	1000	0.55	0.60	0.65

APPENDIX D-2 :Pan Coefficients (K_p) for class A pan for different pan sitting and environment and different levels of mean relative humidity and wind speed (source: Doorenbos and Prutt, 1984).

Class A Pan Wind Speed (m/ sec)	Case B Pan placed in dry fallow area			
	Fetch distance(m) Distance of dry fallow	Mean Relative Humidity		
		Low < 40	Medium 40-70	High >70
Light < 2	1	0.70	0.80	0.85
	10	0.60	0.70	0.80
	100	0.55	0.65	0.75
	1000	0.50	0.60	0.70
Moderate 2-5	1	0.65	0.75	0.80
	10	0.55	0.65	0.70
	100	0.50	0.60	0.65
	1000	0.45	0.55	0.60
Strong 5-8	1	0.60	0.65	0.70
	10	0.50	0.55	0.65
	100	0.45	0.50	0.60
	1000	0.40	0.45	0.55
Very Strong > 8	1	0.50	0.60	0.65
	10	0.45	0.50	0.55
	100	0.40	0.45	0.50
	1000	0.35	0.40	0.45

APPENDIX E: Weekly depths to water table in the three blocks at the experimental study site in (m).

Week	Block 1	Block 2	Block 3
1	0.16	0.16	0.18
2	0.18	0.16	0.18
3	0.18	0.20	0.20
4	0.20	0.21	0.22
5	0.25	0.22	0.16
6	0.25	0.25	0.20
7	0.30	0.25	0.30
8	0.20	0.30	0.30
9	0.15	0.20	0.18
10	0.17	0.16	0.15
11	0.20	0.16	0.16
12	0.22	0.18	0.20
13	0.25	0.20	0.22
14	0.25	0.20	0.24
15	0.25	0.22	0.25
16	0.28	0.25	0.25
17	0.28	0.25	0.26
18	0.30	0.28	0.28