THE USE OF SYMBIOTIC *AZOLLA-CAROLINIANA* AS A WATER MANAGEMENT TECHNIQUE IN PADDY FIELDS: A CASE STUDY OF LOWER MOSHI IRRIGATION PROJECT IN TANZANIA

BY

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ABSTRACT

Traditional water management techniques employed in irrigated rice production are deficient, particularly in controlling moisture loss. In this study, *Azolla caroliniana* backed by conventional approaches (e.g soil puddling, sub-soil compaction and levee coating reinforced with lateral flow barriers) was used to suppress evapotranspiration in rice fields under irrigation. A field experiment was carried out at Lower Moshi irrigation project in Kilimanjaro region in Tanzania between the dry season and short rainy season from September 2000 to January 2001. The study was done at the Kilimanjaro Agricultural Training Centre (KATC) experimental farm, which has medium clay soils. The aim was to evaluate the effect of *Azolla caroliniana* (a green manure with symbiont blue green algae) in economising irrigation water in rice cultivation. The type of rice used in the study was a local indigenous variety known as Wahiwahi. The water balances for the growing period and grain yields at harvest were determined. Yield attributes were assessed for the effect of Azolla. The experiment was conducted in a randomized complete-block design with four replications and three treatments. The plot sizes were each 5.3 m x 5.1 m. The treatments were: Wahiwahi only (T1); Wahiwahi and Azolla (T2) and Azolla only (T3). Ridges were made around the individual plots to allow ponding. A nursery for pre-germinated rice seeds was established for 25 days after which the seedlings were transplanted. Azolla was administered in treatments T2 and T3, 7 days after transplanting. Crop water use measurements were done at 14 days post transplanting and thereafter daily for the whole growing period (three and half months). Parameters monitored in total water use were evapotranspiration and seepage and percolation.

One lysimeter and one percolation cylinder were installed in each treatment to facilitate the measurements. Other data collected included measuring plant growth (plant height, straw dry weight, number of tillers, heading time and weed population); determining yield components (number of panicles and grains, percent of ripe grains and grain weight at harvest) and grain yield. The total water use obtained in treatments T2 and T3 were 8.13 mm/day and 7.05 mm/day respectively, which were not significantly different ($p \le 0.05$). In treatment T1, the total water use observed was 11.99 mm/day, which was significantly higher ($p \le 0.05$) than T2 and T3. There was no significant effect ($p \le 0.05$) of Azolla on seepage and percolation. The lowest evapotranspiration was obtained in treatment T3 with 2.24 mm/day, which was significantly different ($p \le 0.05$) from T1 and T2. Evapotranspiration was 6.48 mm/day in treatment T2 which was 23% lower and significantly different ($p \le 0.05$) from that in T1. Reduced dry matter weight of weeds was registered in T2 and T3 where the weed control efficiency was significantly higher ($p \le 0.05$) than T1. Rice plant growth in T2 was greater and more superior throughout the growing period compared to plants in T1. The grain yield in T2 was 7.93 t/ha which was significantly higher ($p \le 0.05$) than 6.31 t/ha in T1. Azolla management effect gave soil-moisture retentivity of 32% that resulted in increased water use efficiency by the crop. The crop stand was improved and grain yield increased. The use of *Azolla caroliniana* in irrigated rice cultivation is recommended as a water management practice.

DECLARATION

I, LOVEJOY PATRICK TAMBUDZAI MAPARA, 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.

Signature ....LPT Mapara....

Date...26/08/2002.......

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ABREVIATIONS

AICRP = All India Co-ordinated Research Project

ANOVA = Analysis of variance

BGA = Blue green algae

CEC = Cation exchange capacity

CRBD = Completely randomized block design

CV = Coefficient of variation

DAT = Days after transplanting

DAI = Days after inoculation

DAS = Days after sowing

DM = Residual dry matter

DNMRT = Duncan's New Multiple Range Test

E_p = Pan evaporation

ET = Evapotranspiration

ET_o = Potential evapotranspiration

ETcrop = Crop evapotranspiration

FAO = Food and Agricultural Organization

Fig = Figure

FYM = Farm yard manure

FW = Fresh weight

FWR = Field water requirement

HC = Hydraulic conductivity

IRRI = International Rice Research Institute

KATC	= Kilimanjaro Agricultural Training Centre
K_c	= Crop coefficient
K_p	= Pan coefficient
LMIP	= Lower Moshi Irrigation Project
Lsd	= Least significance difference
N	= Nitrogen
RH	= Relative humidity
RWS	= Rain water supply
S	= Slope
WUE	= Water use efficiency

CHAPTER ONE

1 INTRODUCTION

1.1 Background information

Many rice-growing areas in Tanzania including Lower Moshi Irrigation Project (LMIP) in Kilimanjaro region experience periods of chronic water shortages. Introduction of modern rice farming in LMIP resulted in higher incomes and improved living standards of the society. As a result, more people have become interested in irrigated rice farming. Consequently, additional irrigation canals have been constructed especially in the areas outside (upstream) the project without proper co-ordination or planning. Crop production in LMIP has been below expectations as only 43% of the area in the project is currently irrigated, though there exists a vast scope for rice area expansion. Water is scarce at critical rice growth stages and inefficient water management appears to be the major reason responsible for poor yields. Currently, LMIP faces a critical shortage of irrigation water. According to Kilimanjaro Agricultural Training Centre (KATC, 2000), farmers in the project (particularly Chekereni and Oria) consistently experience yield reductions. In some cases, total crop failures have been reported (KATC, 2000). Apparently, water sources and amounts are not enough to irrigate rice fields mostly grown under irrigated lowland conditions by small holder farmers. Therefore, efficient management of water has become a high priority and an essential factor in stabilizing rice yields (Maregesi, 1995; KATC, 2000). The LMIP has a total area of 2 300 ha and covers four villages namely; Mabogini, Rau ya Kati, Oria and Chekereni. The project was originally designed to irrigate 1100 ha during the wet season while in the dry season, the area had to be reduced to 800 ha due to anticipated water shortage. Owing to limited availability of water from the sources, only 473 ha are effectively cultivated for paddy production per one season (URT/JICA, 1988). Even this area, continuously experience water stress during critical growth stages resulting in low crop production (Makongoro, 1997). In LMIP, Makongoro (1997) reported both high (> 1) and low (< 1) relative water supply (RWS) values in a single growing period. According to Sakthivadivel *et al.* (1993) RWS values greater than 1 may be due to low water costs which put farmers at liberty to use inefficient irrigation practices causing over-irrigation. Gates *et al.* (1991) reported that low RWS values reflected a gradual decline in the fraction of the irrigated area due to water scarcity caused by inefficient water management practices. Ever since LMIP was developed in 1984, it has never been fully cultivated due to water scarcity. According to Kimicho (1998), measures to increase the irrigable area and possibly improve the water use efficiency by the crop included amending the originally planned two seasons cropping pattern (main and off-seasons) per year to three seasons. Rice yields had improved from 2 tonnes per hectare in the early 1980s to an average of about 7 t/ha in 1985 (Horibata, 1992). However, the yields per unit area have continuously been declining over the years to the current 5 t/ha. According to Maregesi (1995) and KATC (2000), the following factors contributed to this shortfall.

i) Water rights granted to the project were less than the design requirements:

ii) At the design stage very low actual unit water requirements (1.5 m^3/sec) were adopted but field requirements proved to be higher (3.5 m^3/sec);

iii) Poor water management;

iv) Unauthorized withdrawal of water (for the expanded paddy cultivation area) out-side (upstream) the project which rose from 250 ha (before the project) to more than 1290 ha (after the project).

In LMIP, annual evaporation rates vary from 3 mm/day in May to 9 mm/day in January. This inevitably put annual vapor losses to be more than 2000 mm. According to URT/JICA (1988), one cause of water shortage is the naturally high evapotranspiration (ET). Maregesi (1993) argued that rice responded well to water management practices and attributed higher water losses to poor water management by farmers. Daigo and Phaovattana (1999) reported that poor water management at field level. apart from exaggerating the effect of weather in increasing the amount and rate of ET, also encourages seepage and percolation. Average percolation rate for the rainy and dry seasons measured by LMIP and determined for five years (1987-1990) was 8 mm/day. Makongoro (1997) reported that irrigation was adequately supplied, yet most of the vast quantities of water diverted for use in the field never benefited the crop. Edward *et al.* (1986) cited by Maregesi (1995) attributed the disappointing results obtained from farmer managed irrigated schemes to their failure to realize the importance of water management at the field level. In view of this situation, it is imperative that adequate efforts be made to reduce such water losses in order to improve and stabilize rice yields in the project.

1.2 Problem analysis and justification

Puddling, an activity that was claimed by Wickham and Singh (1978) and Sharma and De Datta (1986) to reduce seepage and percolation losses has been in use in the

LMIP as a land preparation technique. This could have had a great contribution in reducing liquid water losses but has no effect in controlling vapor losses. Low cost and sustainable advances and techniques are needed to complement the effect of puddling. These must focus on modifying the soil physico-chemical and biological properties related to soil and water regime, and suppress evaporation. Covering the water surface between the stools bordering the rice plants or reducing the free water surface can feasibly reduce evaporation, a component of ET. The cover on the surface could reduce the increase in water temperature, especially during daytime, hence reducing evaporation losses. One such technique, which seems the most feasible and appropriate in the LMIP. is the use of the aquatic fern of the Azolla species. The fern, *Azolla caroliniana* (Mvukiye. N.E. personal communication, 2000) is abundant in the LMIP. Under the best field conditions, it grows well in paddy fields and has been in use, particularly at KATC as a weed suppressor and an organic source of nitrogen for irrigated rice (Mvukiye, 1999). Rice plants stimulate and encourage the development of blue green algae (BGA) found in Azolla leaves (IRRI, 1981). Azolla normally grows and forms a thick mat of its fronds on the water surface between rice plants. This characteristic would reduce the area of water surface open to evaporation and subsequently prevent water heating up (Singh. 1979). Consequently, ET is suppressed (Van Hove, 1989). Singh and Ganghi (1964) reported that Azolla ferns produce some dry matter or polymers that improve the soil structure and reduce soil capillary. A demonstration by Wang Keun Oh (1979) on BGA showed the occurrence of some dominant nitrogen (N) fixers which besides fixing N, the algae excreted polymers which modified the soil-moisture regime. Sahoo and Datta (1999) reported that Azolla mat suppressed growth of aquatic weeds that would otherwise compete with the rice plants for water. Despite such indicated potential of using Azolla fronds as moisture conservation technique, they are photosynthetic and inevitably take up some water for their consumptive uses. Many studies related to Azolla focussed on soil fertility (Roger and Kulasooriya, 1980) with little attention to other soil-water relations. More importantly, topics of water cycle successions have not been documented. Several workers reported improvement of soil structure and increased water residues, even in relatively porous soils (Watanabe, 1978; Singh, 1979; Lynchi, 1983; De Datta and Hundal, 1984; Diarra *et al.*, 1984; Watanabe, 1996). In Tanzania, the use of Azolla has been limited and few studies appear to have been done to quantify the contribution of Azolla in water management in paddy fields.

1.3 Objectives of the study

This study was conducted with the general objective of quantifying the influence of *Azolla caroliniana* on the water balance in rice paddies and its effect on the rice crop growth and yield obtained with special reference to LMIP. The specific objectives were:

i) To assess the physical and chemical properties of the soils under irrigation

ii) To assess the evapotranspiration (ETcrop) of rice in combination with Azolla

iii) To assess the combined seepage and percolation losses for the growing period

iv) To assess the effect of Azolla fronds in suppressing weeds

v) To assess open pan evaporation under the climatic and rice growing conditions.

1.4 Organization of the dissertation

In chapter Two, the review of literature is presented. Furthermore, information on environments with distinct advantages for Azolla species and limitations of soil conditions on the green manure is reported. Ecological systems adapted for paddy production and water management practices recommended for irrigated rice are also presented. The materials and experimental methods used in collecting data are presented in Chapter Three. The results and discussions of this study are reported in Chapter Four and the conclusions and recommendations drawn from the study are given in Chapter Five.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 General morphology of Azolla

The genus Azolla is a coherent group of aquatic ferns associated with the family of salviniaceae, or genus *Azollaceae azollae* found in both temperate and tropical-fresh water ecosystems. Azolla, also occur in waterlogged soils and are widely distributed in tropical rice fields. The Azolla plant, often called a frond (Van Hove, 1989), has a branched short stem (rhizome) with deeply bilobed overlapping leaves. Under optimal growth conditions, the ferns float in water and form a mat that usually covers water surfaces (Van Hove, 1989). Nitrogen-fixing blue-green algae (BGA), *Anabaena azollae* grows on the root and tissue surface and air cavities of Azolla leaves. Naturally, a permanent symbiotic relationship exists between Azolla and BGA, hence the two are associated at all stages of their life. Azolla controls the multiplication of *Anabaena azollae* in the leaves and algae population develops abundant nitrogen to inoculate each new leaf of the Azolla fronds. Reproduction of Azolla between generations is by fragmentation (Peters, 1978; Becking, 1979; Van Hove, 1989).

Six extant Azolla species have been identified (Moore, 1969) and these are divided into two groups, namely; Azolla (or Euazolla) and Rhizosperma. Species of Euazolla are *Azolla filliculoides* found from southern South America to Alaska and *Azolla caroliniana*; eastern USA, Mexico and West Indies. Other strains of Euazola are *Azolla mexicana* and *Azolla microphylla* in western and northern South America and West Indies (Becking, 1979). Rhizosperma covers two species namely *Azolla pinatta* and *Azolla nilotica. A. pinatta* is widespread in the Eastern Hemisphere, tropical and southern Africa, Southeast Asia, Japan and Australia. *A. nilotica* occurs on the Nile in Africa (Moore, 1969) and paddy fields in western Kenya (Okhoba and Nkokak, 1980).

2.2 Occurrence of Azolla in Tanzania

Both indigenous and introduced species of Azolla occur in Tanzania. Indigenous species consist of *A. nilotica,* tall-sized (15 cm) and native of East Africa and small-sized Azolla of several sub-species *(A. filliculoides, A. caroliniana, A. mexicana, A. microphylla,* and *A. pinatta).* Introduced strains occur in LMIP, Korogwe, Mkindo and Zanzibar (Alli, 1996; Watanabe, 1996). According to Watanabe (1996) *A. caroliniana* found at KATC was introduced from Mkindo, Morogoro region in 1994.

2.3 Environmental requirements of Azolla

2.3.1 Water

Azolla multiplies vegetatively and increases its biomass rapidly when floating in water. It doubles its weight in 3 - 4 days. Azolla reaches maximum productivity in terms of weight per unit area or time preferably in shallow water depths (Chung Chu, 1987; Lumpkin, 1987b; Ventura and Watanabe, 1991). The shallow depth (2.5-5.0 cm) of water enables Azolla roots to come near, or in contact with the soil and absorb essential plant nutrients (Van Hove, 1989; Wagner, 1996).

2.3.2 Temperature

The optimum temperature for proper growth of Azolla is 20 °C - 35 °C (Van Hove, 1989). According to Meelu *et al.* (1994) high (35 - 40 °C) and low (below 10 °C) temperatures do adversely affect the growth of Azolla. *A. caroliniana* has been reported to thrive in extreme high and low temperatures (Pande, 1978; Lumpkin, 1987b; Van Hove, 1989).

2.3.3 Light intensity

Azolla grows best in less than full sunlight and reaches its maximum growth rate at 25 -50% of full sunlight (Rains and Talley, 1978b). In South Africa, Ashton (1974) reported Azolla growth to be highest at 50% of full sunlight. Demonstrations by Becking (1979) indicated that Azolla growth depends on plant density and growth stage of rice plants. According to Becking (1979) a certain degree (50-75%) of full sunlight may occur without interfering with Azolla growth. Extreme low light intensities, such as those caused by dense rice canopy, may reduce rate of growth (Becking, 1979).

2.3.4 Soil minerals and soil pH

2.3.4.1 Soil minerals

Essential macronutrients for optimum growth of Azolla are phosphorous, potassium, calcium and magnesium. Phosphorous is the most known limiting nutrient element (Becking, 1979). According to Pande (1978), the application of 1.75 to 3.50 kg P/ha is necessary for proper growth of most strains of Azolla in the field.

2.3.4.2 Soil pH

The optimum pH for proper growth of Azolla ranges from 4.5 to 7.0. Light affects photosynthesis, and appears to regulate independently carbon dioxide fixation, that controls pH. At higher pH, proliferation of blue green algae is suppressed and Azolla growth retarded. However, studies indicate that Azolla can thrive over a pH range of 3.5 to 10 (Ashton, 1974; Watanabe *et al.*, 1977; Lumpkin, 1987b; Lumpkin and Plucknett, 1980; Van Hove, 1989).

2.3.5 Relative humidity

Watanabe (1982) reported that the optimum relative humidity for proper growth of Azolla is 85% - 90%. Azolla fronds become fragile and may dry up at relative humidity (RH) less than 60% (Hamdi, 1982). At higher RH values, especially those coupled with high temperatures, growth of insect pests and fungi are stimulated, consequently attacking Azolla.

2.4 Growth indicators for Azolla

The essential indicators for the growth of Azolla are biomass and productivity.

2.4.1 Biomass accumulation

Under optimum environmental conditions, an increase in Azolla biomass per unit area can be represented by a sigmoid curve (Van Hove, 1989). The curve is partitioned into five phases with two phases overlapping in succession. The first phase (exponential growth) starts just after Azolla is introduced into the field at a specified inoculation density (fresh weight per unit area). Individual fronds start multiplying at a slow (but increasing) rate, until they touch each other end to end, yet each frond being able to float independently. At this stage, Azolla growth enters its second phase (linear growth). Azolla fronds expand and interweave rapidly, though at a constant rate, eventually forming a single-layer thick mat. The fern mat gradually covers all the available water surfaces on which it floats. The third phase follows as the fronds start over crowding (piling) by either (progressively) resting on top of one another or developing an erect bearing. Interweaving of the fronds follows and later these activities slow down, indicating the deceleration of growth. Maximum interweaving marks the end of the third phase and multiplication stops. At this point, Azolla would have attained maximum growth and hence maximum biomass. Maximum biomass is maintained (fourth phase) for some period. At the close of the fourth phase, a large part of Azolla fronds in the bottom layers will become shielded from direct light by those above, in a state of piling (Rains and Talley, 1978b). Finally, the overall growth of Azolla is reduced. The shielded layers (fronds) start degenerating in the fifth phase. Van Hove (1989) and Meelu *et al.* (1994) reported accumulation of biomass for Azolla of 12 t/ha to 120 t/ha.

2.4.2 Azolla productivity

Azolla productivity, indicates the rate of accumulation of biomass per unit area over a given time, that is, the time taken to cover completely a given area by Azolla mat. The main determinant for Azolla productivity is the strain used. Other factors include the inoculation density of fronds (fresh weight (FW)/m^2), time of inoculation, cultural practices and environmental conditions. Azolla can be inoculated into paddy fields either by incorporation into the soil before rice transplanting or dual cropping with rice. The best period of inoculation is during the linear growth of Azolla. Studies have shown that high inoculation rates, generally achieve complete cover by Azolla mat earlier than low rates. At an inoculation rate of 200 - 300 g (FW)/m^2, Ventura and Watanabe (1991) observed that Azolla mat covered an area of one hectare in 10 to 15 days. Singh (1979a) reported that Azolla, inoculated as dual crop at 100 g (FW)/m^2 covered one hectare of bunded rice fields in 20 to 30 days after rice transplanting. Van Hove (1989) recommended an inoculation density of 250 - 500g (FW)/m^2 for different environmental conditions regardless of the inoculation technique used.

2.5 Irrigation water requirement of rice

Irrigation water requirement is the total amount of water, which is supplied into the field during the full growing season to prevent plant stress and yield reductions. Each type of crop has its own seasonal water demands required to satisfy its metabolic needs so as to produce optimum grain yield. Irrigation of rice shows some specific characteristics, which deviate from irrigation of other crops (Raes, 1996). Morphologically, rice plants have shallow root systems and long thin leaves. Naturally, rice requires high atmospheric humidity and is very susceptible to water stress. The critical periods at which rice plant is sensitive to water stress are the flowering and late vegetative stages. Rice thrives best under flood (De Datta, 1981). According to Raes (1996), land preparation for rice (paddy) at the start of the irrigation period, requires the saturation of the soil. During land preparation, the water requirement per unit of time is at its maximum, thereafter the soil is usually kept submerged for the whole growing period. Flooding is achieved by puddling the soil and constructing strong ridges (bunds) around the field to retain water supplied by rainfall and irrigation (Berge *et al.,* 1994). Rice in irrigated lowland fields is mostly grown under flood, but it is surprising that water consumption in lowland rice is the same as that required by upland rice (Watanabe, 1992). De Datta (1981) pointed out that rice does not necessarily require continuous flooding because the plant uses less than 5% of the absorbed water. Flooding helps to keep field water temperature at optimum levels required for proper growth. The maintenance of optimum growth temperature normally results in improved plant growth and higher yields. Nishiyama (1984) reported that low temperature is injurious to rice plants because it induces sterility (infertilization). Low temperatures affect the panicle initiation stage and booting (flowering) stage. The site most sensitive to coolness in rice plants, is naturally the panicle, or more specifically, the flower. Nishiyama (1984) pointed out that during cold weather periods, the high specific heat of water causes water temperature to be higher than air temperature. Based on this fact, Sakai (1949b) cited by Nishiyama (1984) reported that deep-water irrigation (above the panicle level) should be applied to protect rice plants from cold temperatures. In order to satisfy water requirements for rice plants, Das (1983) reported that paddy must be flooded from the time when plants are established after transplanting, until one month before harvesting. Consequently, water demand of plants is satisfied, resulting in highest possible yield. Paddy yields decline when soil moisture content decreases to 70 - 80 % of saturation point. At 50 % saturation, yield potential is reduced to 50 – 70 % and at 30 % saturation, no yield is expected. Submergence depth of 10 cm is commonly used. This depth is reduced to 4 –5 cm during tillering stage of the rice crop. Before ripening, water is gradually drained to facilitate harvesting (De Datta, 1981; Das, 1983; Tsuboi, 1992). Raes (1996) reported that irrigation requirement of rice consists of water for evapotranspiration and for seepage and percolation as well as water for cultural water practices. The cultural water needs include saturation of the field before transplanting or sowing and water for establishing a water layer in the field during plant growth. Watanabe (1992) reported that evapotranspiration in addition to seepage and percolation makes the total water required for a paddy site. In Carlifornia, Grist (1965) reported rice seasonal water requirement of 1 500 mm to 1 800 mm, while Hodges (1957) in Texas reported 800 mm to 1 200 mm. In Egypt, Adair and Engler (1955) reported about 1 500 mm to 1 700 mm all under controlled irrigation. Das (1983) reported water requirement of 1 100 mm to 1 600 mm under efficient water management practices in paddy fields in India.

2.6 Water losses in paddy fields

Unavoidable losses from a puddled layer include surface evaporation and seepage and percolation. Surface water is also lost from unbunded paddy fields as runoff (Das, 1983; Berge *et al.*, 1994). Berge *et al.* (1994) reported that irrigation supply and/or rainfall, evaporation, transpiration, seepage and percolation determine the water balance of a puddled rice field. According to Berge *et al.* (1994) substantial water is lost from the root zone by percolation and from uncovered water bodies between rice plants through evaporation. Mahoo *et al.* (2000) reported that evaporation returns part of effective rainfall and/or irrigation from the soil directly to the atmosphere before it is used for any purpose. Further more, evaporation occurs over a period of time ranging from a few minutes after irrigation to the whole growing period. Therefore, evaporation is non-productive and from whatever point of view, this component of field water is wasted. On the other hand, productive plants use transpiration, hence transpiration is not a loss. Kihupi (2000) stated that evaporation is an unavoidable loss, which must be compensated for by rainfall and irrigation. James (1988) pointed out that water is transferred to the atmosphere by direct evaporation of water vapor from soil and plant surfaces as well as by transpiration. Kihupi (2000) further stated that during the early stages of plant development, evaporation is high and comprises a large fraction of evapotranspiration. Daniel (1999) reported that water not usually consumed by plants eventually percolates the soil and reaches the ground as recharge. Again, with respect to rainfed and/or irrigated crop production, water that drains beyond the root zone is wasted. Studies (Lunin and Gallatin 1965a; Jurinak and Wagenet, 1981) cited by Patel *et al.* (2000) showed that high evaporation and percolation in regions with limited fresh water are extremely deleterious to rice plants. Patel *et al.* (2000) reported that poor water management results in higher percolation, which increases the incidence of waterlogging and salinity. According to Kampen (1970), water is considered to have been lost if the water changes its form, becomes unusable or if it is not available for other purposes. Substantial water losses have also been reported in rice fields infested by grasses and sedges. Singh *et al.* (1994) singled out poor weed control as one of the important factors responsible for substantial reduction in crop yields. De Datta (1981) and Ghersa *et al.* (1997) reported that rice and weeds share similar requirements for growth and development. Weeds interfere with rice growth by competing for water. Water is usually the most important and greatest need for aquatic weeds because it is required early for establishment and growth. Odhiambo and Murty (1995) studied water balance components in rice fields and concluded that knowledge of consumption mechanisms, and control of the components of water requirements of rice can help to achieve effective use of the available water.

2.7 Field water loss components in paddy fields

2.7.1 Evaporation

Evaporation is the process of changing water into a gaseous state and subsequent movement of the water vapour from a surface into the atmosphere. The process requires a large amount of solar energy and humidity gradient. Evaporation is a major component in the water balance equation for both small and large surface areas (Robertson, 1970; Weisner, 1979). The 'surfaces' include the surface of an evaporation pan, lake, a leaf or soil (Robertson, 1970). The physical process of evaporation at all surfaces is similar in each case, the difference being in the availability of water from the water surface to the atmosphere. Evaporation occurs whenever energy is transferred to an evaporating surface and if the vapor pressure of the air is below the saturation value. The rate of evaporation is related to relative humidity, whereby relative humidity refers to the percent of water vapour contained in the atmosphere. Evaporation rate is high in hot climate with low relative humidity (Robertson, 1970). According to Mahoo *et al.* (2000) evaporation is driven by heat and can therefore be reduced by controlling the amount of solar energy reaching the evaporating surface. Controlling temperature through the interception of radiation by using a partial or complete barrier greatly reduces evaporation. Soil is the medium for water movement in the soil. It therefore determines the diffusive resistance of the soil to water flow. The soil structure controls the rate of movement of water from the surrounding soils to where active evaporation is taking place. High resistances to water flow tend to reduce evaporation (Kanwar and Ray Chaudhuri, 1971; Weisner, 1979). Wind is critical to the process of evaporation. Wind, readily expels water vapour from evaporating surfaces, and creates vapour pressure gradients that maintain evaporation at or near potential rates (De Datta, 1981). For most practical uses, measurements of evaporation from soil surfaces include transpiration and this implies a rate. However, for most crops, transpiration is more or less constant during the growing period (Weisner, 1979). Evaporation measurements are expressed as millimeters (mm) or centimeters (cm) of water depth per hour, day, month and year. Evaporation rate in any given area is characterized by the nature of local climate and prevailing soil conditions. Evaporation rate varies with soil cover, soil texture, wind velocity, temperature and radiation as well as availability of water (Jackson, 1989).

2.7.2 Evapotranspiration

Doorenbos and Pruitt (1977) defined evapotranspiration as the sum of transpiration by the crop and evaporation from the soil surface. It is the amount of water that a certain crop needs to meet its metabolic and growth processes in one full growing period. The crop water requirement is the depth of water needed to meet water released to the atmosphere through evapotranspiration of a disease free crop, growing in a large field under non-restricting soil conditions. This includes soil, water and fertility and achieving full production potential under the given growing environment (Doorenbos and Pruitt 1977). According to Tomar and O'Toole (1980), crop water requirements consist of transpiration and evaporation and are usually referred to as evapotranspiration. Evapotranspiration involves the twin processes of converting liquid water from soil, water surfaces and plant tissues to vapour state and its mass transfer to the atmosphere. Each of these processes involves evaporation and the two are not easily separated. Transpiration withdraws water from the soil through plant roots and releases water vapour to the atmosphere through the plant foliage (Doorenbos and Pruitt, 1977; Tomar and O'Toole, 1980; De Datta, 1981, Das, 1983; Berge *et al*, 1994). According to Mahoo *et al.* (2000), evapotranspiration is the return flow of water to the atmosphere, which include the productive part as transpiration and non-productive part as direct evaporation from the soil and water surfaces. Evapotranspiration is greatly controlled by the physical atmospheric environment and most particularly by solar radiation and air temperature. Evapotranspiration into the lower atmosphere depends on wind speed and air humidity. Other factors that affect evapotranspiration are soil cover and soil texture.

2.7.2.1 Evapotranspiration by rice plants

Physiological functions of the rice plant have little significance to water losses. Das (1983) pointed out that evapotranspiration under non-limiting water supply conditions of flooded rice fields is essentially a function of net radiation incident in the area. High solar incidence and high temperatures in paddy fields increase evapotranspiration (consumptive water use) and water requirements. The net radiation received in a unit area is utilized in evaporating water. Consequently, consumptive water use is increased (De Datta, 1981; Das, 1983; James, 1988). During full vegetative cover for most crops, evaporation is negligible. After rice transplanting and during the early growing period, evaporation from the soil surface between plants may be considerably high (about 100%), particularly under flooded conditions. Doorenbos and Pruitt (1984) reported that the climate and length of the growing period determine the crop water requirement in rice plants. Generally, evapotranspiration (ETcrop) is higher in dry seasons compared to wet seasons. According to IRRI (1993), average ETcrop measured for most rice strains is 450 mm - 700 mm for the whole growing period. IRRI (1993) reported average ETcrop of 600 mm during 100-day rice-cropping periods. In the tropics, the consumptive use for large irrigated areas during wet and dry seasons are 4 – 5 mm/day and 6 - 7 mm/day respectively (De Datta, 1981). In Japan, Yukawa (1995) reported that maximum daily ETcrop was 7.3 mm and minimum was 4.9 mm. In Asian countries, the highest ETcrop measured was 8.7 mm and lowest was 4.4 mm. The average daily ETcrop was 6 mm. Studies in Asia, Bangladesh and Japan by Yukawa (1995) showed that ETcrop was influenced more by atmospheric demand, ground cover, and water availability than by the specific crop species. ETcrop fluctuated weekly and daily from hour to hour following the solar activity during the growing period. Water use increases as atmospheric evaporative demand increases, so long as soil moisture availability is not limiting (Yukawa, 1995).

2.7.2.2 Evapotranspiration by weeds

De Datta (1981) stated that in wetland rice fields, weeds absorb as much or more water than rice plants. Competition between rice and weeds prevails when water falls short of the combined requirements of both. The competition for water is greatest when roots of crops and weeds are closely intermingled and both obtain their water from the same source. Weed infestation results in increased evapotranspiration and reduced water use efficiency in the rice crop (De Datta and Ampong-Nyarko, 1991; Bhagat *et al.*, 1996).

2.7.3 Seepage and percolation

Berge *et al.* (1994) defined seepage as the lateral movement of subsurface water observed as leakage through earth ridges. Percolation is the vertical movement of water beyond the root zone to the water table. According to Wickham and Singh (1978) seepage and percolation are practically, often inseparable. High seepage and percolation leads to increase in the demand of water supply and, hence are undesirable. Singh *et al.* (1980) reported that substantial quantities of deep percolation result in wasting water, waterlogging and soil salinization. Moreover, the complete elimination of seepage and percolation has proved to be extremely difficult because of significant variations in field intake properties, even on very small areas. Singh *et al.* (1980) pointed out that a certain amount of subsurface drainage is required to maintain optimum salt balances. Therefore, knowledge of water movement in soils is an important aspect of irrigation water management. Thus, it is especially important to be able to assess water movement in soil and its availability to the crop and its corresponding effect on crop yield. According to Smedema and Rycroft (1983), the characteristic that governs movement of water and solutes in the soil is called hydraulic conductivity. Hydraulic conductivity is a parameter that defines the diffusive resistance of movement of water in soils. It is measured as rate of flow of water in soils. Due to variations in soil structure and texture, hydraulic conductivity, hence seepage and percolation may considerably vary across an area as well as in depth. Soil structure, bulk density, organic matter content and soil-water regime affect water flow within the soil. Hydraulic properties depend on the size, distribution and geometry of the conducting pores. Jensen (1983) recommended seepage and percolation of 20 - 25 percent of the irrigation depth. In Malaysia, Sugito

(1969) cited by De Datta (1981) reported high rice yields for low percolation rates (< 10 mm/day) and low yields for high percolation rates (> 20 mm/day). The lower grain yields obtained were attributed to high water and nutrients loss through seepage and percolation. On alluvial elastic soils in the Philippines, Wickham (1978) reported seepage and percolation of less than 2 mm/day in the wet season and 2.6 mm/day in the dry season.

2.8. Irrigation water management in paddy fields

Meeting the physiological and ecological water requirements of lowland paddy rice is a prerequisite for effective demand management where water conservation is needed to extend the use of water for crop production. In view of the limited water resources and unfavorable field conditions in many paddy fields irrigation water management becomes a necessity. Irrigation water management is an integrated process of diversion, conveyance, regulation, measurement and distribution of water to the farm. It involves the application of the right amount of water at the right time, place and removal of excess water from the farm to promote increased production with improved cultural practices (JICA/NIA, 1991). Effective water management, ensures optimal water balance conditions in the soil-water regime. Subsequently, higher water use efficiency is realized and increased plant growth and productivity achieved with less harmful effects on the environment (Odhihambo and Murty, 1995). Water conservation practices are techniques, which operate on the various processes of water management in order to minimize losses. Water conservation, therefore is a distinct phase in the development of a water system aimed at reducing water losses from diversion up to and including the field level (JICA/NIA, 1991). In Africa, Speelman (1990) reported that water conservation practices in many farmer managed irrigation schemes are weak. In the Lower Moshi Irrigation Project, Maregesi (1995) and Makongoro (1997) reported poor water management by farmers.

2.8.1 Water management techniques in paddy fields

Sharma and Rajput (1990) reported the success of water management techniques developed by the All India Co-ordinated Research project (AICRP) on efficient management for higher and sustained rice productivity. Cultural practices used were shallow submergence, intermittent irrigation and termination of the irrigation at 14 days before the maturity of the rice crop all of which gave high yields and improved water use efficiency. Soil and water management techniques, which include compacting, puddling, minimum tillage, bunding and mulching helped to store ponded water and improved yields and stability. Sharma and Rajput (1990) reported that deep submergence (> 10 cm) increased seepage and percolation due to higher hydraulic head. However, prolonged shallow submergence (5 Ý 2 cm) saved 10 – 50% in irrigation water. Intermittent irrigation scheduled at 1 – 4 days after the disappearance of ponded water saved up to 30% of irrigation water. On the other hand, surface mulching coupled with earth bunds (15 - 20 cm depth of rice plants) significantly produced higher yields compared with no mulch and unbunded plots. In India, Kanwar and Ray Chaudhuri (1971) reported that high vapour loss from soil surface both under bare and cropped conditions can be reduced by applying mulches and organic manure. Organic matter transformed the soil structure by breaking the pore capillary that checks liquid flow to the surface and decreased the turbulent transfer of water. Mulching intercepted the solar radiation and provided a barrier to vapor diffusion. Elliot *et al.* 1995 reported that protection of free water surfaces to reduce evaporation is uneconomical except under experimental conditions. In Japan, Yukawa (1995) reported high efficiency of water use and substantial savings of water in the traditional plot to plot irrigation method. This method involves the reuse of water in several rice fields, which are arranged on land with a gradient slope, where a cut in the ridge of the upper plot was used to irrigate the lower plot. According to Sharma and Rajput (1990, the practice of puddling, increases the optimum bulk density of light textured paddy soils and effectively reduces seepage and percolation. Sharma and De Datta (1986) also reported reduction of seepage and percolation after puddling. According to Sharma and De Datta (1986), puddling involves the destruction of light textured soil aggregates and macro-pore volume that leads to large increases in micro-pore spaces. Studies by Sharma and De Datta (1986) showed that water retention was increased to below -10 kPa water potential after puddling and both hydraulic conductivity and seepage and percolation were reduced. Sharma and De Datta (1986) concluded that puddling increases soil bulk density, changes volume, size and shape of conducting pores, and exerts an effect of smaller magnitude that leads to rapid reduction of water flow. Yadav (1972) cited by Singh *et al.* (1980) reported that heavy seepage and percolation under irrigation can be reduced by withholding water applications at certain stages of plant growth (intermittent irrigation). Singh *et al.* (1980) citing Rao *et al.*, 1972; Robertson *et al.*, 1973 suggested the use of subsurface barriers, while Varade and Ghildyal, 1967; Ghildyal, 1971; Mallick *et al.*, 1976 also cited by Singh *et al.* (1980) reported improved water retention after surface or subsurface compaction. Pooled results indicated significant reduction in seepage and percolation, which resulted to increased storage of soil moisture and gave higher corn fodder yields. Singh *et al.* (1980) concluded that subsurface compaction method commonly used by farmers to break clods, significantly reduces seepage and percolation resulting in increased crop yields.

2.8.1.1 Effect of mulching cover on evapotranspiration

Evapotranspiration occurs whenever energy is transferred to an evaporating surface and the vapor pressure of air is below saturation value. The surface temperature governs vapour pressure at the surface. According to Weisner (1979) solar energy as the dominant source of energy sets the broad limits of evapotranspiration. It is however, the net (incoming minus outgoing) radiation, which matters most. Jackson (1989) pointed out that a surface cover acts as barrier between thermal energy and water at deeper layers. In southern Ethiopia, studies by Hussein *et al.* (2000) using different mulches in maize fields showed that mulching protected the soil surface from direct exposure to atmospheric demands. According to Hussein *et al.* (2000) mulching protects the soil from direct sunshine, reduces soil temperature, controls evaporation from the soil surface and conserves moisture compared with bare surfaces. In Zaria, Nigeria, Adeoye (1984; 1990) and Kumar (1993) cited by Hussein *et al.* (2000) reported reduced evapotranspiration and increased maize yields after the application of grass mulch in the fields. In this study, soil temperature in the upper (0 - 20 cm) soil horizon was reduced (by 4 - 10 °C) and soil moisture was maintained at favourable levels during the growing period. Hussein *et al.* (2000) citing Shock *et al.* (1997) reported increased soil water retention properties and higher maize yields using wheat straw mulching placed in irrigation furrows. Hussein *et al.* (2000) attributed the increased amount of water that was made available to the plants to mulching which controlled soil temperature and reduced evapotranspiration. Sow *et al.* (1996) reported that management of crop residues to retain them on the soil surface generally increases water conservation. Mandal *et al.* (1990) reported increased yields in safflower after the application of straw mulches in the field. Environmental conditions under the mulches were influenced by reduction of strong radiation, alleviation of increase of temperature and preservation of soil moisture through evaporation. In Japan, Daigo and Phaovattana (1999) studied for 2 years (1995-96) the effect of covering water surface with floating materials (polystyrene foam, duck-weed) to suppress evaporation from farm ponds. Evaporation in treatments with duck-weed (floating kind of weed) was significantly reduced by about 10% compared with unmulched surfaces.

2.8.1.2 Influence of organic matter on evapotranspiration

Organic matter directly or indirectly changes the physical properties of soil, particularly the soil structure. The transformation of soil structure normally results in changing the total porosity, aggregation and particle size all of which affect evaporation (a component of evapotranspiration). Weisner (1979) reported that free draining soils (e.g. sand), reduce the amount of water available for evaporation whereas finer grained soils, such as silts, exhibit more water for evaporation because they allow water to move more easily by capillary action. Fine-grained soils, generally, have more water available per centimeter depth and so can be expected to lose more by evaporation (Parton *et al.*, 1981). Gupta and Ranade (1987) found that clayely soils (primarily vertisols) lost more water through evaporation by margins of 28 - 55% than sandy soils. However, Nath and Singh (1984) reported that sand, sandy loam and sandy clay loam soils evaporated more water than their clay counterparts. The reduction of ETcrop in clay soils was attributed to the ability of clay to form a crust which reduced evaporation at the surface. De Datta and Hundal (1984) reported decreased thermal conductivity and low soil-water diffusivity after applying Azolla and water hynacinth as organic manure in rice systems. In China, Liu (1979) cited by De Datta and Hundal (1984) reported improved soil structure and increased moisture residues in wetland rice-wheat-rape systems using Azolla. The moisture residue from which the succeeding crops (wheat and rape) benefited was attributed to presence of organic matter. In another study in Chiang Mai, De Datta and Hundal (1984) citing Liu (1979) reported increased aggregate stability, improved soil resistance to water flow and slightly improved water availability after the incorporation of green manure. Meyer and Green (1980) reported that reduction of ETcrop is caused by the decrease in the availability of capillary water due to increased resistance in the flow of water from the soil to the roots.

2.8.1.3 Effect of Azolla on evapotranspiration

Soil cover reduces evaporation although a shade provided by plants may increase water loss through transpiration (Weisner, 1979). Van Hove (1989) reported that Azolla has natural protection techniques against low winter and high summer temperatures. These techniques have promoted the considerable extension of rice area under cultivation in America, Asia, Japan and Indonesia. Van Hove (1989) also reported remarkable improvement in soil-water regimes in temperate and tropical regions of rice fields applied with Azolla. The prolific development of Azolla on water surfaces and its velvet or mat characteristic modifies the microenvironment conditions in rice fields. Studies by Van Hove (1989) in Africa, Asia and America indicated that Azolla mat acted as a buffer in regulating temperature variations. In California, USA, Talley and Rains (1980) reported that the fern increasingly becomes compact and the cover develops into a dense multi-layer mat. Van Hove (1989) concluded that Azolla suppresses evapotranspiration. A review of literature by Singh (1979) and recent findings by Mandal *et al.*, (1998) reported that the green mat acts as a buffer by providing a barrier which checks water temperature. Other workers (Singh and Gandhi, 1964; Singh, 1979; Metting, 1981; Shalan and Aha-EL-Din, 1989; Mandal *et al.*, 1998) reported that Azolla produces some dry matter or extra-cellular polymers that improves the soil structure and aggregation thereby breaks the capillary. Consequently, evapotranspiration is reduced. In India, studies by Singh and Gandhi (1964) and Lynchi (1983) indicated that polymers from Azolla greatly influences the soil-water regime. The polymers reduce the transpiration to evaporation ratio and increases water use efficiency in paddy rice. Linacre *et al.* (1970) found that a swamp evaporated less water compared to a lake. Lower evaporation in the lake was attributed to the lower albedo of the clear water surface of the lake. Moreover, reeds provides cover to the water surface and internal resistance to water movement in the reeds helps to reduce water loss. According to Jackson (1989), the rate of water loss in turbid water is lower than clear water. Suspended silt particles readily reflect heat rays back into the atmosphere, thus keeping water temperature low. Consequently surface evaporation is reduced, and ETcrop of weeds is kept low. Kanwar and Ray Chaudhuri (1971) stated that the presence of barriers to intercept direct radiation and mechanism to break capillaries that check liquid flow to the surface greatly reduces evapotranspiration.

2.8.1.4 Effect of organic matter on seepage and percolation

Organic manure, whatever its origin, has a microbial population which stimulates general microbial activity in soils. Maule *et al.* (2000) reported reduction in seepage and percolation due to the sealing of soils by organic humic excretions. In a 3-year study, De Datta and Hundal (1984) reported that bulk density and resistance to penetration were reduced and water-holding capacity in paddy fields increased after applying Azolla. In a 10-year study of rice-fallow rotations using Azolla and farmyard manure in India, De Datta and Hundal (1984) reported improved water-stable aggregation and reduced hydraulic conductivity. The two treatments improved the water retention characteristics in the alluvial loam soils. However soil properties in Azolla grown plants produced higher crop yields. In a 2 year (1991-92) study by Bhattacharya and Mandal (1997) in West Bengal, India, seepage and percolation in irrigation paddy fields was significantly reduced after the application of green manure. Conservation of water was reflected in the increased grain yield obtained.

2.8.1.5 Influence of Azolla on seepage and percolation

Van Hove (1989) reported that Azolla improves the structure of paddy soils. According to Singh (1979a) the inherent ability of Azolla to fix atmospheric nitrogen is important in tropical rice soils. However, the greater potency in Azolla is more conspicuous in sustaining crop production through conserving soil health. Metting (1981) reported successful use of Azolla in land reclamation of swampy saline and sodic soils in Tashkent and India as well as soil improvement in central and north America. In India, studies by Singh (1979) showed that Azolla produced carbon dioxide (CO_2) which reacted with calcium, replaced sodium adsorbed to clays resulting in low soil dispersion and improved water retention. Singh and Gandhi (1964) reported that Azolla produced some dry matter or polymers that changed the soil structure. A review by Lynchi (1983) showed that extra-cellular polymers have an aggregating property that breaks pore capillaries and improves the soil structure. Mandal *et al.* (1998) reported that Azolla modifies the physical and biological properties of paddy soil and changes the soil-water regime in the fields. Studies done in Egypt by Shalan and Aha-EL-Din (1989) on the isolation of blue green algae ((BGA) in rice fields indicated that BGA produced growth-promoting substances or polymers. The polymers (amino acids, auxins and vitamin B_{12}) considerably changed the soil-water regime. BGA liberates extra-cellular organic compounds including polymers during their growth and after decomposition, while Azolla curbs ammonia volatilization, the fern mat reduces water temperature. Azolla directly or indirectly changes the physical, chemical and biological properties of the soil and soil-water interfaces in rice fields. More importantly, water flow to the surface is reduced. (Singh and Gandhi; 1964; Lynchi, 1983; Van Hove, 1989: Mandal *et al.*, 1998).

2.8.1.6 Effect of Azolla on weeds

In West Bengal, India, Sahoo and Datta, (1999) reported substantial reduction of weed density and weed stand using *A. Caroliniana*. Weeds rigorously competed for water and nutrients and significantly reduced rice yields. but after dual cropping with *A. Caroliniana* crop stands were improved and grain yield increased. In India, Mandal *et al.* (1998) reported that Azolla suppressed weeds in paddy fields. Ghosh and Sharma (1997) studied weed control practices used in paddy fields of Cuttack, India and reported that yield performance of rice was associated with decrease in weed dry matter. In this study, the increase in grain yield was significant where weeds had inadequate plant stands. In tropical rice fields where Azolla forms a thick mat and suppress weeds, Watanabe (1982) reported retarded weed stand and increased crop yield.

2.8.2 Measurement of evapotranspiration

Evapotranspiration is a rate and is expressed as millimeters (mm) or centimeters (cm) of water depth per hour, day, month or year. Jessen (1973) reported that ETcrop can be calculated from crop and climate data (empirical methods) or determined by direct measurement (lysimetry) method. These are briefly discussed in the following sections.

2.8.2.1 Empirical methods

These methods predict ETcrop from climatological data (Jensen, 1973, Doorenbos and Pruitt, 1977). Evaporative water loss is calculated from a reference system, that is, alfalfa (grass) or open water system. For the purpose of this study, the estimation of ETcrop using the reference crop method is sufficient.

(i) Reference crop method

In order to facilitate the calculation of crop water requirement under certain climatic conditions, grass is taken as a standard or reference crop (Parton *et al.*, 1981). The water requirement of this reference crop is called the reference or potential evapotranspiration. The optimum evapotranspiration for a particular grown crop is called the crop or actual evapotranspiration. The actual evapotranspiration is determined by introducing a crop coefficient (K_c) on the potential evapotranspiration (ET_o) (Doorenbos and Pruitt, 1977). Mathematically, crop water requirement or ETcrop is expressed as:

$$ET_{crop} = K_c \times ET_o \qquad (1)$$

where: ET_{crop} = crop water requirement (mm/day);

ET_o = the potential evapotranspiration (mm/day);

K_c = crop coefficient.

For paddy rice the K_c values are as shown in Table 2.1 while the ET_o according to Penman (1963) cited by Doorenbos and Pruitt (1977) is expressed as;

$$ET_o = C[(W.\ Rn) + (1 - W).\ f(u).\ (e_a - e_d)] \qquad (2)$$

where: ET_o = Reference crop evapotranspiration (mm/day);

W = Temperature related weighting factor;

Rn = Net radiation equivalent evapotranspiration (mm/day);

f (u) = wind related function (km/day);

(ed – ed) = Difference between saturation vapour pressure (e_a) at mean air temperature and the actual vapour pressure (e_d) of air (mbar);

C = Adjustment factor to compensate for the effect of day and night weather condition.

Table 2.1. Crop coefficient (K_c) values for rice growth stages

Crop growth stage	Crop coefficient (Kc)
First and second	1.10 – 1.15
Mid-season	1.10 - 1.30
Late season	0.95 - 1.05

Source: Doorenbos and Pruitt (1977)

2.8.2.2 Lysimetry

ETcrop can be determined based on the crop itself and its stage and level of development using lysimeters (Tomar and O'Toole, 1980; Grimmonds and Belding, 1992). Existing lysimetry techniques involve isolating a portion of the crop from its surroundings and determining ETcrop. Lysimetry methods use the principle of conservation of mass as derived from the energy balance of the soil and plant surface. They involve mass transport of water vapor above the soil and plant surface, or a combination of the two (Jensen, 1973). Lysimetry permits direct measurement of evaporation or ETcrop from the field. Lysimeters are conveniently divided into two types according to their sizes: (1) big lysimeters (vol. $>1m^3$) (FAO, 1982) and (2) micro-lysimeters (normally vol. $< 0.01m^3$) (Tomar and O'Toole, 1980). Lysimeters are of two types, weighing and non-weighing. Water is added to the lysimeter by rainfall or irrigation and any subsequent change in weight or volume of water is measured. Water lost represents direct evaporation, ETcrop or percolation (Weisner, 1979). Lysimetry is the only hydrological method, which provides the experimenter with complete knowledge of all terms in the water balance equation. It is the most accurate technique used for measuring evapotranspiration (Grimmonds and Belding, 1992; Sharma *et al.*, 2000). Lysimeters have been compared against other evaporation devices (e.g pan evaporation) and showed more accuracy (Van Zyl and De Jager, 1987).

2.8.3 Measurement of seepage and percolation and hydraulic conductivity

2.8.3.1 Measurement of seepage and percolation

Seepage and percolation vary directly with the magnitude of hydraulic gradient and hydraulic conductivity obeying Darcy's law (1856) cited by Childs (1969). Mathematically,

Qs = - K(q) ÑH/Ñs

where: Qs = volume of water moving through the soil in the s-direction per unit time.

ÑH/Ñs = Hydraulic gradient in s-direction;

K(q) = Hydraulic conductivity which depends on both properties of the fluid and the transport media;

H = Hydraulic head which is the sum of the pressure head, 'h' due to ponded depth and the elevation head, 'z' due to capillary depth. The negative sign indicates flow in the direction of decreasing 'H'.

Wickham (1978) demonstrated three field techniques suitable for measuring seepage and percolation. These are (a) cyclinder method, (b) manometer method (c) water balance technique.

(a) Cylinder method

This method consists of two cylinders partially buried in the soil with rice plants growing inside them. Both cylinders are open to the atmosphere at the top while one is open and the other is closed at the bottom. Water is added to a given reference level and subsequent changes in water height is measured daily. The change in water height in the closed bottom gives the ETcrop rate, whole the open cylinder measures the ETcrop rate plus seepage and percolation. The difference between the readings in the two cylinders gives the total seepage and percolation.

(b) Manometer method

This method measures the fall in water height in flooded rice fields using a simple meter. It is suitable for monitoring submergence depth.

(c) Water balance technique

This method involves the application of a certain amount of water to a known cultivated area (minimum 20-hectare). Field water losses are then determined by measurement.

2.8.3.2 Measurement of hydraulic conductivity

Several methods have been developed to measure hydraulic conductivity both for laboratory and field use. According to Gupta *et al.* (1993) the accuracy of estimating hydraulic conductivity by various methods depends upon the degree to which steady flow is attained. The ability of each method to address various theoretical and field constraints involved in representing the physical system with partial differential equations selected is critically important. Field methods like tension infiltrometers are more preferable than laboratory methods (Klute, 1986). According to Ankey *et al.* (1991) basic infiltration rates obtained from tension infiltrometers can be used to calculate hydraulic conductivity by using the following expressions:

$$q = K_{sf}\, e^{(ay)} (1 + 4\hat{E}\, pr2)$$

and

$$K(y) = K_{sf}\, e^{(ay)} \qquad (5)$$

where: q = basic infiltration rate at a particular (cm/ hr)

K_{fs} = standard hydraulic conductivity (cm/ hr)

a, p = dimensionless constant

y = tension (cm)

r = radius of the tension infiltrometer (cm)

$K(y)$ = hydraulic conductivity at a particular tension (cm/ hr)

2.9 Synthesis of literature review

In the preceding sections, some specific characteristics for rice, which deviate from irrigation of other crops and make rice a leading economical user of water, were discussed. These include saturation of paddy soil before transplanting, water for maintaining a water layer during growth, water for evapotranspiration and for seepage and percolation. Traditional water management techniques used in economizing irrigation water in rice production were reviewed with an aim to improve the efficiency of water use by the crop. The conventional approaches currently in use for higher and sustained rice productivity, which consist of soil and water management practices are highly deficient, particularly in the control of moisture loss in lowland rice. Soil conservation methods reduce seepage and percolation and involve compacting of the sub-soil, use of sub-surface barriers and puddling. Bunding and surface mulching help to store ponded water in upland fields. However, mulches are not feasibly used in flooded rice fields. Other cultural practices include withholding water applications (intermittent irrigation) at certain stages of plant growth, prolonged low submergence and terminating of the irrigation at 14 days before maturity of rice. In Lower Moshi irrigation Project (LMIP), heavy water loss is reported after irrigation water has entered the field. Poor water management by farmers and high evapotranspiration were singled out as the major causes of the alarmingly high rate of irrigation loss. The natural environmental condition that exists in LMIP results in vapour loss that keeps evapotranspiration very high. The review of water requirements by weeds, showed that weeds compete with rice for water, and substantially contribute to the already high evapotranspiration. It is clearly seen that traditional approaches employed for water conservation in rice production are deficient, in controlling evapotranspiration when applied in lowland rice. Covering the water surface in the field can feasibly control temperature, and subsequently reduce evaporation. One such technique, which seems the most appropriate is the use of an aquatic fern of Azolla species. The inherent ability of *Azolla caroliniana* to assume a quick soil cover, improve soil structure and its successful use against extreme low and high temperatures in rice fields were reviewed as possible water management tools to curb field losses. The potency of Azolla in moisture preservation is conspicuous in its ability to grow relatively fast and assume a quick dense cover that checks ground temperatures. Azolla suppresses weeds that would otherwise compete with rice for water. Azolla also conserves soil health that result in increased rice yields. The advantages ascribed to Azolla include improvement of soil fertility, enhanced microbial activity, improved soil structure and improved water retentivity. Based on these and similar results, assessments are made on the effect of *Azolla caroliniana* as a water management technique in rice production.

CHAPTER THREE

3 MATERIALS AND METHODS

3.1. Description of the experimental site

3.1.1 Location

The study was conducted in Kilimanjaro region at Lower Moshi Irrigation Project (LMIP), which is located 17 km south east of Moshi town. The study area is shown in Fig. 3.1. LMIP is a farmer managed irrigation project situated at latitude 3° South and longitude 37.5° East. The altitude varies from 700 m to 800 m above sea level. The experimental site was located at the Kilimanjaro Agricultural Training Centre (KATC) trial farm, which is within LMIP. The irrigation project consists of a relatively narrow strip of land developed on an alluvial plain along the right-bank of Rau river and covers four administrative villages namely; Mabogini, Rau-ya-Kati, Oria and Chekereni. Rau and Njoro rivers supply water for irrigation. Two intake weirs (Rau and Mabogini) collect the water which is distributed to the fields by diversion structures, regulators and canals (URT/JICA, 1988).

3.1.2 Climate

Optimal climatic conditions for rice production exist in the LMIP and are generally favorable both for upland and paddy rice. LMIP experiences three distinct seasons; a long rainy season from March to May, a dry season from June to October and a short rainy season from November to February (URT/JICA, 1988).

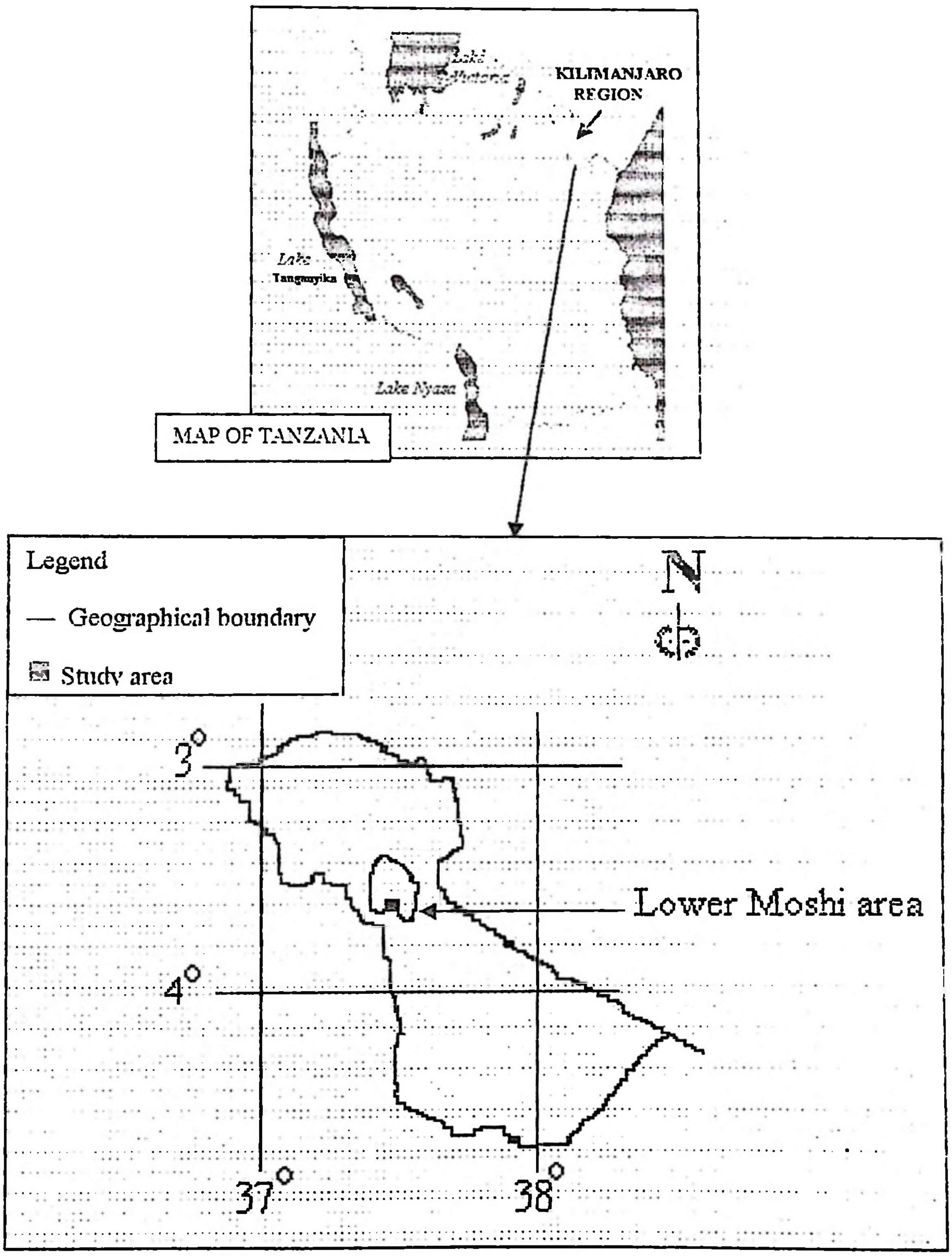


Figure 3.1: Location map of study area

- **Rainfall**

Rainfall pattern in Lower Moshi area is bimodal. Mean annual rainfall is 590 mm of which about 370 mm (63%) falls in the long rainy season, 60 mm (10%) in the dry season and 160 mm (27%) in the short rainy season.

- **Temperature**

Temperatures are constant through out the whole year. Mean air temperature is 21°C but slightly rises during hot months. Months of October to April are hottest with mean daily maximum temperature above 30 °C while mean daily minimum temperature falls to 15°C from May to August.

- **Evaporation**

Annual evaporation rate varies widely from 3 mm/day in May to 9 mm/day in January. This makes mean annual evaporation to be more than 2000 mm which is more than three times higher than mean annual rainfall (URT/JICA, 1988).

3.1.3 Hydrology

The major sources of irrigation water for Lower Moshi project are Rau and Njoro rivers. Rau river flows from mount Kilimanjaro with a gradient slope of 20% - 33% on mountain slope to 0.25% - 0.5% near LMIP. The project area has a gently undulating topography with land slopes from 0.5% near Moshi town to 0.2% NAFCO farm in the project. The seasonal discharge rate for Rau river fluctuates through-out the year. The maximum discharge rate is 1.8 m^3/sec and minimum is 1.3 m^3/sec. Njoro River is a tributary of Rau river and originates from springs scattered on the eastern side of Moshi town. The seasonal discharge flow for Njoro river is relatively constant through-out the year. It varies from 1.2 m^3/sec during the long rainy season to 0.9 m^3/sec in the short rainy season (URT/JICA, 1988; KATC, 2000).

3.1.4 Geology and soils

There are three types of soils in the project area. These are Mollic gleysols, Dystric cambisols and Eutric gleysols. Mollic gleysols developed mainly in narrow depressions (old river trials) along Rau river. These soils are clayey textured and free from salinity. Dystric cambisols were derived from alluvial deposits mainly by the Rau river and cover most of the project area. Generally these soils are silty clay or clay and are slightly acidic. Eutric gleysols were developed on low-lying areas. These soils are clayey textured and free from salinity (KATC, 2000).

3.1.5 Land use

Before introducing rice cultivation, maize and beans were the most commonly grown crops. Rice was cultivated under swampy conditions during wet seasons. Presently, maize, beans and rice are cultivated, under both rainfall and irrigation. However, priority is given to paddy production since water is scarce, therefore paddy has become the major crop grown under irrigation. LIMP commands an irrigated area of 1100 ha of which only 473 ha is effectively cultivated for paddy production. There are three calendar-growing periods in a year. The first starts in January followed by May and lastly September (URT/JICA, 1988).

3.2 Characterization of soils at the experimental site

3.2.1 Soil sampling procedure

The field consisted of two adjacent sites (1 and 2) that made up the experimental site. The site had a gradient slope that traversed from North to south (Fig. 3.2). Samples of soils were collected from the field and these were analyzed for both physical and chemical properties in the laboratory.

For chemical analysis, two soil samples were recovered. One sample taken from site 1 and the other from site 2. Each sample consisted of disturbed soil samples taken to a depth of 30 cm (root depth of rice) from six representative positions in the field. The soil samples were recovered at 10, 20 and 30 cm depth intervals and thoroughly mixed before analysis. For physical analysis, disturbed and undisturbed soil cores were taken at 15-cm depth from 12 positions, six each from site 1 and site 2. Disturbed soil samples were collected for the determination of texture while undisturbed cores were recovered for the determination of total porosity. Standard core samplers (5 cm ID and 5 cm depth) were used to recover undisturbed soils.

3.2.2 Laboratory analysis of soil samples

3.2.2.1 Soil physical analysis

Texture was determined by the hydrometer method (Gee and Baunder, 1986). The oven drying calibration method as described by Danielson and Sutherland (1986) was used to determine total porosity.

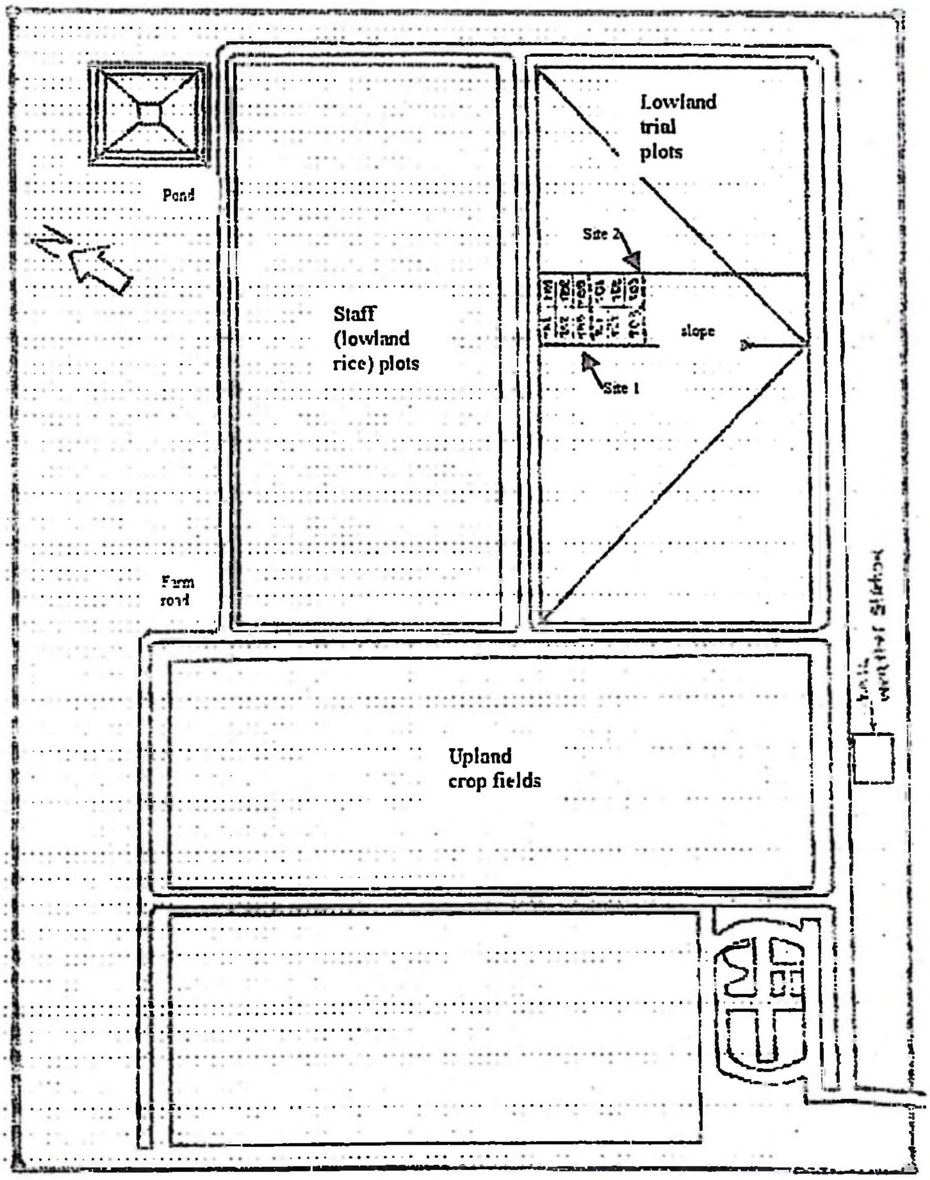


Figure 3.2: Experimental site at KATC, Moshi

3.2.2.2 Soil chemical analysis

Organic carbon (wet oxidation method) was determined as described by Nelson and Sommers (1982) while pH (in water and in 0.01 M Kcl) was determined according to the method described by Mclean (1982). Total nitrogen (micro-Kjeldahl method) and extractable phosphorous (ascorbic acid method) were determined as described by Okalebo *et al.* (1993). Cation exchange capacity (CEC) was determined by the ammonium acetate method (Thomas, 1982) and exchangeable bases (Ca, Mg, K, Na) by atomic absorption spectrophotometer method (Thomas, 1982).

3.2.3 Soil infiltration rate

On site infiltration tests were determined using the modified tension infiltrometer (disc permeameter) (UNCEL type) developed by the University of New Castle Environmental Laboratory after Perroux and White (1988). Infiltration measurement tests were done at the center of each treatment plot just before land preparation. The disc permeameter used had minimal disturbance of soil surface and offered precise application of tension, easy filling of reservoir and had low (1.5 litres) water requirements.

Procedure

Infiltration rate in the field was measured as described by Perroux and White (1988). The reservoir and bubble tower, were filled with water up to the calibrated zero level mark. The zero mark served as the start reference level for the tension tubes (air entry tubes, Fig. 3.3). Before connecting the air – exit tubes, air inside the tower was gently

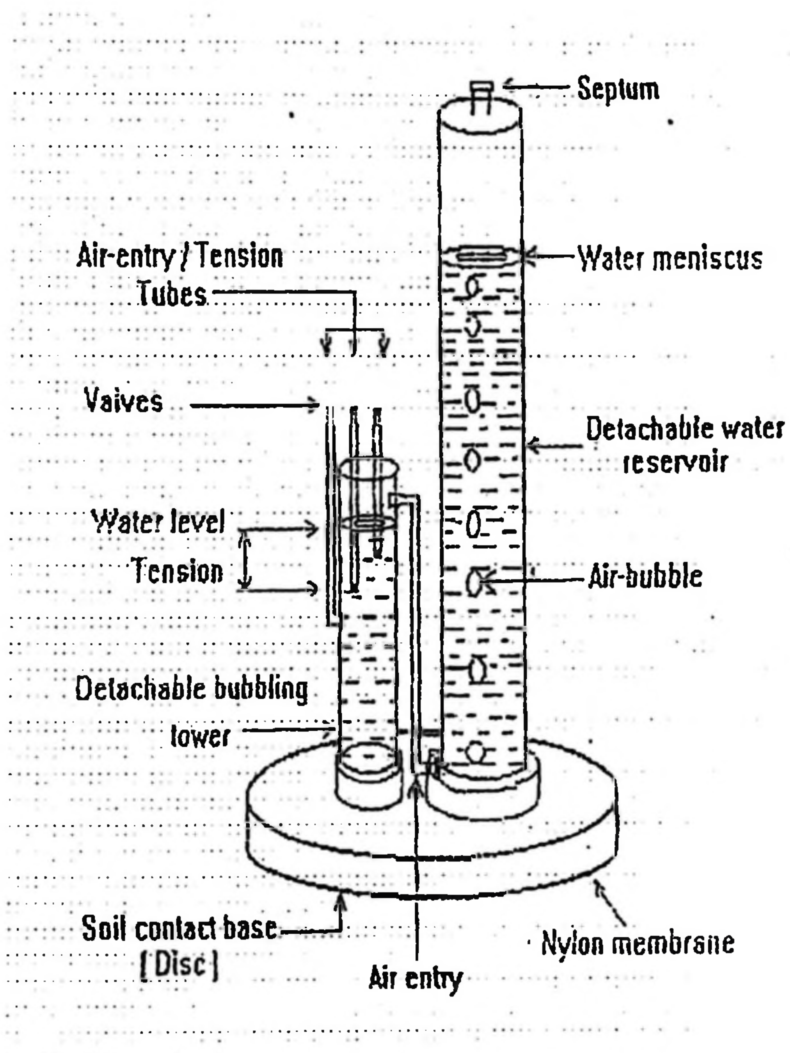


Figure 3.3: The disc permeameter for unsaturated measurements

(After Perroux and White, 1988)

sucked out through the septum, thus eliminating the air and water inside inlet tubes. The infiltrometer was then carefully placed in the field on top of soil surface smoothened with sand and covered with a thin piece of cotton cloth (to avoid damage to membrane). Care was taken to avoid the entry of air into the instrument by sealing all air entry and reservoir tubes with glycerin oil and the infiltrometer was checked for air leakage before infiltration was started. At the start of infiltration, initial water height was recorded on paper and the valve for the smallest negative pressure (5 cm) opened. Shortly afterwards, air was drawn into the tension regulating chamber through the open entry tube and air bubbles were observed. When equilibrium was set, a chronometer was started to record time. The amount of water infiltrating into the soil was recorded against time by reading a measuring tape attached to the water reservoir. The change in height (cm) in the reservoir at 5-minute interval was recorded until successive infiltration rates were the same for at least three successive readings. The constant reading was the basic infiltration rate. After reaching a steady state, 7 cm tension valve was opened and the procedure described for 5 cm tension measurement repeated. The procedure used for determining steady state infiltration for the 10 cm tension was the same as that carried out for 5 cm and 7 cm tension measurement.

3.2.4 Hydraulic conductivity

Hydraulic conductivity was determined indirectly from basic infiltration rate data measured in the field. According to Ankey *et al.* (1991) unsaturated hydraulic conductivity can be calculated from infiltration data by formulating two simultaneous equations to determine the two unknowns (a and K_{fs}) in equation (5) (Section 2.8.3.2).

3.3 Experimental design, layout and treatments

3.3.1 Experimental design

A single factor completely randomized block design (CRBD) experiment with three treatments and four replications was used to assess the effect of Azolla on both crop water use for the growing period and grain yield at harvest. Two-factor split–plot block design experiment was used to evaluate the interaction effect of gradient/ slope on hydraulic conductivity before land preparation.

3.3.2 Experimental layout

The field consisted of two sites (19.3 Ç 13.6 m each). Each site was divided into six plots resulting in 12 plots each measuring 27.03 m^2 (5.1 m x 5.3 m). The slopes were S1 (2%), S2 (1%) and S3 (0.6%) for treatments T1, T2 and T3 respectively. One lysimeter and one percolation cylinder were installed in each treatment.

3.3.3 Treatments

The treatments involved growing rice alone, rice with Azolla and Azolla alone. The type of rice used in the study was an indigenous variety locally known as Wahiwahi. The strain of Azolla (500 g/m^2 fresh weight) was *Azolla caroliniana*.

The treatments (T) were:

(i) T1: Wahiwahi only

(ii) T2: Wahiwahi + Azolla

(iii) T3: Azolla only

3.4 Experimental procedure and measurements

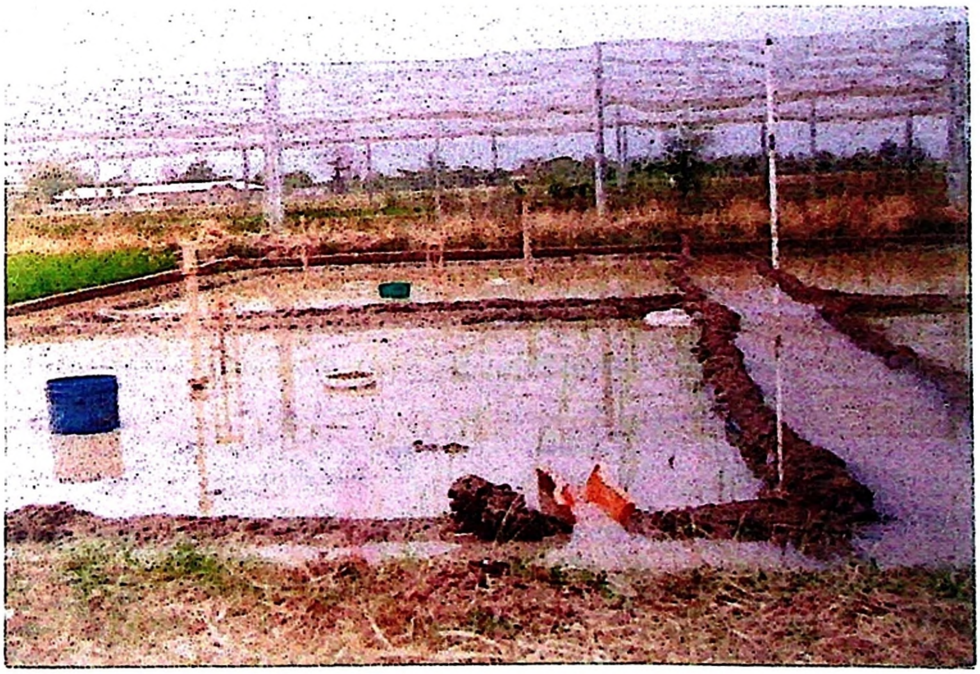
3.4.1 Nursery establishment

A nursery plot was established and seedbed prepared, one day before sowing the rice seeds. Pre-sprouted seeds were sown on 14 September 2000. Nitrogenous fertilizer (urea) at the rate of 57.5 kg N/ha recommended for LMIP (Horibata, 1992), was applied to the nursery 14 days after sowing (DAS). Water depth of between 3 - 5 cm was maintained for the nursery period. Pesticide (Diazinon 20EC) solution was applied at a rate of 0.4 Kg/ha to control pests and diseases.

3.4.2 Land preparation

The field was saturated for 48 hours and allowed to drain. Basal nitrogenous fertilizers were uniformly spread over the surface of the drained field prior to puddling. These were 17 kg N/ha recommended for optimum rice production in the LMIP (Horibata, 1992) and 3 kg N/ha necessary for Azolla growth (Pande, 1978). After puddling and leveling of the field, plots were marked and earth ridges (stools) were constructed on the edges. A 30 cm wide impervious polythene sheeting (Plate 1) was inserted to a depth of 15 cm in the center of the stools. The ridges were built to 30 cm above the soil surface, using earth from bottoms of the ditches. Consequently, deep ditches were constructed between plots. The ditches were kept flooded and regularly built up to maintain equilibrium conditions between the ditches and plot surfaces. Ridges prevented both surface runoff and reduced seepage from the plots.

(a) Installation of impervious polythene sheeting in the plot boundaries



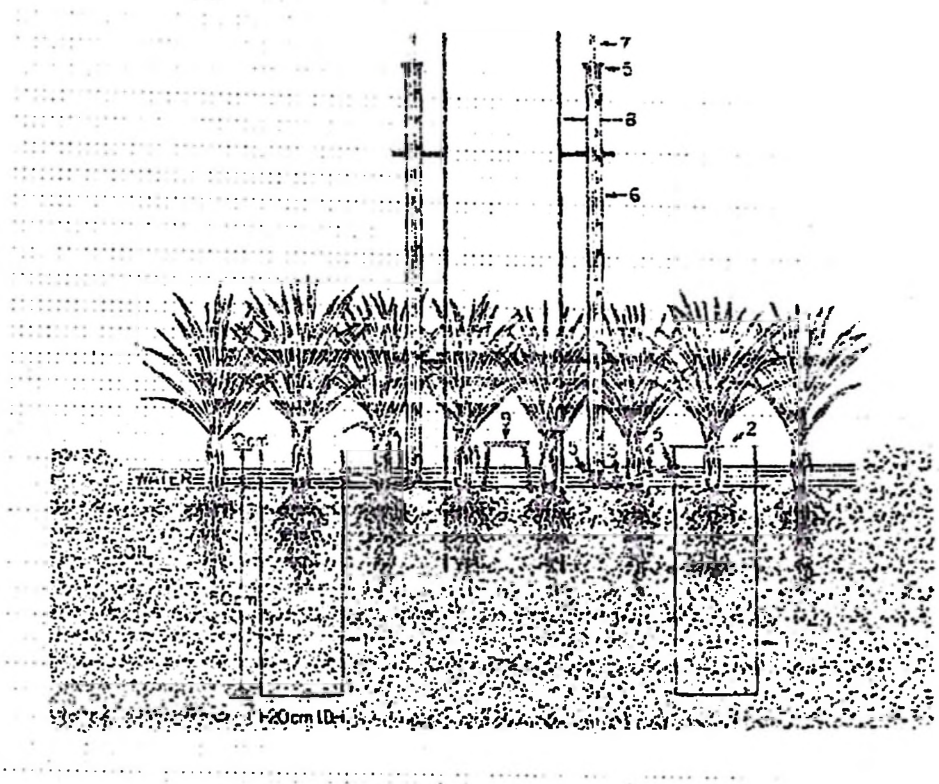
(b) Raising of earth bunds controlled irrigation

Plate 1: The construction of earth bunds (ridges)

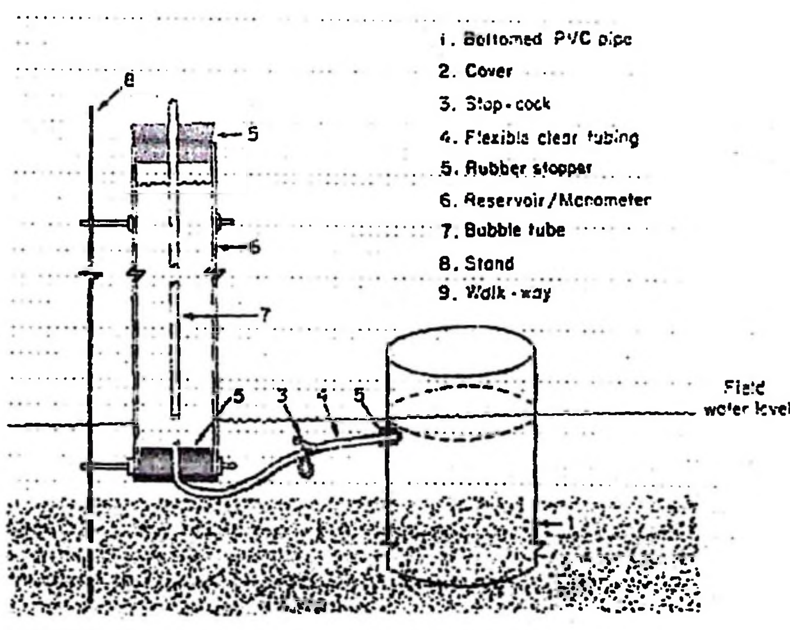
Sieved mesh were introduced at all turnout inlets to prevent the loss of or infestation by Azolla.

3.4.3 Equipment installation

Field equipment was installed after land preparation. One lysimeter was installed in each treatment to monitor evapotranspiration. The procedure by Tomar and O'Toole (1980) was used in installing 12 precision microlysimeters (Fig. 3.4). International Rice Research Institute (IRRI) ceramic (wagna) pots were used instead of polyvinyl chloride (20 cm dia pvc) cylinders. The pots (23.9 cm ID, 1.25 cm thickness and 35 cm deep) had sealed bottoms. The position of each lysimeter pot was such that one rice hill was planted in the lysimeter and became an integral part of the planting pattern. The spacing for rice seedlings was 30 x 30 cm. One percolation cylinder was also included in each treatment to facilitate the measurement of seepage and percolation (Plate 2). The procedure by Wickham (1978) was used in installing the 12 percolation cylinders (Fig. 3.5). The position of each cylinder became an integral part of the planting pattern. The cylinders (30-cm dia and 35 cm deep) were made by cutting off and removing the bottoms of pvc containers. Staff gauges for measuring water depth were installed in the field as described by Wickham and Singh (1978). Wooden walkways (30 cm wide) were installed to provide access to the lysimeters without disturbing the soil-water regimes.



(a) Cross section of lysimeter grown rice plants



(b) Details of mariotte system

Figure 3.4: Field installed microlysimeter for measuring evapotranspiration

(After Tomar and O'Toole, 1980)

(i) Installed equipment: (a) water gauge (b) lysimeter (c) percolation drum (d) flume (note: extent of (green) Azolla (e) 10 DAT).

(ii) Rice plants shown in lysimeter pots after harvest

Plate 2: Lysimeters and seepage and percolation cylinders

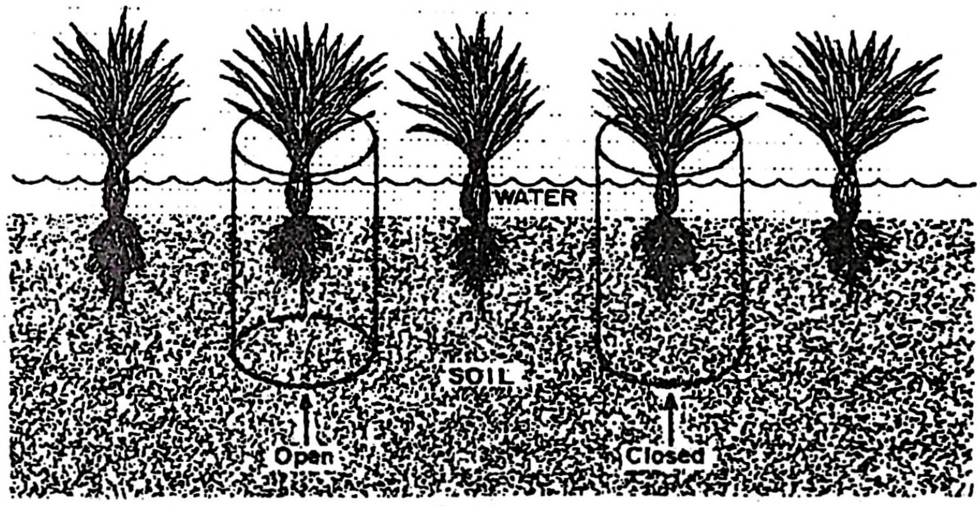


Figure 3.5: Seepage and percolation measurement using open and closed cylinders shown with rice plants (After Wickham, 1978)

3.4.4 Seedlings establishment

Transplanting of rice seedlings was done after the installation of equipment. Rice seedlings were transplanted on (9 October 2000) 25 DAS. Border seedlings (two rows adjacent to nursery bunds on either side of bed) were excluded because they showed unusually better growth. Seedlings were uprooted from the nursery (under 3-cm depth flooding), cleaned and transplanted to a depth of 3 cm in the soil (Horibata, 1992). One rice seedling per hill was planted at a spacing of 30 cm x 30 cm to reduce the effect of competition for water and nutrients. Good seedlings establishment was achieved by allowing shallow flooding (3 – 4 cm) for 7 days after transplanting (Horibata, 1992). From 14 days after transplanting the pond depth was increased to 5 cm and water was gradually added until the depth was about 8 cm. Submergence depth of 8 cm was maintained for the whole growing period. Gap filling for missing hills was done 10 days after transplanting (DAT).

3.4.5 Inoculation and maintenance of Azolla

A. caroliniana was broadcasted in the treatments at a rate of 13.51 kg fresh weight (FW)/plot i.e, 500g FW/m^2 at 7 DAT. The Azolla grew and multiplied into isolated fragmented mats in the plots, simultaneously forming a single mat. All the available spaces between the stools and rice plants were completely covered 21 DAT (Plate 3).

3.4.6 Growth determination of Azolla

The biomass of Azolla (in terms of fresh weight) was determined in the field at 14 DAT and on weekly basis for the whole growing period. The procedure used in sampling was as follows. One sample was collected from a treatment using a pvc cylinder ring (550 cm dia. and 20 cm depth). The ring sampler (Plate 4) was cast on a representative area and the entire Azolla fronds were quantitatively recovered by the aid of a plastic sieved bowl. The fronds were cleaned of soil, drained and weighed on a balance (sensitive to 10 g) to determine the fresh weight of the sample. After weighting, the fronds were returned to the field for subsequent incorporation.

3.4.7 Determination of weed population and biomass of weeds

The weed population was determined by physical counting the weeds. The first weed sampling was done 14 DAT and fortnightly thereafter for the whole growing period. A 550 cm dia. ring was used for the sampling. The ring was cast on a representative area and all the weeds were judiciously uprooted and quantified according to their type and species. After sampling, the rest of the weeds in the plots were removed manually. The weeds from the sample were dried at 70 - 80°C in the oven for

Plate 3: Azolla mat completely covering the available area in the plots 21 DAT

Plate 4: The ring sampler being used to collect Azolla and weed samples

48 hours. The dry weight was then measured by using an electronic balance (accurate to 0.05 g).

3.5 Field water requirement

Following the procedure used at LMIP (URT/JICA, 1998), the field water requirement (FWR) for irrigated rice was determined using the following steps:

Step (1): Monthly mean potential evapotranspiration (ETo) for the irrigation period was calculated from long term (1988 - 98) weather data for the site using Hargreaves method (Doorenbos and Pruitt, 1977). Long-term weather data was recorded by the KATC weather station, located at 50 m from the experimental site.

Step (2): Evapotranspiration (ETcrop) was calculated using equation (1) as the product of mean monthly ETo and crop coefficient (Kc) for the crop grown (Doorenbos and Pruitt, 1977). Kc values were determined from a crop coefficient curve developed using Kc values for paddy given in Table 2.1.

Step (3): In order to be able to select Kc values from the coefficient curve, Doorenbos and Pruitt (1977) divided the crop growth period into four stages. The growth stages for Wahiwahi rice were;

(i) Initial stage (25 days): germination and early growth when the soil surface is not covered by the crop (ground cover < 10%)

(ii) Crop development stage (30 days): from end of initial stage to attainment of

		effective full ground cover (ground cover 70 – 80%)
(iii)	Mid season stage (20 days):	from attainment of effective full ground cover to time of maturity as indicated by discoloring of grains
(iv)	Late season stage (28 days):	from end of mid-season stage until full maturity or harvest.

Step (4): A percolation rate of 8 mm/day conservatively determined at KATC and averaged for 4 years was adopted and used in the calculation.

Step (5): Water for puddling was calculated for the measured total soil porosity of the cultivable layer (30 cm) and submergence depth of 5 cm. The amount of water required for puddling was expressed as:

$$X = 30y + 5 \qquad (6)$$

where X = depth of puddling water (cm);

y = total porosity of cultivable layer (%).

Step (6): Field water requirement (FWR) was determined by adding the actual ETcrop, percolation rate and water needed for puddling. However, puddling water was needed for land preparation only. Therefore, FWR was expressed as:

$$FWR = ETcrop \pm X + 8 \qquad (7)$$

where FWR = field water requirement (mm/day, mm/month)

3.6 Measurement of infield water use

3.6.1 Plot irrigation

A parshall flume (H26-4) was used to measure the amount of water applied into the field while the staff gauge monitored the submergence depth. Irrigation was terminated 15 days before the earliest possible harvesting (maturity) date at which 80% of the grains on a panicle had turned yellow. According to Tsuboi (1992), the discontinuity of water supply enhanced maturity and the dry ground facilitated final sampling and harvest.

3.6.2 Measurement of pan evaporation

The KATC meteorological station was used to record the climatic data at the time of the experiment. Pan evaporation data was measured using a standard US class A pan. Mean daily evaporation was calculated for the growing period.

3.6.3 Measurement of seepage and percolation

The change in water height in the percolation drums was measured to be the total water use (seepage and percolation plus ETcrop) in the treatments. Seepage and percolation only was obtained as the difference between the total water use and ETcrop determined from the lysimeter. Seepage and percolation was first measured 14 DAT. Further readings were taken daily for the whole growing period.

3.6.4 Measurement of evapotranspiration

The lysimeter was used to measure the ETcrop while maintaining a constant water level in the lysimeter (mariotte) as in the surrounding field. The change in volume of water delivered from the mariotte tube into the wagna pot to maintain equilibrium was measured as ETcrop. Water was added to the lysimeter on a weekly basis or when it was necessary to maintain this equilibrium. Incident precipitation was measured for inclusion in the ETcrop calculations. ETcrop of rice was first measured at 14 DAT by which time the rice plants were established. Further ETcrop readings were taken daily (0900h) for the whole growing period. ETcrop of rice was determined from the equation;

$$ET_{crop} = \frac{\left(\pi r_o^2 - \pi r_i^2\right)}{A} \frac{\Delta h}{\Delta t} \qquad (8)$$

where ET_{crop} = evapotranspiration ($cm^3.cm.day^{-1}$);

r_o = inner radius of the outer tube (cm);

r_i = outer radius of inner tube (cm);

A = effective surface area (cm^2) of each hill (lysimeter);

Δh = change in water column height in the reservoir (cm);

Δt = time (day).

In this set up, r_o was 1.75 cm and r_i was 0.53 cm. The effective surface area of the lysimeter was equal to 448.63 cm^2.

3.6.5 Calculation of water use efficiency

Water use efficiency (WUE) of the rice crop was determined from the following equation;

$$WUE = DM/ET_{crop} \qquad (9)$$

where WUE = water use efficiency expressed as weight of dry matter per unit volume of water (Kg DM. m^{-3} water);

DM = dry matter weight of rice straw including the panicle (g).

3.7 Measurement of growth parameters

Plant heights, dry matter accumulation, number of tillers/m^2 and heading date were determined by taking measurements and observations to establish the growth pattern of the rice crop.

3.7.1 Plant height and number of tillers

The sample size was ten (10) hills per plot taken inside the border hills. The random sampling technique as recommended by Gomez and Gomez (1984) was used to select and tag 10 hills. The height (from ground) of the tallest plant in each of the ten tagged hills was recorded (Tsuboi, 1992). Height measurements were started at 14 DAT. Further determinations were taken fortnightly until 50% heading was attained. The plant height (inclusive of culm length) was also taken at harvest. The number of tillers per hill were counted at the stage of panicle initiation and daily thereafter until maturity.

3.7.2 Heading time

Tsuboi (1992) defined heading and earliest possible harvesting (maturity) time as dates at which 50 - 60% of the total panicles are headed and 80% of the grains are yellow respectively. Although heading and maturity dates are characteristic of the variety, they also indicate the level of water use efficiency and nutrients intake by the plants (Tsuboi, 1992). The procedure to determine heading involved selecting 10 hills variety, they also indicate the level of water use efficiency and nutrients intake by the plants (Tsuboi, 1992). The procedure to determine heading involved selecting 10 hills per plot. The number of panicles was recorded daily, starting from the first plant headed until normal heading was complete. The date corresponding to the time when 50% of all plants in the ten hills had headed, was taken as the heading date.

3.7.3 Dry matter accumulation

The dry matter weight (biomass) of rice plants at harvest was determined as the total straw weight including panicles from 10 hills. Rice plants were cut and the panicles bearing the grains separated from the straws. The panicles and straws were air dried. The panicles with grains were then threshed to remove the grains. The weight of the straws and panicles were measured using an electronic balance (correct to 0.05 g).

3.8 Measurements of grain yield and yield determinants

3.8.1 Grain yield

The grain yield at maturity was determined by the reaping test (Tsuboi, 1992). Rice plants from a sampling area of 1 m^2 were harvested and stored in bags. The grains were dried after separating them from plants by threshing. Filled grains were obtained by winnowing. Filled grains were weighed and moisture content measured by a moisture tester (RICETER J301). The moisture content at harvest was determined on fresh weight basis (MC_{fw}). The grain yield at MC_{fw}, was expressed in t/ha using the equation;

$$Gw_{yt} = GW_{th}\ Ç\ [100 - X/(100 - 14)] \qquad (10)$$

where; Gw_{ty} = Grain yield at 14% moisture content

Gw_{th} = Grain weight at harvest

X = Grain moisture content (%) at harvest

3.8.2 Yield determinants

Matsushima (1967) defined the components of total grain yield as the number of panicles, number of grains, percentage of ripe grains (panicle fertility) and grain weight. The yield attributes were recorded from 10 hills per plot. The number of panicles per 1 m^2 was counted. The average of 10 hills panicles, representative of a single hill was multiplied by the number of hills counted per 1 m^2. The number of grains and grain weight, were determined after drying and threshing. Separation of filled and unfilled grains was done by the floating method (Gomez, 1972). The 10 hills grain sample was put in water, fertile grains sank (S) while infertile ones floated (F). The filled and unfilled grains were dried. The total number of floaters (N_f) was counted manually, whilst the total weight of sinkers (Ws_t) was measured using an electronic balance (correct to 0.05 g). 1000 filled grains were weighed (W_{1000}) and counted using a multi-auto counter, **Model OC IUR 80701** and total number of ripen grains (N_s) calculated. Thus,

$$N_s = Ws_f/W_{1000} \text{ Ç } 1000 \quad (11)$$

The total number of grains per panicle (G_p) was calculated as the sum of floaters (N_f) and sinkers (N_s) divided by the number of panicles in the 10 hills (N_P).

Thus:

$$G_p = (N_S + N_f) / N_P \quad (12)$$

The percent of ripe grains (panicle fertility) (pf) was calculated by dividing the average of ripe grains per panicle from 10 hills ($N_p/10$) by the total number of grains per panicle (G_p) and then multiplied the quotient by 100. Thus,

$$pf = (N_s/G_p) \times 100 \qquad (13)$$

3.9 Statistical analysis

Statistical analysis of the experimental data was done using the MSTAT programme. Analysis of variance as outlined by Gomez and Gomez (1984) was used to assess treatment effects of Azolla on the following: total water use, consumptive water use, seepage and percolation, weed suppression, yield components and total grain yields. Duncan's New Multiple Range Test (DNMRT) and the student t-test as described by Gomez and Gomez (1984) were used to separate means of the significant treatments.

CHAPTER FOUR

4 RESULTS AND DISCUSSIONS

4.1 Climate

4.1.1 Long term climatic conditions

The long-term (1988 - 98) climatic data used to determine irrigation requirements for the growing period are given in Appendix 1. Mean monthly meteorological indicators, which include rainfall, relative humidity, pan evaporation and temperature are summarized in Table 4.1.

Table 4.1. 11-year mean monthly rainfall, relative humidity, pan evaporation and temperature recorded at KATC weather station

Month	Jan	Feb	Mar	Apr	Ma	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Rainfall (mm)	118	72	192	372	270	45	22	28	51	63	99	165	1497
Relative Humidity (%)	68	67	70	77	79	76	74	73	69	69	68	69	71
Pan evaporation (mm/day)	6.3	7.5	6.2	4.3	3.1	3.1	3.3	4.0	5.3	6.5	6.6	5.9	5.2
Temperature													
Min (deg)	20.8	19.5	20.0	19.9	18.7	17.0	15.8	16.3	16.9	17.8	19.4	18.9	18.4
Max (deg)	33.3	34.3	34.0	30.9	28.3	27.3	27.0	27.6	29.6	31.5	32.8	32.7	30.8
Average (deg)	27.1	26.9	27.0	25.4	23.5	22.1	21.4	22.0	23.3	24.7	26.1	25.9	24.6

Source: KATC, Chekereni (2000)

4.1.1.1 Rainfall

Rainfall shows weak bimodal pattern. The area experiences a dry season during June to October and a wet period from March to May. There is a light intermittent rainfall period from November to February. The mean annual rainfall is 1497 mm.

4.1.1.2 Relative humidity

The monthly relative humidity is above 67% throughout the year and the mean relative humidity is 71%. The highest relative humidity recorded occurs during the wet season (March - May) and is 77% thus keeping evaporation at or near potential rates.

4.1.1.3 Pan evaporation

Pan evaporation varies widely under the influence of both solar energy and rainfall depth. A peak monthly evaporation of 7.5 mm/day is recorded in February whilst the monthly minimum evaporation is 3.1 mm/day in May and June. The mean daily evaporation is 5.2 mm/day while the annual amount is 1900 mm per year and greatly exceeds the mean annual precipitation of 1497 mm. The low rainfall received coupled with high temperatures and low relative humidity results in high evaporation. Generally, there is clear moisture deficit in LMIP during most of the time.

4.1.1.4 Temperature

Air temperature at LMIP seems to be constant through-out the year. The mean monthly temperature varies from 21.4 °C in the dry season (June - October) to 27°C during the wet season (March to May). The hottest and coldest months are February and July respectively (Table 4.1).

4.1.2 Climatic conditions during the experimental period

Climatic data recorded during the experimental period (September 2000 - January 2001) is discussed in the following subsections. The summary of the meteorological indicators like rainfall, relative humidity and pan evaporation and temperature is shown in Table 4.2.

4.1.2.1 Rainfall

There was very little rainfall during the experimental period. The total rainfall was 84 mm. The maximum rainfall was 53 mm in December and minimum rainfall was 4 mm in January. There was no rainfall in October.

4.1.2.2 Relative humidity

Relative humidity was fairly constant during the experimental period. The average relative humidity was 71.1%. Minimum relative humidity was 65% in October, at the end of the dry season. However, it rose to 81.5% in the short rainy season in January and remained constant until the end of the growing period.

Table 4.2. Mean monthly rainfall, relative humidity, pan evaporation and temperature recorded during the experimental period (September 2000 - January 2001) at KATC weather station

Month/year	Sep 2000	Oct 2000	Nov 2000	Dec 2000	Jan 2001	MEAN
Rainfall (mm)	3	0	24	53	4	16.8
Relative Humidity (%)	71	65	67	71	81.5	71.1
Pan evaporation (mm/day)	6.05	7.0	6.2	6.2	5.2	6.13
Temperature						
Min (deg)	16.6	18.2	20.4	21.0	20.4	19.3
Max (deg)	29.3	31.2	32.9	32.7	31.6	31.5
Average (deg)	23.0	24.7	26.7	26.9	26.0	25.4

Source: KATC, Chekereni (2000)

4.1.2.3 Pan evaporation

Pan evaporation was high for the whole period of the experiment. The highest mean monthly evaporation was 7 mm/day recorded in October whilst the lowest mean monthly evaporation was 5.2 mm/day (January). The average monthly pan evaporation was 6.13 mm/day.

4.1.2.4 Temperature

The average daily air temperature was 23 °C in September, at the end of the dry season. Temperature rose to 26.9 °C in December at the middle of short rainy season and remained constant until the end of January. The maximum temperature recorded was 32.9 °C and minimum temperature was 16.6 °C (Table 4.2).

4.2 Soil physical and chemical properties

The soil parameters analyzed and given in Table 4.3 indicated that the soil at the experimental site is suitable for rice cultivation.

Table 4.3. Some physical and chemical properties of the soil at the experimental site

Characteristic	Unit	Site 1	Site 2
PH (H_2O): 1:2.5	w/v	8.07	8.01
PH (KCL): 1:2.5	w/v	6.65	6.78
ORGANIC CARBON	(%)	0.38	0.19
TOTAL NITROGEN	(%)	0.07	0.05
EXCHANGEABLE BASES			
Ca	$Cmol_ckg^{-1}$	11.31	10.42
Mg	$Cmol_ckg^{-1}$	5.71	5.72
K	$Cmol_ckg^{-1}$	1.63	1.73
Na	$Cmol_ckg^{-1}$	1.24	1.29
C.E.C	$Cmol_ckg^{-1}$	19.60	20.00
EXTRACTABLE.P: PBr1	$Mgkg^{-1}$	65.24	58.15
ELECTRICAL CONDUCTIVITY	Ms/ cm	0.17	0.21
PARTICLE SIZE ANALYSIS			
CLAY	(%)	50	41
SILT	(%)	23	25
SAND	(%)	28	34
TEXTURAL CLASS: CLAY			
POROSITY = 50%			

4.2.1 Soil physical properties

ñ **Soil texture and porosity**

The soil at the site is black expansive clay of semi-arid region. Total porosity for the soil in the experimental site was 50%. URT/JICA (1998) reported that total porosity of paddy soils in LMIP ranged between 30% and 70%. The average porosity was estimated to be 40%. According to Landon (1991), porosity indicates the degree of compaction of soil. Landon (1991) pointed out that the quantity and size of pores in soil usually determines its hydraulic conductivity. However, pore characteristics are not readily quantifiable in their influence on crop productivity because they change between seasons as well as within a cropping period. Iwata *et al.* (1986) reported that water primarily moves downward at a rate determined by the presence and distribution of macropores in the soil as well as by porosity (air exchange capacity) and hydraulic conductivity.

4.2.2 Soil chemical properties

The chemical properties of the soils at the experimental site are summarized in Table 4.3. The average pH of the soil (air dried) in water suspension ranged from 8.01 to 8.07. The organic carbon content in the soil varied from 0.19% to 0.38% and the average total nitrogen content was 0.06%. Carbon: nitrogen (C: N) ratio was less than 5. The average electrical conductivity varied from 0.17 Ms/cm to 0.21 Ms/cm while the exchangeable sodium was 1.24 to 1.29 $Cmol_c kg^{-1}$. Other exchangeable bases indicated moderate amount of available organic manure. Uriyo *et al.* (1979) reported that the pH of soil changes greatly after submergence. It varies from 7.5 to 9.0 under floodwater. Low (less than 10) C: N ratio indicates an advanced stage of decomposition and resistance to microbial attack. According to Uriyo *et al.* (1979) sodic soils are considered normal when the electrical conductivity and sodium exchangeable base are less than 15 Ms/cm and 4 $Cmol_c kg^{-1}$ respectively. The results of the analysis indicate homogeneity and the experimental soils are normal. Horibata (1992) reported that the soils at LMIP are suitable for rice cultivation when supplementary nitrogenous fertilizers are added.

4.3 Basic infiltration rate and hydraulic conductivity

4.3.1 Basic infiltration rate

The average basic infiltration rate obtained in the field is shown in Table 4.4 and a record of the field infiltration data is given in Appendix 2. At any of the 3 different

Table 4.4. Effect of slope on average basic infiltration rate and hydraulic conductivity at the beginning of growing period (October 2000)

TREATMENT	BASIC INFILTRATION RATE (cm/hr)			HYDRAULIC CONDUCTIVITY (cm/hr)		
TENSION	5 cm	7 cm	10cm	5 cm	7 cm	10 cm
SLOPE (%)						
2	15.0	7.8c	4.95e	14.66a	8.22c	3.54e
1	9.3c	5.95cd	4.17e	8.64c	6.59cd	4.46d e
0.6	11.5b	4.95cd	2.52e	12.20b	6.49cd	2.94e
MEAN	11.93	6.23	3.88	11.83	7.10	3.65

Coefficient of variation (CV)= 27.28%

Least square difference (lsd $_{0.05}$) = 2.033

In a row or column, means having a common letter are not significantly different (p = 0.05) according to the DNMR test.

tensions (5, 7 and 10 cm) used, the trend of infiltration was similar and decreased consistently with high tension. Considering infiltration at 10 cm tension for all treatments, infiltration rate was 4.95, 4.17 and 2.52 cm/hr in T1, T2 and T3 respectively. According to Landon (1991) this range is within moderate (2.0 - 6.0 cm/hr) infiltration rate.

4.3.2 Hydraulic conductivity

Generally, hydraulic conductivity varied inversely with tension and slope as shown in Table 4.4. The average hydraulic conductivity at 10 cm tension ranged from 2.94 cm/hr to 4.7 cm/hr There was no significant effect ($p \leqslant 0.05$) of slope on hydraulic conductivity at 10 cm tension. However, at lower tensions of 5 cm and 7 cm, hydraulic conductivity became significantly different ($p \leqslant 0.05$). At 5 cm tension, the lowest hydraulic conductivity was 8.64 cm/hr in S2 (1%), which was significantly different ($p \leqslant 0.05$) from S1 (2%) and S3 (0.6%). In S1(2%) hydraulic conductivity was 14.66 cm/hr which was significantly higher ($p \leqslant 0.05$) than 12.2 cm/hr in S3 (0.6%). At 7 bars tension, the hydraulic conductivity was 6.59 cm/hr and 6.49 cm/hr in S2 (1%) and S3 (0.6%) respectively, which were not significantly different ($p \leqslant 0.05$). In S1 (2%) hydraulic conductivity was 8.22 cm/hr which was significantly higher ($p \leqslant 0.05$) than S2 and S3. There was a notable decrease of hydraulic conductivity with increased tension. Generally, reduced hydraulic conductivity was obtained in low gradient slope. Hydraulic conductivity (HC) rate also varied with the location at which the measurement was taken in the field. Generally, HC was lower at the center compared with the edges of the field. Lower HC might be attributed to better puddling action. Hydraulic conductivity in the upstream slope was highly significant at 5 and 7 bars and this may have been exaggerated by the gradient slope. This is true because leveling in the field was uneven and the flow of water followed the gradient slope. Lundin (1995) reported that water flow in soils is influenced by slope as well as soil physical and chemical properties. Studies by Gustafsson (1946) cited by Lundin (1995) indicated that on sloping land, water flows as infiltration and unsaturated percolation at the upslope areas. It continues as saturated flow along the slope before discharging into downslope areas. The same flow pattern was observed in this study. However, the flow characteristics changed with time as the soil upslope gradually became saturated. Lundin (1995) reported that water flow in the upslope acts as piston flow whereby the last added infiltration, transfers water already stored in the puddled layer. Baruah *et al.* (1996) reported that upslope areas often had coarser soils compared with down slope areas therefore gradient slope and location of structured soils are decisive in the flow and storage of soil water.

4.4 Field water requirements

4.4.1 Percolation rate and water for soil puddling

Average percolation rate of 8 mm/day used in LMIP was adopted. Water used for puddling calculated at a porosity of 50% of the cultivatable layer was 200 mm. According to URT/JICA (1998) water required for soil puddling in LMIP varies from 100 mm to 300 mm in depth.

4.4.2 Evapotranspiration (ETcrop) for Wahiwahi rice

4.4.2.1 Crop coefficients (Kc) for the rice crop (Wahiwahi variety)

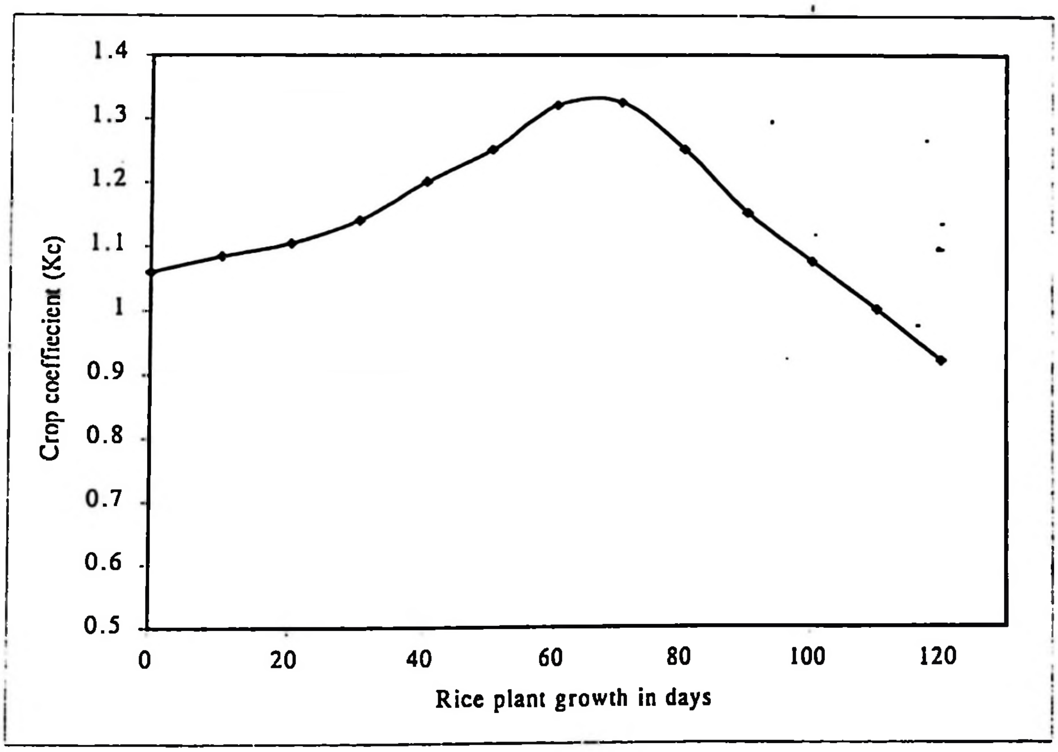
The average monthly Kc values of the rice used to calculate monthly ETcrop are shown in Table 4.5.

Table 4.5. Average crop coefficients (Kc) for Wahiwahi rice

MONTH	OCTOBER	NOVEMBER	DECEMBER	JANUARY
Crop factor (Kc)	1.21	1.27	1.14	1.09

Source: Adapted from Doorenbos and Pruitt (1977)

The crop factor for each month was selected from the coefficient curve. The relationship between the crop factor and the crop growth stage is shown in the conceptual diagram in Fig. 4.1.



Source: Adapted from Doorenbos and Pruitt (1977)

Figure 4.1 : Crop coefficient curve for Wahiwahi rice

The average daily and monthly ETcrop rate is given in a stage wise calculation shown in Table 4.6. The average daily and monthly potential evapotranspiration (ETo) rate used in the calculation is given in Appendix 3

Table 4.6. Calculation of ETcrop from potential evapotranspiration (ETo) and relevant crop factor (Kc) on daily basis

Month	ETo (mm/day)	Kc value	ETcrop (mm/day)	ETcrop (mm/month)
OCTOBER	5.60	1.21	6.78	210
NOVEMBER	7.10	1.27	9.02	271
DECEMBER	5.70	1.24	7.07	219
JANUARY	5.93	1.09	6.46	200

Source: Adapted from Doorenbos and Pruitt (1977)

4.4.3 Irrigation water requirement for Wahiwahi rice

The average field water requirement (FWR) for the rice crop is given in Table 4.7. Water for soil puddling was 200 mm. Irrigation was applied at 2 - 3 days interval to maintain the required submergence depth of 8 cm.

Table 4.7. Calculation of average FWR from crop evapotranspiration (ETcrop) and percolation rate on daily and monthly basis

Month	Percolation (mm/day)	ETcrop (mm/day)	FWR (mm/day)	FWR (mm/month)
OCTOBER	8.0	6.78	14.78	458.18
NOVEMBER	8.0	9.02	17.02	510.60
DECEMBER	8.0	7.07	15.07	467.17
JANUARY	8.0	6.46	14.46	448.26

4.5 Infield water use

Water use parameters measured for the crop were total water use, evapotranspiration and seepage and percolation. A record of the water use data is presented in Appendix 4.

4.5.1 Total water use

The lowest average daily total water use (evapotranspiration plus seepage and percolation) was 7.05 mm in T3 (Azolla only) which was not significantly different ($p \leq 0.05$) from 8.13 mm in T2 (Wahiwahi + Azolla). In T1 (Wahiwahi only), the average total water use was 11.99 mm which was significantly higher ($p \leq 0.05$) than T2 and T3 (Table 4.8). Soil water regimes in the treatments showed some variations in the use of water during the growing period.

Table 4.8. Effect of *A. caroliniana* on average daily total water use for the growing period (October 2000 – January 2001)

Treatment	Daily ETcrop plus seepage and percolation (mm)
WAHIWAHI ONLY	11.99a
WAHIWAHI + AZOLLA	8.13b
AZOLLA ONLY	7.05b
MEAN	9.06

CV = 17.73%

$lsd_{0.05} = 2.778$

In the column, means having a common letter are not significantly different ($p \leq 0.05$) according to the DNMR test.

It appears that both the Azolla mulch and continually decomposing fronds influenced the water use. Apparently, increased seepage and percolation was observed in T2 (Wahiwahi + Azolla) and T3 (Azolla only), where ETcrop was considerably low. The reduction in ETcrop may be ascribed to simultaneous check of soil-moisture losses through evaporation. The presence of the Azolla mat as mulch may have led to the improved soil water retentivity. The improvement of soil by Azolla due to particle aggregation and physical manipulation by microbial activities could have transformed the soil and led to higher seepage and percolation. The relationship of cumulative average daily total water use with time is shown in Fig. 4.2.

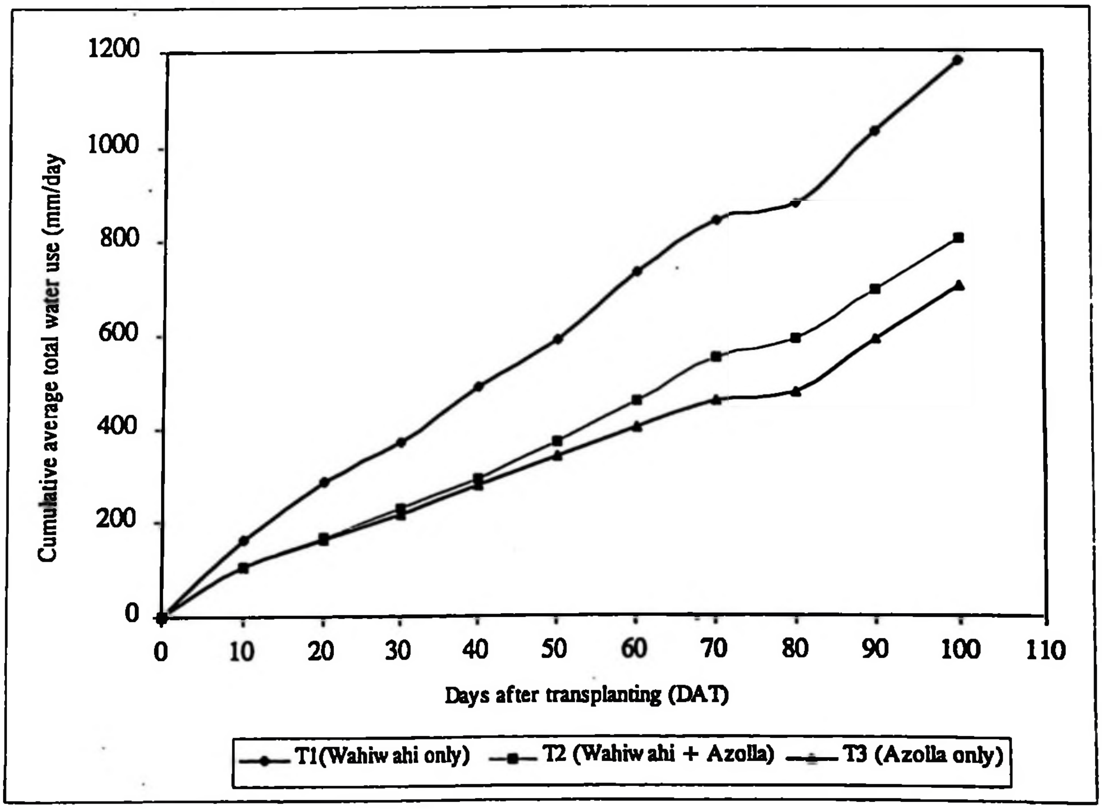


Figure 4.2: Cumulative average total water use (ETcrop plus seepage and percolation)

The trend of total water use by the crop is similar in each treatment and increases consistently with highest water requirement in T1 (Wahiwahi only) and lowest in T3 (Azolla only). Studies done by Sahu and Raut (1969) indicated significant reduction in the use of water by rice after the application of organic manure. In India, Liu (1979) quoted by De Datta and Hundal (1984) reported increased soil moisture residues in rice-Azolla fields. Wheat and rape crops grown in the rice-wheat/rape rotations greatly benefited from the moisture conserved by Azolla. In India, Das (1983) reported seasonal (total) water requirement of 1100 to 1600 mm under efficient water management practices while Hodges (1957) in Texas reported 800 mm to 1200 mm. In this study the total water requirement was 797 mm in T2 (Wahiwahi + Azolla) and 1176 mm in T1 (Wahiwahi only).

4.5.2 Evapotranspiration

The lowest average daily ETcrop was 2.24 mm in T3 (Azolla only) which was significantly different ($p \leq 0.05$) from T2 (Wahiwahi + Azolla) and T1 (Wahiwahi only). The average daily ETcrop was 6.48 mm in T2, which was significantly lower ($p \leq 0.05$) than 8.51 mm in T1 (Table 4.9). The magnitude of the soil cover provided by Azolla mulch considerably influenced ETcrop. It appears that direct solar radiation at the soil-water surface in T1 (Wahiwahi only) increased the water temperature. Subsequently, atmospheric humidity was increased, and this helped to sustain optimum atmospheric conditions at or near potential evapotranspiration resulting in higher moisture loss in the top water layer (Das, 1983).

Table 4.9. Effect of *A. caroliniana* on average daily evapotranspiration for the growing period (October 2000 - January 2001)

Treatment	Daily ETcrop (mm)
WAHIWAHI ONLY	8.51a
WAHIWAHI + AZOLLA	6.48b
AZOLLA ONLY	2.24c
MEAN	5.74

CV = 14.71%

lsd $_{0.05}$ = 1.461

In the column, means having a common letter are not significantly different ($p \leq 0.05$) according to the DNMR test.

This explains why ETcrop was higher in T1 (Wahiwahi only) compared with T2 (Wahiwahi + Azolla). On the other hand, the micro-environment that prevailed under the Azolla mat in T2 (Wahiwahi + Azolla) and T3 (Azolla only) were characterized by the weakening of the strong radiation (Mandal *et al.,* 1990). In comparison to T1, the Azolla mulch in T2 and T3 started acting as a natural sealant and cover, at 14 DAT. This reduced surface temperatures and the subsequent maintenance of atmospheric humidity helped to control moisture .loss. Therefore, evaporation was suppressed and ETcrop was reduced appreciably. Fig. 4.3 shows the cumulative average evapotranspiration and pan evaporation as functions of time after transplanting of rice. ETcrop in T2 (Wahiwahi + Azolla) is consistently lower compared to T1 (Wahiwahi only) due to the shading effect of mulch and suppression of surface temperature. The average ETcrop rate in T1 (Wahiwahi only) was 23%

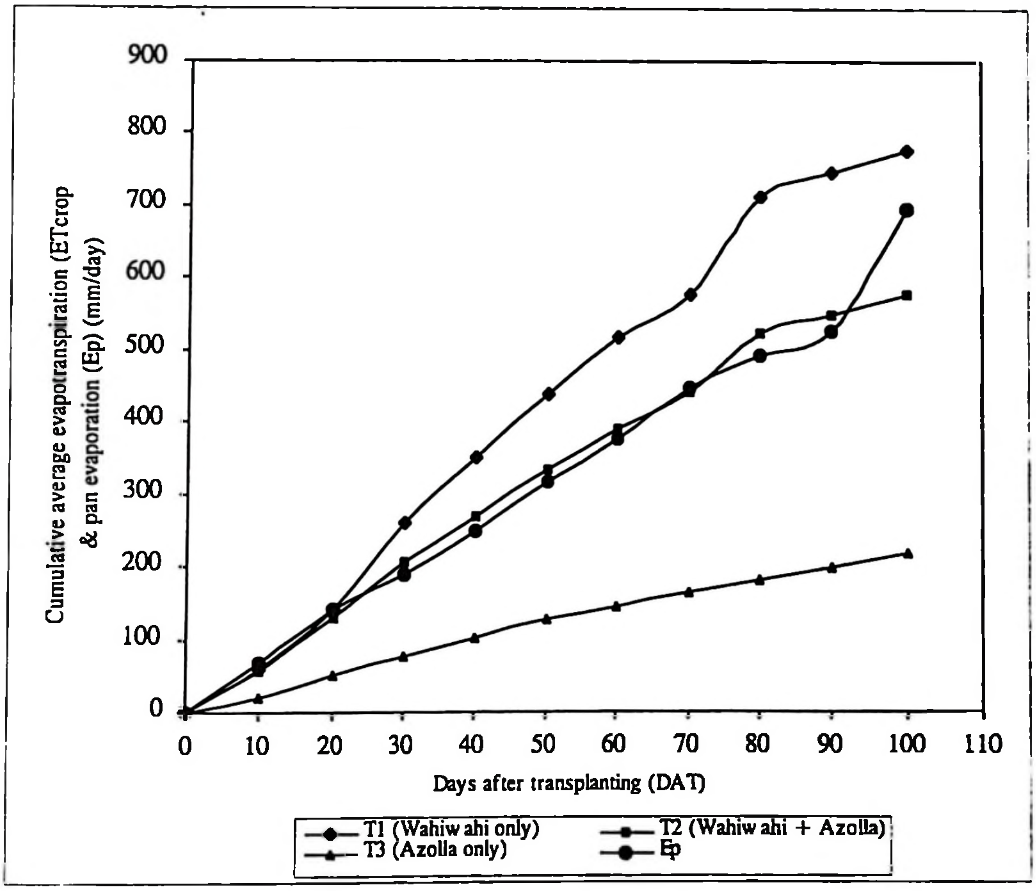


Figure 4.3: Cumulative average evapotranspiration (ETcrop) and pan evaporation (E_p) as a function of time after transplanting

higher than T2 (Wahiwahi + Azolla). Pan evaporation rate was consistently higher than ETcrop rate in T3 (Azolla only). The average pan evaporation rate for the growing period was 6.13 mm/day which was 5% lower than ETcrop rate in T2. However, ETcrop rate in T1 (Wahiwahi only) was about 27% more than pan evaporation rate. Tommar and O'Toole (1979) cited by De Datta (1981) reported that evapotranspiration in rice fields is 10 - 20% more than pan evaporation. There was a close link between temperature and moisture loss. The relationship followed the same trend in each case. There was a notable increase in the rate of evaporation and ETcrop in T1 (Wahiwahi only), T2 (Wahiwahi + Azolla) and T3 (Azolla only) with increased temperature. Both evaporation and ETcrop fluctuated daily from week to week following the solar activity in the growing period. The variation of the 10-day average evapotranspiration and pan evaporation with time for the irrigated period is shown in Fig. 4.4. The effectiveness of Azolla in protecting the soil surface thereby preserving soil moisture was more conspicuous under T2 (Wahiwahi + Azolla) and T3 (Azolla only) compared with T1 (Wahiwahi only). Therefore, the fern must have exerted a certain magnitude of surface cover, which controlled the soil and air

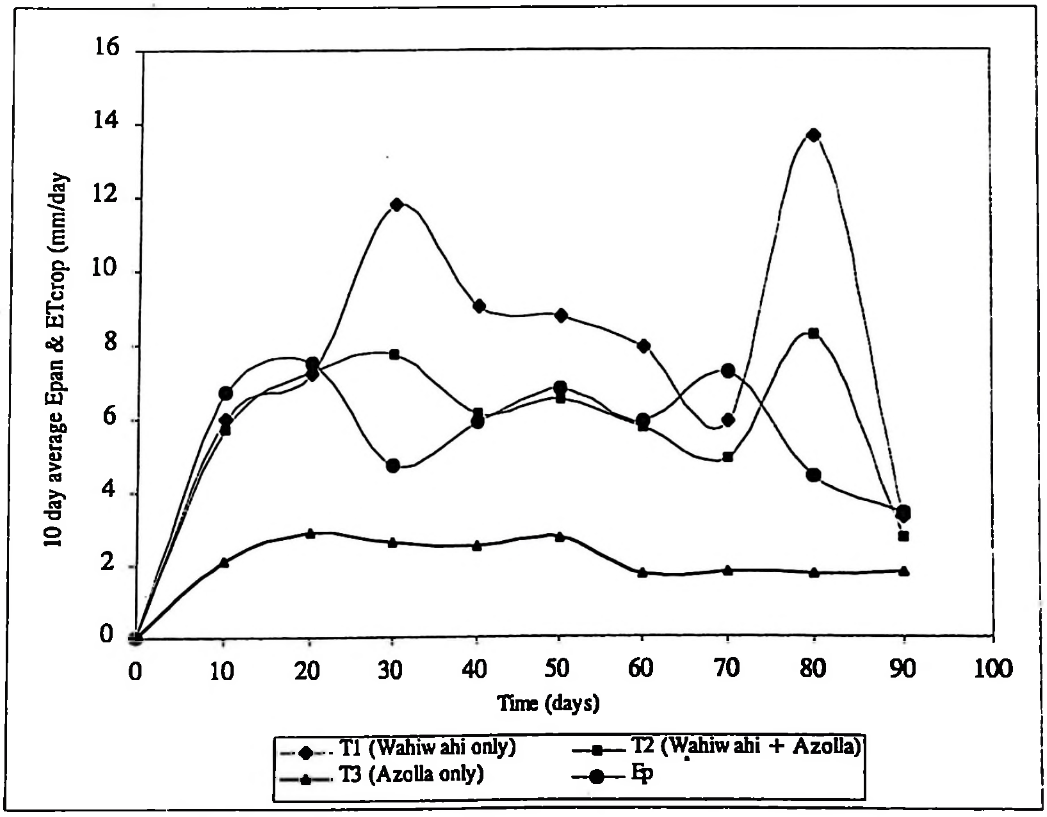


Figure 4.4: Variation of 10-day average evapotranspiration (ETcrop) and pan evaporation (E_p) with time after transplanting

temperature and significantly reduced moisture loss. This is evidenced by the fact that the biomass of Azolla in T2 was 25 % higher than in T3 as discussed in Section 4.5.3. Thus the decrease in ETcrop in T2 (Wahiwahi + Azolla) resulted in the conservation of soil moisture which was made available for a longer period to promote growth in the rice crop. In this study, the evapotranspiration (crop water requirement) for the growing period (98 days) was 834 mm in T1 (Wahiwahi only) compared with 635 mm in T2 (Wahiwahi + Azolla). In Hombolo, Tanzania, Rwehumbiza *et al.* (2000) reported crop water requirement for rice (paddy) equal to 770 mm in the wet season from December - May. Brouwer *et al.* (1986) quoted by CTA (1997) gave crop water requirements for paddy of 450 mm - 700 mm for growing periods of 90 - 150 days. In South Africa, Meyer and Green (1980) used a lysimeter to measure evapotranspiration in wheat plants under different water regimes. The results indicated that the resistance to the movement of water through the soil caused evapotranspiration to fall below potential rates. In Japan, Daigo and Phaovattana (1999) reported reduced evaporation in ponds using duckweed as a floating cover. Mandal *et al.* (1993) reported in West Bengal, India, increased water retention in the soil after the application of Azolla. The results of this study also conform to findings by Okimura and Hanada (1993).

4.5.3 Biomass production of Azolla

The average biomass production of Azolla was 36.9 t/ha in T3 (Azolla only) which was not significantly different ($p \leqslant 0.05$) from 29.5 t/ha in T2 (Wahiwahi + Azolla). The average thickness of the Azolla mat was 15 mm in T3 while it was 10 mm in T2.

The dense cover provided by the Azolla mat might have acted as a barrier between thermal energy and water at deeper layers under the fern.

4.5.4 Water use efficiency

The average water use efficiency (WUE) in T2 (Wahiwahi + Azolla) was 1.33 Kg of dry matter per m^3 of water (KgDM/m^3water) which was not significantly different (p È 0.05) from 0.93 KgDM/m^3water in T1 (Wahiwahi only). There is a close relationship between WUE and the crop yield. The increased WUE in T2 may be attributed to the judicious use of water by the crop. Downes (1969) cited by Gardner *et al.* (1985) reported that WUE ranges from 1.49 - 3.14 KgDM/m^3water. Sahu and Raut (1969) reported reduction in the water requirements of rice per unit of dry matter production after the application of organic matter. Organic manure enhanced the total amount of water transpired resulting in increased dry matter in the plant. Gardner *et al.* (1985) reported that use of organic manure under high atmospheric demand and low water availability, increases crop yields without an increase in seasonal ETcrop. In this study, soil-moisture residues were more conspicuous in T2 compared with T1. The soils in T2 (Wahiwahi + Azolla) remained moist and rice plants did not wilt, while Azolla still looked green at the time of harvest (Plate 5) 14 days after the termination of irrigation. Reitz (1974) quoted by Gardner *et al.* (1985) stated that management techniques (water conservation, control of weeds, pests and improved tillage) that reduce limitations to plant growth significantly increased both yield and WUE. The increased WUE obtained in this study was probably due to efficient moisture extraction, decreased evapotranspiration and increased grain yield.

(a)


(b)


Plate 5: Azolla fronds grown with rice plants looking green and robust at harvest time (that is, 14 days after the termination of irrigation)

Mandal *et al.* (1990) reported significant increase of WUE in rice plants. The non-significance of WUE in this study may be attributed to inefficient irrigation caused by the effect of slope on the drainage of water.

4.5.5 Seepage and percolation

The average seepage and percolation was highest (4.81 mm/day) in T3 (Azolla only) and lowest (1.66 mm/day) in T2 (Wahiwahi + Azolla). In T1 (Wahiwahi + Azolla) seepage and percolation was 3.49 mm/day. There was no significant effect ($p \leqslant 0.05$) of Azolla on seepage and percolation. However, high seepage and percolation in T3 was somewhat expected and is consistent with studies done by Ganai and Singh (1988). Ganai and Singh (1988) reported increased seepage and percolation using farmyard manure in rice-wheat rotation. The increased liquid loss was due to the transformation of the soil structure caused by the effect of organic matter. The change in the soil structure resulted from the aggregation of soil particles, which caused reduction of both the soil penetrometer resistance and soil bulk density. Consequently, the soil capillary system was altered and gravitational water increased (Ganai and Singh, 1988). In T2 and T3, the change in seepage and percolation may be attributed to the transformation of the soil structure due to the effect of decomposed Azolla. However, in T2 (Wahiwahi + Azolla), the extent of the pore arrangement in the soil may have been restricted by root growth of the rice plants, hence lower liquid losses measured. The cumulative average seepage and percolation with time after transplanting is shown in Fig. 4.5. Studies by Lynchi (1983) and Mandal *et al.* (1998) indicated an improvement in the soil physical properties especially in the soil porosity, after the application of Azolla. Mandal *et al.* (1993) ascribed the

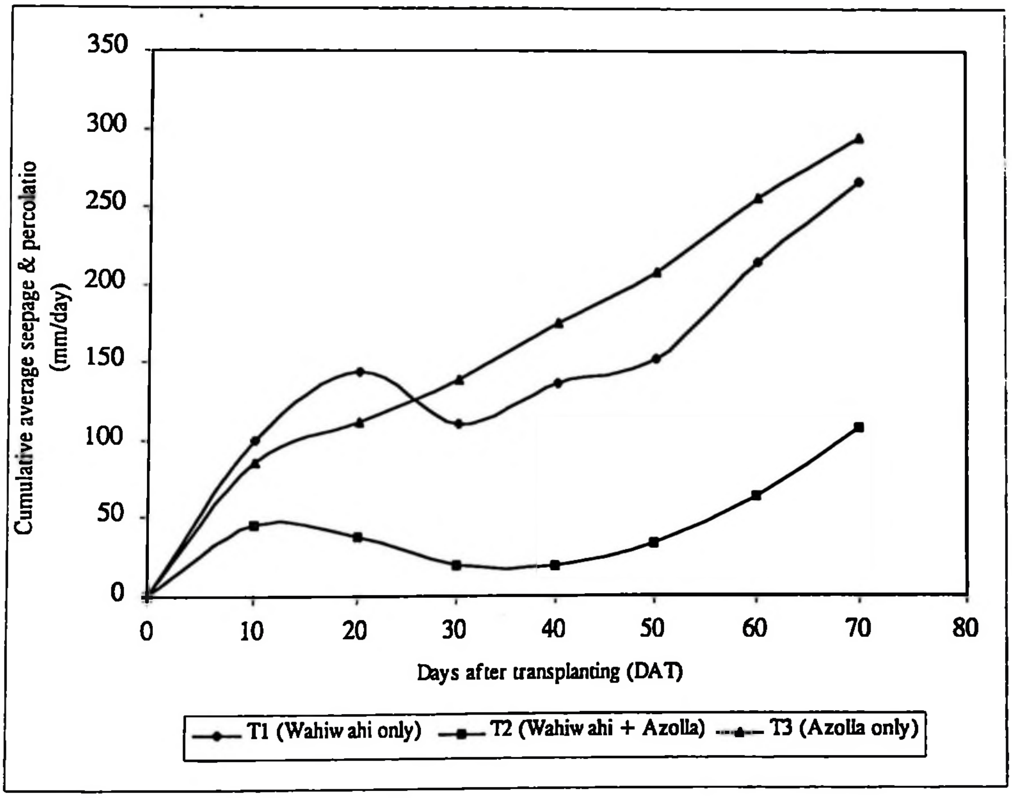


Figure 4.5: Cumulative average seepage and percolation with time after transplanting

improvement of soil by Azolla to the uneven mixing of Azolla with soil and the indirect effect of the fronds on the soil physical and chemical properties. Kanwar and Ray Chaudhuri (1971) reported that organic matter increases seepage and percolation. However, the rate of loss beyond the root zone is appreciably reduced. Subsequently, the availability of water in the soil is prolonged. In Ibariki, Japan, Iwata *et al.* (1986) studied an area of about 50 paddy fields and reported percolation rates of 4 mm/day to 380 mm/day. According to Iwata *et al.* (1986), slowing the rate of seepage and percolation maximizes the time that water is made available to plants and minimizes the total water requirements. In this study, Azolla improved the soil structure, increased the soil infiltration rate and preserved moisture. The presence of soil substrates and polymers produced by Azolla might have altered the movement of water, and possibly increased (hygroscopic) water held in the soil, hence increased moisture availed to the crops.

4.6 Weed population and its dry matter weight

The weeds found in the rice fields were broad-leaved, sedges and grasses. The predominant weed species observed in descending order of infestation were:

(a) *marsilea quadriforlia,* (b) *elegant cyprus*, (c) *eleusine indica (l), gaertn* (d) *bidens tripartitan,* (e) *ludwigu epilobioides maxin.*

4.6.1 Weed population

The lowest average weed population was 55 weeds count/m^2 in T2 (Wahiwahi + Azolla) which was not significantly different ($p \leqslant 0.05$) from 58 weeds count/m^2 in T3 (Azolla only) as shown in Table 4.10. The highest average weed population was

Table 4.10. Effect of *A. caroliniana* on the average population of weeds for the growing period (October 2000 - January 2001)

Treatment	Weed population (count/m^2)
WAHIWAHI ONLY	277a
WAHIWAHI + AZOLLA	55b
AZOLLA ONLY	58b
MEAN	130

CV = 53.45%

lsd $_{0.05}$ = 119.70

In the column, means having a common letter are not significantly different ($p \leqslant 0.05$) according to the DNMR test.

277 weeds count/m^2 in T1 (Wahiwahi only) which was significantly higher ($p \leq 0.05$) than T2 and T3. The significant reduction of weeds by Azolla in T2 (Wahiwahi + Azolla) compared with T3 (Azolla only) may be attributed to the shade provided by rice plants. During the growing period, Azolla fronds in T3 (Azolla only) consistently suffered stress and turned brown due to excessive heat, while the fronds under rice shade persistently looked green and healthy (Plate 6). The significant reduction in the weed stand in treatments with Azolla may be attributed to the development of a thick fern that covered the surface. In South Africa, Ashton (1974) reported improved growth of Azolla under reduced sunlight. In South Parganas, India, Sahoo and Datta (1999) reported increased rice yields and reduced weed stand using *A. caroliniana.* Lumpkin and Plucknett (1980) ascribed weed suppression by Azolla to the smothering effect caused by the fronds mat.

(a) The fronds directly exposed to direct sunlight showed signs of stress

(b) Some healthy looking fronds growing under rice shade

Plate 6: The conditions of the Azolla fronds during the growing period

4.6.2 Dry matter of weeds

The dry weight of weeds (Table 4.11) was 89 kg/ha in T2 (Wahiwahi + Azolla) which was significantly different ($p \leqslant 0.05$) from 67 kg/ha in T3 (Azolla only).

Table 4.11. Effect of *A. caroliniana* on average dry weight of weeds for the growing period (October 2000 - January 2001)

Treatment	Weed dry weight (Kg/ha)
WAHIWAHI ONLY	178a
WAHIWAHI + AZOLLA	89b
AZOLLA ONLY	67b
MEAN	111

CV = 26.55%

$lsd_{0.05} = 0.134$

In the column, means having a common letter are not significantly different ($p \leqslant 0.05$) according to the DNMR test.

In T1 (Wahiwahi only) the dry weight was 178 kg/ha which was significantly higher ($p \leqslant 0.05$) than T2 and T3. There was considerable decrease in dry matter accumulation of weeds in treatments grown with Azolla. The mulching effect of Azolla deprived the weeds of light and reduced their metabolic processes, hence the low dry matter obtained (Sahoo and Datta, 1999).

4.7 Yield attributes and total grain yield

The average grain yield was 20% higher in T2 (Wahiwahi + Azolla) and significantly different ($p < 0.05$) from that obtained in T1 (Wahiwahi only). The average yield attributes and grain yield response of the crop to the treatments are shown in Table 4.12. Growth components, that is, plant height, number of tillers/m^2, heading time and rice straw dry weight/m^2 were 106.8 cm, 319, 70 days and 0.84 Kg/m^2 in T2 (Wahiwahi + Azolla) and 100.8 cm, 209, 77 days and 0.78 Kg/m^2 in T1 (Wahiwahi only) respectively.

Table 4.12. Effect of *A. caroliniana* on the average total grain yield and yield attributes of Wahiwahi rice at harvest time

Treatment	WAHIWAHI ONLY	WAHIWAHI + AZOLLA	MEAN	Standard Deviation
Plant height (cm)	100.8	106.78	103.9	4.23
No. of tillers per 1 m^2	209	319	264	78
Heading time (DAT)	77	70	73.5	4.95
Rice straw dry weight (Kg/m^2)	0.78	0.84	0.81	0.04
No. of panicles per 1 m^2	336	361	349	18
1000 grains weight (Kg)	30.58	29.34	29.96	0.88
No. of grains per 1 m^2 x 10^3	31.99	33.5	32.7	1070
Grain fertility (%)	65.6	71.7	68.7	4.3
Grain yield (t/ha)	6.31	7.93	7.12	1.14

Yield components such as panicles/m^2, 1000 grains weight, number of grains/m^2 and percent grain fertility were 361, 29.34 Kg, 33.5 x 10^3 and 71.7% in T2 and 336, 30.58 Kg, 32 x 10^3 and 65.6% in T2 respectively. The application of Azolla showed increase but had no significant effect ($p \leq 0.05$) on plant height, straw dry weight, panicles/m^2, 1000 grains weight and grain fertility. However, the crop stands were appreciably increased in T2 (Wahiwahi + Azolla) compared with T1 (Wahiwahi only). The substantial effect of Azolla on the rice yield was reflected by the superior yield attributes registered in T2 (Wahiwahi + Azolla) compared with T1 (Wahiwahi only). The heading time, number of tillers, and grain weight at harvest in T2, differed significantly ($p \leq 0.05$) compared with T1 (Wahiwahi only). Further discussion of the yield attributes (i.e. heading time, number of tillers and grain weight at harvest) and grain yield are given in the following subsections.

4.7.1 Heading time

The average heading time for rice plants was 70 days in T2 (Wahiwahi + Azolla) which is significantly lower ($p \leq 0.05$) than 77 days in T1 (Wahiwahi only) as shown in Table 4.13. The plants in T2 (Wahiwahi + Azolla) continued to grow vigorously and maintained their turgidity through-out the growing period, hence matured early.

Table 4.13. Effect of *A. caroliniana* on average heading time of Wahiwahi rice during growing period (October 2000 - January 2001)

Treatment	Heading time (DAT)
WAHIWAHI ONLY	77a
WAHIWAHI + AZOLLA	70b
MEAN	73

CV = 0.96%

$lsd_{0.05} = 1.591$

In the column, means having a common letter are not significantly different ($p < 0.05$) according to the student t-test.

The maximum difference in heading time was 7 days. The difference in the heading time was apparent in growth and became prominent towards maturity as the biomass production increased. The heading date had a significant effect on the maturity date and consequently on the requirement of water by the crop. There was also a close relationship between heading time and dry matter accumulation by the plant. Rice plants in T2 (Wahiwahi + Azolla) matured earlier than plants in T1 (Wahiwahi only). The early maturity of rice plants in T2 may be attributed to the continued availability of water. The prolonged availability of water was apparent in T2 compared with T1 during the growing period and hence the heading date measured and yield advantages obtained. In the LMIP, Mvukiye (1999) reported improved crop growth and significant increase ($p \leqslant 0.05$) of both plant height and heading date after the application of *A. caroliniana*. In this study, the plant height (a strong determinant of the grain yield and attribute of heading date) was not significant ($p < 0.05$). The non-uniformity of irrigation due to gradient slope in the field may have affected the efficiency of water use by the plants.

4.7.2 Number of tillers

The number of tillers/m^2 was 319 tillers/m^2 in T2 (Wahiwahi + Azolla) which was significantly higher ($p \leqslant 0.05$) than 209 tillers/m^2 obtained in T1 (Wahiwahi only) as shown in Table 4.14. The higher number of tillers registered in T2 (Wahiwahi + Azolla) may be attributed to better soil moisture conditions that sustained both the early and late vegetative stages of the rice plants. The optimum moisture availability in T2 (Wahiwahi + Azolla) may have contributed to the increased panicles and

Table 4.14. Effect of *A. caroliniana* on average number of tillers of Wahiwahi rice at harvest time

Treatment	Tiller count (number/m^2)
WAHIWAHI ONLY	209b
WAHIWAHI + AZOLLA	319a
MEAN	264

CV = 7.59%

lsd $_{0.05}$ = 45.089

In the column, means having a common letter are not significantly different ($p \leqslant 0.05$) according to the student t-test.

reduced mortality resulting in unrestricted tiller production. In T1 (Wahiwahi only) the rice plants remained studded and mortality was relatively higher. Consequently, the number of productive tillers were reduced. Mvukiye (1999) reported significant increase in the number of tillers of rice after using *A. Caroliniana* at the LMIP.

4.7.3 Grain weight at harvest

The total grain weight at harvest was 8.6 t/ha in T2 (Wahiwahi + Azolla) which was significantly higher ($p \leqslant 0.05$) than 6.8 t/ha in T1 (Wahiwahi only) as shown in Table 4.15. Azolla played an important role in improving growth and yield attributing characters of rice plants, both of which contributed significantly to the grain yield obtained at maturity. This result was somewhat expected because the average crop yield components were higher in T2 (Wahiwahi + Azolla) than in T1 (Wahiwahi only). These parameters are strong determinants of the total grain weight (fresh)

Table 4.15. Effect of *A. caroliniana* on average total grain weight of Wahiwahi rice at harvest time

Treatment	Grain weight (t/ha)
WAHIWAHI ONLY	6.8b
WAHIWAHI + AZOLLA	8.6a
MEAN	7.7

CV = 8.09%

lsd $_{0.05}$ = 0.14

In the column, means having a common letter are not significantly different ($p \leqslant 0.05$) according to the student t-test.

measured in the field, which must be expressed as the total grain yield at 14% moisture content (Matsushima, 1967).

4.7.4 Grain yield

The average total grain yield in T2 (Wahiwahi + Azolla) was 7.93 t/ha which was significantly higher ($p \leqslant 0.05$) than 6.31 t/ha in T1 (Wahiwahi only) as shown in Table 4.16. Azolla appreciably increased the grain yield of rice. The grain yield performance of rice plants in T2 (Wahiwahi + Azolla) may be attributed to the adequate crop stands which might have been sustained by increased soil moisture. The plants in T1 (Wahiwahi only) were stunted in growth and wilted soon after the termination of irrigation, whereas plants in T2 (Wahiwahi + Azolla) were vigorous and maintained turgor longer than those in T1.

Table 4.16. Effect of *A. caroliniana* on average total grain yield of Wahiwahi rice at harvest time

Treatment	Grain yield (t/ha)
WAHIWAHI ONLY	6.31b
WAHIWAHI + AZOLLA	7.93a
MEAN	7.12

CV = 6.62%

lsd $_{0.05}$ = 1.06

In the column, means having a common letter are not significantly different ($p \leq 0.05$) according to the student t-test.

This was very apparent during the growing period hence the yield advantages obtained. Azolla improved the soil structure and controlled evapotranspiration. In central Uttar Predesh, India Singh and Bhan (1993) reported that plant growth and biomass production are related to evapotranspiration or more specifically, to transpiration. Suppressing ETcrop results in prolonged water availability, and enhanced transpiration by the crop. Consequently, grain yield is increased. It becomes clear from the yield data that plants grown in improved soils have increased water use efficiency (Mandal *et al.*, 1990). Therefore, the increased soil water stored in T2 (Wahiwahi + Azolla) resulted in the yield advantages obtained. In east India, Sharma and Rajput (1990) reported increased rice productivity with increased soil moisture. Diarra *et al.* (1983) in Sierra Leone and Mvukiye (1999) in the LMIP, reported similar results.

CHAPTER FIVE

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The following conclusions can be made from this study:

(1) There was considerable decrease in the total amount of water used in Azolla grown plants compared with plants without Azolla. *Azolla caroliniana* both as surface cover and soil conditioner improved the water retentivity and increased the soil moisture residues. This result suggest that up to 32% of irrigation water could be saved for rice production in the Lower Moshi area by planting *Azolla caroliniana* as dual crop with rice.

(2) The sustained water availability in the root zone by *A. caroliniana* improved the crop growth in the rice plants and increased grain yield at harvest. Generally, all the yield attributes of rice plants grown with Azolla were substantially higher than plants without Azolla.

(3) In the present study, *A. caroliniana* suppressed weeds and promoted rice crop growth. The total weed weight and weed population under Azolla management was four times lower than weed attributes without Azolla.

5.2 RECOMMENDATIONS

From this study, the following are the recommendations:

(1) *Azolla caroliniana* is recommended as a water management practice for irrigated rice cultivation under acute water shortage.

(2) Further studies are needed for different growing seasons at different sites.

(3) Further studies will be needed to determine optimum levels of inoculation rates of *A. caroliniana* required to achieve higher efficiency and economize on the available irrigation water. In this study, an inoculation rate of 500 g (FW)/m^2 (*A. caroliniana*) was used.

(4) Further studies will be needed to evaluate independently the major contributing factor (moisture residue or N_2 accumulation) that has significant effect on the total grain yield. The review of literature on the use Azolla in paddies points at N_2 fixation as the immediate benefit that resulted in improved growth and increased grain yield.

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APPENDICES

Appendix 1

11 year (1988-98) weather data recorded at KATC meteorological station

Mean monthly temperature (°C)

Month		1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	Mean
Jan	max	34.9	31.6	32.4	34.9	33.6	30.0	33.5	34.3	34.4	35.5	31.1	33.3
	min	22.8	19.4	17.3	19.8	18.6	19.2	19.0	17.8	19.4	35.5	19.8	20.8
Feb	max	35.7	33.5	34.6	35.5	35.5	30.9	33.5	34.3	34.4	36.9	32.0	34.3
	min	22.5	19.2	19.1	20.1	20.6	17.1	19.0	19.0	19.4	19.8	19	19.5
Mar	max	34.1	33.7	31.0	35.0	35.4	36.6	33.7	32.9	34.0	35.1	32.9	34.0
	min	21.6	20.1	19.2	20.6	19.9	18.4	19.5	19.3	19.8	20.7	20.5	20.0
Apr	max	29.8	29.5	30.4	32.5	31.5	32.4	31.0	31.7	30.3	30.2	30.4	30.9
	min	20.6	18.9	19.1	21.0	20.2	20.2	19.6	19.8	19.2	19.9	20.9	19.9
May	max	28.0	27.7	29.0	28.6	28.6	30.0	27.6	27.9	28.9	26.8	27.9	28.3
	min	16.5	16.9	18.3	20.1	16.8	19.0	18.1	18.3	17.8	18.2	19.2	18.7
Jun	max	27.7	26.8	28.5	27.8	27.3	26.8	27.2	26.7	28.0	25.7	27.3	27.3
	min	17.6	17.6	16.1	17.4	16.3	16.7	16.0	15.6	17.7	17.9	17.60	17.0
Jul	max	27.5	27.5	27.7	27.5	27.7	26.0	27.2	27.3	26.9	26.1	26.0	27.0
	min	17.4	16.7	14.4	16.9	14.4	15.2	15.3	15.0	15.7	16.6	15.7	15.8
Aug	max	27.6	26.8	26.6	28.6	26.3	27.8	28.2	29.0	27.3	27.7	27.7	27.6
	min	18.5	16.0	15.9	16.4	15.8	16.2	16.8	15.5	15.4	15.9	17.4	16.3
Sep	max	29.4	29.5	28.3	30.1	28.6	29.9	30.3	29.5	29.8	30.3	29.6	29.6
	min	18.3	17.1	16.6	17.3	16.6	15.4	17.0	12.9	16.5	18.1	20.4	16.9
Oct	max	32.9	32.1	30.6	33.1	30.5	31.2	33.0	33.8	32.0	29.2	28.1	31.5
	min	20.0	18.1	18.3	15.1	16.8	18.0	18.9	18.0	17.1	18.9	16.5	17.8
Nov	max	32.5	33.1	33.4	33.7	32.5	33.9	32.4	32.9	33.2	30.2	33.3	32.8
	min	19.0	19.1	20.2	20.2	19.2	19.2	19.4	18.7	19.3	19.4	19.6	19.4
Dec	max	32.5	33.8	32.8	31.9	31.5	32.3	31.2	33.5	35.5	30.7	34.0	32.7
	Min	18.9	18.8	19.5	19.4	20.4	18.7	18.2	17.7	17.8	19.8	18.8	18.9

Mean monthly relative humidity (%)

Month	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	Mean
Jan	65	70	67	62	61	74	64	62	63	63	93	68
Feb	61	65	64	67	60	71	71	64	69	66	83	67
Mar	70	73	76	67	60	73	70	69	68	68	80	70
Apr	79	77	79	73	76	73	74	75	76	84	84	77
May	80	76	75	77	78	75	79	79	77	85	89	79
Jun	77	72	72	74	73	73	72	75	77	84	91	76
Jul	72	69	73	73	70	74	70	74	74	83	86	74
Aug	74	70	76	73	68	73	70	68	71	77	82	73
Sep	68	67	70	66	65	67	66	61	71	79	77	69
Oct	63	63	67	63	64	68	64	69	68	92	77	69
Nov	65	62	67	66	66	64	66	65	60	90	73	68
Dec	69	65	66	69	66	67	71	66	56	92	73	69

Long term weather data cont:

Mean monthly pan evaporation (mm/day)

Month	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	Mean
Jan	8.3	4.9	5.8	7.3	7.4	4.7	6.8	*	*	8.0	3.9	6.3
Feb	8.7	8.7	6.8	7.3	8.0	6.5	8.9	*	*	8.4	4.6	7.5
Mar	6.4	6.2	4.4	7.0	7.1	5.9	6.5	*	*	7.1	5.5	6.2
Apr	3.7	3.7	3.0	5.2	4.5	5.6	4.8	*	*	4.3	3.9	4.3
May	2.7	2.4	3.0	3.0	3.0	4.4	4.1	*	*	1.7	3.3	3.1
Jun	2.6	2.4	3.0	3.2	3.2	3.4	4.5	*	*	2.9	3.1	3.1
Jul	3.1	3.1	2.9	2.9	3.5	3.3	*	*	*	4.4	2.9	3.3
Aug	3.3	3.1	3.1	4.0	4.9	4.9	*	*	*	4.4	4.0	4.0
Sep	4.9	4.1	4.4	5.2	6.4	6.4	*	*	*	5.5	5.4	5.3
Oct	7.4	5.4	5.1	7.1	8.2	8.2	*	*	*	4.5	6.2	6.5
Nov	6.7	6.0	6.2	7.1	7.8	7.8	*	*	*	4.2	6.6	6.6
Dec	6.4	6.3	5.9	4.9	5.8	*	*	*	*	4.4	7.5	5.9

Mean monthly rainfall (mm)

Month	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	Mean
Jan	4	8	4	2	0	8	5	1	2	0.1	8.2	3.8
Feb	0	4	6	0	0	3	6	1	5	0	2.1	2.5
Mar	11	6	18	5	3	6	10	5	4	1.2	1.3	6.4
Apr	17	16	13	8	15	9	11	11	9	10.7	11.8	12
May	4	11	4	18	14	12	12	11	0	5.7	4.1	8.7
Jun	3	2	1	1	1	0	1	0	7	0.5	0.3	1.5
Jul	3	0	0	2	1	0	0	0	0	0.8	0.9	0.7
Aug	1	3	0	1	0	0	0	4	0	0.5	0.1	0.9
Sep	4	3	3	3	0	0	1	0	0	4.3	0.2	1.7
Oct	0	7	7	0	1	2	1	1	2	1.9	0	2.1
Nov	6	3	9	7	0	2	6	1	0	2.5	0.3	3.3
Dec	11	7	9	7	4	5	9	3	0	3.3	0	5.3

NOTE: * – READING NOT RECORDED

Appendix 2

Infiltration data and hydraulic conductivity

Site Station	Slope treatment (%)	Tension (bars)	Basic Infiltration rate (cm/hr)	Derived Hydraulic conductivity (cm/hr)
TA1 & TB1	2	5	22.8	21.7095
	2	7	10.8	12.4293
	2	10	6	5.3845
TA2 & TB2	1	5	6	5.8447
	1	7	3.6	3.9867
	1	10	2.4	2.2460
TA3 & TB3	0.6	5	7.8	6.7324
	0.6	7	1.8	2.7533
	0.6	10	0.48	0.4874
TC1	2	5	9.6	9.3618
	2	7	3.6	4.008
	2	10	1.2	1.1228
TC2	1	5	14.4	13.9997
	1	7	10.2	10.5304
	1	10	7.2	6.8697
TC3	0.6	5	19.2	19.5206
	0.6	7	10.2	12.8385
	0.6	10	7.2	6.8477
TD1	2	5	6	5.8447
	2	7	3.6	3.9867
	2	10	2.4	2.246
TD2	1	5	9	8.8832
	1	7	7.8	7.8301
	1	10	6.6	6.4800
TD3	0.6	5	12	11.8091
	0.6	7	6.6	7.6078
	0.6	10	4.2	3.9339

NOTE: TA1, TB2, TC3, TD3 measured in T1 (WAHIWAHI ONLY); similarly TA2, TB3, TC2, TD2 in T2 (WAHIWAHI + AZOLLA); TA3, TB1, TC1, TD2 in T3 (AZOLLA ONLY)

Appendix 3

Summary of 11 year (1988-98) monthly potential evapotranspiration (ETo) values (mm/day)

MONTH	OCTOBER	NOVEMBER	DECEMBER	JANUARY	MEAN
Date					
1	5.51	5.89	5.65	5.87	5.73
2	5.61	5.33	5.59	5.86	5.72
3	5.53	5.85	5.69	5.65	5.68
4	5.6	6.05	5.53	5.86	5.76
5	5.45	6.15	5.79	5.91	5.83
6	5.42	6.34	5.64	5.86	5.82
7	5.41	6.39	5.72	5.73	5.81
8	5.59	6.35	5.52	5.89	5.84
9	5.58	6.65	5.78	6.17	6.05
10	5.47	6.66	5.62	6.05	5.95
11	5.62	6.77	5.83	5.71	5.98
12	5.57	6.89	5.56	5.85	5.97
13	5.54	6.99	5.64	5.86	6.00
14	5.71	7.08	5.57	6.10	6.12
15	5.59	7.01	5.56	5.92	6.02
16	5.73	6.97	5.49	5.88	6.02
17	5.58	7.13	5.56	5.83	6.03
18	5.66	7.20	5.74	5.91	6.13
19	5.54	7.46	5.51	5.82	6.08
20	5.55	7.55	5.88	6.12	6.28
21	5.49	7.49	5.79	5.93	6.18
22	5.7	7.70	5.82	6.10	6.33
23	5.75	7.70	5.72	6.07	6.06
24	5.66	8.01	5.72	6.01	6.35
25	5.67	7.91	5.74	6.14	6.37
26	5.8	8.02	5.95	6.03	6.45
27	5.67	8.15	5.88	5.84	6.39
28	5.67	8.31	5.41	5.95	6.34
29	5.49	8.19	5.59	6.09	6.34
30	5.55	8.27	5.88	6.08	6.45
31	5.46	*	5.96	5.85	4.32
Mean	5.57	7.10	5.69	5.93	6.01

NOTE: * = READING NOT RECORDED

Appendix 4

Summary of infield water use

REPLICATION TREATMENT	R1	R2	R3	R4	MEAN
Total water use (Evapotranspiration + seepage and percolation) mm/day					
T1: WAHIWAHI ONLY	15.67	9.08	12.02	11.20	11.99
T2: WAHIWAHI + AZOLLA	7.89	7.23	8.57	8.83	8.13
T3: AZOLLA ONLY	7.17	6.04	6.36	8.63	7 05
MEAN	10.24	7.45	8.98	9.55	
Evapotranspiration (Consumptive water use) mm/day					
T1: WAHIWAHI ONLY	9.35	8.50	9.47	6.71	8.51
T2: WAHIWAHI + AZOLLA	7.37	5.00	7.07	5.84	6.48
T3: AZOLLA ONLY	2.45	2.35	2.10	2.05	2.24
MEAN	6.39	5.28	6.21	4.87	
Seepage and percolation (mm/day)					
T1: WAHIWAHI ONLY	6.32	0.58	2.55	4.49	3.49
T2: WAHIWAHI + AZOLLA	0.52	2.23	0.87	2.99	1.66
T3: AZOLLA ONLY	4.72	3.69	4.26	6.58	4.81
MEAN	3.85	2.17	2.56	4.69	