CRANFIELD UNIVERSITY
SILSOE COLLEGE

NATIONAL SOIL RESOURCES INSTITUTE

Ph.D. Thesis
Academic Year 2001-05

JOSHUA DANSO OWUSU-SEKYERE

WATER TABLE CONTROL FOR RICE PRODUCTION IN GHANA

Supervisor:
Prof. P.B. Leeds-Harrison

September 2005

This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

ABSTRACT

Water table control for rice production in Ghana

An investigation has been undertaken to determine the consequence of using water table control for lowland rice production by growing rice varieties Azucena and IR36 in sand cores under a controlled environment in a series of experiments in which the water table was held at fixed levels. Each experiment had a duration of six weeks and in all, four treatments were used: (a) water table at a depth of 30 cm below the surface, (b) water table at a depth of 15 cm below the surface, (c) saturated sand and (c) flooded sand. Growth under the two water table depths compared favourably with the flooded and saturated conditions, with plants under the water table control treatments in some cases performing better in terms of plant performance than the saturated or flooded. Plant growth parameters measured were: Tiller number, root dry mass, shoot dry mass, rooting depth, total root length and plant height. Other parameters measured are: Solution nitrogen concentration, redox potential, growth medium temperature and pH levels.

When IR36 was used the total root length, number of roots and tiller numbers were significantly greater for the plants in the saturated treatment but there were no significant differences in root mass, shoot mass, and shoot length with regards to water depth. When Azucena variety was used, the 15 cm treatment had the highest shoot mass in addition to the highest tiller numbers. In other parameters, the 15 cm treatment did not show a significant difference to the saturated treatment. The 30 cm treatment performed least well in all parameters measured. Plants under the flooded treatment had a significantly greater root dry mass, shoot dry mass and tiller number than the others. The plants grown under 15 cm water table depth had the least root mass. Tiller numbers for the plants under the 30 cm water table depth were greater than those under the 15 cm water table depth. Differences in plant development parameters generally appeared only after the fourth week. The data suggest that irrespective of the water treatment used, plant

development trends remain the same indicating that in the first four weeks of rice growth much less water can be used without affecting plant development.

Where Azucena and IR36 were both used the data suggest that water table control might be suitable for both varieties of rice. Differences in the amount of nitrogen present were seen to have had an impact on growth. Varying the form of nitrogen applied did not alter growth parameters to any appreciable extent implying that supply of nitrogen is more important than the form of nitrogen used.

The effect of root properties and NH_4^+ transport through the soil on N uptake under different water regimes has been modelled. The model adequately predicted the root length densities required to explain N uptake rates. It is shown that root length densities increase with decreasing moisture content, allowing larger root length densities to compensate for low nutrient transport rates and although diffusion of nutrients increased with increasing moisture levels, nutrient uptake rates did not follow the same pattern. Rooting length densities and transport of nutrients are not shown to limit uptake of nutrients under any of the water treatments imposed.

The feasibility of using water table control in the inland valleys of Ghana was also investigated by simulating the depth of the water table required in the dry season of the years 1996 and 1997. A comparison of water use under water table control and flooding irrigation showed that water savings were possible suggesting that water table control is feasible and beneficial in the inland valleys of Ghana.

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF ABBREVIATIONS AND SYMBOLS

Eh   **Redox potential**

AT   **Azucena**

IT   **IR36**

ST   **Bare sand**

EC   **Electrical conductivity**

TON   **Total oxides of nitrogen**

F   **Influx (Moles per unit time)**

L_v   **Root length density**

U   **Uptake**

C_{La}   **Concentration of ammonium in solution at the root surface**

α   **Root absorbing power**

K_M   **Michelis constant for ammonium absorption**

F_{max}   **Maximum influx into the roots**

$\overline{C_L}$ **Mean ammonium concentration in bulk solution**

D   **Soil ammonium diffusion coefficient**

b   **Soil ammonium buffer power**

f_L   **Diffusion impedance factor**

C_s   **Concentration of labile ammonium on soil solid**

R   **Vermiculite content of soil**

P_z   **Fraction of total root mass above depth z**

β   **Coefficient such that 1/ β is the depth containing 63% of the total root mass**.

CHAPTER 1: INTRODUCTION

It has been projected that more than half of the world's population will depend on rice as their principal food source in 30 years and rice production must thus increase by more than 40 percent from the present levels to avoid rice shortage (CGIAR, 1999). Rice production consumes more water than production of any other crop; according to FAO (2004), in traditional wetland rice cultivation it takes about six times the water required by wheat for rice production. Increasing rice production will imply diverting more water for rice production. Fresh water is however a resource that is getting more scarce; currently 31 countries are facing water shortages, a number that is expected to increase to 48 countries by 2025, peaking at 55 countries by mid-century, 2050 (CGIAR, 1999). Demand for water from industry and domestic consumption is also on the increase as populations increase, limiting the amount that is available for agriculture, it may therefore not be feasible to divert more water for agriculture especially rice production. This growing water shortage then implies a pressing need to devise methods of growing rice with less water yet without penalty to production and according to Guerra *et al.,* (1998) the future of rice production will depend heavily on developing and adopting strategies and practices that will use water efficiently in irrigation schemes.

1.1 RICE PRODUCTION IN GHANA

Rice is one of the major food crops in Ghana; it is grown in all the ten regions of the country, covering all the major ecological-climatic zones. Rice in Ghana has been cultivated under three systems, namely: rainfed upland conditions, irrigated conditions and rainfed lowland conditions in inland valleys and flood plains. Production under rainfed upland conditions has been very risky due to unreliable rainfall and shallow and erodible soils of low fertility. Production under rainfed lowlands has also been plagued with unreliable and insufficient water availability and does not hold good prospects for the future. Though the government of Ghana attaches a lot of importance to irrigation as a means of not only increasing the

productivity of agriculture but also providing employment to the rural population, production under the big irrigation schemes has not been very encouraging. It is generally accepted that the nature of the land and surface water resources in Ghana makes the potential for further development of large-scale irrigation schemes costly. This has necessitated the search for other options to improve rice production, and attention has been focused on the valley bottoms, which are part of the inland valleys and flood plains and are scattered across the country covering all the agro-ecological zones. These have been identified as having a high potential for the development of rice-based smallholder farming systems without major capital cost and are irrigable by shallow groundwater or controlled flooding (Sam-Amoah, 2001).

The West Africa Rice Development Association (WARDA) has also emphasised the need to concentrate on the inland valleys of West Africa if the region is to produce enough rice to meets its needs. In its opinion, there is a widespread need to develop technologies to enhance the productivity and exploitation of the inland valleys in ways that ensure their sustainability and improve the well being of the farming communities.

The government of Ghana has embarked on a program to make Ghana self sufficient in rice production and the main policies put in place to achieve this objective include: (i) the exploitation of the vast lands of the inland valleys and swamps; (ii) decreased emphasis on conventional irrigation schemes; and (iii) increased research and technology transfer aimed at efficient utilization of agricultural inputs (Obeng, 1994).

It is in line with these goals that the work reported in this thesis attempts to investigate the effect of water table control on rice production so as to adopt it for use in the inland valleys of Ghana.

1.2 INLAND VALLEY SYSTEMS

Inland valley systems have been defined as complex land forms of the upper parts of river watersheds which comprise of valley bottoms and minor floodplains which may be submerged for part of the year, their hydromorphic fringes, and the contiguous upland slopes and crests that contribute runoff and seepage to the valley bottom.

According to Annan-Afful and Wakatsuki (2002), valley bottoms are characterized by hydromorphic soils that constitute a relatively flat surface with or without a central stream. They are heterogeneous in morphology, soil type, vegetation, hydrology and agronomic practices. They have adequate water supply for the greater part of the year and have fertile soils. There is also a relative ease with which groundwater can be obtained by digging wells or ponds (Agyemang and Smith, 1999).

Valley fringes refer to areas along the slopes of the valley; rainfall either runs off the surface of these areas or interflows on impervious subsurface layers towards the valley bottom and the central stream. According to Thenkabail and Nolte (1995), valley fringes, typically, have two distinct characteristic zones:

1. The lower part of the valley fringe immediately adjoining the bottoms that may have a high likelihood of a seasonal hydromorphic zone with significant potential for dry-season cropping; and

2. The upper part of the valley fringe with steeper slopes characterized predominantly by impervious layers from which rainwater quickly runs off to the valley bottom. Soils in these upper portions of valley fringes dry out rapidly once the rains have ceased, and therefore, have no potential for dry-season cropping.

The inland valley systems have an important potential for the intensification and diversification of agricultural production and are an important environment for biodiversity conservation. To make full use of their potential, it would require designing land development models and methods for water management which would allow farmers to maximize water control and limit risk due to drought as well as to extensive flooding, and to extend the growing season. The accent is placed on improving water supply for the crops, rather than on striving for full water control (Thiombiano *et al*., 1998).

1.3 RICE PRODUCTION IN THE INLAND VALLEYS OF GHANA

In order to make use of the potential of the inland valleys, the 'Valley Bottom Rice Development Project' was initiated in 1989 to develop sustainable technologies for integrated soil, water and crop management in the production of rice and other crops in the inland valleys. Since then, a number of experimental systems have been explored, and an attempt has been made to adopt a system which provides better water, soil and nutrient management to exploit the potential of the inland valleys (Asubonteng *et al.,* 2002). This system, called Sawah, involves bunding, leveling and puddling the fields. The system has proved to be quite successful, and studies conducted reveal that it resulted in greater numbers of productive tillers, higher straw production and higher grain yield. Yield levels increased by as much as 150 percent compared to the traditional system, which though quite similar to Sawah technique did not involve land leveling. The potential area for small-scale irrigated Sawah in inland valley watersheds in Ghana is estimated at 700,000 hectares.

Though the Sawah technology has proven to be successful there is little departure from the traditional system of rice production, which results in wastage of water and utilises excessive energy in land preparation.

It is as a result of this that this study investigates the consequence of irrigating rice using water table control with the aim of reducing primarily, water use.

1.4 WATER TABLE CONTROL

Water table control otherwise called water table management is defined as the process of controlling the shallow ground water table for the enhancement of crop production. It incorporates such methods as (Fouss *et al*., 1990):

Free drainage

Controlled drainage

Controlled drainage and sub-irrigation

Controlled drainage and surface or sprinkler irrigation

Sub-irrigation

Figure 1 is a schematic diagram of a typical water table control system.
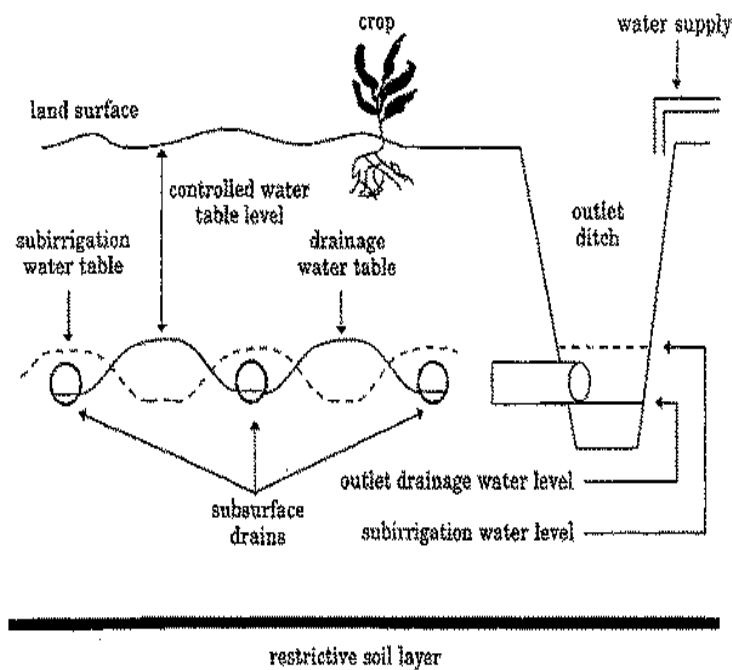
Figure 1.1 Typical water table management system (FAO, 1997)

The overall goal of water table control is to manage and utilise shallow ground water in the soil profile as a source of water for crop production. Specific objectives vary with soil, climate and topography. For humid areas the following two objectives generally apply to most of the systems designed:

1. Minimize the duration of deficit water and water logging that may occur in the root zone during the growing season.

2. Minimize the need for irrigation water from external sources by efficient use of natural rainfall.

The use of water table control in this work is primarily to offer a more efficient irrigation system than the traditional systems. In this sense, full irrigation, according to the actual water requirements for rice will be budgeted for any rainfall that comes will only supplement the water provided through irrigation.

Water table control in this study refers to controlled drainage and sub-irrigation such that water would be prevented from leaving the soil system, or water would be added through sub-irrigation so as to ensure the maintenance of a predetermined water table depth.

1.5 RESEARCH JUSTIFICATION

Though ground water accounts for some of the water supply for rice growth under many conditions, water table control has not yet been directly used for rice production. Use of this system will have advantages such as:

1. Water saving: About 14 to 80 % (depending on soil type) of the water that is applied on rice fields is lost through seepage and deep percolation. A water table control system will potentially stop this loss of water, as water will be provided from below the soil surface. Moreover, water use in land preparation will be drastically reduced, as the land will not have to be soaked for puddling.

2. No puddling means lower cost of production: Puddling is an energy intensive activity, and not having to puddle will lead to tremendous savings in energy and subsequently in cost of production as well as time required for land preparation. Puddling also affects dryland crops planted after rice, this will however not occur under adoption of water table control systems.

3. Methane emissions from rice fields will be reduced: Methane from rice fields is produced from the anaerobic decomposition of organic material. The gas is transported through aerenchyma cells to the atmosphere. Methane is the most important green house gas after CO_2 and is 30 times more efficient at trapping solar radiation than CO_2. Water table control with water levels below saturation will provide aerated conditions, which will prevent methane generation and subsequently play a major role in reducing global warming.

4. Improved health of rice farmers: In some tropical countries, standing water provides breeding grounds for mosquitoes. As no ponding of water is necessary under water table control such man made breeding grounds will be eliminated.

5. Allowing for production on non-paddy soils: The traditional system requires heavy soils for rice production. These soils are able to hold water leading to reduction of losses of water and nutrients. A water table control system will not require such heavy soils allowing more soils to be brought under rice production.

6. Allowing rice to be produced as any other cereal crop: Elimination of puddling and flooding will allow the cultivation of rice just as any other cereal crop using conventional dryland cultivation and planting technologies.

1.6 AIM OF THE STUDY

This thesis sets out to test a new system of water application for rice production with the aim of reducing water use and subsequently energy utilization for rice farmers in the valley bottoms in Ghana.

1.7 RESEARCH OBJECTIVES

1. To determine if water table control will lead to water saving for rice production.

2. To determine the feasibility of using water table control for rice production in Ghana.

3. To determine the effect of the interaction of moisture content and nutrients on rice growth and development under a water table control system.

4. To characterise and determine the effect of the soil rhizosphere environment on rice growth under a water table control system for rice growth.

5. To explore the factors likely to lead to differences in growth of rice under a water table control system.

6. To determine the effect of water table control on the uptake of nutrients for rice under water table control.

1.8 EXPERIMENTS CONDUCTED

A total of five main experiments were conducted each was over a period of six weeks. They were in the following order:

1. Rice variety IR36 was grown under three water treatments, namely: water table depth at 30 cm below the soil surface, water table at depth 15 cm below the surface and a saturated system with the water table at the surface. This was started on 14th October 2002.

2. Rice variety Azucena was grown under similar conditions as stated in 1. above. This was also started on 18th November 2002.

3. Rice variety Azucena was grown under three water treatments, namely: water table at a depth 30 cm below the surface, water table at a depth 15 cm below the surface, and flooded conditions with the water table 2 cm above the surface. This was started on 18th of July 2003.

4. Rice varieties Azucena and IR36 were grown together under similar conditions as stated in 3. above. This was also started on 10th October 2003.

5. The last experiment was conducted after a number of trial experiments. It was conducted under similar water treatments as was used in 3. above. Rice variety Azucena was used and the growth medium used was a mixture of sand and vermiculite. This experiment was started on 24th August 2004.

1.9 THESIS LAYOUT

Chapter one is a general introduction to the work at hand and chapter two reviews literature on water use for rice and previous attempts at reducing water for rice production, it also deals with the expected impact of water table control on the rhizosphere environment. Chapter three compares water use under water table control and basin irrigation and in addition deals with the simulation of water table depth for an inland valley system in Kumasi, Ghana. Chapter four compares growth of rice under four water treatments in a pure sand medium: Flooding at a depth of 2 cm, saturated sand, water table depth of 15 cm and water table depth of 30 cm. Chapter five considers the modification of the soil rhizosphere environment under the water treatments in order to explain differences in growth. Chapter six considers growth of rice where the source of nitrogen is ammonium rather than nitrate, previously used, as well as a growth medium that is slightly different form the previous one. Chapter seven considers a simulation model which attempts to predict the minimum root length densities that will limit growth and attempts to explain growth differences for the imposed experimental treatments based on its output. Chapter eight brings together all the work done through discussions and gives conclusions as well as recommendations.

CHAPTER 2: A REVIEW OF LOWLAND RICE PRODUCTION OPTIONS

2.1 INTRODUCTION

Over the years, lowland rice has been irrigated using the basin method, where bunds are constructed to provide a depth of water for the rice plants to stand in. Reasons for this practice include rice's poor water stress tolerance and therefore efficient growth under these conditions, and its ability to flourish in submerged soil where many competitive grasses and broadleaf weeds cannot survive and as insurance against water shortages (Tracy *et al.,* 1994).

Basin irrigation however has a number of drawbacks; flooding requires intensive equipment, labour and energy inputs, and is costly and time consuming. Bund construction and maintenance and harvest problems associated with bunds, as well as difficulties with rotation from basin to non-basin crops require increased labour, high-energy inputs and high costs. Concerns over water use are also a serious threat to the continued use of this form of irrigation for rice production as excessive water is used.

One method, which could be a viable alternative, is water table control. Using water table control for rice production would require a drastic change or perhaps a total change in the system of rice production. An understanding of the processes of rice production especially with regards to water use is therefore necessary in order to ascertain if this method provides advantages over the traditional system.

The traditional rice cultivation system involves land preparation, which is composed of ploughing and puddling. Seeds, sown in a nursery, are expected to be ready for transplanting at the end of the land preparation period. Transplanting means pulling up the seedlings from the nursery and planting them in neat rows in the rice-fields. The rice-fields are flooded at this time. While the young plants are growing weeding is done and fertilizer is added. The water managements systems vary greatly but about two weeks to harvest, the fields are drained to allow the crop to ripe.

This chapter considers important factors in rice production with regards to water usage and explores how water table control might provide a better option than other methods in supply of water for rice.

Water requirement for rice cultivation for the purposes of the study is put into four main categories:

1. That which is required to nurse the seedlings;
2. That required for land preparation;
3. The water required for seed establishment; and
4. That required through out the crop-growing period.

This chapter considers these categories in detail.

2.2 GENERAL LOWLAND RICE WATER REQUIREMENT

The rice plant is said to require more water than any other crop; it uses two times more water than any other cereal crop (CGIAR, 1999). This perception has however been contested and as water resources are dwindling it becomes necessary to establish the actual water requirement of rice in order not to waste this scarce resource.

Crop coefficient (Kc) values (these are crop specific values which relate the evapo-transpiration of those crops to that of a reference crop) given by FAO (1992) indicate that evapo-transpiration values for rice are higher than for any other crop. The Kc values for rice are: Initial stage, 1.1- 1.15; developmental stage 1.1-1.5; mid-season, 1.1-1.3; late season, 0.95-1.05 and at harvest, 1.05-1.2. These are shown graphically in Fig. 2.1.
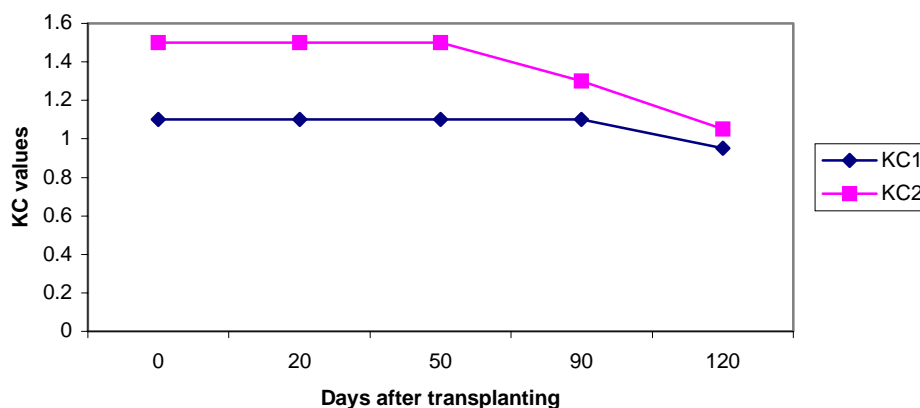
Figure 2.1 Kc values for rice over growth period; KC1 represents Kc values under high humidity > 70% and low wind < 5 m/sec; KC2 represents Kc values under low humidity <20 % and strong wind > 5 m/sec (FAO, 1992).

It has been proposed that the flood culture for rice was adopted only because it was the cheapest method of dealing with weeds on rice fields, and the flooding technique is actually a management tool and not a specific requirement of the rice plant (Uphoff, 1999; Salvatore, undated). It is a fact that the flood culture is used to control weed but in the case that it is not necessarily required, there is then potential for great savings in water use for rice production.

Uphoff (2001) indicates that several gross physiological results of growing rice under hypoxic conditions show that flooding is not ideal for rice growth and performance. Some of these are; by the 29th day after transplanting, 75 % of the rice plant roots growing in saturated soil are concentrated in the upper 6 cm of soil as they remain near the surface to obtain whatever dissolved O_2 they can get from irrigation water (Kirk and Solivas, 1997). Such root systems access nutrients from a limited volume of soil, having to rely mostly on nutrients provided through fertilizer in inorganic form. Conversely, when rice is grown under non-flooded or lightly irrigated conditions, roots extend downward 30 to 50 cm or more. There is a possibility though that root growth under flooded conditions may be limited not

only because of excess moisture but due to that fact that nutrients are more readily available within the depth at which the roots are concentrated thus limiting the extent to which they explore lower depths however this needs to be investigated.

According to Kar *et al.,* (1974), about 75% of the roots of rice plants that are growing in continuously saturated soil are degenerated by the time of panicle initiation when grain production begins, whereas there is little or no degeneration of roots growing in soil that is well-drained. These changes in rice plants' root systems are well known, they are regarded as "senescence" and have not been regarded as constraints on production because rice plants have been assumed to be well adapted for growth in flooded fields (Kirk and Bouldin, 1991). This may however not be the case.

There is therefore the possibility that flooding is not the most ideal condition for growth of rice, if this is so then other methods may be applied for rice production provided they are able to meet the other requirements of the rice crop.

2.3 LOWLAND RICE PRODUCTION

Water use for lowland rice production in this section is grouped into that used to nurse the seed, and that used on the field prior to and after transplanting of the seeds.

2.3.1 Water use for nursing rice seed
Preparation of the nursery starts one month before sowing the nursery (FAO, 1989). The seedlings can be raised using any of three methods: Wet bed, dapog or dry bed (Krishiworld, undated). The choice of any of these depends on availability of water, labour, land and agricultural implements. The methods are explained below.

2.3.1.1 Wet bed method
The wet bed method is mainly used in areas where there is adequate water. Pre-germinated seedlings (seeds soaked for 24 hours and incubated in warm place for

48 hours) are broadcast on thoroughly puddled, levelled and well-drained seedbeds. The seedbeds should be completely drained before seeding, but thereafter should be maintained in moist conditions for about 5 days. The seed beds are flooded after seedling establishment, with the level of floodwater determined related to the height of the plants (normally 2-3 cm). Transplanting is done between 15 and 30 days after establishment.

2.3.1.2 Dry bed method
This method is used in areas where water supply may not be adequate; the nurseries are prepared in dry soil conditions, and dry, or pre-germinated seedlings are sown on moist seedbeds either in rows (10 cm) apart or randomly. The seedbed should be maintained moist throughout the period; generally the nursery-beds are irrigated by sprinkling water on them periodically once in 2-3 days, depending upon the soil and environmental conditions. Light soils may require frequent irrigation. A similar duration for nursing as for the wet bed method is recommended here too. Germination rate under this system is lower than under the wet bed method.

2.3.1.3 Dapog method
The dapog method is used where early transplanting is needed and in addition to that water supply is assured. It involves growing seedlings on a concrete floor or on a raised bed of soil covered with polythene sheets. The preparation of land, if needed, is done essentially in the same way as in the case of the wet-bed method. Raised seedbeds are prepared after final levelling and are packed, levelled and covered with polythene sheets. Banana leaves, with their midribs removed, can also be used instead of polythene sheets. Pre-germinated seeds should be sown on top of these sheets. The germinating seeds are sprinkled with water and pressed down gently with hand or with a wooden flat board twice a day for the first 3-6 days. This helps the roots of the seedling to remain in contact with water retained on the surface and prevents drying. After six days, the seedbed is irrigated up to a depth of 1-2 cm of water. The levelling of the fields is also very essential to avoid the stagnation of water and the mortality of the seedlings.

Under water table control, these methods of raising seedlings can be eliminated in that direct seeding (this is explained later) could be adopted. Water usage during the nursery stage is then virtually eliminated and that leads to water saving in adoption of water table control over the traditional rice growing system.

2.3.2 Flow of water in lowland rice fields

Traditionally water use on rice fields starts from the period of land preparation. Land preparation for lowland rice consists of soaking, ploughing and puddling. Soaking is a one-time operation required to bring the topsoil to saturation and create a flooded layer with a depth of surface ponding, which varies from field to field. The additional hydraulic head created by ponding increases the loss of water from the traditional systems and puddling is required to decrease this loss of water and nutrients through excessive percolation, and also to decrease weeds thus providing conditions that enhance nutrient availability (Kirchoff *et al.,* 2000). Puddling is not always required to achieve flooded conditions, however, and some lowland soils are left unpuddled. If a soil has high clay content or has an impermeable layer in its profile, the internal drainage rate may be so low that water accumulates on the surface (Bouman *et al.,* 2001). After land preparation, there is normally an idle period until transplanting or direct seeding takes place. The growth period runs from crop establishment to harvest. During the idle and crop growth periods, the fields are typically flooded with 5-10 cm of water (Bouman, 2001).

The main components of water flow on rice fields are percolation, seepage, evaporation, transpiration and run-off. Percolation occurs when water flows vertically downward beyond the root zone. On puddled fields, this takes place mainly on small-unpuddled areas. Seepage occurs when water flows under the bunds constructed to retain water. The areas under the bunds are not normally puddled and thus easily allow water to flow out of the basin.

Most of the water loss on rice fields is through seepage and percolation and this results in high water use for rice production. Evaporation occurs during the land

preparation period and the idle period as well as the growing period. Transpiration only occurs during the growing stage, and is the only process that uses water directly for growth and yield.

Bouman (2001) gives typical values for water use on rice fields for crop growth duration of 100 days in the tropics as:

1. Land preparation (soaking and puddling): 175-750 mm
2. Evapo-transpiration (Dry season): 400-500 mm

Seepage and percolation amounts depend on the soil type:
3. Heavy clays: 100-500 mm
4. Loamy and sandy soils: 2,500-3,000 mm

Water loss thus varies from 14 to 28 % for the heavy clays and from 70 to 78 % for the loamy and sandy soils. These losses are large and every attempt needs to be made to reduce them if rice production is to remain sustainable.

Walker and Rushton (1984) gave losses of water from various sites of puddled rice fields in Indonesia between 1973 and 1981 as 15-20 mm/day whilst evapo-transpiration was only 4-5 mm/day. This represents a range of 76 to 80 % loss, which is exceptionally high. They indicated that most of the water is lost through seepage through and under the bund. Moreover relatively small areas of undetected leaky soil, which may exist within a field, can double the overall leakage from a field.

According to Guerra *et al.,* (1998) rice grown under traditional practices in medium to heavy textured soils in the Asian subtropics require 700 to 1,500 mm of water for 100 day rice: The main components of water use are:

1. Land preparation requirement: 150-250 mm
2. Nursery requirement: 50 mm
3. Seepage and evapo-transpiration: 500 – 1,200 mm.

They did not differentiate between seepage and evapo-transpiration but if the values quoted from Bouman (2001) were adopted, that would still imply a high water loss.

It is apparent that most of the water that is applied onto rice fields is lost through seepage and percolation. These two processes do not contribute to the growth and yield of rice and any attempt to control water use on rice fields must address the losses due to the two processes.

In water table control, water is supplied from beneath the soil eliminating or drastically reducing seepage and percolation losses. The water table under water table control is raised to a level such as will provide enough moisture for plant growth through capillary rise. The soil volume beneath the water table depth is saturated and very little moisture from the surface moves into that area. An impermeable layer lies at a depth beneath the soil profile preventing or drastically reducing deep percolation. The water supply system maintains a high head of water in the supply ditches which also prevent excess lateral seepage. Water table control systems would thus be the most ideal systems to prevent losses through these processes and at the same time provide the right quantities of water required for rice growth. Fig. 2.1 shows the flow processes of water in a rice field.
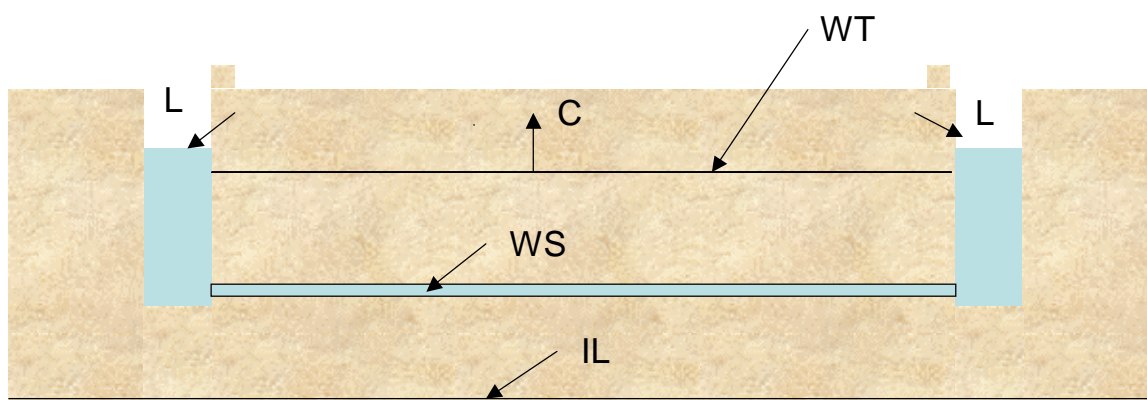
Figure 2.2 Flow of water rice field in water table control conditions. L= seepage, C = capillary rise from groundwater, WT = Water table, WS = Water Supply, IL = impermeable layer.

2.4 WATER EFFICIENT RICE PRODUCTION SYSTEMS

A number of systems have been proposed to enhance efficient water use on rice fields and these are discussed in this section.

Guerra *et al.,* (1998) proposed ways for increasing on farm water productivity for rice production and these may be presented as:

1. Increasing yield per unit evapo-transpiration during crop growth,

2. Decreasing water use in land preparation,

3. Decreasing water use for seed establishment,

4. Decreasing seepage and percolation (S & P) during the crop growing period; and

5. Decreasing surface run-off.

Increasing yield per unit evapo-transpiration he proposes can be achieved by using improved varieties, better soil nutrient management and proper weed control. Decreasing evaporation will entail shortening the period for land preparation and the time needed for distributing water. The amount of water lost through bypass

flow can also be decreased by measures that restrict the formation of soil cracks or impede the flow of water through them. To decrease the water required for seed establishment, a shift from transplanting to direct seeded rice is necessary. Direct seeding could be either wet seeding or dry seeding (this is discussed in detail below).

Decreasing S & P during the crop growing season will also require reducing the infiltration rate of the soil through puddling, or using water saving irrigation techniques which could be either saturated soil culture or alternate wetting and drying irrigation.

Bouman (2001) proposes that large reductions in water input can potentially be realised by reducing the unproductive seepage and percolation flows during crop growth and idle periods, where idle periods are periods before crop establishment. There are two ways, either of which may be used to achieve this goal. They are:

1. Increasing the resistance to water flow in the soil, and
2. Decreasing the hydrostatic pressure head of the ponded water.

Reducing the resistance to water flow can be achieved either through puddling, shallow tillage of the soil to remove cracks or using physical barriers underneath the soil. Some of these soil improvements are however expensive and beyond the financial means of many farmers (Bouman, 2001). Moreover, puddling, though it may be favourable for the rice crop is less favourable for any dryland crop grown in the dry season after rice, leading to low or erratic yields (Ringrose-Voase *et al.,* 2000). Puddling is not only time consuming and capital intensive, but also alters the soil physical condition so that it is not beneficial for the succeeding crop (Bajpai and Tripathi, 2000).

CGIAR (1999) reports on water saving techniques that could save up to 25 percent of the water now used to grow rice. This has mainly to do with the development of an irrigation technique, which involves the application of irrigation water

intermittently to rice fields instead of the traditional continuous submergence. Puddling would still be required in this case to reduce water loss and that implies extra energy use. Land levelling, another technique, offers the potential for significant increases in the efficiency of water use, both directly and through the opportunities it provides for improved crop management. Land levelling is desirable under all other methods and would enhance water table control. Other techniques include management of cracks to avoid high water loss as already indicated above, as well as adoption of weed control methods other than use of floodwater to suppress weed growth.

Water table control provides an alternative to the methods proposed by the researchers above. In the case of the points raised by Guerra *et al.* (1998) water table control is suitable for dry seeding and will lead to drastic reduction of seepage and percolation. Land preparation can be done as for other dry land crops and run-off is non-existent. Bouman's proposals, which are listed above, Bouman (2001) will imply extra cost for rice production, which will not be incurred under water table control.

Bouman (2001) suggests that ultimately, rice will be grown under completely aerated conditions where seepage and percolation will be eliminated which is what water table control is intended to provide.

2.5 STRATEGIES TO DECREASE WATER USE DURING SEED ESTABLISHMENT

There are two main methods of seed establishment: transplanting and direct seeding.

Direct-seeding is popular among rice farmers because in addition to requiring less water, it also requires less labour and hard work, makes planting faster and easier, and advances harvesting by more than one week, and in addition allows dry land

tillage (Matchoc, 2002). There are two ways of direct-seeding rice; wet seeding and dry seeding. In wet-seeded rice, pre-germinated seeds are broadcast on saturated and usually puddled soil.

In contrast, dry-seeded rice (DSR) is grown by sowing non-germinated seeds on dry or moist but unpuddled soil. Under this technique, the land is ploughed when dry to incorporate broadcast non pre-germinated seeds into the ground without any flooding. Dry seeding not only offers a significant opportunity for conserving irrigation water and using more rainfall it also allows early harvesting in rain fed areas and incurs less energy use. This, in turn, permits planting a second crop and use of rainwater that arrives later in the season. This practice is now assuming an important role (IRRI, 2000).

Wet seeding of rice uses about 20-25 percent less water than the traditional transplanting method and drastically decreases labour for establishing the crop from 30-person days to 1-2 person days per ha (Guerra *et al.,* 1998). Dry seeded rice requires less water for land soaking than wet seeded rice, and wet seeded rice requires less than transplanted rice (Guerra *et al.,* 1998).

The reduction in rice yield because of weeds is however more severe in direct-seeded than transplanted rice because soil conditions during crop establishment and early growth are more favourable in direct-seeded rice for the germination and growth of grassy weeds. In addition to weed competition, direct seeding is also constrained by poor germination. For a full benefit of the technology to be achieved however, there should be the development of new methods in the management of nutrients and weeds (Guerra *et al.,* 1998).

It is envisaged that the adoption of water table control would allow for the production of rice as for any other dry land crop thus allowing for the adoption of weed control practices used for the other crops. Yield reduction due to weed competition would thus be reduced or eliminated. In seeding establishment therefore water table control allows for reduction in water usage.

2.6 STRATEGIES TO DECREASE WATER USE DURING THE GROWING SEASON

A number of strategies have been used to decrease water use during the growing season and prominent among them are:

1. The use of raised beds watered by furrows,
2. Saturated soil culture where the soil is saturated but not allowed any depth or in some cases a small depth of water, and
3. Alternating wetting and drying where water is applied intermittently upon the land.

Borrell *et al.,* (1997) grew rice on raised beds of height 0.2 m and width 1.2 m with the water maintained in furrows (0.3 m wide) about 0.1 m below the bed surface. They drew the conclusion that it is not necessary to flood rice to obtain high yields and quality and that a saturated soil culture provides a viable alternative to flooded rice production for growers in semi-arid tropical environments. They concluded that substantial reductions in variable costs of production are attainable by reducing water use without reducing yield and quality.

Bouman and Tuong (2001) studied reports of experiments undertaken in the Philippines, north and central India and Japan, in which saturated soil culture (SSC) and alternating wetting and drying (AWD) were compared to the standard practice of continuous 5-10 cm ponded water. In SSC the soil was given about 1 cm floodwater depth a day or so after the disappearance of standing water. In AWD, irrigation water was applied to obtain 2-5 cm floodwater after a certain number of days after the disappearance of ponded water.

They found out that the water saving treatments were effective in reducing water input while maintaining high yield levels: Of 33 treatments, the mean water

savings were 23% (±14% S.D.) whereas yield reduction was only 6% (±6% S.D). They concluded that irrigated rice yields decline as soon as the field water content falls below saturation and yield is already decreased by 0-12% when the soil is kept at saturation. However the most promising option to save water and increase water productivity without decreasing land productivity too much they concluded is by reducing the ponded water depth above the surface from 5-10 cm to just ponded conditions where the soil is just saturated.

Other studies however are not in agreement with the findings above in that decreasing water use leads to yield increases. According to Wu (undated), alternate wetting and drying suits the physiological water demand of wetland rice. The essence of it is to rationally control the water and oxygen supply to the roots, and adjust the ecological environment of the wetland rice. He indicated that the technique led to water saving of 21.1 % and yield increase of 14 %.

Zhi (1996) also indicates that three main kinds of water efficient irrigation (WEI) systems have been found to be contributing to the sustainable increased water productivity of rice in China. They are:

1. A combination of shallow water depth with wetting and drying, in which, an upper and a lower limit of field moisture, depending on the stage of growth of the crop, is established. When the lower limit is reached, water is applied up to the maximum limit for that growth stage.

2. Alternate wetting and drying in which the field is intermittently submerged and drained but there is no ponded water depth from the beginning of tillering till the milk ripening stage. Water is applied over a number of days, and the fields are left to dry over some other specified number of days depending on the weather and climatic conditions.

3. Semi-dry cultivation (SDC), in which case the water is maintained only during specific parts of the growing season, it is described as an innovation over the other methods.

Irrigation water for the three methods was decreased by 3-18 %, 7-25 % and 20-50 % respectively. He reported marginal increases in yields, less than 9 %, but stated that water productivity increased greatly.

The main causes of water saving were attributed to the decrease of percolation and a greater utilization of rainfall. It was also observed that adopting WEI produced a positive environmental impact, and the main causes of increased yield were that the ecological environment under WEI is more favourable for the growth and development of rice than that under traditional irrigation, especially the improved aeration, which affects the development and growth of rice roots.

Uphoff (1999) proposes some practices, which he claims, lead to yield increases of 100 % or more, and at the same time utilizes only half as much water compared to the conventional methods, to grow a crop of rice. The practices, called the System of Rice Intensification (SRI) have as the focus, the provision of conditions for greater rice root growth. SRI also involves keeping the fields moist but never flooded during the vegetative growth stage. The plant is expected to grow better if the field is from time to time allowed to dry out for several days to contribute to aeration of the root zone.

There is a great potential for the reduction of water use on rice fields if water is managed properly. According to Tuong (Personal communication, 2002) weed competition and nutrient availability provides more of a constraint to rice production than water availability. Any strategy that decreases water use but in the same vein controls weeds and ensures availability of nutrient will be effective on adoption on rice fields.

Though seepage and percolation may be reduced under the systems described above, they would be more so under a water table control system as has already been indicated. Water table control could once again be a viable alternative to the strategies presented above.

2.7 METHOD OF WATER DELIVERY

In an attempt to find more efficient methods of water delivery to rice fields a number of systems have been tested. The section below considers these methods.

2.7.1 Sprinkler Irrigation

Sprinkler irrigation has been used as an alternative irrigation method and has led to substantially lower water consumption. However, reports of yields from several areas have shown highly variable results (McCauley, 1990). There was a small yield reduction with sprinkler irrigation and a comparison of rice yields under flooded and non-flooded conditions using sprinkler irrigation indicate the mean yield of sprinkler-irrigated rice was 20 percent less than the yield of flooded rice on similar soils (McCauley 1990).

Sprinkler irrigation systems have high initial equipment costs and ongoing energy requirements (Tracy *et al.,* 1994) this places it out of the reach of most farmers (particularly in Ghana) and can therefore not be seen as a viable alternative for basin irrigation. The savings in water would have to be put into energy and equipment cost making it unprofitable in most cases.

2.7.2 Furrow irrigation

Wells *et al.,* (1991) indicate that preliminary rice production studies using furrow irrigation, rather than flooding, have shown promising results. Furrow irrigation may offer a method of producing additional rice per unit of irrigation water and applying fluid fertilizers.

Tracy *et al.,* (1994) indicate that the advantages of furrow irrigation over intermittent-flooded or sprinkle-irrigated rice include less labour, energy requirements and initial cost, and easier rotation to crops such as corn, soybeans or cotton. Advantages of furrow-irrigated rice compared to flooded rice include decreased bund construction, use of ground equipment in place of airplanes for agri-chemical applications, quick field drying for timely harvest, less land

preparation when rotating to other crops, and potential use on soils that will not maintain a permanent flood.

Disadvantages of furrow rice culture compared to intermittent flooding or sprinkle irrigation are not apparent. Drawbacks of furrow-irrigated compared to flooded rice systems are yield reductions of 5 to 20 percent, maturity delays, costlier weed control, potential water stress and lack of pertinent information about the system. They indicate that on fields well suited for flooded rice management, furrow-irrigated rice will rarely, if ever, out-produce flooded rice.

Losses under furrow irrigation due to evaporation as well as seepage and percolation will however be higher than for a well-managed water table control system and once again this gives reason for the investigation of water table control for rice production.

2.8 WATER TABLE MANAGEMENT

Water table management systems have as yet not been applied on rice fields. These however have the potential to mitigate the shortcomings of all the other methods. They are able to decrease seepage and percolation and thus save water, decrease nutrient loss thus making nutrients more available, allow for aeration of soil rhizosphere thus providing the environmental conditions required for growth of the crop.

Puddling would not be necessary under a water table management scheme; direct seeding could also be enhanced. Other economic benefits from water table management include savings in production costs: Water table control decreases energy and maintenance costs since it is a very efficient irrigation method compared to other methods of irrigation. Water table management is very affordable compared to the other irrigation systems (LICO, 1998).

2.8.1 Water table and water availability

The soil below the water table is saturated and the layer just above the water table, called the capillary fringe zone is also near saturation, due to a considerable amount of water moving from the saturated zone into this zone. The thickness of this zone varies depending on the soil texture, but generally, it is smallest for coarse textured soils and higher for fine textured soils. Water moves up from the water table by capillary rise and may be lost through evapo-transpiration.

Water flow in soils is governed by Darcy's law (Darcy, 1856), which is represented as:

$$Q = KA\frac{(\phi_1 - \phi_2)}{l_{12}}$$
(2.1)

where Q is the soil water flux density

$\quad$ K is the hydraulic conductivity of the soil

$\quad$ A is the cross-sectional area perpendicular to flow

$\quad$ ϕ is the hydraulic potential

$\quad$ l is the distance between points under consideration

Hydraulic potential is composed of matric and gravitational potentials. Water is lost from the water table directly to the atmosphere by the process referred to as `water table evaporation' or `capillary upflow' (Prathapar and Qureshi, 1999). The rate of water table evaporation on bare soils depends on the hydraulic gradient between soil surface and the water table as well as the unsaturated hydraulic conductivity of the soil profile.

The matric potential at the water table will be zero due to the fact that the soil is saturated at that point, but at the surface, the soil water content of the surface soil will decrease to its residual water content due to evaporation and therefore, the lowest matric potential of the surface soil will correspond to the residual soil water content.

 The gravitational potential between the soil surface and the water table will be equal to the depth to the water table. Consequently, the maximum hydraulic potential, between the water table and the soil surface will be equal to the matric potential at residual water content of the soil surface minus the depth to the water table.

The soil water content will decrease from saturated volumetric water content at the water table, to a drier value at the soil surface. The unsaturated hydraulic conductivity will decrease accordingly, and will reflect the changes in soil structure as well as the water content. The soil layer with the lowest unsaturated hydraulic conductivity will limit the flow of water from the water table to the soil surface.

The shallower a water table therefore, the higher the hydraulic gradient and the higher the unsaturated hydraulic conductivity and therefore loss of water from that water table will be greater. A shallower water table will therefore lose more water under similar climatic conditions than a deeper one.

Owusu-Sekyere (1998) used Darcy Buckhingham equation written in finite difference form to determine the relation between the depth of the water table and the upward flux. His results are presented in the figure below. This buttresses the fact that more water is lost from a shallower water table than a deeper one.
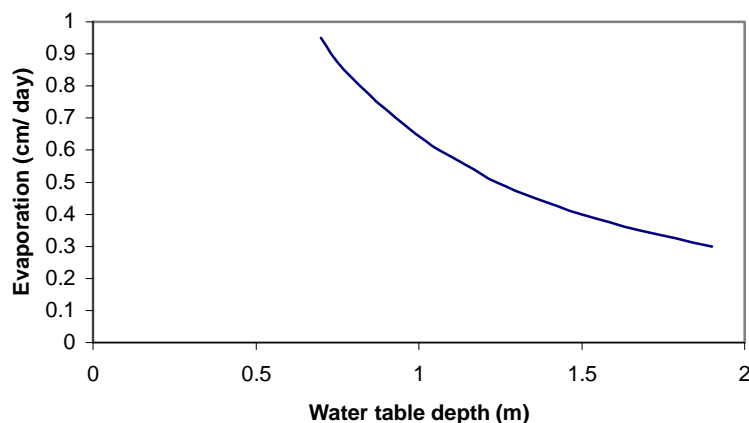
Figure 2.3 Relationship between water table depth and evaporation flux from the water table.

Under constant evaporative demand, the bare soil evaporation process can be divided into three stages: The constant rate stage, controlled by potential evaporation demand; the falling rate stage, controlled by the transmission of water within the soil profile; and the vapour diffusion stage, controlled by the vapour diffusivity of the dried soil surface (Hillel, 1980).

Constant stage evaporation occurs when the soil surface is close to saturation. This is restricted to short periods following heavy rainfalls or irrigation. Falling rate stage as indicated, is controlled by the transmission of water within the soil profile and thus depends on the hydraulic characteristics of the subsoil. In the case when the actual rate of evaporation is restricted by mulching, the rate of water movement within the soil profile will be restricted to the rate of mulch-limited evaporation.

The rate of evaporation during the vapour diffusion stage is controlled by the physical properties of the unsaturated surface layers and the direction of heat flow within the soil profile. However, the relative increase in capillary flow due to evaporation during the vapour diffusion stage will be negligible.

The discussion has mainly been on evaporation on bare soil evaporation, but this can be applied to cropped soils by including a root sink above the water table. Loss of water due to evaporation will thus differ under different water table depths and may have a significant influence on the results of the study.

2.9 WATER TABLE MANAGEMENT AND RICE PRODUCTION

Five main factors that will vary as a result of the variation of the water table depth are:

1. Strength of the soil,
2. Nutrient availability,
3. Soil aeration,
4. Soil temperature, and
5. Water availability.

2.9.1 Soil strength

The relations between water content, soil strength and rooting depth and development are very important for rice, as rice roots usually cannot deeply penetrate a dry soil (Greenland, 1985). Root growth is also restricted by high soil strength, particularly when the soil dries (Sharma and De Datta, 1985).

Soil strength is controlled jointly by a soil's bulk density and moisture content. Root penetration is greatly retarded when bulk density exceeds 1.4 grams per cubic centimetre during dry conditions. The same soil when moist, however, may not impede rooting because soil strength is then decreased (Daniels, 1997).

The strength of the soil affects the seedling emergence as well as determines the tillage practice required. Water content in the plough layer determines cultural practices: soil that is too dry delays tillage or exceeds the work capacity of farm power units. Soil that is too wet decreases tillage quality and affects timeliness of cultural operations (Bolton *et al.,* 1985).

The depth of the water table influences the moisture content at any point above it by capillary action. The higher the water table, the wetter the soil and the lower the water table the drier the soil and the stronger it is. Using different depths of water will lead to different soil strengths, which will influence growth of the crops to differing extents. Water table control will thus indirectly affects growth of the plants through the strength of the soil and relationships between soil strength and crop growth have to be ascertained. The relationship between the water table depth and the strength of the soil was however not investigated in this study.

2.9.2 Nutrient availability

Nitrogen availability is the main factor limiting the realization of yield potentials in rice (Cassman *et al.,* 1997). Constituents of yield components are closely associated with the nitrogen supply at each growth period, and active absorption and metabolism of nitrogen results in a large increase in dry weight, tillering, height and leaf area.

2.9.3 Nitrogen availability and moisture content

Generally nutrient uptake is decreased under waterlogged conditions due to a decrease in the permeability of roots to water. Low soil oxygen, which is mainly the result of excess water, also generally results in decreased respiration and nutrient uptake (Wesseling, 1974).

Rice is able to exploit the chemical benefits of submerged soil because its roots receive oxygen through aerenchyma in the shoot system and lysigenous channels in the roots (Sharma and De Datta, 1985). According to Kirk and Solivas (1997), rice plants are able to absorb fertilizer-N from floodwater at very high rates but the characteristics of the floodwater-soil-root system that allow rapid uptake of N do not necessarily allow efficient uptake of N released from the soil. It is however not clear if uptake of nutrients are reduced under waterlogged condition. This will be investigated in this work by comparing nutrient uptake for three water treatments.

Soil moisture directly affects microbial activity and, in turn, affects soil nitrogen mineralization. Organic matter decays most quickly at water potentials in the

range of -10 to -50 kPa. Decay slows gradually as moisture content deviates in either direction from this optimal range; for example, as soil moisture approaches complete saturation, decay slows as a result of increasingly anaerobic conditions. Nitrogen mineralization declines as water content decreases (Cassman and Munns, 1980). Under the water treatments to be used in the study therefore, we expect variations in growth as a result of differences in moisture contents. The study will enlighten us on the interaction of moisture content and nitrogen availability on growth of rice.

The availability of nitrogen in flooded soils is higher than non-flooded soils (Sharma and De Datta, 1985). Ammonium is the predominant soil mineral N form in continuously flooded or saturated rice systems, while NO_3^- is the major form in non-flooded systems and when lowland soils are in the aerobic phase, they have the immense capacity to accumulate soil NO_3^-. As both flooded and non-flooded systems are used, the study will be conducted with NO_3^- based as well as a NH_4^+ based nutrients so as to determine which of them is most appropriate for adoption under water table control systems for rice production.

2.9.4 Soil aeration and root growth

In a well-drained soil there is enough oxygen available from the atmosphere to supply the needs of microorganisms and higher plants. This condition is changed when the soil is flooded, air movement is restricted and the soil no longer has an adequate supply of oxygen. Oxygen diffusion is 10^4 times slower in a water saturated soil pore than in an aerated soil pore.

Rice plants are however able to supply roots with O_2 through aerenchyma cells. Part of the O_2 supplied is lost through the lateral roots as they tend to be O_2 leaky and their demand for O_2 is therefore high. The supply of O_2 may limit the density of laterals borne by a given primary root and consequently limit root length per unit root mass (Ladha *et al.,* 1998). Root growth will thus be modified by aeration status of the soil, which we have already noted is determined to a large extent by the moisture content. Limiting root growth may also imply limiting uptake of

nutrients thus indicating waterlogged conditions may not be the most ideal for rice production. Limiting root growth also means inability to explore greater volumes of soil for nutrients; another reason put forward to suggest waterlogged conditions may not be optimal for rice production.

The depth of the water table has a very large effect on soil oxygen levels. Soils with shallow water table are expected to have a lower redox potential indicating they are in a reducing condition whereas soil with a deeper water table are expected to have a high redox potential indicating the soil has good aeration.

Modification of redox potentials under water table control systems will therefore be expected to be important in determining rooting characteristics and consequently the growth of the rice plants. Reduced levels of oxygen, which means high water content (lower redox potentials) will lead to a reduction in root length densities, which may also lead to lower nutrient uptakes. Thus a lower water table depth has the potential to provide higher redox potentials in the rhizosphere and thereby improve nutrient uptake, which invariably will lead to better growth as long as moisture conditions are not limiting.

Redox potentials are however not only modified by oxygen, but by other compounds present in solution. In the absence of oxygen, when the soil is flooded compounds such as nitrates act as electron acceptors maintaining the redox potential at a more nearly constant value (a little below 400 mV) as reduction of the nitrates takes place (Mc. Bride, 1994).

There may therefore be a certain level of aeration that would lead to optimum root length densities necessary for optimum nutrient uptake. The moisture content required would be achieved by a having a certain depth of the water table. The relationship between moisture content, depth of the water table, nitrogen uptake, rooting depth densities as well as growth of the rice plants for the different water treatments are investigated in this study.

2.9.5 Soil temperature

Soil temperature is one of the factors that influences the growth and development of crops. A good soil temperature must be warm enough to sustain root growth but not too hot as to hinder the physiological functioning of the root.

Two factors that affect soil temperature are:

1.The amount of heat available at the soil surface, and

2. The dissipation of the available heat.

The dissipation of the heat depends to a large extent on the soil water content. If water is readily available at the soil surface, most of the absorbed heat energy will be utilised in evaporating water. The surface temperature is not decreased implying there is only a small temperature gradient to cause heat flow into the soil. A dry surface on the other hand absorbs energy and is heated up, resulting in a large temperature gradient causing a considerable flow of heat into the soil. Water content influences heat dissipation in soil through its effect on thermal conductivity, heat capacity and thermal diffusivity.

Hussain (1997) observed that soils, cultivated with potatoes with a deep water table were cooler than those soils with a shallow water table. At about 25 cm below the soil surface, the temperature difference was about 1 degree. However, uncultivated soils gave different results. The soil in this instance with the deeper water table was 0.2-0.8 degrees warmer than the soils with the shallow water table. This may arise due to the thermal properties of the wet or dry soil and the differences in surface evaporation between shallow and deep water tables. More moisture is lost from the shallower water table leading to greater evaporative cooling. There is also the possibility of better growth under a lower water table depth (better environmental conditions in the soil rhizosphere due to greater aeration) leading to greater shading of the soil surface and thus less direct incidence of solar radiation on the surface for the cultivated soils with the deeper water table depths. In the case of the uncultivated soils the main temperature-moderating factor will be the depth of the water table and consequently, the lower it is the faster soils heat up.

Robson *et al.,* (2001) observed that small changes in temperature led to a reduction in growth of aboveground biomass. A change in temperature of 1.6 ^{0}C impacted above ground biomass.

Songfa (1995) upon observing the differences between ridge-field rice and flat-field rice found that there were considerable changes to the soil environment that affected the growth of the rice plants. Soil temperature in ridge fields was normally 0.2–0.4 °C higher than in the flat fields. Results were particularly obvious in cold, muddy fields that had low soil temperatures. Growth was faster in ridge-rice cultivation. Seedlings recovered quickly after transplanting and tillers emerged 9 days earlier than in flat fields. Though temperatures could be a factor in achieving these results, some of the other factors enumerated above could also have contributed.

Soil temperature markedly influences the biochemical processes that release plant nutrients or produce substances toxic to rice; it also affects the rate of water and nutrient absorption. A soil temperature of 25 ^{0}C retards nitrogen release without appreciably slowing down the growth of rice (Grist, 1986).

An increase of soil temperature may improve the efficiency of applied nitrogen fertilizer (Waters, 1977). Temperature is also a major factor influencing soil nitrogen mineralization as it directly affects microbial decay as the main release process of N.

In general, heat flow within the soil profile is downwards during daytime but upward during the night when the top layers are cooler. A soil with a deeper water table will normally, under similar climatic conditions, be warmer than a shallow one thus indicating better conditions generally for root growth and subsequently plant growth. As water table control will modify the soil temperatures, it will in this way also have an effect upon the growth of the rice plant and the extent to

which this will go needs to be established in order to conclusively determine the suitability of water table control for rice production.

2.10 CONCLUSIONS

1. Flooding may not be the most ideal regime for growing rice and adopting some other irrigation methods may reduce water and energy loss. One of the viable options is water table control where water is provided from below the soil rather than as in all the other methods from above the soil. The factors that lead to the greatest water loss of water in rice production: seepage and percolation will be minimised or eliminated completely under water table control.

2. Seed establishment will be enhanced under water table control as direct seeding can be adopted. Rice then can be produced as any other dry land crop and methods of weed control used for crops can be adopted. This will eliminate the requirement of specialised machinery for rice and thus lead to savings in production cost.

3. Water table control for rice production may eliminate the need to puddle the soil to avoid loss of water and nutrients. This would also contribute immensely to the reduction of energy and production costs.

4. Adopting water table control may lead to a major change in the rice-growing environment, as water would be supplied not from above the surface but from below the surface of the soil. It thus becomes is necessary to determine the extent to which the environment is modified and the effect of the environmental parameters on the growth of rice.

5. Water table control depending on the depth of the water table used may lead to aerated conditions. The form of nitrogen that dominates under aerated conditions is nitrates, and that which dominates under anaerobic conditions is ammonium. In order to ascertain the effect of water table control on rice production, it becomes necessary to experiment using both forms of nitrogen.

6. Root length densities limit uptake of nitrogen; root length densities also depend on the aeration status of the soil. As different depths of the water table will be used, it is important to determine the root length densities under each one of them and to determine the extent to which they limit nutrient uptake.

In this work the hypothesis is set that water table control does not have a detrimental effect on growth of rice plants (the null hypothesis) and the experiments in the following chapters are designed to test this hypothesis.

CHAPTER 3: WATER USE FOR, AND FEASIBILITY OF WATER TABLE CONTROL IN GHANA

Abstract

An investigation was carried out to predict the depth of the water table using a simulation model for Dwinyam, an inland valley in the Ashanti region of Ghana for the minor farming season of the years 1996 and 1997. The lowest depth of the water table was determined to be at a depth of about 1 m below the surface of the soil at the end of the minor farming season in both years. Adoption of a water table control system would require a system that would ensure that the water table is raised through a maximum distance of 1 m to ensure saturation at the surface.

The typical water use for a basin irrigation system and that for a water table control system were computed and compared in order to identify if water saving was possible under water table control. Data used were mainly adopted from other areas, which have comparable conditions to Dwinyam. It was determined that if a water table, initially at a depth of 1 m below the surface of the soil is raised to the surface, water required would be less than that required to maintain a basin for rice production. Water use for the water table control system was 1635 m^3 and that for the basin system varied from 1997 m^3 – 4212 m^3 depending primarily upon the seepage and percolation values.

Water savings were also determined to be possible with an initial water table level of 2 m below the surface of the soil. This also depended on the seepage and percolation values for the basin system.

3.1 INTRODUCTION

One of the most important points to verify before water table control can be used for rice production is the possibility of saving water under water table control rather than using flooded conditions. If there is no difference in rice performance between

flooded and shallow water table control systems (as suggested in the hypothesis set in chapter 2) it would make no sense to use water table control for rice production if water saving cannot be achieved. As has been alluded to, not puddling the soil will ensure energy saving but as indicated in the previous chapter, the main problem of flooded lowland rice production today is the very large water requirement and water saving techniques must necessarily be found and adopted.

One of the most used parameters for comparison of water use and selection of the most appropriate method of irrigation under certain defined conditions is irrigation efficiency. This relates the amount of water released from the water source for irrigation to that, which is eventually available for crop use. Application efficiency, which is a component of irrigation efficiency, also permits the comparison between two irrigation systems and provides a benchmark for the selection of one system over another. The application efficiency relates the amount of water applied on to the field to that which is eventually stored in the root zone, available for crop use. The higher it is, the better the method of water application is accepted to be.

In order therefore to compare water use under a water table control or sub-irrigation system to that under basin irrigation, the starting point would be the consideration of the application efficiencies of the two methods of irrigation

According to LICO, (1998) typical maximum water application efficiencies for sub-irrigation systems vary from 90 % for clay loam and clays to 75 % for other soils. Water is lost through lateral seepage and to a lesser extent deep percolation. The amount of seepage is dependent on the hydraulic conductivity of the soil, depth to restricting layers, and the soil and water table conditions along the boundaries of the field to be sub-irrigated.

Rogers *et al.,* (1997) gives a range of application efficiencies for various irrigation systems. These are:

Basin ….60-95 %

Border…. 60-90 %

Furrow…. 50-90 %

Surge…60-90 %

Sprinkler…65-95 %

Micro-irrigation…70-95 %

The data show that the application efficiencies for sub-irrigation are likely to be higher than for any other method of irrigation and there is therefore the possibility of water saving under sub-irrigation. This is verified in this chapter where the typical water use under basin irrigation is compared with the typical water use under a water table control system for the dry season of 1996 and 1997 for a typical inland valley bottom in Ghana by simulating the water balance in the soil profile and predicting the depth of the water table.

A number of water table management models, which are able to predict the depth of the water table have been developed: These include DRAINMOD (Skaggs, 1990), which is based on a water balance in the soil profile, and uses climate data to simulate the performance of drainage and water table control systems. There is also SWATRE (Feddes *et al*., 1988), which simulates transient vertical flow in a heterogeneous soil profile using a finite difference technique. WAT (Youngs *et al*., 1989) is another model for the prediction of the water table movement in flat low-lying lands as influenced by rainfall, evaporation and ditch water level. None of these could be used in this study due to the fact that the input data required were more than that available for this study. A simple water balance approach, which is explained below, is therefore used.

3.2 DWINYAM INLAND VALLEY

For this study, a typical inland valley, Dwinyam inland valley is selected. It is in the Ashanti Region of Ghana as is shown in Fig. 1.1 below and is located, along with some other valleys close to Kumasi, the second largest city in Ghana. Dwinyam is

one of the inland valleys, which is used for rice production under the Sawah system. Structures required for successful rice production: access to market, water availability, labour and others are therefore assured.
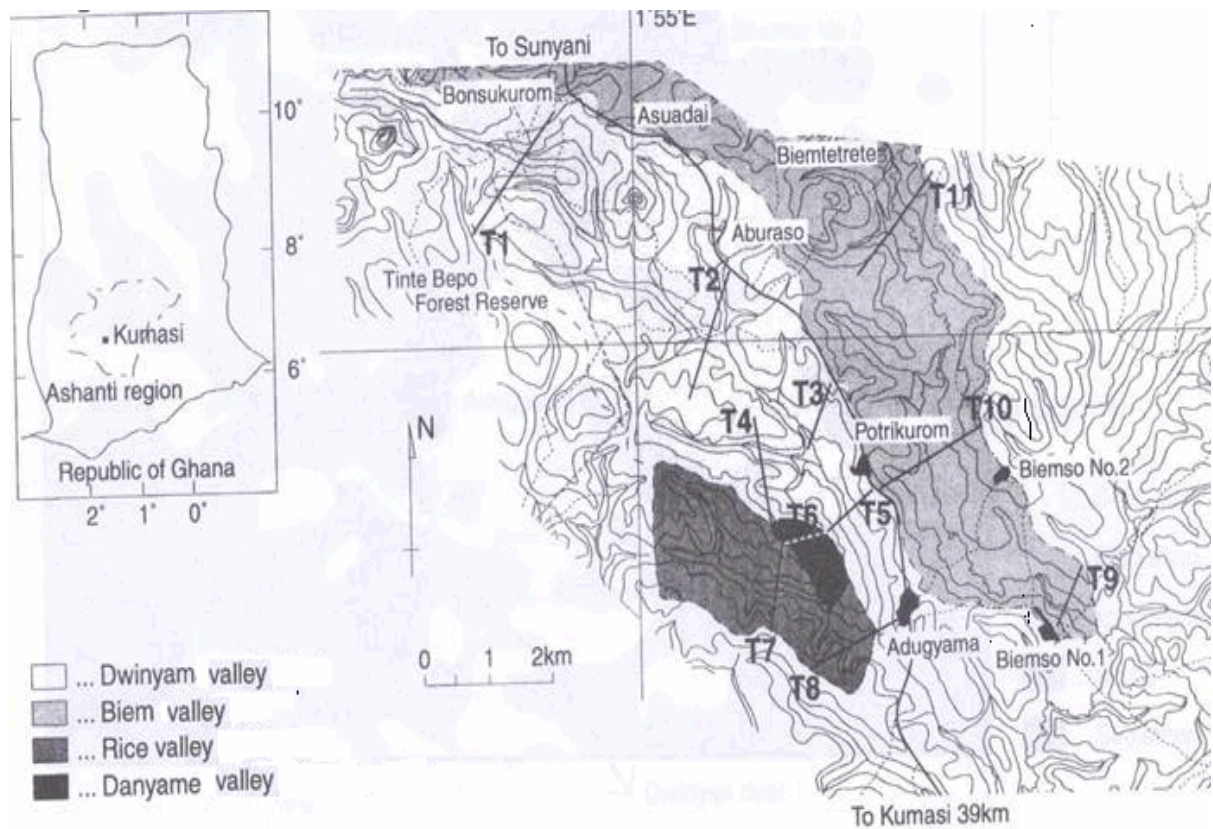
Figure 3.1 Map showing location of Dwinyam valley alongside some other valleys. T1-T10 are transects in the valleys.
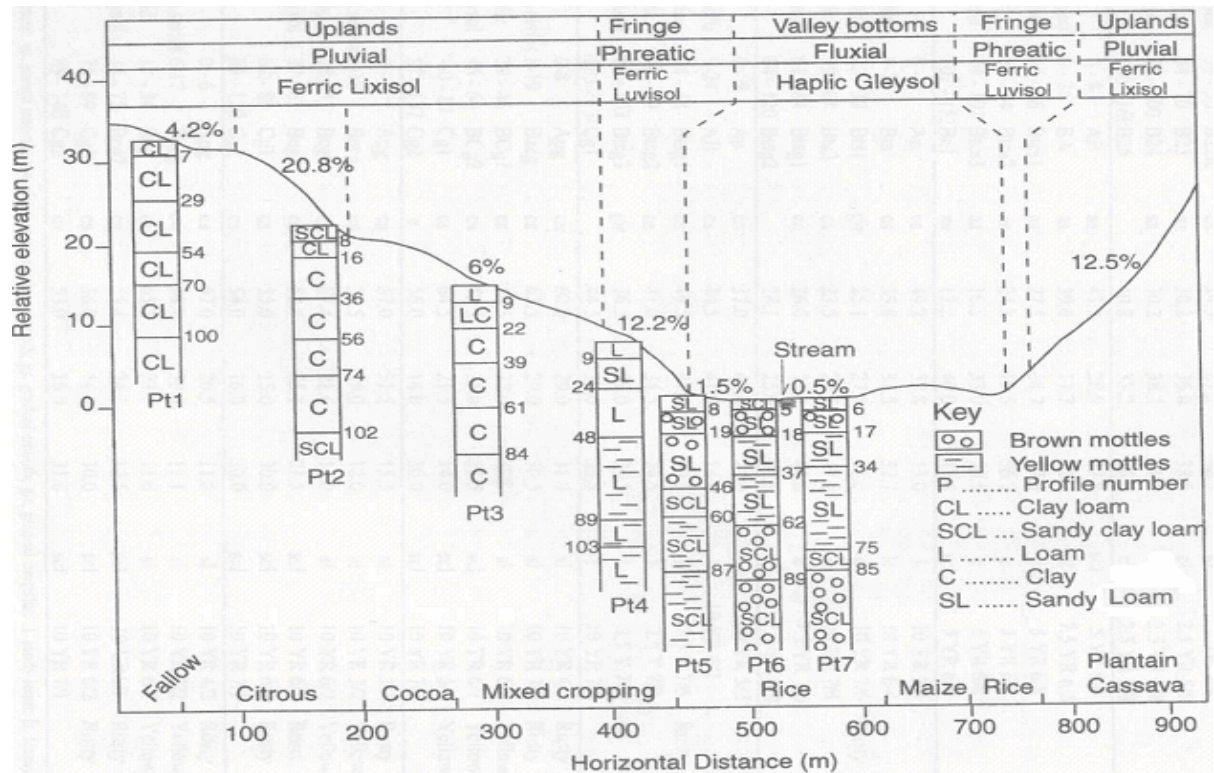
Figure 3.2 A schematic diagram of the profiles of the major soil series in the Dwinyam valley at T5 (Fig. 3.1), Potikuron, Ashanti Region, Ghana.

3.3 FEASIBILITY OF WATER TABLE CONTROL IN THE DWINYAM VALLEY IN GHANA

The approach was to determine if there was an existing depth of the water table, which would ensure that water table control was feasible with regards to water use for the minor faming season in Ghana (August to December). This is the period when water is scarce.

In order to predict the depth of the water table for Dwinyan, estimates of the soil hydraulic properties were predicted from some other soil properties, which were available. This is discussed in the next section.

3.3.1 Soil hydraulic properties

The soil properties data available was percent sand, clay and silt. The soil hydraulic properties were obtained using pedo-transfer functions (Noorallah, 2002). The data and predicted values for two soil layers (top and lower layers) in the soil profile (each of these layers is divided into three depths) are presented in the tables below.

Table 3.1 Soil properties for top layer for Dwinyan watershed, Ashanti region, Ghana for Pt6 shown in Fig. 3.2

Depth (cm)	0-5	5-18	18-37
Texture (FAO)	Sandy loam	Sandy loam	Sandy loam
Percent sand	57	58.5	67.4
Percent clay	13.5	12	11
Percent silt	29.5	29.5	21.6
Saturated hydraulic conductivity (cm/hr)	1.66	2.02	2.33
Drainable porosity	0.21	0.22	0.23

Table 3.2 Soil properties for lower layer for Dwinyan watershed, Ashanti region, Ghana for Pt6 shown in Fig. 3.2

Depth (cm)	37-62	62-89	89-120
Texture (FAO)	Sandy loam	Sandy clay loam	Sandy clay loam
Percent sand	53.4	55	54
Percent clay	21.5	30	30
Percent silt	25.1	15	16
Saturated hydraulic conductivity (cm/hr)	0.64	0.28	0.28

Drainable porosity	0.21	0.21	0.21

3.3.1.1 Saturated hydraulic conductivity

The effective mean hydraulic conductivity (K_e) was determined, as it would be used in the section below. For a layered soil with depths D_1 ,D_2.....D_n with corresponding hydraulic conductivities K_1, K_2 ...K_n , the effective hydraulic conductivity is determined as (Hillel, 1980):

$$K_e = \frac{D_1 + D_{2...}D_n}{(\frac{D_1}{K_1} + \frac{D_2}{K_2} ... \frac{D_n}{K_n})} \tag{3.1}$$

For the top layer, saturated hydraulic conductivity is:

K_{e1} = 2.08 cm/ hr i.e. 0.499 m/day

For the lower layer, saturated hydraulic conductivity is:

K_{e2} = 0.337 cm/ hr

Combined saturated hydraulic conductivity for the two layers is:

K_{et} = 0.45 cm/hr i.e. 0.109 m/day

An effective mean saturated hydraulic conductivity of 0.109 m/day is a low figure but not uncommon for soils with a significant clay content. Movement of water in such soils is rather slow.

3.3.2 Water table depth for 1996 and 1997 for Dwinyan

The depth of the water table for Dwinyan was simulated for the dry season of the years 1996 and 1997 with the drainable porosity obtained above using a simple water balance approach.

3.3.2.1 Model

The model used was based on equating the change in the depth of the water table (WTD_1- WTD_2) to the input (Rainfall) and output (Evapo-transpiration). Starting from an initial water table depth, the input (Rainfall) is added and the output (Evapo-transpiration) deducted, giving the final water table depth. Seepage loss is assumed negligible, in other words the depth of the water table is influenced by rainfall and evapo-transpiration. The equation used was:

$$WTD_2 = WTD_1 - (R - ET)/ f \qquad\qquad (3.2)$$

WTD_2 is the final water table depth (mm), WTD_1 is the initial water table depth (mm), R is the rainfall amount (mm), ET is the amount of evapo-transpiration (mm) and f is the drainable porosity (drainable porosity is the volume of water that will be released per unit volume of soil when the water table is lowered a unit depth).

The equation was programmed using excel and used to determine the depths of the water table. A time increment of one day was used. The rainfall and actual evapo-transpiration values were inputted directly into excel.

3.3.2.2 Initial water table depth

An initial water table depth of 0.55 m was used for 1996 and that of 0.4 for 1997 (Sam-Amoah, pers. communication, 2002).

3.3.2.3 Output

The output obtained, water table depth from August to December 1996 and 1997 are presented in the plots below, with the rainfall and evapo-transpiration data used.
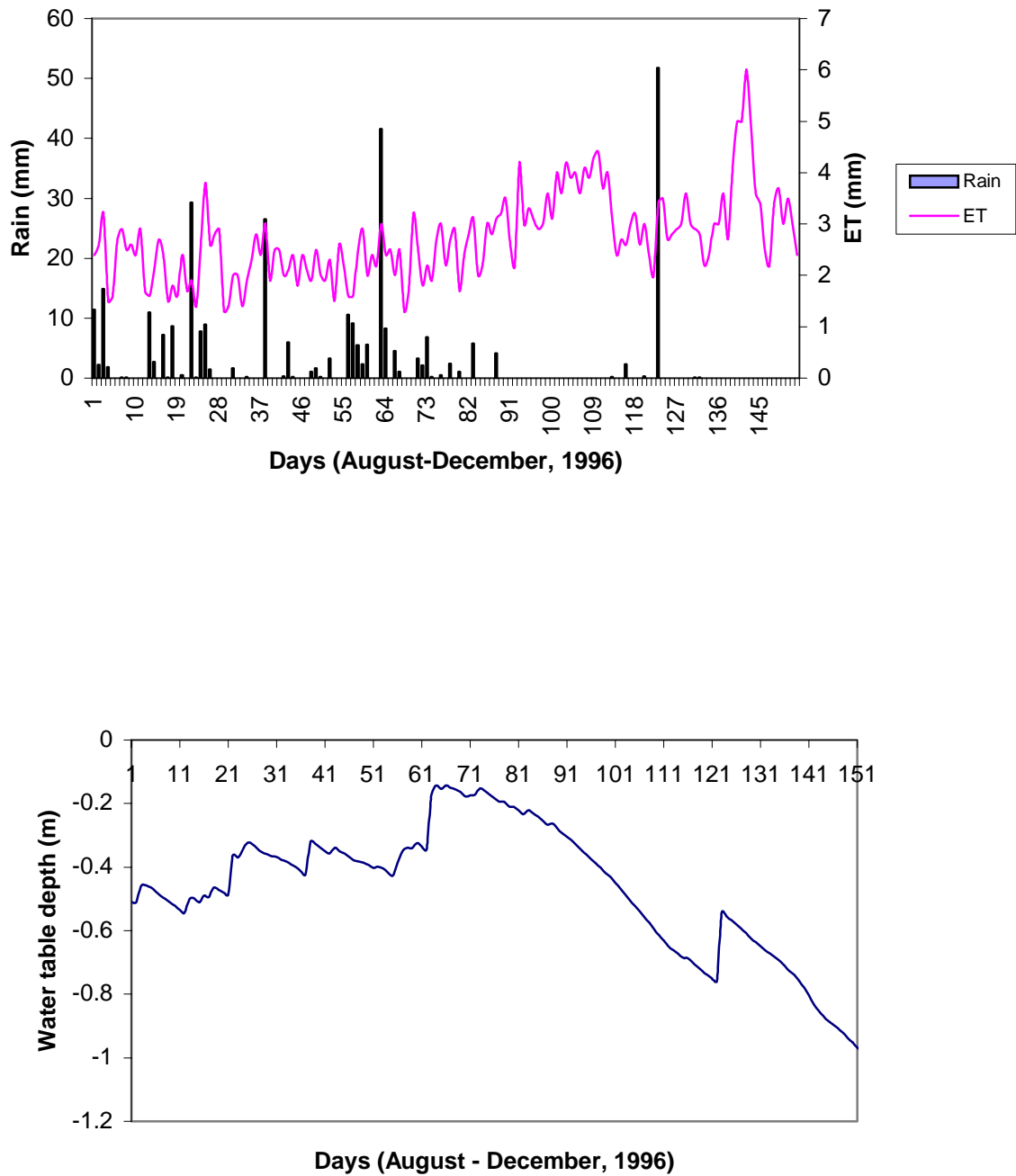
Figure 3.3 Effect of rainfall and evapo-transpiration amounts on water table depth from August to December 1996.
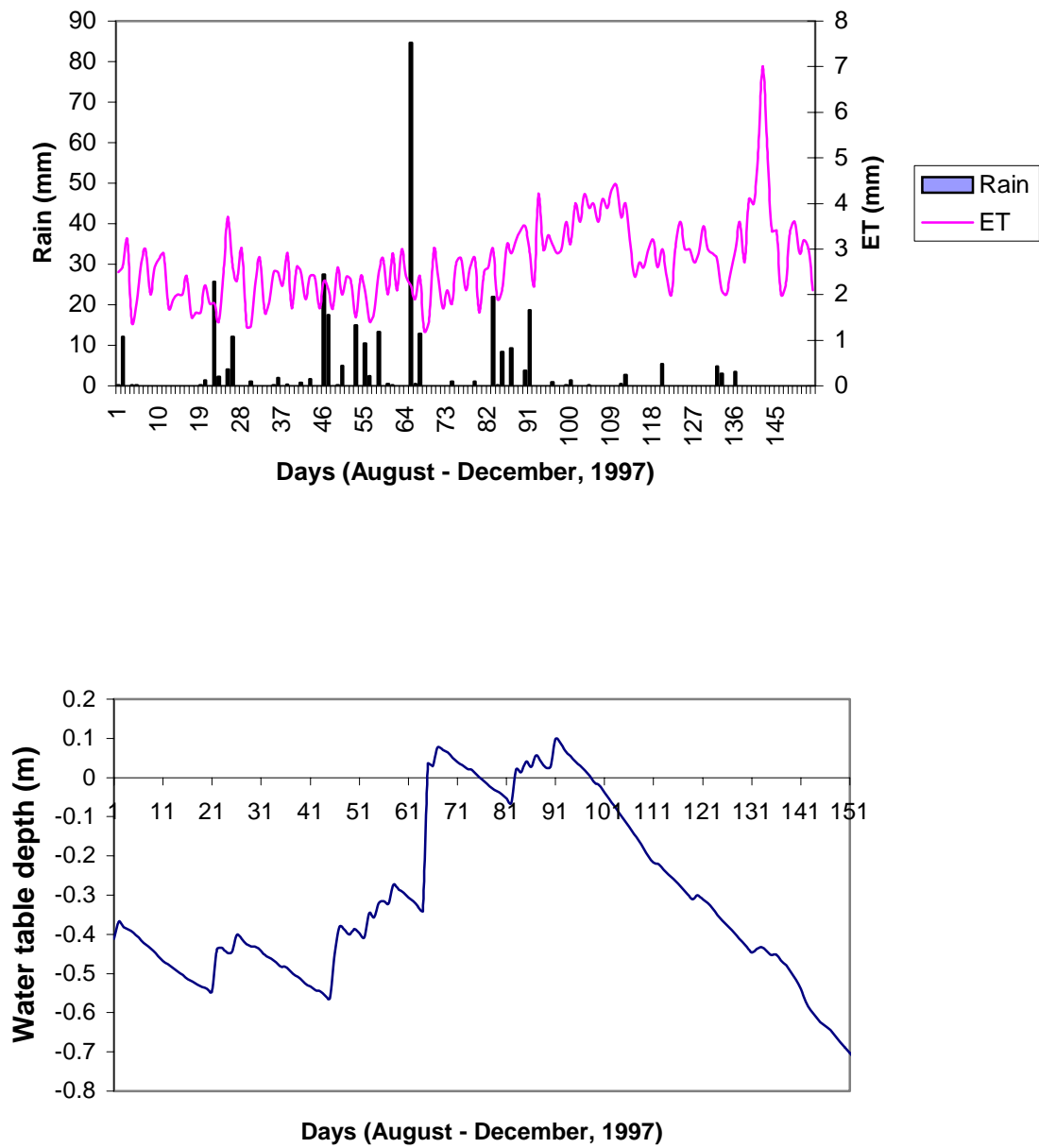
Figure 3.4 Effect of rainfall and evapo-transpiration amounts on water table depth from August to December 1997.

The model responds well to input and output of water and output. The water table falls when moisture is added and drops in relation to moisture removal. In both years, mean rainfall amounts in the early months as can be seen from the Figs. 3.1 and 3.2 are greater than in the latter part of the period. Evapo-transpiration amounts are however smaller for the early part of the period but increase towards the latter part. Water table depths are generally higher for the early part of the period and drop towards the end of the period. The water table, in both years is lowest after 151 days, the lowest depth being about 1 m below the soil surface. There is the likelihood that the water table will drop after December.

Between the 64th and 75th day and also the 83rd and 98th day for the year 1997, there is flooding, with a maximum flood depth of about 10 cm. Flood duration is not long and may not have posed a serious threat to rice production.

To irrigate using water table control, a predetermined depth at which the crops can be supplied moisture through capillary rise is used. No such depth has been determined for rice however, saturated soil may be used as a desired condition for rice production. In such a case, the water table should be set at a depth, which would ensure that the soil is saturated.

A zone of saturation (capillary fringe zone) exists above water tables due to capillary rise and as such it would not be necessary to raise water a depth of 1 m to ensure saturation at the surface. In silt loam soils, this rise can reach between 2.4 and 2.7 meters above the water table. In sandy soils, which have larger pore sizes between soil particles, the pull is less, perhaps reaching 0.46 m to 0.61 m above the water table (Franzen, 2003). The predominant soil type for the area under consideration is sandy loam and the height of the capillary fringe zone could be above that stated for the sandy soils.

3.4 COMPARISON OF WATER USE UNDER WATER TABLE CONTROL AND BASIN IRRIGATION FOR RICE PRODUCTION USING SOIL PROPERTIES FOR DWINYAN.

This section compares water use under basin irrigation and under water table control. Typical conditions on rice fields according to Walker and Rushton (1984) (with the exception of the flood depth and mean depth to the water table) are used in computing water use for the basin irrigation system. Conditions used for the water table control system are also extracted from this data. These are:

1. Floodwater depth is between 0.05 and 0.10 m (Bouman, 2001).
2. Plough layer = 0.14 m deep. This is the depth of soil to be saturated.
3. Thickness of hard pan = 0.06 m
4. Depth from surface to impermeable layer = 5.0 m
5. Mean depth to water table = 1 m
6. Area of basin 20m x 80m =1600 m^2
7. Fillable porosity is 20 %
8. Effective hydraulic conductivity, K = 0.109 m/day

Assumptions:
1. Rain fall = 0
2. Surface run-off = 0

A 100-day period is used in this case in order to provide for comparison with results obtained by Bouman (2001) for water use for rice production in the tropics over 100 days.

Figures 3.3 and 3.4 are schematic diagrams representing basin irrigation and water table control irrigation systems. The components of the water flow that are responsible for the major losses of water are seepage and percolation. Percolation under flood irrigation leads to loss of water to the water table, which is below the hard pan and does not contribute any water to crop production. Under water table

control however, as the water is supplied from beneath the soil and the water table is held above the water supply, percolation is eliminated.

The head of water above the soil surface is eliminated under water table control thus leading to a reduction in lateral seepage under water table control. A higher head is available under flood irrigation giving the potential for greater loss of water.
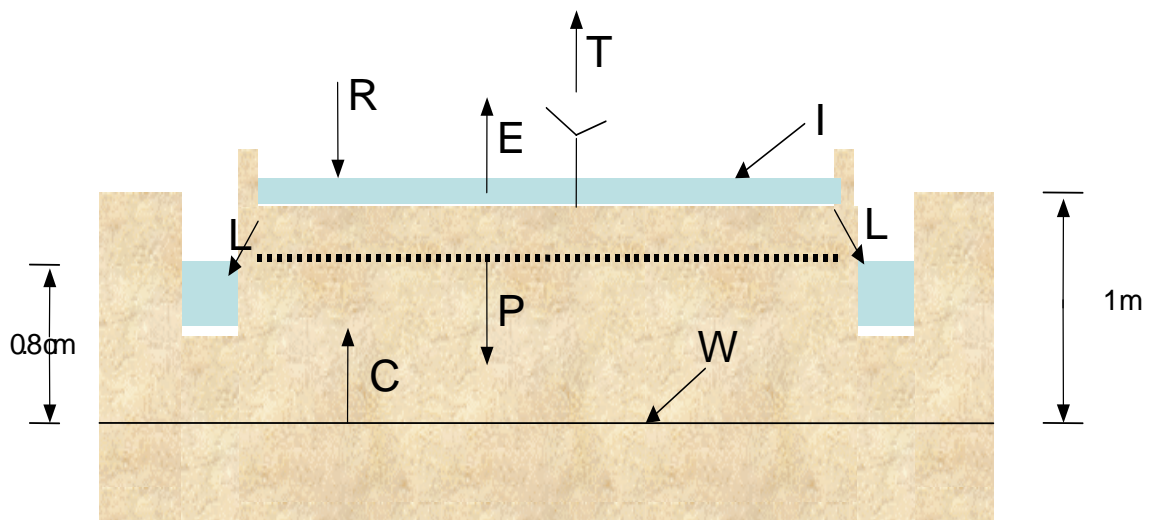
Figure 3.5 Elevation in rice field under flooded basin conditions showing flow of water. I= irrigation, E = evaporation, P = percolation, R = rainfall, L= seepage, T = Transpiration, C = capillary rise from groundwater, W = Water table.
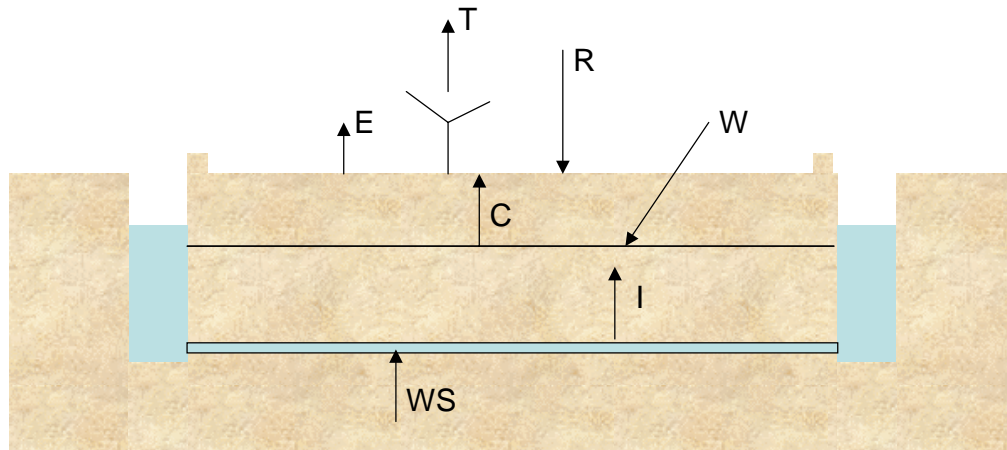
Figure 3.6 Elevation through rice fields in water table conditions showing water flow, where I= irrigation, E = evaporation, R = rainfall, T = Transpiration, C = capillary rise from groundwater, WS = water supply tube, W = water table.

3.4.1 Approach to determination of water use
As already indicated, a water balance approach is also used in this computation. In the case of the basin the components are:

1. The amount of water required to saturate the soil above the hard pan,

2. The amount of water for the floodwater in the basin,

3. The water lost each day through evapo-transpiration and seepage and percolation.

In the case of the water table control system the components are:

1. The amount of water required to raise the water table to the surface,

2. The water lost each day through lateral and vertical seepage and evapo-transpiration.

The amount of floodwater required is simply calculated as the product of the basin area and the depth of surface water required. This assumes that the soil has already been saturated.

In the case of the soil system, the water required is calculated as the product of the basin area and the depth of soil multiplied by the porosity of soil.

3.4.1.1 Basin irrigation

The water balance of a lowland rice field can be written as (Fig. 3.3)

$$DW = I + R+C-E-T-S-P-D \tag{3.2}$$

where (all units in mm/day) DW is the change in stored water, I is irrigation supply, R is rainfall, C is capillary supply, E is evaporation, T is transpiration (Evaporation and transpiration combine to form ET -evapo-transpiration), P is percolation, D is surface drainage and S is seepage.

In this study, interest is in the volume of soil above the hard pan. In this area, C is assumed to be negligible. Rainfall and irrigation are assumed to be zero as stated above. Surface drainage is also assumed to be zero. The components of the water balance equation that are of interest to us are thus: E, T, P and S.

The water requirement for the basin is determined as follows:

a. Land preparation (one time operation)

This requires soaking the field and that involves saturating the soil system in addition to having a depth of floodwater. It is a one-time operation, and a depth of 0.05 m is used for the floodwater depth.

b. Initial water required to fill the basin

As already indicated this is the amount required to saturate the soil above the hard pan plus that required to raise the water level in the basin to a mean depth of 0.075 m.

c. Percolation and seepage losses

The hydrostatic water pressure and resistance to water flow govern seepage and percolation rates. For seepage, the hydrostatic water pressure is determined by the difference in depth of the water table on the field and that in surrounding drains, ditches, or creeks. Another possible seepage loss is leakage through and underneath the bunds: water moving laterally into the bunds and then down to the

water table. The resistance to this seepage flow is governed by the soil physical characteristics of the field and bunds, the state of maintenance, and the relative length of the bunds compared with the surface area of the field (Bouman, 2001). It is difficult to obtain a factual figure for seepage and percolation, as this will vary depending on soil physical characteristics. A representative value is therefore adopted.

According to FAO (1989) for areas where no local data is available percolation and seepage losses from a paddy field for various soils are: heavy clay: 2 mm/day; sandy soils: 8 mm/day. The mean value is: 5 mm/day. Walker and Rushton (1984) gave losses of water from various sites of puddled rice fields in Indonesia between 1973 and 1981 as 15-20 mm/day. The mean value is: 17.5 mm/day. A mean minimum of 5 mm/day and maximum of 17.5 mm/day are used for percolation and seepage losses.

d. ET
A mean value of ET for the period under consideration is 2.5 mm/day (Sam-Amoah, personal comm.)

3.4.1.2 Water table control system
Below is a simple plan layout of a water table control system**.**
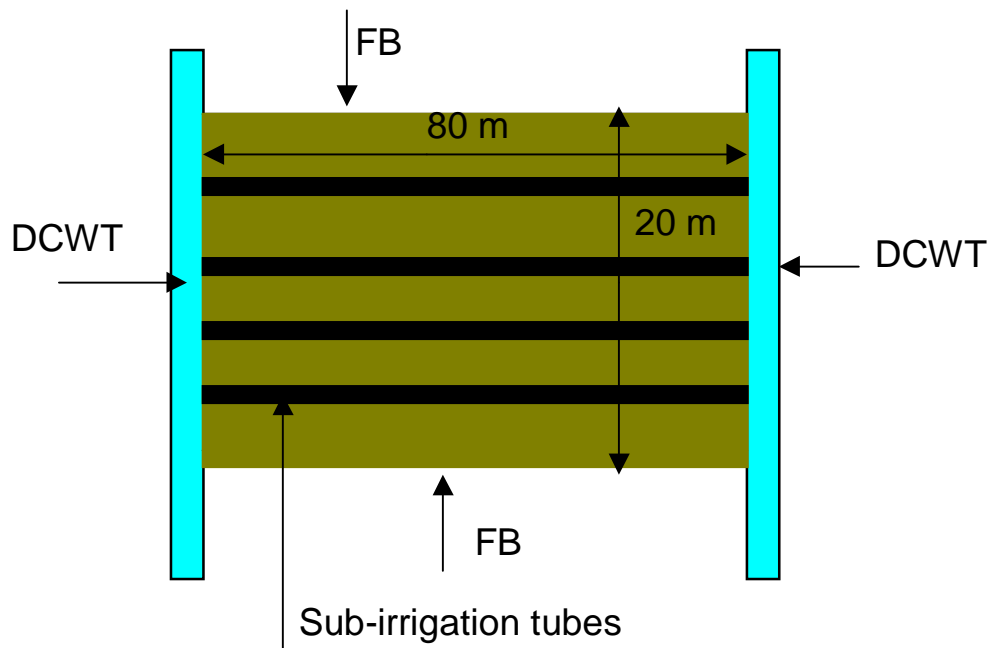
Figure 3.7 Plan layout of water table control system showing boundaries subject to seepage, FB = Field boundary, subject to seepage, DCWT = ditch controlled water.
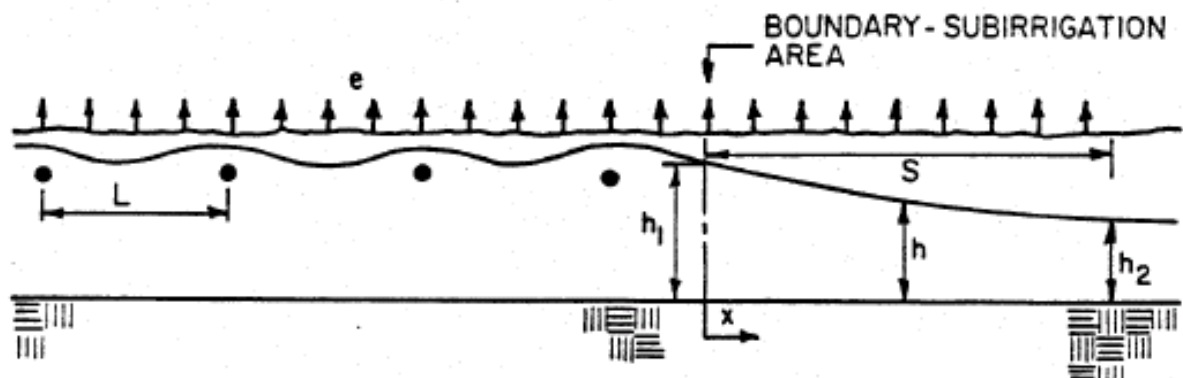
Figure 3.8 Seepage from water table controlled field to adjacent non-irrigated land, which has water table drawdown due to ET. Adapted from Skaggs (1980). h_1 = height of water table above impermeable layer at boundary of irrigated area, h = height of water table above impermeable layer, h_2 = height of water table above impermeable layer at distance S away from boundary of irrigated area, L = spacing between the supply tubes, e = evaporation flux, x = distance away from boundary of irrigated area.

When the water table is raised during sub-irrigation, the hydraulic head in the field is higher than in surrounding areas and water is lost through lateral seepage. The rate of deep seepage or vertical water movement from the soil profile may also be increased. The magnitude of seepage losses depend on (Skaggs, 1980):

1. The hydraulic conductivity of the soil
2. Depth to restricting layers
3. Boundary conditions (e.g. elevation of water table in surrounding fields).

Seepage in this case occurs only along the long boundaries, as the other boundaries are ditches where the water table is controlled in order to supply water to the field. The seepage length of the field is thus 160 m.

a. Computation of lateral seepage losses:
Lateral seepage under consideration is that to the undrained land which is what pertains in Dwinyan, and losses per unit length of the field under such conditions can be obtained using the equation below (Skaggs, 1980):

$$q = \sqrt{((h_1^2 - h_2^2)K_e * e)} \qquad\qquad (3.3)$$

where q is the seepage rate per unit length of the drainage ditch, K_e is the effective lateral hydraulic conductivity, h_1 is the water table elevation above the impermeable layer in the field which is 5 m, and h_2, the depth of the water table in the undrained land which is assumed to be 4 m (mean water table depth 1m below the surface), and e is the evapo-transpiration rate (Fig. 3.6).

The effective vertical mean hydraulic conductivity value determined above for the soil profile at Dwinyam is adopted as the effective lateral hydraulic conductivity in determination of the lateral seepage losses.

b. Deep seepage losses:
Deep seepage can be determined using Darcy's law:

$$Q = K_e \, A(h_1 - h_2)/D \hspace{3cm} (3.4)$$

where h_1 is the mean distance from the bottom of the impermeable layer to the water table, and h_2 is the hydraulic head referenced from the bottom of the impermeable layer. D is the thickness of the impermeable layer and K_e the hydraulic conductivity of the impermeable layer and A is a unit area perpendicular to direction of flow. It is assumed to be negligible, as K_e for an impermeable layer will tend to zero.

c. Evapo-transpiration losses
Unlike the basin system where there is an exposed water surface initially until the crops cover the surface, there is no exposed body of water under water table control implying losses due to evapo-transpiration will be lower than for the basin. A mean value of 2 mm/day is therefore assumed in the computation.

d. Water required for initial saturation of soil in a water table control
The amount of water required for initial saturation of the soil is that required to raise the water table up to the soil surface from a depth of 1 m below the surface of the soil. A depth of 1 m was used as it was determined from the water table depths for Dwinyan that the lowest water table depth observed over the periods for the two years was about 1 m.

3.4.2 Summary of water use for basin and water table control system for rice
Table 3.3 gives the summary of the water use for the two irrigation systems under consideration.

Given the values obtained, water saving of between 362 m^3 (22 %) and 2577 m^3 (61 %) seems possible under a water table control system compared to a basin irrigation system when the water table is required to be raised from 1 m up to the surface. As indicated earlier, due to capillary rise the water table will not have to

be raised through 1 m to obtain saturation at the soil surface, Thus a water saving of more than that stated is possible under the conditions given in this study. Water table control can then be said to be a viable alternative to basin irrigation in terms of water use based the conditions used above.

Table 3.3 Water use under the two systems, water table control and basin irrigation for rice, for each component of operation.

Parameter	Water table control	Basin
Land preparation	0	192
Initial soil filling (m^3)	320	232
Evapo-transpiration ($m^3/100$ days)	320	400
Seepage and percolation ($m^3/$ 100 days)	709	800 – 2800
Net water requirement (m^3)	1349	1624 – 3624
Mean application efficiency (%)	82.5	77.5
Gross water requirement (m^3)	1635	1997 – 4212

According to Bouman (2001), typical outflows from a rice field in the tropics over 100 days vary from 675-4450 mm depending on season and soil characteristics. Given the size of the basin used in this investigation this would translate to 1080 – 7120 m^3.

The values obtained for the basin in this study, 1997 m^3 – 4212 m^3 are much lower than the maximum values for a typical paddy field. This could be due to the fact that the value used for seepage and percolation is lower than that which pertains in the field. In any case, it is clear that water table control leads to water saving in comparison to basin irrigation.

If an initial water table depth of 2 m below the surface were used, it would require an amount of 640 m^3 for the initial filling of the soil for the water table control system. Seepage and percolation would rise to a figure of about 945 m^3. If evapo-transpiration was left unchanged, at a value of 320 m^3 (this would however be lower as the water table depth is lower), it would give a net water requirement of 1905 m^3, and a total water requirement would be 2309 m^3. More water will be used compared to that for the minimum seepage and percolation rate; compared to the maximum seepage and percolation rate however, there is great water saving, about 45 %.

It has already been noted that evapo-transpiration values will always be lower under a water table control system than under a basin system. This is due primarily to the open water surface provided under the basin system. Varying evapo-transpiration values will not change the outcome.

There is the possibility of water saving under water table control systems compared to basin irrigation systems. This will however vary depending on the site conditions especially on the seepage and percolation rate.

3.5 CONCLUSIONS

1. Water use comparison

Water requirement comparison for the basin and water table control under the conditions given shows that it is possible to save water under a water table control system when the mean height through which the water table has to be raised is about 1 m. Water saving will however decrease as the mean height through which the water table has to be raised increases. The seepage and percolation values for the basin system, which depends on the soil characteristics, determine the extent of water saving possible. At an initial depth of 2 m below the surface of the soil, there was no water savings under the minimum seepage and percolation value used; under the maximum value however, water savings of about 49 % was determined.

2. Feasibility of water table control

The maximum level of the water table predicted for the years 1996 and 1997 was 1 m below the surface of the soil. For the conditions estimated for Dwinyam, if the water table is raised through a distance of 1 m to ensure saturation at the surface, there would be water saving compared a typical basin system. It is therefore feasible to adopt water table control at Dwinyam for rice production between August and December. Rice can be grown during the minor season with water table control systems and thereby limit the pressure on water resources over that period.

Having established that it is possible to provide moisture conditions required for growth of rice under water table conditions at Dwinyam, the following chapters explore the effect of water table control on growth and development of rice plants as well as on the growing environment.

CHAPTER 4: GROWTH OF RICE (AZUCENA AND IR36) UNDER FOUR WATER TREATMENTS

Abstract

Three experiments were conducted to determine the possibility of using water table control systems for rice production. In the first and second experiments rice (Oryza sativa L.) cultivars IR36 and Azucena were grown under three water treatments: saturated sand, water table held at 15cm below the sand surface, water table at 30 cm below the sand surface. In the third experiment, the saturated treatment was replaced with a flooded treatment with a flood depth of 2 cm, and the rice variety used was Azucena.

All the experiments were conducted for duration of 6 weeks with plants harvested after every two weeks. Growth parameters measured included total number of roots, length of roots, shoot length, root dry mass and shoot dry mass. Moisture content at a depth of about 3 cm below the surface of the sand was also determined.

In experiment one total root length, number of roots and tiller numbers were significantly greater for the plants in the saturated treatment. There were however no significant differences in root mass, shoot mass, and shoot length with regards to water depth. In experiment two, the 15 cm treatment had the highest shoot mass in addition to the highest tiller numbers. In other parameters, the 15 cm treatment was not significantly lower than the saturated treatment. The 30 cm treatment was much lower in all parameters measured. Significant differences with regards to water treatment occurred only for rooting depth.

In the third experiment, the plants under the flooded treatment had a significantly greater root dry mass, shoot dry mass and tiller numbers than the others. The plants under the 30 cm treatment had a significantly greater root dry mass and shoot dry mass than the 15 cm water table depth treatment. Tiller numbers were

also greater for the plants under the 30 cm treatment than for those under the 15 cm water table depth treatment.

Water table control was able to sustain growth of rice over a period of six weeks after sowing, and growth under water table control was favourable compared with growth under saturated and flooded conditions.

4.1 INTRODUCTION

It was established in the previous chapter that water table control for rice production could lead to lower water use than basin irrigation. Water table control thus provides a feasible alternative to basin irrigation for rice production in terms of water saving. It is then necessary to determine the effect of water table control on yield of rice; this however could not be done due to limitation in time and resources for this study. The focus was rather on biomass production over the first six weeks after transplanting and several other growth parameters, which either directly or indirectly affect yield. No attempt was made to predict yield from these but conclusions were drawn based on growth over the duration of the experiments. However, a high biomass production is necessary for high yield in rice (Iqbal, 2004).

This chapter reports on rice varieties Azucena (upland variety but does well under lowland conditions) and IR36 (lowland variety) grown in three separate experiments under four water treatments with the aim of determining if water table control was capable of sustaining rice growth. The approach was to compare growth under two water table depths: 30 cm and 15 cm respectively, to that under saturated and then flooded conditions. The growth data collected were: length of each nodal root, stem height, shoot length, shoot mass, root mass and number of tillers

The first and second experiments compared growth under the two water table depths to that under saturated conditions, and amongst the parameters measured, the ones of most interest, due to their direct relationship to yield; tiller numbers

and dry shoot mass, plants under the 15cm water table depth fared better than plants under the saturated conditions. The findings obtained were surprising as it was expected that growth under saturated conditions would be greater than any other condition lower than saturation (Pradham *et al*., 1973; Bouman and Tuong, 2001). It was suspected that there were certain periods during the experiment when the level of water under the saturated conditions dropped allowing some aeration thus leading to the results obtained. In order to clarify this issue, the third experiment was designed in which saturated treatment was replaced with a flooded treatment.

Generally flooding reduces the physical variability of soils, increases its fertility, and confers stability to crop systems that can tolerate standing water. Flooding a soil provides an ideal growth medium by supplying abundant water that may carry significant amounts of suspended solids and nutrients, buffering soil pH near neutral, enhancing nitrogen fixation and carbon supply, and increasing diffusion rates, mass flow, and availability of nutrients. Standing water stabilizes the soil moisture regime, moderates soil temperature, and prevents soil erosion (Neue, 1993). A flooded treatment would thus introduce environmental conditions very different from those expected under a water table control system thus leading to the investigation and comparison of some environmental parameters, namely: growth medium temperatures and nitrate concentration in solution.

The results obtained for each experiment are presented and comparisons were made for the two varieties. The data was subjected to ANOVA using GENSTAT 5. The main hypothesis tested in this component of the study was: Growth of rice under two water table conditions: 30cm water table depth and 15cm water table depth, will not vary significantly from growth under saturated conditions and flooding with a flood depth of 2 cm.

4.2 MATERIALS AND METHODS

4.2.1 Water treatments
The treatments used in the experiments were:

1. Saturated sand (saturated treatment)

2. Water table held at 15cm below the sand surface (15cm treatment).

3. Water table held at 30 cm below the sand surface (30 cm treatment).

4. Flooded soil with flood depth of 2 cm.

The first three treatments were used in the first and second experiments and the last three used in the third experiment. The water table depths were selected based on work done by Clark *et al.,* (2002) who used a water table treatment to test the ability of rice roots to penetrate a hard pan.

4.2.2 Experimental design

The plants were grown in the cores, which were fitted into tanks in which the water table level was controlled. A randomised complete block design with three replications was used. There were three tanks in each block, and each tank had six cores. These cores were filled with the growth material and placed in the tanks. The environment in the growth chamber was controlled. Blocking was used due to variations on levels of incident radiation in different areas of the growth chamber.

4.2.3 Growth chamber

The experiments were conducted in growth chambers (Plate 4.1) (Sanyo Gallenkamp PLC, UK) under controlled environment. The controlled conditions were: 16 hour day length, 30°C during the day and 26°C at night, a relative humidity of 70% and a photosynthetic photon flux density of 300-350 mol m^{-2} s^{-1} provided by fluorescent tubes, supplemented by tungsten bulbs. The same growth chamber was used for the first and second experiment; for the third experiment, another chamber, similar in all respects to the first was used.

Plate 4.1 Growth chamber with tanks
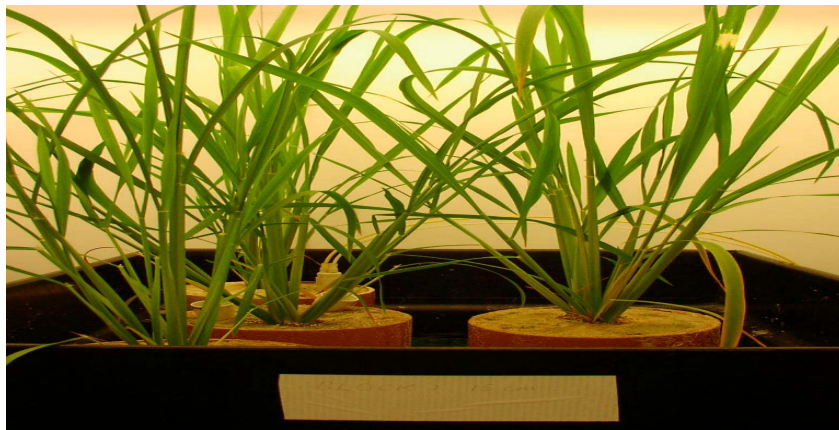
Plate 4.2 Tank showing sand filled cores with rice plants

4.2.4 Core arrangement

The cores, made of plastic were 45 cm long and 15.2 cm in internal diameter. Six of them were fitted into each tank. In setting up, the bottom of the cores were covered with permeable cloth and placed directly into the tank (Fig. 4.1). They were then packed with sand with a packing density of 0.811 kg dm^{-3}; the cloth prevented sand from falling out and helped to retain the sand and plant in the core during harvesting. The sand was initially saturated with nutrient solution, and the cores were gently tapped as the solution was added to ensure that the sand surface was level. Nutrient solution was poured into the tanks, around the cores. The arrangement is as presented in the schematic diagram below.
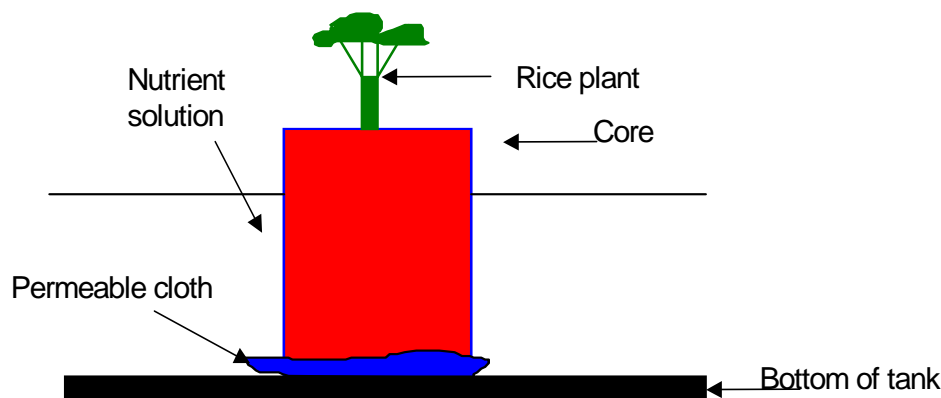
Figure 4.1 Arrangement of individual core in tank

4.2.5 Water supply
The water was supplied through the bottom of the core and the plants were watered by capillary action.

The water table was initially held at a depth of 30 cm below the soil surface in each of the tanks to ensure seedling establishment. The treatments were imposed three days after sowing, when the plants were about 2 cm high, by adding more nutrient solution to raise the water levels in the tanks to their respective depths.

The depth of the water table was held at the specified depths throughout the experiment by topping up at least every two days. A mean drop of about 1 cm a day in the level of the solution was observed, thus when topping up, the level of the solution was raised 1 cm above the desired level so that over the two days, the mean depth would be the desired depth.

Flow of water into the cores was not in any way inhibited by the permeable cloth; this was determined by observing increase and decrease of depth of floodwater in the cores subjected to the flooded treatment.

4.2.6 Nutrient solution
A nutrient solution of composition 1.5 mM Ca $(NO_3)_2$, 0.15mM $CaH_4(PO4)_2$, 1.0mM KCL, 0.3 mM $MgSO_4$, with the following micronutrients: 50μ M B, 50μ

M Fe, 10µM Mn, 1 µM Zn, 1µM Cu and 0.5µM Mo (Clark *et al.,* 2002) was used. This nutrient solution was adopted because it had been used successfully for rice growth under conditions quite similar to those in these experiments.

4.2.7 Growth medium

Sand (RH 65 grade silica sand, Hepworth Minerals and Chemicals, Sandbach, UK) was used as the growth medium. It was selected primarily to test the feasibility of rice growing under the conditions imposed without the influence of other factors that might have been introduced with soil. Secondarily, it was selected because control of the water table depth under sand, due to the higher conductivity of sand, was easier than under soils and this was desired in a first attempt at such an experiment.

4.2.7.1 Hydraulic conductivity

The hydraulic conductivity of the sand was determined to be 32.95 m/day (S.D. = 0.716) indicating that water movement was quite rapid in the sand.

4.2.7.2 Water release characteristics

The water release characteristics of the sand was determined using the van Genuchten equation (van Genuchten, 1980), which describes a continuous change from saturation to a residual moisture content.

The equation is:

$$x = (1/(1+(\alpha\ f(x))^n\ )^m \qquad\qquad\qquad (4.1)$$

where α, n and m are soil specific constants, $f(x)$ is the soil water suction and x the relative saturation.

The relative saturation, $x = (\theta - \theta_r)/(\theta_s - \theta_r)$ where θ_r is the residual water content of the soil, and θ_s is the saturated water content of the soil.

VG solver, a computer program for fitting experimental data to the van Genuchten's model (Leeds-Harrison, pers. comm) was used and the output is as follows:

θ_r = 5

α = 0.01043 cm^{-1}

n = 2.735579

m = 6.301231

The curve gives a good fit with only one point where there appears to be a significant difference between the calculated and experimental value. Based on the model, moisture content at saturation is 34.6%; that at a suction of 15 cm is about 32.74%, and that at 30 cm is about 27%.
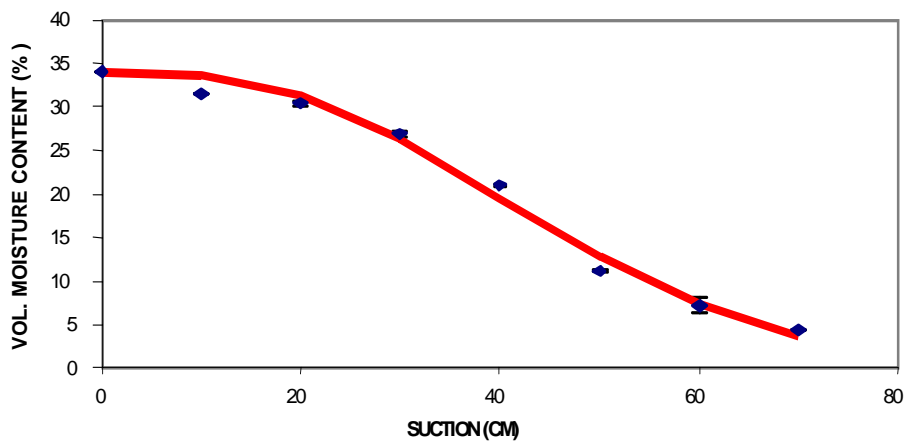
Figure 4.2 Water release characteristics using the van Genuchten's model

4.2.8 Seed

Rice variety IR36 was used in the first experiment. It was chosen because it is a lowland variety and also for the fact that it is grown in Ghana. Azucena was subsequently used; the main reason for its choice being that it had a lower number of roots than IR36 making it more convenient for root counting and measurements. Moreover Azucena, as has already been indicated fares well under

both lowland and upland conditions. The seed was obtained from Silsoe Research Institute, Silsoe, UK.

4.2.9 Germination

The rice seeds were placed in petri dishes (germination requires some moisture) lined with slightly soaked filter paper and wrapped in aluminium foil to exclude light, and kept for 5 days under a 14-hour day with day temperatures of 30 ^{o}C and night temperatures of 20 ^{o}C for germination.

4.2.10 Sowing

Sowing was done by placing pre-germinated seedlings in small holes about 1cm deep, with the coleoptile protruding from the surface. The seedlings were carefully covered and vermiculite placed around the base of the seedling. This was to ensure that the seedling did not dry out. Vermiculite is able to absorb moisture so it is able to keep its surroundings moist as long as there is a moisture supply.

4.2.11 Harvesting

The tanks were drained at each harvest before the cores were lifted out to avoid the breakage of the roots. The cores containing the plants and the growth medium were put into the harvesting equipment (Clark *et al.,* 2002) (Plate 4.3) and the cores pulled out leaving the plant and the sand. The sand was washed away and the plant removed. The plants were stored in a refrigerator and measured at a later date.

A ruler was used to determine the length of each root and the shoot. In the case of the roots, each root was straightened and the ruler used to determine its length. The plants were dried in an oven for 18 hours at a temperature of 102 ^{o}C and the root and shoot dry mass determined by weighing.
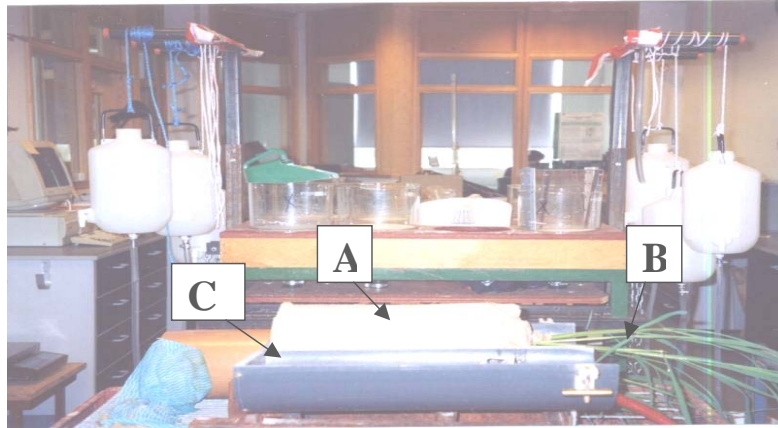
Plate 4.3 Harvesting equipment (C) in foreground containing sand (A) and rice plant (B).

4.3 RESULTS AND DISCUSSION

4.3.1 Moisture content

Moisture content was determined using a theta probe (described in the next chapter) just below the surface of the sand (at a depth of about 3 cm).
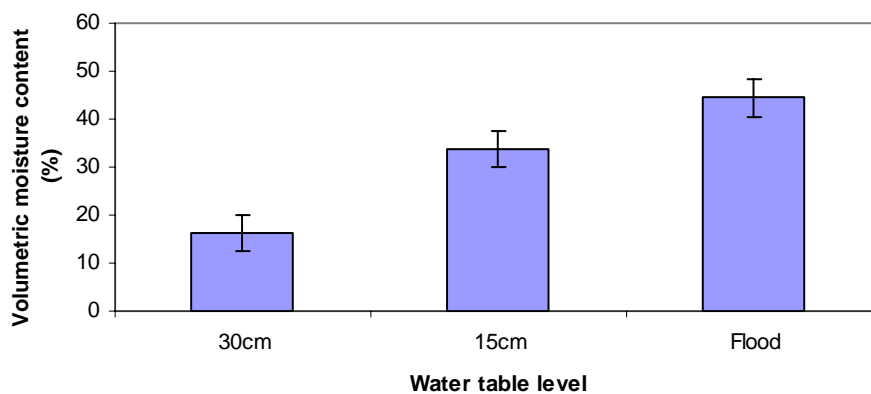
Figure 4.3 Volumetric moisture content just below the surface of the sand against water table level with L.s.d. (p = 5%) as Y error bars.

Moisture content was significantly different for all the treatments and moisture differentials were greater between the 15 cm and the 30 cm water table depths than

between the flooded and the 15 cm water table depth. Moisture content for the saturated treatment would definitely be between that for the flooded treatment and the 15 cm water table depth treatment.

If the moisture level was the main driving factor for growth, then growth would be greatest for the plants under the flooded treatment followed by those under the saturated treatment then the plants under the 15 cm water table treatment and lastly the 30 cm water table treatment.

As was reported in chapter two, reports on yield under water saving rice irrigation has been contradictory; while some report increase in yield under less water use (Wu, undated; Mao, 1996) others (Borrell *et al.*, 1997; Bouman and Tuong, 2001) have reported yield decrease under lower water use. The results presented in this study will go to further clarify the effect of water saving on rice growth.

Moisture content is different from that determined using the water release characteristics. The values were: 16.1 %, 33.8 % and 44.4 % for water table depths of 30 cm, 15 cm and flooded conditions respectively. Experimental errors could account for such differences; as the theta probe gives a more direct measure, the values obtained from it were used in this report.

4.3.2 Maximum rooting depth
Figures 4.4- 4.6 show that two weeks after treatment imposition, the rooting depth of the plants under the 30 cm and 15 cm water table depth treatments for both varieties were over 30 cm long. Moisture stress may be eliminated at this point as roots of the plants had reached the water table where there was excess moisture. Growth differences as a result of moisture differentials in the cores may therefore be diminished after only two weeks of treatment imposition.

4.3.2.1 Azucena

In Fig 4.4, rooting depth for Azucena under the driest conditions was greatest at the end of the 2nd week. At the end of the 4th and 6th weeks there were no differences between the rooting depth for the 15 cm and the 30 cm water table depth treatments.
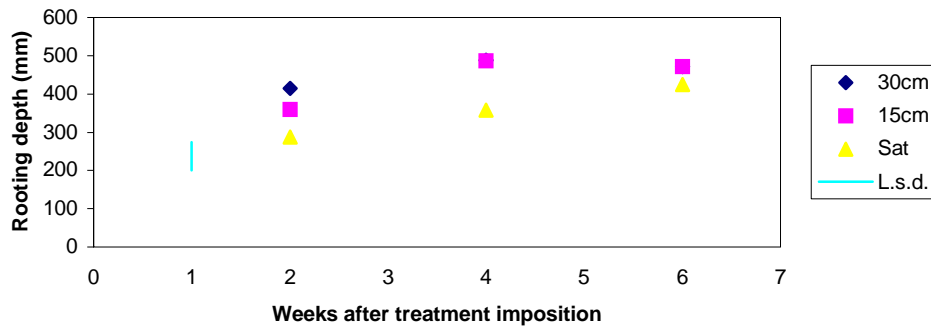
Figure 4.4 Maximum rooting depth vs. weeks after treatment imposition (Azucena) showing L.s.d. (p=5%).

This may be due to the fact that the rooting depths were limited by the depth of the cores. Rooting depth for the saturated treatment on the other hand was lower than the other two at each harvest.
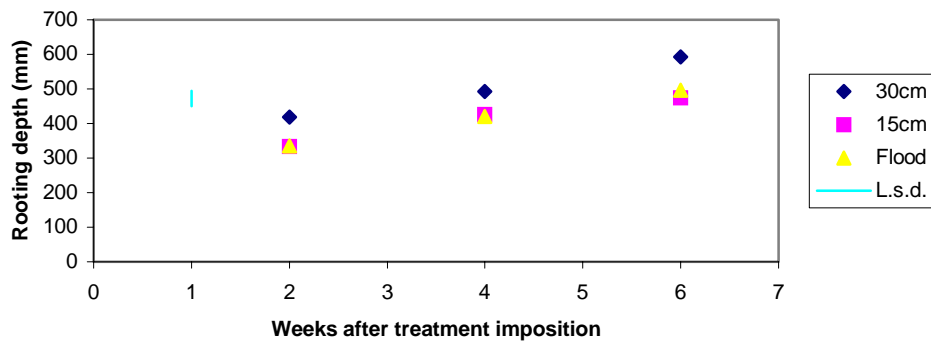
Figure 4.5 Maximum rooting depth vs. weeks (Azucena) after treatment imposition showing L.s.d. (p=5%).

Figure 4.5 compares the rooting depth of Azucena for the two water table treatments: 30 cm and 15 cm below the surface of the sand to flooded conditions.

Rooting depth for the plants under the 30 cm treatment differed significantly from the other plants right from the second to the sixth week. Differences did not appear between the other treatments. Rate of root elongation was slower after the 2nd week and appears to be linear up to the 6th week.

Rooting depth pattern varied for plants under the 30 cm and 15 cm water table depth treatments in Figs. 4.4 and 4.5. These differences in growth pattern were observed in the other parameters measured under the two experiments

4.3.2.2 IR36

In the case of IR36 (Fig. 4.6) the 30 cm treatment had the longest rooting depth at each sampling point. The rooting depths for the plants under the 15 cm and 30 cm water table depths were significantly greater than that of the saturated at the end of the second week. At the end of the 6th week, the depth for the 30 cm treatment was significantly different from the other two.
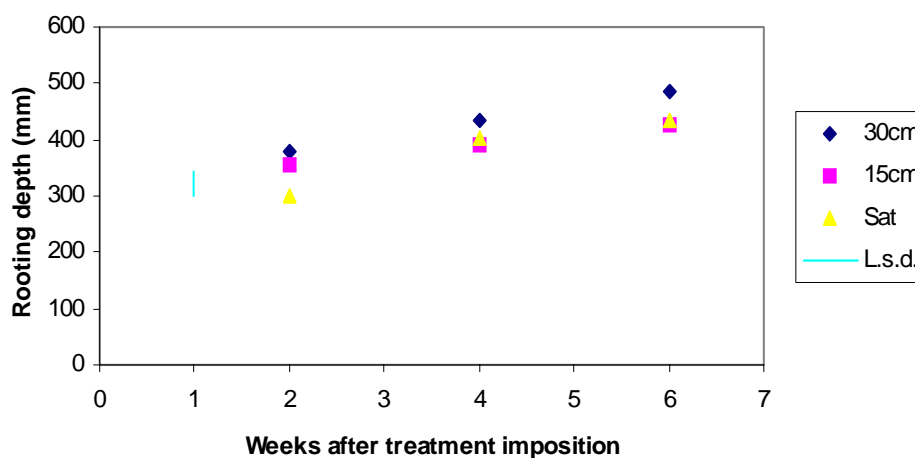
Figure 4.6 Maximum rooting depth vs. weeks after treatment imposition (IR36) showing L.s.d. (p=5%).

4.3.2.3 General discussion

According to Wade *et al.,* (1999) despite having fewer roots in deeper layers, rain fed lowland rice can extract water from below a 15 cm soil depth. Considering the

depth of the roots in these experiments, mean of about 40 cm, it is reasonable to extend this depth to about 40 cm, that is to say, rice should be able to extract water from below a 40 cm soil depth given there are no barriers to root extension.

There is the possibility that the length of the cores limited the depth of the roots, not in a way that would affect the results of the experiment but that under a longer soil depth, the rooting depths could have been greater.

Price *et al.,* (2002) indicate that field grown rice shows that drying soils can promote root growth measured as total root mass or rooting depth, growth chamber experiments however indicate a reduction of root growth under drought. They also observed that water stressed treatments promoted maximum root length. There was no reduction of root growth under the lower water table depth treatments in this experiment even though this was a growth chamber experiment.

It must be noted that the roots for the 30 cm and 15 cm treatments had initially to grow through aerated soil before getting into the water table; the saturated and the flooded treatments had their roots growing directly into saturated soil.

Maximum rooting depth increased as moisture content decreased implying that root length is related to moisture availability. According to Samson *et al.,* (2002), IR36 roots grew longer and deeper into soil as the soil dried and became harder, as indicated, this is confirmed in this experiment not only for IR36 but also for Azucena.

Generally the pattern of rooting under the saturated conditions did not differ from that under the flooded conditions. Flooding did not change rooting depth pattern to an appreciable extent compared to saturated conditions.

4.3.3 Root dry mass
Figures 4.7 - 4.9 show root dry mass over time for rice varieties Azucena and IR36 respectively under the conditions imposed.

4.3.3.1 Azucena

Figures 4.7 and 4.8 both show root dry mass for Azucena: whereas the presentation is between the 30 cm and 15cm water table depth treatments and the saturated treatment in Fig 4.7, in Fig. 4.8 it is for the two water table depths and the flooded treatment.

Figure 4.7 shows that root dry mass for the plants were: 15 cm treatment > saturated treatment > 30 cm treatment. The mean root dry mass was about 1.2 g and 1g for the 15 cm and 30 cm water table depths respectively at the end of six weeks. Significant differences did not exist in root dry mass for the water treatments.

In Fig. 4.8, at the end of the 4th week there were no significant differences. At the end of the 6th week, root dry mass for the flooded treatment differed significantly from the other treatments. Root dry mass for the plants under the 30 cm water table depth was also significantly greater than those under the 15 cm water table depth. Mean root dry mass for the flooded treatment was 40 g, that for the 30 cm plants was 15 g and that for the 15 cm plants, 8 g at the end of the 6th week.

Whereas Fig. 4.7 shows that plants under the 15 cm water table depth had a greater root dry mass than those under the 30 cm water table depth though they were not significantly different, the reverse is observed for the results shown in Fig. 4.6, where the plants under the 15 cm water table depth had a lower root dry mass.
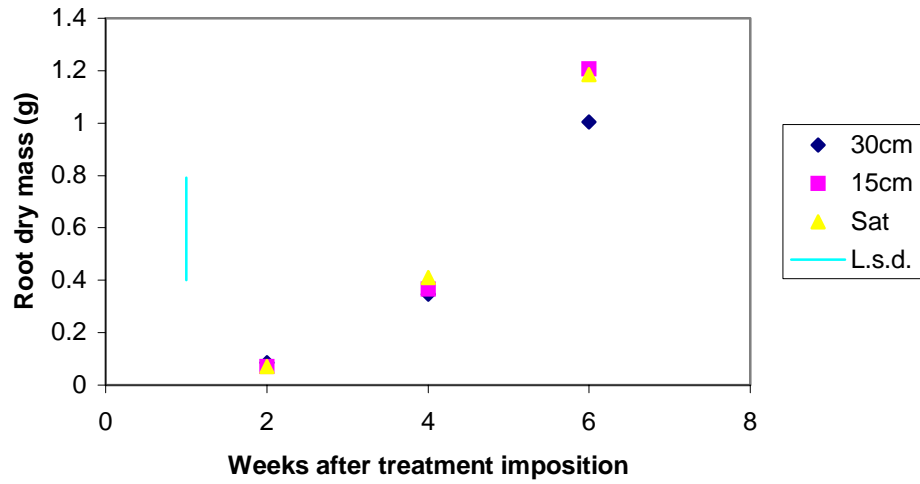
Figure 4.7 Mean root dry mass vs. weeks after treatment imposition for Azucena (Saturated) showing L.s.d. (p=5%).
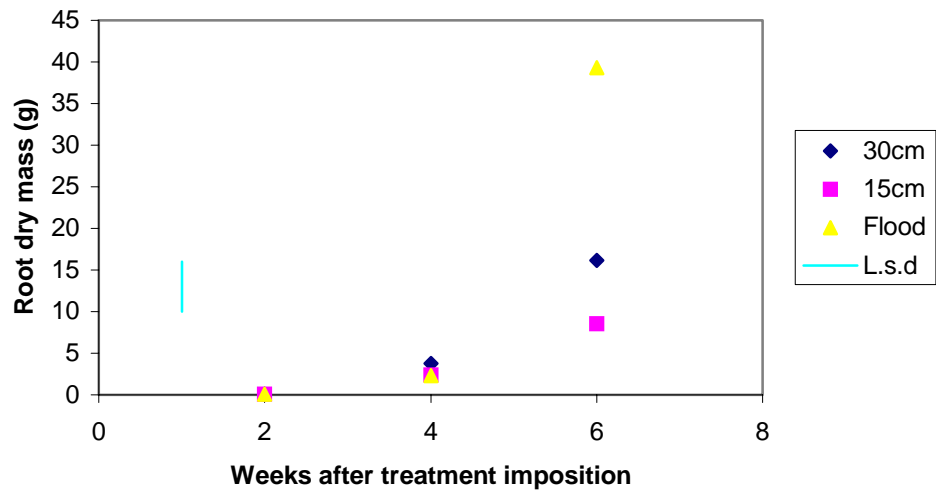
Figure 4.8 Mean root dry mass vs. weeks after treatment imposition for Azucena (Flooded) showing L.s.d. (p=5%).

4.3.3.2 IR36

Figure 4.9 shows that root dry mass for IR36 is lowest for the plants under the 15 cm water table depth but just about the same for those under the saturated and 30 cm water table depth treatments. No significant differences however exist.
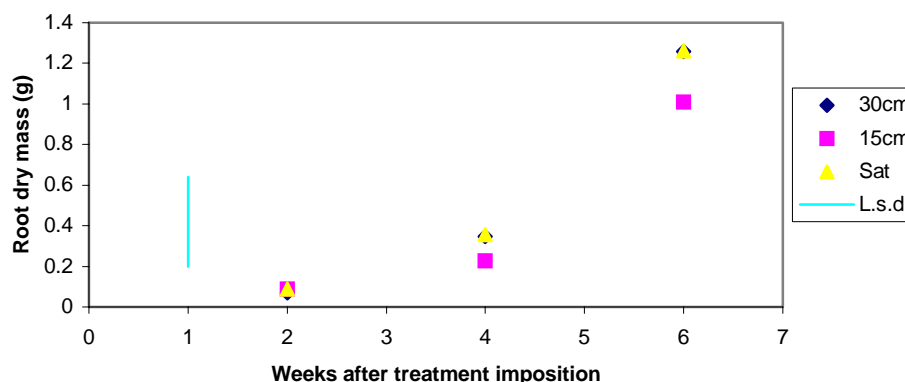
Figure 4.9 Mean root dry mass vs. weeks after treatment imposition for IR36 showing L.s.d. (p=5%).

4.3.3.3 General discussion

Root dry mass development was much faster from the 4th to the 6th week than from the 2nd to the 4th week for all the plants indicating a rapid change in growth rate after about the second week.

Surprisingly no clear relationship between root dry mass and growth medium moisture content was observed for both varieties of rice. According to Pradham *et al.,* (1973) in saturated and submerged conditions, even though oxygen diffusion is low, the number and dry weight of rice root systems are significantly higher than those in unsaturated soil. Okerby and Fukai (2001) also found that dry weight of rice grown on raised beds which had lower amounts of moisture, were lower compared with paddy. It was therefore expected that generally, root dry mass would be greatest for the flooded treatment followed by the saturated, then the 15 cm and 30 cm water table depth treatments respectively.

Root dry mass of the plants under the saturated treatment were not significantly different from that of the other treatments thus contradicting the findings above. Plants under the flooded treatment had a significantly greater root dry mass (Fig. 4.8), but the fact that root dry mass for the plants under 15 cm water table treatment in that experiment is lower than the 30 cm water table treatment makes the drawing of a conclusion difficult because there is no clear growth pattern for root dry mass increase under increasing moisture availability. More results are thus needed for a conclusion to be drawn.

Root dry mass for the experiment with the flooded treatment was about 10 times greater than those in the other experiments. As indicated above, the growth chamber was changed for the flooding experiment and there may have been some undisclosed factors, which influenced growth to such a great level. This however does not affect the discussion as the prime concern is the growth patterns that emerge.

4.3.4 Shoot dry mass
4.3.4.1 Azucena

Figure 4.10 shows that after 6 weeks the mean shoot dry mass for the 15cm water table depth treatment was highest followed by the saturated treatment then the 30cm water table depth treatment.
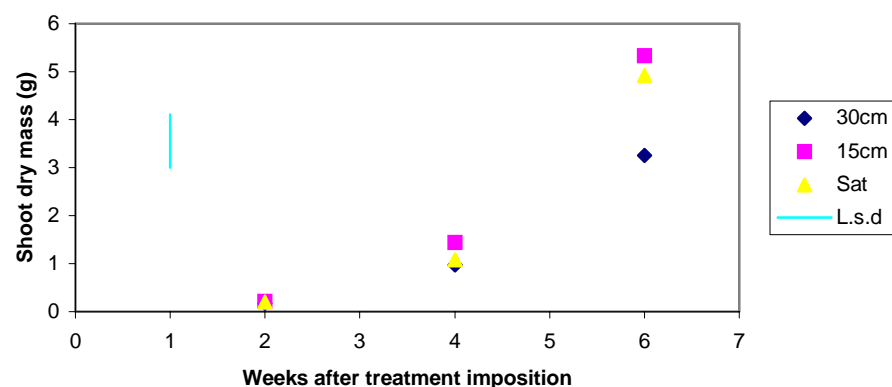
Figure 4.10 Mean shoot dry mass vs. weeks after sowing treatment imposition for Azucena (Saturated) showing L.s.d. (p=5%).

There is a larger rate of increase of shoot dry mass for the saturated and the 15cm treatments than for the 30 cm treatment from the 4th week to the 6th week. This sharp difference in growth could be due to differences in environmental conditions under the three treatments.

There appears to be no clear relationship between water availability and shoot dry mass, indicated by shoot dry mass for the 15 cm treatment being greatest and 30 cm least. Shoot dry mass for the 15 cm water table depth treatment and the saturated treatment were significantly greater than shoot dry mass for the 30 cm water table depth.
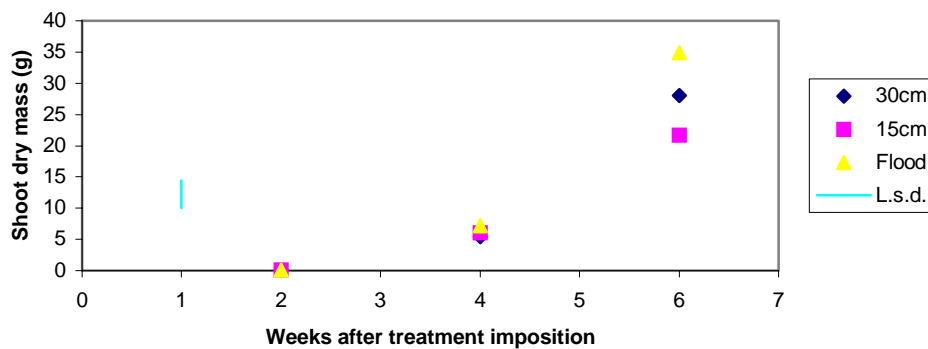
Figure 4.11 Mean shoot dry mass vs. weeks after treatment imposition for Azucena (Flooded) showing L.s.d. (p=5%).

Figure 4.11 shows that at the end of the fourth week there was no significant differences in shoot dry mass for the water treatments. Differences appeared at the end of the sixth week with the plants under the flooded treatment having a significantly greater shoot dry mass than the other two. Shoot dry mass for plants under the 30 cm water table depth treatment were also significantly greater than those under the 15 cm water table depth at the end of the sixth week.

The variations observed in root dry mass are also observed here in that shoot dry mass was significantly greater for the plants under the 15 cm water table in Fig. 4.10 but in the third experiment, Fig. 4.11, shoot dry mass for the plants under the 30 cm water table depth treatment are significantly greater than those under 15 cm

water table depth treatment. Moreover, mean shoot dry masses was also about 5 times greater under the third experiment. The reasons assigned for root dry mass pertain here.

4.3.4.2 IR36

Figure 4.12 shows that for IR36 initial increases in shoot dry mass was also slow but picks up from the 4th to the 6th week.
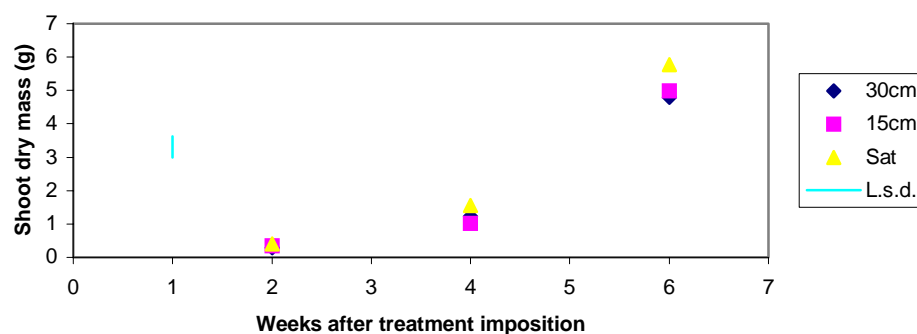
Figure 4.12 Mean shoot dry mass vs. weeks after treatment imposition for IR36 showing L.s.d. (p=5%).

The saturated treatment had the greatest shoot dry mass at the end of the 6th week, and shoot dry mass for plants under the saturated treatment differed significantly from those under the 30 cm water table depth treatment. The mean shoot dry mass values at the end of the 6th week are related to moisture contents in that the more moisture available the greater the shoot dry mass. This pattern was not observed before the end of the 6th week and could have changed beyond six weeks.

4.3.4.3 General discussion

Once again it is clear that growth in the third experiment (Fig 4.11) was better than for the other experiments for both varieties of rice. The minimum shoot dry mass in that experiment at the end of the 6th week was for the plants under the 15 cm water table depth treatment which was about 22 g whereas the maximum under the other experiments was for the plants under the saturated treatment which was about 6 g.

Generally shoot dry mass did not follow the pattern of increasing moisture content as observed by Price *et al.,* (2002). According to Puckridge and O'Toole, (1981) dry matter production until panicle emergence is a function of water used, dry weight is considered to be the most direct measure of water stress: dry weights are linearly related to water application rates. As indicated, the results of the experiment up till the end of the 6th week are not in total agreement with this observation.

Flooding appears to have made a significant impact on the shoot dry mass reflected in mean shoot dry mass for the plants under the flooded treatment being much greater than the mean shoot dry mass for the other treatments at the end of 6 weeks. The variation in growth pattern between Azucena under the saturated treatment and that under the flooded treatment however makes it difficult to draw any valid conclusions.

4.3.5 Root dry mass/shoot dry mass
The root dry mass to shoot dry mass ratio gives an indication of allocation of assimilates.
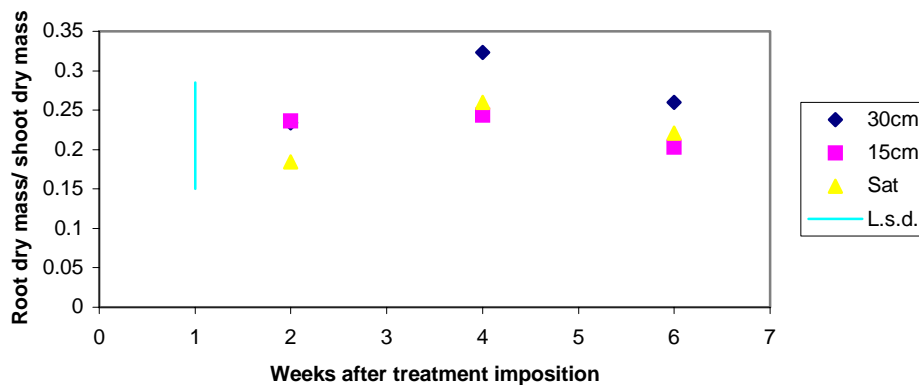
Figure 4.13 Ratio of root dry mass to shoot dry mass vs. weeks after treatment imposition for IR36 showing L.s.d. (p=5%).

There was a general increase of the ratio from the 2nd to the 4th week but this dropped from the 4th to the 6th week. This is to say that the rate of shoot growth was initially lower than root growth but this changed with time. The ratio for the 30 cm water table treatment was higher than for the others for the 4th and 6th weeks and the 15 cm water table depth treatment ratio was lowest. Significant differences existed only for weeks after treatment imposition and not for the water treatments. The water treatments therefore had no significant influence in allocation of assimilates.
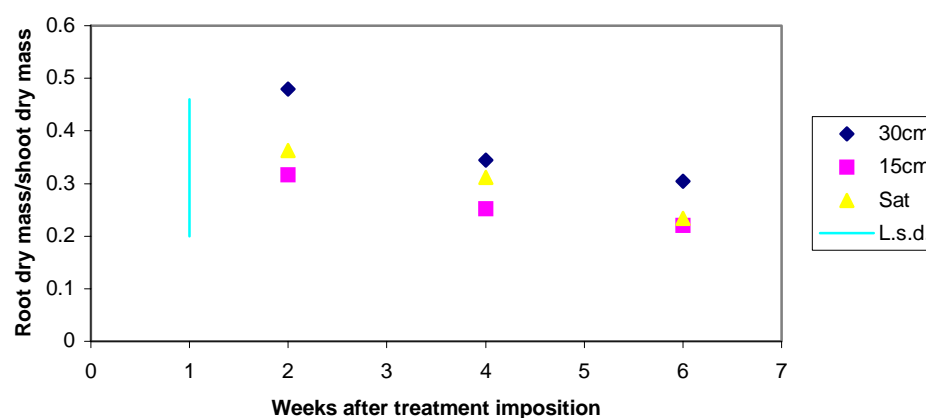
Figure 4.14 Ratio of root dry mass to shoot dry mass vs. weeks after treatment imposition for Azucena showing L.s.d. (p=5%).

Whereas in the case of IR36 there was an initial increase in the ratio of root dry mass to shoot dry mass, root to shoot dry mass decreased from the second week to the sixth week. This is an indication of lower root production for Azucena.

The ratio was highest for the plants under the 30 cm water table depth treatment followed by those under the flooded treatment then those under the 15 cm water table treatment. The fact that the driest treatment had the greatest ratio indicates that more assimilates were allocated to the roots when soils were drier. However, the 15 cm water table depth treatment, which was drier than the saturated treatment had the least ratio. That is to say more assimilates were allocated to the shoots for the plants under that treatment than were done for those under the saturated treatment.

Price *et al.,* (2002) observed that small differences in moisture variation led to a major shift in mass partitioning. They observed there was a major shift in mass partitioning such that there was nearly three times the root to shoot ratio in a water deficit treatment compared with the well-watered treatment. The shift in mass partitioning or allocation of assimilates in these experiments cannot be said to be major.

4.3.6 Mean total root number and sum of length of nodal roots
4.3.6.1 Azucena
Figures 4.15 and 4.16 show the plots for the sum of length of all nodal roots and the total root number of nodal roots for Azucena. The total root length and number gives an indication of the extent to which the roots can explore the medium for nutrients, the greater the number and length of roots available, the greater the extent to which the roots can explore the soil system for nutrients and by implication, the greater the potential for nutrient acquisition.

The two plots follow a similar pattern up to about the 4th week; there are no significant differences between the treatments. At the end of 6 weeks the values for the saturated and the 15 cm water table depth treatments were significantly higher than those for the 30 cm water table depth treatment.

Total root length for the saturated and 15 cm treatments were about twice the total root length for the 30 cm treatment. In addition total root number for the saturated and 15 cm treatments were also about twice that for the 30 cm treatment.
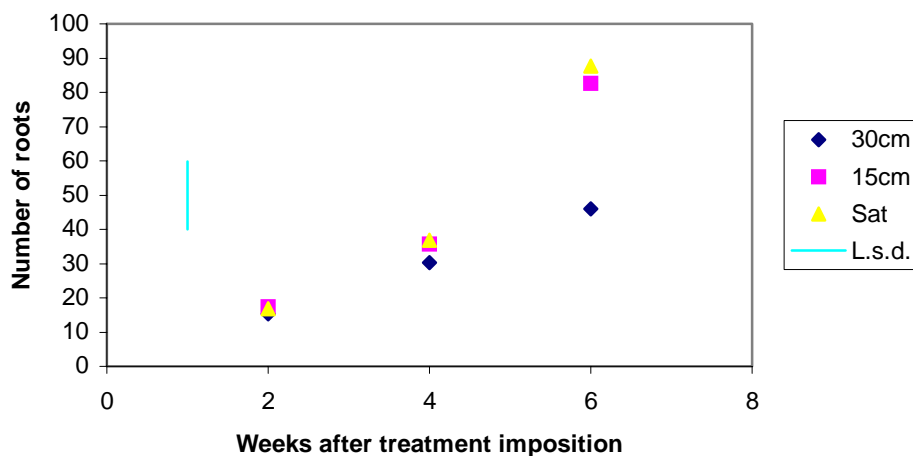
Figure 4.15 Number of roots against vs. weeks after treatment imposition for Azucena showing L.s.d. (p=5%).
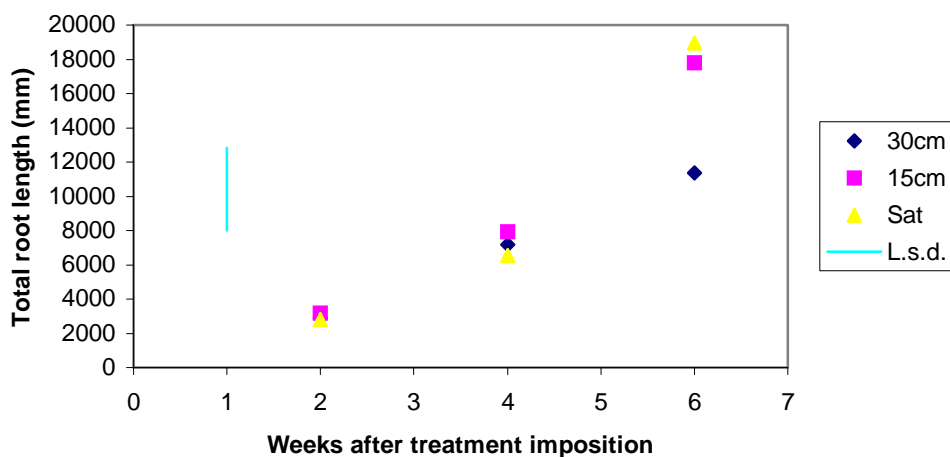
Figure 4.16 Total root length vs. weeks after treatment imposition for Azucena showing L.s.d. (p=5%).

4.3.6.2 IR36

In the case of IR36 (Figs 4.17 and 4.18) there was also a similar growth pattern for the total root number plot and the total root length plot. They indicate that the

more moisture available, the greater the total root length and root number produced.
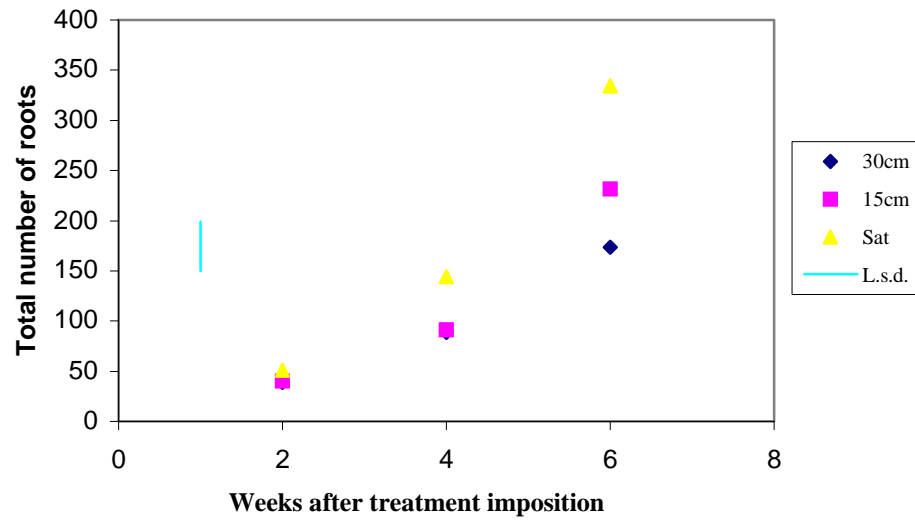
Figure 4.17 Total root number vs. weeks after treatment imposition for IR36 showing L.s.d. (p=5%).
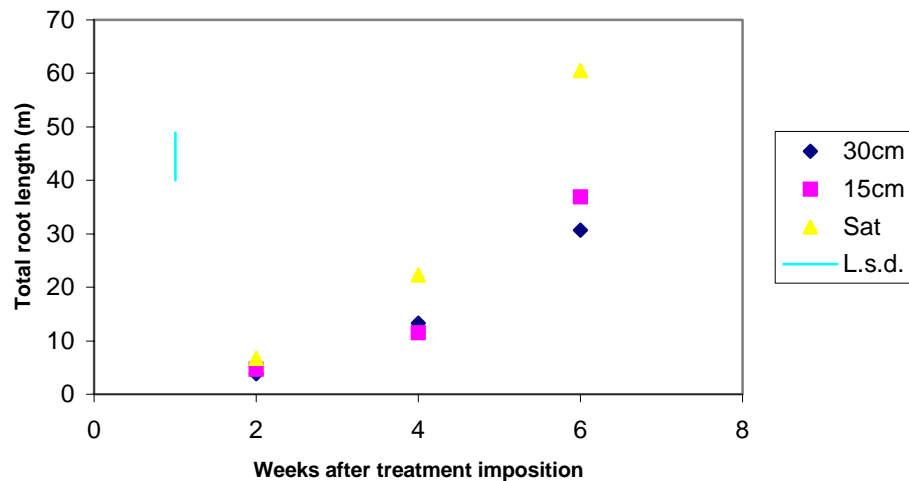
Figure 4.18 Total root length vs. weeks after treatment imposition for IR36 showing L.s.d. (p=5%).

The saturated treatment had higher total root length than the others from the end of the 2nd week. Differences between the total root lengths for the saturated treatment and the others were significant after about the 4th week. Total root length was about two times more for the saturated treatment than for the other treatments, and number of roots more than one and a half times greater for the saturated. The greater number of roots and longer root length implies greater volume of soil covered and greater potential for uptake of nutrients for the plants under the saturated treatment.

A comparison of the two varieties indicate that whereas in the case of Azucena there may be a depth of water table below which differences begin to emerge, this depth lying between 15 cm and 30 cm, in the case of IR36, this depth lies between the saturated and 15 cm. This reflects the differences in the different varieties response to differences in levels of soil water.

4.3.7 Root length greater than 30 cm

According to Samson *et al.,* (2002) oxygen supply via aerenchyma restricts roots to surface layers when the soil is flooded and the soil remains essentially anaerobic. Naklang *et al.,* (1996) concluded that root growth of upland rice was much less than that of lowland crops, indicating the sensitivity of root growth to soil water deficit. They observed that lowland conditions always resulted in a shallow root system with little root development below 30 cm.

Root length above 30 cm is used as an indication of the extent to which the roots can explore deeper depths of soil for water and nutrients. In upland rice, farmers have traditionally used varieties with deep root systems that can avoid drought by extracting more water from deeper soil layers (Puckridge and O'Toole, 1981). Barison (2002) also attributed greater uptake of nutrients of rice under the System of Rice Intensification (SRI) to the fact that there were more roots greater than 30 cm long.

4.3.7.1 IR36

Figure 4.19 shows the sum of roots greater than 30 cm and suggests that the drier the soil, the longer the roots and subsequently the greater the depths to which the roots explore. From the end of the 2nd week the length of roots for the 30 cm treatment had the highest value followed by the 15 cm treatment and then the saturated treatment. It is worth noting the rapid increase of the root lengths from the 4th to the 6th week.
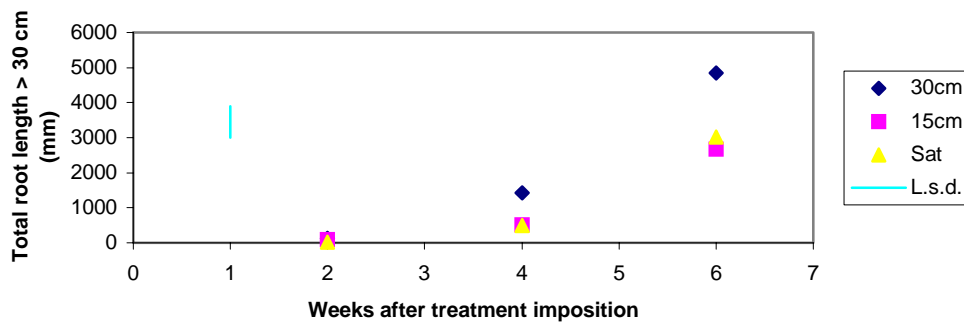
Figure 4.19 Total root length greater than 300 mm vs. weeks after treatment imposition (IR36) showing L.s.d. (p=5%).

Significant differences appear between the 30 cm treatment on one hand and the saturated and 15cm treatment on the other hand. Just as for total root length and root numbers, there appears to be a water depth between 15 cm and 30 cm where the differences start to become significant.
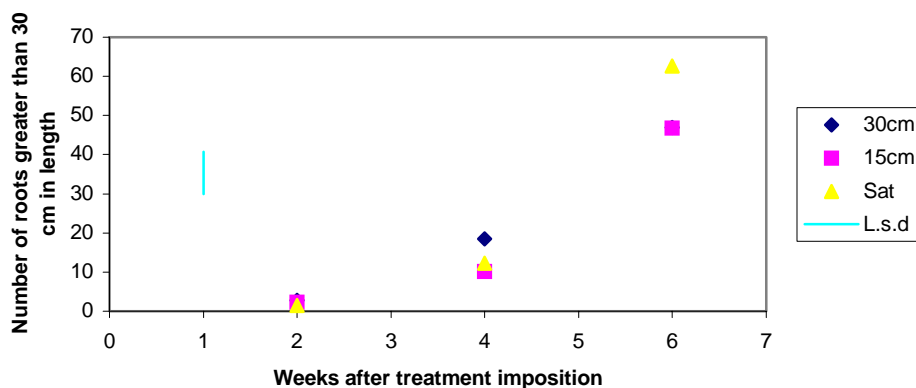
Figure 4.20 Number of roots greater than 300 mm vs. weeks after treatment imposition (IR36) showing L.s.d. (p=5%).

In the case of the number of roots there was no clear pattern of increase however at the end of the 6th week, the plants under the saturated treatment had a significantly greater number of roots greater than 30 cm long. The plants under the saturated treatment, though they had the greatest number of longer roots had the lowest rooting depth (See Fig. 4.6).

4.3.7.2 Azucena

Azucena provides an interesting pattern of increase in number of roots greater than 30 cm, the plants under the saturated treatment having the lowest number of roots greater than 30 cm up till the 4th week.
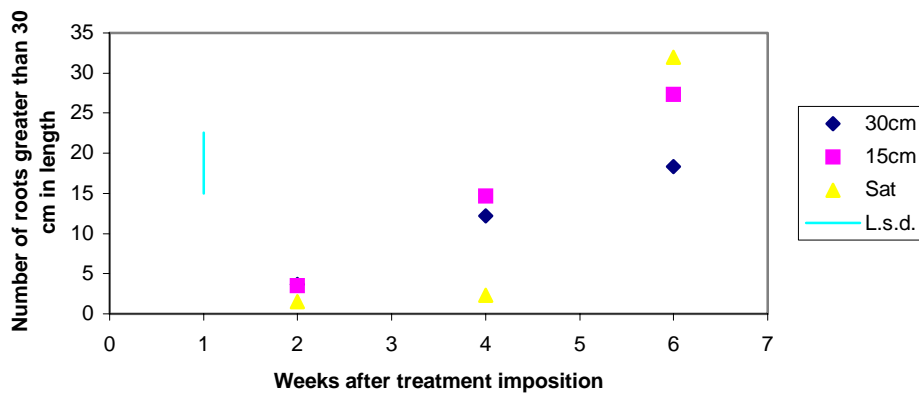
Figure 4.21 Number of roots greater than 30 cm (Azucena) showing L.s.d. (p=5%).

At the end of the 4th week number of roots were significantly lower than those for the other treatments. Between the 4th and the 6th weeks there was rapid increase in number of roots for that treatment resulting in it having the greatest value at the end of the 6th week.

In this case, there were significant differences between the plants under the saturated and the 15 cm treatment on one hand and the 30 cm treatment water table depth treatment on the other. This once again suggests different responses of the varieties to soil water. It therefore appears that even though the saturated treatment starts with the least number of roots greater than 30 cm, the lengths are

such that the sum of these are not much lower that those for the other two treatments (Fig. 4.20). Moreover, whereas growth appears to be steady for the plants under the 30 cm and the 15 cm water table depth treatments, there was a large rate of increase for the plants under the saturated treatment after the 4th week.
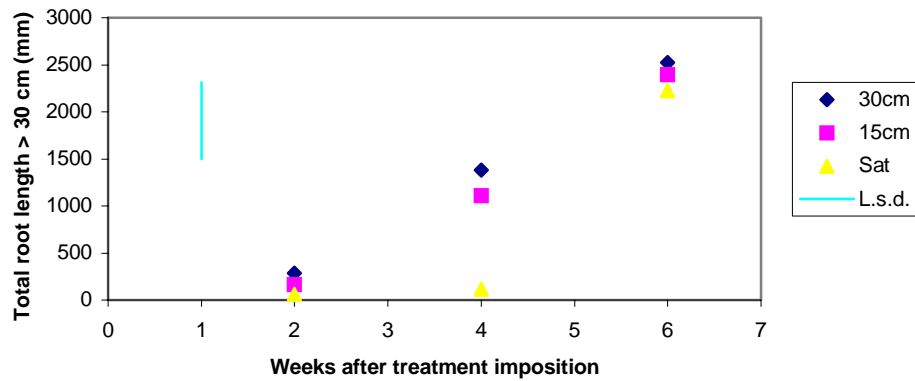
Figure 4.22 Total root length greater than 30 cm for Azucena showing L.s.d. (p=5%).

Though there were more roots greater than 30 cm for the saturated treatment at the end of 6 weeks, the sum of the lengths of the roots was lower than for the 30 cm water table depth treatment, implying the mean length of roots was greater in the case of the plants under the 30 cm treatment. Right from the 2nd week, the total root length for the 30 cm treatment stayed higher than the others. The plants under the 30 cm water table depth had a greater potential to access moisture at lower depths.

4.3.8 Ratio of total length of all roots greater than 30 cm to total length of all roots
The fraction of roots greater than 30 cm for the 30cm water table depth treatment was greatest at each harvest; it is about two times higher than for the 15cm treatment and three times higher than for the saturated treatment.
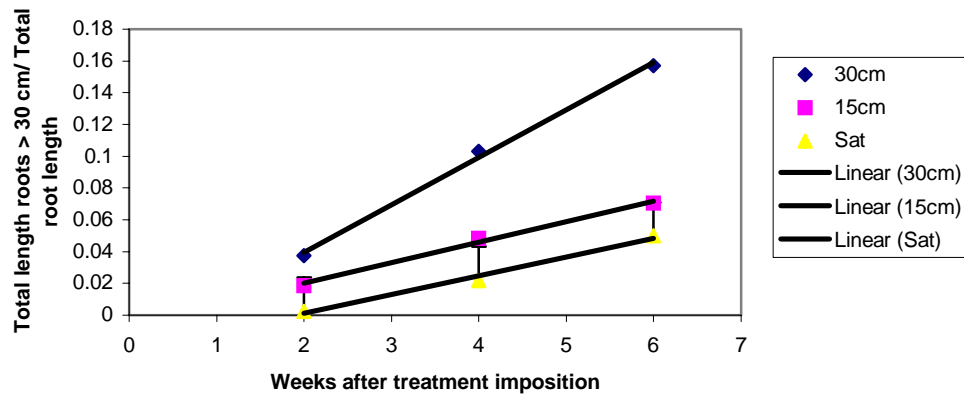
Figure 4.23 Fraction of roots greater than 30 cm (IR36).

The plots were linear in all cases making it possible to predict the ratio of length or roots at any point between the 2nd and 6th weeks.

The equations for the respective plots are as follows:

30 cm water table depth: $y = 0.0299x - 0.0205$

$R^2 = 0.9969$

15 cm $y = 0.013x - 0.0059$

$R^2 = 0.9925$

Saturated $y = 0.0118x - 0.0226$

$R^2 = 0.9894$

Where y is the ratio of the sum of roots greater than 30 cm to the total root length and x is weeks after treatment imposition.

At the end of 6 weeks 16 % of root under the 30 cm water table depth treatment, 7 % under the 15cm water table depth treatment and about 5 % under the saturated treatment are above 30 cm long.
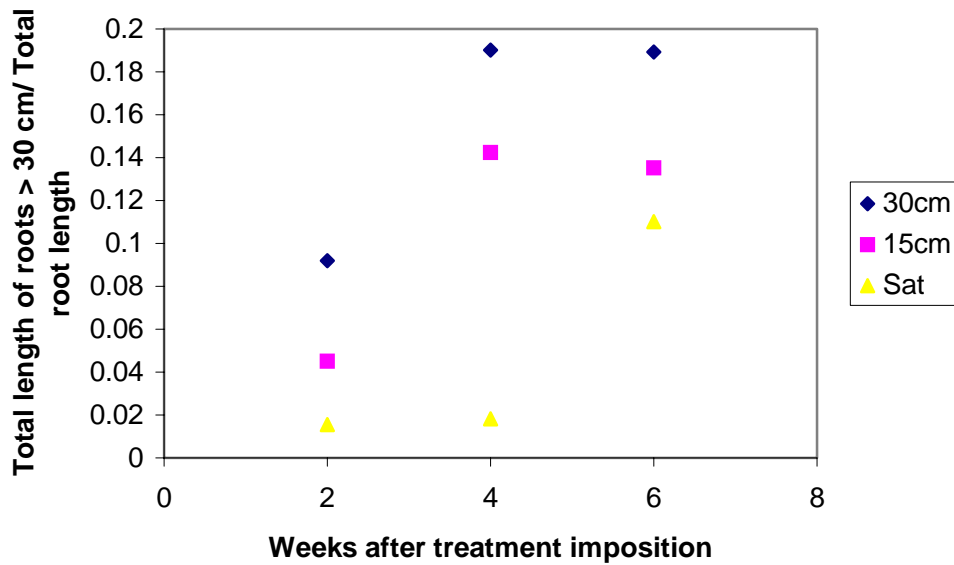
Figure 4.24 Fraction of roots greater than 30 cm vs. weeks after treatment imposition (Azucena).

As in the case of IR36, the ratio of length of Azucena roots greater than 30 cm to total root length was highest for the plants under the 30 cm followed by those under the 15 cm treatment then the saturated ones. The pattern of increase can be expressed logarithmically for both the 30 cm and the 15 cm treatments but in the case of the saturated treatment it is exponential. After four weeks the ratio decreases in the aerated treatments whilst it increases in the saturated treatment. The pattern varied from that for IR36.

18 % of the roots of plants under the 30 cm water table depth treatment, 14 % under the 15 cm water table depth treatment and 12 % under the saturated treatment were more than 30 cm in length at the end of six weeks. A comparison of the percentage of roots greater than 30 cm long shows that generally Azucena roots are longer than roots of IR36.

Unlike the case of IR36, the accuracy in predicting the ratio may not be very high.

4.3.9 Tiller numbers

The number of tillers is approximately constant for any variety of rice under comparable conditions, but tillering is influenced by cultural conditions, spacing of plants, amount of nitrogen fertilizer applied, weeds and water supply (Grist, 1986). Some of the conditions, which varied in this experiment, are the water supply and the amount of available nutrients in that different water table depths were used which led to different levels of nutrients in the cores.

4.3.9.1 Azucena

As Fig. 4.25 shows, tiller numbers were greatest for the 15 cm water table depth treatment followed by the saturated then the 30 cm water table depth treatment for Azucena, the pattern of increase cannot be attributed to water availability. The tiller numbers for the 15 cm treatment were significantly different from the 30 cm treatment but not from the saturated one. It is interesting that tiller production was greater under a condition other than saturated which is expected to provide the optimum conditions both for availability of nutrients and water.
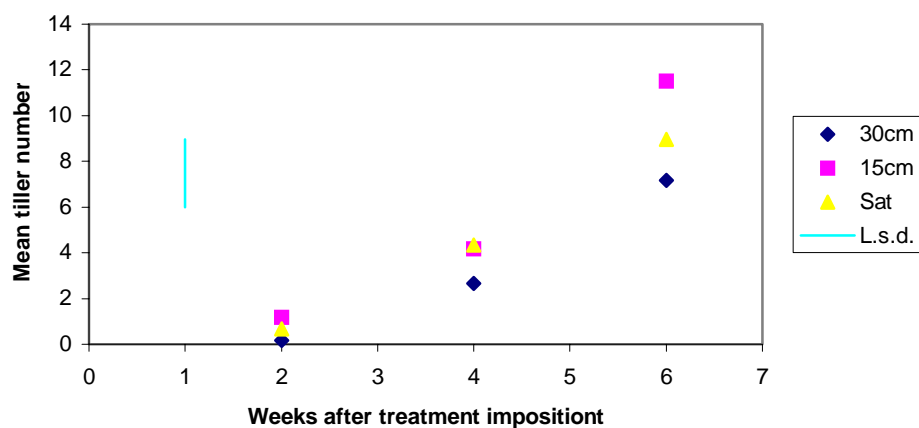
Figure 4.25 Mean tiller number vs. weeks after treatment imposition (Azucena) showing L.s.d. (p=5%).

Figure 4.26 shows the mean number of tillers at different stages of growth for Azucena.
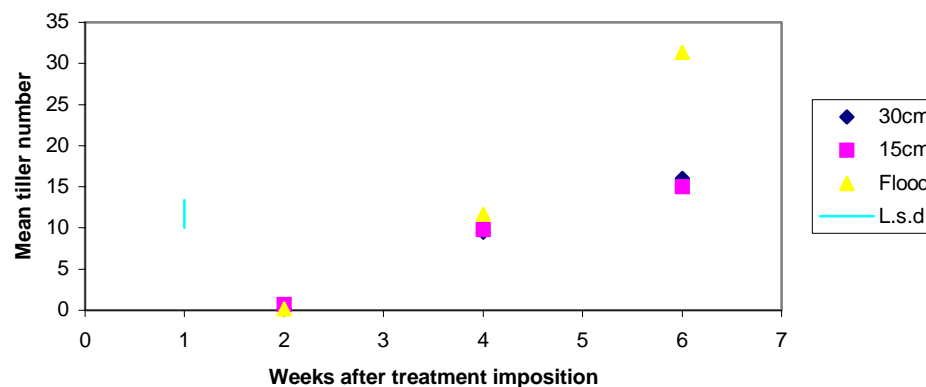
Figure 4.26 Mean tiller number vs. weeks after treatment imposition for Azucena showing L.s.d. (p = 5%).

At the end of the fourth week, there were no significant differences in number of tillers for the water treatments. At the end of the sixth week number of tillers for the flooded plant were significantly greater than for the other treatments. Development of tillers slowed down dramatically for the plants under the 15 cm and 30 cm water table depth treatments whereas it increased for the plants under the flooded treatment from the fourth to the sixth week.

For Azucena whereas tiller numbers (Fig 4.26) were about two times more for the plants under the flooded treatment than for the plants under the other treatments, shoot dry mass for the plants under the flooded treatment (Fig. 4.11) were less than two times more than the others indicating that the mean dry mass of tillers are greater for the plants under the other two treatments, the greatest being for the plants under the 30 cm water table depth.

The discrepancies which appeared for root dry mass and shoot dry mass appear here as well in that tiller numbers for the 15 cm treatment shown in Fig. 4.25 were significantly greater than those for the 30 cm treatment, but in Fig. 4.26, they are

lower, this once again indicating there were major variations in growth between the third experiment and the first two experiments.

4.3.9.2 IR 36

In the case of IR36, (Fig. 4.27) after about 2 weeks, there were no significant differences in tiller numbers for all the treatments. Tiller numbers were greatest for the saturated treatment after 4 weeks and stayed that way till end of the experiment. That for the 15 cm treatment was significantly different from the saturated treatment after about 4 weeks but the differences disappeared after 6 weeks.
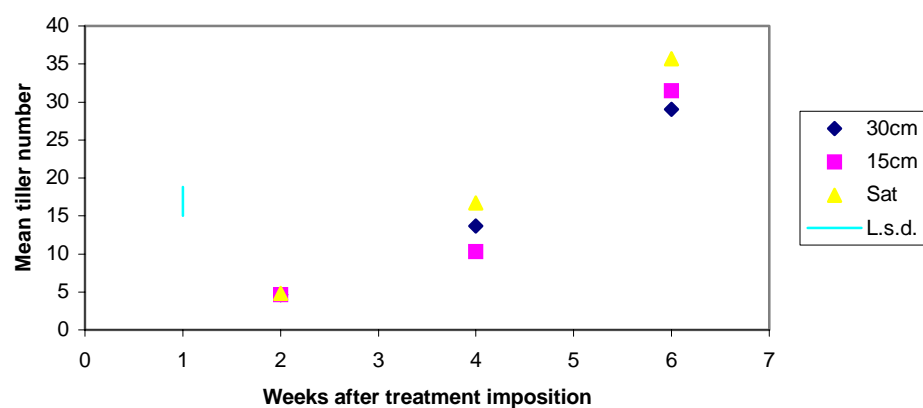
Figure 4.27 Mean tiller number vs. weeks after treatment imposition (IR36) showing L.s.d. (p=5%).

There were no significant differences between the 15 cm and the 30 cm water table depth treatment up to 6 weeks, but the 15 cm treatment shows a rapid increase in tiller production between the 4th and 6th weeks.

4.3.10 Plant height

Plant height was highest for the 15 cm followed by the saturated treatment and then the 30 cm treatment at all the harvests for Azucena (Fig. 4.28); these differences were not significant though. In this case as in some of the others, there is no clear explanation as to why this is so since the saturated conditions were expected to provide better conditions for growth.
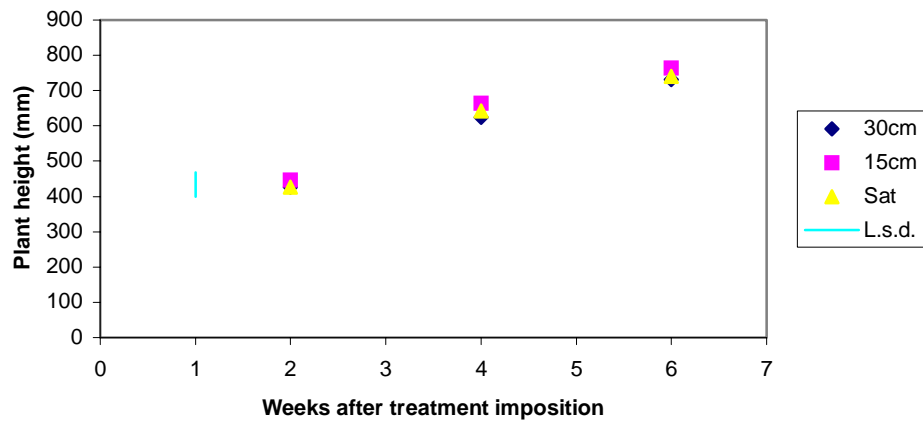
Figure 4.28 Mean Plant height (Azucena) showing L.s.d. (p=5%).
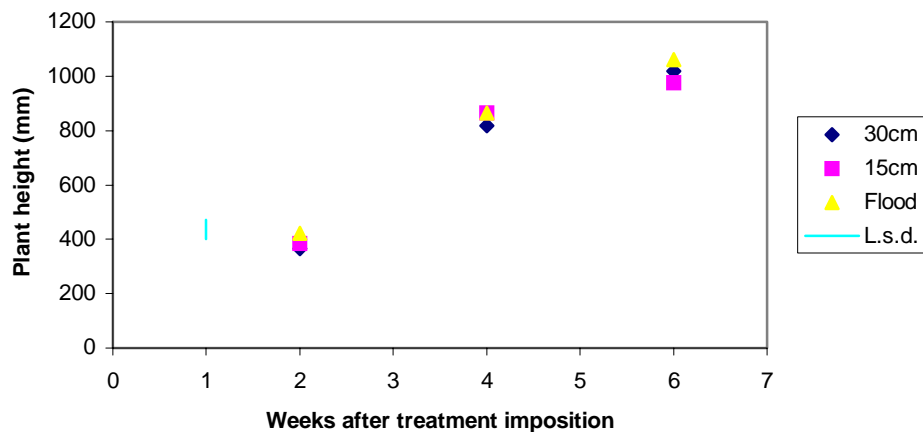
Figure 4.29 Mean Plant height vs. weeks after treatment imposition for Azucena, showing L.s.d. (p=5%).

In Fig 4.29 mean plant height was about 400 mm after two weeks, and after four weeks was around 800 mm indicating that rate of increase in plant height was linear up to the fourth week. The rate of increase was smaller after the fourth week. The heights of the plants under the flooded treatment were significantly different from those under the 15 cm water table at the end of the 6th week. The heights of plants under the 30 cm water table depth did not differ significantly

from the others. They were however greater than those under the 15 cm water table depth.

The mean plant heights shown in Fig. 4.29 are about 20 cm longer than for those presented in Fig. 4.28 once again indicating that generally growth was better in this experiment than in the previous ones.
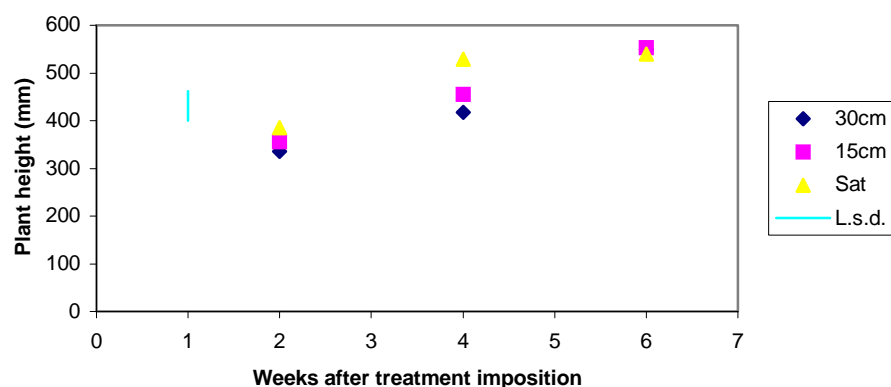
Figure 4.30 Mean Plant height vs. weeks after treatment imposition (IR36) showing L.s.d. (p=5%).

In Fig. 4.30 mean plant height was initially greatest for the wettest treatment but this changed at the end of six weeks. From 4th to the 6th week there was no increase of plant height for the plants under the saturated treatment but large increases occurred for the other two, with the plant height for the 30 cm treatment experiencing the largest increase. This could be due to the fact that more moisture and nutrients were available at this stage so growth rate increased. Significant differences occurred between the plants under the saturated and those under the 30 cm water table depths at the end of the 4th week. There were no differences at the end of the 6th week though.

Price *et al.,* (2002) observed that the rice plant height in a treatment, which was started with a water deficit at sowing, was greatly decreased compared with shoots from a well-watered treatment. This observation was significant at 14 days, and by 49 days, shoot height in the deficit treatment was decreased to 49 % of the well-

watered treatment. Overall, the there were no large differences in plant heights in these experiments.

4.3.11 Environmental factors
The data on environmental factors were collected only under the third experiment.

4.3.11.1 Sand Temperatures
Soil temperature affects plant growth indirectly by affecting water and nutrient uptake as well as root growth. At a constant moisture content, a decrease in temperature results in a decrease in water and nutrient uptake. In this case there is a certain level of complexity in that there are three different moisture levels leading to three different temperature regimes and therefore different levels of influence in growth.
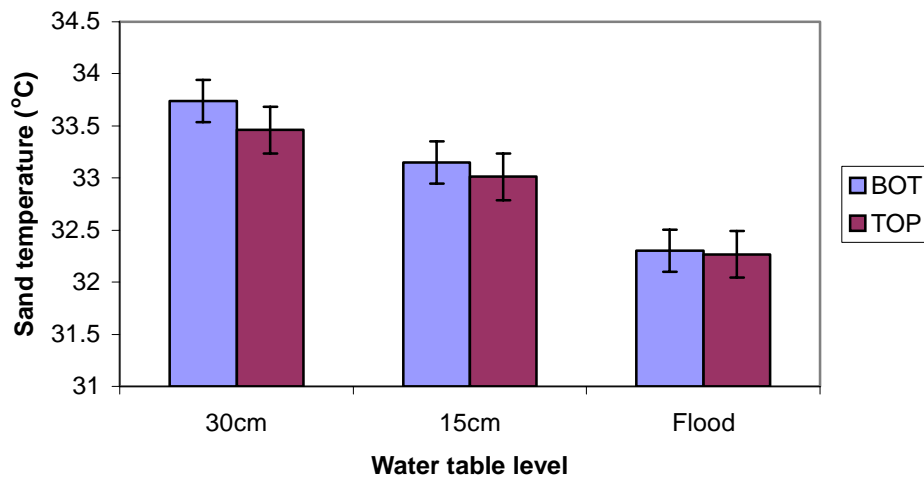
Figure 4.31 Sand temperature at depths of 1cm (TOP) and 10cm (BOT) from surface with Y error bars for L.s.d. (p=5%).

Temperatures were determined at two depths: 1 cm and 10 cm below surface. This was done in order to obtain an idea of the temperature gradient in the rooting zone. Temperatures were significantly different for the different treatments at each depth, they were not significantly different between the two depths in any of the treatments.

As already indicated, generally soils with a deeper water table heat up faster than those with a shallow water table (Hillel, 1980) and there is such a reflection here in that the treatments with the deeper water table depths are significantly hotter than those with the shallow water table depths.

The actual differences in temperatures were quite small, about 0.5 ^{o}C between the 30 cm and the 15 cm water table treatments, and 1.25 ^{o}C between the 15 cm and flooded treatments however, Songfa (1995) observed differences in growth of rice for temperature differences of between 0.2 and 0.4 ^{o}C, with the higher temperatures producing better growth. There is therefore the possibility that temperatures will contribute to differences in growth both directly and also through the influence on soil chemical properties.
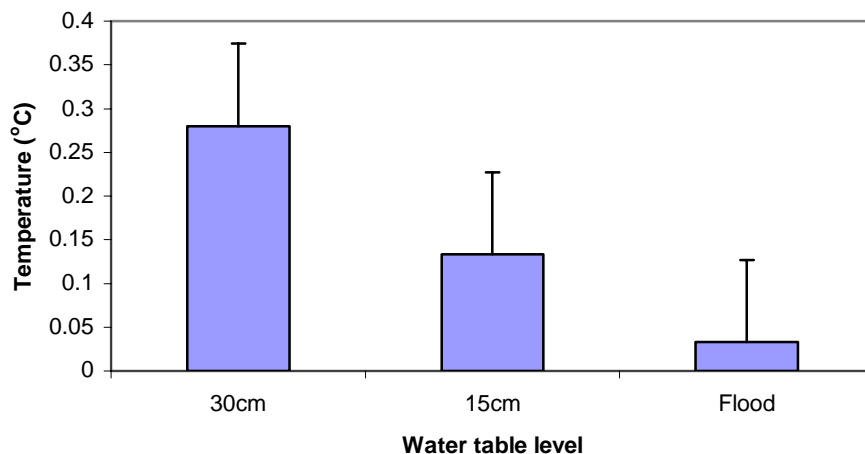
Figure 4.32 Mean difference in temperature (^{o}C) between soil surface and depth 10 cm below the surface for three water table levels with Y error bars for L.s.d. (p=5%).

Differences in temperatures between TOP and BOT vary for the water treatments. The differences were significantly different between the 30 cm water table depth treatment and the flooded treatment. These differences reflect moisture gradients; greatest under 30 cm depth followed by 15 cm and the flooded. Soil temperature gradients increase with decreasing moisture contents.

According to Hillel (1980) the volumetric heat capacity for sand of volumetric moisture content of 0.0, 0.2 and 0.4 are 0.3, 0.5 are 0.7 cal cm^{-3} ^{o}C^{-1} respectively. The volumetric heat capacity is the amount of heat required to raise unit volume of soil by 1 ^{o}C. The volumetric moisture contents for the treatments were: 16.1 % for the 30 cm water table depth, 33.8 %for the 15 cm water table depth and 44.4 % for the flooded treatment.

Figure 4.33 is a plot of the volumetric heat capacities against volumetric moisture content according to Hillel (1980); the volumetric heat capacities for the moisture contents obtained in this experiment may then be estimated, which are: 0.36 for the 30 cm water treatment, 0.638 for the 15 cm water table treatment and 0.744 for the flooded treatment. It would thus require two times as much heat to raise the temperature of a volume of growth medium by 1 ^{0}C in a flooded system than would be required for a water table depth of 30 cm. Thus, even though there would be more heat under the flooded system, this would not be reflected in the temperature values.
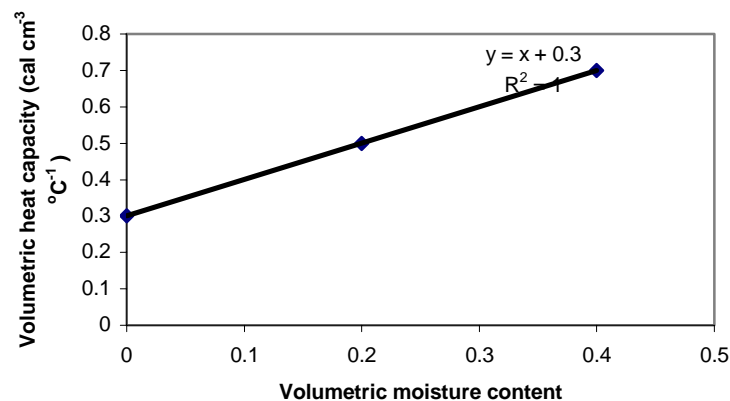
Figure 4.33 Volumetric heat capacity (cal cm^{-3} ^{o}C^{-1}) vs volumetric moisture content. Values were adapted from Hillel (1980).

4.3.11.2 Total Oxides of Nitrogen (TON)

Total oxides of nitrogen in this report refer to NO_3^-; NO_2^- and N_2O. Levels of NO_2^- determined were very low, relatively, (at about 0.1mg L-1) and were assumed to

be negligible, N_2O was not measured and NO_3^- is therefore used interchangeably with TON in the rest of the report.

It has been alluded to that differences in moisture content may not explain differences in growth of the plants under the conditions imposed. Moisture content will however influence other factors, which will have a greater impact on growth. The main determining growth factor then could be level of nitrogen available. It has already been noted that constituents of growth are dependant on levels of nitrogen available. As different levels of nitrogen are available under different levels of the water table growth differences then are expected to appear under the different depths of the water table primarily as a result of differences in levels of nitrogen available.
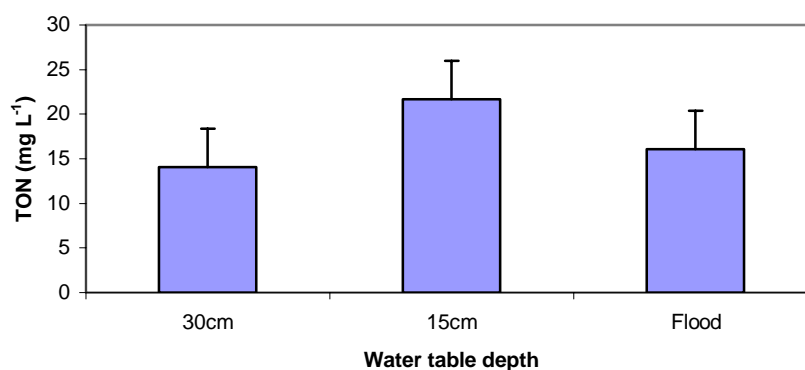
Figure 4.34 TON against water table depth with error bars representing L.s.d. (p=5%).

Mean values of TON (NO_3-N) under a water table depth of 15 cm was significantly greater than for the flooded treatments as well as for the plants under the 30 cm water table depth. NO_3^- under the flooded treatments were higher than for the plants under the 30 cm treatment, this was however not significant.
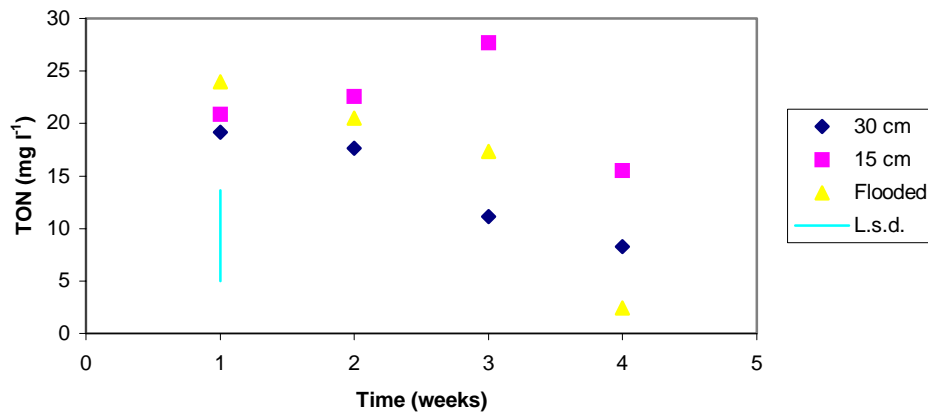
Figure 4.35 TON values against sampling times showing L.s.d.s (p=5%).

Figure 4.35 shows values for NO_3^- at different times during the experiment. Though Fig 4.34 shows that there were significant differences in NO_3^- levels, these appeared only for the third and fourth weeks. After the third week there was a rise in the amount of nitrogen for the 15 cm water table treatment. The Figs. 4.34 and 4.35 above give the concentration of nitrates in solution. Multiplying these figures by the amount of moisture present gives the total amount of nitrates in mg present in the system. This is what has been done and presented in the figures below
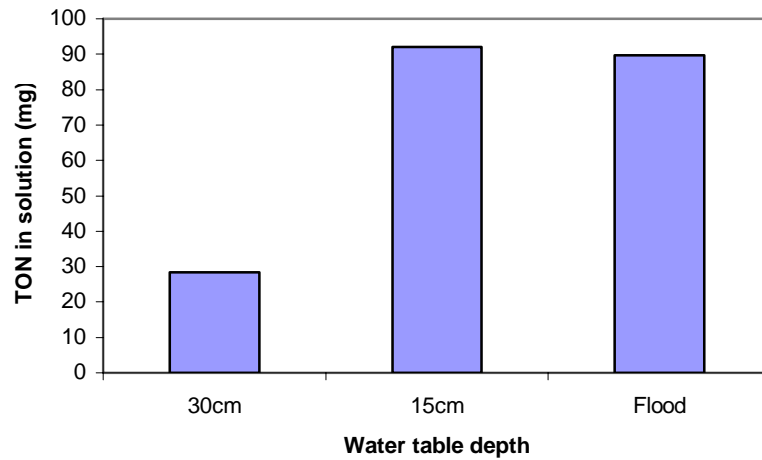
Figure 4.36 TON against water table depth.

.

The patterns do not differ from the plots (Fig. 4.34 and 4.35) above; there are big differences in amounts of nitrates available though. The amount of TON is still higher under the 15 cm treatment, followed by the flooded treatment. The TON value for the 30 cm treatment is much lower than for the other two.
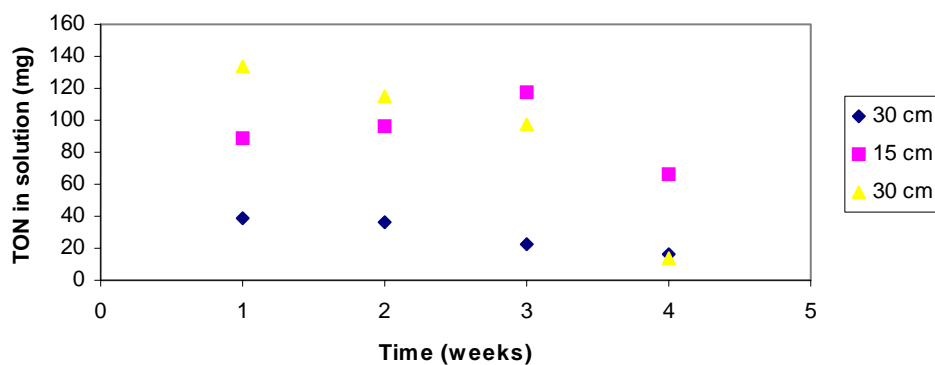
Figure 4.37 TON values against sampling times.

The plot of TON over time shows that the flooded treatment started at the highest point and drops over time. The 15 cm treatment started a little lower but instead of

decreasing, increased initially before finally dropping. The 30 cm treatment started out lowest and dropped but at a slow rate. Plant nitrogen content was not measured and so it is not possible to determine if the drop in nitrate levels for the flooded treatment was as a result of de-nitrification or uptake by the plant. Moreover, water use was also not measured, as that would also give an indication of uptake.

Utilisation of nitrates under the 15 cm water table depth plants were thus lower than the others leading to the lower results than for the plants under the 30 cm water table depth treatment in the third experiment. The drop for the flooded treatment could also be attributed to high levels of uptake leading to the large increase in shoot dry mass from the 4th to the 6th week.

4.3.12 Total biomass production

Figures 4.38 to 4.40 show total biomass for Azucena and IR36 for the water treatments. The pattern displayed is similar to that for shoot dry mass thus the same arguments can be made here. Considering all three plots, just as for shoot dry mass, the plants under the 30 cm treatment had a lower total biomass. Between the 15 cm and the saturated as well as flooded treatments, it is not possible to draw a conclusion due to similar discrepancies as occurred for the shoot dry mass.
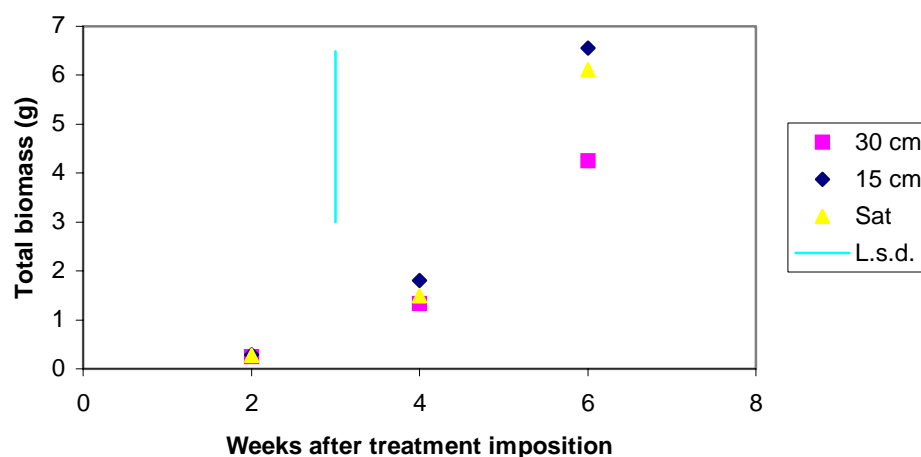
Figure 4.38 Total biomass over time (Azucena) with L.s.d. (p=5%).
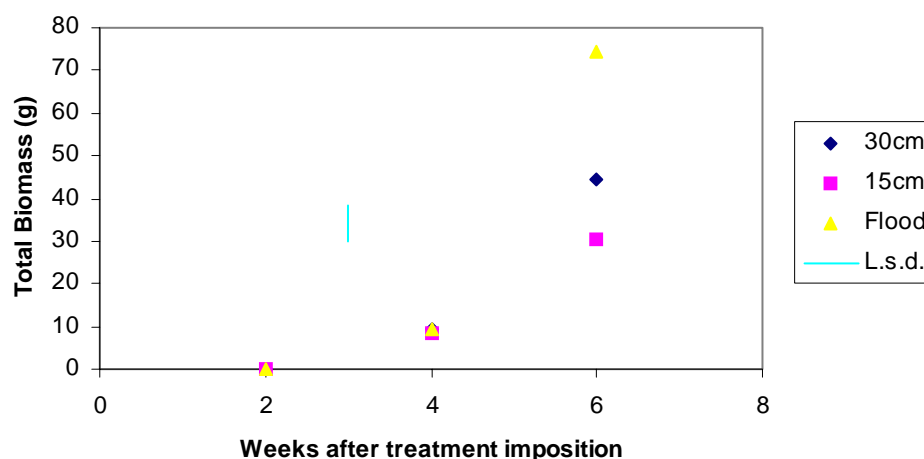
Figure 4.39 Total biomass over time (Azucena) with L.s.d. (p=5%).
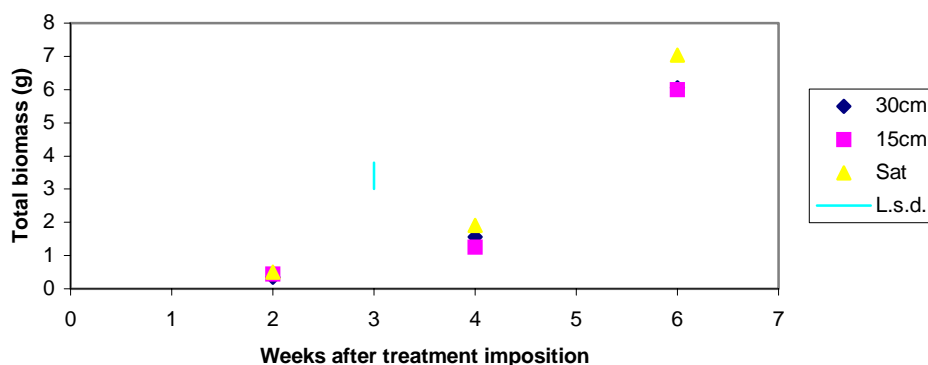
Figure 4.40 Total biomass over time (IR36) with L.s.d. (p=5%).

4.4 CONCLUSIONS

1. Moisture content and growth

Moisture content was greatest under the flooded conditions as expected, followed by the saturated conditions, then the 15 cm water table depth, and finally the 30 cm water table depth, growth parameters were thus expected to be greatest under the saturated treatment followed by the 15 cm then the 30 cm water table treatment. There however was so much variation in growth in relation to availability to moisture content that it is not possible at this point to conclude that the more moisture available, the better the growth of the plants. Generally growth

under the 30 cm water table depth appears to be lower than the others but for that between the 15 cm water table depth, the saturated treatment and the flooded treatment it is difficult to draw a conclusion as to which treatment was best. Growth of rice, generally, may therefore be driven more by some other factors than moisture availability.

2. Rooting depth

In all the treatments the rooting depth under the 30 cm water table depth treatment was greatest followed by the 15 cm water table depth treatments. The drier the soil, the longer rice roots grow. This may be an attempt to reach for more nutrients and moisture. Initial rapid growth of the roots of the 30 cm treatment plants indicates an attempt to reach to deeper depths in search of more moisture and nutrients. The plants under the 30 cm water table treatment had a greater total root length below 30 cm and thus greater access to nutrients below that depth. The plants under the saturated treatment had the greatest total root length overall though this was concentrated towards the surface, giving them advantages in nutrient acquisition closer to the surface.

3. Plant height

Variation in plants height at the end of six weeks is rather negligible, and it can be concluded that the treatments did not have any significant influence on the height of the plants.

4. Root mass / shoot mass

When soil moisture levels are lower, more assimilates are allocated to the roots of the plants. The plants under the 30 cm water table depth treatment had the greatest root to shoot dry mass ratio. As moisture content increase, allocation shifts from roots to shoots indicated by the ratio being least for the 15 cm water table treatment. As moisture content is still increase towards saturation, there is yet a shift in allocation thereby leading to a decrease in the ratio.

5. Tiller numbers

Overall, the plants under the 30 cm water table depth treatment had the least number of tillers. This indicates that tiller production decreases when moisture content is low. As moisture levels increases however the pattern of increase no longer corresponds to the increasing levels of moisture.

6. Nitrogen Availability

Nitrogen availability varied under the three conditions imposed and these had an impact on the growth of thee plants. The plants under the 15 cm water table depth fared worse than the others in the presence of more nitrogen and it appears some factor hindered uptake.

7. Soil temperatures

Mean differences in soil temperatures though significant were rather low and thus could not appreciably influence growth such as to lead to major differences.

8. Growth pattern

This inconsistency in growth pattern could be attributed to variations in the growth chamber especially with regards to the strength of the draught generated by the fans. It was observed that plants in areas where the draught was greater fared worse than those in areas of lower draught.

Growth pattern did not follow water availability in that the plants under the lower moisture contents in some instances fared better than those under more moisture. This implies that water may not be the main driving force in growth of rice. There is the possibility however that environmental factors, especially the availability of nutrients, especially nitrogen could be the main factor influencing growth of rice. This is explored in the next section where the experiment focuses on the effect of the environmental conditions on growth of rice.

CHAPTER 5: CHARACTERISING THE ENVIRONMENT UNDER A WATER TABLE CONTROL SYSTEM

Abstract

The soil rhizosphere environment under water table control for rice production was investigated to determine its influence on the growth of rice. The environment under two rice varieties: Azucena and IR36 were compared to that under bare sand.

The environmental parameters determined included: nitrogen availability, sand temperatures, redox potential and pH values. Moisture content was also determined at a depth of 3 cm.

Moisture content was significantly greater for the flooded treatment than for the 15 cm depth treatment; it was also significantly greater for the 15 cm depth treatment than for the 30 cm depth treatment. pH values were a mean of seven over the duration of the experiment.

Redox potentials decreased in the order: 30 cm treatment > 15 cm treatment > flooded treatment. The differences were not significant. They were also greatest under the bare sand, followed by IR36 then Azucena.

Sand temperatures were significantly greater under the 30 cm depth treatment than the other two. It was greater under the 15 cm treatment than the flooded treatment; this was however not significant.

Nitrogen concentrations were initially highest under the flooded treatment, but after about two weeks, in all cases, fell below the 15 cm depth treatment. They were mostly lowest under the 30 cm treatment. Nitrate levels were also consistently lower under Azucena than IR36. Differences in levels of nitrates could have accounted for growth differences

Under Azucena, shoot dry mass in the order: 30 cm treatment > 15 cm treatment > flooded treatment; the differences were not significant. Tiller numbers followed the same pattern. Under IR36, shoot dry mass was just about the same for all treatments, tiller numbers were also just about the same for the plants under the 15 cm treatment and the flooded treatment, but they were significantly greater than for the plants under the 30 cm treatment.

The water treatments used did not lead to major differences in the rhizosphere environmental parameters measured with the exception of level of nitrates and these may not have contributed substantially to growth differences. Under soil, the situation may have been different.

5.1 INTRODUCTION

According to Manske (2001), plant growth and development is modified by environmental conditions. Changing the growth environment of a plant will thus affect its growth.

Irrigation methods differ and their impact on the environment varies. Changing the method of irrigation used for a particular crop will mean creating a different set of environmental conditions other than the ones the crop is subjected to under its traditional method of irrigation. A change from the traditional method of irrigating wetland rice to using water table control is thus certain to impact the growing environment and ultimately influence the growth of rice.

The depth of the ground-water table per se has no direct influence on crop growth; it however determines the soils prevailing moisture conditions and therefore has an influence on water supply, aeration conditions, and heat properties in soils (Wesseling, 1974). Soil hydraulic and chemical properties as well as physical properties depend to a great extent on the moisture content and are therefore influenced by the water table depth. In determining the effect of water table control on rice growth, it thus becomes necessary to look at factors that are

modified with change in depth of the water table and to determine how these factors affect growth of rice.

For example, the volumetric heat capacity of a soil increases with the moisture content, therefore the drier the soil, the quicker it heats up, the wetter the soil, the slower it heats up (Hillel, 1980). Soils with deeper water tables may heat up more quickly than those with shallow water table. According to Waters (1977) fields with a deeper water table are generally warmer than when the water table is shallow and aeration is improved under a deeper water table as moisture content decreases with deeper water table depths allowing for more air filled pores. Moreover hydraulic conductivity decreases with decreasing moisture content thereby affecting mobility of nutrients.

The previous chapter reported the results of experiments on the growth of two rice varieties under different water treatments. Growth varied under the different water treatments, and the differences in growth has been attributed to the differences in the environmental conditions created due to the variation in moisture contents, which are also dependant on the depth of the water table. This chapter sets out to determine these differences in rhizosphere environmental conditions and to attempt to explain growth differences as a result of them.

The extent to which the plants themselves modified the rhizosphere environment is also investigated by comparing the environment under both Azucena and IR36 to that under bare soil conditions.

In the light of the above discussion, four hypotheses are investigated in this section of the work, these are:

1. The depth of the water table has an effect upon nitrogen availability above it and varying depths of the water table will lead to differences in nitrogen availability and subsequent differences in uptake and thus in rice biomass production.

2. The depth of the water table influences soil aeration in the rhizosphere and this affects the redox potential. Different depths of the water table will give different levels of redox potential in the rhizosphere, and this will lead to differences in biomass development.

3. The depth of the water table will influence the soil temperature, which will in turn have an affect upon growth of rice. Rice grown under different water table depths will exhibit differences in growth parameters as a result of soil temperature differences.

4. Different varieties of rice modify the rhizosphere environment to different extents.

5.2 MATERIALS AND METHODS

5.2.1 Experimental Design

The water treatments imposed were:

1. Water table at depth of 30 cm below the sand surface (30 cm depth),
2. Water table at depth of 15 cm below the sand surface (15 cm depth),
3. Flood water at depth 2 cm above sand surface (Flooded treatment),

   as used in the previous experiment (Chapter 4).

The set up in this experiment differed from the previous ones in that there were only three cores per tank. One core in each tank was sown with rice variety IR36 (IT), another with Aucena (AT), and the last core was bare sand (ST). Rice varieties Azucena and IR36 sourced form Silsoe Research Institute, were used. The plants were all harvested at the end of the 6th week.

5.2.2 Data collected

Data collected included sand temperatures, pH, nitrogen content of solution in the sand and redox (reduction-oxidation) potentials. These were measured at a depth of 10 cm below the sand surface.

Shoot dry mass, root dry mass, tiller numbers as well rooting depth were also determined.

5.2.2.1 Sand temperatures

Sand temperatures were measured using a Jenway thermometer and a temperature probe. The probe was inserted up to a depth of 10 cm and allowed to equilibrate with the sand this usually took about 30 seconds. The temperature was then taken and the hole that had been created was filled up.

5.2.2.2 Nutrient composition

Soil water samplers (Plate5.2), (Soil Monitoring Engineering, 2001), which are instruments used for monitoring the chemical composition of salt water, were used to withdraw solution in the sand for nitrogen analysis. They were inserted into the sand column to a depth of 10 cm below the surface. These were primed by drawing out air using a syringe through one tube and closing it using a clip while keeping the other tube closed. Extraction was done by first inserting the syringe in one of the tubes and opening up both tubes and forcing out the solution drawn in by the cup by pushing air up one of the tubes with the syringe. The extracted solutions were taken into the laboratory for analysis for TON (total oxides of nitrogen) and NH_4 in a segmented flow analyser (Plate 5.2), (Burkard Scientific, 2000).
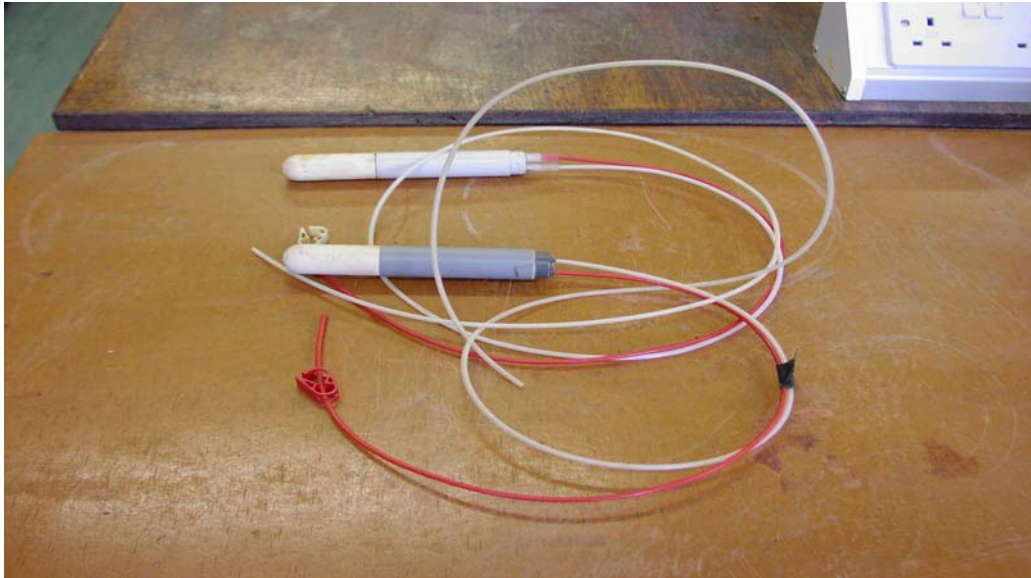
Plate 5.1 Soil water samplers.

Plate 5.2 Segmented Flow Auto-Analyser.

5.2.1.3 Redox potential

Redox potential readings were taken by inserting a platinum electrode and calomel electrode (reference electrode) into the wet sand and measuring the potential difference between them using a digital millivoltmeter. Before any readings were taken, the probes were first inserted into a standard redox solution (this is a solution which contains 0.1 M Fe2+ and 0.1 M Fe3+ in approximately 1M H_2SO_4 and has a potential of 430 mV at 25 ^oC) (Rowell, 1994) and the voltage read. The voltage was allowed to stabilise (about 3mins) before it was recorded. The electrodes were accepted to be functioning correctly when the voltage was in the standard redox solution 430± 10 mV. The readings was converted to that of a hydrogen electrode i.e. Eh = Emeasured + 248 mV.

5.2.2.4 pH values

Values for pH were taken using a Jenway 3150 pH meter. The meter was first calibrated using buffer solutions of pH 4 and pH 7. Solution was drawn out using soil water samplers and the pH readings taken using the meter.

5.2.2.5 Moisture content

Moisture readings were taken using a Theta probe (ML2X) connected to a moisture meter type HH1 (DELTA-T Devices). The volumetric moisture content was taken.

5.2.2.6 Other Parameters

The other parameters, including plant growth parameters were determined as for the experiments in the previous chapter.

5.3 RESULTS AND DISCUSSION

5.2.1 Volumetric moisture content

Moisture contents were significantly different between the 30 cm and the 15 cm treatments, they were not significantly different between the 15 cm and the

flooded treatments though. The results in Chapter 4 however show a significant difference between the moisture levels between the 15 cm and the flooded treatments.
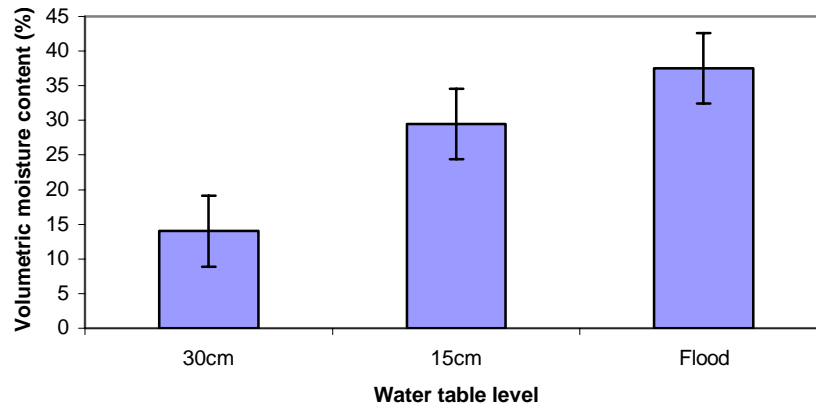
Figure 5.1 Volumetric moisture content measured at about 3 cm below the surface for the three water table depths showing L.s.d.'s (p=5%).

The different depths of the water table lead to different moisture regimes in the rhizosphere, which inevitably creates different sets of environmental conditions. As already indicated, a lot of the activities that occur in any soil are dependant on moisture. Soil moisture is of fundamental importance to many hydrological, biological and biogeochemical processes that occur in the soil. Significantly different levels of soil moisture may thus mean major differences in these processes thereby creating differing conditions for growth. This then means that growth differences will be explained by the prevailing environmental conditions created by each of the treatments.

5.3.2 TON (Total oxides of Nitrogen)

Generally aeration conditions in soils have a large influence on the availability of nitrogen. According to Wesseling (1974), Hoom (1958) estimated a mean supply of nitrogen by the soil of 55 kg ha^{-1} with a water-table depth of 40 cm. The N supply increased to 120 kg ha^{-1} for a 90-cm and to 150 kg ha^{-1} for a 150-cm water-table depth. Nitrate nitrogen is usually rapidly denitrified upon submergence of the soil (Wesseling, 1974). Nitrates are quickly lost under flooding; this is due to the

fact that under anaerobic conditions nitrates act as electron acceptors and are therefore quickly reduced.

Under condition where the amount of nitrates added were the same we would have expected that over time, these levels under the depth of 30 cm treatment would be greater than that under the depth of 15 cm treatment, and those under the flooded system would be negligible. In this case however, the moisture content played a large part in determining the amount of nitrates present, as the nitrates were added in solution, therefore the amount of nitrates present were largely a function of the moisture content.

As indicated in chapter four, total oxides of nitrogen in this report refer to NO_3^-; NO_2^- and N_2O. Levels of NO_2^- determined were very low, relatively, (at about 0.1mg L-1) and were assumed to be negligible, N_2O was not measured and NO_3^- is therefore used interchangeably with TON in the rest of the report.

5.3.2.1 TON over time

The Figs 5.2-5.4 show changes in values of TON over time under the three water treatments for Azucena (AT), IR36 (IT) and bare sand (ST). The values were obtained from the product of the concentration of nitrates in solution (TON in mg L^{-1}) multiplied by the volume of water in each system measured in litres.

NO_3^- levels differed significantly between the 30 cm treatment on the one hand and the 15 cm treatment and the flooded treatments on the other hand. In the previous experiment (Chapter four), nitrate levels were in the order: 15 cm treatment > flooded treatment > 30 cm treatment.

The nitrate levels in the flooded treatment were initially the highest but at the end of the second week drop lower than those for the 15 cm treatment for AT. In the case of IT, the nitrates in the flooded treatment dropped lower than those for the 15 cm treatment after the 3rd week. In these two cases, nitrate levels experienced a

sharp drop at the end of the 4th week, and were near zero at the end of the 5th week.

Nitrate levels for the flooded treatment under ST also experienced a similar drop in values at the end of the 4th week; this was however not as sharp as for AT and IT. Since this occurred both under the planted as well as the unplanted cores, this sharp drop cannot be attributed to crop uptake but to nitrates acting as electron acceptors.

The formation of a colony of de-nitrification microbes may have been limited in the system as organic matter was not initially present. This may have limited the extent of de-nitrification and loss of NO_3^- could be more a function of uptake in the initial stages permitting an appreciable high level of nitrate under the flooded treatment. Carbon compounds were however produced with root growth as root exudates but the effect was expected to be pronounced at the latter stages of growth. Microbes in the unplanted cores were passed on from the planted ones from cross contamination with instruments although they were cleaned.

As oxygen was used up, nitrates acted as electron acceptors and that could have contributed to the rapid decrease in nitrate levels later in the experiment. The fact that nitrate levels dropped earlier for IT than for AT was because IT having more roots produced more radial oxygen than AT and nitrates become electron acceptors at a later time for IT than for AT.

Over time, there was a drop in levels for the 30 cm treatment as well as the 15 cm treatment for both AT and IT. This may be attributed to the fact that de-nitrification was lower under these treatments, and the drops displayed are due to uptake. Generally levels under the 15 cm treatment are higher than under the 30 cm treatment; it was only at one point that the 30 cm treatment had a higher nitrate level than the 15 cm treatment. As nitrates were in solution and as more solution (moisture) was present under the 15 cm treatment, it was expected to have more nitrates at every point than for the 30 cm treatment.

Under ST, there was a rise in levels of nitrates over time for the 15 cm and 30 cm water treatments. This could be attributed to accumulation over time as nutrients were added as uptake was non-existent and moreover reduction of nitrates could not occur as the systems were aerated.

Uptake may be higher for the 30 cm treatment under AT than under IT considering that levels of nitrates under AT are zero at the end of 4 weeks but are about 20 mg under IT at the end of 5 weeks. Nitrate uptake rates may be higher under AT than IT.
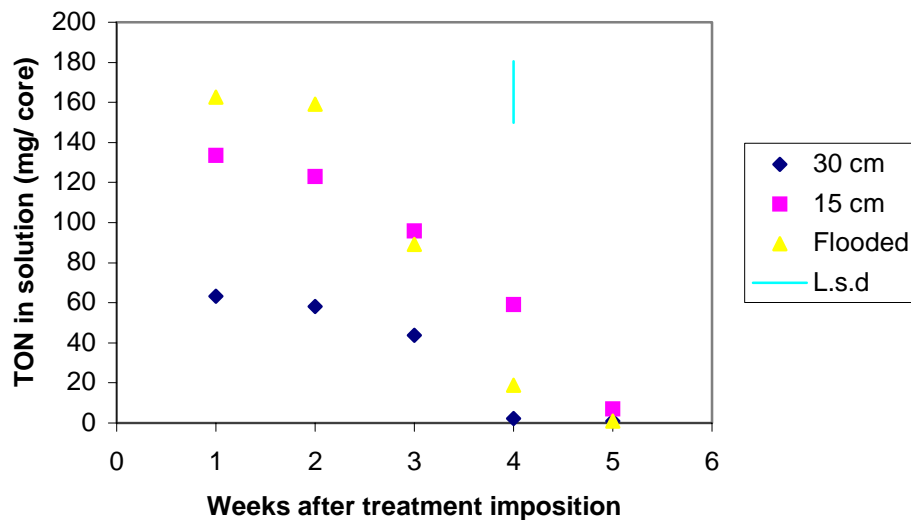
Figure 5.2 Mean TON values against time for three water treatments under AT with error bars as L.s.d.. (p=5%).
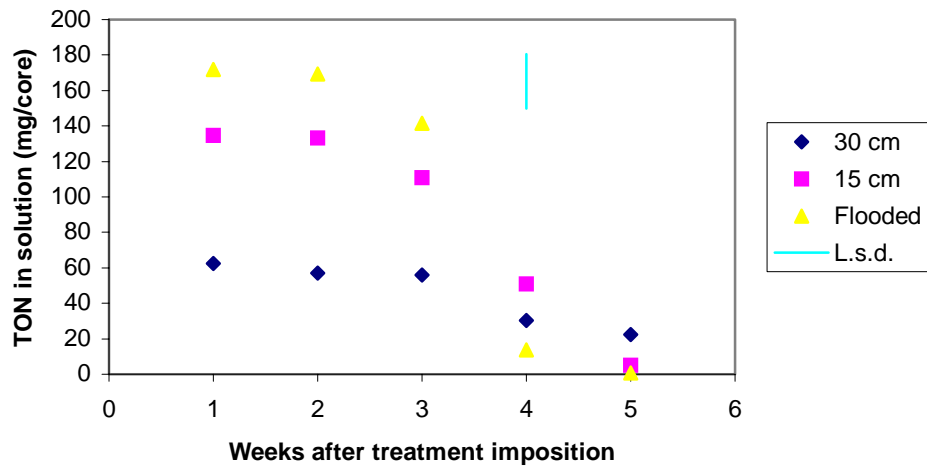
Figure 5.3 Mean TON values over time for three water treatments under IT showing L.s.d.. (p=5%).
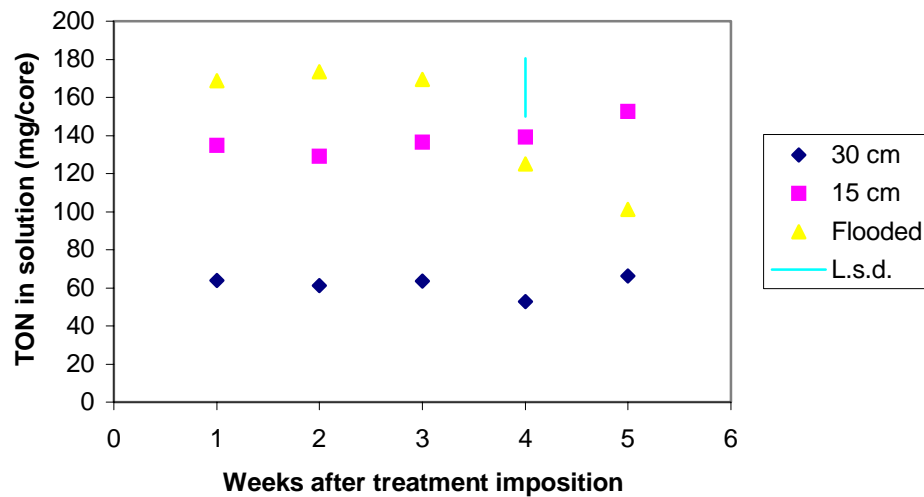
Figure 5.4 Mean TON values over time for three water treatments under ST L.s.d.. (p=5%).

5.3.2.2 TON with respect to variety and water table depth

The levels of NO_3^- under ST for each water treatment were highest followed by IT then AT. There was no uptake under ST due to the absence of plants and that accounted for the high values over time. The drop in levels from the 3rd to the 4th week would be due to introduction of microbes from the other treatments leading to de-nitrification.
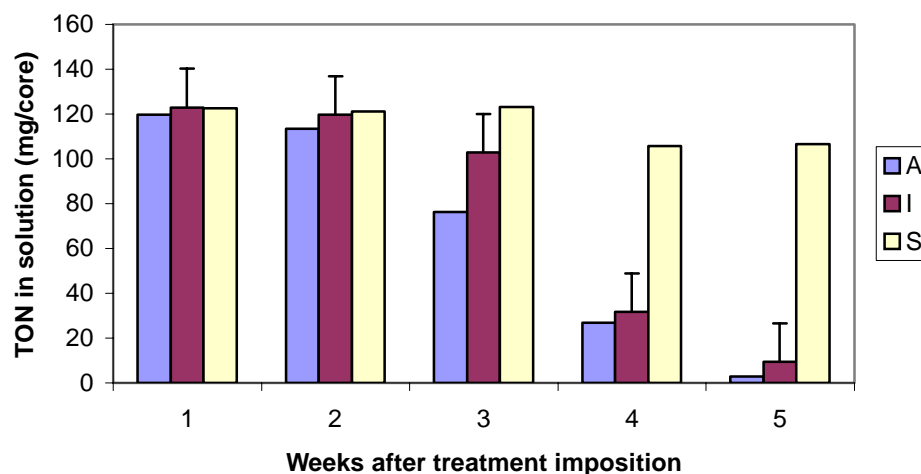
Figure 5.5 Interaction of water table depth core treatment and mean TON values. Y error bars indicate L.s.d.. (p=5%).

Nitrates levels under IT were higher as shown in Fig. 5.5 indicating uptake was generally higher under AT than IT and possibly reduction of nitrates higher under IT than AT. As already noted, IT produces more roots and thus has a lot more radial oxygen loss than AT.

Generally, the nitrate levels drop over time even though the solution was maintained at a constant level; this indicates rate of loss and uptake was greater than rate of application. At the 5th sampling time, NO_3^- values are near zero indicating that beyond this point plants could suffer from lack of nitrogen. The nutrient solution was thus unable to provide the full nitrogen requirement of rice plants under the application method used. The method and rate of application will thus have to be revised for any further experiment.

5.3.3 Temperatures

5.3.3.1 Temperature with respect to water table depth

As Figure 5.6 indicates, at a depth of 10 cm below surface, sand temperatures under the 30 cm treatment were significantly greater than for the other treatments.

Significant differences did not exist between the flooded and the 15 cm treatment at the same depth.
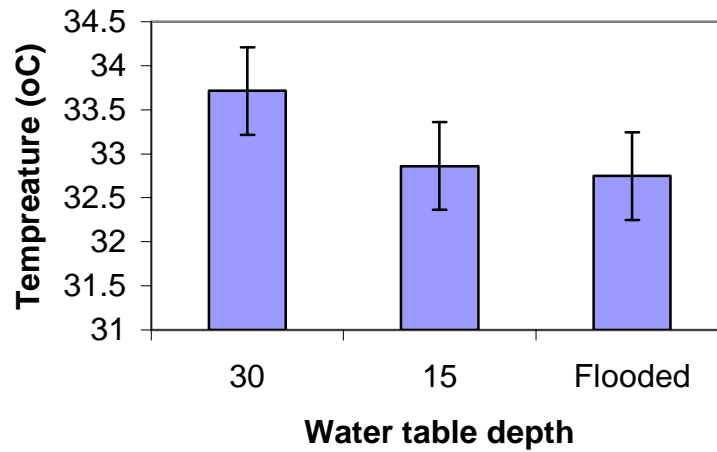
Figure 5.6 Temperatures against level of water table with error bars as L.s.d.. (p=5%).

According to Hillel (1980) the volumetric heat capacity for sand of volumetric moisture content of 0.0, 0.2 and 0.4 are 0.3, 0.5 are 0.7 cal cm^{-3} ^{o}C^{-1} respectively. The volumetric heat capacity is the amount of heat required to raise unit volume of soil by 1 ^{o}C. Given similar conditions the order for sand temperatures at a depth of 10 cm would be: 30 cm treatment > 15 cm treatment > flooded treatment. As indicated in Chapter 4, the pattern for total amount of heat in the systems would be : Flooded treatment > 15 cm treatment > 30 cm treatment.

The effect of the floodwater upon soil temperature was not significant in that the differences between the 15 cm treatment and the flooded treatment were not significant. This is surprising in that thermal properties of water and wet sand differs greatly and this effect should have reflected in the temperatures.

According to Bierhuizen (1971), quoted from Wesseling (1974), a linear increase of growth rate can be assumed for small differences in soil temperature between the maximum and minimum temperatures provided factors like radiation and

moisture supply are not limiting. As these factors were not limiting in these experiments, temperature differences then may have contributed to differences in growth albeit to a very small extent.

5.3.3.2 Temperatures with respect to time

Temperatures were not measured at a set time of the day and this accounts for the variation in temperatures with time for the treatments.
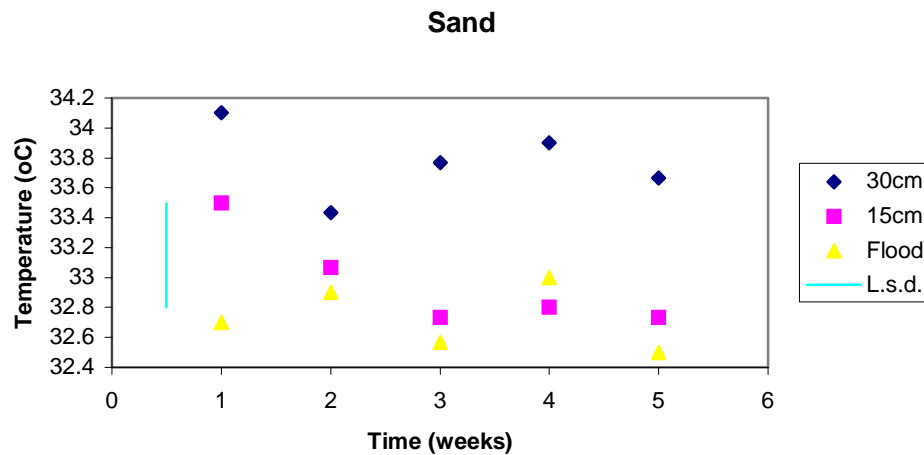
Sand

Figure 5.7 Mean temperature at depth 10cm over time for three water table levels under bare sand showing L.s.d.. (p=5%).
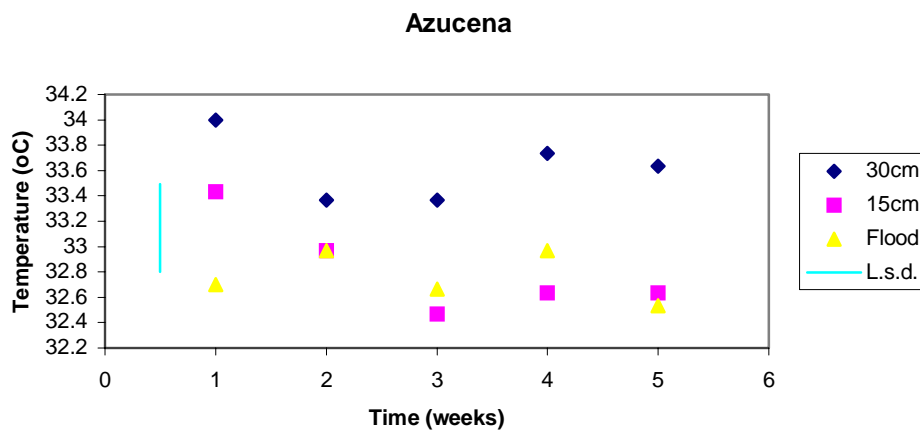
Azucena

Figure 5.8 Mean temperatures at depth 10 cm over time for three water table levels under Azucena showing L.s.d.. (p=5%).
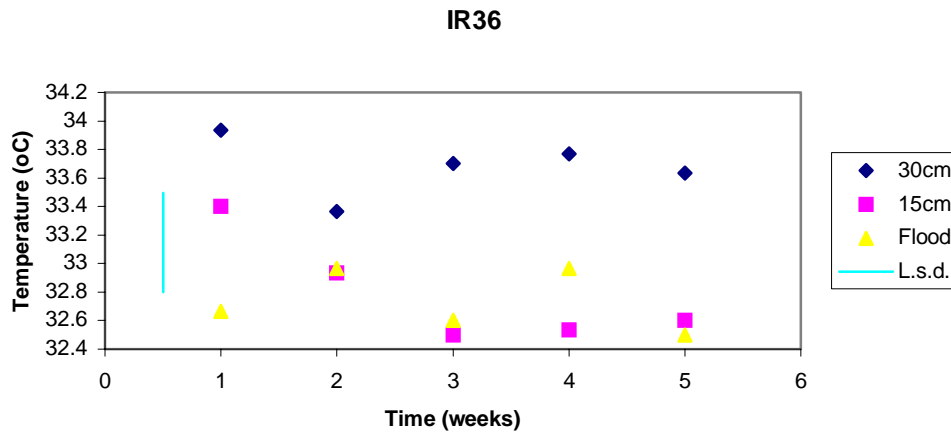
Figure 5.9 Mean temperatures at depth 10cm over time for three water table levels under IR36 showing L.s.d.. (p=5%).

There is a similar pattern over time in the three figures (Figs. 5.7 to 5.9) for all the water treatments; the common factor among them is the water treatment and it moderates the temperatures in similar ways. This implies that the water treatment has a dominant influence under each of the treatments.

5.3.4 Temperatures with respect to variety and water table depth

Under the aerated conditions temperatures were greater for ST than AT and IT indicating that crop cover and possibly the presence of roots have a moderating influence on soil temperatures.
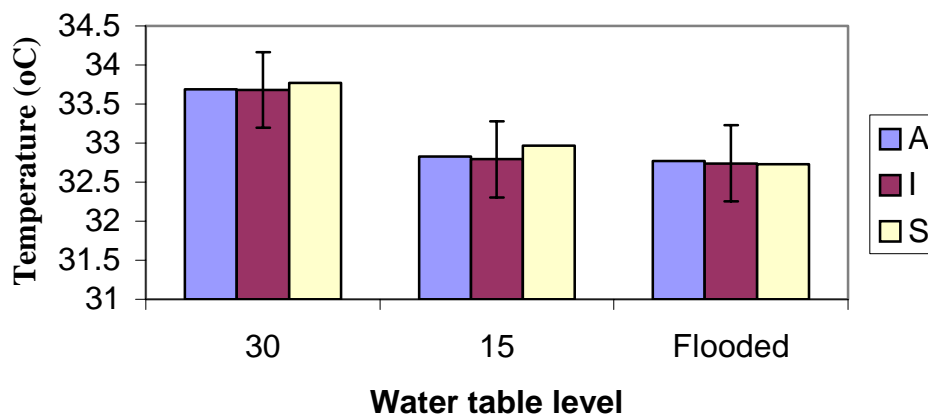
Figure 5.10 Interaction of temperature at depth of 10cm, water table level and variety.

The extent is rather small as differences are not significant. Under flooded conditions the temperatures are similar indicating that floodwater has a greater modifying influence on soils than does crop cover or presence of roots.

5.3.3.3 Tank Solution temperatures

The temperatures of the solution in the tanks were measured to determine if they could have had any influence on the experiment. As can be seen from Fig. 5.11 a., over all, the flooded treatment had the highest solution temperature followed by the 15 cm water table level then the 30 cm water table level.
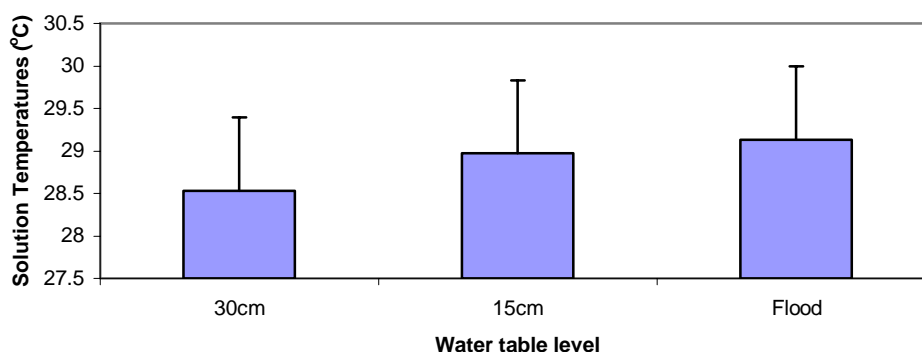
Figure 5.11 a. Solution temperatures with error bars as L.s.d.. (p=5%).
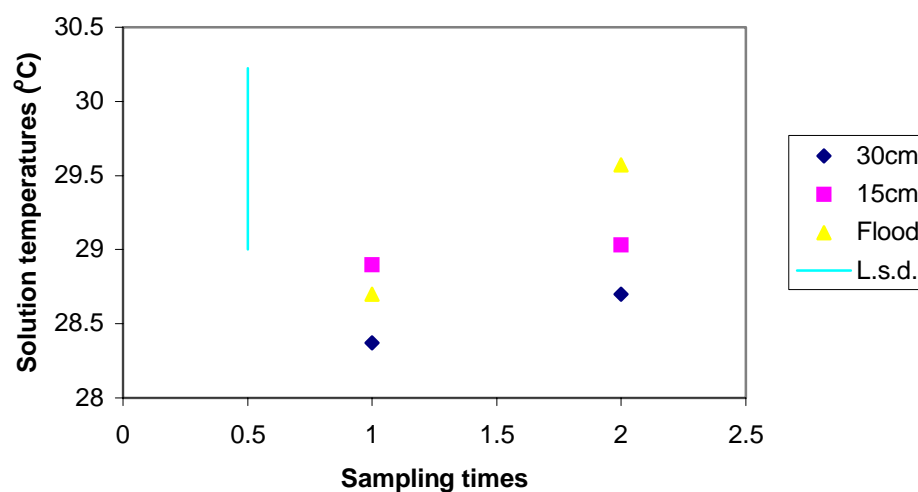
Figure 5.11 b. Solution temperatures in the tanks at two sampling times showing L.s.d.. (p=5%).

Figure 5.11 b. however shows that solution temperatures for the 15 cm water table treatment were higher at the first sampling point but lower at the second, than the flooded treatment. The differences were not significant indicating that solution temperatures did not influence the results obtained.

5.3.4 pH values

According to Bugbee (2003), plants grow equally well between pH 4 and 7, if nutrients do not become limiting. This is because the direct effect of pH on root growth is small; the problem is reduced nutrient availability at high and low pH. A comparison of root growth rate and root metabolism at pH 4 and pH 5.8 with wheat did not show any significant difference. Good rice soils are slightly acidic to slightly alkaline with an optimum pH range of 5.5 – 8. The range of pH observed in this work 6.5 – 9.4 with most measurements falling below a pH of 8 but above 6, this is an indication that the environment was conducive for the growth of rice.
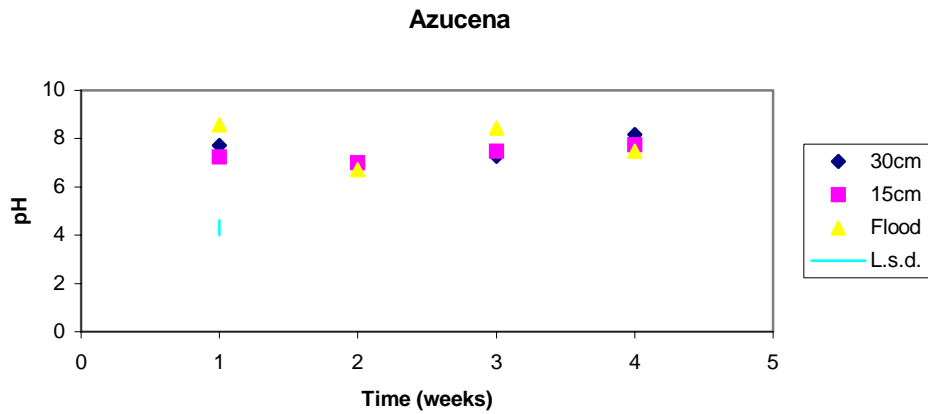
Azucena

Figure 5.12 Mean pH values over time for three water levels under Azucena showing L.s.d.. (p=5%).
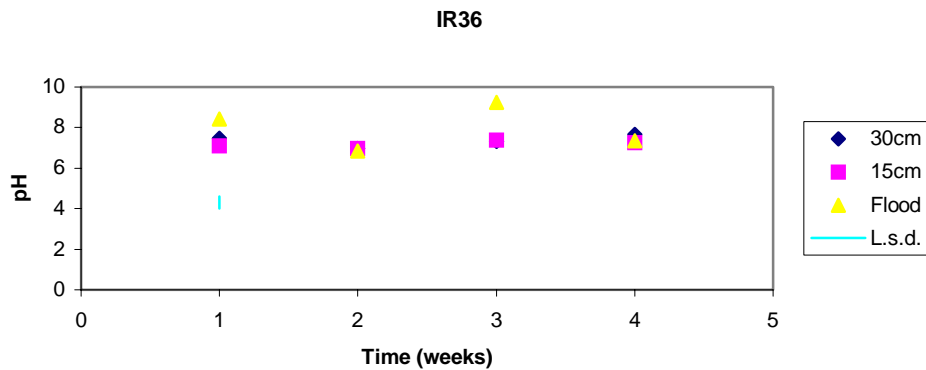
IR36

Figure 5.13 Mean pH values over time for three water levels under IR36 showing L.s.d.. (p=5%).
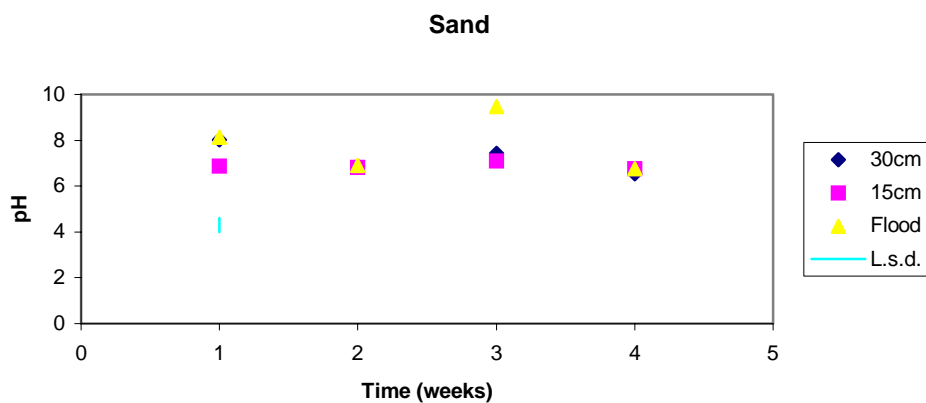
Sand

Figure 5.14 Mean pH values over time for three water levels under bare sand showing L.s.d.. (p=5%).

5.3.5 Redox potentials

"Redox potential, measured as electric potential in volts, characterizes the processes that bring about a given chemical and biochemical milieu in a soil. The higher the value of the redox potential, the greater the presence of strong oxidizing agents in a soil, its magnitude being determined by the amount of easily degradable organic matter, the rate of decomposition, the formation of toxins to micro-organisms, and the amounts and kinds of reducible nitrates, manganese and iron oxides, sulfates, and organic compounds" (Neue, 1993).

 The three water treatments were expected to provide three different environmental conditions at a depth of 10 cm. The 30 cm water depth was expected to provide well-aerated conditions, the 15 cm water depth to provide less aerated conditions and the flooded system to provide anaerobic conditions. Organic matter is initially virtually absent thus preventing presence of microbes making root respiration the major use of oxygen. This may have influenced the outcome of the experiment in that redox potentials were not as low as expected.

Redox potentials can be compared only if they are taken at the same pH. A pH 7 is therefore assumed for all the redox potential measurements given that most of the measured pH values are between 6 and 8.

5.3.5.1 Redox potential with respect to time and water table depth

 Redox potentials decreased as water table depth increased. Generally redox potentials at a depth of 10 cm for a water table depth of 30 cm were significantly greater than that for a flooded system but did not differ from that for a water table depth of 15 cm. Redox potential for a water table depth of 15 cm did not differ significantly from that for a flooded system.
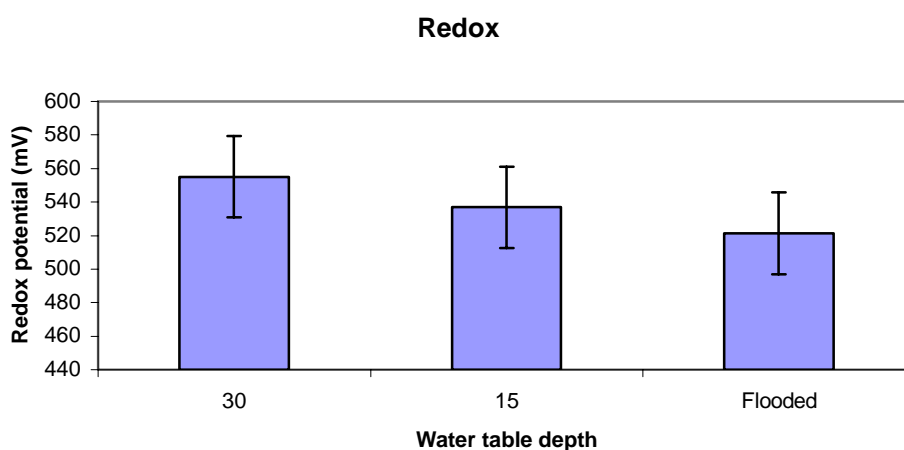
Redox

Figure 5.15 Mean redox potentials under the three water table levels with error bars as L.s.d.. (p=5%).

5.3.5.2 Redox potential with respect to time

The Figs. 5.16 below show changes in redox potential over time under AT, IT and ST. There was an appreciable drop in redox values over time for AT and IT, but in the case of ST only small changes occurred.

Eh for the 30 cm treatment remained stable but there was a significant decrease over time for the other two water treatments. At the end of week five the 30 cm treatment had a significantly higher Eh under AT and IT, under ST however it was significantly different only from the flooded treatment.
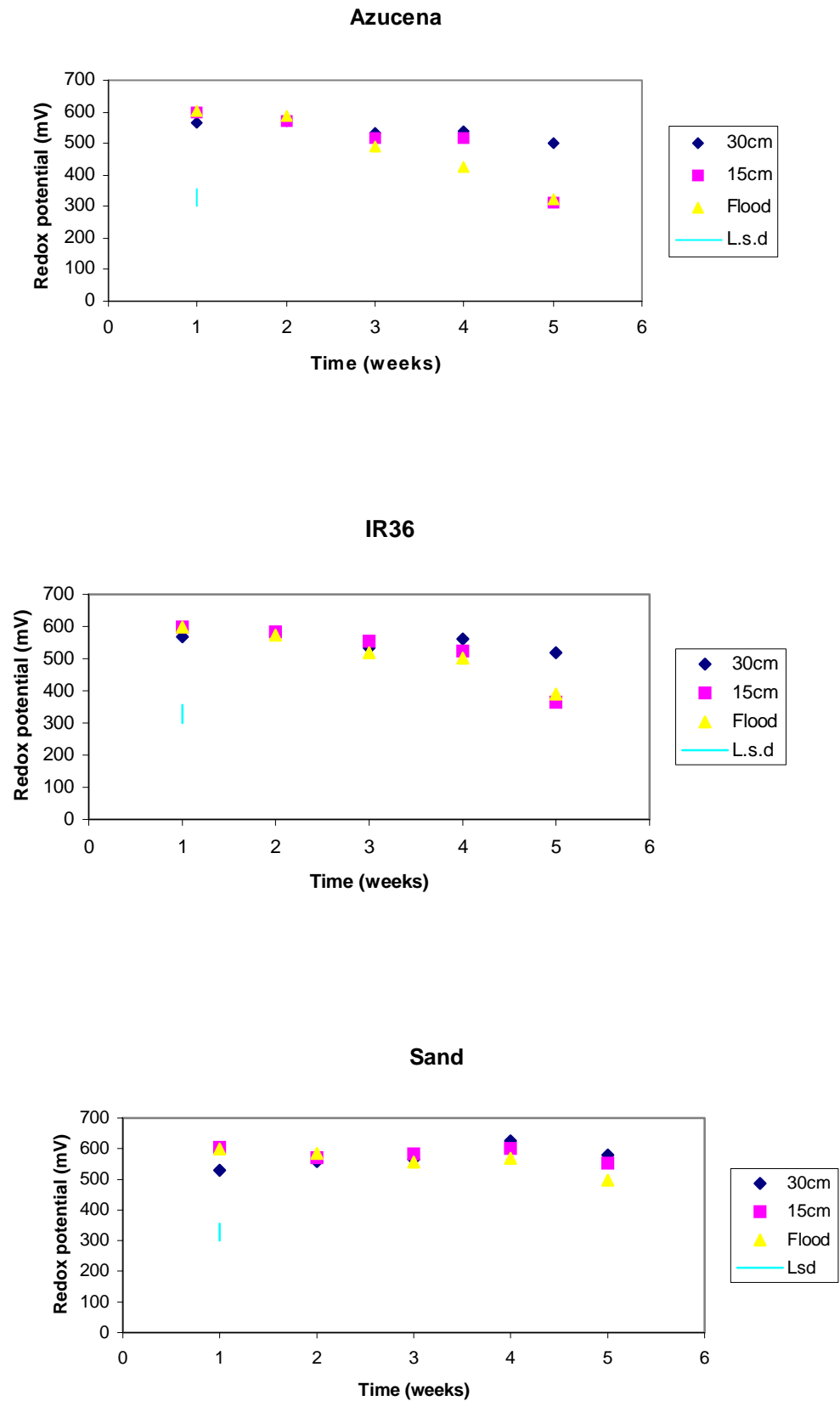
Azucena

IR36

Sand

Figure 5.16 Mean redox potential over time for the three water levels under Azucena, IR36 and under bare sand showing L.s.d. (p=5%).

Table 5.2 Redox potentials at the end of the 5th week for all water levels and varieties.

Treatment	30cm	15cm	Flooded
Azucena	501.3	314.7	324
IR36	518.3	364.3	390.3
Sand only	578.7	553	496.7

Table 5.2 gives the redox potentials at the end of the 5th week. Clearly the highest potential is recorded for ST only followed by IT and then AT. Radial oxygen loss may have contributed to IT having a consistently greater Eh than AT. IT produced more roots and was likely to lose more oxygen.

 The oxidation - reduction potential for reduction of NO_3^- to NO_2^- is 420 mV at pH 7 and 530 mV at pH 5. When NO_3^- or Mn_4^+ ions are present, the redox potential will remain poised, i.e. will decrease slowly. The pattern of redox potential at a depth of 10 cm over time can be explained by the fact that there was the absence of oxygen at that depth and NO_3^- acted as electron acceptors. The slow decrease in Eh also being the result of the presence of NO_3^- and Mn_4^+ in the nutrient solution.

5.3.5.3 Redox potential with respect to water table depth and variety

A look at Fig. 5.16 shows that two patterns emerge, one for AT and IT and another for ST. This is to be expected as oxygen use in an unplanted soil will be less than for a planted one. As already indicated Eh under AT was lower or more reducing than under IT; this has been attributed to the fact that there was more radial oxygen loss for the lateral roots in the case of IR36 leading to a less reducing rhizosphere.

Though Eh (redox potential) values were not significantly different for the 30 cm water table depth for AT and IT, they were different in the case of the 15 cm depth and under flooding, with values for IT being higher. This buttresses the point that radial oxygen loss may have been a contributing factor in dictating redox levels.
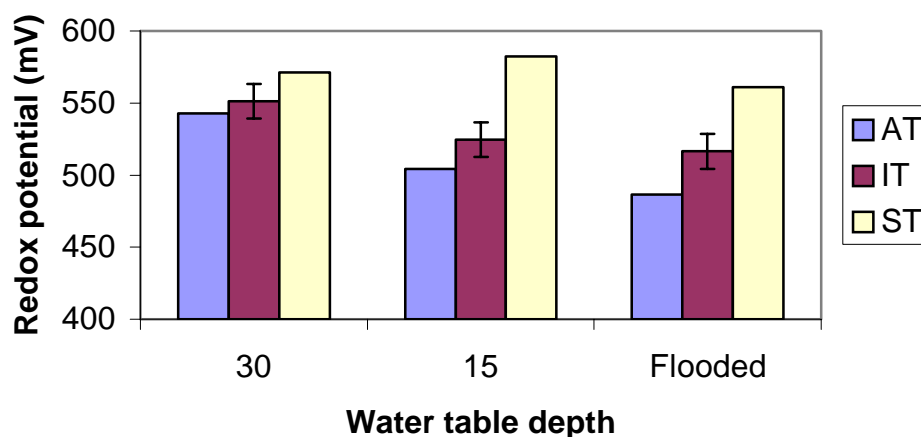
Figure 5.17 Plot showing interaction of redox potential, water table level and variety at with error bars as L.s.d.. (p=5%).

It emerges also that under AT and IT, 15 cm water depth provided a more reducing environment than the 30 cm depth. This is what was expected as the 30 cm treatment is more aerated than the 15 cm one. Redox potentials were significantly greater under the 30 cm water table treatment than the others. Whereas redox potentials were significantly greater under AT for the 15 cm water table treatment and the flooded treatment, there were no differences in the case of the 30 cm treatment. It has already been established that more roots are produced under IT leading to more radial loss of oxygen under flooded conditions, which may account for the results.

Redox potentials under the unplanted conditions were significantly greater for all the water treatments. The 15 cm water table treatment had the greatest redox potential followed by the 30 cm and the flooded treatment. The 30 cm treatment being more aerated was expected to have the greatest value. More nitrates were present overall for the plants under the 15 cm treatment and this could have contributed to the higher redox potentials.

There was a distinct influence of the rice variety on redox potentials moreover it is clear that rice plants modify the redox potentials of the rhizosphere to a great extent.

It must also be noted that redox potential conditions were measured at a depth of 10 cm below the surface, this was because most of the roots were concentrated around this depth, but deeper down the core, there may have been greater variations in environmental conditions though not as much as would be expected in soils. It was observed that at the bottom of the cores, especially for the flooded treatment, some roots had blackened and had a smell of H_2S. This indicates there were reducing conditions at the bottom of the cores, but no measurements were taken at those depths to verify this.

5.3.6 Shoot dry mass

At the end of the sixth week mean shoot dry mass was greatest for the 30 cm water table treatment in the case of AT, but lowest in the case of IT.
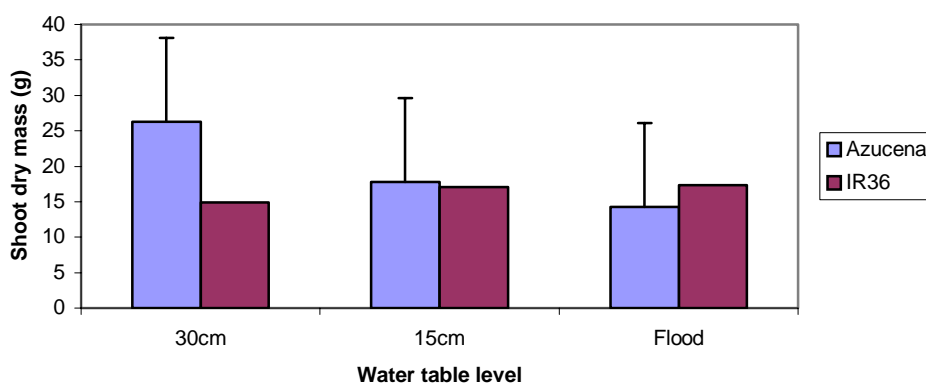
Figure 5.18   Mean shoot dry mass for the two varieties of rice with error bars as L.s.d.. (p=5%).

AT performed better under drier conditions but IT under conditions of more moisture. The differences were however not significant.

5.3.7 Tiller numbers

Just as for the shoot dry mass tiller numbers for AT were greatest under lower moisture conditions, but the values obtained for the 15 cm water table treatment and the flooded treatment were similar.
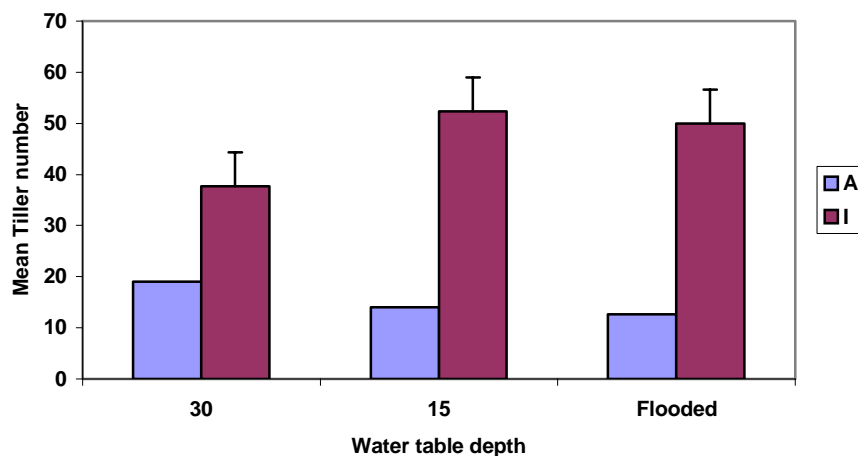
Figure 5.19 Mean tiller numbers for the two rice varieties with error bars as L.s.d.'s (p=5%).

For IT tiller numbers for the plants under the 15 cm water table treatment and the flooded treatment were significantly greater than for the plants under the 30 cm water table treatment.

5.4 CONCLUSIONS

1. The pattern for variation in growth medium temperatures was similar for the two varieties as well as for the unplanted cores under each water treatment. As the common factor in all these was the water table depths, it indicates that the depth of the water table has a greater moderating influence on growth medium temperature in the presence or absence of rice plants.

2. Redox potentials were high throughout the duration of the experiment owing to the presence of NO_3^-, which acts as electron acceptor in the absence of O_2. Eh

under IR36 was generally greater than under Azucena due to the fact there was more radial loss of oxygen under IR36 because it had more roots. Eh values show that the oxidation status of the systems under the different water treatments was similar and growth differences cannot be ascribed to differences in Eh.

3. The pH range observed was between 6.4 and 9, with most values under 8. As a pH range of 5.5 –8 is able to sustain growth of rice, it can be concluded that pH levels did not influence growth differences to any appreciable level.

4. NO_3^- uptake levels play a large part in determining growth differences in growth of rice under water table control. Greater uptake values for Azucena than IR36 under the 30 cm treatment led to better growth reflected in the plants under that treatment having the highest shoot dry mass as well as tiller numbers. The lower uptake levels under IT led the plants under the 30 cm water treatment to having significantly lower tiller numbers and a lower shoot dry mass than for the others.

It has been determined that nitrogen levels have a great influence on growth of rice under water table conditions. The form of nitrogen used in the experiment was NO_3^-; as has been discussed, forms on nitrogen available differ depending on the moisture conditions; nitrates being predominant under aerated conditions, and ammonium under waterlogged conditions. In order to determine the effect of nitrogen availability on growth of rice under water table control, it becomes necessary to determine the effect of ammonium as a nitrogen source. This is what is investigated in the next chapter.

CHAPTER 6: NH$_4^+$ BASED NITROGEN SUPPLY IN RICE PRODUCTION UNDER WATER TABLE CONTROL.

Abstract

Rice variety Azucena was grown using a NH$_4^+$ based nitrogen supply under water table control. Three water treatments were used: water table at a depth of 30 cm below the surface, water table at a depth of 15 cm below the surface and a flooded treatment. A number of trial experiments were also conducted in order to design the main experiment.

Parameters determined were: shoot dry mass, root dry mass, nitrogen content and tiller numbers and rooting depth. Water use was also measured.

The plants under the 30 cm water table depth had the greatest concentration of nitrogen per kilogram plant material followed by those under the 15 cm water table depth then the flooded treatment. The same pattern occurred for total nitrogen content of the plants.

The plants under the 30 cm water table depth treatment had the highest root dry mass followed by those under the 15 cm water tale depth then the flooded treatments. The same pattern was observed for shoot dry mass; the differences were not significant in any of these cases.

The plants under the 15 cm water table depth treatment had the highest tiller numbers followed by those under the 30 cm water table depth then the flooded treatments. The differences were not significant.

Growth of rice under water table control using an ammonium based nutrient resulted in very favourable growth for the plants under water table control compared to those under flooded conditions. It was also observed that rooting depth is a function of nitrogen availability, the more nitrogen available applied, the shallower the depth of the roots of rice.

6.1 INTRODUCTION

Because NO_3^- formed in or added to flooded anaerobic soil tends to be rapidly lost through denitrification to N_2 and N_2O gases, NH_4^+ is the principal form of inorganic plant-available N in flooded soils and is the main form of fertilizer used, the recovery of NO_3^--based fertilizers in flooded soil being very poor (Kirk, 2004). Rice plants are well adapted to growth on NH_4^+ as well as NO_3^-, and can absorb NH_4^+ at comparable rates per unit root surface (Kronzucker *et al*., 1998). But because NH_4^+ is adsorbed on the surfaces of soil minerals, unlike NO_3^-, its concentration in the soil solution for a given total N concentration is far smaller than that of NO_3^- – typically by at least an order of magnitude – and its rate of delivery to the surfaces of absorbing roots is correspondingly slower. Therefore the root surface area required for NH_4^+ uptake may be larger than that for NO_3^- uptake.

The extent to which transport to the roots limits NH_4^+ uptake will tend to increase under drier soil conditions because diffusion rates are smaller. Hence there may be important interactions between NH_4^+ nutrition and the depth of the water table. A further consideration is the effect of the water table depth on nitrification-denitrifcation losses of NH_4^+.

The experiments reported in the previous chapters were all conducted using NO_3^- based nutrients. In this Chapter I determine the effect of a NH_4^+ based nutrient on rice growth and root characteristics under similar experimental conditions and water table management. To simulate the effect of soil minerals in adsorbing NH_4^+ from the soil solution, but without losing the simplicity of the sand culture system, I mixed vermiculite with sand as the growth medium, with the vermiculite loaded with sufficient NH_4^+ to provide the plants with their N during growth. I thereby aimed to simulate the NH_4^+-transport conditions that constrain NH_4^+ uptake from a real soil.

In preliminary experiments with the sand-vermiculite system (Appendix 1), the plants died within a week of planting, evidently due to salt injury. By varying the loading of the vermiculite and the composition of the equilibrating nutrient solution this problem was largely overcome, though there were some mild salinity symptoms in the early stages of the final experiments, now described. The impact of this on the plant growth could not be determined but was probably minor.

6.2 PREPRATION AND APPROPRIATE NH_4^+-LOADING OF SAND-VERMICULITE MIXTURES

All materials and methods were the same as in Chapter 4 except that the growth medium was a mixture of sand and vermiculite loaded with NH_4^+ and the nutrient solution contained no nitrogen, i.e. the only source of nitrogen was the vermiculite. To work out how much vermiculite would be required to provide the plants with a realistic supply of nitrogen, I made preliminary experiments as follows. The aim was to provide sufficient NH_4^+ in the sand-vermiculite mixture contained in one experimental pot to allow growth of about 40 g of plant dry mass with 20 mg N g^{-1} plant dry mass, i.e. 800 mg of N or approx. 60 mmol of NH_4^+. From studies of the kinetics of NH_4^+ absorption by healthy rice roots (Kronzucker *et al*., 1998), absorption will proceed unimpeded at concentrations in the external solution above about 100 μM NH_4^+. To calculate the amount of vermiculite required to maintain the NH_4^+ concentration in solution above this level as the plants withdrew NH_4^+, I needed to measure the NH_4^+ desorption characteristics of the vermiculite under the conditions of the experiment.

6.2.1 Materials and methods
6.2.1.1 Loading vermiculite with NH_4^+
The following method was adopted after a number of trials. Coarse vermiculite (LBS, Stand Royd Mill, Cotton Tree) was gently ground and sieved through a 2 mm mesh.

To remove any contaminants, the vermiculite was first washed with 0.05 M HCl and then rinsed several times with deionised water. Batches of 200 g were then steeped in 2 litres of 1 M NH_4Cl and 1 M $CaCl_2$ solution for about two hours. The solution was decanted off and the process repeated before washing the vermiculite repeatedly with deionised water until the EC of the water was < 0.5 mS cm^{-1}. The vermiculite was then air-dried.

6.2.1.2 Desorption isotherm

The experiment was replicated twice. Sixteen portions of 0.25 g of the vermiculite loaded with NH_4^+–Ca^{2+} were weighed into containers with the following volumes (in litres) of nutrient solution: 10, 20, 50, 100, 200, 500, 1000 and 2000. The nutrient solution contained 1.5 mM $CaCl_2$, 0.15 mM $CaH_4(PO4)_2$, 1.0 mM KCl and 0.3 mM $MgSO_4$ with micronutrients as in Chapter 4. The resulting suspensions were shaken end-over-end for two hours, and the solution filtered. The filtrates were analysed for NH_4^+ on an auto analyzer (Burkard Scientific SFA, 2000). The amounts desorbed from the vermiculite were inferred from the changes in concentration in solution multiplied by the solution volume per unit mass of vermiculite.

6.2.2 Results and discussion

Figure 6.1 gives the NH_4^+ desorption curve of the loaded vermiculite.
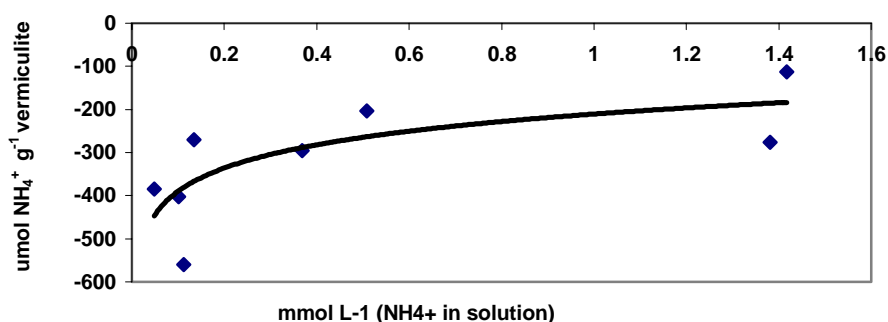
Figure 6.1 Desorption isotherm for vermiculite loaded with ammonium.

The amount of NH_4^+ desorbed when the concentration in solution reached 100 μM (the minimum target concentration to maintain unimpeded NH_4^+ uptake by the rice roots) was approx. 300 μmol g^{-1} vermiculite. Thus to provide the 60 mmol of NH_4^+ required for the target plant growth, an amount of approx. 190 g of vermiculite is required per experimental pot. I therefore used 200 g to be on the safe side.

To confirm that the desorption properties of the sand-vermiculite mixture were as expected from the behaviour of the vermiculite on its own, I repeated the desorption isotherm on the mixture used for the main experiments (200 g vermiculite per 10 kg of sand). The results are shown in Figure 6.2.

The chart shows data with fitted equation:

$$y = 56.55 Ln(x) - 201.51$$
$$R^2 = 0.7477$$

x-axis: mM (NH_4^+ in solution); y-axis: umol NH_4^+ g^{-1} vermiculite
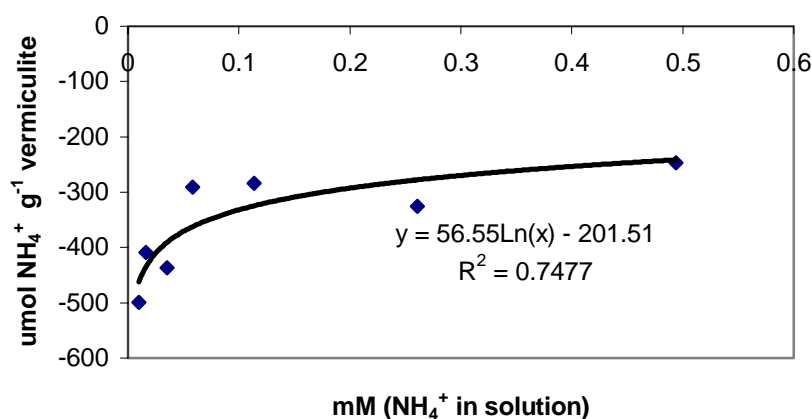
Figure 6.2 Desorption isotherm for sand and vermiculite mixture.

6.3 Plant growth experiments
6.3.1 Materials and methods

6.3.1.1 Preparation of sand-vermiculite mixtures

If 200 g vermiculite is needed for each pot, then given 54 pots, total amount of vermiculite needed is 10.8 Kg. Considering the fact that at least two washings are required and there is the possibility of loss of vermiculite, an estimate of 12 Kg is used.

120 litres each of a solution containing about 120 mols of $CaCl_2$ and NH_4Cl compound was required for 12 Kg of vermiculite. This is because 100g of vermiculite required 1litre solution containing 1M of each of the compounds.

Nitrogen content of the vermiculite was determined by the method of kjeldahl digestion [BS 775: Section 3.7 (1995)] analysis. The results were as follows:

Mean Nitrogen   g/Kg   13.67 (S.D. = 0.3055).

This is equivalent to 759 μmols g-1 vermiculite, which is a little more than two times what had originally been determined to be the N requirement for duration of six weeks for the plants. An upper limit for N required was not determined, but the introduction of $CaCl_2$ as already stated ensured that the vermiculite was not saturated with ammonium.

6.3.1.2 Plant growth conditions

Harvesting, sowing, germination, water supply, core arrangement, experimental design and growth chamber conditions were similar to what was described in Chapter 4. Water release characteristics and hydraulic conductivity were not determined for the sand vermiculite mixture. The amount of vermiculite used was small compared to the quantity of sand and the hydraulic properties were not expected to vary from that for sand.

6.3.1.2.1 Water treatments

The water treatments used in the experiments were:

1. Water table held at 15cm below the sand surface (15cm treatment).

2. Water table held at 30 cm below the sand surface (30 cm treatment).

3. Flooded soil with flood depth of 2 cm.

This is similar to what was used in Chapter 5.

6.3.1.2.2 Seed

Rice variety Azucena was used. The seeds were obtained from IRRI.

6.3.1.3 Data collected

Data collected was

Shoot dry mass

Root dry mass

Plant nitrogen content

Tiller numbers

Rooting depth

Water use

Solution nitrogen concentration

Plant nitrogen content was determined by the method of kjeldahl digestion. Water use was determined by measuring the drop in the solution levels in the tanks.

6.3.2 Results and discussion

6.3.2.1 Water use

Water use was computed from water loss from the tanks, that is, the volume of water required to bring the level of water in each tank to its predetermined level. This was done every two days over the last two weeks of the experiment. It is thus a sum of water loss from the tank due to evaporation and that drawn up the cores for evapo-transpiration (ET).
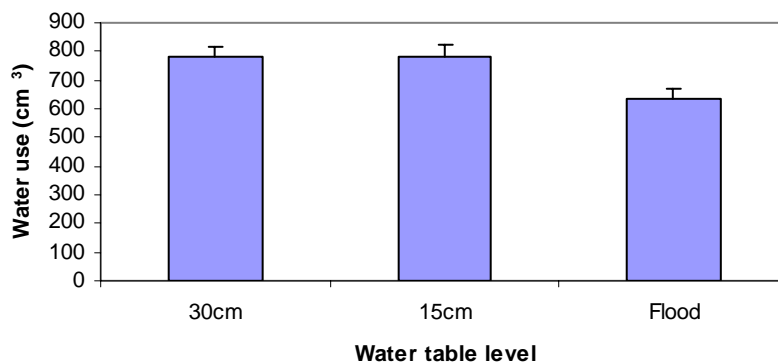
Figure 6.3 Water use with error bars used for L.s.d. (p=5%)
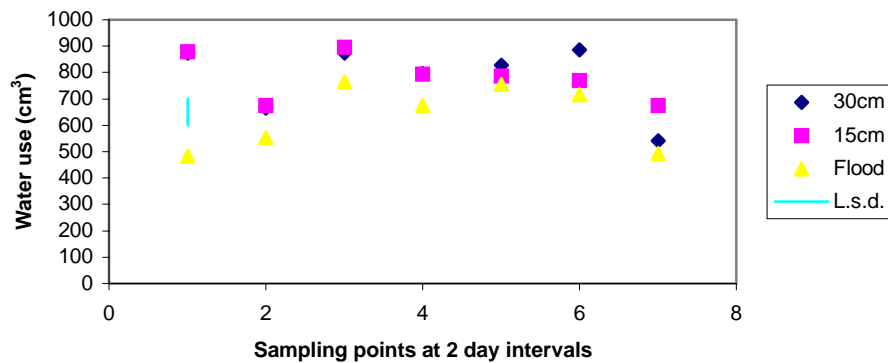
Figure 6.4 Water use at two-day intervals for the three water treatments showing L.s.d (p=5%).

The flooded tanks had the highest area of water exposed in addition to the highest level of water. Evaporation from the tanks were thus expected to be greater from these tanks followed by the tanks under the 15 cm water table depths. The level of water for the tanks under the 30 cm water table level was lower than the others, and the area exposed smaller as such evaporation from the 30 cm tanks were expected to be lower than for the others.

Figure 5.14 a and b (Chapter 5) show that temperatures in the tank at the different water levels were not significantly different and thus could not have significantly influenced rate of evaporation. The area of water exposed and height of water as well as the plant water use were then the differing factors and they may have contributed greatly to the differences in evaporation from the tanks.

Polystyrene beads were placed on floodwater of the cores under the flooded treatment in order to reduce evaporation and thereby prevent excess salt build up in the floodwater. The results presented for water use for the flooded treatments are thus lower than they would have been with free evaporation from the water surface.

Figure 6.3 shows that generally water use over the period of measurement did not differ significantly for the plants under the 30 cm water table treatment and those under the 15 cm water table treatment. They were lower for those under the flooded treatment though. Figure 6.4 also shows that water use for the flooded treatment was lowest at each point, but those for the other two differed only at the last two measurement points.

There does not appear to be any obvious reason for the departure in water use pattern over the last two points considering that the environmental conditions did not undergo any change, and there was no dramatic changes in plant growth leading to major differences in water use over that period.

It has generally been observed that shallower water table depths contribute more ground water to evapo-transpiration than deeper ones under similar climatic conditions and atmospheric demand. Wind (1961) observed that at higher matric potentials (drier soil) the rate of capillary rise in a coarse soil such as sand is dependant on height of the water table and concluded that water tables close to the surface have high capillary rise rate which result in high actual evaporation. Owusu-Sekyere (1988) using the Darcy-Buckingham equation determined the upward flux from the water at varying depths and found that the higher the water table, the greater the upward flux. A water table at a depth of 15 cm should then lose more water than that at a depth of 30 cm under similar climatic conditions.

Williamson and Carreker (1970) however observed that ET was generally higher for crops such as soybean and grain sorghum grown under a water table depth of 30 cm compared to that grown under a water table depth of 15 cm similar to what was observed here. This could be due to the fact there was a lower oxygen amount in the rhizosphere for the plants under 15 cm water table level leading to a reduced water uptake.

According to Hillel (1980), suction at the surface is controlled by the external conditions, the greater the atmospheric demand for water, the greater the suction at

the surface upon which the atmosphere is acting. The actual evaporation rate is determined by the external demand for water or the water-transmitting properties of the soil, and the lower of these two is the limiting factor.

In this experiment, the external conditions were the same for both the 30 cm water table treatment and the 15 cm treatment. The depth of the water table however led to differences in conditions in the cores. Mean volumetric moisture content at the surface was about 34 % for the 15 cm water table treatment but about 14 % for the 30 cm water table treatment. Hydraulic conductivity, which depends on moisture content, was therefore lower for the 30 cm treatment. The soil temperatures at a depth of 10 cm below the surface of the sand were significantly greater for the 30cm water table treatment, though the difference was very small (Mean temperatures were 29.9 ^{o}C for the 30 cm water table treatment and 29.5 ^{o}C for the 15cm treatment) and will not have significantly influenced results.

Evaporation rate was expected to be higher for the 15 cm water treatment, but there is the possibility that transpiration rate was greater for the 30 cm treatment leading to the results observed. Transpiration rates for the plants under the flooded treatment should also be lower than those under the other treatments considering the lower water use from that treatment and the fact that, as already indicated, more water was expected to be lost from the tanks implying very little was actually lost through transpiration.

Considering the fact that the plants under the 30 cm water table depth treatment were significantly taller than the others, there is also the probability that incident radiation was greater for thus requiring greater transpiration leading to a greater use of water.

6.3.2.2 NH_4^+ amounts in solution

NH_4^+ concentration was generally greater under the flooded treatments followed by the 30 cm water table treatment then the 15 cm treatment (Figure 6.5). Figure 6.6 shows the levels of NH_4^+ over time in the sand solution. NH_4^+ concentrations were significantly greater for the flooded treatment at the first sampling point: they were also greater for the 30 cm water table treatment than the 15 cm ones.
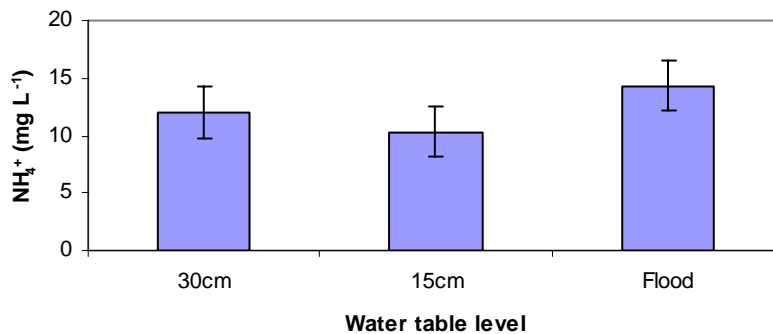
Figure 6.5 NH_4^+ concentrations in solution for the three water treatments with error bars as L.s.d. (p=5%).
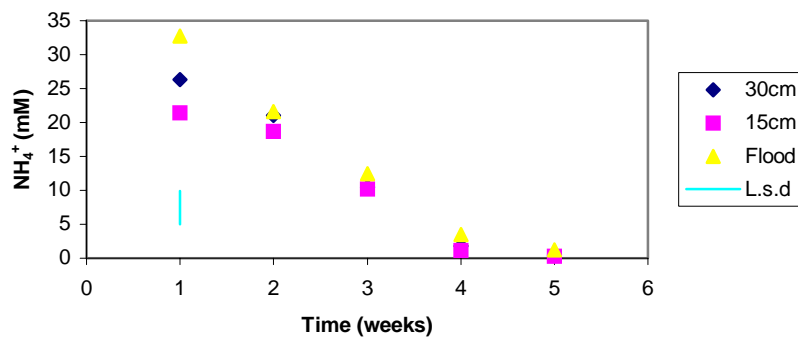
Figure 6.6 NH_4^+ in sand solution over time showing L.s.d. (p=5%).

The differences disappear after that but at every point the flooded treatment has the highest NH_4^+ level. The significantly higher concentration for the flooded treatment may be due to greater evaporation before it was limited by introducing the polystyrene beads.

There is no relationship between NH_4^+ in solution and the treatments imposed. The level of NH_4^+ is lowest for the 15 cm treatment at the end of every week. This does not correspond to the uptake patterns though and is difficult to explain.

It is interesting that after two weeks NH_4^+ concentrations are not significantly different for the three water treatments. As a number of factors including uptake, nitrification and de-nitrification as well as volatilisation are involved in determining the levels of NH_4^+ available it becomes difficult to explain the pattern after the 2nd week.

NH_4^+ concentration drops rapidly over the weeks; at the end of the fifth week it is almost zero for all the treatments. Applied NH_4^+ has an apparent short life span in agricultural soils, 1–4 weeks or more depending on rates of nitrification (Evangelou and Lumbanraja, 2002) and volatilisation in the case of the flooded treatments and this is what happens here.

6.3.2.3 Plant nitrogen content

The level of nitrogen per kg of plant dry mass is shown in Fig. 6.7. The plants under the 30cm water table treatment had the greatest concentration of nitrogen at each sampling point. Those for the flooded treatment are lower at every point. They are significantly lower only at the first sampling point, that is two weeks after treatment imposition.
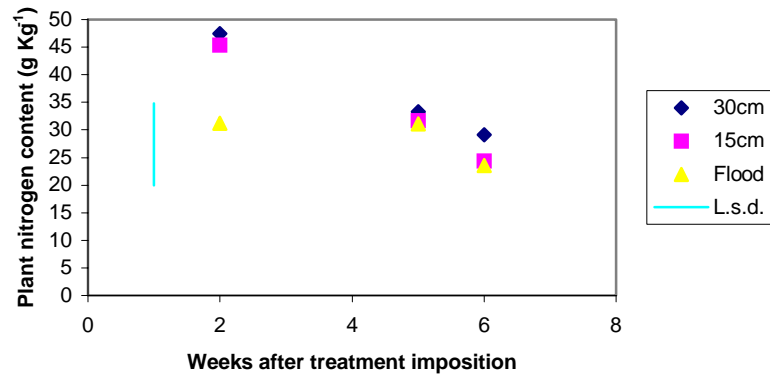
Figure 6.7 Concentration of N in plants over time showing L.s.d. (p=5%).
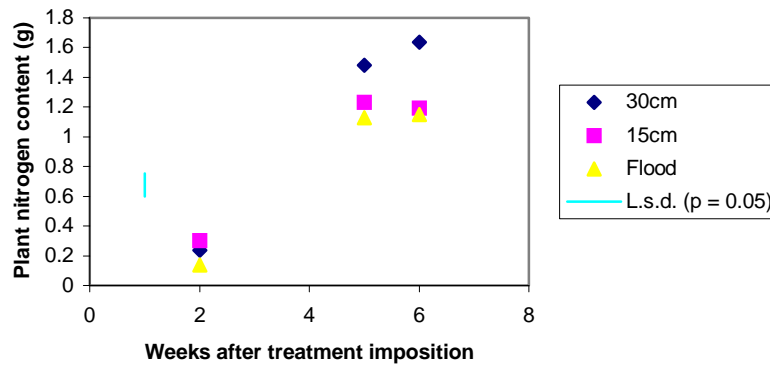
Figure 6.8 Total plant nitrogen content over time showing L.s.d. (p=5%).

Total plant nitrogen content as shown above (Fig. 6.8) is the product of nitrogen concentration in plants and dry weight of plant biomass.

More nitrogen is found in the plants under the 15 cm water table depth treatment initially but there is generally significantly more nitrogen in the plants under the 30 cm water table depth than under the other water treatments at the second and third sampling points. Overall, uptake is greatest under the 30cm water table treatment. Some level of aeration may therefore improve nutrient uptake.

Generally for plants under conditions of excess moisture there is a change in environment, which limits the metabolic activity and development of the root

system impeding the uptake of nutrients; at low O_2 concentrations therefore, there is a decrease in mineral content in plants (Wesseling, 1974). Rice plants differ in that they are able to provide oxygen in the rhizosphere through aerenchyma cells. However there is the possibility that there is a reduction in uptake for flooded plants when compared to aerated ones leading to a greater rate of absorption by the aerated plants thereby giving the pattern observed, that is, more nitrogen for the plants under the aerated treatments.

Though there was a higher concentration of NH_4^+ in solution at every point for the flooded treatment, the plant nitrogen content was lower than for the other treatments. Nitrogen uptake was greater under the 15 cm and 30 cm water table treatments.

6.3.2.4 Rooting depth

Rooting depth at each sampling point was significantly greater for the plants under the 30 cm water treatment followed by those under the 15 cm treatment, indicating that rooting depth is greater under conditions of lower moisture content.
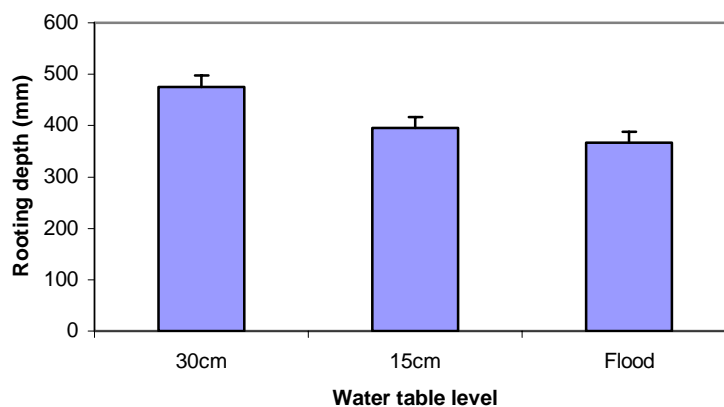
Figure 6.9 Mean rooting depth with respect to the water table depth with error bars as L.s.d. (p=5%).

Just as for the other experiments, after two weeks the rooting depth for all the treatments had gone below the water table in each treatment thus eliminating any potential for water stress.
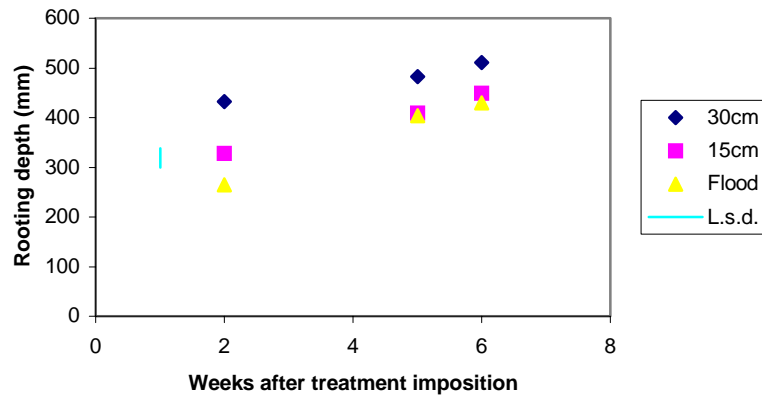
Figure 6.10 Mean rooting depth over time for the water treatments showing L.s.d. (p=5%).

Price *et al*. (2002) indicate that field grown rice shows that drying soils can promote root growth measured as total root mass or rooting depth, this is observed here as well as in the other experiments, where the plants under the 30cm water treatment have the longest rooting depth followed by those under the 15cm water table depth.

6.3.2.5 Root dry mass

Root dry mass is the same at the first sampling point, at the other two points, the mass is greatest for the plants under 30 cm water treatment followed by those under the 15cm water treatment then the flooded treatment. As noted above, drier conditions encourage increase in total root mass.
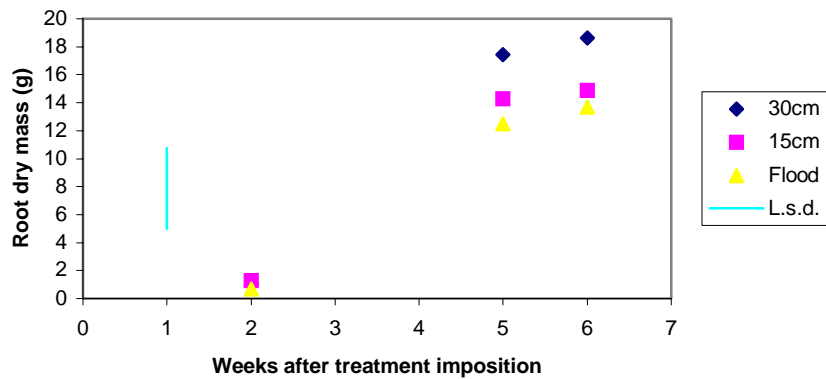
Figure 6.11 Mean root dry mass for the three water treatments with error bars as L.s.d. (p=5%).

The results here differ from those of the previous experiments; root dry mass for the flooded treatment is about 40 g whereas that for the 30cm water table treatment is 15 g for the experiment reported in Chapter five, in this case the plants under the 30cm table treatment have a higher root dry mass. The root dry masses are however not significantly different.

6.3.2.6 Total root length

The sum of the lengths of all the nodal roots was greatest for the plants under the 30 cm water table treatment, followed by the 15 cm water table depth. The differences were however not significant. The picture over time shows that lengths differ depending on time of sampling.

The plants under the 15 cm water table depth had the greatest length at the first sampling point but the least at the second and third sampling points.
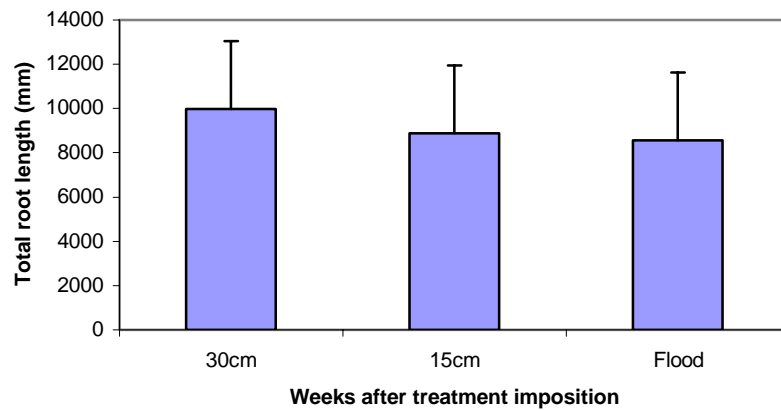
Figure 6.12 Total length of all nodal roots with respect to the water treatments with error bars as L.s.d (p=5%).
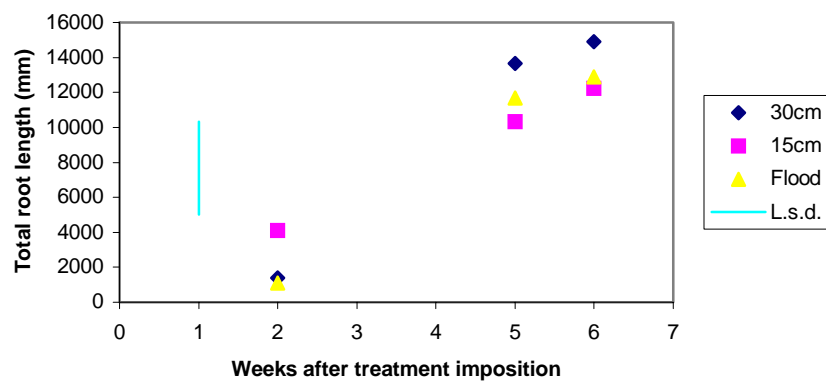
Figure 6.13 Total length of all nodal roots over time for the water treatments showing L.s.d (p=5%).

Longer total root length of nodal roots meant greater volume of soil explored as well as a greater area of root exposed to nutrients as has already been alluded to in the previous chapters. From that perspective the plants under the 30 cm water table depth had a greater potential for moisture and nutrient uptake.

The results presented here differ from those presented in Chapter 4 where the plants under the 15 cm water table depth had a significantly greater total root length than those under the 30 cm water table depth.

6.3.2.7 Root length density

Root length density is the ratio of the total root length of all the roots, nodal as well as lateral, to the total volume of soil. A relationship between total root length of primary roots to lateral roots was determined with data from Drenth *et al*., (1991). This relationship was used to determine the total length of all roots.
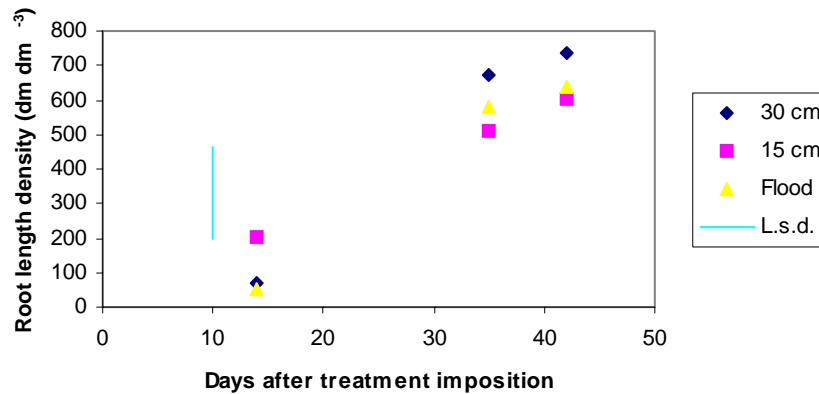
Figure 6.14 Root length density (units dm dm^{-3} were selected just for consistency with model requirements in chapter seven).

Root length density at the first harvest point is greatest for the 15 cm treatment, but at the second and third harvest is greatest for the plants under the 30 cm water table depth treatment followed by those under the 15 cm water table depths then the flooded treatment.

6.3.2.8 Shoot dry mass

Shoot dry mass was greatest for the plants under the 30 cm water table depth followed by those under the 15 cm water table depth. The differences were however not significant.

At the end of the sixth week, plants under the 30 cm water table depth had a greater shoot dry mass than the plants under the other treatments. This may again be attributed to the greater availability of nitrogen for the plants under the 30 cm treatment. There is the possibility that the results would have been different if the experiment had gone beyond six weeks as can be seen from the large increase in

shoot dry mass for the plants under the flooded treatment from the second to the third sampling points.
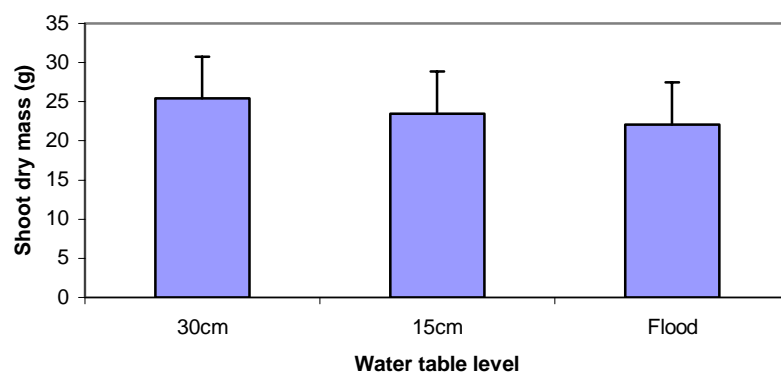
Figure 6.15 Mean shoot dry mass with respect to the water treatment with error bars as L.s.d. (p=5%).
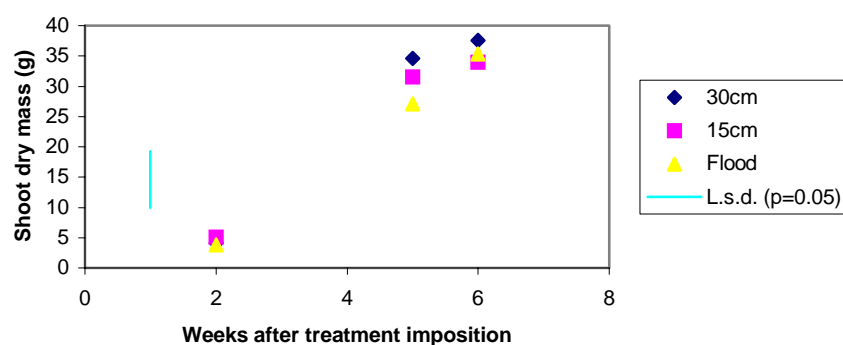
Figure 6.16 Mean shoot dry mass with respect to time for the water treatments showing L.s.d. (p=5%).

6.3.2.9 Plant height

Generally, plant heights were significantly greater under the 30 cm water table depth. Plants under the 15 cm water table treatment are also significantly greater than those under flooded conditions.

Plant height over time also show that at each sampling point, the order is maintained, with the plants under the 30 cm water table depth having the highest length and those under the flooded conditions the lowest length.
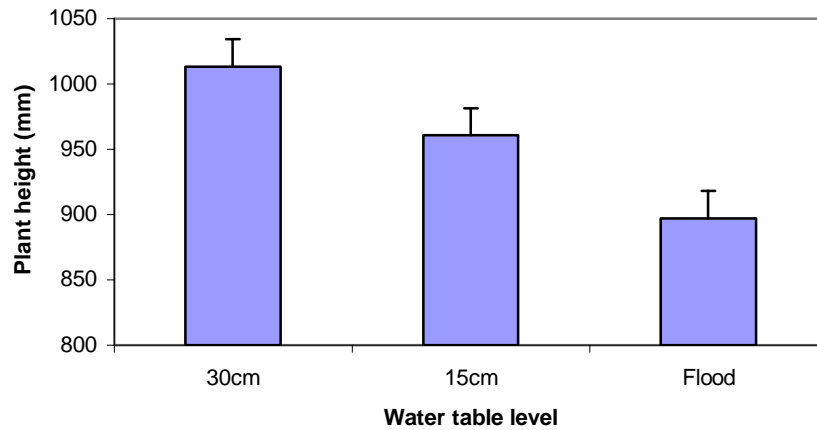
Figure 6.17 Mean plant height under the three water treatments with error bars as L.s.d.(p=5%).
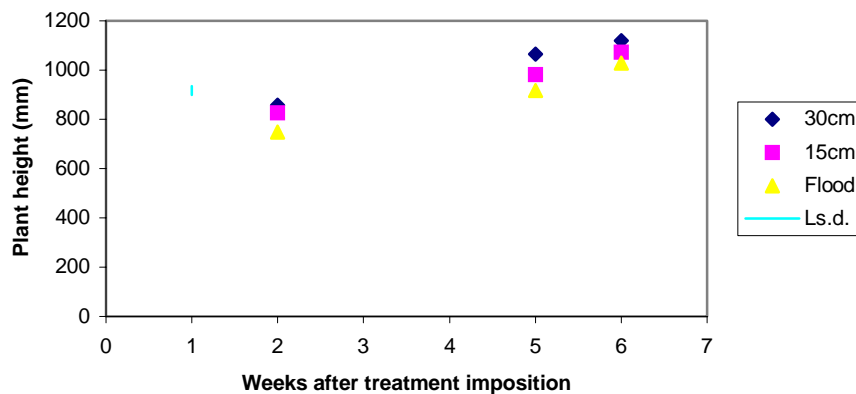
Figure 6.18 Mean plant height over time under the three water treatments showing L.s.d (p=5%).

6.3.2.10 Tiller production

Figure 6.19 shows that number of tillers for the 15 cm water table treatment was significantly greater than the other two treatments.

In Figure 6.20, number of tillers at each sampling point were greater for the 15 cm water table treatment, whereas tiller numbers drop for the two unsaturated treatments at the last sampling point, they increase for the flooded treatment.
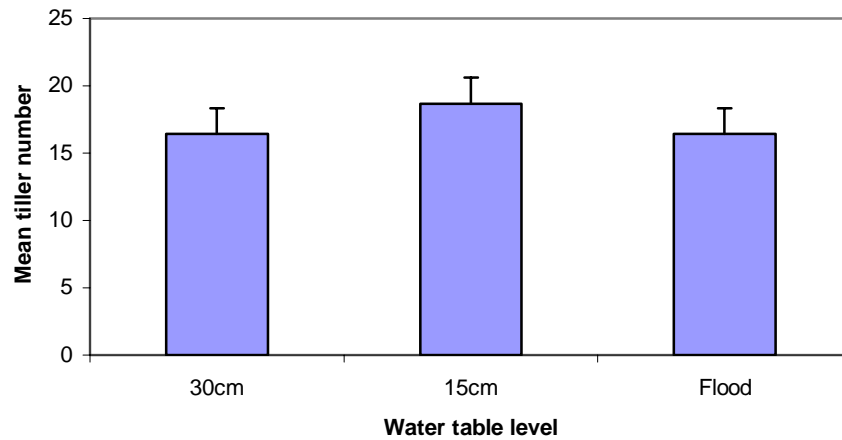
Figure 6.19 Mean tiller number with respect to the water treatments with error bars as L.s.d. (p=5%).
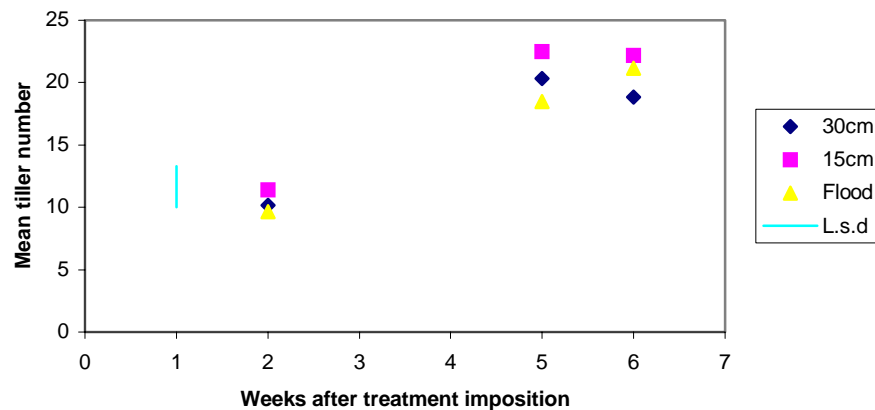
Figure 6.20 Mean tiller number over time for the water treatments showing L.s.d. (p=5%).

Tillering is enhanced with increasing N availability (Sharma and De Datta, 1985) and considering the nitrogen content of the plants, the plants under the 30 cm water table treatment should have had the greatest number of tillers.

The results obtained here differ from those presented in Chapter five though, where tiller numbers were greater for the plants under the 30 cm water table treatment.

It is surprising that tiller numbers at the end of the 6th week are lower than at the end of the 5th week. This suggests that the plants harvested at the end of the 5th week tillered more heavily than those which were harvested at the end of the 6th week. Shoot dry mass indicates that growth was not slowed down even though tiller numbers were lower, in that shoot dry mass at the end of the 6th week is greater than those at the end of the 5th week.

6.3.2.11 Electrical conductivity of flooded cores

The EC in the floodwater as well as a few centimetres below the surface was monitored to determine if it was beyond the tolerance limit of the plants. The tables below shows the results obtained.

Table 6.1 EC of floodwater and that a few cm below the surface for the flooded treatment. FW – Flood water; BS – Below surface.

Core	Tank1 FW	Tank1 BS	Tank2 FW	Tank2 BS	Tank3 FW	Tank3 BS
1	2.06	0.66	2.49	0.8	2.9	1.23
2	2.52	0.82	2.25	0.75	1.58	0.59
3	2.91	0.94	2.59	0.94	2.59	0.92
4	2.32	0.86	3.64	1.25	2.45	0.87
5	2.04	0.72	2.64	0.8	3.30	1.16
6	1.68	0.58	1.99	0.59	2.90	0.97

Tables 6.1 and 6.2 show EC values of the floodwater and at a depth below the surface of the sand. EC below the surface is lower than EC of the floodwater further confirming the fact that the salinity problem was limited to the floodwater cores. EC of the floodwater is in most cases above 2 mS cm^{-1}, and in two cases

above 3 mS cm^{-1}. In one case the EC of the floodwater was less than 1 mS cm^{-1} but it is suspected that some nutrient solution was accidentally poured straight into that core. There is therefore the possibility that growth under the flooded treatments were influenced to some extent by the salinity problem. It was however not possible to determine the extent to which this was.

Table 6.2 EC of floodwater and that a few cm below the surface for the flooded treatment taken two days after the first readings. FW – Flood water; BS – Below surface.

Core	Tank1 FW	Tank1 BS	Tank2 FW	Tank2 BS	Tank3 FW	Tank3 BS
1	2.45	0.98	2.17	1.05	0.634	-
2	2.17	0.95	2.08	0.88	2.54	1.0
3	2.26	0.95	2.12	0.835	2.33	0.86
4	2.4	0.82	2.82	1.02	2.5	0.99
5	2.01	0.86	2.18	0.99	2.87	1.62
6	2.14	0.86	2.37	0.89	2.69	1.18

6.4 CONCLUSIONS

1. The procedure developed for loading vermiculite with ammonium was successful. It was however not possible to develop it such as to obtain precise predetermined quantities of ammonium per gram vermiculite. It may therefore not be possible to repeat this experiment with the same levels of NH_4^+ on the vermiculite. It will also not be possible at this stage to get a predetermined level of NH_4^+ loaded on a predetermined mass of vermiculite.

2. The approach of loading vermiculite with ammonium and using it to grow rice cannot be recommended for growing rice over a long period of time as the

ammonium concentration rapidly decreases to zero after about four weeks. Up to the end of the fourth week it may be used, and probably even up till the end of the sixth week.

3. Water use under a water table depth of 30 cm was greater than that under flooded and a water table depth of 15 cm. A water table depth of 30 cm will not lead to water stress.

4. Rooting depth of Azucena is determined by the interaction of nitrogen content as well as moisture content; a low moisture content as well as a low nitrogen content leads to a greater rooting depth. Nitrogen content of the soil has a greater influence than amount of moisture available under the conditions imposed in this experiment.

5. Rice variety Azucena may not be able to withstand a floodwater EC of greater than about 3.9 mS cm$^{-1.}$

6. Plant nitrogen uptake was greatest for the 30 cm water table treatment followed by the 15 cm water table treatment then the flooded treatment. Plant nitrogen uptake was higher for the deeper water table treatments. Moreover, increasing uptake led to better growth indicating that growth in rice is more a function nutrient availability rather than water availability.

7.Water table control may be used in areas where floodwater may be too saline for rice growth.

The moisture regimes imposed lead to differences in transport of nutrients to the root as well as differing root length densities. Uptake of nutrient is limited by these factors, and as nutrient levels have been identified as being the primary factor influencing growth of rice, the next chapter uses a model to explore rooting characteristics, moisture content as well as uptake on nutrients in order to explain growth differences.

CHAPTER 7: MODELLING THE EFFECT OF ROOT PROPERTIES AND NH$_4^+$ TRANSPORT THROUGH THE SOIL ON N UPTAKE UNDER DIFFERENT WATER REGIMES

Abstract

A mathematical model was modified and used to explore the interactions of NH$_4^+$ transport to the roots, as well as to calculate root length densities required to match the measured rate of N uptake to measured mean concentrations of NH$_4^+$ in solution around the rooting medium for each of three water treatments: water table 30 cm below the surface, 15 cm below the surface and a flooded system.

Measured uptake was greatest for the plants under the 30 cm treatment followed by the 15 cm treatment then the flooded treatment. Solution concentrations were highest under the flooded treatment followed by the 30 cm treatment then the 15 cm treatment. Total nitrogen may however have been greatest under the flooded treatment and least for the 30 cm water table depth treatment.

The differences between calculated bulk NH$_4^+$ concentrations and concentrations at the root surface varied in size for the three treatments with the lowest moisture content treatment having the largest difference. Transport rates thus varied with moisture content. As uptake rates did not reflect these differences in transport rates, it is concluded that transport through the growth medium did not limit uptake of nitrogen by the plants.

Calculated root length densities were greatest for the plants under the 30 cm water table treatment followed by those under the 15 cm treatment then the flooded treatment. Measured root length densities were similarly greatest for the plants under the 30 cm water table treatment followed by those under the 15 cm water table depth treatment then the flooded treatment. Calculated root length densities matched measured ones initially but reached a peak then dropped below that for the measured value. Root length densities did not limit uptake of NH$_4^+$.

7.1 INTRODUCTION

The experiment reported in Chapter 6 was set up to assess the effects of water regime on growth of Azucena rice under NH_4^+ nutrition. In this chapter, a mathematical model of NH_4^+ transport through soil and its absorption by roots is used to explore interactions between NH_4^+ transport to the roots, root length densities and water regime in the experiments in Chapter 6. The model is based on that of Kirk and Solivas (1997).

According to Kirk and Solivas (1997) root properties and transport through the soil can limit nitrogen uptake by rice growing in flooded soil. In my previous experiments, I found that rooting characteristics varied under the three water conditions imposed. Moreover, in the treatments with lower water tables, there were gradients of soil moisture content between the soil surface and the water table, implying differences in rates of solute transport through the soil and hence possibly of nutrient transport to absorbing roots. It has already been noted that nitrogen availability is often the main factor limiting the realization of yield potentials in irrigated rice (Cassman *et al*., 1997), and according to Sharma and De Datta (1985), components of yield are closely associated with the nitrogen supply at each growth period. Moreover, active absorption and metabolism of nitrogen results in a large increase in dry weight, tillering, height and leaf area. Growth differences under a water table control system might therefore be due to differences in these nitrogen uptake-limiting processes.

Kirk and Solivas (1997) developed the model to determine the extent to which root properties and transport through the soil limit nitrogen uptake by lowland rice. They used the model to calculate the root length densities required to match measured rates of N uptake and measured mean concentrations of NH_4^+ in the soil solution, as well as to determine the solution concentration at the root surfaces. An indication of the extent to which root length densities limited uptake was obtained by comparing their measured and calculated values. A comparison of the

measured bulk concentration and calculated concentration at the root surfaces also gave an indication of the extent to which diffusion through soil limited uptake.

A modified version of this model is used to explore the interactions of NH_4^+ transport to the roots, and in addition calculate root length densities required to match the measured rate of N uptake to measured mean concentrations of NH_4^+ in solution around the rooting medium.

7.2 KIRK AND SOLIVAS' MODEL

7.2.1 Theory behind the model

Uptake of NH_4^+ by roots uniformly or randomly distributed in volume V of soil at a density L_v (length per unit volume) is considered. If the influx of NH_4^+ across unit root surface, F (moles per unit time), is uniform along the root length, then the rate of uptake is:

$$\frac{dU}{dt} = 2\pi aFL_vV \qquad\qquad (7.1)$$

where a, is the mean root radius and U is uptake. The influx is related to the concentration of NH_4^+ in solution at the root surface C_{La} by a 'root absorbing power', α, such that:

$$F = \alpha C_{La} \qquad\qquad (7.2)$$

The root absorbing power is accepted as the best compromise between representing root properties with accuracy and the need for a boundary condition, which allows relatively simple analytical solutions of diffusion equations (Nye and Tinker, 1977). Over the relevant concentration range α often varies with C_{La} according to equations of the form:

$$\alpha = F_{max}/(K_M + C_{La}) \qquad\qquad (7.3)$$

where F_{max} is the maximum influx into the roots and K_M the Michelis constant for NH_4^+ absorption. These will vary with the plant's internal nitrogen status and other factors that change over the course of growth but they are considered constant in this model and assigned values such that uptake per unit root length is maximal within experimentally determined limits for rice under conditions similar to the present experiment.

If each root is surrounded by a cylinder of NH_4^+ depletion zone of radius x, and the concentration profile of NH_4^+ in the cylinder corresponds to that for steady state diffusion, then C_{La} is related to the mean concentration in solution in the cylinder, $\overline{C_L}$ by:

$$C_{La} = \frac{\overline{C_L}}{\left[1 - \frac{1}{2}\frac{\alpha a}{Db} + \frac{x^2\frac{\alpha a}{Db}}{\left(x^2 - a^2\right)}\ln\frac{x}{a}\right]} \qquad (7.4)$$

where D is the soil NH_4^+ diffusion coefficient, and b is the soil NH_4^+ buffer power, which is explained below.

$$D = D_L \theta\, f_L\, /\, b \qquad (7.5)$$

where D_L is the NH_4^+ diffusion coefficient in water ($= 2.0 \times 10^{-7}$ dm^2 s^{-1}), θ is the soil water fraction by volume, and f_L is the diffusion impedance factor. The latter takes into account the tortuous pathway the nutrient ions must follow through the soil pores, as well as the effects of increased viscosity of water at the soil surface, and negative adsorption effects on anions. The impedance factor increases with increasing soil moisture.

The buffer power b, is given by dC/dC_L, where C is the total concentration of mobile NH_4^+ in the soil and C_L is the concentration of NH_4^+ in the soil solution. The value of x increases with time according to:

$$x = 2\sqrt{Dt} + a \qquad\qquad (7.6)$$

until it coincides with the boundary of the equivalent cylinders around adjacent roots; at this point, $x = 1/\sqrt{\pi Lv}$ and $\overline{C_L}$ equals the mean value over the whole soil cylinder.

If dU/dt and $\overline{C_L}$ are measured in an experimental system, and if the soil NH_4^+ diffusion coefficient and root NH_4^+ uptake parameters are known, then the minimum root length densities required to explain the observed uptake rates can be calculated.

7.2.2 Assumptions in the model

Two main assumptions with regard to transport of NH_4^+ to the roots and the form of nitrogen absorbed are made. First, the theory is based on transport of NH_4^+ to the roots solely by diffusion. It does not allow for mass flow of the soil solution towards the roots in the transpiration stream. Kirk and Solivas (1997) concluded that if mass flow were considered, under similar conditions to those pertaining here, it would increase the influx rate by only about 4%. It is therefore reasonable to ignore mass flow for the sake of simplicity.

Second, it is assumed that NH_4^+ is the only form of nitrogen absorbed by the roots. Under waterlogged conditions, rice roots release some O_2 from their internal gas channels into the surrounding anaerobic soil, and as a result some of the NH_4^+ near the roots is converted to NO_3^- by the process of nitrification. Lowland rice roots have an exceptional capacity for absorbing NO_3^- (Kirk and Kronzucker, 2005), and therefore much of this NO_3^- is absorbed. Otherwise it may diffuse away from the roots into the anaerobic soil where it is denitrified to N_2 and lost as gas. It is

therefore not totally correct to assume that all the N is absorbed as NH_4^+. However, since nitrification can only occur close to the roots, the NH_4^+ that is nitrified must be transported to the roots and the same limitations apply.

7.3   MODIFICATION   OF   THE   MODEL   FOR   THE   PRESENT EXPERIMENT

7.3.1 Varying soil moisture and rooting density with depth

Figure 1 shows the approximate profiles of soil moisture with depth in the different water treatments, assuming the gradient of moisture above the water table is linear, i.e.

$$\theta_z = \theta_0 + (\theta_{sat} - \theta_0)\, z/z_{sat} \quad 0 < z < z_{sat} \tag{7.7}$$

where z_{sat} is the depth of the water table and θ_z, θ_0 and θ_{sat} are the moisture contents at depth z, the soil surface (z = 0) and the water table (z = z_{sat}), respectively.
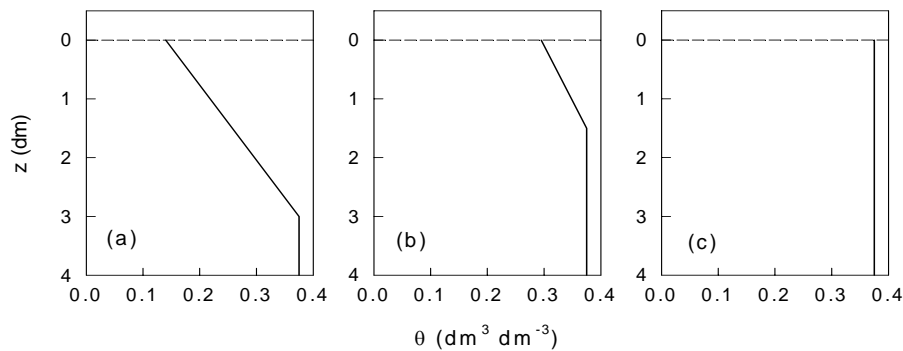
Figure 7.1 Profiles of volumetric soil moisture content (θ) with depth below the soil surface (z) in the different water treatments. Depths of water-table below the soil surface (z = z_{sat}) are (a) 30 cm, (b) 15 cm and (c) 0 cm (i.e. soil water-saturated throughout).

In addition, plant-root density decreases with depth below the soil surface and is affected by the water treatment (Chapter 6). In particular, under water-saturated conditions the roots must aerate themselves internally and this constrains the

maximum length of root that can be kept aerated and hence the maximum rooting depth. Hence generally, the observed order of N uptake between the water treatments – Treatment (c) < Treatment (b) < Treatment (a) – might be explained by restricted rooting depth in the more-saturated treatments, in spite of faster diffusion of NH_4^+ to root surfaces in these treatments. The model can be used to assess the relative importance of rooting depth versus soil transport rates under the conditions of the experiment. Commonly root density is found to decline exponentially with depth and is satisfactorily described by the following equation (Tinker and Nye, 2000).

$$P_z = 1\text{-}\exp(\text{-}\beta z) \tag{7.8}$$

where P_z is the fraction of the total root mass above depth z and β is a coefficient such that $1/\beta$ is the depth containing 63% of the total root mass.

The model was adapted, with the help of Prof. G. Kirk, to allow for the varying moisture and root length density with depth by dividing the soil depth into small intervals, over which moisture and root length could be taken to be effectively constant, and the model solved for uptake separately for each depth layer. The first step in the calculations was to divide the total rate of N uptake by the root system, $(dU/dt)_{total}$ – which is found from the differentiated logistic curve for N uptake (Equation 7.17) – across the soil-depth layers according to the distribution of root mass. Hence, from Equation (7.8), the ratio of uptake in the ith depth layer (where i=1 is the soil surface layer) and above to the total uptake is:

$$\frac{\sum\limits_{i=i}^{i=1}(dU/dt)_i}{(dU/dt)_{total}} = 1 - \exp(-\beta z_i) \tag{7.9}$$

Equation (7.9) is solved as follows. We have

$$\sum\limits_{i=i}^{i=1}(dU/dt)_i = (dU/dt)_i + (dU/dt)_{i-1} + \sum\limits_{i=i-2}^{i=1}(dU/dt)_i = \{1 - \exp(-\beta z_i)\}(dU/dt)_{total}$$

(7.10)

also

$$\sum_{i=i-1}^{i=1}(dU/dt)_i = (dU/dt)_{i-1} + \sum_{i=i-2}^{i=1}(dU/dt)_i = \{1 - \exp(-\beta z_{i-1})\}(dU/dt)_{total} \quad (7.10a)$$

Subtracting Equation (7.10a) from Equation (7.10) and rearranging gives

$$(dU/dt)_i = \{\exp(-\beta z_{i-1}) - \exp(-\beta z_i)\}(dU/dt)_{total} \qquad (7.11)$$

Equation (7.11) is solved for each soil depth.

The concentration of NH_4^+ in solution at the root surface, C_{La}, in each depth layer required to explain this rate of uptake is then calculated from the mean concentration in solution in the layer, $\overline{C_L}$, which is taken to be constant with depth. The corresponding influx per unit root (surface) length, F, is found for each depth layer, and thence the root length density, L_V, is found. These steps are repeated as necessary if the spread of the depletion zone, x, found from $x = 2\sqrt{Dt} + a$, exceeds the mean inter-root distance, found from $x = 1/\sqrt{\pi L_V}$.

If the calculated maximum rooting depth exceeds the depth of the soil core, the distribution of uptake with depth is adjusted pro rata for the 'missing' roots.

The total root length density in the soil core is then found from the sum of the values in each depth layer.

The equations were solved in this way using a depth increment of 1 cm (i.e. 40 depth layers in total). Runs with depth increments of 0.25 cm (i.e. 160 layers) gave the same results to within 0.1%.

7.3.2 Calculation of the soil NH_4^+ buffer power

From the soil NH_4^+ desorption isotherm (Figure 7.4), the relation between the concentration of labile NH_4^+ in the soil solid, C_S (mmol kg^{-1} vermiculite), and the concentration in the soil solution, C_L (mmol dm^{-3} solution), is:

$$C_S = m \ln C_L + \text{constant} \tag{7.12}$$

The total concentration in the soil, C (mol dm^{-3} soil), is

$$C = \theta C_L + \rho R C_S \tag{7.13}$$

where θ is the volumetric moisture content (dm^3 solution dm^{-3} soil), ρ is the dry bulk density (kg dm^{-3} soil) and R is the vermiculite content of the 'soil'(kg vermiculite kg^{-1} soil). Combining Equations (7.12) and (7.13) gives

$$C = \theta C_L + \rho R \ (m \ln C_L + \text{constant}) \tag{7.14}$$

Hence the soil NH_4^+ buffer power, b, is given by

$$b = dC/dC_L = \theta + \rho R m / C_L \tag{7.15}$$

From Equation (7.15), b is concentration-dependent. Most simply, a mean value of b can be calculated for each soil depth by substituting the value of $\overline{C_L}$ in Equation (7.15).

7.4 MODEL INPUT DATA

7.4.1 Rates of nitrogen uptake

The rates of uptake were determined from the changes in plant nitrogen content over time. Figure 7.1 shows the values of plant nitrogen content (the product of

plant N concentration and plant dry weight). Logistic equations of the form shown below were fitted to the data:

$$Y = A + C/(1 + EXP(-B*(X - M))) \tag{7.16}$$

where X is the time in weeks following treatment imposition, Y the cumulative N uptake in mmol plant^{-1} and A, B, C and M are coefficients. The coefficients are given in Table 7.1 and the fitted curves in Appendix 3.
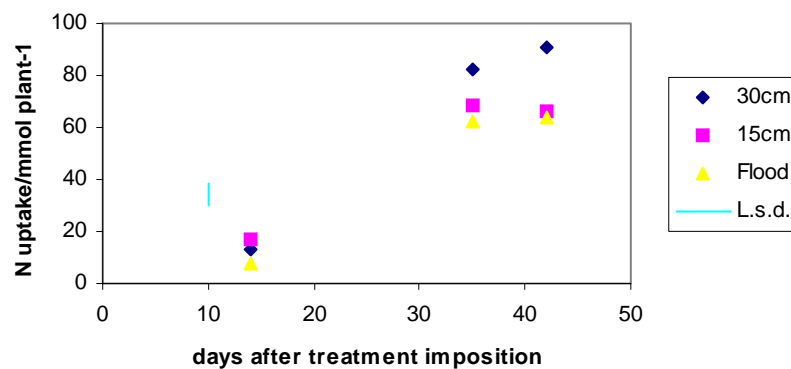
Figure 7.2 Measured cumulative plant N uptake points for the three water table depths: a) 30 cm b) 15 cm and c) 0 cm showing L.s.d (p=5%).

Table 7.1 Coefficients for logistic curve for N uptake in the three water treatments (with time in days)

Coefficient	Water treatment		
	z_{sat} = 30 cm	z_{sat} = 15 cm	z_{sat} = 0 cm
B,M,C,A	0.1604, 23.999, 98.37, -2.36	0.1908,19.955 70.47, -1.24	0.2082, 22.816, 66.73, -0.84

The rate of uptake at a particular time if found from the differential of Equation (7.16) with respect to time:

$$\frac{dU}{dt} = -BC\left[\frac{\exp\{B(t-M)\}}{[1+\exp\{B(t-M)\}]^2} \right] \tag{7.17}$$

7.4.2 NH$_4^+$ concentration in solution

The changes in mean nitrogen concentration in solution at a depth of 10 cm from the surface over time are shown in Fig. 7.3. Logistic equations of the form of Equation (7.16) were fitted to the data and the curves are also shown in Fig. 7.3. The coefficients are given in Table 7.2.
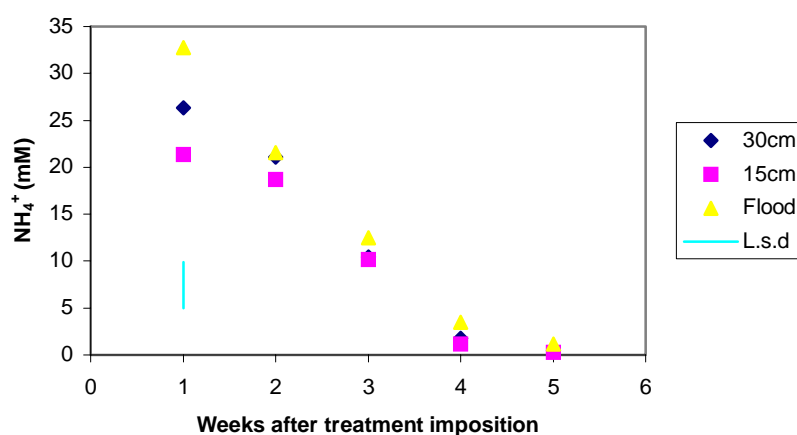
Figure 7.3 Measured solution NH$_4^+$ concentrations for the three water table depths: a) 30 cm b) 15 cm and c) 0 cm showing L.s.d. (p=5%).

Table 7.2 Coefficients for logistic curve for NH$_4^+$ concentration in solution in the three water treatments (with time in days)

Coefficient	Water treatment		
	z_{sat} = 30 cm	z_{sat} = 15 cm	z_{sat} = 0 cm
B,M,C,A	-0.266, 18.838, 1.393, 0.078941	-0.2873, 20.447, 1.1586, 0.0336	-0.1545, 16.45, 1.8811, 0.0778

7.4.3 Bulk density of sand-vermiculite cores

The weight of the sand-vermiculite mixture was 10.40 kg per core and the core dimensions were: length 4 dm and radius 0.55 dm. Hence the volume of the cores was 12.57 dm^3 and their bulk density ρ = 0.827 kg dm^{-3}. The mixture contained 0.2 kg of vermiculite per core, i.e. 0.0192 kg vermiculite kg^{-1} mixture.

7.4.4 Volumetric moisture content of sand-vermiculite cores

Moisture content was measured as described in Chapter 5. The flooded cores were saturated throughout, i.e.; $\theta = \theta_S = 0.375$ at $0 < z < 40$ cm. In the cores with the water table at 15 cm $\theta = \theta_S$ at 15 cm $< z < 40$ cm, and in those with the water table at 30 cm, $\theta = 0.14$ at $z = 0$ and $\theta = \theta_S$ at 30 cm $< z < 40$ cm. Between $z = 0$ and $z = z_{sat}$, θ is given by Equation (7.7).

7.4.5 Diffusion impedance factor

According to data in Tinker & Nye (2000, Section 4.2), the approximation $f_L = \theta$ is reasonable over the range of soil moisture contents in the present experiments.

7.4.6 NH_4^+ buffer power, b

The NH_4^+ buffer power was estimated from the desorption isotherm of the sand-vermiculite mixture (Fig. 7.4).
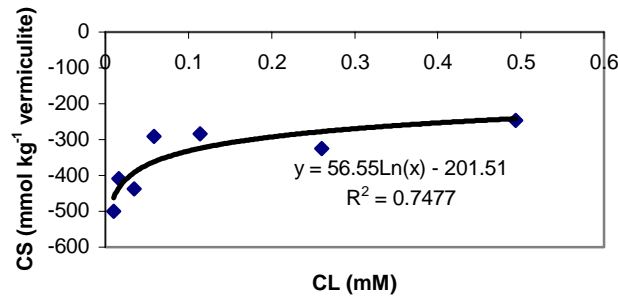
Figure. 7.4 Ammonium desorption isotherm of sand vermiculite mixture.

From Equation (7.15), the mean buffer power is

$$\overline{b} = \theta + \rho Rm / \overline{C_L} \qquad (7.18)$$

where, from Fig. 7.4, m = 56.55 with C_S in units mmol kg^{-1} vermiculite and C_L in mM, and R = 0.0192 kg vermiculite kg^{-1} soil. With C_S in units mol kg^{-1}

vermiculite and C_L in M (the working units in the computer program for the model), m = 0.0566 (and constant = 0.189).

7.4.7 Root radius

The mean root radius reported by Kirk and Solivas (1997) for rice grown in flooded soil under comparable conditions was 0.11 mm. I used this value for each of the water treatments.

7.4.8 Root NH_4^+ absorbing properties

As mentioned in Section 7.2.1, plants can regulate the inflow of nutrients into roots in accordance with their nutrient requirements. Hence the root NH_4^+ absorbing properties vary with the plant's growth rate, internal N content, and other factors. Wang *et al.,* (1993) grew rice plants for 3 weeks in nutrient cultures with fixed NH_4^+ concentrations and then measured the short-term influx of ^{13}N-labelled NH_4^+ from solutions of different NH_4^+ concentrations, and obtained the following values of F_{max} and K_m in nmol dm^{-2} s^{-1} and μM respectively, the former converted from a per gram of root fresh wt basis using tissue density = 1 g cm^{-3} and root radius = 0.11 mm: 2.0 and 32 at 2 μM NH_4^+ in the growth solution, 1.28 and 90.2 at 100 μM NH_4^+, and 0.53 and 188 at 1000 μM NH_4^+. Hence the roots 'up-regulated' their membrane transport systems as the plants' internal N concentration decreased. For the present purposes I am interested in the minimum root length required to account for the observed uptake and hence the maximum influx per unit root length. I used the values of F_{max} and K_m for plants grown in 2 μM NH_4^+. I used the same values for each water treatment.

7.4.9 Coefficient for root distribution, β

Table 7.3 shows the results of a preliminary experiment in which I measured root mass in sand cores of the same dimensions as in the main experiments with water table at 0, 15 and 27.5 cm below the surface. The experiment was conducted under nutrient deficient conditions but the results are not expected to vary much from what pertained in these experiments. The results show no obvious differences in the distribution of root mass with depth, and the depth containing 63% of the roots

was approximately 2 dm, giving $\beta = 0.5$ dm^{-1}. I used this value for each water treatment.

Table 7.3 Root dry mass over sections 10 cm in depth for three water treatments

Depth (dm)	% of root mass per layer		
	$z_{sat} = 0$ cm	$z_{sat} = 15$ cm	$z_{sat} = 27.5$ cm
0-1	35	35	49
1-2	27	29	23
2-3	26	20	20
Total over 0-3 dm	88	84	92

7.5 RESULTS AND DISCUSSION

7.5.1 Solution NH_4^+ concentration

Figure 7.5a shows the mean concentrations of NH_4^+ in the soil solution ($\overline{C_L}$) over time for the three water treatments (i.e. the logistic curves fitted to the experimental data in Appendix 4). The order of initial $\overline{C_L}$ values is flooded > 30 cm water table > 15 cm water table, but the order of their rates of decline matches the order of N uptake rates, initially ('15 cm' > '30 cm' > flooded) and finally ('30 cm' > *15> 'flooded'). This order is similar to that for root length densities (Fig. 7.8). In due course as the plants deplete NH_4^+ from the soil all three tend to zero. The order of initial $\overline{C_L}$ values may reflect differences between the treatments in cation exchange equilibria between the vermiculite -- which is initially saturated with NH_4^+ and Ca^{2+} -- and the differing volumes of nutrient solution.

(a)
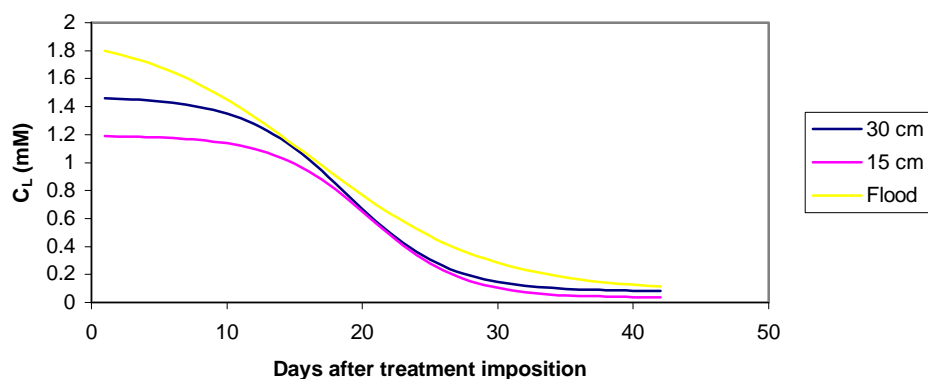
(b)
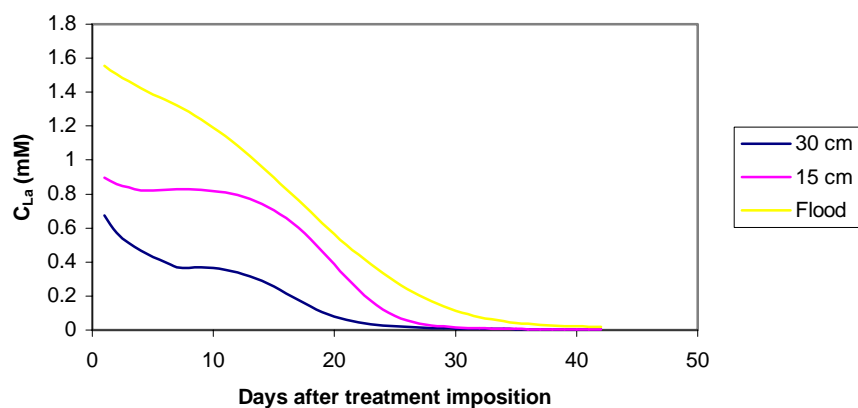
Figure 7.5 Concentrations of NH_4^+ in the soil solution for the three water treatments: (a) the mean bulk soil value ($\overline{C_L}$), (b) the value at the root surface (C_{La}).

Over time, NH_4^+ is extracted from the vermiculite as it is removed from the soil by plant uptake and possibly also by nitrification-denitrification and NH_3 volatilisation.

The latter is expected only if the pH rises well above neutral, which it did not in any of the treatments (Chapter 6). Nitrification – denitrification may be important where there is an oxic-anoxic interface, as there would be if the water-saturated soil became anaerobic. However measurements of redox potentials in the cores

showed that this did not happen (Chapter 6) and so nitrification-denitrification losses were probably minimal.

Figure 7.5b shows the calculated changes in concentration at the root surface (C_{La}) (plotted on the same axes as $\overline{C_L}$ in Appendix 2). The values vary with depth but only those at 10 cm depth are shown for simplicity (the values of $\overline{C_L}$ are taken to be independent of depth). After about 20 days the changes over time follow similar patterns to the changes in $\overline{C_L}$: they decline as the plants extract NH_4^+ and the rates of decline reflect the rates of uptake. However in the earlier stages, after an initial sharp drop, C_{La} is constant somewhat over time in the unsaturated water treatment, and the difference $\overline{C_L}$ - C_{La}, which indicates the concentration gradient, required to drive diffusion through the soil to the roots is maintained (Appendix 2). This presumably reflects a rate of uptake (dU/dt, shown in Fig. 7.6 for 10 cm depth). The difference $\overline{C_L}$ - C_{La} increases as the moisture content decreases between water treatments and diffusion becomes increasingly limiting.
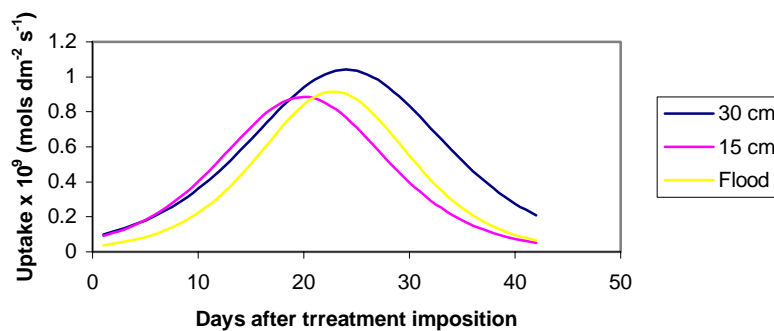
Figure 7.6 Rates of NH_4^+ uptake by the plants at 10 cm depth calculated from the differentiated logistic curve (Equation 7.17).

7.5.2 Measured and calculated root length densities (L_v)

Figure 7.7 shows the measured root length densities at different times in the different treatments and the calculated minimum root length densities required to explain the measured NH_4^+ uptake. Figure 7.8 shows the calculated root length on

larger-scale axes, and shows that it followed the pattern of uptake rates (Fig. 7.6) fairly well in all the water treatments, peaking after 20-25 days.

The measured root length densities decrease in the order: '30 cm' > '15 cm' > flooded. This is in agreement with the increasing limits on root length imposed by the need for internal aeration under water-saturated conditions, and also with the decreasing soil diffusion limitations for NH_4^+ uptake as the water content increases. I showed in earlier chapters that individual roots were shorter under the wetter moisture conditions, probably reflecting restrictions due to the need for internal gas transport.

The calculated root length densities agree reasonably well with the measured ones, but the accuracy of the prediction increases as moisture content decreases. However, this suggests the model describes the important processes reasonably well and that the parameter values are right. However in the following sensitivity analyses I show that errors in the assumed values for the root radius and root absorption parameters as moisture levels increased may well have contributed to the under-prediction of root length in the later stages.

(a)
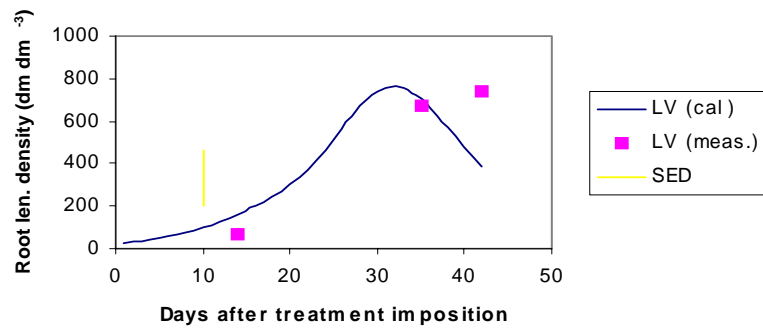
(b)
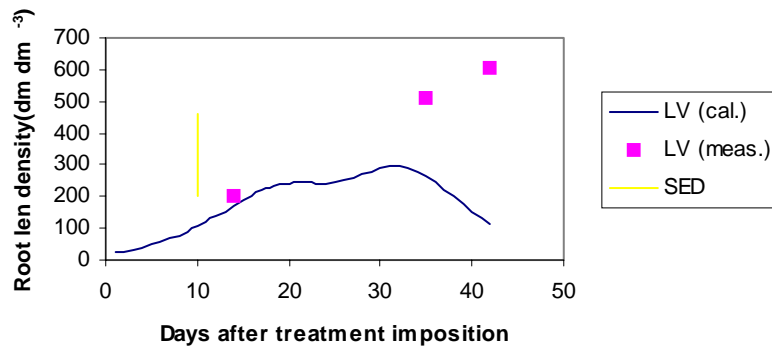
(c)
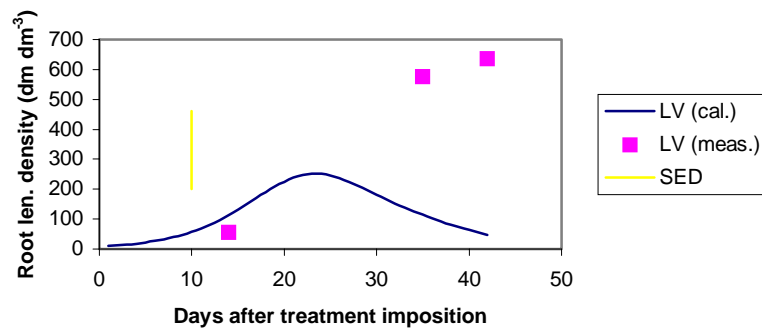
Figure 7.7 Measured root length densities (points) and calculated minimum values required to explain uptake of NH_4^+ (lines) for the three water treatments: (a) 30 cm, (b) 15 cm and (c) flooded treatment.
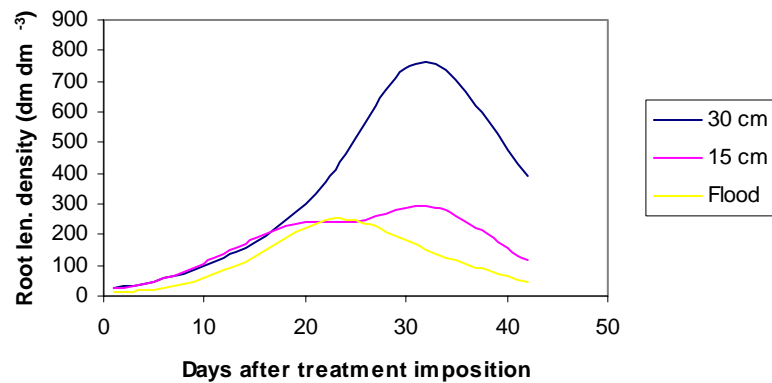
Figure 7.8 Calculated minimum root length densities in Figure 7.6 plotted on larger-scale y-axes

7.5.3 Sensitivity analysis

It has already been noted that the N content of the plant determines the uptake characteristics of the roots. At small N levels, uptake is maximal; as N levels increase, uptake is suppressed, and this is depicted by smaller F_{max} values and larger K_M values. As indicated, the values for K_M and F_{max} are taken from studies for roots grown in 2μM solutions.

The results show that, for all the water treatments, as F_{max} becomes smaller and K_M increases, there is a decrease in influx, reflected in increasing C_{La}, and a larger L_v is required to maintain the intake rate.

Equation 7.1 indicates the rate of uptake is sensitive to the mean radius of the roots. A radius of 0.11 mm was assumed for the calculations so far. In Appendix 5, I give results for radius 0.06 mm. These show a large increase in L_v as the mean root radius decreased.

These results indicate that part of the under-prediction of the measured L_v values as moisture levels increased may have been due to inappropriate root radius or F_{max} and K_M values or both.

This may have compounded the effect already discussed regarding root length past the peak rate of uptake. Further, the actual root length involved in uptake may have been only a small portion of the total root length as is generally observed for plant root systems (Marschener, 1995).

7.6 CONCLUSIONS

1.   The model predicted accurately root length densities in the case of the 30 cm treatment. In the case of the 15 cm and the flooded treatments, the accuracy diminished towards latter growth stages. This was attributed to the root radius and the diffusion parameters used for those treatments. Varying those parameters however improved the predictions.

2.   In all the three water treatments, the measured root length densities were either lower or just about the same as the calculated minimum ones required to match the measured rate of N uptake with the measured mean concentrations of NH_4^+ in solution around the roots. As indicated, total root length is mainly made up of the lateral roots, which are the ones, which absorb nutrients, and thus, root length densities were for the most part above that required to ensure uptake of nutrients. Root length densities therefore did not limit uptake of nutrients.

3.   There were large differences between values for the solution NH_4^+ concentration and that for NH_4^+ concentration at the root surface. This indicates there was some limitation in transport of nutrients to the roots. This limitation increased as moisture content decreased. As uptake values were higher for the lower moisture content treatments however; it is clear that these limitations did not hinder uptake of nutrients. Even though diffusion rates differed amongst the three water treatments, rates of transport of nutrients were not such as could limit uptake.

CHAPTER 8: GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

8.1 INTRODUCTION

With the increasing world population and a dwindling supply of fresh water, it becomes necessary to reduce water supplied for agriculture, which consumes a large percentage of the fresh water that is drawn annually. According to FAO (2005) water consumption in agriculture represents 40 % of the total water consumption in Europe, and rice requires six times the amount of water used for wheat production. This will mean developing efficient water management systems, which are able to supply the required amount of water required by the crops without much wastage and with no reduction to yield. In rice production, a number of new methods for reduction of the amount of irrigation water applied have been tested and have had varying successes; in areas where there is a predominantly high water table, water table control would probably be the best option for adoption for rice production. It has already been stated that, in addition to water saving, adoption of water table control would lead to energy savings, due to the fact that puddling would not be required, methane production would also be much reduced due to the fact that the soils would not be waterlogged, and rice could also be cultivated like any other dryland cereal crop and not require use of specialised equipment.

Water table control has been suggested particularly for areas where there is alternating excess and lack of moisture, in that, it serves to conserve water during dry periods and aids in quickly draining water during periods of excess moisture.

In the inland valleys scattered across West Africa, especially in Ghana, where there is a predominantly high water table for the greater part of the year, water table control should seriously be considered as an option for rice production.

This study has investigated the use of water table control for lowland rice production by planting rice in sand cores placed in tanks in a growth chamber

under controlled atmosphere conditions. The results obtained, though peculiar to the conditions under which the experiments were conducted, can be relied on as a basis for further experiments on the fields.

8.2 GENERAL DISCUSSION

A comparison of the growth of wetland rice under two water table depths and saturated and flooded conditions was made. The saturated and flooded conditions used vary from traditional systems where the saturated and flooded systems would have a restricted depth of soil for the roots to grow in due to an impermeable layer at a depth of about 14 cm below the soil surface. Conditions for growth under the saturated and flooded systems were thus better than would normally pertain in the fields, and growth under these systems would thus exceed that under the traditional system.

8.2.1 Plant growth parameters

Growth under the two water table depths compared favourably with the flooded and saturated conditions, with plants under the water table control treatments in some cases performing better than the others in the growth parameters measured. In experiment one (Chapter 4) IR36 was used, and the total root length, number of roots and tiller numbers were significantly greater for the plants in the saturated treatment. There were however no significant differences in root mass, shoot mass, and shoot length with regards to water depth. In experiment two (Chapter 4) where Azucena was used, the 15 cm treatment had the highest shoot mass in addition to the highest tiller numbers. In other parameters, the 15 cm treatment was not significantly lower than the saturated treatment. The 30 cm treatment was much lower in all parameters measured. Significant differences with regards to water treatments occurred only for rooting depth. In the third experiment (Chapter 4) the plants under the flooded treatment had a significantly greater root dry mass, shoot dry mass and tiller numbers than the others. The plants under the 30 cm treatment however had a significantly greater root dry mass and shoot dry mass than the plants under the 15 cm water table depth. Tiller numbers for the plants

under the 30 cm water table depth were also greater than those under the 15 cm water table depth.

For all the experiments 1-3, apart from one instance in the case of tiller numbers for IR36 (Chapter 4) differences in growth for the water treatments appeared only after the fourth week. This shows that water requirement for rice over that period may be grossly overestimated and most of the water applied may actually be wasted. Wetland rice may then be grown with much less water up till the fourth week and that would not have any impact on plant development. This concept could be extended beyond four weeks but this has yet to be properly investigated.

In the fourth experiment (Chapter 5), under Azucena, shoot dry mass was of the order: 30 cm treatment > 15 cm treatment > flooded treatment; the differences were not significant. Tiller numbers followed the same pattern. Under IR36, shoot dry mass was just about the same for all treatments, tiller numbers were also just about the same for the plants under the 15 cm treatment and the flooded treatment, but they were significantly greater than for the plants under the 30 cm treatment. The response of two rice varieties to water table control varied for tiller numbers but was just about the same for the other parameters. This suggests that water table control might be suitable for all varieties of rice.

Azucena is an upland variety that performs well under lowland conditions and is genetically adapted to these conditions. The fact that it performs better in some cases under the 30 cm water table depth than the flooded conditions might be an indication that upland rice varieties might benefit from this system of rice production.

In experiment five (Chapter 6), the plants under the 30 cm water table depth treatment had the highest root dry mass followed by those under the 15 cm water table depth then the flooded treatments. The same pattern was observed for shoot dry mass; the differences were not significant in any of these cases. The plants under the 15 cm water table depth treatment had the highest tiller number followed

by those under the 30 cm water table depth then the flooded treatments. The differences were not significant. Varying the form of nitrogen applied did not alter growth parameters to any appreciable extent implying that supply of nitrogen is more important than the form of nitrogen used.

When significant differences appeared for tiller numbers, the plants under the 30 cm water table depth had the least number of tillers. It appears therefore that tiller production increases with increasing moisture content. This however did not always lead to an increase in shoot dry mass implying that though tiller production is promoted by increasing water availability it does not necessarily lead to an increase in above ground biomass. Though yield does increase with increase in the number of tillers produced, not all tillers are productive; there are sometimes unproductive tillers, which utilize nutrients for growth but give no yield. It is not known whether increasing the amount of moisture available will lead to the production of productive or unproductive tillers. This may also have to be investigated by conducting the experiment to yield.

The results obtained for the plant growth parameters determined give a clear indication that water table control with the water table at or above depths of 30 cm below the surface is able to sustain rice production for the duration over which the experiments were conducted. A depth of 30 cm was obtained using pure sand, however, the moisture profile under pure sand with a water table at a depth of 30 cm will vary from that of soil with a water table at depth of 30 cm. This is primarily because pore spaces differ in size and numbers and capillary rise depends on the size and number of pores (Franzen, 2003); sand with larger pores will have a lower capillary fringe than loamy soil or clayey soil with finer pores. The profile corresponding to that with a water table at a depth of 30 cm for sand will be that for a water table at a depth lower than 30 cm in a soil with smaller pore spaces. Less water may be required on soils with finer pore spaces.

The large variation in growth parameters with respect to the water table level between experiments shows there is no clear relationship between moisture

availability and growth of rice. This suggests that it is not water availability that is important but probably the oxygen status, and the physiological response to the aeration stress that matters.

It was observed that there were large variations in results between experiments. It has been noted that after the second experiment the growth chamber was changed and this could have contributed to the variations observed. There is also the fact that as the number of experiments conducted increased the husbandry techniques were improved allowing the crops to respond better to the treatments imposed.

8.2.2 Water use

The results for water use (Chapter 6) were in the order: 30 cm water table depth > 15 cm water table depth > flooded treatment. However it must be noted that the floodwater in the flooded treatment was covered with polystyrene beads, which were used mainly to reduce water loss and the consequent rise in salinity levels. The fact that water loss for the plants under the 15 cm water table depth and those under the 30 cm water table depth were about the same indicate that more moisture was transpired from the plants under the 30 cm water table depth than those under the 15 cm water table depth. It has already been established that more moisture is lost from shallower water table than deeper ones under the same climatic conditions. More moisture is likely to be evaporated from the 15 cm water table depth treatment. It has also been stated (Chapter 5) that there is the probability that more moisture was transpired by the plants under the 30 cm water table depth due to the fact the plants were taller and thus closer to the radiation source and so required more water. This however indicates that the transpiration requirement for rice was met when the depth of the water table was kept at 30 cm below the surface buttressing the fact that water table control with the water table at a depth of 30 cm below the surface is able to support growth of rice.

8.2.3 Environmental conditions

The environmental conditions measured were modified to some extent under the water treatments used although the extent of modification was not such as could

have a great impact upon growth. This could be due to the fact that the growth media used, wet sand, did not lend itself to such modification. The chemistry of flooded sand however differs from that of other soils, indicating that the environmental conditions under some other type of soil could have varied from those observed and may have contributed immensely to growth. Redox potentials for example (Chapter 5) were all above 300 mV at the depth of measurement, meaning that the systems were never in a reducing condition. Others soils, especially under flooded conditions, would certainly have obtained reducing conditions due to increased microbial activity, which could have altered rooting characteristics. According to Kim *et al.,* (1999) rice plant adaptation and physiological functions are governed by soil redox condition. They observed that root length and weight decreased under strongly reduced conditions (-150 mV). More reduced conditions would have led to a concentration of roots at the surface in the flooded treatment, in order to obtain oxygen. That would imply a smaller root length density at depth which also would mean lower uptake at depth and possibly lower over all uptake levels which would lead to lower growth than occurred with sand as the growth medium.

8.2.4 Effect of form of N source

The plants grew well under both nitrate-nitrogen and ammonium-nitrogen indicating that the source of nitrogen was not of any significance as long as there was a supply for rice growth under water table control. Under the use of nitrates, the supply was continuous as they were supplied with the nutrient solution, but in the case of ammonium, the total estimated amount was supplied at the beginning of the experiment. This did not lead to major differences in growth as a comparison of shoot dry mass and tiller numbers depict. It has been noted that under both sources of nitrogen, levels fell towards zero getting to the end of the experiments; they however fell faster under ammonium-nitrogen than nitrate-nitrogen. This indicates a greater depletion of ammonium-nitrogen than nitrate-nitrogen. In all cases, there is the possibility that the actual nitrogen demand of the plants was not supplied, and growth potential was not fully exploited with regards to nutrient supply.

Total root length was of the order: saturated treatment > 15 cm water table depth > 30 cm water table depth under nitrate nitrogen. Under ammonium nitrogen, the order changed to 30 cm water table depth > 15 cm water table depth > flooded treatment. This may be related to the method of application of the nutrients in that with the ammonium nitrogen, the nitrogen supplied was concentrated in the core whereas with the nitrates, the bulk of it was in the nutrient solution in the tank thus leading to different root responses in both cases. It was observed that under increasing amounts of nitrogen, rooting depth decreased.

Application of nitrogen under water table control would probably be best if applied through the irrigation water and this would have to be in small quantities matching the crop requirement over time. This would encourage root development in addition to ensuring optimal use of the nutrients.

8.2.5 Uptake rates

The last experiment (Chapter 6) was set out to explore the effect of ammonium-based nutrition on growth of rice under water table control. In that experiment, moisture content measured at the surface for the three water treatments used were significantly different at the surface; in Chapter 7 it was established that the diffusion impedance factor was directly proportional to the moisture content. Diffusion of nutrients was in this order: flooded treatment > the 15 cm treatment > 30 cm treatment. Rooting characteristics were also seen to differ under the different water treatments, with the root length density for the plants under the 30 cm water table depth treatment about 2000 dm dm^{-3} greater (Chapter 6) than those for the plants under 15 cm water table treatments and the flooded treatments. A greater rooting length density would lead to greater potential for the roots to acquire nutrients, which would in this case favour the plants under the 30 cm water table depth. This treatment, having the lowest moisture content at the surface, had the lowest diffusion impedance factor, implying that transport of nutrients to the roots would be slower. Uptake levels were however greatest under

this treatment indicating that the greater root length density may have offset the lower nutrient transport rates.

Rooting length density may have to be one of the main criteria in selecting rice varieties for use for under water table control. A large rooting length density may compensate for lack of moisture with regards to transport of nutrients, in addition, it would have a greater volume of soil covered which would enhance acquisition of both water and nutrients.

8.2.6 Modelling

Two models were used in the study; the first was to simulate the depth of the water table in Dwinyam, an inland valley in the Ashanti Region of Ghana for the dry season of the years 1996 and 1997. The soil hydraulic properties required were determined by pedo-transfer functions and most of the other data used were for conditions similar to what pertains at Dwinyam making the results applicable. It was established that the lowest depth of the water table during the farming period was 1 m below the soil surface. The second model was used to determine the effect of root properties and NH_4^+ transport of nutrient through the soil on uptake of N. The model quite accurately predicted the root length densities required to explain the uptake rates, and measured and predicted root length densities were similar for most parts of the period investigated. It was observed that under the parameters used, the prediction improved as the moisture levels in the system decreased. This probably indicates that the influence of moisture content on the parameters was underestimated, and prediction as moisture content increased could be improved with parameters adjustment.

8.2.7 Adoption of water table control for rice production on the field

The first step in field adoption of water table control for rice production is to establish the depth of the water table that would sustain rice production. This depth will vary with soil texture and the hydraulic properties. Though it has been established from this study that a water table depth of 30 cm below the surface is able to satisfy the evapo-transpiration demand of rice, it has also been mentioned

that there is the possibility that a lower water table depths could be used under soils.
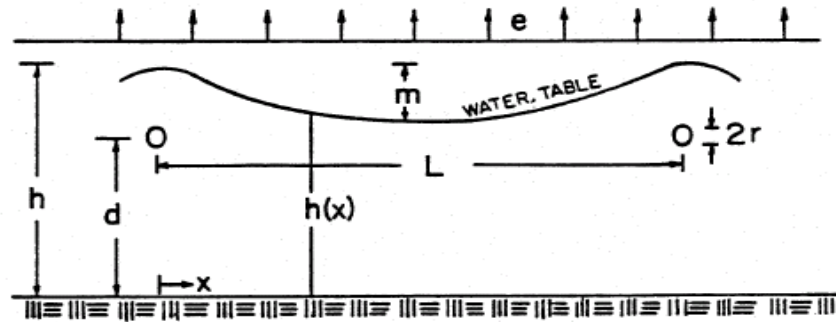
Figure 8.1 Water table control system: d = height of drain tubes above impermeable layer, h = height of water table above impermeable layer, h(x) = function of h along the direction of x, L = spacing between the supply tubes, e = evaporation flux, m = difference between height of the water table above the drains and that midway between the drains and r = radius of the tubes.

Water table control is achieved by having irrigation supply tubes laid at a depth beneath the soil surface and set at a spacing that would ensure a predetermined depth of the water table, which is capable of supplying the evapo-transpiration requirement of the crop (Figure 8.1). The depth and spacing of the tubes can be computed using the Ernst model once evapo-transpiration requirement as well as depth to the impermeable layer is known (Skaggs, 1980). The number of tubes required would be determined by the size of the field. The main materials used as supply tubes for water table control are polyvinylchloride (PVC) tubes, which are easily obtainable in most parts of the world.

Germination for the experiments was achieved under controlled conditions, and the seedlings planted about four days after germination. On a field scale, direct seeding (either wet-seeding or dry seeding) could be used, with the seedlings placed in rows to allow for inter-row cultivation. Uphoff (1999) recommends a square pattern with seeds set out singly and having a spacing of 25 cm.

Supply of nutrients as already indicated could be done through the irrigation water. Nitrates are recommended considering the rapid loss of ammonium and also for the fact that Lowland rice roots have an exceptional capacity for absorbing NO_3^- (Kirk and Kronzucker, 1995) and moreover under waterlogged conditions, some of the ammonium that is near rice roots is converted to nitrates by the process of nitrification.

Installing a water table control system would require purchase of PVC tubes and the system for water control in the water conveying channels. Installation of the tubes would also require excavation of trenches. These are the main cost components of adopting water table control systems. The economic viability of using water table control was not investigated due to the lack of data for such a computation. Owusu-Sekyere (1998) conducted a cost benefit analysis for water table control for wheat production and found out that water table control for wheat production was profitable. It is expected that rice production will also be profitable under water table control. A full analysis will however need to be conducted when yield levels are established for rice growth under water table control. It has however been established that water and energy savings are possible under water table control.

Weed control is one of the main problems to contend with in rice production, and as has already been mentioned, flooding is one of the methods used to control weeds. Adopting water table control will thus mean introducing other weed control measures. It has been recommended that rice under water table control be planted in rows allowing inter row cultivation with equipment that are used for other dryland cereal crops.

The main problem anticipated in the adoption of water table control is the build up of salts in the soil and therefore salinity problems. This problem can however be avoided with good soil and water management practices. Leaching using the tubes as drains will rid the soil of excess salts. In the rainy season annual leaching

requirement is expected to be met in the target basin areas of Ghana. The saline waters can be diluted by adding fresh water and used to irrigate again.

8.3 CONCLUSIONS

1. Use of water table control at Dwinyam

The water requirement comparison for the basin and water table control systems show that it is possible to save water under a water table control system when the mean height through which the water table has to be raised is about 1 m. Water saving will however decrease as the mean height through which the water table has to be raised increases; at an initial water table depth of 2 m there may be no water saving under the conditions given for Dwinyam in the Ashanti Region of Ghana. As the lowest level of the water table determined for two years at Dwinyan for the dry season is above that required to ensure water saving water table control may be adopted for use between August and December.

2. Water table control, moisture content and rice growth

Over the six weeks used for each of the experiments, rice was successfully grown proving rice can be grown using water table control systems. The order of water availability was: Flooded conditions > saturated conditions > 15 cm water table depth > 30 cm water table depth: growth parameters were thus expected to follow the same order. This was however not so: there was so much variation in growth in relation to availability of moisture that it is not possible at this point to conclude that the more moisture available, the better the growth of the plants. There was such a large variation that it is not possible to draw a conclusion as to which treatment gave the best results. Rice does not necessarily require flooded conditions over the first six weeks, and moisture availability is not the main factor that influences rice growth.

3. Rooting depth

Rooting depth for rice has always been known to be related to the amount of moisture available; rice under flooded systems are known to have shorter rooting depths in order to avail themselves of oxygen at the surface, aerated systems have

deeper roots which explore depths for moisture. The study however shows that rooting depth is influenced to a greater extent by nutrient availability (N especially), with deeper roots found in systems where there is low N and shallower roots under systems with excess N. Moreover, varying the form of nitrogen varied the order for total root length: under nitrates, the total root length increased with moisture content, but under NH_4^+, the total root length increased with decreasing moisture content.

4. Main factor affecting growth

It has been determined that nitrogen levels have a greater influence on growth of rice under water table conditions than water availability. In Chapter 5, nitrogen uptake rates were seen to be large for Azucena under the 30 cm water table treatment, and this led to it having the greatest root dry mass as well as the greatest number of tillers compared to the plants under the other treatments. Nitrate-nitrogen was used in this experiment. In Chapter 6 as well, where ammonium-nitrogen was used, uptake rates were seen to be greatest for the plants under the 30 cm water table depth treatment, and this also led to the plants under that treatment having the greatest root dry mass as well as shoot dry mass. In the case of tiller numbers, the plants had the lowest figures. Considering the fact that in the other treatments the plants under the 30 cm treatment fared worse than the other plants, the only conceivable reason for the change could be the fact that uptake of nitrogen is greater implying nitrogen uptake rates influence growth of rice plants under water table control.

5. Root length density and transport to roots

Given that rooting characteristics and moisture content varied under the water treatments used, it was hypothesised that growth differences could be explained by transport of nutrients to roots as well as root length densities. This was explored using a computer model, and it was found that neither root length density or transport to the roots limited growth under any of the treatments ruling these out as factors that could influence growth to any appreciable extent. Water table systems

with the water table below the surface do not provide conditions that limit uptake or transport of nutrients to the roots compared with flooded systems.

8.4 RECOMMENDATIONS

1. Suitability of water table control for rice production

Though it has been ascertained that water table control with a water table depth of 30 cm is able to sustain rice production at least over the periods for which the experiments were conducted, growth results varied from experiment to experiment. This does not permit the drawing of a valid conclusion as to which system, flooded or water table control performs better in rice production. Because of limitations in time and resource, this fact could not be determined. Six weeks, the duration of the experiments is too short a duration to predict the final dry matter production as well as grain yield. It is thus recommended that further experiments to be conducted specifically to determine if water table control for rice production leads to either an increase or reduction in yield.

Moreover the period of maximum rice water requirement is in the reproductive stage. This stage is beyond the six-week duration used in these experiments thus making it pertinent for these experiments to be conducted for durations beyond that which was used.

2. Growth medium

Nutrient interaction with the growth medium was virtually absent in these experiments as sand was used as the main growth medium. The chemistry of flooded soils differs from that of pure sand; nutrient and water interaction in real soils, nutrient diffusion properties as well as root growth differ making the drawing of valid conclusions impossible till these experiments have been conducted in real soils. It is thus recommended that this also be done.

3. Depth of water table required for rice production

As has been done for some other crops, it may also be necessary to determine the depth of the water table below which rice production cannot be sustained. This depth will definitely vary with soil type but that would be a guide for anyone intending to adopt water table control for rice production.

4. Loading vermiculite with ammonium

Though the procedure developed for loading vermiculite with ammonium was successful, it was not possible to develop it so as to obtain precise predetermined quantities of ammonium per gram vermiculite. It may therefore not be possible to repeat this experiment with the same levels of NH_4^+ on the vermiculite. It will also not be possible at this stage to get a predetermined level of NH_4^+ loaded on a predetermined mass of vermiculite. A number of trials may have to be conducted in order to get a prescribed procedure.

5. Form of nitrogen for water table control

It may not be feasible to use ammonium as the only source of N for growing rice, as loss of ammonium is rapid most probably through nitrification. The level of ammonium in all the water treatments was down to almost zero at the end of four weeks even though that which had been supplied was to last for six weeks. Nitrates may be the better source of nitrogen for growing rice under water table control.

6. Depth of water table required for economic use of water

Water table control has been determined to be more efficient in water use for rice production than basin irrigation. There is however a depth below which when the water table falls, the situation changes. This depth will be situation dependant and it thus is necessary to determine this depth for each situation before adopting water table control for rice production.

7. Field experimentation

All the experiments were conducted in growth chambers under controlled atmosphere conditions. The growth cores were of a limited diameter as well as of a limited depth. The atmospheric conditions were constant more or less during the daytime and also during the night. The results obtained can only be limited to the conditions under which they were obtained and only relied on as a basis for conducting trials on the field where conditions are very different. Field experimentations are thus recommended in order to concretise the results and conclusions obtained.

REFERENCES

Agyemang K. and Smith J.W. (1999) Counting the costs and benefits of implementing multi-country collaborative research projects: The case of the peri-urban Inland Valley Dairy Project in West Africa, In: Urban agriculture in West Africa (ed. Olanrewaju B. Smith), IDRC/CTA, 240 pp

Alam, S. M., Ansari, R. S., Mujtaba, M. and Shereen, A. (2001) Saline lands and rice: *The Pakistan Gulf Economist.* Issue no. 16, Apr 23-29

Annan-Afful and Wakatsuki (2002) Toposequence as influenced by land use in the inland valley watershed of Ashanti Region, Ghana. Conference paper no. 1146-presented at the 17th World Congress of Soil Science, August, Thailand.

Asch, F. and Wopereis, M.S.C. (2000) Yield response of irrigated rice to salinity depending on development stage and stress level. Conference paper - presented at the 3rd International Crop Science Congress in Hamburg 17th – August 22nd

Asubonteng, K. O., Otoo, E., Masunaga, T. and Wakatsuki, T. (2002) Meeting the rice production and consumption demands of West Africa with an improved soil and water management technology. Conference paper no. 1496 - presented at the 17th World Congress of Soil Science, August, Thailand.

Bajpai, R. K. and Tripathi, R. P. (2000) Evaluation of non-puddling under shallow water tables and alternative tillage methods on soil and crop parameters in a rice-wheat system in Uttar Pradesh. *Soil and Tillage Research*, volume 55, issues 1-2, pp 99-106

Barison, J. (2002) Evaluation of nutrient uptake and nutrient-use efficiency of SRI and conventional rice cultivation methods in Madagascar. *Agriculture and Development,* Cornell International Institute for Food, 607-255-0831

Beyrouty, Craig A., Wells, B. R., Norman, R. J., Teo, Y. H. and Gbur, E. E. (1995) Growth and Distribution of Irrigated Lowland Rice Roots in the United States. Conference paper - presented at the 3rd JSRR Symposium: A mini-symposium in the 2nd Asian Crop Science Conference at Fukui Prefectural University August 22, 1995

Bolton, F.R., Morris, R.A. and Vivekanandan, P. (1985) Soil-water relations in rice-based cropping systems. Soil Physics and Rice. IRRI

Borrell, Andrew, Garside, A., Fukai S. (1997) Improving efficiency of water use for irrigated rice in a semi-arid tropical environment. *Field Crops Research*, 52 pp231-248

Bouman, B. A. M (2001) Water-efficient management strategies in rice production. International Rice Research Notes,16.2, pp 17-22

Bouman, B.A.M. and Tuong T.P. (2001) Field water management to save water and increase its productivity in irrigated lowland rice. *Agricultural Water Management* 49 (1) pp. 11-30.

Brix, H., Dyher-Jensen K., and Lorenzen, B. (2002) Root-zone acidity and nitrogen source affects Typha latifolia L. growth and uptake kinetics of ammonium and nitrate. *Journal of Experimental Botany*, Vol. 53, No. 379, pp. 2441-2450

Brown, L. C., Ward, A. and Fausey, N. R. (undated) Agricultural Water Table Management Systems. Ohio State University Fact Sheet AEX 321-97.

Bugbee, B. (2003) Nutrient Management in Recirculating Hydroponic Culture. Conference paper - presented at the South Pacific Soil-less Culture Conference Feb 11, 2003 in Palmerston North, New Zealand.

Burkard Scientific (2000) SFA 2000 Segmented flow analyser, Uxbridge, Middx

Cassman, K.G. and Munns, D.N. (1980) Nitrogen mineralisation as affected by soil moisture, temperature, and depth. *Soil Sci. Soc. Am. J.* 44, 1233-1237

Cassman, K.G. Peng, S., Olk, D.C., Ladha, J.K., Reichardt, W. Dobermann, A. and Singh, U. (1997) Opportuinites for increased nitrogen use efficiency from improved resource management in irrigated rice systems. *Field Crops Res*. 56: 7-39

Clark, L.J., Cope, R.E., Whalley, W.R., Barraclough, P.B. and Wade, L.J. (2002) Root penetration of strong soil in rainfed lowland rice: comparison of laboratory screens with field performance. *Field Crops Research* 76, 189-198

Consultative Group on International Agricultural Research (CGIAR) (1999) New Rice Techniques Promise up to 25 Percent Less Water Usage. Press Release: May 17. World Bank, Washington.

Daniels W. L. (1997) Managing Compacted and Heavy (Clayey) Soils. *The Virginia Gardener Newsletter*, Volume 8, Number 6

Darcy, H. (1856) Les fontaines publiques de la villa de Dijon, Delmont, Paris.

Drenth H., ten Berge, H.F.M. and Meijboom, F.W. (1991) Effects of growth on porosity and branching of rice roots (Oryza sativa L.). In: Simulation and systems analysis for rice production (SARP) (eds: Penning de Vries, H.H. van Laar and M.J. Kropff), pp 162-175.

Evangelou, V. P. and Lumbanraja, J. (2002) Ammonium–potassium–calcium exchange on vermiculite and hydroxy-aluminum vermiculite, *Soil Sc. Soc. Am. J.* 66:455-463

Evans, R. and Skaggs, W. N. R. (1996) Operating controlled drainage and subirrigation systems. *Drainage and Hydraulic Structures,* North Carolina Cooperative Extension Service AGE 4233:

FAO (1989) Determination of the irrigation schedule for rice. In: *Irrigation scheduling: Irrigation Water management Training Manual 4*. FAO Rome

FAO (1992) CROPWAT: A computer program for irrigation planning and management. *FAO Irrigation and drainage paper 46*. FAO Rome.

FAO (1997) Management of agricultural drainage water quality. *Water reports 13*. FAO Rome.

FAO (2004) International year of rice 2004, Agenda item 10, Twenty-fourth FAO regional conference for Europe 2004, Montpellier, France, 5-7 May

FAO (2005) 20 things to know about the impact of salt water on agriculture land in Aceh Province: Field Guide on salinity in Aceh- Draft publication RAP 05.

Feddes, R. A. , Kabat, P., Van Bakel, P.J.T., Bronswijk, J.J.B. and Halbertsma (1988) Modelling soil water dynamics in the unsaturated zone-State of the art, *Journal of hydrology*. 10:69-111

Fouss, J.L., Skaggs R.W., Ayers, J.E. and Belcher, H.W. (1990) Water table control and shallow ground water utilization In:. Management of farm irrigation systems (eds. Hoffman, G.F., Howell, T.A. & Solomon, K.H.). ASAE Monograph. New York pp783-824

Franzen, D. (2003) Managing Saline Soils in North Dakota, North Dakota State University, NDSU Extension Service, SF-1087

Greenland, D.J. (1985) Physical Aspects of soil Management for rice-based cropping systems. Soil Physics and Rice. IRRI

Grist D.H. (1986) Rice, Tropical Agriculture Series, sixth edition.

Guerra, L. C. Bhuiyan, S. I., Tuong, T. P. and Barker, R. (1998) Producing more rice with less water from irrigated systems, SWIM paper, IRRI

Hillel, Daniel (1980) Applications of Soil Physics, Academic Press

Hussain, Mohammud Che (1997) Controlled drainage for water table management on sandy soils. PhD dissertation, Cranfield University at Silsoe, UK.

IRRI (2000) New Technique Changes Traditional Rice Growing, IIRI Press Release January 2000

Iqbal, Md Toufiq (2004) Yield and Biomass in Rice interactions of Nitrogen, Phosphorous and Water Application, *Pakistan Journal of Biological Sciences* 7 (12):2115-2120

Kar S., Varade S.B., Subramanyam T.K., Ghildyal B.P. (1974) Nature and growth pattern of rice root system under submerged and unsaturated conditions, *In*: IL RISO (Italy), 23 (2), pp. 173-179.

Kim, J.D., Jugsujinda, A., Carbonell-Barrachina, A.A., DeLaune, R.D., and Patrick, W.H., Jr. (1999) Physiological and gas emissions in rice. *Bot. Bull. Acad. Sin.* 40: 185-191

Kirchhof, G., Priyonob, S., Utomob, W. H., Adisarwantoc, T. E., Dacanayd,V. and Soa, H. B. (2000) The effect of soil puddling on the soil physical properties and the growth of rice and post-rice crops. *Soil Tillage Research*, volume 56, issues 1-2

Kirk, G.J.D (2003) Rice root properties for internal aeration and efficient nutrient acquisition in submerged soil. *New Phytologist* 159: 185-194

Kirk, G.J.D. (2004) The Biogeochemistry of Submerged Soils. Wiley, Chichester

Kirk, G.J.D. and Bouldin, D.R. (1991) Speculations on the operation of the rice root system in relation to nutrient uptake. In F.W.T. Penning de Vries et al. (eds) Simulation and Systems Analysis for Rice Production (pp195-203). Wageningden: Pudoc

Kirk, G.J.D. and Kronzucker, H.J. (2005) The potential for nitrification and nitrate uptake in the rhizosphere of wetland plants: a modelling study. *Annals of Botany*., in press.

Kirk, G.J.D. and Solivas, J.L. (1997) On the extent to which root properties and transport through the soil limit nitrogen uptake by lowland rice. *European Journal of Soil Science* 48: 613-621

Krishiworld (undated) The pulse of Indian agriculture, field crops. http://www.krishiworld.com/html/field_crops5.html

Kronzucker, H.J., Kirk, G.J.D., Siddiqi, M.Y. and Glass, A.D.M. (1998) Effects of Hypoxia on NH4 Fluxes in Rice Roots. *Plant physiology* 116: 581-587

Ladha, J.K, Kirk G.J.D., Bennett, Peng, J. S., Reddy, C.K., Reddy, P.M., Singh,U. (1998) Opportunities for increased nitrogen-use efficiency from improved lowland rice germplasm. *Field Crops Research* 56, 41-71

LICO (1998) Water Table Management Increases Yield and Saves Fertilizer, **Factsheet No. 7.**

Mao Zhi (1996) Water efficient irrigation and environmentally sustainable irrigated rice production in China, http://www.icid.org/wat_mao.pdf

Manske L.L. (2001) Range plant growth and development are affected by environmental factors. 2001 Annual report, Dickinson Research Extension Center, Grassland section, North Dakota State University

Marschner, H. (1995) Mineral Nutrition of Higher Plants. 2nd edn. Academic Press, New York

Matchoc O.R. (2002) 7 tips in direct-seeding rice, PHILRICE Media Releases, March 5 2002

McBride M.B. (1994) Environmental chemistry of soils. New York: Oxford Univ. Press

Mc Cauley G.N (1990) Sprinkler vs flooded irrigation in traditional rice production regions of southeast. *Texas Agronomy J.* 82-677-683

Minoru Y., Darryl V., Pablo R. C., Pompe C., Cruz, C.A. Jr., and Rolando T. C. (2000), Seedling establishment and grain yield of Tropical Rice Sown in Puddled Soil. Tropical Soil and Crop Management. Agronomy Journal 92:275-282

Miyamoto, N., Steudle, E., Hirasawa, T. and Lafitte, R. (2001) Hydraulic conductivity of rice roots. *Journal of Experimental Botany*, Vol. 52, No. 362, pp. 1835-1846,

Naklang, K., Fukai, S. and Nathabut, K. (1996) Growth of rice cultivars by direct seeding and transplanting under upland and lowland conditions. *Field Crops Research* 48, 115-123

Noorallah, J. (2002) (Ed.) Pedosphere-hydrosphere interactions-Issue 002. Online soil science magazine: http://www.pedosphere.com/volume02/main.html

Neue, H.U. (1993) Methane emission from rice fields: *BioScience* 43 (7):466-73

Nye, P.H. and Tinker P.B. (1977) Solute movement in the soil-root system. Blackwell Scientific, Oxford.

Obeng, H. (1994) Soils suitable for large-scale rice cultivation in Ghana. Paper presented at the International Seminar Towards Rice Self-Sufficiency in Ghana, 6-7 June 1994, Akosombo, Ghana

Ockerby, S.E. and Fukai, S. (2001) The management of rice grown on raised beds with continuous furrow irrigation; *Field Crops Research*, pp215-226, volume 69, Issue 3

Otoo, Ernest (1994) Towards increased rice production in Ghana: research on the sustainable development of the inland valleys for rice production. Paper presented at the International Seminar, Towards Rice Self-Sufficiency in Ghana, 6-7 June 1994, Akosombo, Ghana.

Owusu-Sekyere, J.D. (1998) Study on moisture control in wheat fields through experimentation, simulation and optimization, M.sc Thesis, Hohai University, Nanjing, China.

Pang, H. and Zhang, T.C. (1997) Measurements of pH and redox potential distributions in TNT-contaminated plant-soil systems using microelectrode techniques. Proceedings of the 12th Annual Conference on Hazardous Waste Research (eds. Erickson, L. E., Rankin, M. M., Grant, S.C. and McDonald, J. P.)

Patel, R.M., Prasher, S.O. and Broughton, R.S. (2001) Upward movement of leached nitrate with subirrigation. *Transactions of the ASAE* Vol. 44(6): 1521-1526

Pradham, S.K., Varade, S.B. and Karr, S. (1973) Influence of soil water conditions on growth and root porosity of rice: *Plant and Soil*: 38, 501-507

Price, A.H, Steele, K.A., Bridges, J.M., Moore, B.J., Evans, J.L., Richardson, P. and Jones, R.W (2002) Root distribution, water use and plant water status. *Field Crops Research*, volume 76, Issue 1, pages 11-24

Prathapar SA and Qureshi AS (1999) Mechanically reclaiming abandoned saline soils: a numerical evaluation. Research Report 30. Colombo, Sri Lanka: International Water Management Institute (IWMI). ISBN 92-9090-202-7, 21 pp.

Puckridge, D.W. and O'toole, J.C. (1981) Dry matter production of rice using a line source sprinkler in drought studies: *Fields Crops Research*: 3: 303-319

Ranathunge, K., Steudle, E. and Lafitte, R. (2003) Control of water uptake by rice (Oryza sativa L.): role of the outer part of the root, *Planta* 217: 193–205

Ringrose-Voase, A. J., Kirby, J. M., Gunomo Djoyowasito, Sanidad, W. B. C., Serrano and Tabran M. Lando (2000) Changes to the physical properties of soils puddled for rice during drying. *Soil and Tillage Research* volume 56, issues 1-2, pp83-104

Robert, P. H. (undated) Substrate and Fertilization Introduction, http://www.aquabotanic.com/sfintro.htm

Robson, A.J., Williams, R.L. and Farrell, T.C (2001) Unique root mass in Australia's rice, Proceedings of the 10th Australian Agronomy Conference

Rogers, Danny, Freddie, H., Lamm, R., Alam, M., Trooien, Todd P., Clark, Gary A., Barnes, Philip L. and Mankin, Kyle (1997) Efficiencies and water losses of irrigation systems. Irrigation management series. FAO Rome.

Rowell, D.L. (1994) Soil Science Methods and Applications. Addison Wesley

Pradham, S.K., Varade, S.B. and Karr, S. (1973) Influence of soil water conditions on growth and root porosity of rice: *Plant and Soil*: 38, 501-507

Salvatore, R. (undated) Preliminary studies on rice varieties adaptability to aerobic irrigation. *Cahiers Options Méditerranéennes*, pp35-39 vol. 15, n° 1

Sam-Amoah, L.K. (2001) Assessment of potential and actual performance of rice production systems in Ghana. PhD Thesis. Department of Agriculture and Environmental Science. University of Newcastle Upon Tyne, England.

Samson, B.K., Hassan, M. L., Wade, J. (2002) Penetration of hardpans by rice lines in rainfed lowlands: *Field Crops Research* 4046, 1-14

Schueneman, T. J. and Snyder, G. H. (2000) Water-Use Considerations for Florida-Grown Rice. University of Florida cooperative Extension Service SS-AGR-87.

Sharma, P.K. and De Datta, S.K. (1985) Effects of Puddling on Soil Physical Properties and Processes. Soil Physics and Rice. IRRI.

Skaggs, W.N.R. (1990) DRAINMOD users manual (eds: Workman, S.R., Parsons, J.E., Skaggs R. W. and Rice J.) North Carolina State University, Raleigh, North Carolina 27695 pp84

Soil Monitoring Engineering (2001) Tensiometers and Water Samplers, Church End House, Eversholt.

Songfa S. (1995) Development of Rice–Fish Farming in Guizhou Province Rice–Fish Culture in China, IDRC, 240 pp.,

Springer, A. (undated) Environmental hydrology, vadose zone, (lecture notes), ENV 302, Institution: Northern Arizona University, http://jan.ucc.nau.edu/~doetqp-p/courses/env302/lec17/LEC17.html

Thenkabail, P.S. and Nolte C. (1995) Mapping and characterising Inland Valley agroeosystems of West and Central Africa: A methodology integrating remote sensing, global positioning system and ground truth data in a geographic information systems framework. RCMD monograph N0 16, International institute of Tropical Agriculture, Ibadan, Nigeria 62 pp.

Thiombiano, L., Jamin, J.Y., Windmeijer, P. (1998) The consortium for the sustainable development of inland valley agro-ecosystems: A tool for regional cooperation. In: Wetland characterization and classification for sustainable agricultural development, FAO SAFR, Harare

Tinker P.B. and Nye, P.H. (2000) Solute movement in the rhizosphere. Oxford: Oxford University Press.

Tracy, P., Sims, B. D., Hefner, S. G. and Cairns, J. P. (1994) Guidelines for Producing Rice Using Furrow Irrigation, Agricultural publication G4361. University Extension, University of Missouri-Columbia

Uphoff, Norman (1999) Agroecological implications of the System of Rice Intensification (SRI) from Madagascar. *Environment, Development and Sustainability* 1, 297-313

Uphoff, Norman (2001) Opportunities for raising yields by changing management practices: The system of rice intensification in Madagascar. In Agroecological Innovations. Uphoff (ed.). London: Earthscan

van Genuchten, T.H. (1980) A closed form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am J* 44:892-898

Wade, L.J., S. Fukai, B.K. Samson, A. Ali, and M.A. Mazid (1999) Rainfed lowland rice: physical environment and cultivar requirement. *Field Crops Research.* 64:3–12.

Walker, S. H. and Rushton, K. R. (1984) Verification of lateral percolation losses from irrigated fields by a numerical model. *Journal of hydrology* 71 pp335-351

Wang, Y.M., Siddiqui, M.Y., Ruth, T.J. & Glass, A.D.M. (1993) Ammonium uptake by rice roots. II Kinetics of $^{13}NH_4^+$ influx across the plasmalemma. *Plant Physiology*, 103, 1259-1267.

Waters, P. (1977) The effect of drainage on soil temperature at Drayton. *EHF Technical Bulletin* NO. 77/6. ADAS, UK.

Watt, Michelle (2003) More competitive crop roots Research Update - Southern Region - http://www.grdc.com.au/home.cfm

Wells B.R., Kamputa D., Norman R J., Vories E.D. and Baser R (1991) Fluid fertilizer management of furrow irrigated rice. *J. Fertil.* Issue, 8:14-19

Wesseling J. (1974) Crop growth and wet soils. In: van Schilfgaarde, J(ed.) Drainage for agriculture, American Society of Agronomy. *Agronomy* No. 17 pp 7-37

Williamson, R.E. and Carreker, J.H. (1970) Effect of water table levels on evapotranspiration and crop yield. *Transactions of the ASAE*: 168-178

Wind, G. P. (1961) Capillary rise and some application of the theory of moisture movement in unsaturated soils. *Technical Bulletin*. 22, Institute for Land and Water Management Research, Wageningen, The Netherlands.

Wu Xijin (undated) Development of water saving irrigation technique on large paddy rice area in Guanxi region of China. http://www.icid.org/wat_xijin.pdf

Youngs, E. G., Leeds-Harrison, P.B and Chapman, J.M (1989) Modelling water-table movement in flat low-lying lands. Hydrological Processes 3:301-305. John Wily & Sons Ltd.

TRIAL EXPERIMENTS

These trials were conducted because of the initial failure of the main experiment in Chapter 6. The aim was to identify the cause of failure (death of plants) and to correct it in order to continue with the main experiment.

Trial 1

This trial was conducted with different levels of vermiculite and hence nitrogen content. The experiment was conducted for a period of two weeks, and the water table depth used was 30 cm below the surface. The aim was to ascertain the effect of different amounts of ammonium-loaded vermiculite in the mixture on growth of the plants. It was suspected that the death of the plants was due to some toxic substance from the vermiculite, and a lower amount of vermiculite would reduce the level of the toxic substance permitting the plants to grow.

A water table depth of 30 cm was used because it was erroneously concluded that because moisture content was lowest under the 30 cm treatment, the effect of toxicity would be greatest under that treatment.

Data Collected

The data collected for this trial was:

Root dry mass

Rooting depth

Plant height

Shoot dry mass

This was done at the end of two weeks of growth.

Results and discussion

Rooting depth increased as amount of nitrogen decreased. The depth for the 200 g vermiculite treatment was significantly lower than those of the other ones except for the 75 g vermiculite treatment. It appears that the rooting depth of a rice plant

is a function of the amount of nitrogen available. The more nitrogen there is, the shallower the roots. This suggests that roots grow longer so as to explore the soil for nutrients; where there are no nutrients roots grow longer.
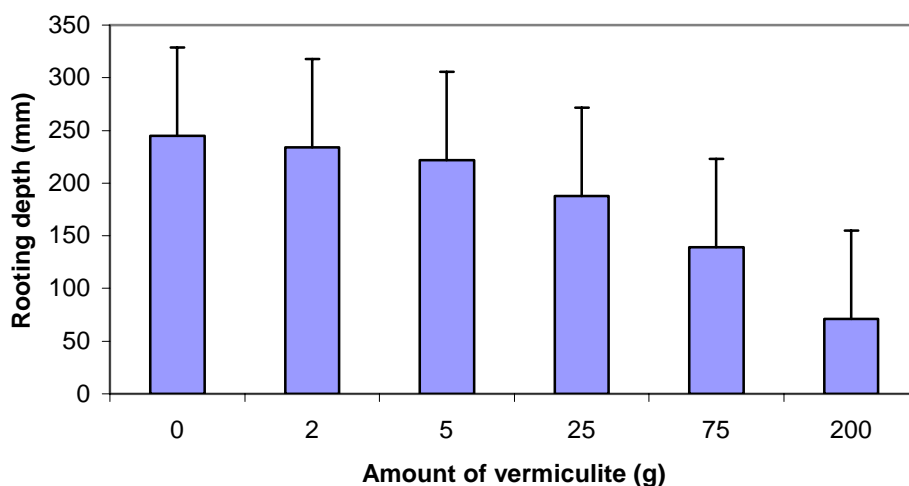

Figure 1 Maximum rooting depths under different levels of vermiculite with error bars as l.s.d. (p=5%). Estimated nitrogen content is 300 µmol g-1 vermiculite.

The result in all the previous experiments show that rooting depth for the treatment with the least amount of moisture was greater than for the other two leading to the conclusion that rooting depth was influenced by the amount of moisture available. Under similar moisture levels another influence on rooting depth, nitrogen content clearly emerges.

Moreover, in all the other experiments, rooting depth was greater than 200 mm after two weeks. This does not happen in this case. Treatments with more than 25 g vermiculite and above have a rooting depth of less than 200 mm at the end of two weeks.
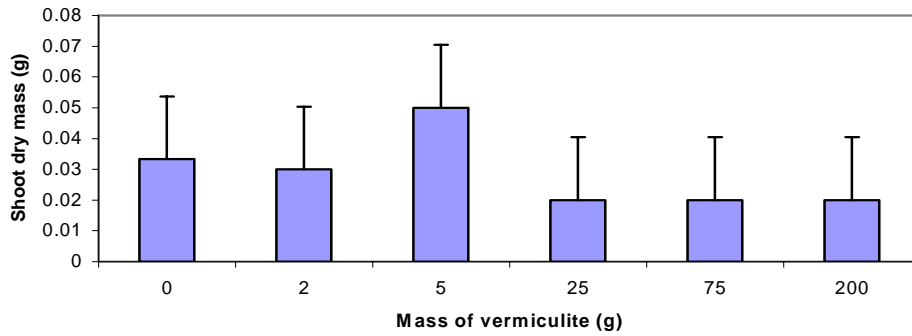
Figure 2 Root dry mass under different levels of vermiculite in sand vermiculite mixture with error bars as l.s.d. (p=5%).
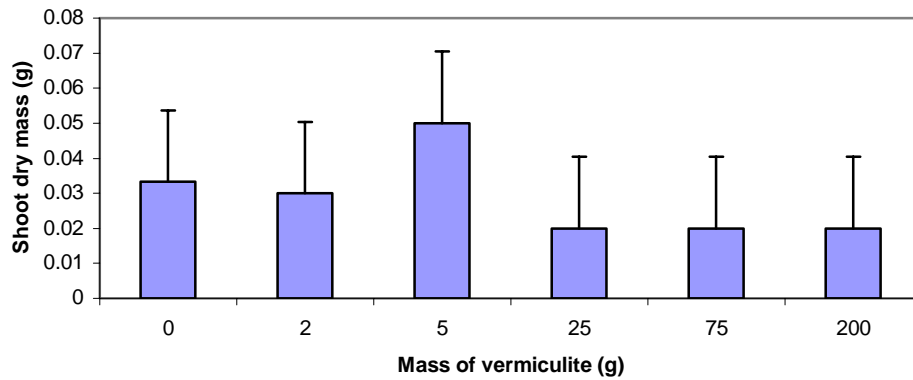
Figure 3 Shoot dry mass under different levels of vermiculite in sand vermiculite mixture with error bars as l.s.d. (p=5%).
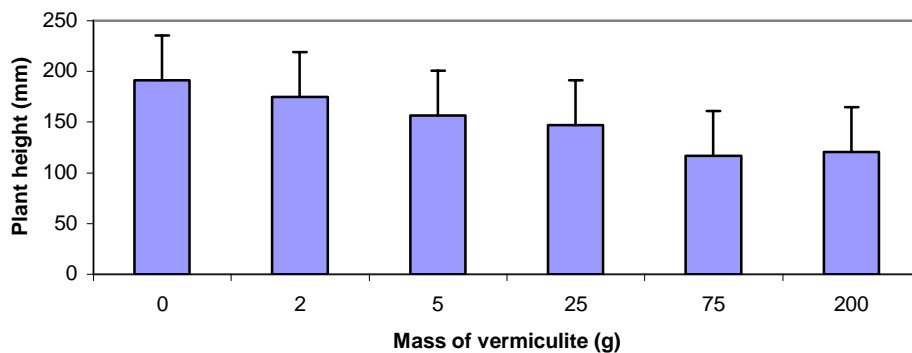
Figure 4 Plant height under different levels of vermiculite in sand vermiculite mixture with error bars as l.s.d. (p=5%).

Figures 2-4 show the root dry mass, shoot dry mass and the plant height under different levels of vermiculite. In all of these, the lowest values of the parameters were recorded for the 75 and 200 g vermiculite treatments. Generally, increasing the amount of vermiculite in the mixture had a negative effect on plant growth. Increasing amounts of vermiculite meant increasing amounts of nitrogen, which should have led to greater growth, this implies there were some other factors that were introduced with the increasing vermiculite amounts, which limited plant growth.

The plants in this experiment survived indicating that the 30 cm water treatment had moderated the effect of the unknown factor that had led to the death of the plants.

Trial 2

As the plants survived under the 30 cm water table treatment, the experiment was once again set up with all three-water treatment using 200 g of vermiculite per core.

The set up was the same as used in all the other main experiments. It was observed in this experiment that the plants under the 30cm and 15cm water table depths survived, however those under flooded conditions died 2 days after imposition of flooding.

The tanks under the 15cm water table depth were then flooded with the nutrient solution in order to ascertain if flooding was injurious to the plants under the conditions used. The plants died two days after imposition of flooding on the original 15 cm water table death treatment leading to the conclusion that flooding introduced a factor that was injurious to the plants.

Trial 3

In order to investigate the factor under flooding that was responsible for the death of the plants, another trial with varying amounts of vermiculite loaded with ammonium just as was used in Trial 1 was set up under flooded conditions. A flood depth of 2 cm was used.

Salinity levels in the floodwater were recorded and the results are presented in the tables below.

Table 1 EC (mS/cm) of the floodwater in the cores for the three tanks under different levels of vermiculite taken three days after treatment imposition**.**

Vermiculite (g)	Tank1	Tank2	Tank3
0	0.747	0.959	0.77
2	0.97	1.035	1.347
5	0.932	0.971	2.21
25	2.78	2.2	2.49
75	4.74	4.54	5.42
200	10.87	8.71	6.16

Table 2 EC (mS/cm) of the floodwater in the cores for the three tanks under different levels of vermiculite taken five days after treatment imposition.

Vermiculite (g)	Tank 1	Tank 2	Tank 3
0	0.971	1.88	1.3
2	1.4	2.14	1.14
5	1.95	1.85	2.76
25	3.9	2.55	3.4
75	5.4	6.24	6.5
200	11.3	13.32	11.3

Table 3 State of the plants, five days after treatment imposition: 0 – dead plant, 1 – healthy plant.

Vermiculite (g)	Tank 1	Tank 2	Tank 3
0	1	0	1
2	1	1	1
5	1	1	1
25	0	1	1
75	0	0	0
200	0	0	0

Table 4 EC of the solution in the tank outside the core.

	Tank 1	Tank 2	Tank 3
EC (mS/cm)	0.86	0.755	0.879

Tables 1 and 2 show EC values for a flooded treatment with different levels of vermiculite taken three and five days respectively after treatment imposition. The readings were taken for the floodwater in the cores. EC increased with increasing vermiculite content. There was a dramatic rise in EC from the treatment with 25 g of vermiculite to that with 75 g of vermiculite. There was another dramatic rise in EC from the treatment with 75 g vermiculite to that with 200 g vermiculite.

There was a general increase in EC from the third to the fifth day. This was attributed to a greater concentration in the floodwater due to the loss of moisture through evaporation.

Table 3 shows the conditions of the plants five days after treatment imposition. All the plants under the treatments with 25 and 75 g of vermiculite, where the EC was greatest had died (a plant in tank two in the core with no vermiculite with an EC of

1.88 mS/cm had also died, this was attributed to some factor other than what was being investigated). It was therefore clear that the flooded treatments with high vermiculite amounts lead to exceptionally high EC values in the floodwater, which were injurious to the plants.

According to Alam *et al.,* (2001) salinity delays germination, but does not appreciably reduce the final germination percentage The electrical conductivity values for a 50 % reduction in germination one week after planting ranged from 20-30 mS/cm, while the critical level of salinity for seedling growth was about EC 5 mS/cm. Most rice cultivars are however severely injured in submerged soil cultures at an EC of 8-10 mS/cm at 25° C; (sensitive ones are hurt even at 2 mS/cm). Rice varieties are generally tolerant to salinity during germination but growth parameters such as dry matter, seedling height, root length and emergence of new roots decrease significantly at an electrical conductivity value of 5-6 mS/cm. According to Asch and Wopereis (2000) floodwater EC less than 2 mS /cm can be tolerated by rice plants, EC above 2 mS/cm will affect the plants. EC values of less than 4 at time of transplanting, according to FAO (2005) is not injurious to rice plants.

EC values obtained for the 25 g vermiculite had a marginal effect on the plants in that one out of three plants did not survive, but under the 75 g and 200 g of vermiculite EC was higher than the plants could tolerate and none of them survived. It is however not possible from these results to determine the level of EC above which the plants were affected. An EC of over 3.9 mS/cm it appears will lead to death of Azucena plants when they are under a week old.

Table 4 shows that the EC of the solution in the tanks were much lower than that in the floodwater, indicating that the source of the salts was not***the nutrient solution.

Trial 4

In order to determine the source of the salts causing the high EC, each stage of loading the vermiculite with ammonium was monitored.

Table 5 EC at different stages of the process of loading vermiculite with ammonium.

Treatment	1	2	3	4	5
EC	1.02	7.36	0.498	0.551	0.545
Stand. Dev.	0.03	0.31	0.007	0.016	0.0007

The following treatments were applied to the vermiculite:

Treatment 1: Vermiculite loaded with NH_4^+ and washed with de-ionised water

Treatment 2: Vermiculite loaded with NH_4^+ but not washed with de-ionised water.

Treatment 3: Untreated vermiculite.

Treatment 4: Vermiculite washed with 0.05M HCl but not loaded with NH_4^+.

Treatment 5: Nutrient solution as described above.

About 50 g of each of the above treated samples of vermiculite was put into 500 cm3 of nutrient solution and stirred for about five minutes. The EC was then taken. The highest EC obtained was Treatment 2***, with EC of 7.36. This led to the conclusion that the source of the salt was the $CaCl_2$ used in loading the vermiculite with ammonium. After a thorough washing with de-ionised water, the EC of the solution for vermiculite loaded with ammonium fell to 1.02.

The conclusion drawn was that it was necessary to thoroughly wash the vermiculite after loading it with ammonium in order to avoid toxicity problems. An EC meter should be used to monitor the EC, and it would be preferable to get the EC of the vermiculite in nutrient solution below 1 mS/cm before use for rice growth.

BULK SOLUTION CONCENTRATION AND CONCENTRATION AT THE
ROOT SURFACE FOR THE THREE WATER TREATMENTS: 30 CM, 15 CM
AND FLOODED RESPECTIVELY
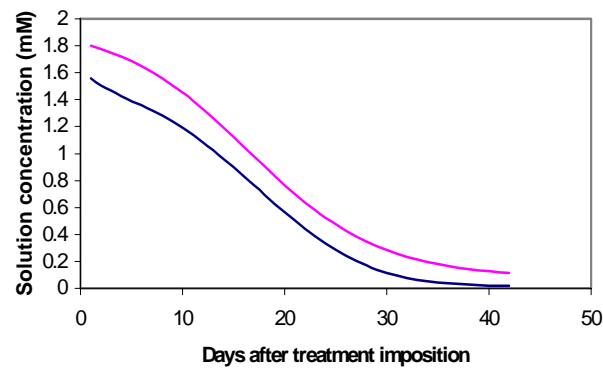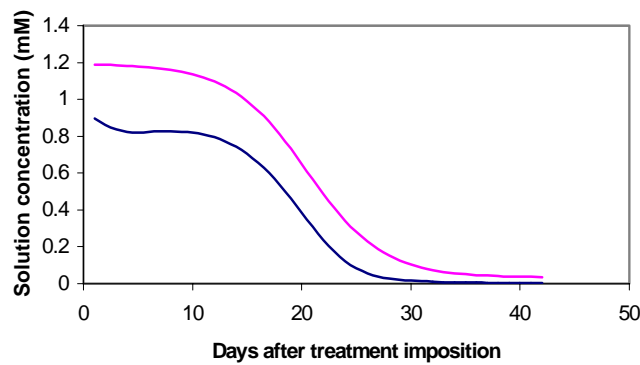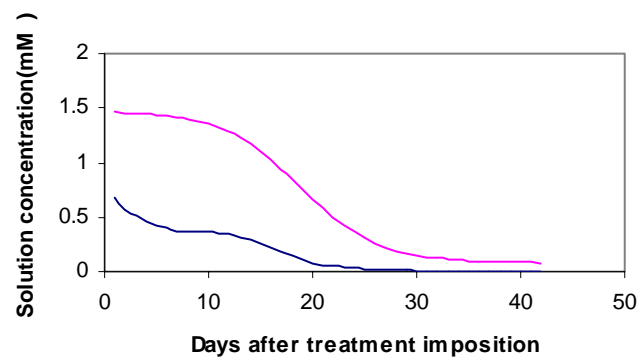
MEASURED CUMULATIVE PLANT N UPTAKE POINTS AND FITTED
LOGISTIC CURVES FOR THE THREE WATER TABLE DEPTHS: A) 30 CM
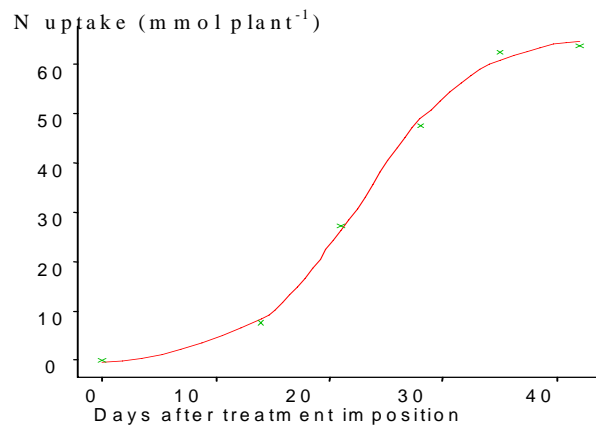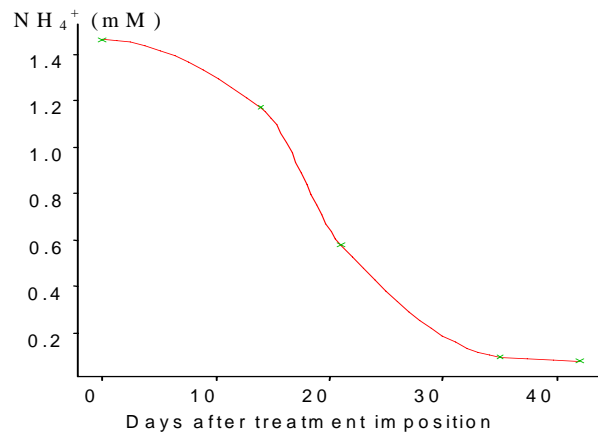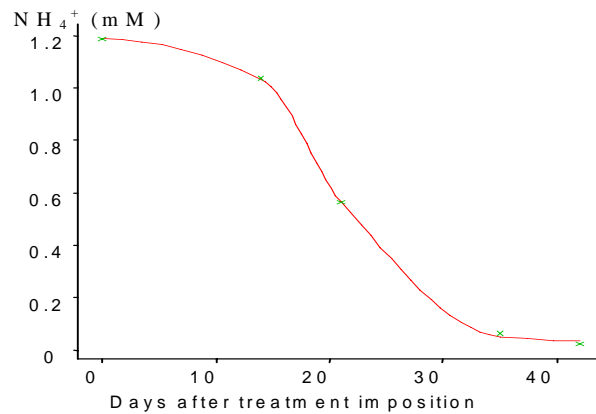B) 15 CM AND C) 0 CM. EACH POINT IS THE MEAN OF 3 REPLICATES.

(a)

(b)

(c)
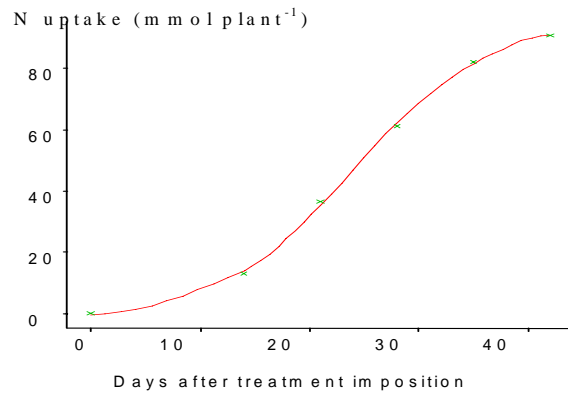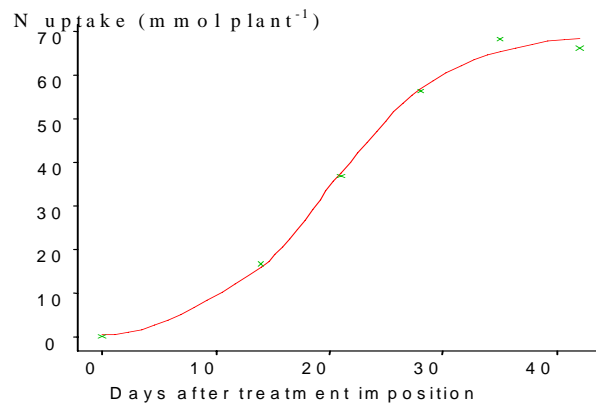
MEASURED SOLUTION NH_4^+ CONCENTRATIONS (POINTS) AND FITTED CURVES (LINES) FOR THE THREE WATER TABLE DEPTHS: A) 30 CM B) 15 CM AND C) 0 CM
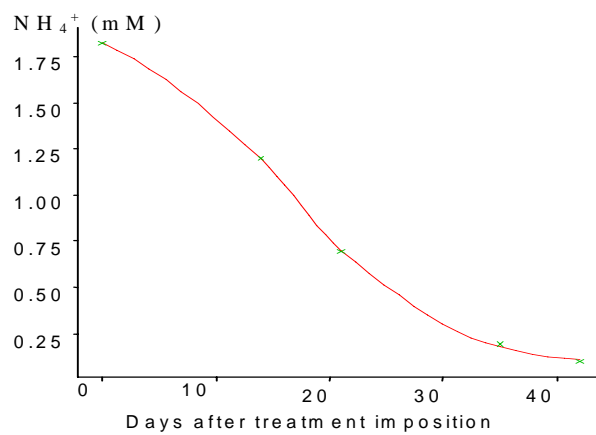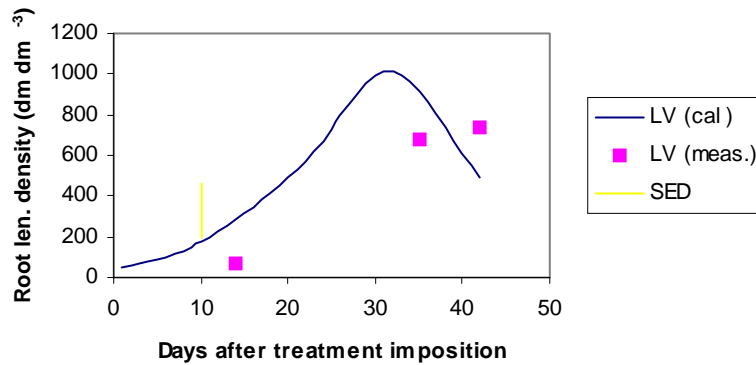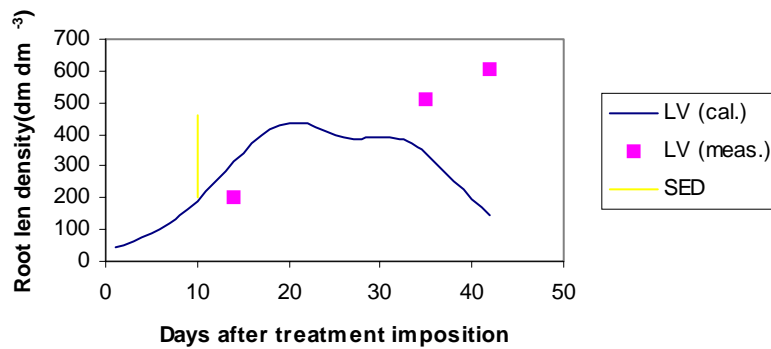
(a)

(b)

(c)

MEASURED ROOT LENGTH DENSITIES (POINTS) AND CALCULATED
MINIMUM VALUES REQUIRED TO EXPLAIN UPTAKE OF NH_4^+ (LINES)
FOR THE THREE WATER TREATMENTS: (A) 30 CM, (B) 15 CM AND (C)
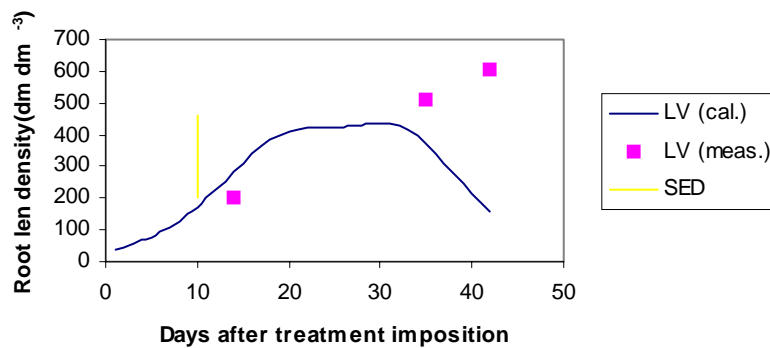FLOODED TREATMENT FOR ROOT RADIUS 0.6 MM.

(a)

(b)

(c)
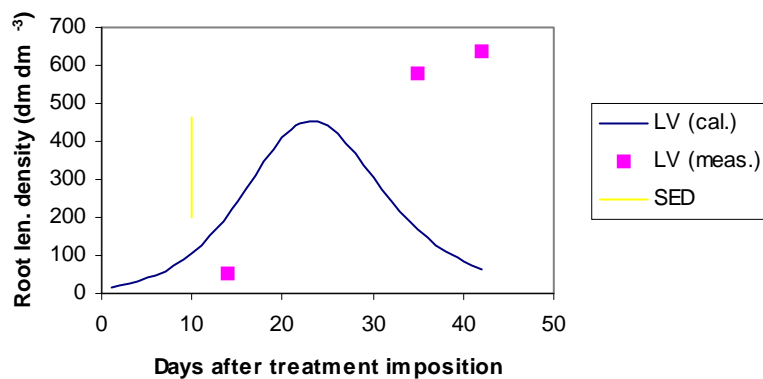
APPENDIX 6

MEASURED ROOT LENGTH DENSITIES (POINTS) AND CALCULATED MINIMUM VALUES REQUIRED TO EXPLAIN UPTAKE OF NH_4^+ (LINES) FOR THE THREE WATER TREATMENTS: (A) 30 CM, (B) 15 CM AND (C) FLOODED TREATMENT FOR $F_{MAX} = 1.28$ AND $K_M = 90.2$.
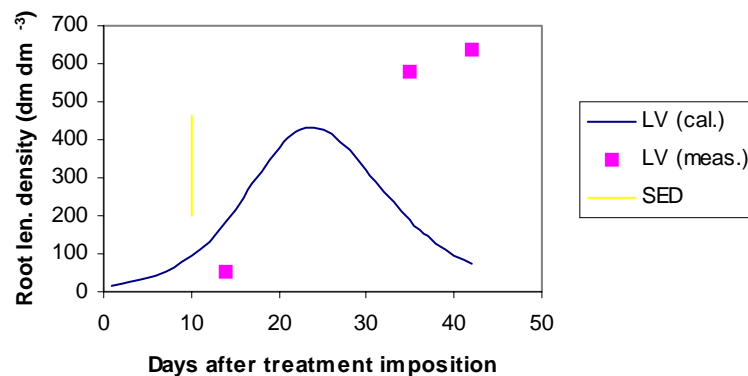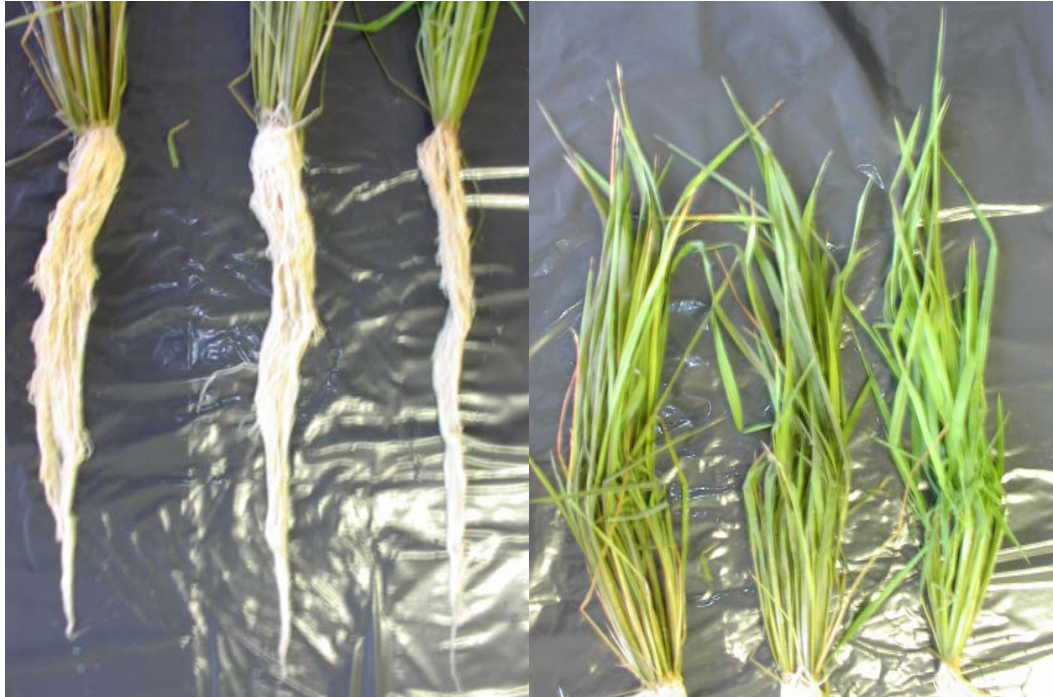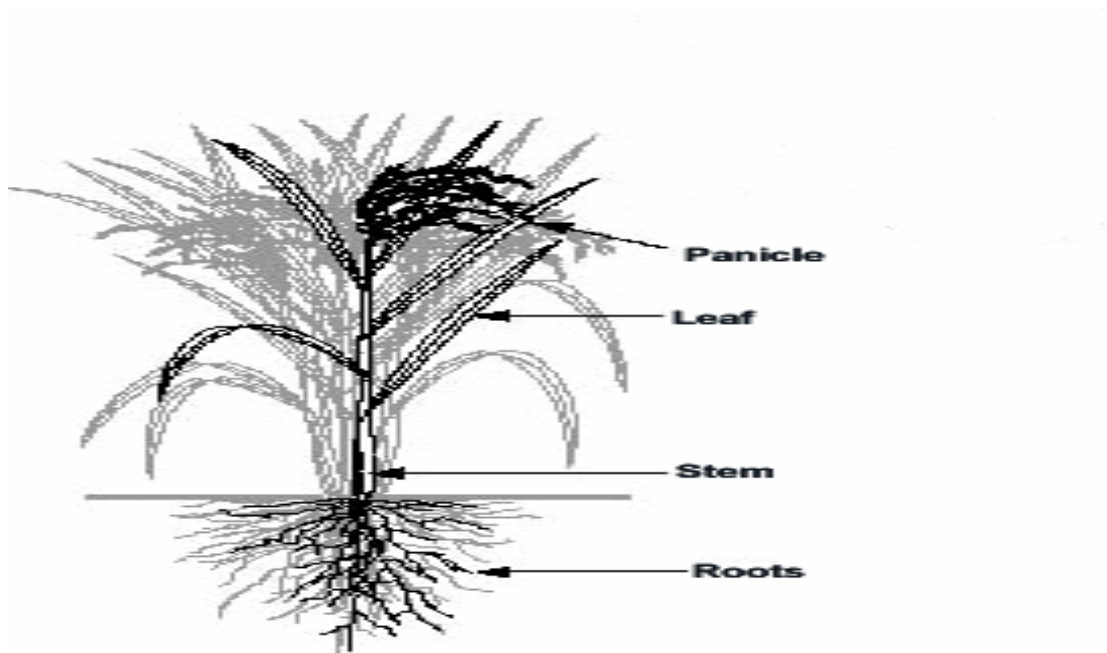
(a)
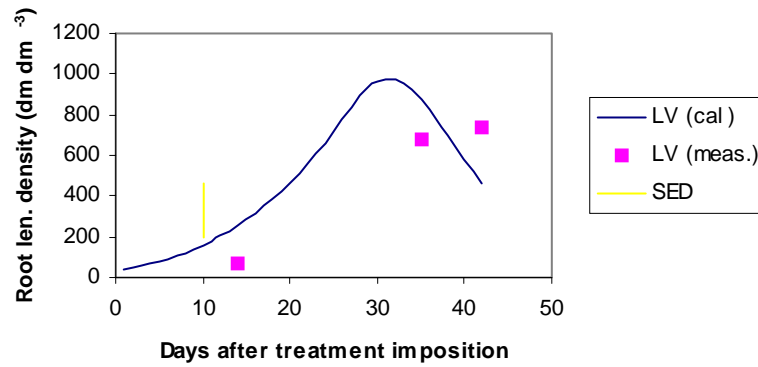
(b)

(c)

RICE PLANT

Pictures of harvested rice plants showing roots and shoots

Schematic diagram of mature rice plants showing the different parts