Integrated Irrigation and Drainage to Save Water - Phase 1

(KAR Project R7133)

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Report OD/TN 96
November 1999

HR Wallingford

DFID Department for International Development

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Executive Summary

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Introduction
Current global population growth rates require an increase in agricultural food production of about 40-50% over the next thirty to forty years (World Bank, 1988). Irrigated agriculture has to play a vital role in meeting this target, FAO estimates that 60% of future gains will have to come from irrigation. Irrigated agriculture currently uses about two thirds of all water abstracted from rivers and underground aquifers in developing countries, and in many areas available water resources are nearly or fully utilised. If irrigated food production is to increase, irrigated agriculture must use water more efficiently, while maintaining the income and livelihoods of poor rural communities, and sustaining the quality of water and soil resources.

This report describes findings from the first stage of a project to develop integrated irrigation and drainage management methods incorporating controlled drainage, which has potential to sustain agricultural production and livelihoods in conditions of reduced water availability. Activities comprising the first stage of the study included a literature review, an assessment of the potential and constraints to the introduction of controlled drainage in the Nile Delta in Egypt, and the initial development of a tool to predict the impacts of different controlled drainage strategies. (Activities planned for the second stage are the formulation of promising controlled drainage strategies, field verification in the Nile Delta, Egypt, and preparation of operational guidelines.)

The project is being carried out by the Water Management Department of HR Wallingford in collaboration with the Drainage Research Institute of the National Water Research Centre, Egypt, (DRI).

Controlled Drainage
Controlled drainage involves an extension of on-farm water management to include management of drainage flows. Farmers control the amount of water leaving the land in the drainage system, using a weir or blocking device to control drainage flows. Gravity or pumped drainage occurs only when the water table in the field has risen to a level where drainage has to be provided to prevent crop damage or provide salt leaching. As controlled drainage is relatively new there are many theoretical and practical issues to be addressed before it can be applied in semi arid regions. The technique involves maintaining high water tables in the soil profile for extended periods of time (using On/Off gated devices or weir control), and management is required to ensure that crop growth is not affected by

anaerobic conditions. Also to prevent accumulation of solutes (particularly salts) in the root zone it is necessary to maintain leaching processes. With proper management, controlled drainage could improve efficiency of solute removal in drain flow, protecting the crop root zone and groundwater resources.

There has been research into controlled drainage, primarily in temperate areas, and it has been adopted in several locations. Countries include USA, Canada, Bulgaria, Poland, Finland and Holland. The main benefits (depending on location) have been identified as:

- Yield increases (particularly in watershort seasons).
- Water and energy savings.
- Water quality benefits – increased soil salt leaching efficiencies and reduced transport of agrochemicals to river systems.

Potential and Constraints Survey
Controlled drainage is likely to be beneficial in many arid and semi-arid regions of the world, where water tables are high. Potential areas of application include Egypt, Pakistan and India. In the Nile Delta, Egypt controlled drainage trials under rice have achieved large water savings and farmers are being encouraged to adopt the technique, but to date no work has been done on application of controlled drainage under other crops. An assessment of the potential and constraints to the wider use of controlled drainage in the Nile Delta, Egypt, and in particular an extension of the use of controlled drainage to dry-foot crops, was carried out as part of this project. The main conclusions were:

Potential:

There are strong pressures to improve water use efficiency in irrigated agriculture. Water saving is essential in the next 20 years. Increased water scarcity is inevitable in areas of the Nile Delta.

Agricultural areas of the Nile Delta have an extensive subsurface drainage system and high drainage flows constituting a major water loss at field and basin scale. Controlling drainage may thus provide significant on-farm water savings. More importantly it also offers the possibility of sustaining yields, and thus rural livelihoods, as the quantities of water available to farmers reduce in future years.

The concept of controlling drainage is not alien to Nile Delta farmers. It has been applied under rice both unofficially (blocking drains with mud and straw) and as part of experimental trials (using On/Off gated pipes) conducted by DRI.

Experience of controlled drainage under rice has demonstrated large water savings (up to 40 %) with no reduction in yields or increases in soil salinity. Smaller, but significant, savings can be expected if controlled drainage is also applied under dry-foot crops.

The rice controlled drainage work has demonstrated that where savings can be made in fuel and labour inputs, farmers respond by using less water. Controlled drainage is beneficial and attractive to farmers.

The institutional set-up in the Delta is good, with farmers receiving support from the extension services and district irrigation offices.

As farm sizes are small, farmers will need to work together to implement controlled drainage. Previous work in Egypt showed use of existing co-operatives such as the water user associations (WUAs) worked much better than attempting to create new ones.

Constraints:

Egypt has a fixed allocation of water from the Nile River, its primary source of water. This resource is stretched to the limit due to continued population pressures, an ambitious horizontal expansion programme and demands from other sectors.

The Government of Egypt has introduced major water saving programmes in the agricultural sector. New initiatives including the extension of controlled drainage under rice must complement the ongoing programmes such as the Drainwater Reuse Programme and Irrigation Improvement Project.

Crop consolidation along drainage lines will be necessary in some areas if the full benefits of controlled drainage are to be realised.

Water saved by the introduction of controlled drainage must be used effectively further downstream, possibly by reducing reliance on saline and contaminated drainage flows, if the full benefits are to be realised.

Benefits to farmers must be large enough to ensure take up.

Predictive Design Tool

The main body of this report concerns the development of a predictive design tool for controlled drainage. The tool is being developed for use by researchers and engineers to design controlled drainage strategies appropriate to physical and social conditions in their areas. The tool is able to consider a large number of crop rotations, irrigation strategies (quality, quantity and timing of applications), drainage designs and controlled drainage strategies for specific locations characterised by a given set of climatic and soil parameters.

The tool is made up of the following components:

- A simulation module (incorporating a field water balance model) that models the water and salt balance, and crop response.
- A cost component that allows a basic cost comparison of different management options.
- A screening component that identifies controlled drainage strategies meeting user-set performance criteria.

The framework for the tool is straightforward and useful. It provides the user with the means to consider the impacts of a large number of controlled drainage designs, and rapidly assess the merits of each compared to conventional drainage, according to user-set limits for selected key parameters.

The tool was used to carry out a demonstration application involving 57 controlled drainage (and 6 conventional drainage) options for possible application to the western Nile Delta. The results should not be used to indicate the global magnitude of benefits that are achievable under controlled drainage. More simulations, covering a full range of soil types, drainage systems, cropping patterns and water applications etc would be necessary before this can be achieved. However the demonstration confirmed that controlled drainage has the potential to save water, and to sustain crop yields in periods of water shortage in a semi-arid environment. The second of these is likely to be the most important in the longer term. In particular, for the conditions simulated:

- Promising *water saving* controlled drainage strategies were identified, using less water compared to conventional irrigation and drainage practice, whilst maintaining crop yields, soil and water resources. Costs to farmers would be reduced through reductions in pumping costs proportional to the water saved. Four sustainable controlled drainage designs were developed, that provided annual water savings of up to 14%.

- For scenarios of *reduced water availability* there were 24 proposed controlled drainage designs that sustained or improved crop yields whilst controlling salinity levels.

Recommendations
It is recommended that the second phase of the project, as outlined in the project proposal is implemented, taking account of the recommendations listed below.

- An alternative water balance model to DRAINMOD-S (which only allows for controlled drainage using weirs) should be assessed for inclusion in the simulation component. This model should allow for controlled drainage using simple On-Off devices such as gated pipes.

- The cost component should be expanded to address wider economic issues such as value of the water saved, increased crop yields and labour/time requirements.

Fieldwork is underway in the western Nile Delta to test one controlled drainage strategy. This should provide some initial validation of the simulation tool. As the trial is being carried out on a small-scale at an experimental farm it will not test the potential of controlled drainage under farmer control. Provided the results obtained in the second phase of the study confirm the levels of benefit that are expected, it is recommended that testing at a pilot scale by farmers is carried out as an extension of this project.

Glossary

DRI	Drainage Research Institute, Cairo
EPADP	Egyptian Public Authority of Drainage Projects
MPWWR	Ministry of Public Works and Water Resources
WUA	Water user association
CUG	Collector user group
IIP	Irrigation Improvement Project
CONV	Conventional irrigation and drainage management
CD	Controlled drainage management
Berseem	Egyptian fodder crop similar to alfalfa
Sakia	Egyptian water lifting device
Meska	Egyptian tertiary irrigation canal
Feddan	Egyptian unit of land (2.36 feddans = 1 hectare)

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1. Introduction

1.1 The Project

This Technical Note is an output from the DFID Knowledge and Research Contract R7133 – Integrated Irrigation and Drainage to Save Water. The project is being implemented by HR Wallingford in collaboration with the Drainage Research Institute of the National Water Research Centre, Egypt.

The research aims to develop integrated irrigation and drainage management strategies incorporating controlled drainage, to save water and protect soil and water resources in semi-arid regions. At the farm level the introduction of controlled drainage has the potential to improve the livelihoods of farmers by reducing pumping costs and maintaining agricultural production in water short years. The planned project outputs are:

- A predictive design tool to assess water saving, resource protection and crop production under controlled drainage.

- Practical guidelines for integrated irrigation and drainage management incorporating controlled drainage.

The project is being carried out in two stages. The activities comprising the first stage were a literature review, an investigation of the potential and constraints to the introduction of controlled drainage in the Nile Delta in Egypt, and the initial development of a tool to predict the impacts of controlled drainage. The results of these activities are reported in this interim report. Activities planned for the second stage are the formulation of promising controlled drainage strategies, field verification in the Nile Delta, Egypt, and preparation of operational guidelines. Recommendations for implementation of the second phase of the study are made at the end of the report.

1.2 Background

Current global population growth rates require an increase in agricultural food production of about 40-50% over the next thirty to forty years, in order to maintain present levels of food intake (World Bank, 1988). To meet the target irrigated agriculture will play a vital role, for example FAO estimates that 60% of future gains will have to come from irrigation. Irrigated agriculture uses about two thirds of all water abstracted from rivers and underground aquifers in developing countries, and in many areas available water resources are nearly or fully utilised. If irrigated food production is to increase, irrigated agriculture must use water more efficiently, while maintaining the quality of water and soil resources.

Surface irrigation methods such as basin and furrow predominate in the arid and tropical regions of the developing world. As it is difficult to match irrigation applications with evapotranspirative demand, and water is not always available when it is needed, farmers often minimise risk by applying more water than is necessary. In semi-arid areas there is also a need to supply additional water for leaching, to prevent the build-up of salts in the root zone. Over-irrigation is thus common, and inevitably leads to excess water percolating below the crop root zone to the local water table, which rises over time close to the soil surface, and results in water logging and salinisation. These problems are addressed by providing artificial drainage to control the level of the water table.

Field-scale inefficiencies in irrigated agriculture can be addressed in several ways:

- *Introduction of modern irrigation techniques such as drip and sprinkler.* This will increase irrigation efficiency in many cases (but must be combined with appropriate irrigation scheduling). Modern methods are having an impact in some parts of the world, but fundamental technical, cultural and economic issues will continue to limit wide-spread uptake.

- *Better scheduling of surface irrigation applications.* It is always theoretically possible to improve application efficiencies through scheduling applications more frequently and trying to match evapotranspirative demand more closely. However farmers are constrained by practical issues that mean they cannot easily improve scheduling. They may experience water shortage in the delivery system or receive water on a rotation basis, meaning they must make maximum use of the water when it is available to them.

- *Reduction in water losses.* Loss of excess water through drainage is a major cause of inefficiency in some irrigation systems. Integrating irrigation and drainage management through controlled drainage opens up new opportunities for water saving and increased insurance against crop losses due to water shortage.

The last option, controlled drainage to reduce water losses to drains, is the focus of this study.

1.3 Controlled Drainage

Artificial drainage commonly takes the form of open ditches at field edges and subsurface slotted plastic pipes or clay tiles laid horizontally across fields at a depth of 1-2m and spacing of 20-50m. Systems are designed to remove water rapidly from the soil profile to keep the local water-table at or close to drain depth. Drainage flows are related to irrigation applications, crop abstractions and the capacity of the drainage system.

In practice drainage systems are usually over-designed, as they are sized for the crops most sensitive to water logging, and also usually have additional capacity to allow for deterioration of the drainage function over time. With conventional layouts it is not possible to control the amount of water removed from the fields by the drainage network, and water is often lost from the soil profile without the crop having the chance to use it.

Controlled drainage is a practice that allows farmers to control drainage outflows, storing water in the soil profile for use by the crop and reducing losses from the system. Drainage flows are controlled so that drainage occurs *only after* the ground water level in a field has risen to the level where drainage is needed to prevent crop damage, or to provide salt leaching. Irrigation applications can thus be reduced, and the relatively good quality water that is “saved” becomes available for use by downstream irrigators.

1.4 Types of Controlled Drainage

Drainage outflows can be controlled in at least two ways:

(A) By blocking drains. Lateral or collector pipes are periodically blocked and unblocked using mud or straw, or preferably a device designed for the purpose. Figure 1 shows a gate designed to block drainpipes in rice areas in Egypt. With this approach the water table rises and falls in response to irrigation releases and operation of the drains which are either “on” or “off”.

(B) By using weirs. A fixed or adjustable weir is used to control the water table depth in a field. The weir is placed in the drainage ditch receiving the drainage flow, or, if the subsurface system has catchpits along collectors, along the collector lines (see Figure 2). When the water table rises above the level of the weir, water flows over the weir and out of the system. Flow ceases when the watertable drops below the level of the weir, and only commences again when rainfall or irrigation causes the watertable to rise again above the weir level.

Figure 1 Flapgate used to block drainpipes and control drainage in rice areas in the Nile Delta

Figure 2 Weir device used to control water levels along collector drains

1.5 Benefits of Controlled Drainage

There has been research into controlled drainage, primarily in the northern temperate zones, and it has been adopted in several countries including USA, Canada, Bulgaria, Poland, Finland and Holland. The main benefits (depending on type of system, crops and location) have been identified as:

- Yield increases.
- Water and energy savings.
- Water quality benefits – increased soil salt leaching efficiencies and reduced transport of agro-chemicals to river systems.

Some examples of applications of controlled drainage are given in the table below.

Table 1 Example Applications of Controlled Drainage.

Country	Type of Controlled Drainage	Comments
Egypt	"On/Off" controlled drainage. Rice only.	Large water savings, farmer uptake, programme expanding
USA, California	"On/Off" controlled drainage.	Modelling only. Large benefits predicted.
USA, Iowa	Watertable control using weirs.	Reduced nitrate movement to groundwater. 0.6m watertable depth best.
USA, North Carolina	Controlled drainage and sub-irrigation. 150,000 acres, various crops.	System required large amount of management. Large reductions in drainflow.
Canada, Ontario	Controlled drainage on silt-loam soil. Watertable control.	Large reductions in drainflow. Nitrate losses decreased.
Canada, Ontario	Watertable control using riser pipes, and subirrigation.	Increased corn, tomato and soybean yields. Reduction in nitrate losses.
Poland	Controlled drainage by watertable control and sub-irrigation.	Low cost technique. Improved soil moisture conditions for crop growth.
Finland	On-farm trials. Controlled drainage by watertable management and sub-irrigation.	Reduced nitrate loads to rivers. Increased crop yields.

Further information and key references are given in Appendix 1.

Controlled drainage is also beneficial in irrigated areas with high water tables in arid and semi-arid regions of the world. Potential areas of application include Egypt, Pakistan and India. At the basin level the benefits should be an increase in the availability of relatively unpolluted canal water resulting from reduced irrigation applications. At the farm level the introduction of controlled drainage should improve livelihoods by reducing farmers pumping costs and sustaining agricultural production in water short years.

Controlled drainage has been introduced under rice in Egypt and has provided substantial benefits to farmers in terms of reduced labour inputs and pumping costs during irrigation, without reducing yields or increasing soil salinity when compared with conventional irrigation. (This will be discussed in more detail in chapter 2.). This study focuses on the benefits of extending controlled drainage to dry-foot crops in semi-arid areas.

1.6 Management Issues for Controlled Drainage

1.6.1 Water table control

As controlled drainage involves maintaining high water tables in the soil profile for extended periods of time it requires careful management to ensure that crop growth is not affected by anaerobic conditions. According to experience with controlled drainage in California, if the drains are not opened for consecutive growing seasons, crops will be subjected to excessive water logging during the third season (Manguerra and Garcia 1996).

Evans and Skaggs (1996) described a controlled drainage/sub-irrigation system for use in North Carolina. Controlled drainage was employed to conserve water by reducing drainage outflows, and sub-irrigation was used in dry periods to raise the water level in the field. Controlled drainage was achieved by placing weirs in the drainage ditches. Intensive monitoring and management of the system was found to be necessary for effective operation. The most important management decisions included:

- When to raise/ lower the weir level
- At what height to maintain the weir
- When to add water to the system

Controlled drainage clearly requires more management than conventional systems, but this requirement need not be particularly onerous if farmers have access to clear guidelines on water levels to be maintained in drainage ditches, or the periods when drains can be safely blocked.

1.6.2 Salinity control

Soil salinisation is a major agricultural constraint in semi-arid regions (Egypt, Pakistan etc). Secondary salinisation from shallow, saline water tables is coupled with primary salinisation from salts added with irrigation water. Re-use of drain water for irrigation is common in the Nile Delta, with salinity of applied water ranging from 1 to 5 dS/m. If these added salts are allowed to accumulate, soil structure and fertility is threatened and crop yields suffer. Additional water has to be applied to wash the salts out of the root zone (Manguerra and Garcia 1997), which results in the water table rising steadily over a couple of growing seasons. A period of drainage is therefore required to flush out the excess water and salts.

In a controlled drainage system the quantities of water applied, the interval between irrigations, and control of drainage flows have to be based on both crop water requirements and the frequency at which excess salt needs to be removed from the root zone. As an entire season’s salt load might be removed at one time during drainage in a controlled system, leaching can be very efficient as a high concentration of salts are removed in a relatively small volume of drainage water (Manguerra and Garcia 1997). Effective control of salinity is crucial for the success of controlled drainage in semi-arid areas and is the second key management issue.

2. POTENTIAL OF AND CONSTRAINTS TO, APPLICATION OF CONTROLLED DRAINAGE IN EGYPT

The potential of, and constraints to, the introduction of controlled drainage in the Nile Delta, Egypt were assessed. This, and a fuller description of the development of irrigated agriculture in Egypt, pressures for water saving, the institutional setting and the results of previous applications of controlled drainage under rice are presented in full in appendix 2. The key findings are summarised here.

2.1 Irrigated Agriculture in Egypt

Egypt's existence depends on the River Nile, the principle source of water for agricultural, industrial and domestic use in this extremely arid land. The agricultural sector is the largest water consumer, using about 85% of surface water resources at present. A network of about 30,000km of irrigation canals and 17,500km of drainage channels serve the estimated 7.8 million feddans of irrigated land. Construction of the Aswan High Dam allowed perennial watering of crops, and intensification of agriculture along the Nile valley and across the Delta. The need for drainage soon became evident with rising water tables and soil salinity problems. Surface drainage (open main and branch drains) has been under construction since the turn of the century and currently the coverage is about 4.2 million feddans - 54% of the irrigated area.

Agriculture and livestock production is intensive, but due to traditional inheritance practices farms are becoming smaller: they now cover on average less than 1 ha (Abu–Zeid and Rady, 1991). All crop production is irrigated, the main crops being maize, cotton and rice in the summer, and wheat, berseem and vegetables in the winter. Following recent reforms farmers are now free to grow any crop they choose, (except rice), which may be sold at the prevailing market prices. Rice production helps to reclaim lands affected by salinity, but requires a large amount of irrigation water. Thus there are controls on the locations where rice may be grown, and on the total area of production, but these are not strictly enforced.

Farmers' water use strategies depend on the relative availability of water provided by the irrigation system. Many tail-end farmers, poorly served by the irrigation system, irrigate by lifting water from drains. Individuals have to pay fuel costs and may also hire a pump for the purpose. Most recognise that crop yields will be lower, since the water is partly saline. It is also likely to be polluted with domestic and industrial waste.

2.2 Need for water saving

The 1959 treaty with Sudan fixed Egypt's share of Nile water at 55.5 billion m^3/yr. To alleviate pressure on existing agricultural lands, the Government has initiated several strategic (horizontal expansion) programmes. These include the construction of new settlements and reclamation of desert lands, using water from Lake Nasser and drainage flows. Major projects include the Toshka Project, the Salam Canal Project and the Umoum Drain Project, which in total will provide more than 0.7 million ha of new irrigated land. These projects will have major impact on the water balance of the Nile, and it is estimated that developing industry, expanding agricultural land and the need to feed a growing population will lead to an annual demand for water estimated to reach 74.5 bcm by the year 2025. More efficient use of existing water resources is thus essential over the next 30 years, and existing irrigators can expect reductions in supply as the pressures on water increase.

At present 4.5 bcm per year of drain water is made available in the Nile Delta for re-use through the MPWWR's official drainage reuse program. The average annual drainage reuse amount has increased from 3 bcm in 1984-1990 to 4 bcm in 1991-1996, and will be increased further as part of the horizontal expansion programme. Unofficial reuse, where farmers individually lift water from drains for immediate reuse, is a major component of re-use within the Delta. It is difficult to estimate the exact extent of this practice, but it has been estimated (Drainage Task Force Committee, 1997) at about 2.8 bcm/yr.

Although drain water reuse increases overall water use efficiencies it is better to save water earlier in the cycle, due to increasing water quality problems when water is reused. Controlled drainage offers one means of achieving this. The impact of the introduction of controlled drainage on re-use at the basin scale will be assessed in the second stage of the study.

2.3 Irrigation Improvement Project to Save Water

In the “traditional” system irrigation system water is supplied to distributary canals with four days ‘on’, eight days ‘off’ rotations to the head, middle and tail thirds. Water is available in tertiary canals (meskas) whenever the distributary canal is ‘on’ at a minimum depth below ground of 80cm, and lifted to field channels by a variety of devices, under the control of individual farmers. With this system farmers tend to over-irrigate when water is available, as with the rotation they are not always sure of the next available supply, leading to wastage and water shortages at the tailend of the canal networks.

These issues are being addressed by the Irrigation Improvement Project (IIP), which is introducing quite radical technical and operational changes to farmers’ irrigation practices. The project aims at increasing efficient use of irrigation water by minimizing water losses and spillage to the drainage system and other measures. It is estimated that 5 bcm/yr fresh irrigation water might be saved, (Abdel-Aziz, 1995), however drainage water will decrease in quantity and increase in salinity as a result of irrigation improvement, which will ultimately affect the drainwater reuse program.

The project is based on replacing the traditional rotation system with an on-demand continuous flow system controlled by automatic gates. Canals are lined to reduce seepage losses, and on-farm irrigation practices are being improved**.** The new water control arrangements move farmers’ control further up the system, but at the same time introduces a need for co-ordination of demand by groups at the distributary level. There is now discussion about co-ordinating the functioning of irrigation and drainage groups in so-called meska ‘federations’.

Farmers under IIP may elect to pay for the water service by:

- season
- irrigation
- time

At present the rates are set such that rice cultivators, who use most water, invariably choose to pay the fixed seasonal charge, which they find more economic. Incentives to use less water therefore come from the reduced cost to farmers of pumping. Experience in IIP areas confirms farmers do reduce water usage when they benefit through reduced costs and labour inputs.

2.4 Rural Organisations and Water User Groups

Farmers will need to collaborate to implement controlled drainage, but this is already a feature of irrigation in the Delta. Informal water groups have existed in Egypt for a long time. Traditional “sakia rings” owned, controlled, and operated by water users were organised around lifting points from meskas. The supply, responsibilities and costs were allocated amongst participants according to defined principles. In recent years, similar practices have been continued in places where diesel pumps have replaced sakias. Long-standing procedures for allocating water within canal commands, termed Arab el Haq, are also still practised, though they are increasingly losing ground to expediency.

The institutional set-up in the Delta is good, with farmers receiving support from the extension services and district irrigation offices. Individual farm sizes are small, but farmers in many areas have grouped together into water user associations (WUAs) and collector user groups (CUGs). Previous work in Egypt showed use of existing co-operatives such as the WUAs worked much better than attempting to create new ones. However farmers often seek help from neighbours, relatives or friends if they want advice on agricultural matters. Attempts to introduce new techniques such as controlled drainage should thus also involve locally respected experienced farmers as well as the formal organisations.

2.5 Experience of Controlled Drainage in the Nile Delta

There have been studies into application of controlled drainage in Egypt, but these have only considered controlled drainage under rice, and not addressed potential benefits for dry-foot crops.

In Egypt, rice is grown along with dry-foot crops, creating field water management conflicts. These are worst in areas with sub-surface drains, where the drainage systems are designed for the most water-sensitive crops. Rice is not sensitive to water-logging,and should be drained as little as possible. The farmers' solution to this problem is to block drains serving rice fields with straw, mud and other debris to maintain standing water in the fields. This practice leads to clogging and blockage of drainage systems, and associated maintenance problems. Concern for these issues led to initiation of a water management study of rice fields in 1977-79 (El-Guindi and Risseeuw, 1987).

Several studies into controlled drainage under rice (see Appendix 2) have been carried out by the Drainage Research Institute. The results are very promising. Water savings of up to 40% have been achieved with no reduction in crop yields or increases in soil salinity. Key points from this work that are relevant to the application of controlled drainage to dry-foot crops are:

- Water management requirements for rice are very different to other (dry-foot) crops, and controlled drainage strategies will also be different.
- Crop consolidation (rice areas/non-rice areas) along drainage lines was found to be an essential component of controlled drainage management for rice. This may be less of an issue for dry-foot crops grown on heavy soils, but will be important in areas with high lateral seepage rates.
- Controlled drainage (under any crop) will require farmers to work together. Use of existing organisations, such as water user associations (WUAs), is more successful than creating new organisations for the purpose.
- The closing device (gated pipe) designed for the rice studies is equally appropriate for controlled drainage in non-rice areas.
- If savings can be made in fuel and time as a result of controlled drainage the technique is attractive to farmers.
- Water savings and other impacts are likely to be different in IIP areas, and this should be considered.

2.6 Conclusions

Principle conclusions from the assessment of potential and constraints are listed below with additional information included as appendix 2.

Potential

There are strong pressures to improve water use efficiency in irrigated agriculture. Water saving is essential in the next 20 years.

Agricultural areas of the Nile Delta have an extensive subsurface drainage system and high drainage flows constituting a major water loss at field and basin scale. Controlling drainage could thus provide significant on-farm water savings. It also offers the possibility of sustaining yields, and thus rural livelihoods, as the quantities of water available to farmers reduce in future years.

The concept of controlling drainage is not alien to Nile Delta farmers. It has been used under rice both unofficially (blocking drains with mud and straw) and as part of DRI experimental trials (using On/Off gated pipes).

Experience of controlled drainage under rice has demonstrated large water savings (up to 40 %) with no reduction in crop yields or increases in soil salinity. Smaller, but still significant savings can be expected if controlled drainage is also applied under dry-foot crops.

Previous studies have demonstrated that where savings can be made in fuel and labour inputs, farmers respond by using less water. Controlled drainage is beneficial and attractive to farmers.

The institutional set up in the Delta is good, with farmers receiving support from the extension services and district irrigation offices.

As farm sizes are small, farmers will need to work together to implement controlled drainage. Previous work in Egypt showed use of existing co-operatives such as the WUAs worked much better than attempting to create new ones.

Constraints

Egypt has a fixed allocation of water from the Nile River, its primary source of water. This resource is stretched to the limit due to continued population pressures, an ambitious horizontal expansion programme and demands from other sectors.

The Government of Egypt has introduced major water saving programmes in the agricultural sector. New initiatives including the extension of controlled drainage under rice must complement the ongoing programmes such as the Drainwater Reuse Programme and Irrigation Improvement Project.

Crop consolidation along drainage lines will be necessary in some areas if the full benefits of controlled drainage are to be realised.

Water saved by the introduction of controlled drainage must be used effectively further downstream, possibly by reducing reliance on saline and contaminated drainage flows, if the full benefits are to be realised.

Benefits to farmers must be large enough to ensure take up.

3. A PREDICTIVE DESIGN TOOL FOR CONTROLLED DRAINAGE

3.1 Introduction

The potential benefits of controlled drainage have been outlined, but fundamental work is needed before recommendations can be made on design and operation of controlled drainage systems. The ability to design and quantify the performance of strategies which save water, and protect resources is a critical first step. This is being addressed with the development of an outline predictive design tool. When the tool has been verified it can be used to develop practical methodologies for controlled drainage, and a set of guidelines for designers, irrigation agencies and farmers.

An outline specification for the tool was developed following a literature review of previous controlled drainage research and applications, discussions with DRI researchers, and engineers working with farmers testing controlled drainage in rice areas of the Nile Delta, and informal interviews with farmers in the Nile Delta – in areas where controlled drainage has been tried under rice, as well as those where it hasn't.

The outline specification is:

- The tool should allow assessment of a wide range of management strategies for controlled drainage, covering water use, soil and water quality, and crop response, and allow direct comparison with conventional drainage options.
- It should allow simulation of the two practical approaches to controlled drainage (discussed in Section 1.4). These are periodically blocking drains to create distinct "drainage" and "no-drainage" periods, and use of weirs to control water table levels in the field.
- It should be usable by researchers and engineers who do not have specialist expertise in simulation modelling, and be user-friendly.
- Have the ability to model a range of crops and rotations over long time periods eg up to 20 years, with different soil types, irrigation and drainage regime, and different climates.
- Should ideally be based on models that have been verified in the field in semi-arid areas.
- The tool should include provision for farmer cost calculations and economic analysis of options.

3.2 Framework for the Predictive Design Tool

The structure of a preliminary design tool is shown in Figure 3. It consists of three components:

- A simulation module (incorporating a field water balance model) that models the water and salt balance, and crop response.
- A cost module that, at this stage, allows a basic assessment of farmer costs for different management options.
- A screening tool that aids selection of strategies according to user-specified criteria.

The tool is applied by simulating a wide range of controlled drainage scenarios, with the corresponding conventional drainage cases, and then screening the model outputs to identify options that meet user-specified criteria.

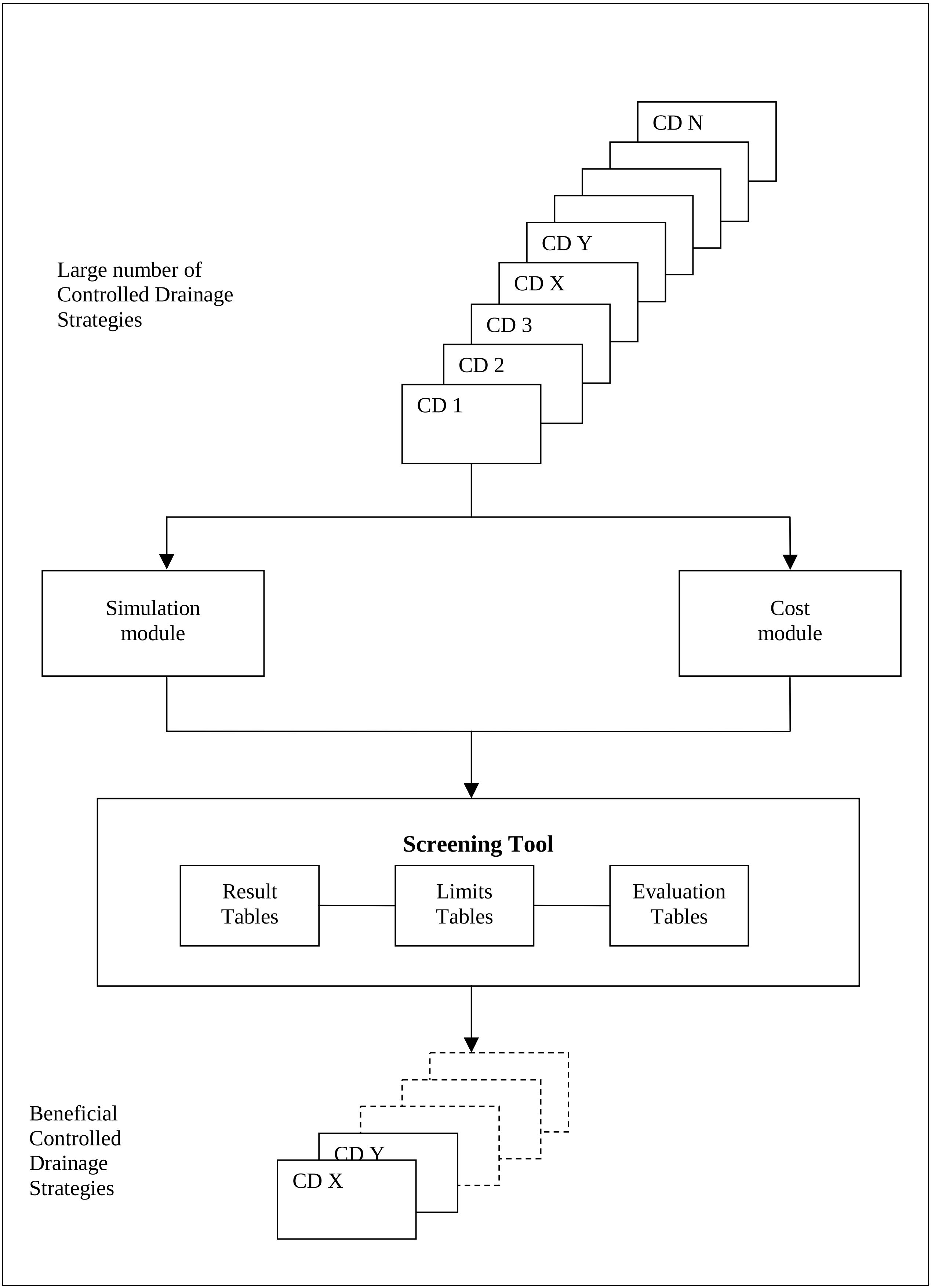

Figure 3 Framework for a predictive design tool for controlled drainage

3.3 Simulation Module

Controlled drainage affects complex physical processes of water movement and solute behaviour, and crop dynamics. A simulation model is required which represents these processes, and has been verified in semi-arid zones.

DRAINMOD is a field water balance model developed, tested and refined over many years. It computes daily water and salt balance and water table depths, and seasonal crop yields. It allows simulation of conventional and controlled drainage using weirs, and has been applied and verified in semi-arid regions including the Nile Delta. The Drainage Research Institute has been directly involved in development and field application of the model (including the salinity version DRAINMOD-S). This model has thus been used for the initial development of the tool.

DRAINMOD allows simulation of controlled drainage achieved with the use of a weir placed in the outlet drainage ditch. The user can alter the weir depth on a monthly basis for each crop in the rotation. It was also thought that DRAINMOD-S could be used to simulate the effects of blocking drains, but this is proving difficult, and alternative models that allow simulation of drain blocking may need to be considered for the second phase of the study.

DRAINMOD-S (Kandil et al, 1992) is a modified version of the original DRAINMOD (Skaggs, 1978) which is based on a water balance in the soil profile. Originally developed for the design and evaluation of multi-component water management systems on shallow watertable soils in humid regions, it has subsequently been extended and successfully applied in semi-arid areas eg Kandil et al and Gupta et al, 1995. DRAINMOD-S allows salt concentrations in the soil profile and drainage water to be calculated throughout the season. It includes an explicit solution to the advective-dispersive equation of solute transport.

Input data requirements include:

- Drainage design parameters – drain depth, spacing and radius.
- Soil parameters – soil water characteristic curves, hydraulic conductivity, depth to impermeable layer, initial soil salinity levels.
- Climate and management variables – rainfall, evapotranspiration, quantity, quality and timing of irrigation applications.

Infiltration, drainage, surface runoff, evapotranspiration and seepage are simulated along with watertable position and soil salinities. Relative crop yields are estimated from calculation of stresses due to excessive and deficit water conditions, planting delays and soil salinity levels.

Predictions of the model have been tested and found to be reliable under a wide range of soil, crop and climatological conditions (Skaggs et al, 1981, Skaggs, 1982, Rogers, 1985, Gayle et al, 1985, Fouss et al, 1987, McMahan et al, 1987, Abdel Dayem and Skaggs, 1990 and Gupta et al, 1993). The salinity aspects of version DRAINMOD-S were tested by Kandil, 1992 and Merz, 1996 using data from Egypt and India.

3.4 Cost Module - Calculation of costs and benefits

The adoption and subsequent sustainability of any change in agricultural practice, requires direct benefits to the implementers, in this case the farmers. At present in locations where there is adequate water a farmer will look for significant financial or other benefits before adopting controlled drainage. These could be improved crop yields, reduced irrigation costs, or savings in labour. There will also be off-site impacts including the availability of additional good quality water from on-farm water savings, but these will not be seen as a direct benefit by farmers who are asked to reduce their irrigation applications. In future, when the quantity of water per hectare that is available to farmers reduces the principle benefits from controlling drainage flows would be the possibility of sustaining crop yields when irrigation applications are reduced.

Thus at present cost calculations are limited to a simple comparison of the costs to farmers from different controlled drainage interventions, following the procedure adopted by the Drainage Research Institute (DRI, 1997) to assess financial benefits of controlled drainage strategies under rice. They assume that all farmer costs (seeds, fertilisers, operation and maintenance) under controlled drainage are the same as under conventional drainage, except irrigation pumping costs. These are directly proportional to the quantity of water pumped, and are calculated as:

Cost of 1 litre diesel	= LE 0.40
Cost of 1 kilo oil	= LE 3.50
Consumption of diesel	= 16 litre/5 hours pumping
Consumption of oil	= 4 kilo/60 hours pumping
Capacity of pump	= 0.1m^3/s
Total pumping cost	= 4.197 LE/1000 m^3 water

Costs based on information from IIP office, Damanhur (DRI, 1997).

Cost and benefit calculations will be expanded to cover a wider range of impacts in the second phase of the project.

3.5 Screening Tool

This enables controlled drainage strategies to be screened according to a number of user set criteria. The module is written using Microsoft Excel (with Visual Basic), allowing ease and speed of use, and enables the user to rapidly alter the key parameters, selection rules and acceptable limits.

The input to the screening tool are data output from the simulation model and cost module, which are placed in a results table. Lower and upper limits for the parameters that are to be used for screening are set in a limits table, and the tool then selects strategies that satisfy the chosen criteria, highlighting the “successful” options in an evaluation table. Examples of a results table, a limits table and an evaluation table, are shown in figures 4, 5 and 6. Controlled drainage designs can thus be assessed in many ways by changing the limits set for each parameter to reflect their relative importance.

For the example application, screening was based on four criteria considered the most important in assessing alternative controlled drainage interventions. The objectives in this case were water saving, maintaining or increasing crop yields, reduction of farmer costs, and sustaining water and soil resources.

Water Saving
The primary objective of introducing controlled drainage strategies in semi-arid irrigated areas is to save water. Thus we are looking for water management strategies which maximise the water table contribution to evapotranspiration demand, and minimise drainage, deep percolation and runoff losses.

Crop Yield
A sustainable controlled drainage strategy must either improve crop yields or maintain them at acceptable levels. At present the screening module assesses yields using both average and minimum acceptable crop yields, over a 20 year simulation period.

Protection of soil and water resources (sustainability)
Although the primary aim of controlled drainage is to save water by reducing drainage losses, soil salinity levels have to be controlled, and some drain flow is required to leach salts out of the soil profile. Screening is thus based on an assessment of soil salinity levels at the end of the 20 year simulation compared to levels at the start.

Irrigation File	File1	ALL_WIN_PRE(20years)

Criteria		Controlled Drainage Strategy 1CONV	1CD1	1CD2	1CD3	1CD4	1CD5	1CD6	1CD7	1CD8	1CD9	1CD10
Average Yield %	Crop 1	95.7	100	100	95.7	95.7	95.7	95.7	95.7	95.7	100	100
	Crop 2	98.5	91.1	98.5	100	100	98.5	98.5	98.5	98.5	100	100
	Crop 3	97.6	97.6	97.6	97.6	97.6	90.5	99.7	97.6	97.6	97.6	99.7
	Crop 4	100	100	100	100	100	100	100	99.1	99.1	100	100
Minimum Yield in One Season %	Crop 1	95.7	100	100	95.7	95.7	95.7	95.7	95.7	95.7	100	100
	Crop 2	98.4	90.9	98.4	100	100	98.4	98.4	98.4	98.4	100	100
	Crop 3	97.4	97.4	97.4	97.4	97.4	90.5	99.7	97.4	97.4	97.4	99.7
	Crop 4	100	100	100	100	100	100	100	99.1	99.1	100	100
Irrigation Water Use mm	Crop 1	779.3	779.3	779.3	779.3	779.3	779.3	779.3	779.3	779.3	779.3	779.3
	Crop 2	559.6	559.6	559.6	559.6	559.6	559.6	559.6	559.6	559.6	559.6	559.6
	Crop 3	750.6	750.6	750.6	750.6	750.6	750.6	750.6	750.6	750.6	750.6	750.6
	Crop 4	365.8	365.8	365.8	365.8	365.8	365.8	365.8	365.8	365.8	365.8	365.8
Average Soil Salinity ppm	Penultimate	648	518	630	573	631	1290	1013	812	765	565	795
	Final	648	521	633	577	630	1278	1012	813	766	571	798
	Final/initial	0.64	0.51	0.62	0.57	0.62	1.26	1	0.8	0.76	0.56	0.79
	Final/penult	1	1	1	1.01	1	0.99	1	1	1	1.01	1
Drainwater (Whole model run) mm	Total Flow	559	523	526	545	546	544	544	559	559	511	496
Farmer Costs LE / fed	Crop 1	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7
	Crop 2	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
	Crop 3	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2
	Crop 4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
	Total	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3

Figure 4 Example simulation results table from the screening tool

Criteria		Limiting Values Lower	Upper
Average Yield %	Crop 1	95	100
	Crop 2	95	100
	Crop 3	95	100
	Crop 4	95	100
Minimum Yield in One Season %	Crop 1	90	100
	Crop 2	90	100
	Crop 3	90	100
	Crop 4	90	100
Irrigation Water Use mm	Crop 1		779.3
	Crop 2		559.6
	Crop 3		750.6
	Crop 4		365.8
Average Soil Salinity ppm	Penultimate		
	Final		
	Final/initial		1
	Final/penult		
Drainwater (Whole model run) mm	Total Flow	1	559
Farmer Costs LE / fed	Crop 1		13.7
	Crop 2		9.8
	Crop 3		13.2
	Crop 4		6.4
	Total		43.2

Figure 5 Example limits table from the screening tool

			Controlled Drainage Strategies Passing Limits			
			3CD3	3CD9	5CD9	5CD10
Rainfall File			File 3	File 3	File 5	File 5
Criteria	Average Yield %	Crop 1	95.6	100	95.7	100
		Crop 2	100	100	100	100
		Crop 3	97.6	97.6	97.6	97.6
		Crop 4	100	100	100	100
	Minimum Yield in One Season %	Crop 1	95.6	100	95.7	100
		Crop 2	100	100	100	100
		Crop 3	97.4	97.4	97.4	97.4
		Crop 4	100	100	100	100
	Irrigation Water Use mm	Crop 1	779.3	779.3	779.3	779.3
		Crop 2	511.8	511.8	429	429
		Crop 3	750.6	750.6	750.6	750.6
		Crop 4	224.1	224.1	142.6	142.6
	Average Soil Salinity ppm	Penultimate	731	690	827	839
		Final	737	694	834	847
		Final/initial	0.73	0.68	0.82	0.83
		Final/penult	1.01	1.01	1.01	1.01
	Drainwater (Whole model run) mm	Total Flow	356	321	190	156
	Farmer Costs LE / fed	Crop 1	13.7	13.7	13.7	13.7
		Crop 2	9	9	7.6	7.6
		Crop 3	13.2	13.2	13.2	13.2
		Crop 4	3.9	3.9	2.5	2.5
		Total	39.9	39.9	37	37

Figure 6 Example evaluation table from the screening tool

Farmer costs and benefits
As described earlier this is at present based on costs to farmers of pumping, the benefit being a reduction in costs when controlled drainage is used. In water short years the benefits may be increased insurance against the impacts of water shortage on crop yields. At present this is not considered in the computation of costs and benefits as it is brought out in yield comparisons when yields with and without controlled drainage are compared for water short years.

3.6 Demonstration Application

The tool was used to predict the longterm impacts of different controlled drainage strategies on yields of dry-foot crops, water use, soil salinity, drain flows and farmer costs in the western Nile Delta, and compare these with conventional drainage practice. This initial application had several objectives:

- To demonstrate utility of the design tool.
- To assess the potential water saving benefits of controlled drainage for one soil type, crop rotation and drainage arrangement, when compared to conventional operation.
- To assess the extent to which controlled drainage can benefit farmers in the future when the quantities of water available are expected to reduce.

All simulations were run over a period of twenty years, using a 2-year crop rotation of cotton, wheat, maize and berseem. This is one of the most common crop rotations in the Nile Delta.

3.7 Input Data

Input data were taken from the western Nile Delta, north west of Damanhur, at or close to Mariut Experimental Farm, where the field experiment on controlled drainage for dry-foot crops is being conducted.

Climate Data

Monthly average (10 yearly) climate data from Sakha meteorological station (CLIMWAT, FAO, 1993) was used for the climate input file (see appendix 3). CLIMWAT calculates reference evapotranspiration (ET_o) according to the Penman Monteith method.

Soil Data

72 soil samples were taken from the Mariut experimental farm, to a depth of 1.65m. The soil type in the area is sandy loam. Analysis results are shown in appendix 4.

Irrigation Practice

Farmers in the area generally receive water on a 5-days-on, 10-days-off rotation which means water is usually available for irrigation every 10-14 days. Surface irrigation is practised with basins and furrows, depending on the crop. Irrigation water quality is generally good in the area. An EC_w of 300ppm was adopted for the demonstration. Seasonal irrigation scheduling amounts and dates were derived from Ministry of Agriculture records and discussions with engineers. The adopted rotation schedule is shown in appendix 5.

Drainage Design

Watertables are high and subsurface lateral drainage systems are common. A standard design in the area (including the experimental station) is a lateral spacing of 35m and a drain depth of 1.2m. This was thus adopted for the simulations.

Crop data

Crop data required for DRAINMOD are the planting and harvesting dates, rooting depths, crop factors throughout the season, and wet, dry and salt stress yield functions. These were developed for the four crops using FAO guidelines and local knowledge (appendix 6).

3.8 Strategies and Scenarios Tested

The tool was used to develop controlled drainage strategies for 6 scenarios of water availability – ranging from the current water use scenario, through scenarios of summer and winter water shortage to a year-round reduction in water available for irrigation. These scenarios are summarised in table 2 below and detailed in appendix 5.

Table 2 Irrigation amounts (mm) applied under the demonstration scenarios.

	Normal* (current situation)	Summer Shortage	Winter Shortage	Increased Summer Shortage	Increased Winter Shortage	Year-Round Shortage
Cotton	779.3	701.8	779.3	613.9	779.3	613.9
Wheat	559.6	559.6	511.8	559.6	429	429
Maize	750.6	662.7	750.6	607.3	750.6	607.3
Berseem	365.8	365.8	224.1	365.8	142.4	142.4
Rotation Total (% water use)	2455.3 (100%)	2290 (93%)	2265.8 (92%)	2145 (87%)	2101.5 (86%)	1791.3 (73%)

*These figures are based on official recommendations. As in many cases farmers use more water than the figures that are tabulated, the simulations will tend to underestimate actual water savings.

Simulations were run for each water use scenario, and eight to ten controlled drainage designs based on controlling the water table levels using weirs in drains. Weir depths - the distance that the crest is set below the average level of the field during each crop seasons - were set as shown in table 3 below:

Table 3 Controlled drainage (CD) strategies tested.

Drainage Strategy	Controlled Drainage Crops	Months CD applied	Weir depth
CONV*	None	None	None
CD1	Cotton	April – Oct	60cm
CD2	Cotton	April – Oct	90cm
CD3	Wheat	Oct – April	60cm
CD4	Wheat	Oct – April	90cm
CD5	Maize	May – Sept	60cm
CD6	Maize	May – Sept	90cm
CD7	Berseem	Oct – Feb	60cm
CD8	Berseem	Oct – Feb	90cm
CD9	Combination	Varies	Varies
CD10	Combination	Varies	Varies

*CONV is conventional irrigation and drainage management, CD is controlled drainage.

A total of 63 cases (6 water-use scenarios, with conventional irrigation and drainage (CONV), and eight to ten proposed controlled drainage (CD) designs) were assessed over a 20 year simulation period.

The screening tool was then used to evaluate the designs according to the key parameters described earlier.

3.9 Results

Output data from the simulation model is listed in appendix 7a. For the purposes of the demonstration we will assess the proposed controlled drainage designs in two ways - to identify designs that provide:

1. Water saving strategies. To develop sustainable controlled drainage strategies that reduce irrigation water use.

2. Increased crop yields in periods of water shortage. To assess whether controlled drainage can help the farmer in times of water shortage when crop yields are threatened.

3.9.1 Water Saving Strategies

Screening was carried out initially to identify designs that provided water savings while maintaining crop yields and controlling salinity. Controlled drainage strategies were thus identified that:

- Reduced irrigation water use compared to current irrigation applications under conventional irrigation and drainage. (This also reduces farmer pumping costs.)

- Are sustainable. This was defined as no overall increase in soil salinity levels over the 20-year simulation period.

- Maintained crop yields (compared to conventional drainage operation with current water use). Criteria used were that average seasonal crop yields should be greater than 95%, and no single crop season should have less than 90% crop yield.

The limit values adopted for screening, and the resulting evaluation tables are included in appendix 7b (table 1). Four controlled drainage designs satisfied the criteria, offering water savings of between 8% and 14% on an annual basis as summarised below:

Table 4 Water Saving Controlled Drainage (CD) Strategies

Strategy	Description	Water Saving
3CD3	CD during wheat season Oct-April, weir set at 60cm	8%
3CD9	CD during wheat season Oct-April, weir set at 60cm **and** CD during cotton season April-Oct, weir set at 90cm	8%
5CD9	CD during berseem season Oct-Feb, weir set at 90cm **and** CD during wheat season Oct-April, weir set at 60cm	14%
5CD10	CD during berseem season Oct-Feb, weir set at 90cm **and** CD during wheat season Oct-April, weir set at 60cm **and** CD during cotton season April- Oct, weir set at 90cm	14%

All four strategies allowed reduced irrigation applications during the winter months, when wheat and berseem were grown. The most beneficial, (of the ones tested), was found to be a weir setting of 60cm during the wheat crop season from October to April. This option featured in all four beneficial strategies. The "best" design (high water saving, highest crop yields) was found to be a combination of controlled drainage in three crop seasons – weir depths of 90cm during berseem, 60cm during wheat and 90cm during cotton seasons.

It should be noted that these results are for a specific combination of soil type, crop rotation etc. and should not be taken as indicating the maximum water savings that could be achieved. These could be significantly larger in some areas, and this will be investigated in the second phase of the project.

3.9.2 Strategies that help the farmer in times of reduced water availability

In the Nile Delta water resources are currently stretched to the limit and in future the quantity of water available per ha for agriculture will decline. Farmers will have to manage with less. Controlled drainage strategies were thus assessed with levels of reduced water availability listed earlier. Simulation results were then screened using the following criteria:

- For the given situation of water shortage, the strategy increases crop yields over those obtained with conventional management.
- The strategy is sustainable – ie no increase in soil salinity over the 20 year period.

Summer Water Shortage Scenarios:

Results shown in appendix 7b (tables 2 and 4) and summarised below:

Table 5 Controlled Drainage (CD) Strategies that increase crop yields in periods of summer water shortage.

Degree of water shortage	CD Strategy	Description	Relative increase in crop yield*			
			Cotton	Wheat	Maize	Berseem
Moderate – 11% water reduction in summer (7% annual)	2CD2	CD – cotton season April-Oct, weir 90cm	23%	-	-	-
	2CD3	CD – wheat season Oct-April, weir 60cm	-	1.5%	-	-
	2CD4	CD – wheat season Oct-April, weir 90cm	-	1.5%	-	-
	2CD5	CD – maize season May-Sept, weir 60cm	-	-	36%	-
Increased – 20% water reduction in summer (13% annual)	4CD2	CD – cotton season April-Oct, weir 90cm	38%	-	-	-
	4CD3	CD – wheat season Oct-April, weir 60cm	-	1.5%	-	-
	4CD4	CD – wheat season Oct-April, weir 90cm	-	1.5%	-	-
	4CD5	CD – maize season May-Sept, weir 60cm	-	-	93%	-
	4CD6	CD – maize season May-Sept, weir 90cm	-	-	51%	-

*Predicted conventional drainage crop yields with moderate summer water shortage are cotton 69.5%, wheat 98.5%, maize 71.1%, berseem 100%. With increased summer water reduction – cotton 42.8%, wheat 98.5%, maize 50.1%, berseem 100%. Yield improvements (relative increase in crop yield) are expressed as a % increase in this yield under controlled drainage. Eg 4CD5 gave a maize yield increase from 50.1% to 96.8%, representing a 93% increase due to controlled drainage.

When water resources were reduced during the summer (up to 20% less water available) the summer crops (cotton and maize) were hit hardest (as expected) with conventional drainage. Berseem yields were unaffected (99-100% yield maintained) with some reductions for wheat. It is thus cotton and maize crops that benefit most from controlled drainage in periods of summer water shortage. Cotton yields were increased by up to 38% and maize by up to 93%.

The "best" designs were controlled drainage with weir depth at 90cm during cotton season, and 60cm during maize season.

Winter Water Shortage Scenarios:

Results shown in appendix 7b (tables 3 and 5) and summarised below:

Table 6 Controlled drainage (CD) Strategies that increase insurance against crop failure in periods of winter water shortage.

Degree of water shortage	CD Strategy	Description	Relative increase in crop yield*			
			Cotton	Wheat	Maize	Berseem
Moderate – 20% water reduction in winter (8% annual)	3CD2	CD – cotton season April-Oct, weir 90cm	4.5%	-	-	-
	3CD3	CD – wheat season Oct-April, weir 60cm	-	6%	-	-
	3CD9	CD - wheat season Oct-April, weir 60cm **and** cotton season April-Oct weir 90cm	4.5%	6%	-	-
Increased – 38% water reduction in winter (14% annual)	5CD2	CD – cotton season April-Oct, weir 90cm	6%	-	-	-
	5CD3	CD – wheat season Oct-April, weir 60cm	-	55%	0	-
	5CD4	CD – wheat season Oct-April, weir 90cm	0	45%	0	-
	5CD7	CD – berseem season Oct-Feb weir 60cm	0	0	0	83%
	5CD8	CD – berseem season Oct-Feb weir 90cm	1%	0	0	83%
	5CD9	CD – berseem season Oct-Feb weir 90cm **and** wheat season Oct-April, weir 60cm	1%	55%	0	83%
	5CD10	CD – berseem season Oct-Feb weir 90cm **and** wheat season Oct-April, weir 60cm **and** cotton season April-Oct weir 90cm	6%	55%	0	83%

*Predicted conventional drainage crop yields with moderate winter water shortage are cotton 95.6%, wheat 94.5%, maize 97.6%, berseem 100%. With increased winter water reduction – cotton 94.6%, wheat 64.6%, maize 97.6%, berseem 54.6%. Yield improvements (relative increase in crop yield) are expressed as a % increase in this yield under controlled drainage.

When water resources were reduced during the winter (up to 38% less water available) the winter crops were hit hardest (as expected), with minor yield effects for maize and cotton. It is thus wheat and berseem that benefit most from controlled drainage in periods of winter water shortage. Wheat yields were increased by up to 55% and berseem by up to 83%.

The “best” design involved introduction of controlled drainage over three crop seasons – with weir depths of 90cm during berseem, 60cm during wheat and 90cm during cotton seasons.

Year-Round Water Shortage Scenarios:

Results shown in appendix 7b (table 6) and summarised below:

Table 7 Controlled Drainage (CD) Strategies that increase crop yields in periods of year-round water shortage.

Degree of water shortage	CD Strategy	Description	Relative increase in crop yield*			
			Cotton	Wheat	Maize	Berseem
Year-round water shortage - 27% annual water reduction	6CD2	CD – cotton season April-Oct, weir 90cm	41%	0	0	0
	6CD3	CD – wheat season Oct-April, weir 60cm	0	55%	0	0
	6CD4	CD – wheat season Oct-April, weir 90cm	0	45%	0	0
	6CD7	CD – berseem season Oct-Feb weir 60cm	3%	0	0	83%
	6CD8	CD – berseem season Oct-Feb weir 90cm	3%	0	0	83%

* Predicted conventional drainage crop yields – cotton 41.6%, wheat 64.6%, maize 50.1%, berseem 54.6%. Crop yield increases under controlled drainage are relative to these values.

With *year-round* water shortage all crop yields were severely reduced under conventional drainage, probably leading to crop failure in some cases. None of the tested controlled drainage strategies helped the maize crop, although yields were improved for the other three crops. Cotton yields were increased with controlled drainage using a weir depth of 90cm. Wheat yields were improved by controlled drainage using weir depths of 60 or 90cm. Biggest yield gains were identified with controlled drainage during the berseem crop (weir depth at 60 and 90cm) which increased berseem yields by 83%.

4. CONCLUSIONS

Conclusions from the first phase of the study are brought together in this section.

4.1 General

Controlled drainage has been proposed as a water saving management technique for irrigated areas with high water tables and subsurface drainage systems. (This includes important agricultural areas in Egypt, India and Pakistan.) To date the technique has been applied (mainly) in humid areas, with benefits including:

- Yield increases (particularly in periods of water shortage).
- Water and energy savings.
- Water quality benefits – increased soil salt leaching efficiencies and reduced transport of agro chemicals to river systems.

Application in semi-arid regions is likely to produce similar benefits, but management strategies must incorporate the additional requirement to provide adequate leaching of salts from the soil root zone.

The technique is relatively new and undeveloped. Management issues such as when to raise and lower weirs in the drain channels to control water levels, (or when to block and un-block drains), and when to add irrigation water need to be addressed for different crops and different situations. The development of a generic design tool to assess impacts of different strategies, and guidelines recommending optimum management strategies for a range of scenarios is needed before controlled drainage can be tested at the pilot scale.

4.2 Potential of, and constraints to, the application of controlled drainage to dry-foot crops in the Nile Delta, Egypt

An assessment of the potential of, and constraints to, the introduction of controlled drainage under dry-foot crops in the Nile Delta showed that:

Potential

There are strong pressures to improve water use efficiency in irrigated agriculture. Water saving is essential in the next 20 years. Increased water scarcity is inevitable in areas of the Nile Delta.

Agricultural areas of the Nile Delta have an extensive subsurface drainage system and high drainage flows constituting a major water loss at field and basin scale. Controlling drainage may thus provide significant water savings. More importantly it also offers the possibility of sustaining yields, and thus rural livelihoods, as the quantities of water available to farmers reduce in future years.

The concept of controlling drainage is not alien to Nile Delta farmers. It has been applied under rice both unofficially (blocking drains with mud and straw) and as part of experimental trials (using On/Off gated pipes) conducted by DRI.

Experience of controlled drainage under rice has demonstrated large water savings (up to 40 %) with no reduction in yields or increases in soil salinity. Smaller, but significant, water savings can be expected if controlled drainage is also applied under dry-foot crops.

The rice controlled drainage work has demonstrated that where savings can be made in fuel and labour inputs, farmers respond by using less water. Controlled drainage is beneficial and attractive to farmers.

The institutional set-up in the Delta is good, with farmers receiving support from the extension services and district irrigation offices.

As farm sizes are small, farmers will need to work together to implement controlled drainage. Previous work in Egypt showed use of existing co-operatives such as the water user associations (WUAs) worked much better than attempting to create new ones.

Constraints:

Egypt has a fixed allocation of water from the Nile River, its primary source of water. This resource is stretched to the limit due to continued population pressures, an ambitious horizontal expansion programme and demands from other sectors.

The Government of Egypt has introduced major water saving programmes in the agricultural sector. New initiatives including the extension of controlled drainage under rice must complement the ongoing programmes such as the Drainwater Reuse Programme and Irrigation Improvement Project.

Crop consolidation along drainage lines will be necessary in some areas if the full benefits of controlled drainage are to be realised.

Water saved by the introduction of controlled drainage must be used effectively further downstream, possibly by reducing reliance on saline and contaminated drainage flows, if the full benefits are to be realised.

Benefits to farmers must be large enough to ensure take up.

4.3 A Predictive Design Tool For Controlled Drainage

A predictive tool for assessing the benefits of controlled drainage has been developed, and its application demonstrated. At present the tool comprises three components – a simulation module, a cost component and a screening tool.

A trial application verified the utility of the tool. Some effort is required to prepare the input data files for the simulation model, but once this has been completed large numbers of simulations can be run, and the outputs rapidly screened to indicate the "best options" for a range of user-specified criteria.

Some enhancements to the predictive design tool have been identified that should be implemented in the second phase of the study:

At present the simulation module uses the field water balance model – DRAINMOD-S, selected for the reasons outlined in section 3.3. DRAINMOD requires a large quantity of data, and considerable expertise and effort is needed to set up the input data files, which may prove to be a disincentive to non-specialist users, constraining uptake of the developed design tool. DRAINMOD also does not allow simulation of controlled drainage using "On /Off" control devices which is the method being used at present for rice in the Nile Delta.

An option to overcome both these constraints would be to adopt a simpler model, with less exacting data requirements, that could be used to simulate both "weir" and "On/Off" controlled drainage. The WASIM drainage model developed under the DFID funded "Aids to Drainage" project could meet these requirements, and its use for this application is being investigated. (WASIM will require some enhancement to simulate controlled drainage, but has the advantage that source code is available to HR Wallingford and thus changes that are needed can be made fairly easily.)

The cost component is very basic at present, comparing the costs of controlled drainage and conventional practice on the basis of reduced pumping costs. Other factors such as maintenance of yields in water short periods, labour/time requirements and operation and maintenance costs are of direct relevance to the farmer and should be considered in economic analysis of impacts to the farmer. At the basin scale wider economic issues such as value of the water saved, and impacts of reduced drainage flows will need to be considered. These issues will be taken up in the second phase of the project.

The screening tool worked well, but could be supplemented with a module providing conventional multi-criteria selection analysis later.

4.4 Results from demonstration application

The demonstration has confirmed the usefulness of the predictive design tool and confirmed that controlled drainage has the potential to save water, and to sustain crop yields in periods of water shortage in semi-arid environments. The second of these is likely to be the most important in the longer term. In particular, for the conditions simulated:

- Promising *water saving* controlled drainage strategies were identified, using less water compared to conventional irrigation and drainage practice, whilst maintaining crop yields, and soil and water resources. Costs to farmers would be decreased through reductions in pumping costs, proportional to the water saved. Four sustainable controlled drainage designs were developed, that provided water savings of up to 14% on an annual basis.

- For scenarios of *reduced water availability* there were 24 proposed controlled drainage designs that sustained or improved crop yields whilst controlling soil salinity levels.

Results from the demonstration application should not be used to indicate the full range of benefits that are achievable under controlled drainage. More simulations, covering a wide range of soil types, drainage systems, cropping patterns and water applications etc would be necessary before this can be achieved.

5. RECOMMENDATIONS

It is recommended that the second phase of the project, as outlined in the project proposal is implemented, taking account of the recommendations listed below.

- An alternative water balance model to DRAINMOD-S should be assessed for inclusion in the simulation component. This model should allow for controlled drainage using simple on-off devices such as gated pipes.

- The economic component should be expanded to address wider economic issues such as value of the water saved, increased crop yields and labour/time requirements.

- Fieldwork is underway in the Western Nile Delta to test one controlled drainage strategy (see appendix 8). This should provide some initial validation of the simulation tool. As the trial is being carried out on a small-scale at an experimental farm it will not test the potential of controlled drainage under farmer control. Provided the results obtained in the second phase of the study confirm the levels of benefit that are expected it is recommended that testing at a pilot scale by farmers is carried out as an extension of this project.

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Appendices

Appendix 1

Example applications of controlled drainage.

Appendix 1 Example applications of controlled drainage.

There has been research into controlled drainage, primarily in humid areas, and it has been adopted in several locations. Countries include USA, Canada, Bulgaria, Poland, Finland and Holland. The main benefits (depending on location) have been identified as:

- Yield increases.
- Water and energy savings.
- Water quality benefits – increased soil salt leaching efficiencies and reduced transport of agrochemicals to river systems.

The following are perceived benefits of a controlled drainage system from the literature:

- There is a water saving due to a reduction in irrigation application. Farmers are more careful with their irrigation management (Manguerra and Garcia 1996). In theory there is no water is lost through drainage in the growing season, so if too much water is applied then the crops will become waterlogged.

- The effectiveness of the drains is improved (Manguerra and Garcia 1996). As a result of reduced irrigation application, there is a reduction in the amount of drain water to be removed. The quantity of salt removed per unit volume of drain water is therefore increased.

- Throughout the period of no-drainage, the problem of disposing of drainage water is removed (Manguerra and Garcia 1996). The farmer has control over the release of drain water (Manguerra and Garcia 1997).

- Boosts crop yield in some cases. In an experiment in Canada, tomato yields were increased by 11% and corn yields by 64% (Tan, Drury et al 1997). In Finland, controlled drainage had a remarkable effect on crop yield in fine sand fields (Paasonen-Kivekas, Karvonen et el 1996).

- Improves water quality by reducing nitrate loss and pollution during the growing season (Tan, Drury et al 1997; Meja and Madramootoo 1998).

- There is a time saving for farmers. Much less time is required to saturate the soil profile for rice under controlled drainage system (Drainage Research Institute 1997).

- There can be a significant cost saving. Lower investment and operation costs are needed than for subirrigation (Paasonen-Kivekas, Karvonen et el 1996), (Kochev 1990), (Brandyk, Skapski et al 1993).

- There is a possibility of reusing the drainage runoff for subirrigation in the drainage area (Kochev 1990). In an open system, water running off the land can be collected in drainage ditches and used for subirrigation.

There are, however, a small number of limiting factors associated with a controlled drainage system:

- Although controlled drainage reduces the number of irrigations, the depth applied per irrigation can be larger (Manguerra and Garcia 1997).

- The absolute amount of salt removed by the traditional system is higher then that of a controlled system. This is because more water is applied in a traditional system and therefore there is a greater volume of drainage effluent (Manguerra and Garcia 1997).

- If the drain spacing is reduced a controlled system will remove the same net amount of salt as a traditional system (Manguerra and Garcia 1997). Although a narrower drain spacing would improve the salt removal in a controlled system this would increase the costs.

- Improving subsurface drainage lowers surface runoff and decreases peak runoff rates. According to a simulation carried out by Konyha et al (1992) controlling drainage will counter the effect of subsurface drainage.

- Controlled drainage and subirrigation systems can require a high level of management (Evans and Skaggs 1996).

Wenberg (1993) discusses controlled drainage of soils with a naturally high water table. The management of such a system is examined for ways of optimising crop production and maintaining or improving water quality. Controlled drainage improves off-site water quality by providing a greater opportunity for infiltration, reducing surface runoff along with erosion and therefore reducing dissolved and absorbed chemicals. Water quality seems to be improved the longer dissolved chemicals are held within a raised water table. Controlled drainage also seems to improve the crops use of nutrients. Maintaining a high water table during the winter or dormant season appears to encourage denitrification. Different management needs are however required for groundwater protection under naturally well drained soils. A nutrient and pesticide management scheme is recommended to improve water quality.

A study by Grismer (1992) describes the results of numerical simulations that examine the influence of drain spacing and depth on drain water quality. It was found that under steady state and transient flow conditions that drainage water salinity and cumulative salt load increase with increasing drain depth and spacing. Increasing drain spacing from 20m to 80m had a greater effect on drain water salinity and salt load than increasing drain depth from 2.5m to 4m. Water quality factors may therefore be as important as other drainage system design parameters.

CONTROLLED DRAINAGE EXAMPLES

The following are specific country by country examples of controlled drainage practices.

U.S.A.

SAN JOAQUIN VALLEY, CALIFORNIA

The San Joaquin valley is an intensely irrigated, arid region of California. The area is now threatened by environmental problems associated with the disposal of highly saline drainage water. Simply reducing drainage volumes is likely to exacerbate traditional problems of waterlogging and salinity that occur as a result of a high water table. The objective of Manguerra and Garcia's study (1996) was therefore to reduce the volume of subsurface drainage water whilst maintaining an acceptable salt balance.

A simple irrigation management solution of drainage and no-drainage cycles was proposed. The drains are blocked during the no-drainage cycle and no water is released. This may last a number of growing seasons. During the off season a drainage cycle occurs when the drains are opened to drain off the saline water and restore the suitability of the soil for crop growth. The system thus reduces drainage but does not completely eliminate it. Manguerra and Garcia (1997) describe it as an 'integrated system'.

A model was applied to a hypothetical farm based on the San Joaquin Valley field conditions. A modified version of the Colorado State University Irrigation and Drainage Model (CSUID) was used. The CSUID model was developed by Garcia et al (1995). The proposed management system was simulated over a period of eight years and the results analysed.

The model predicted a 50 to 58% reduction in drainage volume. It is also predicted that the integrated system is able to intercept more salt per unit volume of water and that the irrigation requirement is reduced without any reduction in crop yield. If the drain spacing is reduced the integrated system should approximate the salt balance of a traditionally managed system. In spite of the reduction in drain spacing, a cost benefit analysis has also shown that the integrated system is economically more attractive than the traditional system (Manguerra and Garcia 1997).

Ayars et al (1997) review existing design methods and drainage criteria for subsurface drainage systems in arid and semiarid irrigated areas. They present new design methods and criteria that include management of drain water quality. Recommendations include changing the design minimum water table depth from 1.2 to 0.9m and the depth of drains from 2.4 to 1.5m. Adopting these changes was shown to result in less drain water and lower salt loads being discharged. The concepts were demonstrated successfully with simulations based on data from the San Joaquin valley for cotton growing in the presence of shallow groundwater. The SWMS-2D Model was used for transient analysis of the flow to the drains in order to identify the primary soil layers contributing to flow in the drains.

BATON ROUGE, LOUISIANA

In humid areas farmers need to subirrigate when the evapotranspiration is high and drain when a rainfall event provides excess water to the root zone. In Louisiana, a rainfall probability forecast was used together with a DRAINMOD simulation in an attempt to improve watertable management in a free drainage, controlled drainage and a subirrigation system (Cooper and Fouss 1988).

The study found that a period of free drainage before a storm event reduced the duration of waterlogging and increased simulated maize yield from 0 to 11%, when compared to controlled drainage where the water level at the drain outlet was maintained at a level above the drain. Although the Rainfall Probability Index (RPI) provided warning for many significant rainfall events, its use as a management tool was only as good as the weather forecast (Cooper and Fouss 1988).

AMES AND ANKENY, IOWA

Kalita and Kanwar (1993) conducted field experiments over a period of three years in an attempt to evaluate the effects of Water Table Management (WTM) on groundwater quality. The research was carried out on corn for farms near Ames and Ankeny in Iowa. The study found that NO_3-N concentrations were reduced in groundwater by maintaining a shallow water table of 0.3 to 0.6m during the growing season. The crop yield, however, was shown to decrease with shallow water table depths reaching a maximum under a level of 0.9m. It was therefore concluded that for the study conditions, the use of a 0.6m water table as a best management practice was a suitable compromise.

NORTH CAROLINA

Konya et al (1992) used DRAINMOD to simulate the hydrology of two North Carolina mineral soils over a 33 year period. Four water management methods were investigated:

Conventional ditch drainage
Subsurface drainage
Controlled drainage for maximum yield – Weir control only used during the growing season.
Controlled drainage for improved water quality – Weir control used for entire year, excluding planting and harvesting periods.

The report concludes that the effect that water management practices have on the hydrology of agricultural lands depends on the properties of the soils. Improving subsurface drainage, lowers surface runoff and decreases peak runoff rates. Both controlled drainage systems had more surface runoff and higher peak flows than the subsurface drainage system. Controlling drainage therefore seems to counter the effect of subsurface drainage. Controlled drainage systems do, however, reduce the amount of nitrate entering a receiving stream.

Research on the use of subirrigation and controlled drainage to provide water for crops and to meet drainage needs has been carried out in North Carolina since the early 1970s (Evans et al 1996).

Evans and Skaggs (1996) describe a dual-purpose system for use in North Carolina. Controlled drainage is used to conserve water by reducing drainage outflows and subirrigation is used in dry periods to raise the water level in the field. Controlled drainage is operated by placing weirs in the drainage ditches so that the water level in the drainage outlet has to rise higher than the weir crest before the water will flow out of the field. Because the role of the system often changes, intensive monitoring and management of the system is necessary for effective operation. The most important management decisions include:

When to raise/ lower the control structure
At what height to maintain the weir in the control structure
When to add water to the system

Systems are designed to satisfy the water management needs of rooting depth and crop tolerance to water stress. Soil properties and rainfall distribution will vary according to location. Controlled drainage and subirrigation systems can require a high level of management. Evans and Skaggs (1996) suggest that the level of management in the final system can be controlled slightly by its design. Drain spacings can be increased slightly (up to 10 to 15 percent) on a system if the operator wishes to devote more time to management of the system.

A guideline report by Evans et al (1996) describes any combination of management practices such as drainage, controlled drainage and subirrigation as *water table management*. The report backs previous findings, indicating that water table management practices can improve water quality when properly designed and maintained. Water table management, in particular controlled drainage, has thus been designated a Best Management Practice (BMP) for soils with improved drainage. Unlike many BMPs, controlled drainage benefits both production and water quality. Since 1989 more than 2,500 control structures have been installed to provide controlled drainage on approximately 150,000 acres in North Carolina. Controlled drainage, in this area, has been predominately practised with a crop rotation of corn, wheat and soybeans, although increasing acreages of potatoes, peanuts and vegetable crops are being included.

The report states that when controlled drainage is managed all year it reduces total outflow by approximately 30 percent compared to uncontrolled systems, although outflows vary widely depending on soil types, rainfall, type of drainage system and management intensity. Drainage control has little net effect on total nitrogen and phosphorus concentrations in drainage outflow but may reduce NO_3-N concentrations by up to 20 percent. Controlled drainage tends to decrease phosphorus concentrations on predominately surface systems but has the opposite effect on predominately subsurface systems. Controlled drainage reduces nitrogen and phosphorus at the field edge, primarily because of the reduction in outflow volume.

In humid areas such as North Carolina, there is no optimum depth for water table control because it may fluctuate several inches daily in response to rainfall, evapotranspiration and drainage. The report concludes by stating that strategies for water table management are complex. It therefore suggests that in order to ensure maximum production and water quality benefits from controlled drainage, professional advice should be sought.

Doty and Parsons (1979) show that a “water mound” can be built by controlling the head above the drain outlet. A controlled and reversible drainage system (CaRDS) was designed and operated during 1975 and 1976. It was found that drainage was necessary to produce maximum yields when CaRDS is used. About the same amount of water was required by CaRDS as estimated for a normal surface-applied irrigation system. Losses of water to deep seepage did not seem to be excessive. The total water input to CaRDS was

5 cm more than pan evapotranspiration in 1975 and 22 cm more in 1976. The highest corn yields were produced between tile lines spaced 32m apart on both sandy loam and sandy clay loam soils.

CANADA

BAINESVILLE, ONTARIO

Lalonde et al (1996) conducted a water table management field study on a silt loam soil in Ontario, Canada during 1992 and 1993. Conventional free outlet subsurface drainage was compared to controlled water tables of 0.5 and 0.25m above the drain level. The study revealed that controlled drainage had a significant effect on drain flow and water quality. In 1992, the 0.25 and 0.5m controlled drainage levels reduced drain flow by 58.7% and 65.3% respectively. In 1993 they reduced drain flow by 40.9% and 95% respectively. Both controlled drainage levels also reduced the peak drain flows. In 1992, nitrate losses were decreased by 75.9% and 68.9% for the 0.25m and 0.5m levels, respectively and in 1993 the reductions were 62.4% and 95.7% respectively. Nitrate concentrations were often lower and significantly different at the 0.25m level. The net environmental benefit of controlled drainage on nitrate leaching was primarily due to decreased drain flow.

HARROW, ONTARIO

Tan, Drury, Gaynor et al (1997) describe a field study in Harrow, Ontario. Installation of riser pipes on an existing tile drainage system helped to demonstrate that it is possible to use controlled drainage in the field to produce higher yields. The idea was tried out on a large scale on three farms in the area. Results so far have shown that controlled drainage systems have increased corn yields by 10 to 15% and soybean yields by 15 to 20% on clay loam soils. In dry summers, on sandy soils, corn yields have been increased by over 60%. The controlled drainage and subirrigation system also enabled a 25 to 50% reduction in nitrate loss. Tile drainage water on clay loam fields was even found to exceed drinking water guidelines (over 10 ppm nitrate).

A detailed report of three on farm demonstration sites is given by Tan, Drury, Soultani et al (1997). The three site were established as follows:

Controlled drainage on a clay loam with conventional tillage.
Controlled drainage on a clay loam with no-tillage.
Controlled drainage and subirrigation on a sandy loam.

INNOTAG control drainage units were installed to control the volume of drainage water from the field. Drainage water enters the unit and raises water inside a riser column which lifts a float At a certain predetermined level, the float opens a flap gate which drains water out from the unit restoring the water level. A similar unit was installed to regulate the controlled drainage subirrigation system. OASIS not only regulates the water levels but includes a sensor that commences and terminates subirrigation.

The conventional tillage, controlled drainage system reduced tile drainage volume by 13% and tile nitrate loss by 4% compared to a corresponding conventional drainage system. The no-tillage, controlled drainage system was found to perform better with controlled drainage reducing drainage volume by 22% and tile nitrate loss by 27%. Thus, the combination of no-tillage and controlled drainage improves soil structure and prevents excessive nitrate leaching through the tile drainage water.

On the sandy loam site, the controlled drainage and subirrigation system reduced flow weighted mean (FWM) nitrate concentration by 31% and total nitrate loss by 24% compared to a conventional free drainage system. Marketable tomato yields were increased by 11% and corn yields by 64% in 1996.

ST. LAWRENCE, ONTARIO

A two year study was conducted by Mejia and Madramootoo (1998) in St. Lawrence, Ontario to evaluate the effects of water table management on the quality of subsurface drain flows. Two controlled water table treatments were applied at 50 cm and 75 cm from the surface. These were compared to a conventional free-drainage treatment. Relative to conventional drainage, the NO_3-N concentrations in the 50 cm and 75 cm level drainage water were reduced by 84% and 75%, in 1995 and in 1996 by 61% and 52% respectively. In 1996, the nitrate loads to the receiving lake were reduced by 95% and 30% for the 50 cm and 75 cm levels, respectively. The improved water quality was attributed to a combination of decreased drain flow, dilution effect and enhanced denitrification in the controlled water table sections.

BULGARIA

Kochev (1990) proposes a concept for an environmentally sound controlled drainage system to cancel out the negative effects of classical drainage systems. The concept aims to target the impact of a fluctuating water regime on the soil and environment and the extraction of considerable amounts of nutrients by the drainage runoff, causing pollution and eutrophication of water sources. Kochev suggests that classical drainage systems put a strain on the vegetation through unnecessary overdrainage leading to desiccation of the root zone. It therefore follows that drainage systems can only be ecologically effective when they can control the drainage action and thus cater for the needs of the crops. A combined controlled drainage and subirrigation system does exactly this.

Tubed systems with fully covered, main and collector drains need high investments and are not suited for controlled drainage operation. Controlled drainage is more suited and ecologically efficient when applied to systems that have tube collectors draining the field and ditches for the secondary and main drains. Kochev (1990) highlights advantages of the controlled system over conventional drainage. The principle advantage being the possibility for reusing the drainage runoff for subirrigation in the drained area. Lower investment and operation costs are also required. Kochev (1990) concludes by warning that applicability of controlled drainage for different climatic regions must consider local economic conditions and the threat of soils salinization.

POLAND

Brandyk et al (1989) described a drainage-subirrigation system of open ditches and checks in the Upper Notec region of Poland. The system fulfilled the regions specific requirements which included meeting plant water requirements and the protection of the peat muck soils against the mineralisation process. The study concluded that for effective operation and maintenance of such systems estimations should be made of the basic parameters that characterise water flow. Systematic measurements of the groundwater levels and the soil moisture heads were also deemed necessary for the proper scheduling of the system under changing weather conditions.

Three different techniques used in the design and operation of drainage-subirrigation systems for use in low-lying areas of Poland are presented by Brandyk et al (1993).

Controlled Drainage – water table is lowered to the minimum required level during spring. The control structures are closed for the entire growing season. The water level is thus dependent on precipitation and evapotranspiration.

Subirrigation with a controlled water level – water table is kept close to its optimum level with constantly adjusted control structures.

Subirrigation with a regulated water level – water table is lowered to minimum required level at the beginning of the growing season. The control structures are then closed until the water level exceeds the optimum.

Controlled drainage is applicable to small agricultural watersheds with very limited water resources for subirrigation. It is a low cost technique because only one control structure is needed in the drainage ditch and it is easy to perform. It is, however, not possible to maintain the required groundwater level in the dry periods.

Subirrigation with a constant water level is recommended when the available flux for subirrigation is greater than $0.35ls^{-1}ha^{-1}$. It is also recommended for soils where it is possible to assess a groundwater level that guarantees the required air content in the root zone during rainfall as well as sufficient capillary rise during drought. Subirrigation with a regulated water level is recommended where the flux available for subirrigation is greater than $0.5ls^{-1}ha^{-1}$. It is also recommended for soils which require water table changes with changing weather conditions.

FINLAND

Three on-farm trials were established to evaluate the suitability of water table management for Finnish growing conditions (Paasonen-Kivekas et al 1996). Reservoirs were used to store drainage water for recycling back on to the fields through subirrigation. It was found that controlled drainage had a remarkable effect on groundwater level and crop yield in fine sand fields. Evidence of a relationship between groundwater level and N concentration was observed. The N yield of cereals was found to be 10 to 50% higher in the controlled drainage and subirrigation areas compared to reference areas. Most of this extra N was allocated to grains and removed from the fields therefore reducing the N load into the environment. The nitrogen concentration in the drain water was reduced. The effect of controlled drainage on total outflow varied widely depending on weather conditions and management intensity. Although controlled drainage requires much lower investment costs than subirrigation, a lower increase in crop yield is also expected.

NETHERLANDS

Visser (1992) summarises the results of a 12 year long experiment with apple trees on a loamy to clayey soil in the East Flevoland Polder. A general comparison was made between subirrigation levels of 0.4, 0.7, 1.0 and 1.3m below the soil surface. The findings indicate that soil compaction became worse at higher ground water levels, nitrogen levels along with soil subsidence and crack formation increased as the ground water regime became deeper. After ten years below the ground water level, the structure of the loamy to clayey soil in the drains had not changed and maintained a hydraulic conductivity of 3m a day. The final conclusion of the study was that subirrigation in a clay soil is possible. Profits will, however, depend on climate and the type of crop.

Most of the work to date has been in temperate areas, but controlled drainage is likely to be beneficial in many arid and semi-arid regions of the world, where watertables are high. Potential areas of application include Egypt, Pakistan and India.

In semi-arid areas additional water has to be applied (leaching) to wash the salts out of the root zone (Manguerra and Garcia 1997). This extra water means that the water table will rise steadily over a couple of growing seasons. A period of drainage is therefore required to flush out the excess water and salts. According to predictions in California, if the drains are not opened for consecutive growing seasons, the crop will be subjected to excessive waterlogging during the third season (Manguerra and Garcia 1996).

In a conventional system, the interval between irrigations and the amount of water applied is theoretically based on the crop water requirements. In a controlled system the interval is based on the frequency at which excess salt needs to be removed from the root zone. An entire season’s salt load needs to be removed at one time during drainage of a controlled system. The system is therefore very efficient as a high concentration of salts are removed in a relatively small volume of water (Manguerra and Garcia 1997).

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Appendix 2

Potential and constraints for application of controlled drainage in Egypt

Appendix 2 Potential and constraints for application of controlled drainage in Egypt

Agriculture in Egypt and Pressures on Water

Egypt's existence depends on the River Nile, the largest renewable source of fresh water in northern Africa. It provides, almost exclusively, the source of water for agriculture, industrial and domestic use in this extremely arid land, and is a major fishery throughout its length. The agricultural sector is the largest water consumer, using about 85% of Egypt's surface water resources at present. A network of about 30,000km of irrigation canals and 17,500km of drainage channels serve the estimated 7.8 million feddans of irrigated land in Egypt.

Until recent times agricultural production in Egypt was sustained by the annual flooding of the River Nile, but the construction of the Aswan High Dam allowed perennial watering of crops and intensification of agriculture along the Nile valley and across the Delta. The need for drainage soon became evident with rising watertables and soil salinity. Surface drainage (open main and branch drains) has been under construction since the turn of the century, with investigations for sub-surface drains starting in the 1930s. In 1965 a programme was launched to provide 5 million feddans with sub-surface drains. 2.2 million feddans were completed by 1984 and currently the coverage is about 4.2 million feddans (54% of irrigated area).

The Delta is typified by intensive agriculture and livestock production, as well as fish production in some areas. Farmers generally practise mixed farming, with a total number of about 700,000 cattle and buffalo for meat and milk, a similar number for sheep and goats, and poultry for eggs and meat. All crop production is irrigated, with a cropping intensity of about 220% and good yields. Major crops are maize, cotton and rice in the summer, and wheat, berseem and vegetables in the winter. Rice is grown along with dry-foot crops with the main rice belt in the northern part. Average yields of wheat, seed cotton, rice and maize are respectively 3.7 tons/feddan, 2.5 tons/feddan, 5.7 tons/feddan and 4.5 tons/feddan.

The 1959 treaty with Sudan fixed Egypt's share of Nile water at 55.5 billion m^3/yr. Developing industry, expanding agricultural land and the growing population in Egypt is stressing this allocation. The annual demand for water is estimated to reach 74.5 bcm by the year 2025. To alleviate the pressure on the Nile water and the pressure on the old agricultural land, the Government initiated various strategic programmes. This includes the construction of new settlements and reclamation of desert lands. The government plans to reclaim an additional 2.9 million feddan by the year 2025, increasing pressures on water even more.

Horizontal Expansion Program

The Government of Egypt has embarked on an ambitious horizontal expansion program to increase the total irrigated land area using the fixed water allocation of 55.5 bcm/yr. Major projects include:

- Toshka Project – designed to develop 0.5 million feddans of desert land in Upper Egypt for agricultural production in the next 10-20 years taking up to 5 bcm/yr of river Nile flow from Lake Nasser.

- Salam Canal Project – to divert 2 bcm/yr drain water from the Bahr Hadus and Lower Serw drain basins in the Eastern Delta for 200,000 feddans irrigated area in west Suez and 420,000 feddans reclamation in Sinai. Irrigation has started in west Suez and reclamation will commence shortly in Sinai.

- Umoum Drain Project – to reuse 1 bcm/yr of drain water from Umoum drain basin in the Western Delta for 500,000 feddans irrigation in Nubaria. Physical works are underway.

These projects will have major impact on the water balance of the Nile Delta. Water savings are imperative. Major strategies adopted within the country include reusing drainwater for irrigation, and improving irrigation management in the Delta.

Drainwater Reuse to Save Water

Drainwater reuse is one of the main items of water policy for the Ministry of Public Works and Water Resources (MPWWR). More than forty lifting pump stations and twenty-two main reuse mixing stations are in operation in the 22 drain catchments of the Nile Delta. Each year the drain network removes more than 30 million tons of salt from the Nile irrigation system.

At present an annual amount of 4.5 bcm of drainwater reuse is made available in the Nile Delta through the MPWWR's official drainage reuse program, based on main drain reuse using main reuse pump stations. The average annual drainage reuse amount has increased from 3 bcm in 1984-1990 to 4 bcm in 1991-1996.

Unofficial reuse, where farmers individually lift water from secondary or tertiary (branch) drains for immediate reuse is now a major reuse component within the Delta. It is difficult to estimate the exact extent of this practice, but it has been estimated (Drainage Task Force Committee, 1997) at about 2.8 bcm/yr.

Although drainwater reuse is increasing overall irrigation efficiencies in the Nile Delta, it is better to save water earlier in the cycle, mainly due to water quality problems.

Water pollution from intensified industrial, domestic and agricultural activities is a growing problem in the Nile Delta. Large amounts of urban municipal and industrial wastewater and rural domestic wastes discharge into the agricultural drainage network.

Irrigation Improvement Project to Save Water

The Irrigation Improvement Project (IIP) is one of the most important strategies in the policy of MPWWR, introducing quite radical technical and operational changes to farmers' irrigation practices. This ongoing program (scheduled until 2017) aims at increasing efficient use of irrigation water by minimising water losses and spillage into the drainage system and elsewhere. The program is based on the following main concepts:

- Water should be available in the distributary canal all the time, rather than in four days 'on', eight days 'off' rotations to the head, middle and tail thirds of a canal under the traditional system of operation. The required canal capacity remains the same. Flow and levels in the distributary are now controlled by automatic float-controlled gates operated on demand from downstream, rather than by an operated-gate at the upstream end. The automatic gates are surrounded by a locked cage to prevent unauthorised interference. This replaces the traditional rotation system which encouraged farmers to over-irrigate when water was available, leading to wastage and tailend problems.

- Delivery canals are lined as much as possible, reducing losses in the distribution system.

- On-farm water management improvements such as land levelling to improve distribution, and improved irrigation and agronomic practises.

It is estimated that 5 bcm/yr fresh irrigation water could be saved in this way (Abdel-Aziz, 1995). It has to be noted that drainage water will decrease in quantity and quality (increased salinity) as a result of irrigation improvement, which will in the longterm impact the government's drainwater reuse program.

The program requires increased farmer co-operation. Traditionally, water was available in meskas (tertiary canals) whenever the canal was 'on', at a minimum depth below ground of 80cm. From the meskas, water was lifted to the marwas (field channels) by a variety of devices, under the control of individual farmers. The meska head gate would have been under the control of a water guard. Under IIP farmers have to pump water from the distributary into a raised meska, whence it can be supplied under gravity in turn to the marwas, under the control of the meska group. A single, communal pump is sited at the head of each meska, under the control of the IIP meska group. The new arrangement moves farmers' control further up the system, but at the same time introduces a need for coordination of demand by groups at the distributary level. Such meska 'federations' are proposed, but have yet to become part of formal government policy. The original policy of rotation meant that the meskas in any given area might in theory receive water once every 12 days, although in practice farmers would exploit any water available.

Farmers under IIP may elect to pay for the water service by:

- season
- irrigation
- time

However, at present the rates are set such that rice cultivators, who use more water, invariably choose to pay the seasonal charge, which they find more economic. Any incentive to use less water therefore comes not from the size of the water service fee, but from the reduced cost of pumping. Experience in IIP areas shows that in practice the water table falls in response to reduced water usage.

It would be logical to assign to meska leaders the responsibility for both irrigation and drainage, to avoid conflicts between individuals. However, that is not easy owing to the fact that the areas served by irrigation and drainage system are different. Under IIP agreements, farmers are responsible for O&M of the meskas. Newly-constructed subsurface drains are also the responsibility of farmers. Maintenance of drains is more difficult for farmers, particularly when blockages occur (possibly resulting from informal methods of controlled drainage). Also, in the older established areas, farmers see drain maintenance as the responsibility of government. There is now discussion about co-ordinating the functioning of irrigation and drainage groups in so-called meska 'federations'.

Farming Policies, Traditional Practices and Rural Organisations

In 1952 major changes involving the reallocation of land were made to Egyptian agriculture. Over 50% of those now farming received three or four plots each, to grow prescribed crops under rotation, for sale at fixed prices. In 1986 the Government responded to a slowdown in agricultural growth by reforming the price structure. By 1991, owing to population increase and a shift by farmers to horticultural crops, the country was importing two third of its requirements for wheat and vegetable oil.

More recently, the government has lifted controls over the type of crops which farmers can grow and over pricing. Farmers are now free to grow any crop they choose, except rice, which may be sold at the prevailing market prices. Rice helps to reclaim lands affected by salinity, but it also demands a large amount of irrigation water. There are therefore still controls on the locations where rice may be grown and on the total area of production, though they are not strictly enforced. In practice, the area under rice cultivation shows wide variation from the reported area. Some farmers choose to grow rice, although not sanctioned to do so. The fines supposed to discourage such behaviour appear to offer little deterrent. Rice is a staple food in farming families. In poorer areas, up to 66% of production may be retained for domestic consumption.

In rural areas the government is represented in village councils, agricultural co-operatives and the district irrigation office. Village councils are responsible for administrative affairs, health education, services such as roads and electricity. Co-operatives are responsible for providing extension services, agricultural inputs, enforcing quotas (now relaxed), marketing of grain. In practice, farmers are likely to seek help from neighbours, relatives or friends if they want advice on agricultural matters. This tendency means that attempts to introduce new techniques should be made through experienced farmers. The district irrigation office administers rotational supply in the network below the main canal in areas of traditional operation.

Those who traditionally wield influence in rural communities include the Omda (mayor), large landowners, village elders, businessmen, politicians and religious leaders.

According to Mayfield and Naguib (1984), most farmers associate progressive farming techniques with larger and more affluent farmers. In surveys, small farmers commonly mention extra risk as a deterrent to the adoption of new techniques. Unsurprisingly, they are reluctant to take chances when a single poor harvest can jeopardise their entire livelihood.

Owing to traditional inheritance practices, Egypt's farms are becoming smaller: they now cover on average less than 2.5 feddans each (1 ha) (Abu–Zeid and Rady, 1991).

Informal water groups have existed in Egypt for a long period. Traditional "sakia rings" owned, controlled, and operated by water users were organised around lifting points from mesqas. The supply, responsibilities and costs were allocated amongst participants according to defined principles. In recent years, similar practices have been continued in places where diesel pumps have replaced sakias. Long-standing procedures for allocating water within canal commands, termed Arab el Haq, are also still practised, though they are increasingly losing ground to expediency.

Farmers' water use strategies depend on the relative availability of water provided by the irrigation system. In well-supplied areas they respond by allowing excess water to pass to the drainage system. At times of shortage, they may react in a variety of ways - the 'correct' procedure would be to request water from the district irrigation engineer, via the Omda and the cooperative. The engineer would need to seek authorisation for extra releases from his superiors in the Governorate office, so such appeals are unlikely to succeed.

Many tail-end farmers who are poorly served by the irrigation system irrigate by lifting water from drains. Individuals have to pay fuel costs and may also hire a pump for the purpose. Most clearly recognise that crop yields will be lower, since the water is partly saline. It is also likely to be polluted to some extent by domestic and industrial waste.

Institutional Structure

The institutional structure is shown in figure A.

Irrigation Sector

The Irrigation Sector is the agency that is responsible for distributing the country's water resources among different sectors, i.e. municipal, industrial, agricultural and the navigation sector. The irrigation sector is responsible for pre-setting the water management option according to the available water and the target condition of the Ministry of Agriculture and the general economic directions. The Agency is able to permit drainage water to be mixed with fresh water to supplement water shortages.

Egyptian Public Authority for Drainage Projects (EPADP)

In 1973, a Presidential Decree was issued to establish EPADP under the umbrella of the MPWWR to enable the implementation of a wider program. EPADP was given comprehensive responsibility for field drainage works including planning of projects, collection of data, preparation of design, contracting and supervising the installation of subsurface drains, monitoring the impact of drainage, budgeting and operation of project accounts. In addition, EPADP was charged with any remodelling of open drains receiving collected drainage water from subsurface pipe drains and also new pumping stations which may be required on the open drains.

EPADP supports MPWWR's policies in construction, operation, maintenance and rehabilitation of the entire drainage system. Related policies include:

- Construction of subsurface drainage systems for the remaining agricultural land in need of tile drainage.

- Operation and maintenance of the open drains and subsurface drainage system. Serious consideration is given to the involvement of farmers for operation and maintenance at the farm level through a drainage users' association.

- Rehabilitation of systems as necessary.

- Assessment of new drainage options, such as vertical drainage of newly reclaimed and affected areas.

- Cost benefit analysis of alternative ways of expanding the available drainage systems.

- Cost recovery of the installed drainage system by beneficiaries

- Enforcing laws and regulations related to agricultural drainage system and drain water quality.

Drainage Research Institute

The Drainage Research Institute (DRI) was established in 1976 to carry out applied research in the area of drainage engineering to advise EPADP and other departments of the MPWWR on issues related to the drainage system and drainage water. The DRI is one of the twelve member institutes of the National Water Research Centre (NWRC) the research arm of the MPWWR.

Most of the research activities of DRI relate to the establishment of pilot research areas where drainage design criteria, materials and construction methods are tested under different conditions. In addition, performance of systems is studied and evaluated in a number of selected survey areas.

The DRI has also been heavily engaged in research related to reuse of drainage water where a Simulation of Water Management Model has been developed and applied to predict the drainage water quantity and quality as a result of changing water management options.

The DRI is also responsible for design, operation and maintenance of the National Monitoring Drainage Water Network, which covers both the Nile Delta and Fayoum in addition to establishment of data and information systems of drainage water status. This system includes a powerful database management system, a tailor-made geographical information system and, a water quality management model.

Application of Controlled Drainage in the Nile Delta, Egypt

Agricultural areas of the Nile Delta have four attributes that immediately suggest controlled drainage would be appropriate and beneficial:

- High watertables in many locations.
- Extensive subsurface drainage system.
- High drainage flows – constituting a major water loss at field scale.
- Increasing pressures on available water resources.

In fact there have been (and still are) studies into controlled drainage in Egypt, but these have only considered controlled drainage under **rice**, and not addressed potential benefits under dry-foot crops.

In Egypt, rice is grown along with dry-foot crops, creating field water management problems. These are worst in sub-surface drained areas, where drainage systems are designed for the most water-sensitive crops. Rice is not at all sensitive to waterlogging and should be drained as little as possible. The farmers' solution to this problem is to block drains serving rice fields with straw, mud and other debris to maintain standing water in the fields. This practice led to clogging and blockage of drainage systems, and associated maintenance problems. Concern for these issues led to initiation of a water management study of rice fields in 1977-79 (El-Guindi and Risseeuw, 1987).

In the rice fields under study (in the North West of the Delta, near Damanhur) it was found that there was a continuous loss of irrigation water through percolation to the sub-surface drains. This was estimated at 5-10mm/day. To compensate this loss there was a subsequent increase in irrigation water application. In watershort areas this additional water requirement proved critical. The objective was thus to minimise the drainage outflow from rice fields, without flooding dry-foot crops in the surrounding areas. This was found to have the following requirements:

- A modified drainage system. This was developed and tested in experimental fields and pilot areas between 1980 and 1988. A total of 5400ha was constructed with the modified system.
- A crop consolidation plan.

Drainage of rice should be based on the following principles (Abdel Dayem and Ritzema, 1987):

1. The sub-surface drains in rice fields should be operated independently from the rest of the drainage system. This can be achieved by using a sub-collector drain for each crop area.

2. Drainage outflow from cropped fields should be controlled by a closing device installed in the downstream part of the sub-collector. If rice is grown, the closing device should be closed. If other crops are grown the device should be left open allowing unrestricted drainage (unless controlled drainage of other crops is found to be beneficial).

3. The design criteria for pipe drain capacity of a modified layout can be the same as that applied for non-rice areas. In the conventional design, a higher drainage duty of 4mm/day is applied for the calculation of the drain capacity for areas with rice in the crop rotation versus 2mm/day for non-rice areas. With the modified system this increase in capacity is not necessary. Even when rapid drainage is required, this can be achieved by accepting temporary overpressure for short periods.

These concepts were tested out (under rice) in experimental and farmer's fields in the Nile Delta between 1980 and 1986 with the following conclusions (DRI, 1988):

- Introduction of controlled drainage under rice (modified drainage system and gated pipes) could save between one and three billion cubic metres of irrigation water across an area of 1 million feddans in the Nile Delta. This amount is calculated from the difference in drainage rate between the conventional and modified drainage system of 1-3 mm/day over a growing season of 100 days.

- Use of gated pipes solves clogging and other maintenance problems caused by farmer's use of mud and straw to block drains.

- Controlled drainage in the rice fields reduced damage caused to other crops by improperly blocked conventional collector drains.

These results were obtained whilst maintaining crop yields under rice, maize and cotton, and without detrimental soil salt accumulation.

Following these studies little was done in Egypt on controlled drainage until the mid 1990s. By this time there were two developments of direct relevance:

- In 1992 the government abandoned the mandatory crop pattern system, allowing farmers to choose their own crop patterns.

- The government encouraged farmers to have more involvement in on-farm water management and to take responsibility for operation and maintenance of the field irrigation and drainage systems.

This created additional challenges for the modified drainage system and controlled drainage. Farmer's co-operation was now critical to have crop consolidation. It was also felt that farmers' increased involvement in O&M would encourage them to adopt improved practices, once the benefits were proven. Thus, in 1995, the Advisory Panel on Land Drainage agreed that DRI undertake additional studies into controlled drainage of rice with emphasis on farmers' participation and involvement.

Two major studies were carried out (rice seasons 1996 and 1997) in farmer's fields in the Balaktar area of the Western Delta, east of Damanhur City in Beheira Governerate.

For the 1996 study (DRI, 1997), a total area of 125 feddans, farmed by 123 farmers and served by seven sub-collector drains was selected. One of the primary objectives of the study was to assess the practicality of farmers' participation in operation and maintenance of the modified drainage system through collector user groups (CUGs). These CUGs were voluntary groups of farmers formed with the assistance of the agricultural co-operative. Five of the seven CUGs agreed to consolidate cultivation of rice only in the catchment of the sub-collector and operate controlled drainage using gated pipes. The main results and recommendations of the study were:

- The role of the agricultural co-operative in forming CUGs was very positive, as the co-operative was well established and had the trust of farmers.

- The average amount of irrigation water used for rice in modified areas was 4298 m^3/feddan versus 7545 m^3/feddan in conventional drained areas.

- Yield gains (up to 20%) were reported in the modified system areas.

- The savings in irrigation water translated to savings in fuel and time for the farmers which was very attractive to them.

- The farmers were keen to implement the approach in subsequent rice seasons.

The main objectives of the 1997 study (DRI, 1998) were:

- To assess the benefits of controlled drainage in Irrigation Improvement Project (IIP) areas, and see the combined effects of IIP and controlled drainage on water consumption.

- To investigate the involvement of existing Water User Associations (WUAs) in operation of controlled drainage in IIP areas.

- To investigate the need for new cost criteria for rice irrigation per feddan (farmers in IIP areas pay a fixed fee to the WUA), to give incentive to farmers to save water through controlled drainage.

Five sub-collector drains serving a total area of 79 feddans were selected near Balaktar, in an IIP area close to the 1996 study fields. The soil type was heavy clay and rice was normally grown in rotation every three years. Controlled drainage was applied by farmers on two of the sub-collectors, and conventional drainage on three sub-collectors. Conclusions of the study were as follows:

- Making use of existing organisations (such as WUAs) to operate the modified system was better than creating a collector user association.
- The average amount of irrigation water used for rice areas with controlled drainage in IIP areas was 3420.5 m^3/feddan against 5922.6m^3/feddan for rice areas under conventional drainage. This represents a water saving of 42%.
- Because farmers in IIP areas pay a fixed fee to the WUA regardless of crop grown or amount of water applied, the only savings to the farmer from controlled drainage were in time and pumping costs.
- The total irrigation time for one feddan of rice was 22.9 and 15.75 hours for conventional and controlled drainage respectively, a time saving of 32%. As a result farmers in controlled drainage areas finished earlier than others.
- The farmer's cost saving in pumping costs was estimated at LE 10.5 per feddan.
- There was no significant difference in crop productivity and soil salinity between the conventional and controlled drainage areas.
- Watertable depth was comparable between the two areas, suggesting that farmers tried to control the watertable to a certain depth, regardless of the amount of water.

The DRI research outlined above demonstrated the significant potential for controlled drainage (with modified drainage design) to save water under rice. This programme is ongoing, with efforts focusing on mechanisms to implement the approach on a large-scale in rice areas. Although work to date on controlled drainage in Egypt has identified major potential savings in water under rice, no work has been done to assess possible benefits under other crops.

Key points from this work, which are relevant to application of controlled drainage under dry-foot crops, are:

- Water management requirements for rice are very different to other (dry-foot) crops, and controlled drainage strategies will also be different.
- Crop consolidation (rice areas/non-rice areas) along drainage lines was found to be an essential component of controlled drainage management for rice. It is likely to be less of an issue for dry-foot crops, but is an important management aspect to address.
- Controlled drainage (under any crop) will require farmers to work together. Use of existing organisations, such as water user associations (WUAs), is more successful than creating new organisations for the purpose.
- The closing device (gated pipe) designed for the rice studies is equally appropriate for controlled drainage in non-rice areas and should be adopted.
- If savings can be made in fuel and time as a result of controlled drainage the technique is attractive to farmers.
- Water savings and other impacts are likely to be different in IIP areas, and this should be considered.

Conclusions in Summary

Potential

There are strong pressures to improve water use efficiency in irrigated agriculture. Water saving is essential in the next 20 years.

Agricultural areas of the Nile Delta have an extensive subsurface drainage system and high drainage flows constituting a major water loss at field and basin scale. Controlling drainage could thus provide significant water savings. It also offers the possibility of sustaining yields, and thus rural livelihoods, as the quantities of water available to farmers reduce in future years.

The concept of controlling drainage is not alien to Nile Delta farmers. It has been used under rice both unofficially (blocking drains with mud and straw) and as part of DRI experimental trials (using On/Off gated pipes).

Experience of controlled drainage under rice has demonstrated large water savings (up to 40 %) with no reduction in crop yields or increases in soil salinity. Smaller, but still significant savings can be expected if controlled drainage is also applied under dry-foot crops.

Previous work has demonstrated that where savings can be made in fuel and labour inputs, farmers respond by using less water. Controlled drainage is beneficial and attractive to farmers.

The institutional set up in the Delta is good, with farmers receiving support from the extension services and district irrigation offices.

As farm sizes are small, farmers will need to work together to implement controlled drainage. Previous work in Egypt showed use of existing co-operatives such as the WUAs worked much better than attempting to create new ones.

Constraints

Egypt has a fixed allocation of water from the Nile River, its primary source of water. This resource is stretched to the limit due to continued population pressures, an ambitious horizontal expansion programme and demands from other sectors.

The Government of Egypt has introduced major water saving programmes in the agricultural sector. New initiatives including the extension of controlled drainage under rice must complement the ongoing programmes such as the Drainwater Reuse Programme and Irrigation Improvement Project.

Crop consolidation along drainage lines will be necessary in some areas if the full benefits of controlled drainage are to be realised.

Water saved by the introduction of controlled drainage must be used effectively further downstream, possibly by reducing reliance on saline and contaminated drainage flows, if the full benefits are to be realised.

Benefits to farmers must be large enough to ensure take up.

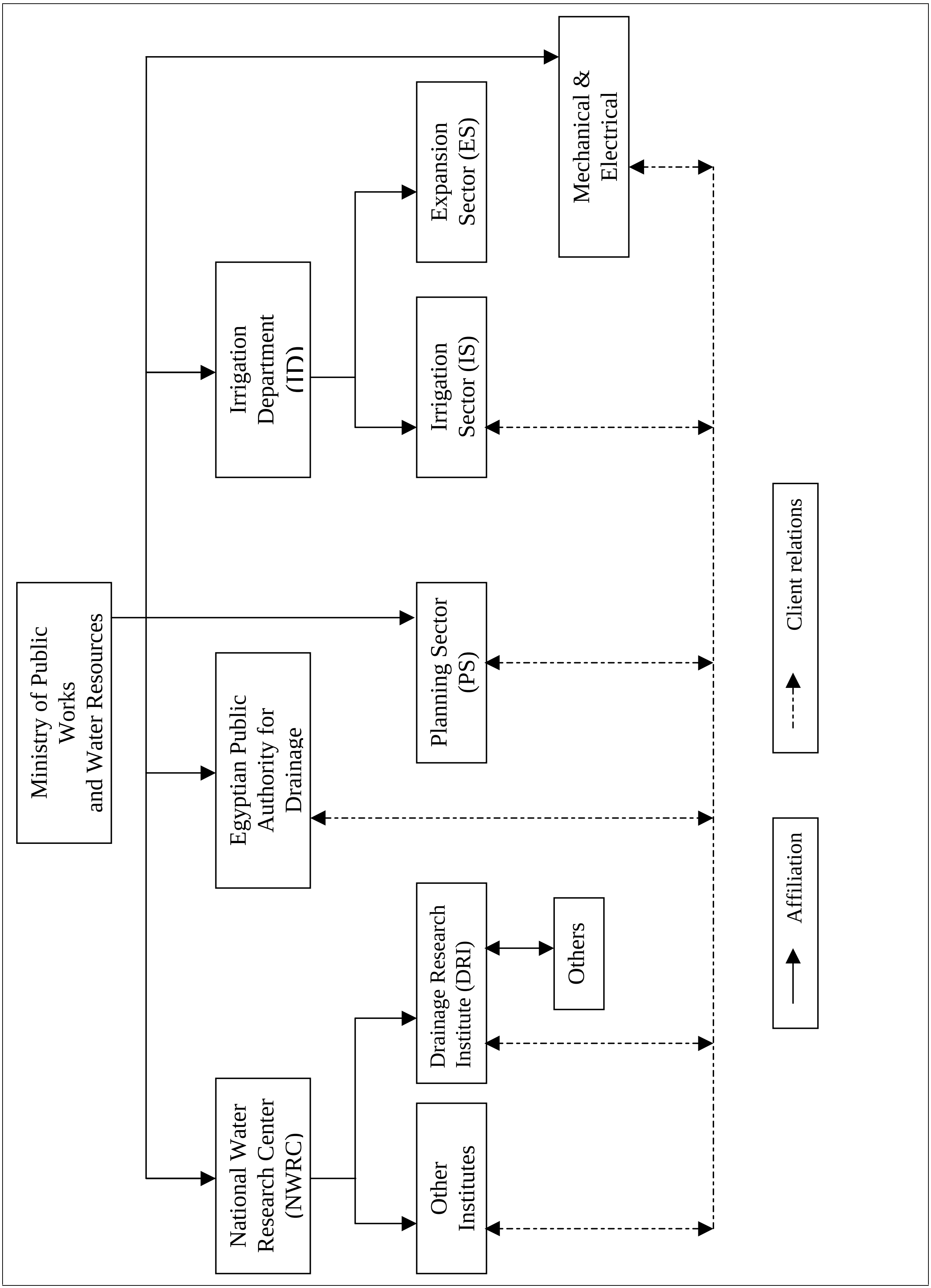

Figure A Institutional structure of the Ministry of Public Works and Water Resources (MPWWR) in Egypt

Appendix 3

Climate data adopted for the demonstration

Appendix 3 Climate data adopted for the demonstration.

Ten year average monthly climate data from Sakha meteorological station, northwest Nile Delta (CLIMWAT, FAO,1993).

Month	Max Temp ^oC	Min Temp ^oC	Humidity %	Wind km/day	Sunshine hours	Solar Radiation $MJ/m^2/day$	ET_o mm/day
January	19.3	6.0	82	112	7.0	12.1	1.8
February	20.5	6.2	82	121	7.7	15.2	2.3
March	23.0	7.8	76	147	8.6	19.3	3.3
April	27.0	10.3	68	130	9.6	23.0	4.4
May	31.1	14.1	59	130	10.6	25.7	5.5
June	32.0	17.0	65	130	11.9	27.9	5.9
July	34.0	19.0	68	112	11.6	27.2	5.9
August	33.5	18.3	75	112	11.3	25.7	5.5
September	32.0	17.6	75	95	10.3	22.3	4.5
October	29.8	15.5	75	86	9.3	17.9	3.4
November	25.8	12.5	76	95	8.0	13.7	2.4
December	21.5	8.2	81	95	6.6	11.0	1.7

Appendix 4

Soils from the Mariut site

Appendix 4 Soils data from the Mariut site.

Soil water characteristic (pF curve) for Mariut soil.

Moisture Content cm^3/cm^3	Head cm
0.3158	0
0.2314	-50
0.2212	-100
0.2141	-150
0.1831	-250
0.1576	-500
0.1314	-1000

Soil salinity profile for Mariut soil.

Depth m	Average EC_e dS/m
0.15	1.789
0.45	1.574
0.75	1.686
1.05	1.844
1.35	1.835
1.65	1.616

Green and Ampt parameters A = 3.60cm^2/hr, B = 1.69cm/hr.
Drainable porosity = 0.15 (FAO 38).
Saturated hydraulic conductivity (K_{sat}) = 8.33cm/hr.

Appendix 5

Irrigation Practice for the demonstration

Appendix 5 Irrigation Practice for the demonstrations.

Typical irrigation schedule for 2-year crop rotation of cotton, wheat, maize and berseem in northwest Nile Delta. (Irrigation amounts applied under the "normal" scenario.)

COTTON	Amount mm	WHEAT	Amount mm
March 14 (pre)	6.9 (22.1)	October 31 (pre/planting)	181.4
March 15 (planting)	83.3	November 1	42.4
April 15	77.2	December 1	47.8
May 15	71.9	December 22	47.8
June 14	50.8	February 1	39.9
June 30	50.8	February 22	39.9
July 12	77.5	March 13	82.8
July 28	77.5	April 5	77.7
August 9	89.4	April 30 (harvest)	
August 25	89.4		
September 11	89.4		
October 9 (harvest)			
Total	764.1 (779.3)	Total	559.7

MAIZE	Amount mm	BERSEEM	Amount mm
May 13 (pre/planting)	52.6	October 13 (pre)	27.4
May 14	66.3	October 15 (planting)	13.2
May 29	66.3	October 31	35.8
June 14	87.9	November 14	35.8
June 29	87.9	November 29	30.2
July 14	87.9	December 20	60.2
July 29	135.6	January 10	81.5
August 10	55.4	January 31	81.5
August 22	55.4	February 21 (cut)	
September 2	55.4		
September 13 (harvest)			
Total	750.7	Total	365.6

Irrigation amounts applied under the “summer water shortage” scenario.

COTTON	Amount mm	WHEAT	Amount mm
March 14 (pre)	6.9 (22.1)	October 31 (pre/planting)	181.4
March 15 (planting)	83.3	November 1	42.4
April 15	77.2	December 1	47.8
May 15	71.9	December 22	47.8
June 14	50.8	February 1	39.9
June 30	50.8	February 22	39.9
		March 13	82.8
July 28	77.5	April 5	77.7
August 9	89.4	April 30 (harvest)	
August 25	89.4		
September 11	89.4		
October 9 (harvest)			
Total	686.6 (701.8)	Total	559.7

MAIZE	Amount mm	BERSEEM	Amount mm
May 13 (pre/planting)	52.6	October 13 (pre)	27.4
May 14	66.3	October 15 (planting)	13.2
May 29	66.3	October 31	35.8
June 14	87.9	November 14	35.8
June 29	87.9	November 29	30.2
		December 20	60.2
July 29	135.6	January 10	81.5
August 10	55.4	January 31	81.5
August 22	55.4	February 21 (cut)	
September 2	55.4		
September 13 (harvest)			
Total	662.7	Total	365.6

Irrigation amounts applied under the "winter water shortage" scenario.

COTTON	Amount mm	WHEAT	Amount mm
March 14 (pre)	6.9 (22.1)	October 31 (pre/planting)	181.4
March 15 (planting)	83.3	November 1	42.4
April 15	77.2	December 1	47.8
May 15	71.9		
June 14	50.8	February 1	39.9
June 30	50.8	February 22	39.9
July 12	77.5	March 13	82.8
July 28	77.5	April 5	77.7
August 9	89.4	April 30 (harvest)	
August 25	89.4		
September 11	89.4		
October 9 (harvest)			
Total	764.1 (779.3)	Total	511.8

MAIZE	Amount mm	BERSEEM	Amount mm
May 13 (pre/planting)	52.6	October 13 (pre)	27.4
May 14	66.3	October 15 (planting)	13.2
May 29	66.3	October 31	35.8
June 14	87.9	November 14	35.8
June 29	87.9	November 29	30.2
July 14	87.9		
July 29	135.6		
August 10	55.4	January 31	81.5
August 22	55.4	February 21 (cut)	
September 2	55.4		
September 13 (harvest)			
Total	750.7	Total	224.1

Irrigation amounts applied under the “increased summer water shortage” scenario.

COTTON	Amount mm	WHEAT	Amount mm
March 14 (pre)	6.9 (22.1)	October 31 (pre/planting)	181.4
March 15 (planting)	83.3	November 1	42.4
April 15	77.2	December 1	47.8
May 15	71.9	December 22	47.8
June 14	50.8	February 1	39.9
June 30	50.8	February 22	39.9
		March 13	82.8
July 28	77.5	April 5	77.7
August 9	89.4	April 30 (harvest)	
September 11	89.4		
October 9 (harvest)			
Total	598.7 (613.9)	Total	559.7

MAIZE	Amount mm	BERSEEM	Amount mm
May 13 (pre/planting)	52.6	October 13 (pre)	27.4
May 14	66.3	October 15 (planting)	13.2
May 29	66.3	October 31	35.8
June 14	87.9	November 14	35.8
June 29	87.9	November 29	30.2
		December 20	60.2
July 29	135.6	January 10	81.5
August 10	55.4	January 31	81.5
		February 21 (cut)	
September 2	55.4		
September 13 (harvest)			
Total	607.3	Total	365.6

Irrigation amounts applied under the "increased winter water shortage" scenario.

COTTON	Amount mm	WHEAT	Amount mm
March 14 (pre)	6.9 (22.1)	October 31 (pre/planting)	181.4
March 15 (planting)	83.3	November 1	42.4
April 15	77.2	December 1	47.8
May 15	71.9		
June 14	50.8	February 1	39.9
June 30	50.8	February 22	39.9
July 12	77.5		
July 28	77.5	April 5	77.7
August 9	89.4	April 30 (harvest)	
August 25	89.4		
September 11	89.4		
October 9 (harvest)			
Total	764.1 (779.3)	Total	429.1

MAIZE	Amount mm	BERSEEM	Amount mm
May 13 (pre/planting)	52.6	October 13 (pre)	27.4
May 14	66.3	October 15 (planting)	13.2
May 29	66.3	October 31	35.8
June 14	87.9	November 14	35.8
June 29	87.9	November 29	30.2
July 14	87.9		
July 29	135.6		
August 10	55.4		
August 22	55.4	February 21 (cut)	
September 2	55.4		
September 13 (harvest)			
Total	750.7	Total	142.4

Irrigation amounts applied under the "year-round water shortage" scenario.

COTTON	Amount mm	WHEAT	Amount mm
March 14 (pre)	6.9 (22.1)	October 31 (pre/planting)	181.4
March 15 (planting)	83.3	November 1	42.4
April 15	77.2	December 1	47.8
May 15	71.9		
June 14	50.8	February 1	39.9
June 30	50.8	February 22	39.9
July 28	77.5	April 5	77.7
August 9	89.4	April 30 (harvest)	
September 11	89.4		
October 9 (harvest)			
Total	598.7 (613.9)	Total	429.1

MAIZE	Amount mm	BERSEEM	Amount mm
May 13 (pre/planting)	52.6	October 13 (pre)	27.4
May 14	66.3	October 15 (planting)	13.2
May 29	66.3	October 31	35.8
June 14	87.9	November 14	35.8
June 29	87.9	November 29	30.2
July 29	135.6		
August 10	55.4		
		February 21 (cut)	
September 2	55.4		
September 13 (harvest)			
Total	607.3	Total	142.4

Appendix 6

Crop data for simulations

Appendix 6 Crop data for simulations.

Adopted crop rooting depths. (A “rooting depth” of 3cm is adopted in fallow periods.)

Cotton			Wheat			Maize			Berseem		
Month	Day	Depth cm	Month	Day	Depth cm	Month	Day	Depth cm	Month	Day	Depth cm
Jan	1	3	Jan	1	30	Jan	1	3	Jan	1	42
Mar	1	3	Mar	20	42	May	20	3	Jan	13	45
Mar	27	22	Mar	31	30	June	9	12	Jan	14	40
June	8	55	April	30	15	June	24	15	Feb	21	45
July	25	76	May	1	3	July	8	25	Feb	22	3
Aug	28	63	June	18	3	July	26	30	Nov	15	27
Oct	27	51	Nov	2	3	Aug	22	30	Dec	15	37
Oct	15	3	Dec	17	14	Sept	8	20	Dec	31	42
Dec	31	3	Dec	31	30	Sept	15	3			
						Oct	20	3			
						Dec	31	3			

Crop yield reductions due to salinity – adopted threshold levels and slopes.

CROP	Cotton	Wheat	Maize	Berseem
Salinity threshold dS/m	7700	6000	1700	6000
Slope	0.0052	0.0071	0.012	0.02

Appendix 7a

Simulation results tables from the demonstration

HR Wallingford

Normal (current situation)- 2 Year Irrigation Water Application = 2455.3 mm

Irrigation File	File1

ALL_WIN_PRE(20years)

Criteria		Controlled Drainage Strategy										
		1CONV	1CD1	1CD2	1CD3	1CD4	1CD5	1CD6	1CD7	1CD8	1CD9	1CD10
Average Yield %	**Crop 1**	95.7	100	100	95.7	95.7	95.7	95.7	95.7	95.7	100	100
	Crop 2	98.5	91.1	98.5	100	100	98.5	98.5	98.5	98.5	100	100
	Crop 3	97.6	97.6	97.6	97.6	97.6	90.5	99.7	97.6	97.6	97.6	99.7
	Crop 4	100	100	100	100	100	100	100	99.1	99.1	100	100
Minimum Yield in One Season %	**Crop 1**	95.7	100	100	95.7	95.7	95.7	95.7	95.7	95.7	100	100
	Crop 2	98.4	90.9	98.4	100	100	98.4	98.4	98.4	98.4	100	100
	Crop 3	97.4	97.4	97.4	97.4	97.4	90.5	99.7	97.4	97.4	97.4	99.7
	Crop 4	100	100	100	100	100	100	100	99.1	99.1	100	100
Irrigation Water Use mm	**Crop 1**	779.3	779.3	779.3	779.3	779.3	779.3	779.3	779.3	779.3	779.3	779.3
	Crop 2	559.6	559.6	559.6	559.6	559.6	559.6	559.6	559.6	559.6	559.6	559.6
	Crop 3	750.6	750.6	750.6	750.6	750.6	750.6	750.6	750.6	750.6	750.6	750.6
	Crop 4	365.8	365.8	365.8	365.8	365.8	365.8	365.8	365.8	365.8	365.8	365.8
Average Soil Salinity ppm	**Penultimate**	648	518	630	573	631	1290	1013	812	765	565	795
	Final	648	521	633	577	630	1278	1012	813	766	571	798
	Final/initial	0.64	0.51	0.62	0.57	0.62	1.26	1	0.8	0.76	0.56	0.79
	Final/penult	1	1	1	1.01	1	0.99	1	1	1	1.01	1
Drainwater (Whole model run) mm	**Total Flow**	559	523	525	545	546	544	544	559	559	511	495
Farmer Costs LE / fed	**Crop 1**	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7
	Crop 2	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
	Crop 3	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2
	Crop 4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
	Total	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3

Moderate Summer Water Shortage - 2 Year Irrigation Water Application = 2290 mm

Rainfall File	File2

ALL_1WIN_PRE(20years)

Criteria		Controlled Drainage Strategy									
		2CONV	2CD1	2CD2	2CD3	2CD4	2CD5	2CD6	2CD7	2CD8	2CD9
Average Yield %	**Crop 1**	69.5	100	85.2	69.5	69.5	69.5	69.5	69.5	69.5	100
	Crop 2	98.5	91.1	98.5	100	100	98.5	98.5	98.5	98.5	89.2
	Crop 3	71.1	71.1	71.1	71.1	71.1	96.8	82.1	71.1	71.1	95.8
	Crop 4	100	100	100	100	100	100	100	99.1	100	100
Minimum Yield in One Season %	**Crop 1**	69.5	99.9	85.2	69.5	69.5	69.5	69.5	69.5	69.5	99.9
	Crop 2	98.4	90.9	98.4	100	100	98.4	98.4	98.4	98.4	89.2
	Crop 3	70.9	70.9	70.9	70.9	70.9	96.8	82.1	70.9	70.9	95.8
	Crop 4	100	100	100	100	100	100	100	99.1	100	100
Irrigation Water Use mm	**Crop 1**	701.8	701.8	701.8	701.8	701.8	701.8	701.8	701.8	701.8	701.8
	Crop 2	559.6	559.6	559.6	559.6	559.6	559.6	559.6	559.6	559.6	559.6
	Crop 3	662.7	662.7	662.7	662.7	662.7	662.7	662.7	662.7	662.7	662.7
	Crop 4	365.8	365.8	365.8	365.8	365.8	365.8	365.8	365.8	365.8	365.8
Average Soil Salinity ppm	**Penultimate**	634	513	622	557	612	1049	1109	747	3607	588
	Final	639	514	624	562	615	953	1170	756	3674	599
	Final/initial	0.63	0.51	0.62	0.55	0.61	0.94	1.15	0.75	3.62	0.59
	Final/penult	1.01	1	1	1.01	1.01	0.91	1.06	1.01	1.02	1.02
Drainwater (Whole model run) mm	**Total Flow**	540	425	497	525	527	455	497	539	363	327
Farmer Costs LE / fed	**Crop 1**	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4
	Crop 2	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
	Crop 3	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7
	Crop 4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
	Total	40.4	40.4	40.4	40.4	40.4	40.4	40.4	40.4	40.4	40.4

HR Wallingford

Moderate Winter Water Shortage - 2 Year Irrigation Water Application = 2265.8 mm

Rainfall File	File 3

ALL_2WIN_PRE(20years)

Criteria		Controlled Drainage Strategy									
		3CONV	3CD1	3CD2	3CD3	3CD4	3CD5	3CD6	3CD7	3CD8	3CD9
Average Yield %	Crop 1	95.6	100	100	95.6	98.2	95.6	95.6	95.7	95.7	100
	Crop 2	94.5	87.5	94.6	100	97.7	94.5	94.5	94.5	94.5	100
	Crop 3	97.6	97.6	97.6	97.6	98.8	88.9	88.9	97.6	97.6	97.6
	Crop 4	100	100	100	100	100	100	100	99.9	100	100
Minimum Yield in One Season %	Crop 1	95.6	100	100	95.6	98.2	95.6	95.6	95.7	95.7	100
	Crop 2	94.3	87.2	94.8	100	97.7	94.3	94.3	94.3	94.3	100
	Crop 3	97.4	97.4	97.4	97.4	98.8	86.5	86.5	97.4	97.4	97.4
	Crop 4	100	100	100	100	100	100	100	99.9	100	100
Irrigation Water Use mm	Crop 1	779.3	779.3	779.3	779.3	779.3	779.3	779.3	779.3	779.3	779.3
	Crop 2	511.8	511.8	511.8	511.8	511.8	511.8	511.8	511.8	511.8	511.8
	Crop 3	750.6	750.6	750.6	750.6	750.6	750.6	750.6	750.6	750.6	750.6
	Crop 4	224.1	224.1	224.1	224.1	224.1	224.1	224.1	224.1	224.1	224.1
Average Soil Salinity ppm	Penultimate	907	665	557	731	1246	2473	1825	765	852	690
	Final	895	665	562	737	1295	2491	1821	771	861	694
	Final/initial	0.88	0.66	0.55	0.73	1.28	2.46	1.8	0.76	0.85	0.68
	Final/penult	0.99	1	1.01	1.01	1.04	1.01	1	1.01	1.01	1.01
Drainwater (Whole model run) mm	Total Salt Total Flow Ratio	376	339	341	356	346	360	360	375	375	321
Farmer Costs LE / fed	Crop 1	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7
	Crop 2	9	9	9	9	9	9	9	9	9	9
	Crop 3	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2
	Crop 4	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
	Total	39.9	39.9	39.9	39.9	39.9	39.9	39.9	39.9	39.9	39.9

Increased Summer Water Shortage - 2 Year Irrigation Water Application = 2145 mm

Rainfall File	File 4

ALL_4WIN_PRE(20years)

Criteria		Controlled Drainage Strategy									
		4CONV	4CD1	4CD2	4CD3	4CD4	4CD5	4CD6	4CD7	4CD8	4CD9
Average Yield %	**Crop 1**	42.8	100	59.3	42.8	42.8	42.8	42.8	42.8	42.8	100
	Crop 2	98.5	91.3	98.5	100	100	98.5	98.5	98.5	98.5	91.3
	Crop 3	50.1	50.1	50.1	50.1	50.1	96.8	75.2	50.1	50.1	96.8
	Crop 4	100	100	100	100	100	100	100	99.1	100	100
Minimum Yield in One Season %	**Crop 1**	42.8	100	59.3	42.8	42.8	42.8	42.8	42.8	42.8	100
	Crop 2	98.4	91.2	98.4	100	100	98.4	98.4	98.4	98.4	91.2
	Crop 3	48.9	48.9	48.9	48.9	48.9	96.8	74.4	48.9	48.9	96.8
	Crop 4	100	100	100	100	100	100	100	99.1	100	100
Irrigation Water Use mm	**Crop 1**	612.4	612.4	612.4	612.4	612.4	612.4	612.4	612.4	612.4	612.4
	Crop 2	559.6	559.6	559.6	559.6	559.6	559.6	559.6	559.6	559.6	559.6
	Crop 3	607.3	607.3	607.3	607.3	607.3	607.3	607.3	607.3	607.3	607.3
	Crop 4	365.8	365.8	365.8	365.8	365.8	365.8	365.8	365.8	365.8	365.8
Average Soil Salinity ppm	**Penultimate**	629	543	637	551	608	906	943	746	729	817
	Final	637	549	649	558	615	897	951	755	734	820
	Final/initial	0.63	0.54	0.64	0.55	0.61	0.88	0.94	0.74	0.72	0.81
	Final/penult	1.01	1.01	1.02	1.01	1.01	0.99	1.01	1.01	1.01	1
Drainwater (Whole model run) mm	**Total Salt Total Flow Ratio**	521	318	479	507	508	360	398	521	521	195
Farmer Costs LE / fed	**Crop 1**	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8
	Crop 2	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
	Crop 3	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7
	Crop 4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
	Total	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8

Increased Winter Water Shortage - 2 Year Irrigation Water Application = 2101.5 mm

Rainfall File	file 5

ALL-5WIN_PRE(20years)

Criteria		Controlled Drainage Strategy										
		5CONV	5CD1	5CD2	5CD3	5CD4	5CD5	5CD6	5CD7	5CD8	5CD9	5CD10
Average Yield %	Crop 1	94.6	100	100	94.6	94.6	94.6	94.6	95.7	95.7	95.7	100
	Crop 2	64.6	59.9	64.7	100	94	64.6	64.6	64.6	64.6	100	100
	Crop 3	97.6	97.6	97.6	97.6	97.6	90.9	90.9	97.6	97.6	97.6	97.6
	Crop 4	54.6	54.6	54.6	54.6	54.6	54.6	54.6	100	100	100	100
Minimum Yield in One Season %	Crop 1	94.5	99.9	100	94.5	94.5	94.5	94.5	95.7	95.7	95.7	100
	Crop 2	64.4	59.7	64.5	100	93.6	64.4	64.4	64.4	64.4	100	100
	Crop 3	97.4	97.4	97.4	97.4	97.4	90.9	90.9	97.4	97.4	97.4	97.4
	Crop 4	54.6	54.6	54.6	54.6	54.6	54.6	54.6	100	100	100	100
Irrigation Water Use mm	Crop 1	779.3	779.3	779.3	779.3	779.3	779.3	779.3	779.3	779.3	779.3	779.3
	Crop 2	429	429	429	429	429	429	429	429	429	429	429
	Crop 3	750.6	750.6	750.6	750.6	750.6	750.6	750.6	750.6	750.6	750.6	750.6
	Crop 4	142.6	142.6	142.6	142.6	142.6	142.6	142.6	142.6	142.6	142.6	142.6
Average Soil Salinity ppm	Penultimate	1098	679	896	800	915	2372	2027	865	937	827	839
	Final	1095	682	901	803	911	2387	1950	866	947	834	847
	Final/initial	1.08	0.67	0.89	0.79	0.9	2.35	1.92	0.85	0.93	0.82	0.83
	Final/penult	1	1.01	1.01	1	1	1.01	0.96	1	1.01	1.01	1.01
Drainwater (Whole model run) mm	Total Salt Total Flow Ratio	285	245	247	211	238	269	269	265	265	190	156
Farmer Costs LE / fed	Crop 1	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7
	Crop 2	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
	Crop 3	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2
	Crop 4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	Total	37	37	37	37	37	37	37	37	37	37	37

Year Round Water Shortage – 2 Year Irrigation Water Application = 1791.3 mm

Rainfall File	File 6

ALL_6WIN_PRE(20years).rai

Criteria		6CONV	6CD1	6CD2	6CD3	6CD4	6CD5	6CD6	6CD7	6CD8
		Controlled Drainage Strategy								
Average Yield %	Crop 1	41.6	100	58.6	41.6	41.6	41.7	41.7	42.8	42.8
	Crop 2	64.6	60	64.7	100	94	64.6	64.6	64.6	64.6
	Crop 3	50.1	50.1	50.1	50.1	50.1	97.1	75.2	50.1	50.1
	Crop 4	54.6	54.6	54.6	54.6	54.6	54.6	54.6	100	100
Minimum Yield in One Season %	Crop 1	41.5	100	58.5	41.5	41.5	41.5	41.5	42.8	42.8
	Crop 2	64.4	59.9	64.4	100	93.6	64.4	64.6	64.4	64.4
	Crop 3	48.9	48.9	48.9	48.9	48.9	96.7	74.4	48.9	48.9
	Crop 4	54.6	54.6	54.6	54.6	54.6	54.6	54.6	100	100
Irrigation Water Use mm	Crop 1	612.4	612.4	612.4	612.4	612.4	612.4	612.4	612.4	612.4
	Crop 2	429	429	429	429	429	429	429	429	429
	Crop 3	607.3	607.3	607.3	607.3	607.3	607.3	607.3	607.3	607.3
	Crop 4	142.6	142.6	142.6	142.6	142.6	142.6	142.6	142.6	142.6
Average Soil Salinity ppm	Penultimate	1085	863	957	840	964	1693	1793	859	896
	Final	1099	869	963	859	965	1705	1855	858	903
	Final/initial	1.08	0.86	0.95	0.85	0.95	1.68	1.83	0.85	0.89
	Final/penult	1.01	1.01	1.01	1.02	1	1.01	1.03	1	1.01
Drainwater (Whole model run) mm	Total Salt Total Flow Ratio	247	41	203	173	200	124	185	227	227
Farmer Costs LE / fed	Crop 1	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8
	Crop 2	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
	Crop 3	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7
	Crop 4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	Total	31.6	31.6	31.6	31.6	31.6	31.6	31.6	31.6	31.6

Appendix 7b

7b Limits and resulting evaluation tables from the demonstration

Table 1 : Use of Screening Tool to Design Water Saving Controlled Drainage Strategies

Criteria		Limiting Values Lower	Limiting Values Upper
Average Yield %	Crop 1	95	100
	Crop 2	95	100
	Crop 3	95	100
	Crop 4	95	100
Minimum Yield in One Season %	Crop 1	90	100
	Crop 2	90	100
	Crop 3	90	100
	Crop 4	90	100
Irrigation Water Use mm	Crop 1		779.3
	Crop 2		559.6
	Crop 3		750.6
	Crop 4		365.8
Average Soil Salinity ppm	Penultimate		
	Final		
	Final/initial		1
	Final/penult		
Drainwater (Whole model run) mm	Total Flow		559
Farmer Costs LE / fed	Crop 1		13.7
	Crop 2		9.8
	Crop 3		13.2
	Crop 4		6.4
	Total		43.2

			Controlled Drainage Strategies Passing Limits			
			3CD3	3CD9	5CD9	5CD10
Criteria	Rainfall File		File 3	File 3	File 5	File 5
	Average Yield %	Crop 1	95.6	100	95.7	100
		Crop 2	100	100	100	100
		Crop 3	97.6	97.6	97.6	97.6
		Crop 4	100	100	100	100
	Minimum Yield in One Season %	Crop 1	95.6	100	95.7	100
		Crop 2	100	100	100	100
		Crop 3	97.4	97.4	97.4	97.4
		Crop 4	100	100	100	100
	Irrigation Water Use mm	Crop 1	779.3	779.3	779.3	779.3
		Crop 2	511.8	511.8	429	429
		Crop 3	750.6	750.6	750.6	750.6
		Crop 4	224.1	224.1	142.6	142.6
	Average Soil Salinity ppm	Penultimate	731	690	827	839
		Final	737	694	834	847
		Final/initial	0.73	0.68	0.82	0.83
		Final/penult	1.01	1.01	1.01	1.01
	Drainwater (Whole model run) mm	Total Flow	356	321	190	156
	Farmer Costs LE / fed	Crop 1	13.7	13.7	13.7	13.7
		Crop 2	9	9	7.6	7.6
		Crop 3	13.2	13.2	13.2	13.2
		Crop 4	3.9	3.9	2.5	2.5
		Total	39.9	39.9	37	37

Table 2 : Use of tool to design CD Strategies that improve crop yields in times of Moderate Summer Water Shortage

Limits Table

Criteria		Limiting Values: Lower	Limiting Values: Upper
Average Yield %	Crop 1	69.5	100
	Crop 2	98.5	100
	Crop 3	71.1	100
	Crop 4	100	100
Minimum Yield in One Season %	Crop 1	69.5	100
	Crop 2	98.4	100
	Crop 3	70.9	100
	Crop 4	100	100
Irrigation Water Use mm	Crop 1		701.8
	Crop 2		559.6
	Crop 3		662.7
	Crop 4		365.8
Average Soil Salinity ppm	Penultimate		
	Final		
	Final/initial		1
	Final/penult		
Drainwater (Whole model run) mm	Total Flow	1	540
Farmer Costs LE / fed	Crop 1		12.4
	Crop 2		9.8
	Crop 3		11.7
	Crop 4		6.4
	Total		40.4

Evaluation Table

Criteria		Controlled Drainage Strategies Passing Limits: 2CONV	2CD2	2CD3	2CD4	2CD5
Rainfall File		File 2	File 2	File 2	File 2	File 2
Average Yield %	Crop 1	69.5	85.2	69.5	69.5	69.5
	Crop 2	98.5	98.5	100	100	98.5
	Crop 3	71.1	71.1	71.1	71.1	96.8
	Crop 4	100	100	100	100	100
Minimum Yield in One Season %	Crop 1	69.5	85.2	69.5	69.5	69.5
	Crop 2	98.4	98.4	100	100	98.4
	Crop 3	70.9	70.9	70.9	70.9	96.8
	Crop 4	100	100	100	100	100
Irrigation Water Use mm	Crop 1	701.8	701.8	701.8	701.8	701.8
	Crop 2	559.6	559.6	559.6	559.6	559.6
	Crop 3	662.7	662.7	662.7	662.7	662.7
	Crop 4	365.8	365.8	365.8	365.8	365.8
Average Soil Salinity ppm	Penultimate	634	622	557	612	1049
	Final	639	624	562	615	953
	Final/initial	0.63	0.62	0.55	0.61	0.94
	Final/penult	1.01	1	1.01	1.01	0.91
Drainwater (Whole model run) mm	Total Flow	540	497	525	527	455
Farmer Costs LE / fed	Crop 1	12.4	12.4	12.4	12.4	12.4
	Crop 2	9.8	9.8	9.8	9.8	9.8
	Crop 3	11.7	11.7	11.7	11.7	11.7
	Crop 4	6.4	6.4	6.4	6.4	6.4
	Total	40.4	40.4	40.4	40.4	40.4

Table 3 : Moderate Winter Water Shortage - CD Strategies to increase yields

Limits Table

Criteria		Limiting Values Lower	Limiting Values Upper
Average Yield %	Crop 1	95.6	100
	Crop 2	94.5	100
	Crop 3	97.6	100
	Crop 4	100	100
Minimum Yield in One Season %	Crop 1	95.6	100
	Crop 2	94.3	100
	Crop 3	97.4	100
	Crop 4	100	100
Irrigation Water Use mm	Crop 1		779.3
	Crop 2		511.8
	Crop 3		750.6
	Crop 4		224.1
Average Soil Salinity ppm	Penultimate		
	Final		
	Final/initial		1
	Final/penult		
Drainwater (Whole model run) mm	Total Flow		
Farmer Costs LE / fed	Crop 1		13.7
	Crop 2		9
	Crop 3		13.2
	Crop 4		3.9
	Total		39.9

Evaluation Table

Criteria			Controlled Drainage Strategies Passing Limits				
			3CONV	3CD2	3CD3	3CD8	3CD9
	Rainfall File		File 3	File 3	File 3	File 3	File 3
	Average Yield %	Crop 1	95.6	100	95.6	95.7	100
		Crop 2	94.5	94.6	100	94.5	100
		Crop 3	97.6	97.6	97.6	97.6	97.6
		Crop 4	100	100	100	100	100
	Minimum Yield in One Season %	Crop 1	95.6	100	95.6	95.7	100
		Crop 2	94.3	94.8	100	94.3	100
		Crop 3	97.4	97.4	97.4	97.4	97.4
		Crop 4	100	100	100	100	100
	Irrigation Water Use mm	Crop 1	779.3	779.3	779.3	779.3	779.3
		Crop 2	511.8	511.8	511.8	511.8	511.8
		Crop 3	750.6	750.6	750.6	750.6	750.6
		Crop 4	224.1	224.1	224.1	224.1	224.1
	Average Soil Salinity ppm	Penultimate	907	557	731	852	690
		Final	895	562	737	861	694
		Final/initial	0.88	0.55	0.73	0.85	0.68
		Final/penult	0.99	1.01	1.01	1.01	1.01
	Drainwater (Whole model run) mm	Total Flow	376	341	356	375	321
	Farmer Costs LE / fed	Crop 1	13.7	13.7	13.7	13.7	13.7
		Crop 2	9	9	9	9	9
		Crop 3	13.2	13.2	13.2	13.2	13.2
		Crop 4	3.9	3.9	3.9	3.9	3.9
		Total	39.9	39.9	39.9	39.9	39.9

Table 4 : Increased Summer Water Shortage- CD Strategies to Increase Yields

Limits Table

Criteria		Limiting Values Lower	Limiting Values Upper
Average Yield %	Crop 1	42.8	100
	Crop 2	98.5	100
	Crop 3	50.1	100
	Crop 4	100	100
Minimum Yield in One Season %	Crop 1	42.8	100
	Crop 2	98.4	100
	Crop 3	48.9	100
	Crop 4	100	100
Irrigation Water Use mm	Crop 1		612.4
	Crop 2		559.6
	Crop 3		607.3
	Crop 4		365.8
Average Soil Salinity ppm	Penultimate		
	Final		
	Final/initial		1
	Final/penult		
Drainwater (Whole model run) mm	Total Flow		
Farmer Costs LE / fed	Crop 1		10.8
	Crop 2		9.8
	Crop 3		10.7
	Crop 4		6.4
			37.8

Evaluation Table

Criteria		Controlled Drainage Strategies Passing Limits: 4CONV	4CD2	4CD3	4CD4	4CD5	4CD6	4CD8
Rainfall File		File 4	File 4	File 4	File 4	File 4	File 4	File 4
Average Yield %	Crop 1	42.8	59.4	42.8	42.8	42.8	42.8	42.8
	Crop 2	98.5	98.5	100	100	98.5	98.5	98.5
	Crop 3	50.1	50.1	50.1	50.1	96.8	75.2	50.1
	Crop 4	100	100	100	100	100	100	100
Minimum Yield in One Season %	Crop 1	42.8	59.3	42.8	42.8	42.8	42.8	42.8
	Crop 2	98.4	98.4	100	100	98.4	98.4	98.4
	Crop 3	48.9	48.9	48.9	48.9	96.8	74.4	48.9
	Crop 4	100	100	100	100	100	100	100
Irrigation Water Use mm	Crop 1	612.4	612.4	612.4	612.4	612.4	612.4	612.4
	Crop 2	559.6	559.6	559.6	559.6	559.6	559.6	559.6
	Crop 3	607.3	607.3	607.3	607.3	607.3	607.3	607.3
	Crop 4	365.8	365.8	365.8	365.8	365.8	365.8	365.8
Average Soil Salinity ppm	Penultimate	629	637	551	608	906	943	729
	Final	637	649	558	615	897	951	734
	Final/initial	0.63	0.64	0.55	0.61	0.88	0.94	0.72
	Final/penult	1.01	1.02	1.01	1.01	0.99	1.01	1.01
Drainwater (Whole model run) mm	Total Flow	521	479	507	508	360	398	521
Farmer Costs LE / fed	Crop 1	10.8	10.8	10.8	10.8	10.8	10.8	10.8
	Crop 2	9.8	9.8	9.8	9.8	9.8	9.8	9.8
	Crop 3	10.7	10.7	10.7	10.7	10.7	10.7	10.7
	Crop 4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
		37.8	37.8	37.8	37.8	37.8	37.8	37.8

Table 5 : Increased Winter Water Shortage - CD Strategies to increase yields

Limits Table

Criteria		Limiting Value Lower	Limiting Value Upper
Average Yield %	Crop 1	94.6	100
	Crop 2	64.6	100
	Crop 3	97.6	100
	Crop 4	54.6	100
Minimum Yield in One Season %	Crop 1	94.5	100
	Crop 2	64.4	100
	Crop 3	97.4	100
	Crop 4	54.6	100
Irrigation Water Use mm	Crop 1		779.3
	Crop 2		429
	Crop 3		750.6
	Crop 4		142.6
Average Soil Salinity ppm	Penultimate		
	Final		
	Final/initial		1.08
	Final/penult		
Drainwater (Whole model run) mm	Total Flow		
Farmer Costs LE / fed	Crop 1		13.7
	Crop 2		7.6
	Crop 3		13.2
	Crop 4		2.5
			37

Evaluation Table

Criteria		Controlled Drainage Strategies Passing Limits: 5CONV	5CD2	5CD3	5CD4	5CD7	5CD8	5CD9	5CD10
Rainfall File		File 5	File 5	File 5	File 5	File 5	File 5	File 5	File 5
Average Yield %	Crop 1	94.6	100	94.6	94.6	95.7	95.7	95.7	100
	Crop 2	64.6	64.7	100	94	64.6	64.6	100	100
	Crop 3	97.6	97.6	97.6	97.6	97.6	97.6	97.6	97.6
	Crop 4	54.6	54.6	54.6	54.6	100	100	100	100
Minimum Yield in One Season %	Crop 1	94.5	100	94.5	94.5	95.7	95.7	95.7	100
	Crop 2	64.4	64.5	100	93.6	64.4	64.4	100	100
	Crop 3	97.4	97.4	97.4	97.4	97.4	97.4	97.4	97.4
	Crop 4	54.6	54.6	54.6	54.6	100	100	100	100
Irrigation Water Use mm	Crop 1	779.3	779.3	779.3	779.3	779.3	779.3	779.3	779.3
	Crop 2	429	429	429	429	429	429	429	429
	Crop 3	750.6	750.6	750.6	750.6	750.6	750.6	750.6	750.6
	Crop 4	142.6	142.6	142.6	142.6	142.6	142.6	142.6	142.6
Average Soil Salinity ppm	Penultimate	1098	896	800	915	865	937	827	839
	Final	1095	901	803	911	866	947	834	847
	Final/initial	1.08	0.89	0.79	0.9	0.85	0.93	0.82	0.83
	Final/penult	1	1.01	1	1	1	1.01	1.01	1.01
Drainwater (Whole model run) mm	Total Flow	285	247	211	238	265	265	190	156
Farmer Costs LE / fed	Crop 1	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7
	Crop 2	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
	Crop 3	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2
	Crop 4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
		37	37	37	37	37	37	37	37

Table 6 : Year Round Water Shortage
CD Strategies to increase yields

Limits Table

Criteria		Limiting Values Lower	Upper
Average Yield %	Crop 1	41.6	100
	Crop 2	64.6	100
	Crop 3	50.1	100
	Crop 4	54.6	100
Minimum Yield in One Season %	Crop 1	41.5	100
	Crop 2	64.4	100
	Crop 3	48.9	100
	Crop 4	54.6	100
Irrigation Water Use mm	Crop 1		612.4
	Crop 2		429
	Crop 3		607.3
	Crop 4		142.6
Average Soil Salinity ppm	Penultimate		
	Final		
	Final/initial		1.08
	Final/penult		
Drainwater (Whole model run) mm	Total Flow		
Farmer Costs LE / fed	Crop 1		10.8
	Crop 2		7.6
	Crop 3		10.7
	Crop 4		2.5
			31.6

Evaluation Table

Criteria		Controlled Drainage Strategies Passing Limits: 6CONV	6CD2	6CD3	6CD4	6CD7	6CD8
Rainfall File		File 6	File 6	File 6	File 6	File 6	File 6
Average Yield %	Crop 1	41.6	58.6	41.6	41.6	42.8	42.8
	Crop 2	64.6	64.7	100	94	64.6	64.6
	Crop 3	50.1	50.1	50.1	50.1	50.1	50.1
	Crop 4	54.6	54.6	54.6	54.6	100	100
Minimum Yield in One Season %	Crop 1	41.5	58.5	41.5	41.5	42.8	42.8
	Crop 2	64.4	64.4	100	93.6	64.4	64.4
	Crop 3	48.9	48.9	48.9	48.9	48.9	48.9
	Crop 4	54.6	54.6	54.6	54.6	100	100
Irrigation Water Use mm	Crop 1	612.4	612.4	612.4	612.4	612.4	612.4
	Crop 2	429	429	429	429	429	429
	Crop 3	607.3	607.3	607.3	607.3	607.3	607.3
	Crop 4	142.6	142.6	142.6	142.6	142.6	142.6
Average Soil Salinity ppm	Penultimate	1085	957	840	964	859	896
	Final	1099	963	859	965	858	903
	Final/initial	1.08	0.95	0.85	0.95	0.85	0.89
	Final/penult	1.01	1.01	1.02	1	1	1.01
Drainwater (Whole model run) mm	Total Flow	247	203	173	200	227	227
Farmer Costs LE / fed	Crop 1	10.8	10.8	10.8	10.8	10.8	10.8
	Crop 2	7.6	7.6	7.6	7.6	7.6	7.6
	Crop 3	10.7	10.7	10.7	10.7	10.7	10.7
	Crop 4	2.5	2.5	2.5	2.5	2.5	2.5
		31.6	31.6	31.6	31.6	31.6	31.6

Appendix 8

Integrated irrigation and drainage field study, western Nile Delta
Progress Report – July 1999

Appendix 8 Integrated irrigation and drainage field study, western Nile Delta: Progress Report - July 1999

Introduction

Maruit experimental station, which located in western delta of Egypt, has been selected to carry out the field study for three cropping seasons, summer 1999, winter 99/2000 and summer 2000. According to the work plan two drainage system will be applied during the study. The conventional drainage system and the controlled drainage system, The objective of this report to summarize the activities which have been done during the last period including main drain cleaning, installation of a new subsurface drainage system, installation of field equipment, starting the new season and the measurement program

Field work activities

- **open drain cleaning**

Maruit experimental station is served by main drain called taammeer El-sahary 2 and along the drain there were weeds, sediments in the upstream of syphones and some obstructions. For that reasons the water level in the drain was very high and the ground water table was about 50 cm from the ground surface. So it was very important to clean the drain and reduce the water level in the drain to be able to install a new subsurface drainage system discharge free to the main drain.

By the cooperation with the Egyptian Public Authority of Drainage Project, an excavator has bee arranged to clean the drain for about one month. After cleaning the drain and removing the weeds, the sediments and the obstruction, the water level in the drain lowered about 1.0 m and it became suitable to install the new subsurface drainage system.

- **Installation of the new subsurface drainage system**

By cooperation with EPADP a new subsurface drainage system has been installed consists of two main collectors discharge direct to the main drain. The main collectors have been installed by using an excavator from PVC pipe 10-inch diameter and the lateral drains have been installed by using the lateral drain machine form PVC 72 mm diameter covered by synthetic envelope materials. The lateral drain sparing ranged between 31 to 35 m and the drain depth is about 1.15 m. All lateral drains discharge free to the main collector through reinforced concrete manholes 1.0 diameter

- **Installation of field equipment**

According to the study work plane, the study area was divided to two treatments conventional drainage and controlled drainage. Each treatment has been covered by groups of observation wells, one water level recorder and one tensiometer profile for 6 depths . Four water table control devices have been installed in the controlled drainage treatment and 2 laysimeters have been used to simulate each treatment. The field equipment have been installed as following

- **Installation of observation wells**

Two groups of observation wells have been installed in each of the conventional and the controlled drainage treatments, one group at ¼ of the drain length and the other group at ¾ of the drain length. Each group of observation wells covered 4 lateral drains at midway between each two drains and just beside the drain. The observation well are mode from PVC pipe 1 ½ inch and 2.0 m length, small holes are made at 1.0 and covered with thin sheet to allow for the water to enter to the pipe and to prevent sediments from entering the pipe The observation wells are made by making 2.0m depth hole by using the auger and putting the pipe and small gravel around the pipe . The observation wells will be used to measure the ground water level.

- **Installation of water level recorders**

Two water level recorders have been installed in the area, one in middle of the conventional drainage treatment and the other in the middle of the controlled drainage treatment. The water level recorder will be used to measure the change in the ground water level automatically.

- **Installation of laysimeters**

The laysimeters have been mode from special iron, 2 mm thickness, 1.0 width, 1.0 m length and 1.5 m height. Four laysimeters have been used to simulate the field application of the conventional and the controlled drainage. Two laysimeters are used for each treatment as replicates.
The laysimeter is painted from inside by using special chemical to protect the iron and the outside is covered by special material to protect from sunshine and prevent the increase of water evaporation. The drainage system is simulated by using PVC pipe 2-inch diameter with holes and covered by synthetic material and installed at depth 1.20 from the surface and a tape is used to open and close the drain discharge. The controlled drainage is simulated by using special connection from P V C pipe 2-inch diameter to control the water table to the desired depth.
In each laysimeter one observation well has been installed to measure the water table depth and another manometer has been installed from out side to monitor the water table depth. In one laysimeter from each treatment, three tensiometer have been installed for 3 depths 30 cm, 60 cm and 90cm to measure the soil moisture

- **Installation of tensiometer profile**

Two tensiometer profile group have been installed, one at the middle of the conventional drainage treatment and the other at the middle of the controlled drainage treatment. Each tensiometer profile group consists of 6 depths 70 cm , 30 cm, 45 cm,80 cm,120cm and 160cm. The tensiometers have been used to measured the metric pressure in the soil at different depths

- **Installation of water table controlled device**

Four water table control devices have been installed in 4 drains in the controlled drainage treatment. The control device is mode from PVC pipe connection and has been connected to the drain line outlet to allow rising the water table to the desired depth (60-cm for the first season).

- **Maize Cropping Season (summer 99)**

- Site preparation (4 – 9/6/99)
- Supper phosphate fertilizer application (200 kg/fed) (5/6/99)
- Maize planting (9/6/99)
- Pre-plant irrigation (10 – 11/6/99)
- Additional irrigation (19/6/99)
- First Nitrate fertilizer application (150 kg/fed) (30/6/99)
- First irrigation (30/6 – 1/7/99)
- Second Nitrate fertilizer application (200 kg/fed) (18/7/99)
- Second irrigation (20 – 21/7/99)

- Measuring program

- Ground water measurement
  - Ground water levels
    - At the observation wells (daily)
    - At the water level recorders (automatic)
- Ground water salinity (2 times/week)

- Soil measurement
  - soil salinity
    - 32 soil samples at the beginning of season
    - 32 soil samples at the end of season

- Tensiometer profile reading (daily)

- Irrigation water measurement

  - Amount of applied irrigation water (during irrigation time)
  - Irrigation water salinity (during irrigation time)

- Drainage water measurement

  - Amount drainage water from each lateral drain (after irrigation)
  - Drainage water salinity (after irrigation)

- Weather measurement

  - wind speed (average daily)
  - Wine direction (average daily)
  - Air temperature (max, min , average)
  - Relative humidity (average daily)
  - Rainfall (daily)
  - Solar radiation (average daily)

- **Crop yield measurement**

- Crop yield from each treatment (at harvest time)
- Root depth development (each 10 days)

- **Water quality measurement (for DRI)**

  - Chemical analysis for soil (32 soil sample before each fertilizer application)
  - chemical analysis for ground water (before and after of each fertilizer) application)
  - chemical analysis for drainage water
    (Before and after each fertilizer application)

- **Laysimeter measurement**

  - Soil salinity (at the beginning of season)
  - Soil salinity (at the end of season)

- Ground water depth (daily)
- Ground water salinity (2/week)
- Soil moisture (by using tensioneter) (daily)
- Amount applied irrigation water
- Salinity of applied irrigation water
- Amount of drainage water (after irrigation)
- Salinity of drainage water (after irrigation)
- Crop yield (at harvest time)

- **Field equipment and instrument**

Item	No
Observation wells	(30)
Water level recorder	(2)
Tensiometer profile	(2)
Laysimeter	(4)
Ec meter	(1)
Current meter	(1)
Auger hole set	(1)
Measuring tope	(2)
Stop watch – bucket	(2)
Tensiometer	(8)
Computer	(1)
Water tale control device	(4)
Staff gauge	(10)

HR Wallingford is an independent company that carries out research and consultancy in civil engineering hydraulics and the water environment. Predictive physical and computational model studies, desk studies and field data collection are backed by large scale laboratory facilities and long term programmes of advanced research. Established in 1947 as a Government research centre, the Company now employs more than 200 engineers, scientists, mathematicians and support staff, many of whom are recognised international experts. Based on a 36 hectare site near Oxford, HR Wallingford has extensive national and international experience, with offices and agents around the world.

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