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Guidelines for Controlled Drainage

(KAR Project R7133)

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Summary

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Introduction
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.

Controlled Drainage Benefits
The main benefits of controlled drainage in irrigated agricultural areas are as follows:

- Increased water use efficiency.
- Improvements in crop yield.
- Controlling soil water through-flow rates to ensure that nitrate and phosphate levels are maintained, and that soil fertility is not degraded in high irrigation or high rainfall areas.
- Reduced nitrate and phosphate losses to downstream water bodies, reducing eutrophication and ecological damage.
- Conservation of wetlands and water–sensitive regions.

It is particularly beneficial in areas where farmers experience periodic water shortages, which limit crop production, or where water application costs are high. In terms of the basin water balance, the benefits are greatest where rice forms a significant part of the crop rotation, and also in areas where reused water is of poor quality.

Guidelines for Controlled Drainage
These guidelines are intended to assist planners and water resource managers in irrigated (or rainfed) areas in developing countries, who wish to assess the benefits and requirements of controlled drainage. Other potential users include extension services wishing to advise farmers on management of controlled drainage,

irrigation and drainage engineers designing controlled drainage systems, and research institutes and universities who may find the guidelines and accompanying software useful as educational tools.

The guidelines enable users to:

- Gain an understanding of the concepts involved in controlled drainage.
- Assess the benefits and issues involved in implementing controlled drainage at a particular location.
- Use the simulation tool CDWaSim to develop site-specific controlled drainage strategies to maximise water saving and crop yield improvement, whilst minimising negative impacts.
- Carry out an economic assessment of the costs and benefits of controlled drainage at the farm and system level.

An overview of controlled drainage explains the basics and the practicalities of the technique, including a description of the two main types of controlled drainage ("on/off" operation and use of weirs) with an outline of appropriate control devices for application in the developing world.

Institutional and management issues are presented including discussion of:

The role of farmer groups and extension services.
The option of farmer incentives to take up the approach.
Requirements for irrigation and drainage infrastructure, together with consideration of modification of the drainage system at design stage.
Applicability to irrigated and rainfed areas.
Consideration of the irrigation water source and water quality issues.
Application on different soil types and the issue of lateral seepage.
Application to different crops and cropping patterns.

A Tool to Develop Controlled Drainage Strategies

The simulation model CDWaSim has been developed to allow the user to develop controlled drainage management strategies for different crops in different situations and compare the water balance, crop and soil response with the conventional drainage option. A technical guide and user manual are included. For a given location (soil, crop rotation, irrigation water source, climate) CDWaSim can be used to:

- Try out different crops under controlled drainage, and assess impacts of different weir depths and irrigation schedules.
- Simulate "on/off" controlled drainage and evaluate effects of opening and closing drains at different times.

Summary *continued*

- Predict water savings and crop response under controlled drainage.

- Project long term soil and groundwater salinity levels under controlled drainage, and resultant crop impacts.

- Develop controlled drainage strategies to maintain crop yields in periods of reduced water availability.

A demonstration application is provided considering 2 common crop rotations from the Nile Delta, Egypt. Information is provided on input data requirements and sources, running the simulation for current (conventional) irrigation and drainage management, and development of controlled drainage options for different crops, and combinations of crops. Output data are included with discussion of the implications of the results.

Economic Assessment of Controlled Drainage
A discussion of the main costs and benefits of controlled drainage is provided. This is considered from the point of view of the farmer and from the level of the economy/society.

A spreadsheet tool is presented for economic appraisal of controlled drainage. It takes account of variations in cropping patterns, farming productivity and systems, financial and economic prices, water use efficiencies and the cost of drainage technology. It provides estimates of returns to farmers and the wider society, and the Net Present Value (NPV) and Internal Rate of Return (IRR) of an investment in controlled drainage. The model facilitates sensitivity analysis with respect to key assumptions, for example it can be used to rapidly assess the impact of different cropping patterns, water-use efficiencies, and cost assumptions. User notes are provided together with a demonstration application.

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1. INTRODUCTION

1.1 Background

Current global population growth rates require an increase in agricultural food production of about 50% over the next forty years to maintain present levels of per capita food production, (World Bank, 1988). Irrigation will play a vital role in achieving this increase. As water resources are already close to being fully utilised in most developing countries, irrigated agriculture will have to use water much more efficiently in future than has been the case in the past.

Surface irrigation methods predominate in the arid and semi-arid regions of the world. In many locations irrigation has resulted in rising watertables, waterlogging and soil salinity problems, which have led in turn to the installation of drainage systems. Smedema and Ochs (1998) estimate that 20-30 million hectares of agricultural land are affected by waterlogging and salinisation, with less than half the drainage need currently met. The area of irrigated land that is drained is expected to increase significantly over the next two or three decades.

Artificial drainage commonly takes the form of open ditches at field edges, and subsurface slotted plastic pipes or clay tile drains laid horizontally across fields at a depth of 1-2m and spacing of 20-50m. Drains are designed to remove water rapidly from the soil profile, to keep the local watertable at or close to drain depth. In practice drainage systems are often over-designed, as they are sized for the crops most sensitive to waterlogging, and also have additional capacity to allow for deterioration of the drainage system over time. With conventional operation it is not possible to control the amount of water removed from the fields by the drains, and water that could be used to irrigate the crop is lost from the soil profile.

Over-irrigation is also common as farmers compensate for unreliable supplies and shortages in distribution systems. This increases the volumes of water percolating below the root zone, and leaving the soil profile via the drains. Drainage flows often constitute a major component of water "losses" at field level.

Water use efficiencies can be improved if "losses" to drains are reduced, by integrating the management of irrigation and drainage. The technique, called controlled drainage, is the subject of these guidelines. Controlled drainage allows farmers to control drainage outflows, storing water in the soil profile for use by the crop, and reducing losses from the system. 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. With controlled drainage irrigation applications can be reduced, and the maximum benefit derived from rainfall. The good quality irrigation water that is "saved" becomes available for use by other irrigators, or to grow crops with larger water demands, that give the farmer better economic returns.

1.2 Guidelines for controlled drainage

These Guidelines are an output from the DFID Knowledge and Research Contract R7133 – Integrated Irrigation and Drainage to Save Water. The project was carried out by HR Wallingford, working in collaboration with the Drainage Research Institute of the National Water Research Centre, Egypt.

The guidelines are intended to assist planners and water resource managers in irrigated (or rainfed) areas in developing countries, who wish to assess the benefits and requirements of controlled drainage. Other potential users include extension services wishing to advise farmers on management of controlled drainage, irrigation and drainage engineers designing controlled drainage systems, and research institutes and universities who may find the guidelines and accompanying software useful as an educational tool.

The guidelines enable users to:

- Gain an understanding of the concepts involved in controlled drainage.
- Assess the benefits and issues involved in implementing controlled drainage at a particular location.
- Use the simulation tool CDWaSim to develop site-specific controlled drainage strategies to maximise water saving and crop yield improvement, whilst minimising negative impacts.
- Carry out an economic assessment of the costs and benefits of controlled drainage at the farm and system level.

2. CONTROLLED DRAINAGE – AN OVERVIEW, BENEFITS AND ISSUES

The purpose of this section is to explain the concepts of controlled drainage, provide preliminary guidance on the benefits and costs that might be involved in introducing controlled drainage to parts or all of an agricultural area, and to identify the critical management issues that will have to be addressed.

2.1 What is controlled drainage?

Controlled drainage involves an extension of on-farm water management to include management of drainage flows. With controlled drainage farmers control the volumes of water leaving the land in the drainage system, using a weir or blocking device. Drainage occurs only when the watertable in the field has risen to a level where drainage has to be provided to prevent crop damage or provide salt leaching.

There are essentially two types of controlled drainage:

"On/off" operation. Lateral or collector pipes are periodically blocked and unblocked. When the drains are unblocked, drainage is "on". During this time drains flow as normal and the watertable rises and falls as with conventional operation. When drains are blocked, drains are "off" and there is no drainflow. During this time the watertable rises and falls due to irrigation and crop water abstraction only. This is illustrated for three irrigation cycles in Figure 1, and compared to watertable movement under conventional operation. "On/off" controlled drainage could lead to longer periods of high water-tables, and is thus only recommended for shallow rooting crops, and crops that are not sensitive to wet stress.

Use of weirs. A fixed or adjustable weir is placed in the pipe system or drainage ditch. When the watertable rises above the level of the weir, water flows over the weir and out of the drainage system. When the watertable is below the level of the weir, there is no drainage flow and the watertable recedes due to crop water abstraction only. This is illustrated for three irrigation cycles in Figure 1. Controlled drainage using weirs provides less risk of crop wet stress (so long as the weir depth is not too shallow), and is thus the safe option for deep and shallow rooting crops, including crops with sensitivity to wet stress.

Although there are similarities, controlled drainage should not be confused with sub-irrigation. The critical difference is that with sub-irrigation the watertable does not fall below the depth of the weir, as it is maintained at weir depth by entrance of water into the soil profile from the drainage system. Watertable movement during sub-irrigation is also shown in Figure 1.

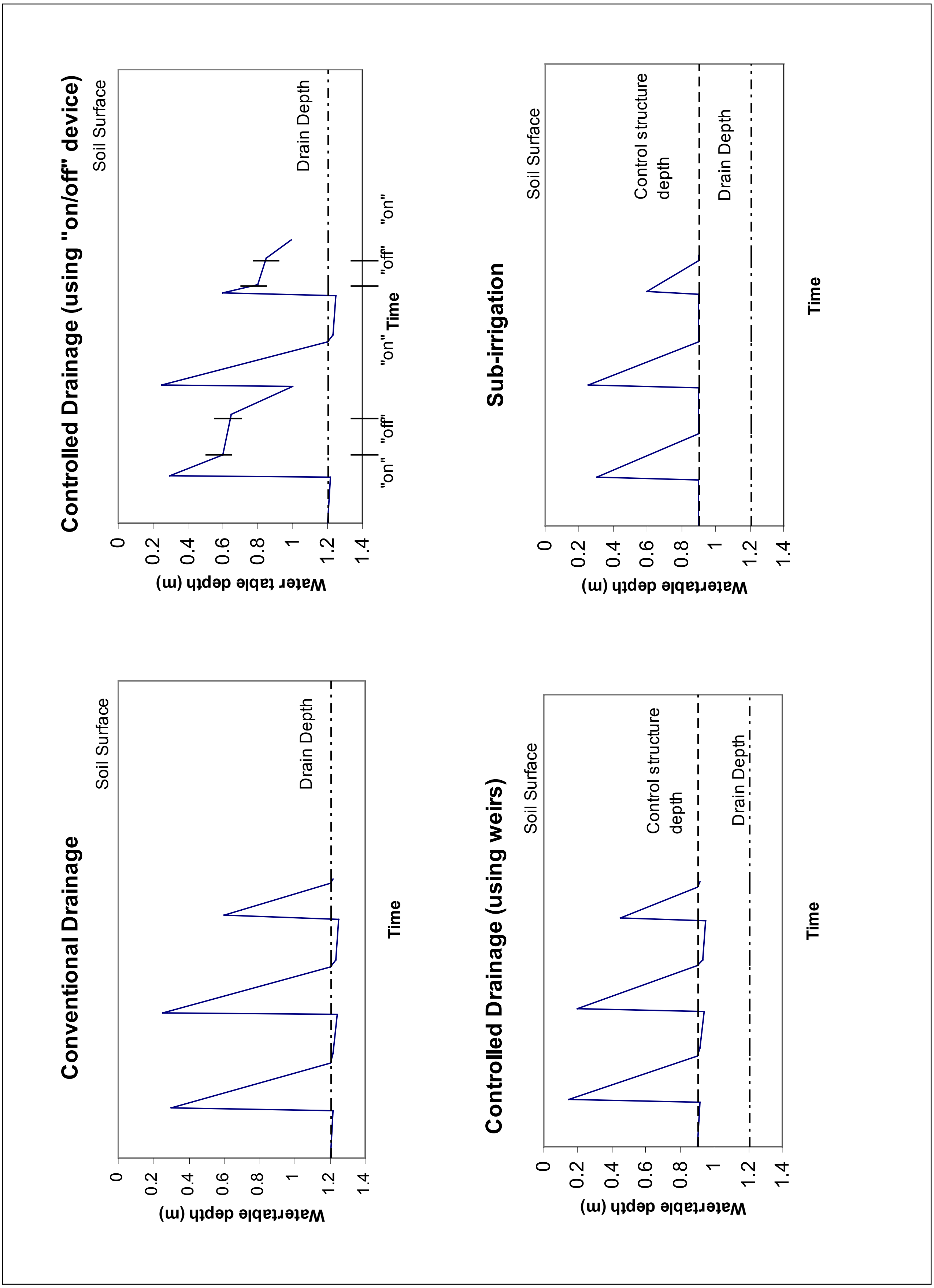


Figure 1 **Watertable movement under controlled drainage using "on/off" devices and weirs, and comparison with conventional management and sub-irrigation**

2.2 Controlled drainage devices

To allow drainage flows to be controlled by farmers in developing countries simple, robust and inexpensive devices are required that can be constructed from local materials. Flapgates have been used to block and unblock drains in rice areas in the Nile Delta. One of these devices is shown in Figure 2.

Figure 2 Flapgate used to block drainpipes and control drainage outflows

A second controlled drainage device is shown in figure 3. This is a prototype weir device constructed from PVC pipe, commonly available across the developing world. The device is fitted onto the end of each field lateral (or sub-collector) pipe where it meets the collector pipe. Access is straightforward if the subsurface drainage system has suitable access manholes at these points. Farmers can thus fit and maintain the devices themselves. Different lengths of vertical pipe allow the device to control drainage at varying watertable depths, either during or between crop seasons.

Figure 3 Prototype controlled drainage weir device

2.3 Potential benefits of controlled drainage

The application of controlled drainage has potential benefits in semi-arid, humid and temperate regions in both irrigated and rainfed agricultural areas. A companion report discusses areas of potential application around the world (Abbott *et al*, 2002). In these guidelines we focus on controlled drainage in arid and semi-arid regions in developing countries where water is a limiting resource, and the introduction of water saving technologies will have the largest impact on livelihoods. The main benefits are:

Water saving. Irrigation applications can be decreased, and the saved water used to irrigate additional crops, or shift to more profitable (higher water use) crops. Under rice, irrigation applications have been reduced by over 40% under controlled drainage (DRI, 1998a,b). For dry foot crops water savings of 10 – 20% are predicted (see chapter 3).

Savings in irrigation time and costs. Irrigation volumes decrease along with associated time, labour and pumping (if applicable) inputs.

Increased water use efficiency. Controlled drainage can increase water use efficiency at basin level. This is true even in areas where drainage water is commonly reused, as the degradation in water quality which occurs as water is reused decreases its productivity.

Maintained agricultural production in watershort years. Reducing the risk of crop failure due to periodic water shortage improves livelihoods of farmers.

Increase in crop yields. Controlled drainage can improve crop yields.

Reduced pollution of water courses. In many places water courses are heavily polluted by agrochemical runoff from agricultural land. Controlled drainage reduces transport of chemicals to rivers, lakes and the oceans.

Reduced volumes of drainwater. Disposal of drainwater is an issue in many areas. Although volumes of drainwater reduce under controlled drainage, quality is usually reduced. Generally it is better to concentrate pollutants in small volumes of drainwater to ease disposal.

Savings in agrochemical application rates. Application rates for agrochemicals, in particular fertilisers, can be reduced under controlled drainage. As a guideline the % reduction can be taken as equivalent to the % reduction in drainflow under controlled drainage.

2.4 Costs of controlled drainage

Various costs are associated with the introduction of controlled drainage, which must be offset against the benefits. The main costs are:

Drainage infrastructure. If the drainage system is modified at design stage (see section 2.6) there may be incremental costs. These will be very site-specific depending on required lengths and sizes of drainage pipes. Although the modified system requires longer lengths of pipe, there are less of the larger more expensive pipes (20-50cm) used, and more of the smaller cheaper pipes (15cm) required.

Controlled drainage devices. These should be robust, reliable, low cost and simple to use. A prototype weir device was developed as part of the HR/DRI study of controlled drainage for dry foot crops. The cost of a prototype device (materials and construction) was around US$40. Design simplifications and production in large quantities could reduce this cost considerably. Also in areas where control is possible at the sub-collector level, (rather than at lateral drain), one device could serve many farmers, which also reduces the cost considerably.

The costs of controlled drainage will be discussed in section 4. As a general guideline it has been estimated (GRID, 2002) that the additional costs of the technique (including the modified drainage system) can be recouped by farmers in 2-3 rice seasons.

2.5 Institutional requirements

Farmer groups

Controlled drainage requires management by individual farmers in case of large farms or more usually, in smallholder irrigation systems, by groups of small farmers. With small and possibly fragmented plots and diverse cropping patterns, farmers need to work together to:

- decide on cropping patterns and planting schedules,
- agree on the operational guidelines to be adopted,
- operate or oversee operation of the controlled drainage devices, or to organise for operation by e.g. employing specialist staff,
- decide on the distribution of the costs related to the operation of controlled drainage,
- where appropriate to agree on the distribution of benefits.

Wherever possible use should be made of an existing farmer group, rather than trying to create one specifically for controlled drainage. The organisation will need mechanisms for decision making, conflict resolution, and enforcement. The existence of well established farmer groups or WUA’s, or well established local traditions of farmers working together will obviously help the introduction of controlled drainage.

Extension Services

There will be a need to train and support farmers when controlled drainage is introduced, and this is best done through an existing extension service.

Incentives to farmers
Economic analysis described in section 4 of the report indicates that in most circumstances the benefits to individual farmers from controlled drainage are relatively small unless their crop production is already constrained by water shortages. Controlled drainage involves an additional management burden and, if farmers are expected to pay for additional infrastructure, additional costs. Farmers may not perceive that a technology which reduces the quantity of water delivered to them, at an additional charge, with relatively limited direct benefits, is particularly attractive. Indeed, the technology may increase their exposure to perceived risk. However large potential benefits accrue from water savings off-farm, and it may be appropriate to recover the additional cost of controlled drainage at sector or regional level, rather than discriminate against those farmers who adopt the technology. Thus it may be necessary to subsidise the costs of installing controlled drainage, to provide the suitable incentives to farmers to take up the new technology.

2.6 Management issues

Irrigation and Drainage Infrastructure
As controlled drainage is only viable in areas where irrigation or rainfall raises the local watertable above drain depth, it is most applicable in areas under surface irrigation, as well as some areas using overhead systems. It does not apply to areas irrigated by micro-irrigation methods.

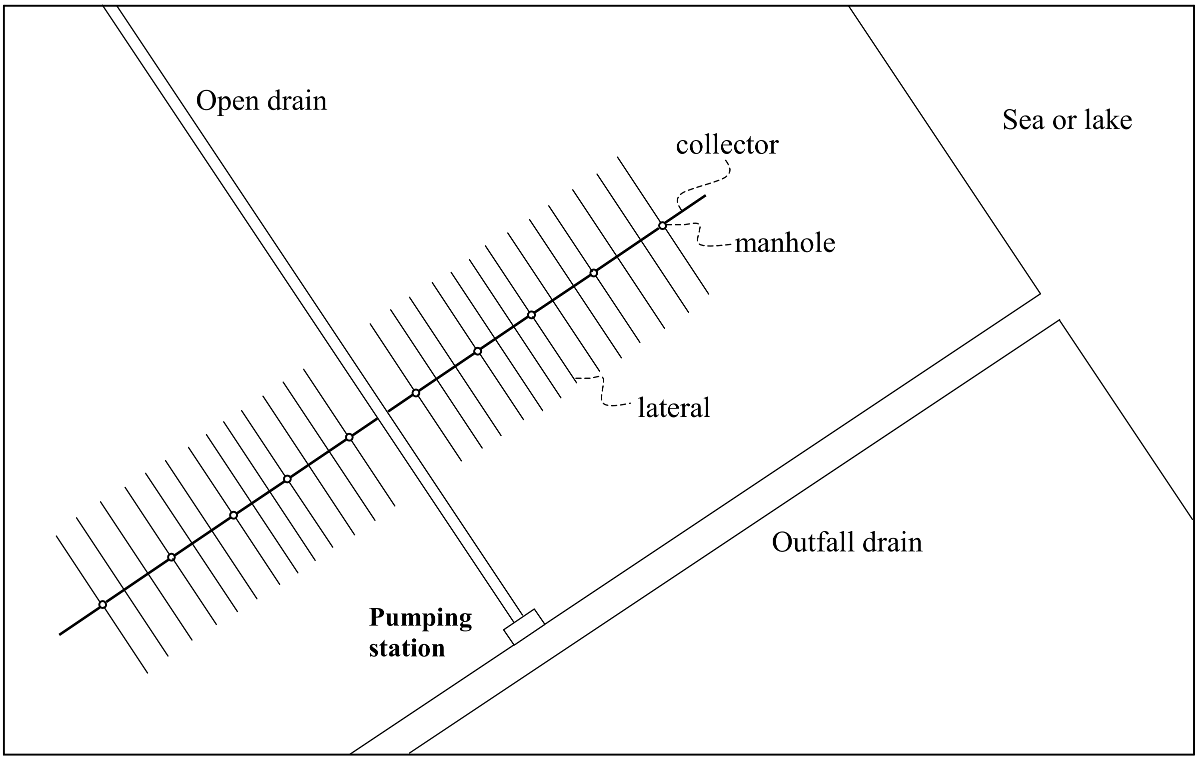
In order to control drainage flows out of an agricultural area, it is vital to have an understanding of the drainage paths from the area. If the main route for subsurface drainage flow is via a subsurface drainage system, then controlled drainage can be applied to that system. If drainage flow is mainly to open drainage channels (at the field boundaries) then controlled drainage structures will need to be positioned in the open drains, and flow rates from fields controlled within the channels.

Size and distribution of cropping units (fields) and the spatial interaction with the irrigation and drainage systems is a prime consideration. The ideal situation occurs where large areas have contiguous irrigation and drainage command areas, under the control of a single farmer or co-operative. However controlled drainage can still be beneficial on smaller land areas, so long as there is overlap of the irrigation and drainage command area, so that the same farmer(s) controls the irrigation and drainage for the area.

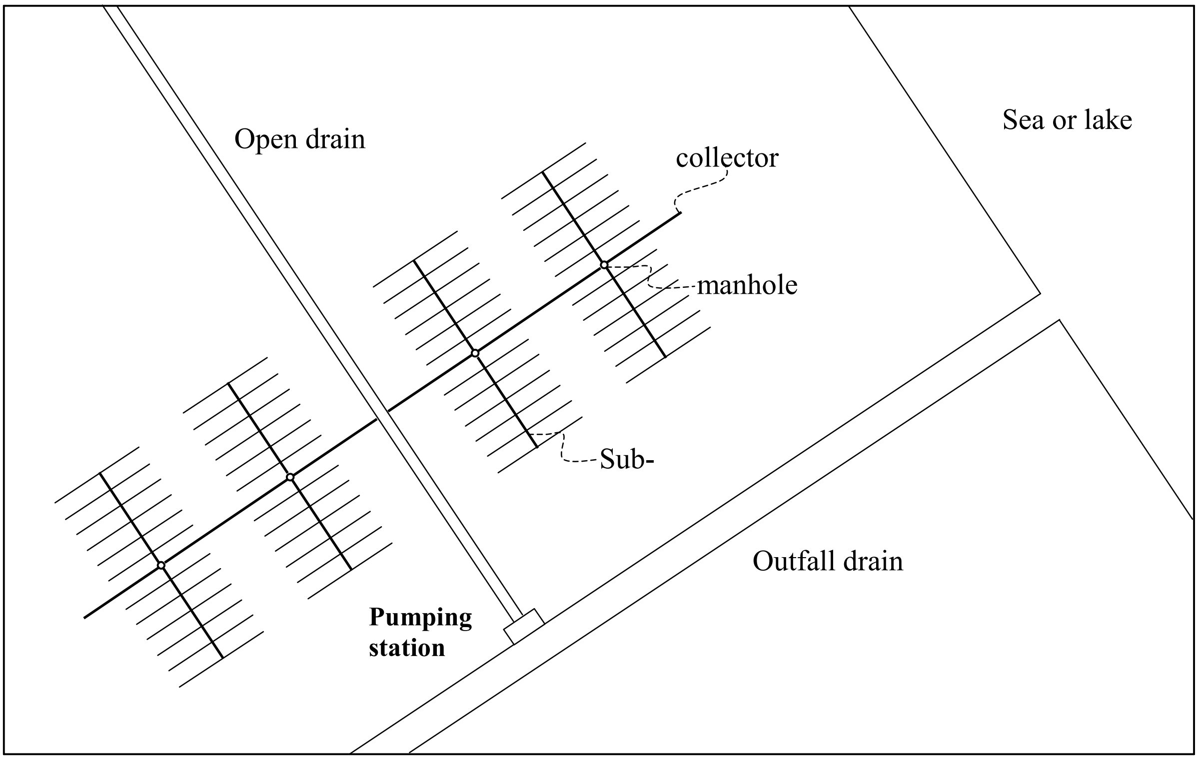
The technique is better suited to larger fields (> 1 hectare), especially if different crops are grown in surrounding fields.

Modification of the Drainage System
One option is to modify the design of the drainage system when it is installed to ease management of controlled drainage in areas with a wide range of crops grown on small land holdings. This has been done in some areas of the Nile Delta as follows:

With the conventional drainage layout (4) the drainage water flows from laterals into a collector, and subsequently into an open drain. There is thus only a limited number of access manholes per collector, and blockage of the drainage flow would normally have an impact on all fields along the collector upstream of the blockage - on average between 20 and 120 hectares (Amer and de Ridder, 1989).



Conventional Drainage System Layout



Modified Drainage System Layout

Figure 4 The conventional and modified drainage system layout used in Egypt.

With the modified system (also shown in 4) sub-collectors are added to the layout serving smaller land areas. It is then possible to control drainage flows from these sub-collectors by introducing control devices at the manhole junctions with the main collector, whilst allowing unrestricted flow to continue along the main collector, which acts purely as a transport conduit for upstream areas. The impact of blocking the drainage flows is thus restricted to the area served by the sub-collector only (i.e. generally not more than 20 hectares (DRI, 2000)). Crop consolidation is easier to accomplish at the level of the sub-collector than at the level of the collector due to the smaller land areas involved. With the chances for effective co-operation between farmers enhanced due to the smaller number involved, the potential for conflict is much less.

Rainfed Areas
In arid and semi-arid areas where rainfall meets little or none of the crop water demand, controlled drainage strategies are developed solely in conjunction with the irrigation schedule.

Controlled drainage can be particularly beneficial in areas where crop water requirements are met by a mixture of irrigation and rainfall. A higher percentage of rainfall can be utilised by the crop, by reducing drainage losses following rainfall events. This is particularly true where rainfall tends to occur in large, high intensity events. Where rainfall regularly supplies part of crop water requirements, development of controlled drainage strategies must take both irrigation schedules and rainfall patterns into account.

Irrigation Water Source(s)
The source(s) of water for irrigation is a primary consideration, in particular the reliability and quality. Areas which suffer irregular or unreliable supply can be targeted for controlled drainage, as crop yields will benefit. Increased confidence in crop production will improve incomes in these areas.

Water quality is also an issue in many areas. Groundwater sources are generally of better quality than surface water sources. Controlled drainage is particularly beneficial where poor quality water (eg drainage water) is used to supplement a higher quality supply, when there is inadequacy in the main supply. In this case controlled drainage allows the farmer(s) to make optimum use of the good quality supply, and reduce his dependence on the inferior source. This will enable him to maintain soil fertility and maximise crop yields.

Soils and Lateral Seepage
Soil texture and structure are of particular importance in irrigation and drainage management, and thus also in controlled drainage management. Soils with good hydraulic properties (loams and coarse soils) will be easier to manage with controlled drainage. For soils with poor hydraulic properties (clays and fine soils) where water is slow to drain, the possibility of crop damage due to periods of wet stress (waterlogging of rootzone) is increased.

If watertable depths differ significantly between plots then some lateral flow of water may occur between the plots depending on the hydraulic gradient and the horizontal conductivity of the soil. This is unlikely to lead to crop damage as the system will always move toward the deeper water-table depth, but it could reduce the water saving benefit of controlled drainage for the plot with the higher (shallower) controlled drainage weir.

Lateral seepage flows between cropped areas are potentially greater on lighter soils with good hydraulic properties. Larger field sizes are thus required on lighter conductive soils, whereas smaller field sizes are acceptable on heavier less conductive soils.

In semi-arid areas with high water-tables, soil salinity levels are often high. Adequate drainage is required to achieve salt leaching. For this reason the potential water savings under controlled drainage are lower in saline areas. This is not to say controlled drainage is not an option in such areas, it is just that the potential benefits are reduced and extra care is needed to ensure detrimental soil salinity levels are not attained.

Cropping Patterns
Rice offers greatest potential for water saving and improved yields under controlled drainage, as it has a large crop water requirement and is not threatened by a raised water-table. In regions where winter and summer crops are grown, crops grown in summer (with greater evapotranspirative demand) will potentially bring greatest benefit.

Crop consolidation is an issue, particularly where rice is grown adjacent to dry-foot crops on light, conductive soils. In this case it is better to consolidate rice areas along drainage lines if possible. This is not to say controlled drainage is not beneficial in areas where a range of crops are grown in close proximity, but greater care is needed to manage lateral seepage flows.

In areas growing a range of dry-foot crops, or where soils are heavier, lateral flow will be less and crop consolidation may not be necessary.

One of the main management objectives for agriculture is to maintain optimum soil moisture conditions for crop development. High water-tables during the crop season can have deleterious impact, under conventional management or controlled drainage, as lack of oxygen in the saturated soil reduces the crop's ability to transpire to full capacity and yields can be reduced. With minimal care, controlled drainage should only result in high water-tables for short periods of time during irrigation applications or intense rainfall, which should not affect yields of even deep rooting crops.

2.7 Summary requirements for controlled drainage

In summary the factors that are essential for the successful adoption of controlled drainage are:

Surface irrigation using traditional basin or furrow methods.

Artificial drainage systems installed (or planned) with suitable control points.

Significant drainage losses (usually comes with above two points).

Possibility of crop consolidation along drainage lines.

The following additional factors will facilitate the introduction of controlled drainage, and indicate that substantial benefits may be possible:

Irrigation water with low or moderate salinity content.

Medium textured soils with low to moderate salt content.

Existing consolidation of similar crops.

Rice grown as part of crop rotation.

Depressed crop yields due to unreliable water supplies or shortages.

Farmers have the possibility of growing additional crops, or switching to more valuable crops if additional water is made available.

Farmers benefit if they use less water (eg reduced water charges or pumping costs or possibly government incentives to save water).

3. DEVELOPMENT OF CONTROLLED DRAINAGE STRATEGIES

In this chapter a methodology to develop site specific controlled drainage strategies for different locations and crops is presented.

3.1 Introduction

Controlled drainage strategies can be developed using the software tool CDWaSim (included as Appendix G). A user guide and technical notes are included as appendices A and B. CDWaSim is a simulation tool for controlled drainage, adapted from the parent software WaSim (which was developed by HR Wallingford and Cranfield University with DFID funding).

The CDWaSim simulation software was developed to provide a capability to:

Simulate the two practical approaches to controlled drainage – "on/off" operation, ie periodically blocking and unblocking drains, - and use of weirs to control drainage flows from the system.

Model a range of crops (including rice) and rotations over long time periods eg up to 20 years, with different soil types, irrigation and drainage regimes, and different climates.

Assess response over a wide range of conditions, and allow direct comparison with the conventional drainage options.

The tool is relatively easy to use, and has been tested in the field (Abbott *et al*, 2001).

3.2 Functions of CDWaSim

CDWaSim is used to develop and assess controlled drainage management strategies for different crops in different situations, and compare the water balance, crop and soil response with the conventional drainage option. For a given location (soil, crop rotation, irrigation water source, climate) CDWaSim can be used to:

- Try out different crops under controlled drainage, and assess impacts of different weir depths and irrigation schedules.
- Simulate "on/off" controlled drainage and evaluate effects of opening and closing drains at different times.
- Predict water savings and crop response under controlled drainage.
- Project long term soil and groundwater salinity levels under controlled drainage, and resultant crop impacts.
- Develop controlled drainage strategies to maintain crop yields in periods of reduced water availability.

3.3 Demonstration application

CDWaSim was used to develop a set of controlled drainage strategies for two common crop rotations found in the Nile Delta, Egypt. Controlled drainage using weirs was considered, with guidance developed on appropriate weir depths and irrigation schedules for each crop.

The model was run to predict the water balance, watertable response, crop response and soil salinity levels over a 20-year period, and compare these to the conventional drainage option. The developed controlled drainage strategies selected were those that maximised water savings, whilst maintaining acceptable levels of crop production and protecting the soil from the build up of salinity.

3.4 Input data

The first stage was to identify, collate and enter input data describing the soil type, crops grown and rotations, irrigation schedules, drainage design and climate. Details of the input data are given in Appendix C.

Soil Simulations were run with a medium textured sandy silt loam soil. Required soil parameters and adopted values are shown. (Advice on appropriate values for different soil parameters is also given in the WaSim users manual.)

Drainage System Design A standard design of drainage system from the Nile Delta was adopted. A drain depth of 1.4m, and spacing of 33m was used. The additional parameters, values adopted and source are given.

Climate Data CDWaSim requires daily rainfall and reference evapotranspiration (ETo) data. For the purposes of the demonstration rainfall was assumed to be negligible, and evapotranspiration was calculated from monthly average climate data from Gemmeiza meteorological station (CLIMWAT, FAO 1993). ETo is computed using the Penman Monteith method. The climate file runs from 28th February 1978 to 28th May 1998.

Crop Data Two common 2-year crop rotations were considered. Rotation 1 comprised cotton, wheat, maize and short berseem, whilst Rotation 2 was wheat, maize, long berseem and rice. These rotations are illustrated.

Other data CDWaSim requires data on crop development, crop co-efficients and transpiration factors, yield response, ponding and mulch depths. These were developed for the six crops using local knowledge and FAO guidelines. Details of the values adopted are given.

Initial Conditions Initial conditions data include the start and finish dates for the simulation, initial soil wetness and watertable depth, and antecedent soil salinity levels. Adopted values are shown. The irrigation water source was assumed to be of reasonable quality with an EC_w of 0.7 dS/m.

3.5 Conventional irrigation and drainage management simulation

The initial runs were for a simulation of the current conventional irrigation and drainage management practice. (This enables comparison of developed controlled drainage strategies with the current conventional management situation.) Current irrigation schedules were used and drainage was not controlled. The adopted irrigation schedules for conventional management of the two crop rotations are shown in appendix C.

A pre-irrigation was included for each crop, approximately a week before planting, to return the soil profile to a field capacity moisture content at the start of each crop season.

3.6 Controlled drainage simulations

The next step was to run the model with controlled drainage management. For the purposes of this demonstration, a controlled drainage weir was introduced separately for each crop at a range of depths, and simulations were run to assess the impacts on irrigation water applications, crop response (yields) and soil salinity levels.

To find the optimum controlled drainage weir depth for each crop, the output data were screened using the criteria listed below:

The soil salinity level (soil profile down to drain depth) should not increase over the 20-year simulation period.

The crop yield of any crops in the rotation should not reduce by more than 5% from the conventional management level (ie crop yield reduction < 5%).

(The user is of course free to adopt these rules or develop his own to suit local requirements.)

For the demonstration the "optimum" weir depth was defined as the deepest weir depth for which the maximum water saving was achieved.

3.7 Results

The key output data for all the simulations are shown in the results tables in Appendix D. Each table presents the predicted water balance, crop response and salinity buildup for the 20-year simulation of conventional irrigation and drainage management of the two crop rotations, together with a series of controlled drainage options for a given crop. Each table also presents the potential water saving of each controlled drainage strategy compared to the conventional management option in each situation.

Optimum weir depths and potential water savings

The relation between controlled drainage weir depth for each crop and associated water saving is shown in 5. The shows that for each crop as the weir depth decreases, the potential water savings increase. The water savings level off as the weir depth decreases, and the drainflow reduces to a minimum level necessary to maintain adequate water movement through the system and maintain salt leaching.

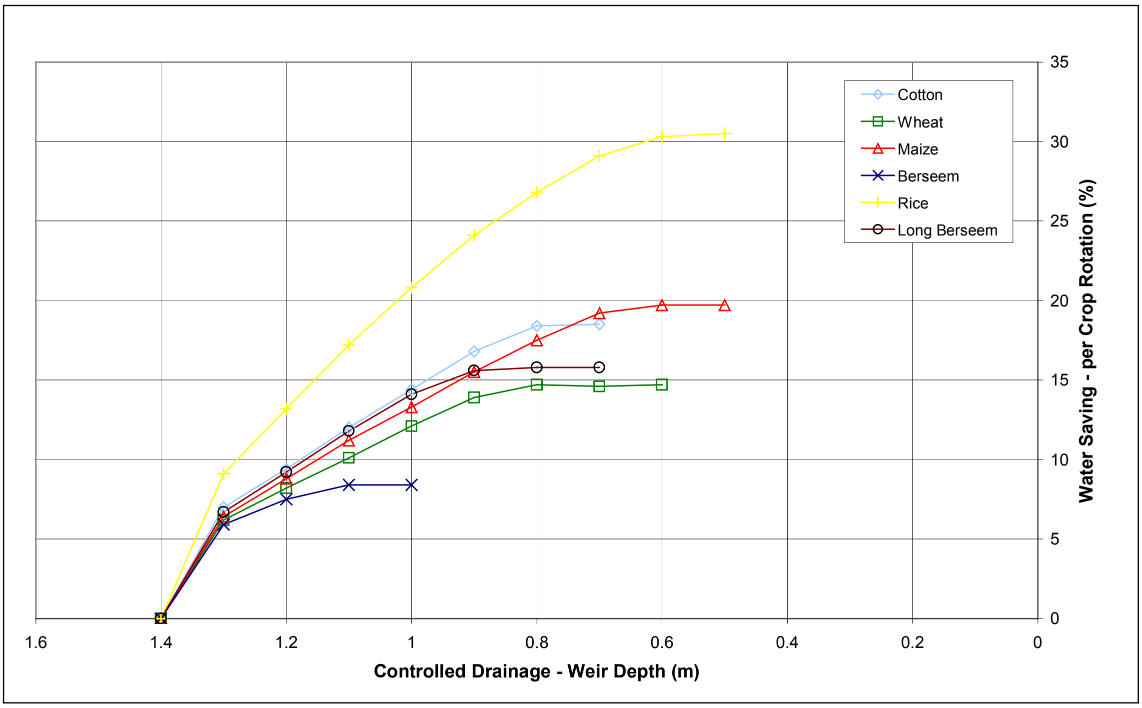


Figure 5 Relation between controlled drainage weir depth and water saving

To determine appropriate weir depths for each crop in each rotation, a weir depth in each case was selected which maximises the potential water saving, whilst maintaining acceptable crop production and protecting soils from salinity buildup over the 20-year simulation period.

The table below presents the summary results from simulations of the two crop rotations. Recommended weir depths are given for each crop (assuming controlled drainage is applied for just that crop in the rotation) together with the potential water saving in each case.

Table 1 Summary results from CDWaSim simulations of controlled drainage on single crops in each crop rotation

2-year crop rotation	Conventional irrigation application (mm)	Recommended controlled drainage weir depth (m)	Potential water saving (mm)	Potential water saving (% of total rotation water use)
ROTATION 1				
Cotton	1265	0.8	640	18.4
Wheat	728	0.8	512	14.7
Maize	1098	0.6	686	19.7
Short Berseem	392	1.1	293	8.4
Total rotation water use	3483			
ROTATION 2				
Long Berseem	1055	0.8	787	15.8
Rice	2108	0.6	1509	30.3
Wheat	719	-	-	-
Maize	1098	-	-	-
Total rotation water use	4980			

The table shows that water savings of up to 30% of total rotation water use are predicted by CDWaSim for the defined conditions. The greatest potential water saving comes from controlled drainage of rice. This is because rice has the largest irrigation water use, with large predicted losses to drainage. Significant water savings (18-20%) can also be made if controlled drainage is applied during the cotton or maize seasons, again because these crops have high drainage losses under conventional management. The full irrigation schedules for these controlled drainage strategies are given in Appendix E.

Controlled Drainage of Multiple Crops

The results above are for application of controlled drainage to one of the crops in the rotation. The simulation tool can also be used to assess the impacts of controlling drainage of two or more crops in the rotation.

For crop rotation 1, controlled drainage was simulated for combinations of crops as below:

- Controlled drainage of winter crops - wheat and short berseem.
- Controlled drainage of summer crops - cotton and maize.
- Controlled drainage of all 4 crops in the rotation.

A range of weir depths was tested in each case and the results tables are shown in Appendix D. Irrigation schedules for these simulations are shown in Appendix E. Summary results from simulations with the greatest potential water savings without detrimental salt buildup or yield depression (subject to earlier rules) are shown in the table below:

Table 2 Summary results from CDWaSim simulations of controlled drainage on several crops in each crop rotation

Controlled drainage strategy	Controlled drainage weir depths (m)	Potential water saving (mm)	Potential water saving (% of total rotation water use)
Controlled drainage of winter crops	Wheat – 0.8m Berseem – 1m	669	19.2
Controlled drainage of winter crops	Wheat – 1m Berseem - 1m	579	16.6
Controlled drainage of summer crops	Cotton – 0.7m Maize – 0.6m	1191	34.2
Controlled drainage of summer crops	Cotton – 1m Maize - 0.9m	899	25.8
Controlled drainage of all crops	Cotton – 0.7m Wheat – 0.8m Maize – 0.6m Berseem – 1m	Salt buildup becomes prohibitive	(49.8)
Controlled drainage of all crops	Cotton – 1m Wheat – 1m Maize – 0.9m Berseem – 1m	Salt buildup becomes prohibitive	(38.6)

There is thus potential to achieve large water savings when controlled drainage is applied to 2 or more crops in the rotation. Controlled drainage of summer crops has larger potential water saving than for winter crops, because more water is applied in summer to match higher evapotranspiration demands, and drainage losses are subsequently higher. In this example controlled drainage for all crops gives water savings of up to 50%, but also leads to large predicted increases in soil salinity, and crop yield reductions, particularly for maize and berseem. In other circumstances, controlled drainage of all crops in the rotation could provide significant water savings, without detrimental impacts to soils or crops.

3.8 Conclusions from demonstration application

The demonstration considered two common crop rotations used in the Nile Delta, Egypt and developed controlled drainage strategies appropriate to the selected typical soil type and irrigation water source. The developed strategies maximised potential water savings for each crop rotation, whilst maintaining crop production (crop yield reduction less than 5%) and protecting the soil from salinity buildup over the 20-year simulation period.

The results obtained will be very dependent on site specific parameters such as soil type, irrigation water quality and the crops grown, the quality of the irrigation water and the particular crop rotation. The CDWaSim software assists in making informed decisions on application of controlled drainage in different areas, based on predicted crop and soil response under different controlled drainage strategies.

Having developed a controlled drainage strategy the next stage is to carry out an economic assessment of the costs and benefits of at the specific location. This is described in the next chapter.

4. ECONOMIC ASSESSMENT OF CONTROLLED DRAINAGE

4.1 Background

A framework has been developed for economic appraisal of controlled drainage in irrigated (or rain-fed) areas. It is available as a spreadsheet model that takes account of variations in cropping patterns, farming productivity and systems, financial and economic prices, water use efficiencies and the cost of drainage technology. It provides estimates of returns to farmers and the wider society, and the Net Present Value (NPV) and Internal Rate of Return (IRR)[1] of an investment in controlled drainage. The model facilitates sensitivity analysis with respect to key assumptions, for example it can be used to rapidly assess the impact of different cropping patterns, water-use efficiencies, and cost assumptions.

4.2 Benefits and costs

A summary of the main costs and benefits of controlled drainage is given in the following table.

Table 3 Benefits and Costs of Controlled Drainage

Benefits to farmers	**Costs to farmers**
Savings in pumping costs (if applicable). Savings in irrigation labour. Savings in fertiliser and other inputs. Increased yields (where water deficits or poor water quality constrain yields). Maintenance of crop yields in water short years. Switch in cropping pattern to water intensive crops with higher returns.	Charges to farmers to recover capital costs of controlled drainage. Cost of weir installations. On farm operation and maintenance costs.
Benefits to 'economy/society'	**Costs to 'economy/society'**
Value of farmer benefits expressed in economic/social values (eg adjusting for economic price of labour saved, fertiliser, commodity prices). Value of water saved for other uses. Reduced pollution of water resources. Potential longterm reductions in irrigation and drainage capacity, and related capital and operating costs. Reduced environmental damage. Public health benefits.	Value of farmer costs expressed in economic/social values (eg net of taxes). Potential risks associated with waterlogging and salinity problems.

[1] Calculation of the IRR on an investment is the method most commonly used to compare projects competing for funds. The calculation applies discount rates to flows of money in and out of the project, so that the expected costs and benefits can be brought to present day values. Summing costs and benefits over the project life gives a net present value (NPV), which will be negative if the costs exceed the benefits. The IRR is calculated as the interest or discount rate that would result in an NPV of zero. The IRR should exceed the prevailing discount rate for the type of project being considered if the project is to be economically worthwhile. It should be noted that due to the discounting of future costs and benefits neither the costs incurred nor benefits obtained in the later years of a project have much impact on the result. A high IRR does not provide any indication of sustainability or future environmental impacts. Other indicators need to be considered to determine if a controlled drainage project will be sustainable and environmentally acceptable.

Both benefits and costs of controlled drainage are seen at different levels in the irrigation sector. Farmers may obtain some direct benefit due to savings in irrigation labour and other input costs. They may also benefit from improvements in water quality and/or quantity, leading to improved yields or quality of crop production. However in some locations they may incur additional costs through charges to recover the costs of investment in and maintenance of controlled drainage. The largest benefits of controlled drainage are obtained by the wider irrigation sector, rural society and the economy as a whole, rather than directly by individual farmers. Much will depend on how the potential benefits to the wider community are passed on to individual farmers in the form of incentives to adopt and use the technology.

4.3 Economic assessment module for controlled drainage

The module consists of linked worksheets within an Excel spreadsheet containing a number of linked tables. The module is included in Appendix G. The user has access to the areas into which data are entered, and the results - the rest of the calculation sheets are hidden and protected. It was developed initially to carry out indicative assessments of controlled drainage in the context of Egyptian agriculture. However it can be adapted for use in any location, through input of appropriate local data and selection of appropriate units for currency and land area. Notes on the use of the spreadsheet are given in Appendix F.

Financial and technical data are required for a wide range of parameters. This information will be drawn from a number of sources. For example information on cropping patterns, crop yields and irrigation efficiencies may be available from irrigation departments, while economic data might be obtained from a National Statistics office or Ministry of Finance. Alternative sources may be University departments or external organisations such as the World Bank. A full list of the input data needed and discussion as to how this can be obtained is contained in Appendix F.

Output from the module provides a range of indicators comparing conventional irrigation and drainage management with controlled drainage. These include:

Volumes of water “saved” at system and field level.

Net margins (financial and economic) with and without controlled drainage, at the farm level (excluding the value of water “saved”) and at the higher level, (including the value of water “saved”).

Financial and economic appraisal of investment (NPV and IRR), again including and excluding the value of water “saved”.

4.4 Economic analysis of controlled drainage in Egypt

The benefits and costs of introducing controlled drainage will vary between locations, and an economic appraisal should be carried out for the sites of interest. Some guidance on the economic benefits can be obtained from the results of an initial appraisal of controlled drainage for different crop rotations in Egypt (Morris, 2001). For these assessments a modified drainage system design was considered (see section 2.6) with associated cost implications, no change in crop yield was assumed, and all performance indicators relate to comparison with the conventional management scenario.

A summary of the key results is given in the table below.

Table 4 Key results from trial application of the economic assessment module to controlled drainage of different crop rotations in the Nile Delta

Cropping pattern *		Unit	A	B	C	D	E
			3 yr	3 yr	2 yr	2 yr	New-lands
Winter 100%	Wheat	% of land area	33	67	50	50	50
	Berseem, short	% of land area	33	17	50	0	0
	Berseem, long	% of land area	17	0	0	25	25
	Beans	% of land area	17	16	0	25	25
Summer 100%	Maize	% of land area	34	33	50	50	75
	Rice	% of land area	33	67	0	50	0
	Cotton	% of land area	33	0	50	0	0
Performance Indicators							
Water saving		m^3/ha/yr	3370	5048	1631	4300	1492
Financial savings (excluding water)		*$/ha/yr*	19	29	10	25	9
Economic savings (excluding water)		*$/ha/yr*	23	34	11	29	10
Financial savings (including water)		*$/ha/yr*	157	186	92	178	83
Economic savings (including water)		*$/ha/yr*	133	136	87	129	61
Financial IRR% (excluding water)		%	10.4	19	0	15	-2
Economic IRR% (excluding water)		%	13.4	23	2	19	0.5
Financial IRR% (including water)		%	121	143	70	138	63
Economic IRR% (including water)		%	101	104	65	96	44

* For example cropping pattern A is a 3 year crop rotation – for the first year cotton (summer season) and wheat (winter) season are grown, for the second year maize (summer season) and short berseem (winter season) are grown, and for the third year rice is grown in summer and in the winter half the fields are long berseem and half are beans.

The main conclusions are:

Controlled drainage offers greatest advantage in rice growing areas (rotations A, B and D) because of the much larger scope for increased water use efficiency. In these cases the IRR (including the value of water saved) exceeds 100%.

Direct benefits to farmers are relatively modest, and relate to savings in labour (16%), pumping costs (72%), and fertiliser (12%), depending on cropping patterns. This is just sufficient to recover the additional average annual capital and maintenance costs of controlled drainage[2]. Controlled drainage involves an additional management burden and cost which in Egypt is borne by farmers. Farmers may not perceive that a technology which reduces the quantity of water delivered to them, at an additional charge, with relatively limited direct benefits, is particularly attractive. Indeed, the technology may increase their

[2] In systems with gravity supply where farmers do not need to pump water the benefits to individual farmers in areas with a reliable water supply will be very small unless improved yield are obtained. .

exposure to perceived risk. Large potential benefits accrue off-farm, and may be appropriate to recover the additional cost of controlled drainage at sector or regional level, rather than discriminate against those farmers who adopt the technology.

The key assumption determining the financial and economic performance of controlled drainage is whether or not the technology actually "saves" water that otherwise would be lost. The analysis shows large financial and economics returns when the value of the water "saved" is included. For example with a typical 3 year rice rotation, controlled drainage would produce a benefit from the water saved of around US$ 190/ha/year). Where this is the case, the IRR% of the extra investment exceeds 100%. In the majority of cases in Egypt, given the common practice of drainage water re-use, the extent to which controlled drainage adds to total water availability is probably limited to the Lower Delta and New-lands. However there are other benefits, not quantified in the analysis, in terms of the better quality of "saved" water when compared with water that has been re-used.

Where farmers can achieve improved yields the benefits of controlled drainage are potentially very large. This is illustrated in the table below which shows the impact of reduced and increased crop yields on the analysis for crop rotation A.

Table 5 The impact of changes in crop yield on the economic analysis of controlled drainage for crop rotation A

Performance Indicators	**Unit**	**No change in crop yield**	**With 5% reduction in crop yield**	**With 5% increase in crop yield**
Water saving	m^3/ha/yr	3370	3370	3370
Financial savings (excluding water)	*$/ha/yr*	19	-73	111
Economic savings (excluding water)	*$/ha/yr*	23	-61	106
Financial savings (including water)	*$/ha/yr*	157	49	264
Economic savings (including water)	*$/ha/yr*	133	36	230
Financial IRR% (excluding water)	%	10.4	0	83.4
Economic IRR% (excluding water)	%	13.4	0	79.2
Financial IRR% (including water)	%	121	34	204.5
Economic IRR% (including water)	%	101	23.1	177.6

A modest increase in average yields due to controlled drainage would thus make investment in controlled drainage very attractive to a farmer.

The impact of controlled drainage varies considerably according to local circumstances. Location specific data is essential on order to apply the analysis at locations where controlled drainage could make a significant contribution. In Egypt there appear to be substantial benefits in rice production areas. The potential benefits in non-rice areas depend on the extent to which water quantity or quality is a constraint, and the extent to which saved water can be used productively.

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Other inputs were provided by Christian Counsell, Phil Lawrence, Felicity Chancellor, Ed Atkinson and Crispin Angood.

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Appendices

Appendix A

CDWaSim User Notes

Appendix A CDWaSim User Notes

Introduction

The WaSim User Manual, Tutorial Manual and Technical Manual contain the information required to run the WaSim model, together with algorithms used by the model, and a training tutorial. These notes present additional information required to run the controlled drainage version (CDWaSim) of WaSim, and should be used in conjunction with the above manuals.

What is CDWaSim?

The CD version of WaSim enables a number of features that are not normally available in WaSim. These were introduced primarily to allow the simulation of controlled drainage but may be useful for other simulations. In particular, it allows;

- Setting the head at the drain outfalls to simulate the use of weirs in drainage channels.
- Drainage flow to be turned off ('CLOSED') for periods of time to simulate blocking of the drains.
- Specification of a daily lateral seepage into, or out of the area that varies on a daily basis over time.
- Variation of the salinity of irrigation water over time.
- Four crops in the rotation.
- Separation of the effects of salinity and water stress.
- Calculation of an excess water index for waterlogging stress (SEW_{30}).

Starting CDWaSim

The WaSim programme has been modified to allow the use of a controlled drainage version. A CD containing the software is included as Appendix G. Follow the installation instructions on the CD. Once installed this option can be enabled by right clicking on the WaSim shortcut icon, selecting **Properties, Shortcut, Target** and adding ' _CD' at the end of the existing text. The procedure is completed by clicking 'OK'.

The program confirms that the user has enabled the controlled drainage version of WaSim by displaying the statement "This is the controlled drainage version of WaSim" as the program is opened.

The CDWaSim main screen appears identical to the WaSim main screen, except that the menu contains an additional **controlled drainage** item. This menu item provides "shortcuts" to the **Define inputs** and **View results** screens

Setting Up and Input Data

Input data on soil, weather, crops, irrigation and run parameters are entered as normal except for the following points:

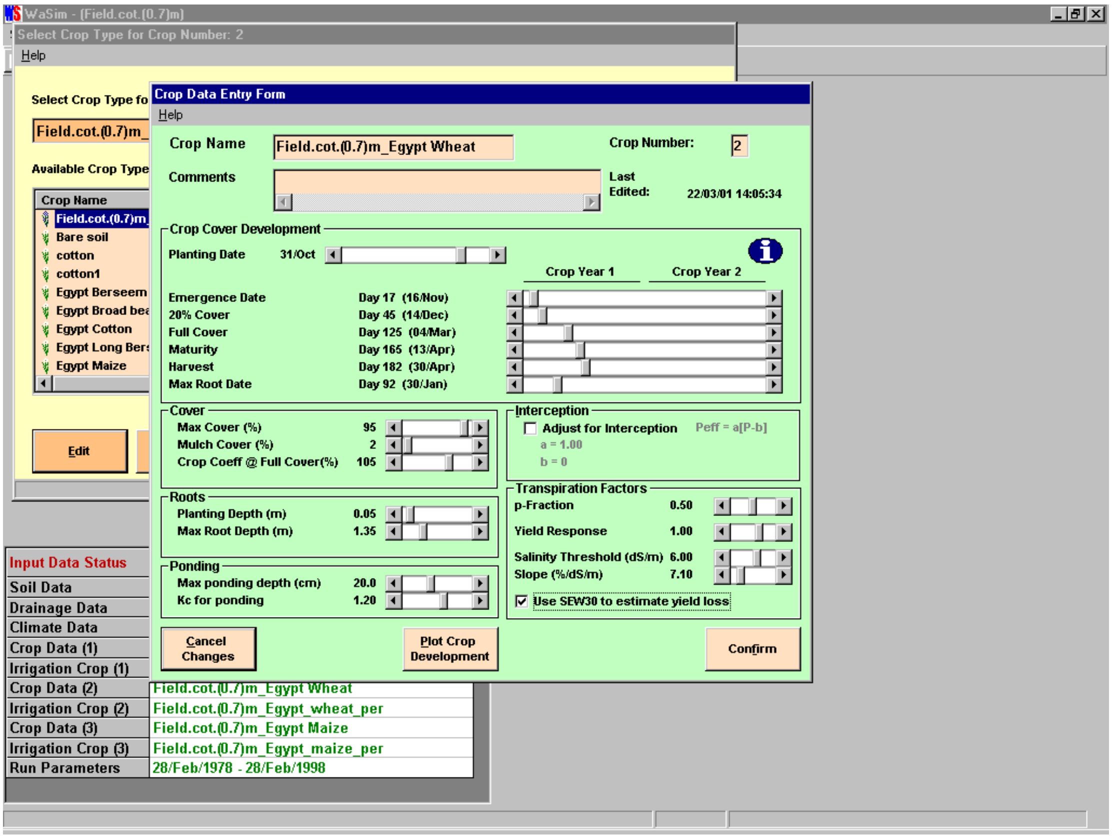
Fourth crop
CDWaSim allows the user to include a fourth crop in the rotation. (WaSim allows for just three crops in the rotation.) This crop is entered by selecting **Input**, **Crops, Fourth Crop (CD)** and defining a crop file as before. (Note: this fourth crop does not appear in the **Input, Crops, View cropping sequence** option.)

Irrigation schedule for fourth crop
The irrigation schedule for the fourth crop is entered by selecting **Input, Irrigation, Fourth crop schedule (CD)** and defining the irrigation schedule as before.

Wet stress

CDWaSim includes the option to calculate the crop wet stress using the SEW_{30} method (see Appendix B). To enable this option, tick the check box 'Use SEW_{30} to estimate yield loss' in the crop data entry screen. An example is shown in figure A1. This is done separately for each crop in the rotation. If the check box is left unchecked, no yield loss due to wet stress is calculated for that crop.

Figure A1 Example crop data entry screen

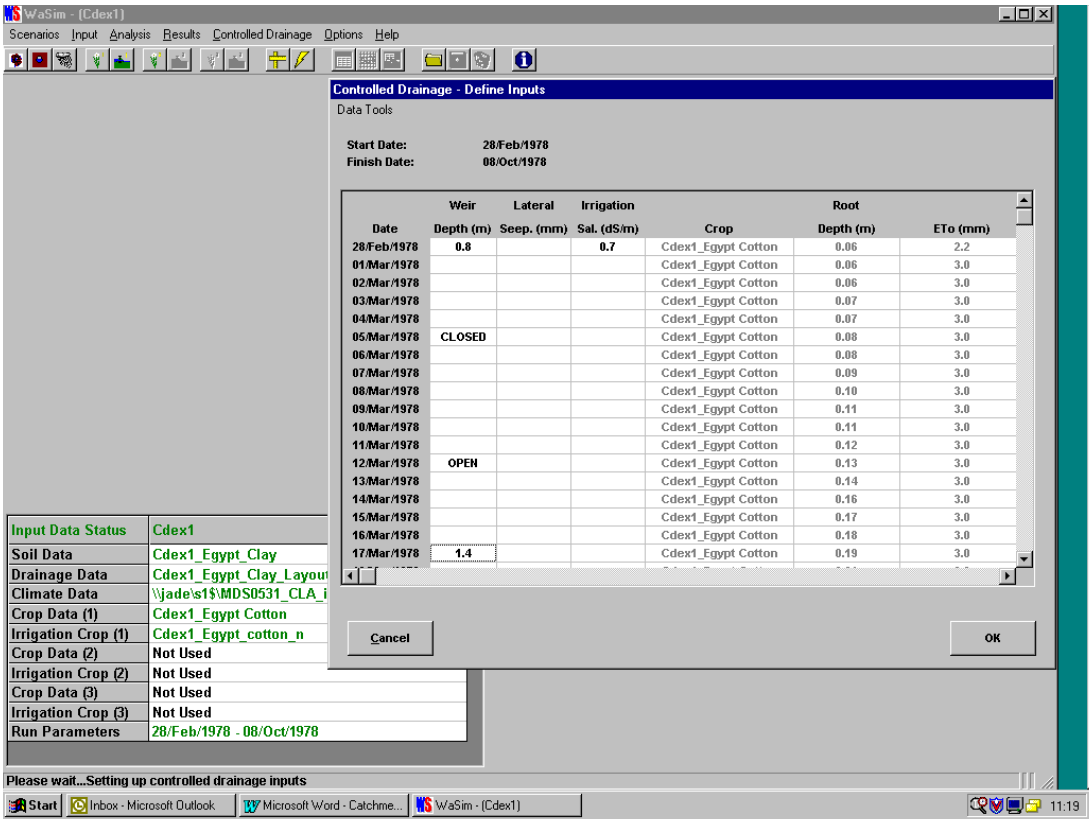


Controlled drainage inputs

This option can be used if drainage has been installed and the drain flow is going to be regulated by controlled drainage.

Once the user has defined the run parameters (including duration of the run) the controlled drainage input screen is accessed by selecting **Controlled Drainage, Define inputs** from the tool bar. This screen is shown in figure A2.

Figure A2 Example controlled drainage input screen



The controlled drainage input screen displays the start and finish dates for the simulation, the crop (file), root depth and ETo for each day of the simulation, from the data previously entered, see figure A1. The screen enables the user to input **weir depth, lateral seepage** and **irrigation salinity** as follows:

Weir depth
Controlled drainage is simulated using weirs or "on/off" devices such as flap gates. In the **weir depth** column the user enters:

- a controlled drainage weir depth (metres below surface) which must be less than or equal to the drain depth, or
- 'OPEN' to indicate normal drainage flow ("on"), or
- 'CLOSED' to indicate no discharge from drains ("off").

If no entry is added on a given day, the last entered value is carried forward. If there is no entry on day 1 of the simulation, drainage is assumed to be 'OPEN' until the next entry.

Daily lateral seepage
CDWaSim allows a varying daily **lateral seepage** amount (mm) to be included in the daily water balance calculation. (WaSim only allows one constant daily value to be applied per simulation.) A positive (+) value indicates seepage is into the plot, whilst a negative value (-) indicates seepage is out of the plot. Zero is assumed if no number is entered on a given day.

Irrigation water salinity
CDWaSim allows the **irrigation water salinity** (dS/m) to be altered on a daily basis. (WaSim allows only one value to be applied per crop, entered in the irrigation schedule.) With CDWaSim this data overrides

the entry in the irrigation schedule. If no entry is added on a given day, the last entered value is carried forward.

Running the model

CDWaSim is run in the same manner as the parent model. Results are saved as before.

Viewing Results

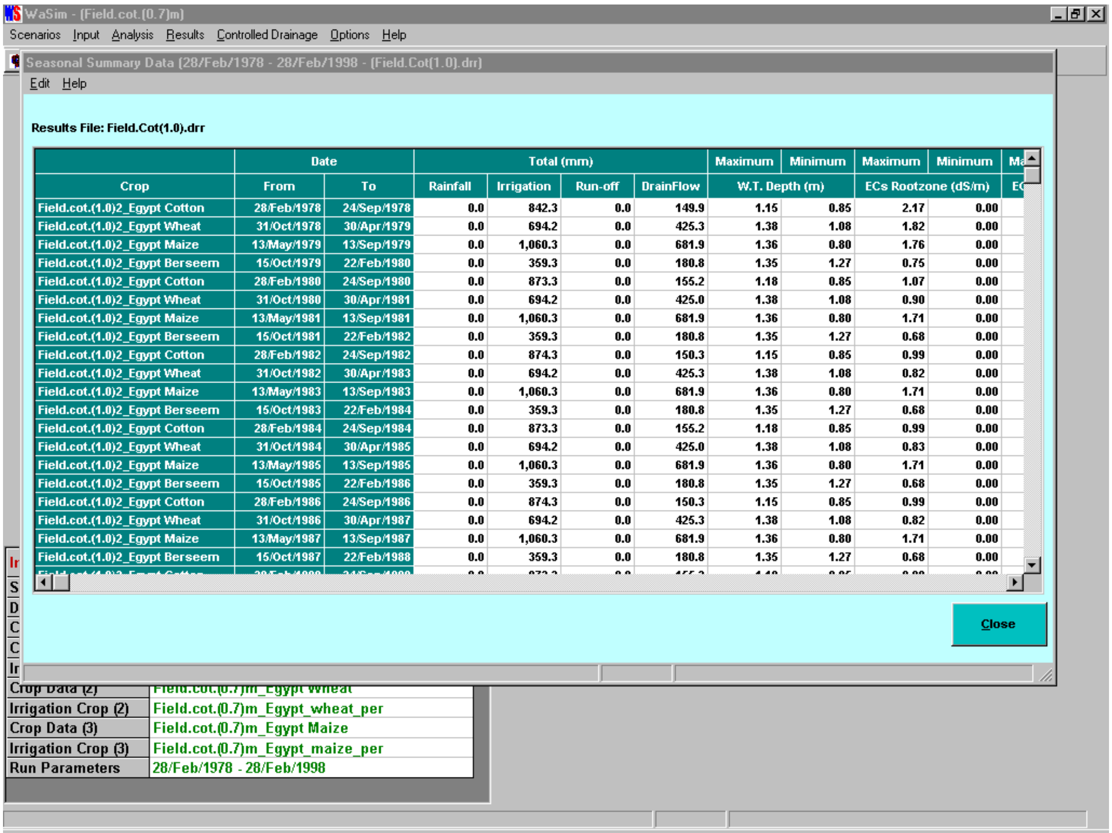
The results file is imported as before. With CDWaSim the results can be viewed in two ways. Results can be viewed in a summary format or on a daily basis as below:

Results Summary

To view the results summary select **Results, View summary results**. Then select which run to view, and whether to view a **seasonal** (crop season), **monthly** or **annual** summary.

As with WaSim the summary table gives information on rainfall, irrigation, runoff, deep percolation and relative yield. However with CDWaSim the relative yield is subdivided into 3 columns. The first column “moisture” is a measure of the stress due to water deficit, the second column “salinity” is a measure of the stress due to salinity, and the third column “total” is the product of the two stresses. These can be used to estimate the impact on yield. An example is shown below.

Figure A3 Example controlled drainage results summary screen

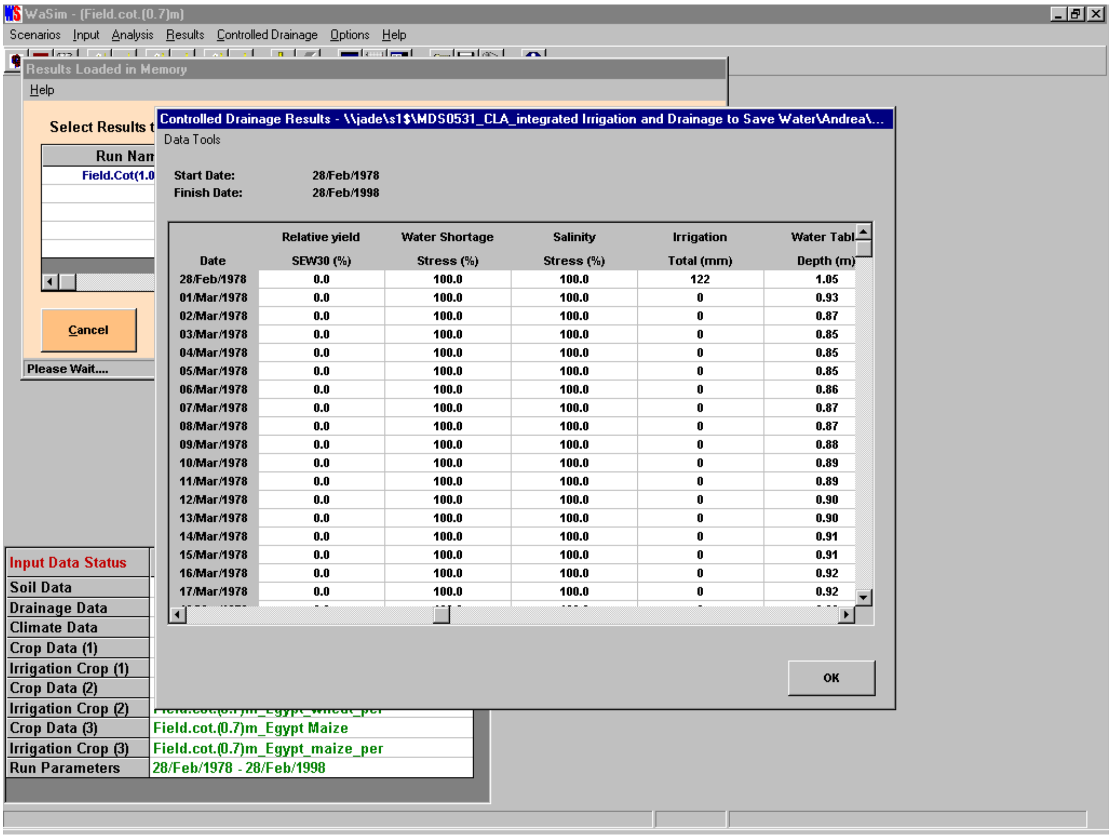


	Date		Total (mm)				Maximum	Minimum	Maximum	Minimum
Crop	From	To	Rainfall	Irrigation	Run-off	DrainFlow	W.T. Depth (m)		ECs Rootzone (dS/m)	
Field.cot.(1.0)2_Egypt Cotton	28/Feb/1978	24/Sep/1978	0.0	842.3	0.0	149.9	1.15	0.85	2.17	0.00
Field.cot.(1.0)2_Egypt Wheat	31/Oct/1978	30/Apr/1979	0.0	694.2	0.0	425.3	1.38	1.08	1.82	0.00
Field.cot.(1.0)2_Egypt Maize	13/May/1979	13/Sep/1979	0.0	1,060.3	0.0	681.9	1.36	0.80	1.76	0.00
Field.cot.(1.0)2_Egypt Berseem	15/Oct/1979	22/Feb/1980	0.0	359.3	0.0	180.8	1.35	1.27	0.75	0.00
Field.cot.(1.0)2_Egypt Cotton	28/Feb/1980	24/Sep/1980	0.0	873.3	0.0	155.2	1.18	0.85	1.07	0.00
Field.cot.(1.0)2_Egypt Wheat	31/Oct/1980	30/Apr/1981	0.0	694.2	0.0	425.0	1.38	1.08	0.90	0.00
Field.cot.(1.0)2_Egypt Maize	13/May/1981	13/Sep/1981	0.0	1,060.3	0.0	681.9	1.36	0.80	1.71	0.00
Field.cot.(1.0)2_Egypt Berseem	15/Oct/1981	22/Feb/1982	0.0	359.3	0.0	180.8	1.35	1.27	0.68	0.00
Field.cot.(1.0)2_Egypt Cotton	28/Feb/1982	24/Sep/1982	0.0	874.3	0.0	150.3	1.15	0.85	0.99	0.00
Field.cot.(1.0)2_Egypt Wheat	31/Oct/1982	30/Apr/1983	0.0	694.2	0.0	425.3	1.38	1.08	0.82	0.00
Field.cot.(1.0)2_Egypt Maize	13/May/1983	13/Sep/1983	0.0	1,060.3	0.0	681.9	1.36	0.80	1.71	0.00
Field.cot.(1.0)2_Egypt Berseem	15/Oct/1983	22/Feb/1984	0.0	359.3	0.0	180.8	1.35	1.27	0.68	0.00
Field.cot.(1.0)2_Egypt Cotton	28/Feb/1984	24/Sep/1984	0.0	873.3	0.0	155.2	1.18	0.85	0.99	0.00
Field.cot.(1.0)2_Egypt Wheat	31/Oct/1984	30/Apr/1985	0.0	694.2	0.0	425.0	1.38	1.08	0.83	0.00
Field.cot.(1.0)2_Egypt Maize	13/May/1985	13/Sep/1985	0.0	1,060.3	0.0	681.9	1.36	0.80	1.71	0.00
Field.cot.(1.0)2_Egypt Berseem	15/Oct/1985	22/Feb/1986	0.0	359.3	0.0	180.8	1.35	1.27	0.68	0.00
Field.cot.(1.0)2_Egypt Cotton	28/Feb/1986	24/Sep/1986	0.0	874.3	0.0	150.3	1.15	0.85	0.99	0.00
Field.cot.(1.0)2_Egypt Wheat	31/Oct/1986	30/Apr/1987	0.0	694.2	0.0	425.3	1.38	1.08	0.82	0.00
Field.cot.(1.0)2_Egypt Maize	13/May/1987	13/Sep/1987	0.0	1,060.3	0.0	681.9	1.36	0.80	1.71	0.00
Field.cot.(1.0)2_Egypt Berseem	15/Oct/1987	22/Feb/1988	0.0	359.3	0.0	180.8	1.35	1.27	0.68	0.00

Daily Results

To view the daily results select **Controlled Drainage, View Results** and then the run to view. The daily data displayed are the same as in the controlled drainage input screen, with the addition of information on actual evapotranspiration, relative transpiration, irrigation, water table depth, and moisture content and salinity in different soil layers. An example is shown below.

Figure A4 Example controlled drainage daily results screen



Information on predicted daily crop stresses is given in three columns. The first column "relative yield SEW_{30} (%)" is a measure of the wet stress estimated using the SEW_{30} method. (If the user chose not to calculate the wet stress, the column contains the entry 100% throughout). The second column "water shortage stress (%)" is an estimation of crop stress due to water shortage. The third column "salinity stress (%)" is a measure of the stress due to salinity. These columns can be used to estimate the impact on crop yield.

Appendix B

CDWaSim Technical Notes

Appendix B CDWaSim Technical Notes

Introduction

The WaSim User Manual, Tutorial Manual and Technical Manual contain the information required to run the WaSim model, together with algorithms used by the model, and a training tutorial. These notes present additional technical information on the algorithms used in the CDWaSim model. They should be viewed in conjunction with the above manuals.

Drainage flow in response to weir depth setting

The daily change in water table level due to drainage is calculated from (Youngs et al., 1989).

$$\Delta h = \frac{K}{\mu\left(\frac{L}{2}\right)^{\beta}}\left(\left(\frac{\varphi}{2}\right)^{\beta} - h^{\beta}\right)$$

where

h	mid-drain head, m
K	saturated hydraulic conductivity, m d^{-1}
μ	drainable porosity, dimensionless
L	drain spacing, m
ϕ	ditch water level or drain diameter, m
β	exponent dependant on the depth to the impermeable layer, m^{-1}

For each day of the simulation the head at the drain outfall can be specified by a weir depth (depth below surface). Three conditions are permitted;

- 'OPEN'. Free discharge from the drains. Model operates as for normal drained situation. h = water table position, m above drain depth.
- 'CLOSED'. No discharge from the drains. Model operates as for undrained situation and $h = 0$.
- Weir level. A value between 0 and drain depth gives the weir level (m below surface). If the water table is below the weir level, $h = 0$, otherwise, h = water table position, m above weir level.

Variable irrigation water salinity

The electrical conductivity of the irrigation water, EC_w, can be varied daily (in the controlled drainage input screen). This over-rides any value set in the irrigation screen.

Lateral seepage

The daily lateral seepage ($+^{ve}$ value indicates flow is into the plot) can be varied daily. This over-rides any value set in the drainage screen.

Wet Stress

With CDWaSim the user has the option to estimate the crop stress due to excess water using a modification of the SEW approach.

The most widely accepted approach for assessment of the impacts of a fluctuating watertable on crop response over the growing season is the use of the concept of SEW (sum of the excess water). This was originally defined by Sieben (1964), and developed by Wesseling (1974) and Bouwer (1974) as a means of quantifying wet stress.

This may be expressed (Evans and Fausey, 1999) as:

$$SEW_x = \sum_{j=1}^{n} X - y_{ij}$$

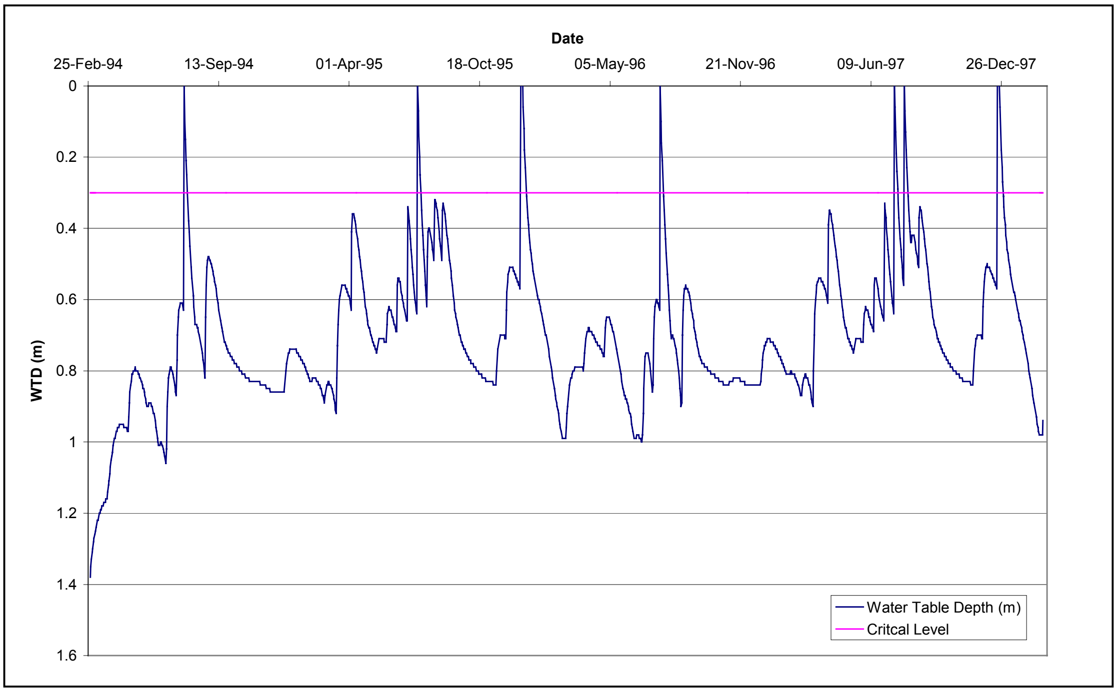
where

X is the critical watertable depth that will cause wet stress (SD_w) during growth stage *i*.
y_{ij} is the watertable depth below the soil surface on day *j* during growth stage *i*.
n is the number of days in the growth period being considered.

Thirty centimetres has been adopted as the critical depth for most crops by most workers, so the SEW_{30} value has units of cm-days.

An example watertable plot highlighting periods of wet stress is shown in figure B1.

Figure B1 Watertable depth through the crop season, showing periods of wet stress



The calculated value of SEW_{30} (x) is translated into a crop yield (Y%) using the relationship below:

$SEW_{30} < 50 \qquad Y\% = 100$

$50 < SEW_{30} < 100 \qquad Y\% = 99$

$100 < SEW_{30} < 830 \qquad Y\% = -0.0002 \cdot x^2 + 0.0522 \cdot x + 95.3$

$SEW_{30} > 830 \qquad Y\% = 0$

This is illustrated in Figure B2

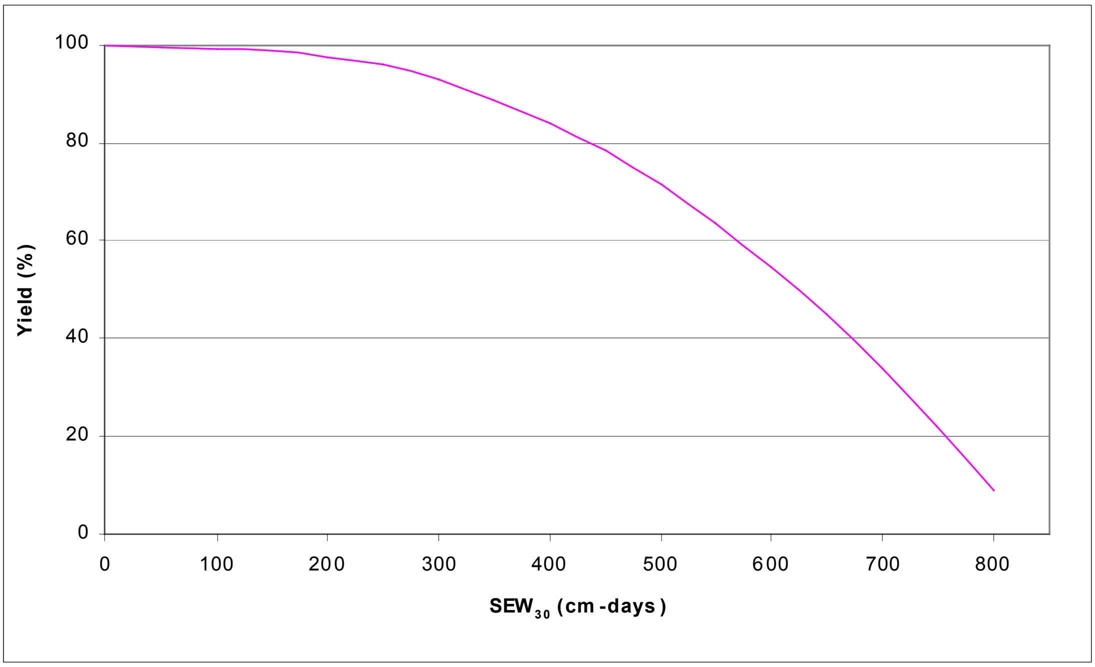


Figure B2 Crop yield v SEW_{30} relation used in CDWaSim

Appendix C

Input data used for the CDWaSim demonstration

Appendix C Input data used for the CDWaSim demonstration

Soil Data

Soil parameter	Sandy silt loam
Saturation (%)	48
Field capacity (%)	33
Permanent Wilting point (%)	26
Saturated paste (%)	88
Drainage coefficient τ	0.51
Hydraulic conductivity (m/d)	2
Curve number	89
Leaching efficiency (%)	90

Drainage System Data

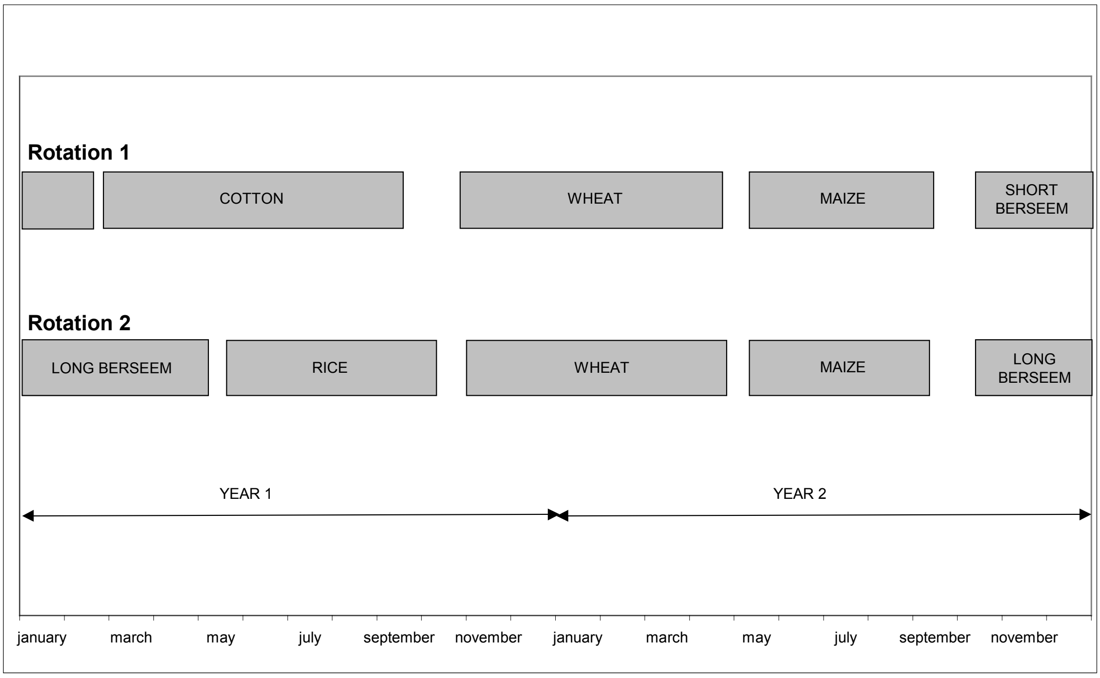
Drainage Parameter	Value adopted	Source
Depth	1.4m	Standard Egyptian design -Drainage in Egypt book
Diameter	0.08m	Used at field site
Spacing	33m	Used at field site
Depth to impermeable layer	10m	Local knowledge

Climate Data

Date	Daily ET_o (mm)	Rainfall (mm)
January	1.6	0
February	2.2	0
March	3	0
April	4	0
May	4.9	0
June	5.6	0
July	5.6	0
August	5.3	0
September	4.4	0
October	3.3	0
November	2.2	0
December	1.6	0

Data repeated for each day of the month and for every year of the simulations.

Crop Rotations



Other Data

Crop Parameter	Value adopted for cotton	Value adopted for wheat	Source
Crop Cover Development			
Planting date	28 Feb	31 October	Local knowledge
Emergence date	26 Mar	16 Nov	"
20% cover	4 May	14 Dec	"
Full cover	20 Jul	4 Mar	"
Maturity	2 Sept	13 April	"
Harvest	24 Sept	30 April	"
Max root date	26 May	30 Jan	"
Cover			
Max cover	95%	95%	Local knowledge
Mulch cover	2%	2%	' '
Crop coefficient at full cover	115	105	FAO Guidelines
Roots			
Planting depth m	0.05	0.05	Default value
Max root depth m	1.2	1.35	FAO Guidelines
Ponding			
Max ponding depth m	0.2	0.2	Field observation
Kc for ponding	1.2	1.2	FAO Guidelines
Transpiration Factors			
p-fraction	0.65	0.5	FAO Guidelines
Yield response	0.85	1.0	Local knowledge
Salinity threshold	7.7dS/m	6 dS/m	FAO Guidelines & Local knowledge
Slope	5.2 %/dS/m	7.1 %/dS/m	

Crop Parameter	Value adopted for maize	Value adopted for short berseem	Source
Crop Cover Development			
Planting date	13 May	15 Oct	FAO Guidelines
Emergence date	2 June	2 Nov	‘ ’
20% cover	7 Jul	28 Dec	‘ ’
Full cover	24 Jul	1 Feb	‘ ’
Maturity	31 Aug	21 Feb	‘ ’
Harvest	13 Sept	22 Feb	‘ ’
Max root date	14 Aug	20 Feb	‘ ’
Cover			
Max cover	95%	95%	Field observation
Mulch cover	2%	2%	‘ ’
Crop coefficient at full cover	114	115	FAO guidelines
Roots			
Planting depth m	0.05	0.05	Default value
Max root depth m	1.2	0.75	FAO guidelines
Ponding			
Max ponding depth m	0.2	0.2	Field observation
Kc for ponding	1.2	1.2	FAO guidelines
Transpiration Factors			
p-fraction	0.56	0.5	FAO guidelines
Yield response	1.25	1.0	Local knowledge
Salinity threshold	1.7 dS/m	1.5 dS/m	FAO guidelines
Slope	12 %/dS/m	5.7 %/dS/m	

Crop Parameter	Value adopted for rice	Value adopted for long berseem	Source
Crop Cover Development			
Planting date	15 May	15 Oct	FAO Guidelines
Emergence date	3 June	3 Nov	‘ ’
20% cover	3 Jul	3 Dec	‘ ’
Full cover	2 Aug	22 Jan	‘ ’
Maturity	11 Sept	13 Mar	‘ ’
Harvest	11 Oct	29 Apr	‘ ’
Max root date	22 Aug	2 Jan	‘ ’
Cover			
Max cover	95%	95%	Field observation
Mulch cover	2%	2%	‘ ’
Crop coefficient at full cover	105	115	FAO Guidelines
Roots			
Planting depth m	0.05	0.05	Default value
Max root depth m	1.0	1.4	FAO Guidelines
Ponding			
Max ponding depth m	0.2	0.2	Field observation
Kc for ponding	1.2	1.2	FAO Guidelines
Transpiration Factors			
p-fraction	0.2	0.55	FAO Guidelines
Yield response	1.0	1.0	Local knowledge
Salinity threshold	3 dS/m	1.5 dS/m	FAO Guidelines
Slope	12 %/dS/m	5.7 %/dS/m	

Initial Conditions Data

Initial Conditions	"fresh"
Irrigation water salinity dS/m	0.7
Rootzone salinity dS/m	2.27
Saturated soil salinity dS/m	2.27
Groundwater salinity dS/m	6.95
Simulation start date	28 February 1978 (rot 1), 15 May 1978 (rot 2)
Simulation end date	28 February 1998 (rot 1), 15 May 1998 (rot 2)
Initial soil water content	Field capacity
Initial watertable depth	Drain depth – 1.4m

Irrigation Schedules for Conventional Management

Rotation 1

Irrigation schedule for 2-year crop rotation of cotton, wheat, maize and short berseem.
(Average irrigation amounts applied in "conventional" scenario.)

COTTON	Amount mm	WHEAT	Amount mm
28-Feb	155.3	24-Oct (pre-irrigation)	(29)
26-Mar	116.7	31-Oct	127.9
21-Apr	118.3	28-Nov	106.6
17-May	128.0	26-Dec	108.0
12-Jun	159.2	23-Jan	109.9
8-Jul	190.0	20-Feb	126.9
3-Aug	199.0	20-Mar	148.4
29-Aug	198.0		
Total	1264.8	Total	727.9 (756.9)

MAIZE	Amount mm	SHORT BERSEEM	Amount mm
4-May (pre-irrigation)	(69)	07-Oct (pre-irrigation)	(63.0)
13-May	172.0	15-Oct	82.8
29-May	133.0	31-Oct	51.0
14-Jun	135.0	16-Nov	52.0
30-Jun	136.0	02-Dec	54.0
16-Jul	147.0	18-Dec	51.0
1-Aug	187.0	03-Jan	50.0
17-Aug	188.0	19-Jan	51.0
Total	1098.3 (1167.3)	Total	392.1 (455.1)
		Rotation Total	3483.1 (3644.1)

Rotation 2

Irrigation schedule for 2-year crop rotation of rice, wheat, maize and long berseem.
(Average irrigation amounts applied in “conventional” scenario.)

RICE	Amount mm	WHEAT	Amount mm
15-May	171.6	24-Oct (pre-irrigation)	(6)
18-May	54.0	31-Oct	118.0
21-May	60.0	28-Nov	107.0
24-May	58.0	26-Dec	108.0
27-May	59.0	23-Jan	110.0
30-May	59.0	20-Feb	127.0
2-Jun	59.0	20-Mar	149.0
5-Jun	59.0		
8-Jun	59.0		
11-Jun	58.0		
15-Jun	52.0		
19-Jun	56.0		
23-Jun	54.0		
27-Jun	54.0		
1-Jul	54.0		
5-Jul	52.0		
9-Jul	52.0		
13-Jul	52.0		
16-Jul	61.0		
19-Jul	53.0		
22-Jul	55.0		
25-Jul	56.0		
28-Jul	57.0		
31-Jul	58.0		
3-Aug	58.0		
6-Aug	59.0		
9-Aug	59.0		
12-Aug	59.0		
15-Aug	60.0		
18-Aug	59.0		
21-Aug	60.0		
25-Aug	17.0		
29-Aug	47.0		
2-Sep	34.0		
6-Sep	33.0		
10-Sep	33.0		
14-Sep	33.0		
18-Sep	33.0		
Total	2108.1	Total	719.2 (725.2)

MAIZE	Amount mm	LONG BERSEEM	Amount mm
4-May (pre-irrigation)	(69)	15-Oct (pre-irrigation)	(63.0)
13-May	172.0	31-Oct	122.0
29-May	133.0	16-Nov	87.0
14-Jun	135.0	2-Dec	87.0
30-Jun	136.0	18-Dec	84.0
16-Jul	147.0	3-Jan	84.0
1-Aug	187.0	19-Jan	91.0
17-Aug	188.0	4-Feb	92.0
		20-Feb	95.0
		7-Mar	100.0
		23-Mar	105.5
		23-Mar	107.0
Total	1098.3 (1167.3)	Total	1054.5 (1117.5)
		Rotation Total	4980.1 (5118.1)

Appendix D

Output data from the CDWaSim demonstration

Appendix D Output data from the CDWaSim demonstration

Results Table

Rotation 1 – Cotton, wheat, maize, short berseem

Controlled Drainage During Cotton Season

	Crop	Conventional management	Controlled Drainage of Cotton – Weir Depths						
			1.3	1.2	1.1	1	0.9	0.8	0.7
Average Irrigation per Season (mm)	Cotton	1264	1128	1044	954	870	787	731	725
	Wheat	727	693	693	693	693	692	692	692
	Maize	1098	1060	1060	1060	1060	1060	1060	1060
	Berseem	392	358	358	358	358	358	358	358
Average ETa per Season (mm)	Cotton	648	655	666	668	671	670	658	659
	Wheat	318	319	319	319	319	319	319	319
	Maize	412	413	413	413	413	413	413	413
	Berseem	194	193	193	193	193	193	193	193
Average Drain Flow per Season (mm)	Cotton	612	457	351	249	152	65	22	15
	Wheat	460	425	425	425	425	425	425	425
	Maize	720	681	681	681	681	681	681	681
	Berseem	212	180	180	180	180	180	180	180
Crop "Yield" (%) – Cotton	Salinity + Dry Average *	92.8	93.9	95.5	95.8	96.3	95.6	92.9	92.7
	Salinity + Dry Minimum	92.3	93.5	95.3	95.6	96.1	95.3	92.3	92.1
	Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Crop "Yield" (%) – Wheat	Salinity + Dry Average *	97.1	97.4	97.4	97.4	97.4	97.4	97.4	97.4
	Salinity + Dry Minimum	97.0	97.3	97.3	97.3	97.3	97.3	97.3	97.3
	Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Crop "Yield" (%) – Maize	Salinity + Dry Average *	97.9	98.0	98.0	98.0	98.0	98.0	98.0	98.0
	Salinity + Dry Minimum	97.7	97.7	97.7	97.7	97.7	97.7	97.7	97.7
	Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Crop "Yield" (%) – Bersee	Salinity + Dry Average *	92.0	91.8	91.8	91.8	91.8	91.8	91.8	91.8
	Salinity + Dry Minimum	91.7	91.5	91.5	91.5	91.5	91.5	91.5	91.5
	Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Soil Salinity Fraction (final/initial)		0.261	0.285	0.288	0.290	0.292	0.293	0.294	0.294
Groundwater Salinity Fraction (final/initial)		0.25	0.29	0.31	0.33	0.35	0.37	0.37	0.38
Drainwater Salinity (final/initial)		0.27	0.30	0.32	0.43	0.45	0.46	0.47	0.47
Water Table Depth (final/initial)		0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Controlled Drainage Water Saving (%) per Crop Rotation		0.0	7.0	9.4	12.0	14.4	16.8	18.4	18.5
Controlled Drainage Water Saving (%) per Cotton Season		0.0	10.8	17.4	24.6	31.2	37.7	42.1	42.6

* Transpiration rate (%) including effect of salinity and dry stress.
** Transpiration rate (%) including effect of wet stress
[shaded box] = "optimum" weir depth

Results Table

Rotation 1 – Cotton, wheat, maize, short berseem

Controlled Drainage During Wheat Season

	Crop	Conventional management	Controlled Drainage of Wheat Weir Depths							
			1.3	1.2	1.1	1	0.9	0.8	0.7	0.6
Average Irrigation per Season (mm)	Cotton	1265	1227	1227	1227	1227	1227	1227	1227	1227
	Wheat	728	626	558	490	423	361	334	335	334
	Maize	1098	1056	1055	1054	1054	1054	1053	1054	1053
	Berseem	392	359	359	359	359	359	359	359	359
Average ETa per Season (mm)	Cotton	649	649	649	649	649	649	649	648	648
	Wheat	319	319	320	321	321	322	320	321	322
	Maize	413	413	413	413	413	413	413	412	412
	Berseem	194	194	194	194	194	194	194	194	194
Average Drain Flow per Season (mm)	Cotton	612	574	574	574	574	574	574	574	574
	Wheat	460	346	266	188	110	40	12	12	12
	Maize	721	682	682	682	682	682	682	682	682
	Berseem	212	180	180	180	180	180	180	181	181
Crop "Yield" (%) – Cotton	Salinity + Dry Average *	92.8	92.9	92.9	92.9	92.9	92.9	92.7	92.7	92.7
	Salinity + Dry Minimum	92.3	92.4	92.4	92.4	92.4	92.4	92.4	92.4	92.4
	Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Crop "Yield" (%) – Wheat	Salinity + Dry Average *	97.1	97.4	97.7	97.9	98.1	97.6	95.9	95.5	95.6
	Salinity + Dry Minimum	97.0	97.3	97.6	97.8	98.0	97.4	95.7	95.5	95.5
	Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Crop "Yield" (%) – Maize	Salinity + Dry Average *	97.9	98.0	98.0	98.0	98.0	98.0	98.0	98.1	98.1
	Salinity + Dry Minimum	97.7	97.7	97.7	97.7	97.7	97.7	97.7	98.1	98.1
	Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Crop "Yield" (%) – Bersee	Salinity + Dry Average *	92.0	91.8	91.8	91.8	91.8	91.8	91.8	91.2	91.2
	Salinity + Dry Minimum	91.7	91.5	91.5	91.5	91.5	91.5	91.5	91.2	91.2
	Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Soil Salinity Fraction (final/initial)		0.261	0.288	0.292	0.296	0.300	0.303	0.304	0.303	0.302
Groundwater Salinity Fraction (final/initial)		0.25	0.28	0.30	0.31	0.32	0.34	0.34	0.34	0.34
Drainwater Salinity (final/initial)		0.27	0.30	0.31	0.32	0.34	0.35	0.35	0.35	0.35
Water Table Depth (final/initial)		0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Controlled Drainage Water Saving (%) per Crop Rotation		0.0	6.2	8.2	10.1	12.1	13.9	14.7	14.6	14.7
Controlled Drainage Water Saving (%) per Wheat Season		0.0	14.0	23.3	32.6	41.9	50.4	54.2	54.0	54.1

* Transpiration rate (%) including effect of salinity and dry stress.

** Transpiration rate (%) including effect of wet stress

[shaded box] = "optimum" weir depth (0.8)

Results Table
Rotation 1 – Cotton, wheat, maize, short berseem

Controlled Drainage During Maize Season

	Crop	Conventional management	Controlled Drainage of Maize Weir Depths								
			1.3	1.2	1.1	1	0.9	0.8	0.7	0.6	0.5
Average Irrigation per Season (mm)	Cotton	1265	1227	1227	1227	1227	1227	1227	1227	1227	1227
	Wheat	728	697	697	697	697	697	697	697	697	698
	Maize	1098	978	895	810	737	664	593	534	516	514
	Berseem	392	359	358	358	358	358	358	358	358	359
Average ETa per Season (mm)	Cotton	649	649	649	649	649	649	649	649	649	649
	Wheat	319	319	319	319	319	319	319	319	319	321
	Maize	413	414	416	418	420	424	432	449	463	461
	Berseem	194	194	194	194	194	194	194	194	194	194
Average Drain Flow per Season (mm)	Cotton	612	574	574	574	574	574	574	574	574	574
	Wheat	460	429	429	429	429	429	429	429	429	429
	Maize	721	585	487	390	306	218	130	45	13	23
	Berseem	212	180	180	180	179	180	180	179	180	181
Crop "Yield" (%) – Cotton	Salinity + Dry Average *	92.8	92.9	92.9	92.9	92.9	92.9	92.9	92.9	92.9	92.9
	Salinity + Dry Minimum	92.3	92.4	92.4	92.4	92.4	92.4	92.4	92.4	92.4	92.4
	Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Crop "Yield" (%) – Wheat	Salinity + Dry Average *	97.1	97.4	97.4	97.4	97.4	97.4	97.4	97.4	97.4	97.2
	Salinity + Dry Minimum	97.0	97.0	97.0	97.0	97.0	97.0	97.0	97.0	97.0	96.9
	Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Crop "Yield" (%) – Maize	Salinity + Dry Average *	97.9	98.2	98.8	99.3	99.7	99.8	99.9	100.0	99.9	99.9
	Salinity + Dry Minimum	97.7	97.9	98.6	99.1	99.6	99.7	99.8	99.9	99.8	99.9
	Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Crop "Yield" (%) – Bersee	Salinity + Dry Average *	92.0	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.2
	Salinity + Dry Minimum	91.7	91.5	91.5	91.5	91.5	91.5	91.5	91.5	91.5	91.2
	Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Soil Salinity Fraction (final/initial)		0.261	0.296	0.310	0.324	0.336	0.347	0.358	0.370	0.376	0.42
Groundwater Salinity Fraction (final/initial)		0.25	0.29	0.30	0.32	0.33	0.35	0.37	0.40	0.40	0.40
Drainwater Salinity (final/initial)		0.27	0.30	0.31	0.33	0.35	0.37	0.39	0.41	0.42	0.42
Water Table Depth (final/initial)		0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Controlled Drainage Water Saving (%) per Crop Rotation		0.0	6.4	8.8	11.2	13.3	15.5	17.5	19.2	19.7	19.7
Controlled Drainage Water Saving (%) per Maize Season		0.0	10.9	18.5	26.2	32.9	39.6	46.0	51.4	53.1	53.2

* Transpiration rate (%) including effect of salinity and dry stress.
** Transpiration rate (%) including effect of wet stress
[shaded] = "optimum" weir depth

Results Table
Rotation 1 – Cotton, wheat, maize, short berseem

Controlled Drainage During Short Berseem Season

		Crop	Conventional management	Controlled Drainage of Berseem – Weir Depths			
				1.3	1.2	1.1	1
Average Irrigation per Season (mm)		Cotton	1265	1223	1221	1221	1221
		Wheat	728	697	697	697	697
		Maize	1098	1064	1064	1064	1064
		Berseem	392	294	240	209	207
Average ETa per Season (mm)		Cotton	649	649	649	649	649
		Wheat	319	319	319	319	319
		Maize	413	413	413	413	413
		Berseem	194	193	192	190	189
Average Drain Flow per Season (mm)		Cotton	612	574	574	574	574
		Wheat	460	429	429	429	429
		Maize	721	686	686	686	686
		Berseem	212	105	42	9	8
Crop "Yield" (%)	Cotton	Salinity + Dry Average *	92.8	92.9	92.9	92.9	92.9
		Salinity + Dry Minimum	92.3	92.4	92.4	92.4	92.4
		Wet Average **	100.0	100.0	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0	100.0	100.0
	Wheat	Salinity + Dry Average *	97.1	97.4	97.4	97.4	97.4
		Salinity + Dry Minimum	97.0	97.0	97.0	97.0	97.0
		Wet Average **	100.0	100.0	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0	100.0	100.0
	Maize	Salinity + Dry Average *	97.9	98.0	98.0	98.0	98.0
		Salinity + Dry Minimum	97.7	97.7	97.7	97.7	97.7
		Wet Average **	100.0	100.0	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0	100.0	100.0
	Bersee	Salinity + Dry Average *	92.0	90.8	90.4	88.9	88.4
		Salinity + Dry Minimum	91.7	90.5	90.1	88.6	88.0
		Wet Average **	100.0	100.0	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0	100.0	100.0
Soil Salinity Fraction (final/initial)			0.261	0.306	0.322	0.327	0.327
Groundwater Salinity Fraction (final/initial)			0.25	0.28	0.29	0.29	0.29
Drainwater Salinity (final/initial)			0.27	0.29	0.30	0.30	0.30
Water Table Depth (final/initial)			0.99	0.99	0.99	0.99	0.99
Controlled Drainage Water Saving (%) per Crop Rotation			0.0	5.9	7.5	8.4	8.4
Controlled Drainage Water Saving (%) per Berseem Season			0.0	25.1	38.8	46.7	47.2

* Transpiration rate (%) including effect of salinity and dry stress.
** Transpiration rate (%) including effect of wet stress
[grey box] = "optimum" weir depth

Results Table
Rotation 2 – Rice, wheat, maize, long berseem

Controlled Drainage During Rice Season

	Crop	Conventional management	Controlled Drainage of Rice Weir Depths								
			1.3	1.2	1.1	1.0	0.9	0.8	0.7	0.6	0.5
Average Irrigation per Season (mm)	Rice	2108	1782	1575	1374	1198	1027	895	778	716	710
	Wheat	719	685	685	687	688	692	691	692	693	692
	Maize	1098	1060	1060	1060	1060	1060	1060	1060	1060	1060
	Berseem	1055	1001	1001	1001	1001	1001	1001	1001	1001	1001
Average ETa per Season (mm)	Rice	689	692	693	695	697	694	691	685	699	699
	Wheat	394	394	394	394	394	394	394	394	394	394
	Maize	304	304	304	304	304	304	304	304	304	304
	Berseem	265	265	265	265	265	265	265	265	265	265
Average Drain Flow per Season (mm)	Rice	1442	1108	891	684	502	344	211	104	25	19
	Wheat	461	425	425	425	425	425	425	425	426	425
	Maize	721	682	682	682	682	682	682	682	682	682
	Berseem	688	635	635	635	635	635	635	635	635	635
Crop "Yield" (%) – Rice	Salinity + Dry Average *	100.0	100.0	100.0	100.0	100.0	99.7	99.8	99.4	99.3	99.2
	Salinity + Dry Minimum	100.0	100.0	100.0	100.0	100.0	99.7	99.8	99.4	99.3	99.1
	Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Crop "Yield" (%) – Wheat	Salinity + Dry Average *	97.0	97.3	97.3	97.3	97.3	97.3	97.3	97.3	97.3	97.3
	Salinity + Dry Minimum	97.0	97.3	97.3	97.3	97.3	97.3	97.3	97.3	97.3	97.3
	Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Crop "Yield" (%) – Maize	Salinity + Dry Average *	98.0	98.1	98.1	98.1	98.1	98.1	98.1	98.1	98.1	98.1
	Salinity + Dry Minimum	98.0	98.1	98.1	98.1	98.1	98.1	98.1	98.1	98.1	98.1
	Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Crop "Yield" (%) – Bersee	Salinity + Dry Average *	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Salinity + Dry Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Soil Salinity Fraction (final/initial)		0.237	0.255	0.256	0.257	0.258	0.259	0.260	0.261	0.261	0.261
Groundwater Salinity Fraction (final/initial)		0.17	0.19	0.20	0.22	0.23	0.25	0.26	0.28	0.29	0.29
Drainwater Salinity (final/initial)		0.20	0.21	0.22	0.23	0.25	0.27	0.29	0.30	0.32	0.30
Water Table Depth (final/initial)		1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Controlled Drainage Water Saving (%) per Crop Rotation		0.0	9.1	13.2	17.2	20.8	24.1	26.8	29.1	30.3	30.5
Controlled Drainage Water Saving (%) per Rice Season		0.0	15.5	25.3	34.8	43.2	51.3	57.6	63.1	66.1	66.3

* Transpiration rate (%) including effect of salinity and dry stress.
** Transpiration rate (%) including effect of wet stress
[shaded box] = "optimum" weir depth

Results Table
Rotation 2 – Rice, wheat, maize, long berseem

Controlled Drainage During Long Berseem Season

		Crop	Conventional management	Controlled Drainage of Berseem – Weir Depths						
				1.3	1.2	1.1	1.0	0.9	0.8	0.7
Average Irrigation per Season (mm)		Rice	2108	2022	2019	2017	2013	2015	2016	2016
		Wheat	719	688	688	688	688	688	688	688
		Maize	1098	1064	1064	1064	1064	1064	1064	1064
		Berseem	1055	874	749	626	516	437	425	425
Average ETa per Season (mm)		Rice	689	690	690	690	690	690	690	690
		Wheat	394	394	394	394	394	394	394	394
		Maize	304	304	304	304	304	304	305	305
		Berseem	265	265	265	265	265	265	265	265
Average Drain Flow per Season (mm)		Rice	1442	1358	1358	1358	1358	1358	1358	1358
		Wheat	461	429	429	429	429	429	429	429
		Maize	721	686	686	686	686	686	686	686
		Berseem	688	497	361	228	109	28	15	15
Crop “Yield” (%)	Rice	Salinity + Dry Average *	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
		Salinity + Dry Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
		Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Wheat	Salinity + Dry Average *	97.0	97.2	97.2	97.2	97.2	97.2	97.2	97.2
		Salinity + Dry Minimum	97.0	96.9	96.9	96.9	96.9	96.9	96.9	96.9
		Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Maize	Salinity + Dry Average *	98.0	98.1	98.1	98.1	98.1	98.1	98.1	98.1
		Salinity + Dry Minimum	98.0	98.0	98.0	98	98	98	98	98
		Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Bersee	Salinity + Dry Average *	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
		Salinity + Dry Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
		Wet Average **	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Soil Salinity Fraction (final/initial)			0.237	0.278	0.302	0.327	0.347	0.358	0.359	0.359
Groundwater Salinity Fraction (final/initial)			0.17	0.18	0.19	0.20	0.20	0.21	0.21	0.21
Drainwater Salinity (final/initial)			0.20	0.21	0.22	0.23	0.23	0.23	0.24	0.24
Water Table Depth (final/initial)			1.00	0.99	1.00	0.99	1.00	0.99	0.99	0.99
Controlled Drainage Water Saving (%) per Crop Rotation			0.0	6.7	9.2	11.8	14.1	15.6	15.8	15.8
Controlled Drainage Water Saving (%) per Berseem Season			0.0	17.1	29.0	40.6	51.1	58.6	59.7	59.7

* Transpiration rate (%) including effect of salinity and dry stress.
** Transpiration rate (%) including effect of wet stress
[shaded box] = “optimum” weir depth (0.8)

Results Table

Rotation 1 – Cotton, wheat, maize, short berseem

Controlled Drainage of Winter Crops – Wheat and Short Berseem

		Crop	Conventional management	Weir Depths: Wheat - 0.8m Berseem – 1m	Weir Depths: Wheat - 1m Berseem – 1m
Average Irrigation per Season (mm)		Cotton	1265	1221	1221
		Wheat	728	334	423
		Maize	1098	1053	1054
		Berseem	392	206	206
Average ETa per Season (mm)		Cotton	649	649	649
		Wheat	319	320	321
		Maize	413	413	413
		Berseem	194	189	189
Average Drain Flow per Season (mm)		Cotton	612	574	574
		Wheat	460	12	110
		Maize	721	682	682
		Berseem	212	8	8
Crop "Yield" (%)	Cotton	Salinity + Dry Average *	92.8	92.7	92.9
		Salinity + Dry Minimum	92.3	92.4	92.4
		Wet Average **	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0
	Wheat	Salinity + Dry Average *	97.1	95.9	98.1
		Salinity + Dry Minimum	97.0	95.7	98.0
		Wet Average **	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0
	Maize	Salinity + Dry Average *	97.9	98.0	98.0
		Salinity + Dry Minimum	97.7	97.7	97.7
		Wet Average **	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0
	Bersee	Salinity + Dry Average *	92.0	88.4	88.4
		Salinity + Dry Minimum	91.7	88.1	88.1
		Wet Average **	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0
Soil Salinity Fraction (final/initial)			0.342	0.445	0.437
Groundwater Salinity Fraction (final/initial)			0.25	0.38	0.36
Drainwater Salinity (final/initial)			0.27	0.39	0.37
Water Table Depth (final/initial)			0.99	0.99	0.99
Controlled Drainage Water Saving (%) per Crop Rotation			0.0	19.2	16.6
Controlled Drainage Water Saving (%) per Winter Season			0.0	51.8	43.8

* Transpiration rate (%) including effect of salinity and dry stress.

** Transpiration rate (%) including effect of wet stress

[grey box] = "optimum" weir depth

Results Table

Rotation 1 – Cotton, wheat, maize, short berseem

Controlled Drainage of Summer Crops – Cotton and Maize

		Crop	Conventional management	Weir Depths: Cotton - 0.7m Maize – 0.6m	Weir Depths: Cotton -1m Maize – 0.9m
Average Irrigation per Season (mm)		Cotton	1265	725	870
		Wheat	728	692	693
		Maize	1098	515	663
		Berseem	392	358	358
Average ETa per Season (mm)		Cotton	649	659	672
		Wheat	319	319	319
		Maize	413	463	424
		Berseem	194	194	194
Average Drain Flow per Season (mm)		Cotton	612	15	153
		Wheat	460	426	425
		Maize	721	13	218
		Berseem	212	180	180
Crop "Yield" (%)	Cotton	Salinity + Dry Average *	92.8	92.7	96.3
		Salinity + Dry Minimum	92.3	92.1	96.1
		Wet Average **	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0
	Wheat	Salinity + Dry Average *	97.1	97.4	97.4
		Salinity + Dry Minimum	97.0	97.3	97.3
		Wet Average **	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0
	Maize	Salinity + Dry Average *	97.9	99.9	99.8
		Salinity + Dry Minimum	97.7	99.8	99.7
		Wet Average **	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0
	Bersee	Salinity + Dry Average *	92.0	91.8	91.8
		Salinity + Dry Minimum	91.7	91.5	91.5
		Wet Average **	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0
Soil Salinity Fraction (final/initial)			0.342	0.563	0.487
Groundwater Salinity Fraction (final/initial)			0.25	0.62	0.48
Drainwater Salinity (final/initial)			0.27	0.64	0.49
Water Table Depth (final/initial)			0.99	0.99	0.99
Controlled Drainage Water Saving (%) per Crop Rotation			0.0	34.2	25.8
Controlled Drainage Water Saving (%) per Summer Season			0.0	47.5	35.1

* Transpiration rate (%) including effect of salinity and dry stress.

** Transpiration rate (%) including effect of wet stress

[grey box] = "optimum" weir depth

Results Table
Rotation 1 – Cotton, wheat, maize, short berseem

Controlled Drainage of All 4 Crops

		Crop	Conventional management	Weir Depths	
				Cotton - 0.7m Wheat – 0.8m Maize – 0.6m Berseem – 1m	Cotton - 1m Wheat – 1m Maize – 0.9m Berseem – 1m
Average Irrigation per Season (mm)		Cotton	1265	720	865
		Wheat	728	332	422
		Maize	1098	493	656
		Berseem	392	205	206
Average ETa per Season (mm)		Cotton	649	660	672
		Wheat	319	320	323
		Maize	413	439	405
		Berseem	194	187	186
Average Drain Flow per Season (mm)		Cotton	612	15	153
		Wheat	460	12	110
		Maize	721	14	217
		Berseem	212	8	8
Crop "Yield" (%)	Cotton	Salinity + Dry Average *	92.8	92.7	96.3
		Salinity + Dry Minimum	92.3	92.1	96.1
		Wet Average **	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0
	Wheat	Salinity + Dry Average *	97.1	95.8	98.1
		Salinity + Dry Minimum	97.0	95.7	98.0
		Wet Average **	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0
	Maize	Salinity + Dry Average *	97.9	92.6	99.8
		Salinity + Dry Minimum	97.7	90.8	99.7
		Wet Average **	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0
	Bersee	Salinity + Dry Average *	92.0	85.8	88.2
		Salinity + Dry Minimum	91.7	85.3	87.8
		Wet Average **	100.0	100.0	100.0
		Wet Minimum	100.0	100.0	100.0
Soil Salinity Fraction (final/initial)			0.342	1.757	1.751
Groundwater Salinity Fraction (final/initial)			0.25	0.99	0.89
Drainwater Salinity (final/initial)			0.27	1.03	0.93
Water Table Depth (final/initial)			0.99	0.97	0.97
Controlled Drainage Water Saving (%) per Crop Rotation			0.0	49.8	38.3

* Transpiration rate (%) including effect of salinity and dry stress.
** Transpiration rate (%) including effect of wet stress
= "optimum" weir depth

Appendix E

Irrigation schedules for controlled drainage strategies developed in the CDWaSim demonstration

Appendix E Irrigation schedules for controlled drainage strategies developed in the CDWaSim demonstration

Rotation 1
Controlled drainage of Cotton: weir depth = 0.8m
Irrigation schedule for a 2-year crop rotation of cotton, wheat, maize and short berseem.
(Average irrigation amounts applied in controlled drainage scenario.)

COTTON	Amount mm	WHEAT	Amount mm
28-Feb	150.8	24-Oct (pre-irrigation)	(20.6)
25-Mar	28.7	31-Oct	121.2
20-Apr	32.3	28-Nov	101.0
16-May	49.0	26-Dec	102.0
11-Jun	83.7	23-Jan	104.0
7-Jul	122.0	20-Feb	121.5
2-Aug	133.0	20-Mar	142.4
28-Aug	132.0		
Total	731.8	Total	692.3 (712.9)

MAIZE	Amount mm	SHORT BERSEEM	Amount mm
4-May (pre-irrigation)	(68.5)	07-Oct (pre-irrigation)	(63.3)
13-May	167.2	15-Oct	77.0
29-May	128.0	31-Oct	46.0
14-Jun	129.0	16-Nov	47.5
30-Jun	130.0	2-Dec	49.0
16-Jul	141.0	18-Dec	47.0
1-Aug	182.0	3-Jan	45.0
17-Aug	183.0	19-Jan	47.0
Total	1060.5 (1129.0)	Total	358.8 (422.1)
		Rotation Total	2843.4

Rotation 1
Controlled drainage of Wheat: weir depth = 0.8m
Irrigation schedule for 2-year crop rotation of cotton, wheat, maize and short berseem.
(Average irrigation amounts applied in controlled drainage scenario.)

COTTON	Amount mm	WHEAT	Amount mm
28-Feb	150.8	24-Oct (pre-irrigation)	(32.7)
25-Mar	111.5	31-Oct	122.5
20-Apr	113.6	28-Nov	23.0
16-May	123.2	26-Dec	28.1
11-Jun	154.7	23-Jan	34.2
7-Jul	184.6	20-Feb	49.2
2-Aug	194.5	20-Mar	76.4
28-Aug	193.5		
Total	1226.7	Total	333.6 (366.3)

MAIZE	Amount mm	SHORT BERSEEM	Amount mm
4-May (pre-irrigation)	(48.5)	07-Oct (pre-irrigation)	(63.3)
13-May	159.7	15-Oct	77.0
29-May	128.0	31-Oct	46.0
14-Jun	129.0	16-Nov	47.5
30-Jun	130.0	2-Dec	49.0
16-Jul	141.0	18-Dec	47.0
1-Aug	182.0	3-Jan	45.0
17-Aug	183.0	19-Jan	47.0
Total	1053.0 (1101.5)	Total	358.8 (422.1)
		Rotation Total	2972.1

Rotation 1
Controlled drainage of Maize: weir depth = 0.6m
Irrigation schedule for 2-year crop rotation of cotton, wheat, maize and short berseem.
(Average irrigation amounts applied in controlled drainage scenario.)

COTTON	Amount mm	WHEAT	Amount mm
28-Feb	150.8	24-Oct (pre-irrigation)	(32.7)
25-Mar	111.5	31-Oct	122.5
20-Apr	113.6	28-Nov	101.6
16-May	123.2	26-Dec	102.6
11-Jun	154.7	23-Jan	104.6
7-Jul	184.6	20-Feb	122.0
2-Aug	194.5	20-Mar	143.0
28-Aug	193.5		
Total	1226.7	Total	696.5 (729.2)

MAIZE	Amount mm	SHORT BERSEEM	Amount mm
4-May (pre-irrigation)	(68.5)	07-Oct (pre-irrigation)	(34.4)
13-May	167.7	15-Oct	76.0
29-May	32.0	31-Oct	46.0
14-Jun	36.0	16-Nov	47.5
30-Jun	39.0	2-Dec	49.0
16-Jul	54.0	18-Dec	47.0
1-Aug	93.0	3-Jan	45.0
17-Aug	93.5	19-Jan	47.0
Total	515.5 (584.0)	Total	357.8 (392.2)
		Rotation Total	2796.5

Rotation 1

Controlled drainage of Short berseem: weir depth = 0.8m

Irrigation schedule for 2-year crop rotation of cotton, wheat, maize and short berseem.
(Average irrigation amounts applied in controlled drainage scenario.)

COTTON	Amount mm	WHEAT	Amount mm
28-Feb	145.4	24-Oct (pre-irrigation)	(32.7)
25-Mar	111.5	31-Oct	122.5
20-Apr	113.6	28-Nov	101.6
16-May	123.2	26-Dec	102.6
11-Jun	154.7	23-Jan	104.6
7-Jul	184.6	20-Feb	122.0
2-Aug	194.5	20-Mar	143.0
28-Aug	193.5		
Total	1221.3	Total	696.5 (729.2)

MAIZE	Amount mm	SHORT BERSEEM	Amount mm
4-May (pre-irrigation)	(68.5)	07-Oct (pre-irrigation)	(63.3)
13-May	167.7	15-Oct	77.6
29-May	128.5	31-Oct	20.0
14-Jun	129.6	16-Nov	20.0
30-Jun	130.6	2-Dec	21.0
16-Jul	141.6	18-Dec	22.0
1-Aug	182.5	3-Jan	22.3
17-Aug	183.5	19-Jan	25.7
Total	1064.3 (1132.8)	Total	208.9 (272.2)
		Rotation Total	3191

Rotation 2

Controlled drainage of Rice: Weir depth = 0.6m

Irrigation schedule for 2-year crop rotation of rice, wheat, maize and long berseem.
(Average irrigation amounts applied in controlled drainage scenario.)

RICE	Amount mm	WHEAT	Amount mm
15-May	166.2	24-Oct (pre-irrigation)	(20)
18-May	13.0	31-Oct	121.0
21-May	12.6	28-Nov	101.0
24-May	12.4	26-Dec	102.0
27-May	14.0	23-Jan	104.0
30-May	14.0	20-Feb	122.0
2-Jun	14.0	20-Mar	143.0
5-Jun	15.6		
8-Jun	15.0		
11-Jun	14.4		
16-Jun	2.0		
20-Jun	12.0		
24-Jun	13.0		
28-Jun	15.0		
2-Jul	17.0		
6-Jul	17.0		

10-Jul	18.0		
14-Jul	38.6		
17-Jul	15.4		
20-Jul	16.0		
23-Jul	16.0		
26-Jul	17.0		
29-Jul	16.6		
1-Aug	17.4		
4-Aug	16.6		
7-Aug	17.0		
10-Aug	16.4		
13-Aug	17.0		
16-Aug	17.0		
19-Aug	17.0		
22-Aug	17.0		
3-Sep	3.0		
7-Sep	17.6		
11-Sep	18.4		
15-Sep	18.0		
19-Sep	17.0		
Total	715.6	Total	693.2 (713.2)

MAIZE	Amount mm	LONG BERSEEM	Amount mm
4-May (pre-irrigation)	(69)	15-Oct (pre-irrigation)	(63.0)
13-May	167.0	31-Oct	116.0
29-May	128.0	16-Nov	82.0
14-Jun	129.0	2-Dec	81.0
30-Jun	130.0	18-Dec	80.0
16-Jul	141.0	3-Jan	79.0
1-Aug	182.0	19-Jan	87.0
17-Aug	183.0	4-Feb	88.0
		20-Feb	90.0
		7-Mar	95.0
		23-Mar	100.5
		23-Mar	102.0
Total	1060.3 (1129.3)	Total	1000.5 (1063.5)
		Rotation Total	3469.6

Rotation 2
Controlled drainage of Long Berseem: Weir depth = 0.8m
Irrigation schedule for 2-year crop rotation of rice, wheat, maize and long berseem.
(Average irrigation amounts applied in controlled drainage scenario.)

RICE	Amount mm	WHEAT	Amount mm
15-May	159.0	24-Oct (pre-irrigation)	(6.9)
18-May	51.3	31-Oct	112.5
21-May	57.3	28-Nov	101.6
24-May	56.2	26-Dec	102.6
27-May	56.3	23-Jan	104.6
30-May	56.3	20-Feb	122.5

2-Jun	56.3	20-Mar	143.6
5-Jun	56.3		
8-Jun	56.3		
11-Jun	55.3		
15-Jun	48.4		
19-Jun	53.3		
23-Jun	51.3		
27-Jun	51.3		
1-Jul	52.2		
5-Jul	49.3		
9-Jul	49.3		
13-Jul	49.3		
16-Jul	59.2		
19-Jul	51.2		
22-Jul	53.2		
25-Jul	54.2		
28-Jul	54.3		
31-Jul	56.2		
3-Aug	56.2		
6-Aug	56.3		
9-Aug	57.2		
12-Aug	57.3		
15-Aug	58.2		
18-Aug	58.2		
21-Aug	58.2		
25-Aug	15.3		
29-Aug	45.1		
2-Sep	33.2		
6-Sep	31.1		
10-Sep	31.3		
14-Sep	32.1		
18-Sep	31.2		
Total	2015.7	Total	687.6 (694.5)

MAIZE	Amount mm	LONG BERSEEM	Amount mm
4-May (pre-irrigation)	(69)	15-Oct (pre-irrigation)	(63.0)
13-May	167.5	31-Oct	116.6
29-May	128.5	16-Nov	20.0
14-Jun	129.6	2-Dec	21.0
30-Jun	130.6	18-Dec	24.0
16-Jul	141.6	3-Jan	23.0
1-Aug	182.5	19-Jan	26.0
17-Aug	183.5	4-Feb	27.0
		20-Feb	31.0
		7-Mar	40.0
		23-Mar	44.6
		23-Mar	51.4
Total	1064.1 (1133.1)	Total	424.6 (487.6)
		Rotation Total	4192

Rotation 1
Controlled drainage of summer crops: Cotton, weir depth = 1.0m and Maize, weir depth = 0.9m
Irrigation schedule for 2-year crop rotation of cotton, wheat, maize and short berseem.
(Average irrigation amounts applied in controlled drainage scenario.)

COTTON	Amount mm	WHEAT	Amount mm
28-Feb	150.8	24-Oct (pre-irrigation)	(21.4)
25-Mar	55.0	31-Oct	121.9
20-Apr	57.0	28-Nov	101.0
16-May	70.0	26-Dec	102.0
11-Jun	101.3	23-Jan	104.0
7-Jul	136.0	20-Feb	121.5
2-Aug	151.0	20-Mar	142.4
28-Aug	148.9		
Total	870.3	Total	693.0 (714.4)

MAIZE	Amount mm	SHORT BERSEEM	Amount mm
4-May (pre-irrigation)	(68.5)	07-Oct (pre-irrigation)	(42.1)
13-May	167.2	15-Oct	76.1
29-May	60.0	31-Oct	46.0
14-Jun	62.0	16-Nov	47.5
30-Jun	64.0	2-Dec	49.0
16-Jul	78.0	18-Dec	47.0
1-Aug	117.0	3-Jan	45.0
17-Aug	114.8	19-Jan	47.0
Total	663.3 (731.8)	Total	357.9 (400.0)
		Rotation Total	2584.5

Rotation 1
Controlled drainage of summer crops: Cotton, weir depth = 0.7m and Maize, weir depth = 0.6m
Irrigation schedule for 2-year crop rotation of cotton, wheat, maize and short berseem.
(Average irrigation amounts applied in controlled drainage scenario.)

COTTON	Amount mm	WHEAT	Amount mm
28-Feb	150.8	24-Oct (pre-irrigation)	(20.6)
25-Mar	24.4	31-Oct	121.2
20-Apr	31.6	28-Nov	101.0
16-May	48.7	26-Dec	102.0
11-Jun	83.1	23-Jan	104.0
7-Jul	122.0	20-Feb	121.5
2-Aug	132.5	20-Mar	142.4
28-Aug	132.0		
Total	725.4	Total	692.3 (712.9)

MAIZE	Amount mm	SHORT BERSEEM	Amount mm
4-May (pre-irrigation)	(68.5)	07-Oct (pre-irrigation)	(34.4)
13-May	167.2	15-Oct	76.0
29-May	32.0	31-Oct	46.0
14-Jun	36.0	16-Nov	47.5

30-Jun	39.0	2-Dec	49.0
16-Jul	54.0	18-Dec	47.0
1-Aug	93.0	3-Jan	45.0
17-Aug	93.5	19-Jan	47.0
Total	515.0 (583.5)	Total	357.8 (392.2)
		Rotation Total	2290.5

Rotation 1
Controlled drainage of winter crops: Wheat, weir depth = 1.0m and short berseem, weir depth = 1.0m
Irrigation schedule for 2-year crop rotation of cotton, wheat, maize and short berseem.
(Average irrigation amounts applied in controlled drainage scenario.)

COTTON	Amount mm	WHEAT	Amount mm
28-Feb	145.4	24-Oct (pre-irrigation)	(32.7)
25-Mar	111.5	31-Oct	122.5
20-Apr	113.6	28-Nov	44.6
16-May	123.2	26-Dec	45.0
11-Jun	154.7	23-Jan	54.0
7-Jul	184.6	20-Feb	67.5
2-Aug	194.5	20-Mar	89.1
28-Aug	193.5		
Total	1221.3	Total	422.9 (455.6)

MAIZE	Amount mm	SHORT BERSEEM	Amount mm
4-May (pre-irrigation)	(51.6)	07-Oct (pre-irrigation)	(63.3)
13-May	160.2	15-Oct	77.0
29-May	128.0	31-Oct	20.0
14-Jun	129.0	16-Nov	20.0
30-Jun	130.0	2-Dec	21.0
16-Jul	141.0	18-Dec	21.1
1-Aug	182.0	3-Jan	22.0
17-Aug	183.0	19-Jan	25.0
Total	1053.5 (1105.1)	Total	206.4 (269.7)
		Rotation Total	2904.1

Rotation 1
Controlled drainage of winter crops: Wheat, weir depth = 0.8m and short berseem, weir depth = 1.0m
Irrigation schedule for 2-year crop rotation of cotton, wheat, maize and short berseem.
(Average irrigation amounts applied in controlled drainage scenario.)

COTTON	Amount mm	WHEAT	Amount mm
28-Feb	145.4	24-Oct (pre-irrigation)	(32.7)
25-Mar	111.5	31-Oct	122.5
20-Apr	113.6	28-Nov	23.0
16-May	123.2	26-Dec	28.1
11-Jun	154.7	23-Jan	34.2
7-Jul	184.6	20-Feb	49.2
2-Aug	194.5	20-Mar	76.4
28-Aug	193.5		
Total	1221.3	Total	333.6 (366.3)

MAIZE	Amount mm	SHORT BERSEEM	Amount mm
4-May (pre-irrigation)	(48.5)	07-Oct (pre-irrigation)	(63.3)
13-May	159.7	15-Oct	77.0
29-May	128.0	31-Oct	20.0
14-Jun	129.0	16-Nov	20.0
30-Jun	130.0	2-Dec	21.0
16-Jul	141.0	18-Dec	21.1
1-Aug	182.0	3-Jan	22.0
17-Aug	183.0	19-Jan	25.0
Total	1053.0 (1101.5)	Total	206.4 (269.7)
		Rotation Total	2814.3

Rotation 1
Controlled drainage of all crops: Cotton, weir depth = 1.0m, Wheat, weir depth = 1.0, Maize, weir depth = 0.9m and short berseem, weir depth = 1.0m
Irrigation schedule for 2-year crop rotation of cotton, wheat, maize and short berseem.
(Average irrigation amounts applied in controlled drainage scenario.)

COTTON	Amount mm	WHEAT	Amount mm
28-Feb	144.6	24-Oct (pre-irrigation)	(21.0)
25-Mar	55.0	31-Oct	122.0
20-Apr	57.0	28-Nov	45.0
16-May	70.0	26-Dec	45.0
11-Jun	101.5	23-Jan	54.0
7-Jul	136.0	20-Feb	68.0
2-Aug	151.0	20-Mar	90.0
28-Aug	149.0		
Total	864.4	Total	424.2 (445.2)

MAIZE	Amount mm	SHORT BERSEEM	Amount mm
4-May (pre-irrigation)	(52.0)	07-Oct (pre-irrigation)	(36.7)
13-May	160.0	15-Oct	76.2
29-May	60.0	31-Oct	20.1
14-Jun	62.0	16-Nov	20.0
30-Jun	64.0	2-Dec	21.0
16-Jul	78.0	18-Dec	21.0
1-Aug	113.4	3-Jan	21.9
17-Aug	109.9	19-Jan	24.0
Total	647.6 (699.6)	Total	204.5 (241.2)
		Rotation Total	2140.7

Rotation 1

Controlled drainage of all crops: Cotton, weir depth = 0.7m, Wheat, weir depth = 0.8, Maize, weir depth = 0.6m and short berseem, weir depth = 1.0m

Irrigation schedule for 2-year crop rotation of cotton, wheat, maize and short berseem.
(Average irrigation amounts applied in controlled drainage scenario.)

COTTON	Amount mm	WHEAT	Amount mm
28-Feb	144.6	24-Oct (pre-irrigation)	(20.6)
25-Mar	24.6	31-Oct	121.2
20-Apr	31.4	28-Nov	22.9
16-May	48.7	26-Dec	28.2
11-Jun	83.3	23-Jan	34.4
7-Jul	122.0	20-Feb	49.0
2-Aug	132.8	20-Mar	76.3
28-Aug	132.0		
Total	719.7	Total	332.2 (352.8)

MAIZE	Amount mm	SHORT BERSEEM	Amount mm
4-May (pre-irrigation)	(52.0)	07-Oct (pre-irrigation)	(27.9)
13-May	159.8	15-Oct	76.6
29-May	32.2	31-Oct	20.1
14-Jun	36.0	16-Nov	19.9
30-Jun	39.0	2-Dec	21.1
16-Jul	52.3	18-Dec	21.0
1-Aug	87.2	3-Jan	21.8
17-Aug	85.8	19-Jan	24.2
Total	492.6 (541.1)	Total	205.0 (232.9)
		Rotation Total	1749.5

Appendix F

Notes on the use of the economic evaluation module

Appendix F Notes on the use of the economic evaluation module

Background

The module facilitates economic analysis of controlled drainage, and was developed as a simple-to-use tool to aid decision making. The module consists of linked worksheets within an Excel spreadsheet containing a number of linked tables. The user has access to the areas into which data are entered, and the results - the rest of the calculation sheets are hidden and protected. It was developed initially to carry out indicative assessments of controlled drainage in the context of Egyptian agriculture. However it can be adapted for use in any location, through input of appropriate local data and selection of appropriate units for currency and land area. This appendix provides guidance on the use of the module.

Running the Economics Module

To run the economics module included on the enclosed CD:

- Click on the Windows “Start” button and select the “Run” command
- Type “d:\CDBenefitCostModule.xls”, then click the “OK” button
  (Replace “d” with the letter of your cd-rom drive if necessary)

Data Entry

The module consists of linked tables within an Excel spreadsheet. Data is entered in both the “Input and results” sheet, and the “ Farm data sheet”. Data is entered first in the “Input and results” sheet.

<u>In all cases data is only entered in the cells highlighted in Yellow.</u> Data in other cells is either computed by the spreadsheet or is entered elsewhere.

The first data entry table is used to enter the currency and land area unit, and names of up to seven crops in the crop rotation that are to be used in the analysis. The example shown below is for the crops grown in a 3 year rotation used in Egypt.

Table F1 Example Crop/Currency/Land Units Input Table

Give names for up to seven crops		Crop 1	Crop 2	Crop 3	Crop 4	Crop 5	Crop 6	Crop 7
		Wheat	Berseem Short Season	Berseem Long Season	Beans	Maize	Rice	Cotton
Unit of currency	Le							
Unit of land	feddan							

Data then has to be entered in tables 1.1 to 1.4 in the “Input and results” sheet and tables 2.1 and 2.2 in the “Farm data” sheet. This is described below:

Table 1.1- Basic Assumptions on cropping patterns, water requirements, yields, and crop prices

<u>Cropping pattern.</u> The percentage of the total planted area devoted to each crop in each season for each year of the rotation is entered. For example if wheat is grown over the whole plot during the winter season once in every three years, a value of 33 % would be used.

Crop water requirement. This is the average seasonal crop water requirement. These data should be available from the national or local irrigation agencies for the area, or may be estimated using standard procedures.
Number of irrigation applications. The number of irrigation applications per season.

Crop yields. Yields with and without controlled drainage are needed. Yield data for conventionally managed crops should be readily available from agricultural statistics or can be collated from farm surveys. The simulation model CDWaSim (see chapter 3) provides estimates of yields with controlled drainage. If model results are unavailable then estimated values can be used.

Crop prices (financial). Financial prices are those received by farmers at the farm gate or in the market, and will be locally available. The use of average prices has limitations where markets are imperfect, and results obtained should not be used as a basis for individual farm forecasts. For example average prices may not reflect variations for quality and timing.

Crop prices (economic). Economic prices are those that reflect the value of an additional unit of output or input to society, and should be obtained from national statistics

Irrigation Efficiencies. Entries are required for the system efficiency to the field boundary, and the infield irrigation efficiencies, with and without controlled drainage.

The system efficiency is likely to be the same value for all crops unless there are circumstances that differentiate the supply and the crop simultaneously by area. Irrigation departments and ministries commonly have estimates of the system efficiency.

Field efficiency varies in response to soil type and water management techniques and other factors. Care should be taken when applying reported efficiencies for conventional management when shallow rooting crops, such as some vegetables, are part of the rotation, and where there is extensive use of inter-cropping. If the water saving under controlled drainage is predicted by CDWaSim then this can be used as the starting point to calculate crop water requirements at the field boundary for the controlled drainage case.

Table 1.2 - Input Prices and Fertiliser Savings

This table requires economic information that applies to the agricultural sector, which may be available from a National statistics office or Ministry of finance. Alternative sources may be University departments or external sources such as the World Bank.

Discount rate. A range of values around the current interest rate can be used in the module to compare performance in changing economic conditions. If interest rates are known to be rising it may be relevant to look at the impact of rates up to double the current rate.

Life in years. The life of the project is determined by technical design parameters and information relating to this should be readily available from the relevant ministry. The life of projects is influenced both by the level of maintenance required, and the capacity to fund and organise that level of maintenance. Small variations to project life are generally insignificant in determining the IRR because benefits a long time in the future are subject to heavy discounting.

Labour Price. Labour prices generally refer to an average rural wage but where family labour constitutes a large proportion of total labour, the opportunity cost of labour should be applied. The opportunity cost generally refers to the wage that could be earned doing the best-paid alternative work. In peri-urban areas, this wage may be significantly higher than the average rural wage.

Fertiliser. Fertiliser prices should be obtained locally for greatest authenticity, as transaction costs may be significant.

Fertiliser saving. In certain circumstances this may be proportionate to water saving at the field level. Although, in the long run, fertiliser may be used more effectively because less will be lost to the drainage system, fertiliser saving may be highly variable and not necessarily proportionate to the water saved. In areas where farmers are not presently applying fertiliser at the recommended rates, saving may be notional rather than real. It may also take time for farmers to adjust their fertiliser application. Other technical factors such as the potential for de-nitrification should inform the entry for fertiliser saving.

Pumping Costs. The pumping cost per m^3 of water will largely consist of the fuel cost element, but should also include the capital cost spread over the project life and any additional labour cost. Fuel costs are likely to fluctuate during the life of a project and so sensitivity tests using a range of different costs are recommended.

Table 1.3 - Economic Prices - weighting factors

The economic price of a good or service reflects the value of that good or service to society at large. It is expressed as a percentage of the financial price of the good or service, and is often weighted to reflect some income distribution or savings objective, and so may be either above or below the financial price. Calculation of the weightings required is generally done at national or regional level and information can be obtained from ministries of finance, academic institutions, or tables available in the public domain.

Table 1.4 - Controlled drainage costs

The costs to be entered in this table will generally be estimates. They should represent the costs of providing the additional infrastructure used to control drainage. (Not the costs of components that would be present in a conventional drainage system.)

Capital cost. This is the estimated additional cost of providing controlled drainage, per unit of drained land area.

Rehabilitation/ replacement cost and year. This is included only if it is anticipated that rehabilitation of the additional infrastructure needed to control drainage will be needed during the lifetime of the project.

Extra annual O&M. Conventionally O and M costs are set at 5% of construction costs. Given the historic failures of routine maintenance in irrigation projects, it may be desirable to make an allowance for a larger percentage.

The information required to complete the two tables in the “Farm Data” sheet is essentially agricultural and financial price data, that should be available locally. Where reference is made to input on the main sheet it infers that the information has already been entered in tables 1.1 to 1.4.

Table 2.1 - Crop input and output data per unit cropped area

It is important to be consistent about the units being used as local prices may apply to a variety of measure as well as showing considerable inconsistency in price/unit. Deviation from the average can be quite significant particularly where farmers are using small quantities.

Yields. Yields for the main crops have already been entered in table 1.1. By-product yields may be less readily available, and will be zero for some crops.

Inputs. Information on agricultural inputs to each crop is required on a seasonal basis. Consistency of units is important. Items of machinery may have to be allocated on a proportional basis.

Table 2.2 - Crop input and output prices: financial

If national prices are to be used care should be taken to verify that these are indeed the prices paid by the producers in the area under consideration.

Results

Results are presented in three output tables in the sheet “Input and results”. These are:

Table 1.5 - Impact of Controlled Drainage: extra benefits and water savings per unit land area per year

The table provides estimates of total financial and economic savings to be expected on-farm and additionally provides financial and economic estimates for the value of ‘saved’ water.

The following results are provided.

Net Margin at farm-level. The monetary value per land unit of the harvested crop, less all the costs (including taxes, levies and devaluation).

Water delivered to the field. The average volume of water delivered over a year by the system to the field edge for application to the crop by the farmer.

Water in supply system. This is the water requirement in the delivery system to ensure the required volume reaches the fields.

Impact at irrigation sector level. The value of water saved at average net margins. This is computed assuming that the value of water saved is represented by the average returns to the most commonly grown crops. (The user has to check and justify the assumption that water is really saved for economic purposes. Water can only be regarded as saved if it was formerly lost to the irrigation system. Drainage flows that were formally re-used have an economic value, which has to be accounted for in a separate analysis as it is not included in the spread sheet computations)

Table 1.6 - Investment appraisal

This table provides information on the performance of the investment. The following results are provided:

Present Value of Benefits. This is the sum of discounted benefit value per unit land area for each year of the project.

Present Value of Costs. This is the sum of discounted cost value per unit land area for each year of the project.

Net present value (NPV). The difference between the present value of benefits and costs. In principle, a project is worthwhile if the NPV has a positive value.

Internal rate of return (IRR). The interest or discount rate that would result in an NPV of zero. The IRR should exceed the prevailing discount rate if the project is to be economically worthwhile. (The high IRR achieved for controlled drainage when saved water is included in the Egyptian example indicates that the project outcome is very favourable providing water is really saved and that it can be used elsewhere at the assumed value.)

Sensitivity Analysis

Table 1.7 - Sensitivity analysis

This table allows impacts of key assumptions to be checked by imposing % variations in the input data used. The results are shown in the part of the table headed “Key Results from Sensitivity Analysis”.

(Sensitivity analysis can also be carried out by varying the values entered in the data entry tables, and viewing the copies of the “Key Results from Sensitivity Analysis” table that are displayed on the right of the data entry tables.)

It will almost always be necessary to use this facility to check the robustness of conclusions drawn from the economic analysis, and to identify the key assumptions that will determine the economic viability of an investment in controlled drainage.

Appendix G

CD containing CDWaSim and the economic evaluation module

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