THE ECONOMIC EFFECTS OF POOR AND FLUCTUATING IRRIGATION WATER SALINITY LEVELS IN THE LOWER VAAL AND RIET RIVERS

by

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I declare that this dissertation hereby submitted by me for the M.Sc.Agric degree at the University of the Free State is my own independent work, conducted under the guidance and supervision of a steering committee and a study leader, and has not previously been submitted by me at any other university/faculty. Copyright of this study lies jointly with the Water Research Commission who have funded this work and the University of the Free State.

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ACRONYMS, TERMS AND ABBREVIATIONS

WRC	Water Research Commission
DWAF	Department of Water Affairs and Forestry
GWK	The old Griqualand Wes Co-operative, now GWK Ltd.
SALMOD	Salinity and Leaching Model for optimal Irrigation Development
OVIB	Orange Vaal Irrigation Board

Water quality terms

Water quality	High concentrations of inorganic salts have been identified as the main water quality problem for irrigation in the study area, thus unless otherwise specified, the term water quality as used in this document refers to the salinity status of the irrigation water measured in EC or TDS.
ECiw	Electrical conductivity of the irrigation water (measured in mS/m)
ECe	Electrical conductivity of the saturated soil extract (measured in mS/m)
TDS	Total dissolved solids (mg/l)
SAR	Sodium adsorption ratio
CEB	Crop Enterprise budget
GMASC	Gross Margin Above Specified Costs
TGMASC	Total Gross Margin Above Specified Costs

Definitions

CEB - **Crop Enterprise Budget**. The CEBs set up in this study incorporate all crop enterprise income minus all directly allocatable costs, and are set up to per hectare gross margin (GM) level.

GM - **Gross Margin.** The GM for the enterprise referred to is the gross value of production for that enterprise minus all the directly allocatable costs. In this study fuel and lubrication, and maintenance and repairs have been allocated, but permanent labour not, only temporary labour. Permanent labour is included in the fixed cost component.

TGMASC - Total Gross Margin Above Specified Costs. In SALMOD the TGMASC generated is at case study farm level and is the difference between all farm income and allocatable production costs, including water, electricity, an interest component and harvesting costs, as well as the annualised capital repayment costs of management options brought into the optimal solution. The specified costs include all annual non-allocatable costs, and are a constant in SALMOD, obtained from the financial analysis survey. TGMASC is equivalent to net farm income (NFI) excluding the depreciation component.

Shadow price / **Dual value** / **Reduced costs** **-** Used interchangeably to indicate the marginal value of a resource i.e. what the user of the resource can afford to pay for one extra unit of the resource. If the resource is not constraining the shadow price will be zero, if constraining then a positive value and if the resource is forced into use then a marginal cost can arise, indicated by a negative dual value.

<u>Sub-areas[1] of the OVIB:</u>

OL	Olierivier (from Soutpansdrift in the Lower Riet River to the Vaal Riet confluence)	-	Sub-area 1
VL	Vaallus (from De Bad in the Lower Vaal River to the Vaal Riet confluence)	-	Sub-area 2
AT	Atherton (northern side of the Lower Vaal River below the Vaal Barrage wall)	-	Sub-area 3
BL	Bucklands (southern side of the Lower Vaal River below the Vaal Barrage wall)	-	Sub-area 4
NB	New-Bucklands (southern side of the Lower Vaal River below Bucklands)	-	Sub-area 5

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[1] Olierivier, Vaallus, Atherton and Bucklands are descriptive names used to define sub-areas of the OVIB study area

CHAPTER 1. INTRODUCTION

We shall never understand the natural environment until we see it as a living organism.
Land can be healthy or sick, fertile or barren, rich or poor, lovingly nurtured or bled white.
Today you can murder land for private profit.
You can leave the corpse for all to see and nobody calls the cops.
Paul Brooks: The Pursuit of Wilderness

1.1. PROBLEM STATEMENT

In the course of economic growth and development, there is an increasing use of water and thus also returnflows, which contribute to fluctuation and the gradual deterioration of water quality. This applies in particular to the Vaal River system, where water quality worsens as river flow reduces, but improves again with floods. These observations are pronounced below the confluence of the Riet and the Harts Rivers (Du Preez *et al*, 2000), which indicates that irrigation itself, contributes to the fluctuations in water quality. Even if water quality does not worsen progressively over time, it is expected that the irrigability of soils can be affected, which in turn impacts on the financial sustainability of crop production.

There are clear indications, that the tariff of water for all uses including irrigation will be adjusted upwards to better reflect the cost of supply according to Backeberg *et al, (*1996). The water quality problem together with the current “price-cost squeeze” effect has led to the questioning of the long-term sustainability of current irrigation practises in the OVIB region. The price currently charged of irrigation water is far below that paid by industry and municipal users and farmers are also not accountable for the returnflows coming off their lands. The National Water Act of 1998 however addresses these issues and thus the need for functional models to help guide policy in the right direction, as well as to prepare farmers for the possible impacts of various water pricing and supply scenarios.

Seasonal or cyclical changes in water quality contribute to both private and external costs. Private costs involve e.g. artificial drainage, amelioration and application of additional water to leach salts while external costs refer to e.g. increasing salt loads in down stream river reaches. The rapid fluctuation in water quality, especially in the Lower Riet River arm makes crop production most unpredictable, leading to instability in the region. This has resulted in crop choice away from crops with the highest returns towards crops with the most predictable returns under the current water quality situation. Because the Lower Vaal River operates within a closed system (Du Preez *et al,* 2000:5) and there are no restrictions on agricultural returnflows, all leachate that does result from either over irrigation, distribution losses or leaching returns into the river system, exacerbating the problem. The concentration of salts could eventually lead to a dramatic change in agricultural practises in the area if the problem persists.

The question that therefore arises is, to what level can the causes and consequences of fluctuating water quality be managed by adapting on-farm production practises and by introducing policy instruments, and which farm, regional and policy level management options are most suitable to address the water quality problem in the Lower Vaal and Riet Rivers?

1.2. AIMS OF THE STUDY

The main aim of this study is to develop and apply models to determine the long-term financial and economic viability of irrigation farming in the Lower Vaal River area.

Specific aims are to:

- evaluate the relationship between changing water quality, soil conditions and crop production,
- determine the impact on yield, crop choice, agronomic and water management practises, expected income and costs,
- develop models for typical farms in different river reaches, and
- apply the models to test the outcome of alternative scenarios regarding internal water quality management practises and external policy measures.

1.3. THE DELINEATION OF THE STUDY

Figure 1.1 indicates the main focus of this study as indicated by the path of the solid line. The other activities included in the flow chart along the broken lines, delineate the scope of this study. No forestry, and very little aquaculture or intensive agricultural production systems are practised in the area, and will therefore not be included in this study. The effects of water quality on livestock production have been taken into account in a study by Gouws *et al,* (1998:4), which states that the impact of Vaal River water salinity (even up to a TDS of 1200 ppm) will not directly influence the health or performance of livestock or game, but will rather manifest through indirect factors, such as the cost of production feed. Wheat, maize and lucerne are produced as cash crops and are not kept on the farm for livestock feed. No intensive livestock activities are thus included in this study.

In the study area, mainly seasonal irrigated crop production is affected by the poor water quality. Orchards have only recently been established as a long-term strategy to curb the effects of poor water quality and no yield reduction from vines takes place according to the farmers interviewed.

Factors influencing soil salinity, the management options that exist to prevent and control soil salinity and the effects on crops are dealt with in Du Preez *et al, (*2000). Yield reduction as a result of poor and fluctuating irrigation water quality through identified soil, crop and water interactions are then expressed in this research in financial and economic terms to determine the farm level impact.

When interpreting the financial and economic outcome, the secondary effects resulting from the change in production practises and management options also need to be taken into account. For example, the increased salinity of returnflows resulting from increased leaching and an expansion of the artificially drained area will result in down-stream environmental degradation and other socio economic effects that need to be taken into consideration. It is of utmost importance to accurately identify and also determine the secondary effects of recommendations based on the model results to guaranteeing the sustainability of implementing the recommended course of action.

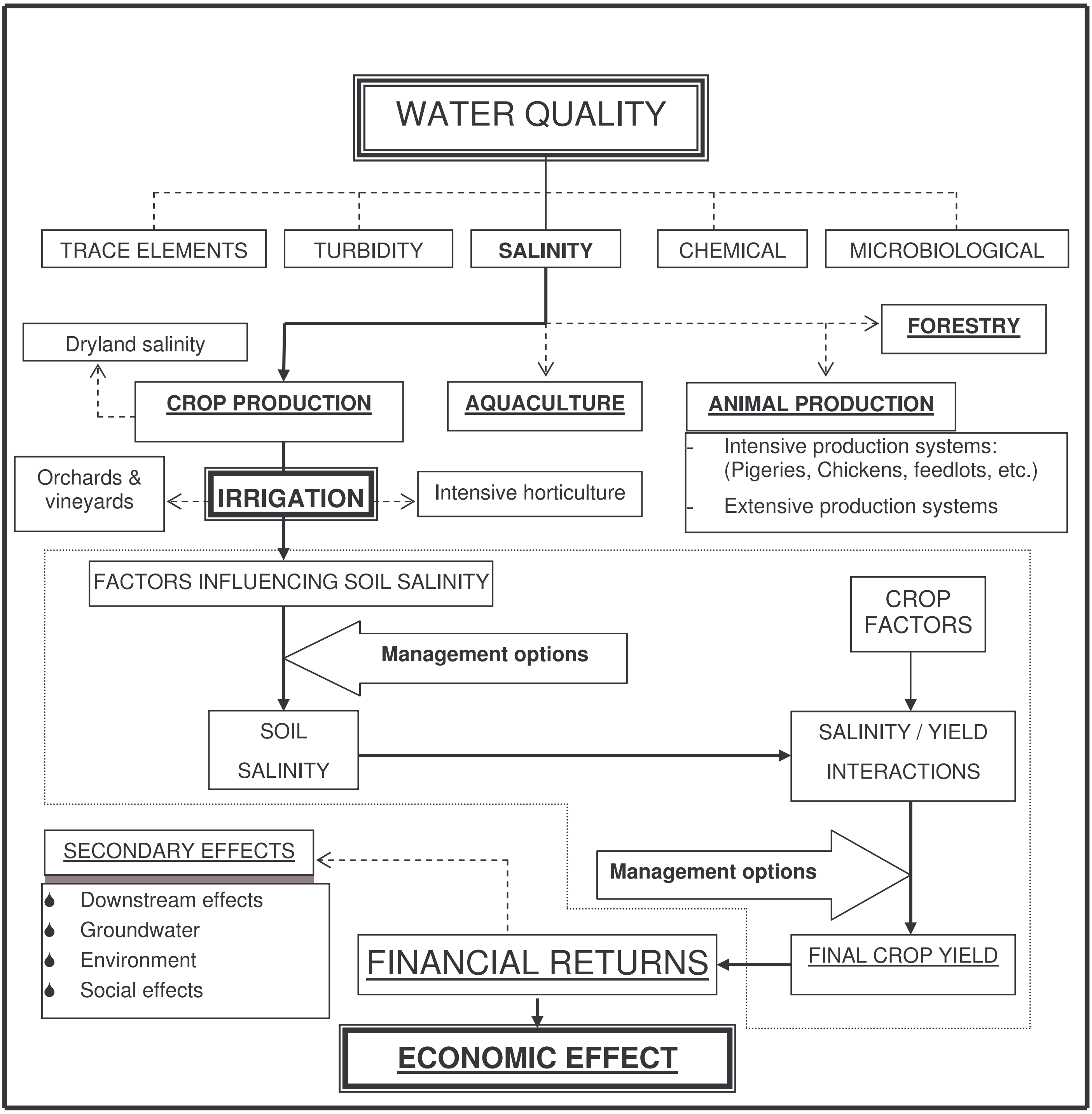


Figure 1.1 A schematic layout of the focus of this research within the broader water quality spectrum (Adapted from Basson *et al,* 1997:3)

1.4. THE IMPORTANCE OF THE STUDY

Global climate change and the imminent threat of droughts or floods, necessitate the continued existence of irrigated agriculture because of the stability of supply it contributes to national food security. In Sub-Saharan Africa the potential irrigated area is estimated at 33 million ha with the presently irrigated area accounting for only 13% of this. With Sub-Saharan Africa by far having the highest population growth rate in the world (2.9%

per annum) compared to the world average of 1.5%, food shortages in this region loom in the not too distant future (Seckler *et al,* 1999). Mechanised, water efficient, irrigation agriculture is a potential solution to ensuring the nutritional needs and stability of Southern Africa. Tremendous pressure will however be placed on expanding the potentially irrigated area and increasing the productivity of existing schemes to meet nutritional needs. This could be at a disastrous cost to the environment and hence on the sustainability of such schemes if the necessary precautions are not taken.

In the study by Seckler *et al,* (1999) titled Water Scarcity in the Twentieth Century, South Africa is classified under category 1; these countries face absolute water scarcity and will not be able to meet water needs in the year 2025. Water use efficiency in irrigation agriculture will thus become crucial as per capita demand for water increase (Basson, *et. al*., 1997). Currently irrigation agriculture in Sub-Saharan Africa is by far the largest user of stored water, using 83%, and in South Africa 51% (Backeberg *et al,* 1996:4). With total water demand exceeding supply before 2020, industry and urban users in South Africa are going to be competing strongly for this most valuable resource. There are clear indications according to Backeberg *et al,* (1996:12), that the price of water for all uses including irrigation will be adjusted upwards to better reflect the cost of supply or perhaps even its value. The “price-cost squeeze” experienced by farmers over the last few decades, recent drastic fuel price increases and the increasing cost of labour further jeopardise the economic sustainability of irrigation agriculture, an industry so crucial to socio-economic stability in many rural areas.

Water of a very high quality, diverted from the Orange River into the Lower Vaal and Riet Rivers has a very important dilution effect, improving the water quality in the rivers markedly. With the possible diversion of Orange River Water via the Lesotho Highlands Water Scheme into the Vaal River for higher value industrial and urban use, the reduction in the dilution effect could hasten the pace of soil salinisation in the Lower Vaal and Riet Rivers and lower downstream in the Orange River.

In South Africa alone, 1995 data reveals that about 110 000 ha of irrigated land was affected by waterlogging and/or salinisation. In the Orange Vaal Irrigation Board (OVIB) service area, the study area on which this research is based, 13% of the 8 091 ha irrigation water rights allocated in the OVIB area are slightly affected by salinisation and waterlogging to the extent that agricultural production can still take place, but that the production potential and/or choice is restricted, and a further 10% of the OVIB area is severely affected to such an extent that agricultural production can no longer take place without special remediation actions such as artificial drainage or gypsum application being applied (Van Heerden *et al,* 2000). With nearly a quarter of the irrigated area in the study area thus affected by salinisation and a trend of declining water quality (Du Preez *et al,* 2000) the questionable economic and environmental sustainability of irrigation in the study area necessitates attention.

Douglas, the main town within the study area is almost entirely dependent on the forward and backward linkages of the irrigation industry, drawing water from the lowest reaches of the highly controlled and heavily utilised Vaal River, with water being the life blood of the higher value mining and processing industries of Gauteng. With one of the objectives of the National Water Act (39 of 1998) being to direct water to the highest value users, one of the foremost tasks of this research is to identify possible productivity increases in water use in the study area under current water quality conditions and to determine what the effect of possible increases in water tariffs would be on the financial sustainability of various case study farms in the study area.

Examples of the importance of the results of this study for irrigators, the OVIB and policy makers are:

For the irrigation farmer the results are important to:

- see how productivity gains can be made with existing resources through available management techniques,
- highlight the importance of leaching and evaluate the financial feasibility of installing artificial drainage,
- help in the decision of replacing or improving an old irrigation system, and
- highlight the importance of irrigation return flow management and options for on-farm storage.

Important decision-making data for the OVIB are as follows:

- what prices to charge farmers for water of different qualities,
- to determine the water transfer costs and water quality benefits of the various water transfer schemes, and
- to indicate to what extent a volumetric water rights allocation system would be better than the current system based on per hectare water rights held.

At a national level this study can be useful in providing an indication of:

- the value of the dilution effect of Orange River water,
- the importance of leaching in irrigation and the need for subsidisation of artificial drainage,
- the need for management options or controls of irrigation returnflows, and
- the right incentives for the promotion of leaching as a salinity management tool and at the same time the careful management of the resulting leachate.

To conclude, although from a national perspective, irrigation is not the highest value user of water, the secondary effects from irrigation, the food security that irrigation creates and the infrastructure and socio-economic services provided to rural regions of the country through irrigation are an argument for the continued need for national resources to be spent on researching and managing irrigation and irrigation induced and irrigation affecting water quality problems.

With the need for water use efficiency highlighted above and the importance of leaching described in the literature study, the importance of a financial optimisation model is evident to solve the paradox between saving water due to it’s scarcity value and “wasting” water to leach out the salts that build up in soils through irrigation.

1.5. METHODOLOGY USED FOR THE DETERMINATION OF THE ECONOMIC EFFECTS OF CHANGING IRRIGATION WATER QUALITY

This section gives a summary of the methodology followed in this study. The layout of the rest of this chapter follows that of the flow diagram in Figure 1.2.

1.5.1. PROBLEM IDENTIFICATION

The first step in the methodology for the determination of the economic impact of irrigation water quality on farming returns was the familiarisation with the theory and previous work conducted on the problem and also familiarisation with the study area. This was done by conducting a literature study on water quality and visiting the study area and holding panel discussions with farmers and experts affected by and involved with irrigation water quality. Results from the Du Preez *et al,* (2000) study indicated that the Spitskop Dam was the water body with the worst irrigation water quality and which had the potential for the greatest degradation. The area served by the Spitskop Dam however is very small and the dam is managed in such a way that the impacts of water releases are very small on irrigators downstream. It was therefore decided to choose the Orange Vaal Irrigation Board (OVIB) as a study area due to the complex nature of the hydraulics in the area and since the second poorest water quality conditions after the Spitskop Dam prevail in the area. A more detailed discussion on the study area appears in chapter 2.

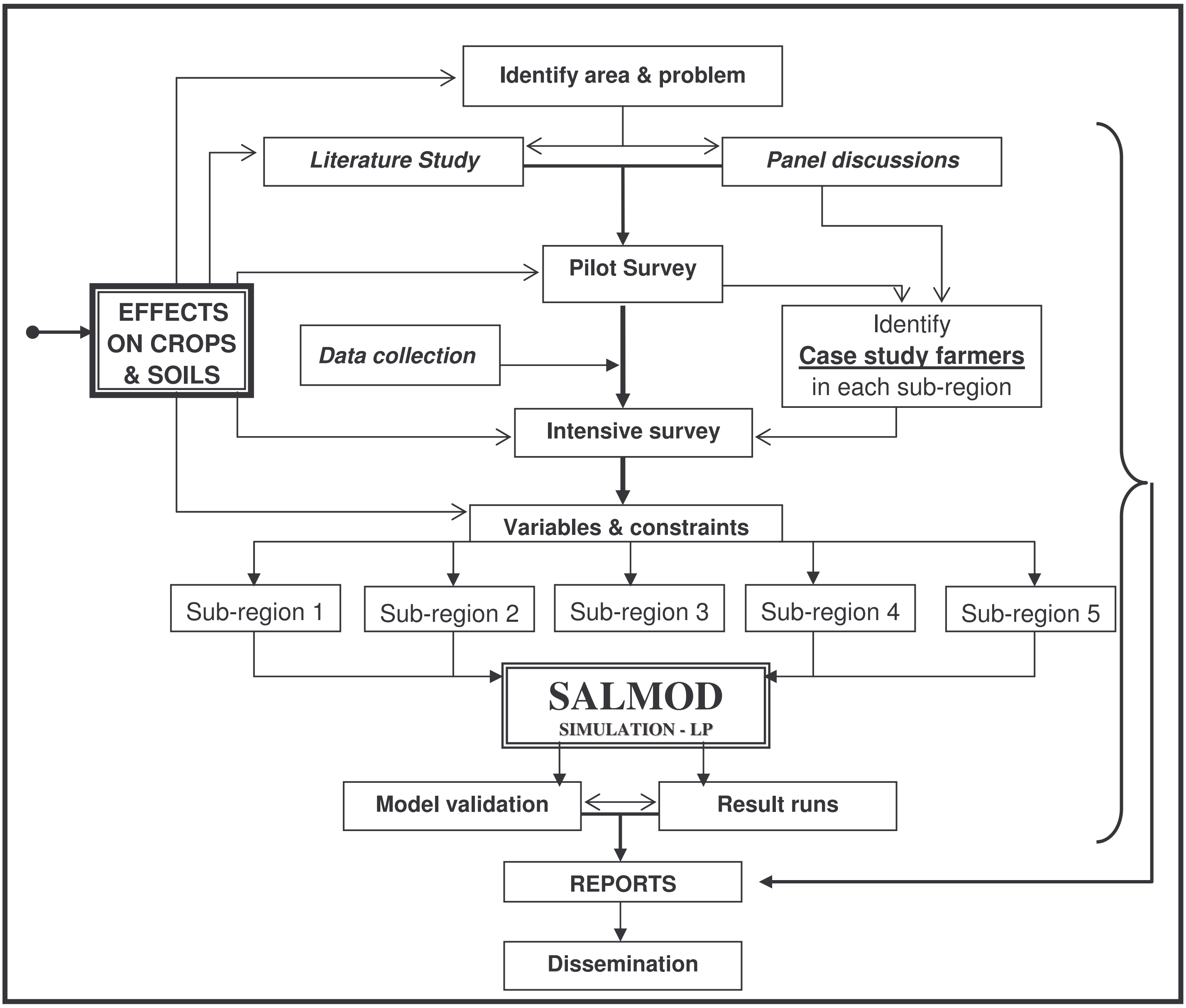


Figure 1.2 A schematic layout of the methodology preceding SALMOD, the model-building phase

The literature study that was conducted appears in chapter 3. The first step was to define water quality and identify what particular aspect of water quality were problematic in the study area. The water quality constituent identified as the most problematic in the study area, after conducting a study on water quality literature, a familiarisation tour of the study area and a panel discussion with farmers and experts, was agricultural salinisation. Previous research conducted on agricultural salinisation was then identified and reviewed and a methodology was formulated to quantify the economic effects of poor and fluctuating irrigation water quality using a mathematical simulation model and a linear programming model constructed as one model using GAMS.

1.5.2. PILOT SURVEY

A pilot survey was conducted to gain insight into the range and magnitude of the water quality problem across the study area, to identify the worst areas and select a suitable range of case study farms to draw data from and to analyse. The type of questions asked in the survey were to gauge the farmers understanding of the problem, how badly farmers in different regions are affected, what solutions the farmers propose and what management and remediation practises the farmers are aware of and which they are already implementing. Survey participants were selected by the irrigation board staff that they thought would be knowledgeable, and also by word of mouth. At least one farmer in each sub-area of the study area was selected as well as the farmers experiencing the worst water quality problems.

1.5.3. SELECTING CASE STUDY FARMS

Conducting the pilot survey and analysing the results gave a better understanding of the water quality problem in the study area and helped with the orientation of the study. An indication of data availability and data needs was also gained.

To aid in selecting the case study farmers, data was obtained from the OVIB that included a membership list of all irrigators in the OVIB area, listing irrigation rights and contact details and a list of the 1998 irrigation seasons crops planted and water requirements for each farmer.

Using this data most of the case study farmers were selected from the farmers who had completed the pilot survey, and who were the most representative of their sub-area according to farm size, crop composition, irrigation system used and receiving water quality. Chapter 2 gives a description of the five case study farms that were selected for each OVIB sub-area.

1.5.4. DATA COLLECTION

The aim of this section is to describe the sources of the data required for this study. The secondary data is first discussed and then the primary data. After all the data needed was accumulated and ready for implementation in SALMOD a technical meeting was held with members of the Project Steering Committee and irrigation farmers to verify this data.

1.5.4.1 Secondary Data

Water quality data collected and processed by the DWAF for all gauging points in the study area was obtained and analysed. After electronically plotting a map of the study area, this data which included X and Y mapping co-ordinates, was arranged in the proper format to be viewed spatially using WISH, a Windows interpretation System for Hydrogeology (www.uovs.ac.za/igs/software.htm). All readings of the following water quality constituents, pH, EC (mS/m), and Total dissolved solids (TDS), Calcium (Ca), Magnesium (Mg), Sodium (Na), Potassium (K), Alkalinity, Chlorine (Cl), Sulphate (SO_4), Cations, Anions, Balance, Fluorine (F), Aluminium (Al), Iron (Fe), Magnesium (Mn) and Nitrogen (N) all measured in mg/l and N measured as mg/l NO_3 are colour coded according to the DWAF (1993) Water Quality Guidelines so they can easily be identified if the acceptable water quality limits are exceeded. In doing this, electrical conductivity (EC), a measure of irrigation water salinity, was identified as the most problematic water quality constituent for irrigation.

The data sources used in the collection of secondary data are the OVIB, DWAF, GWK Ltd., the literature study, and the Du Preez *et al, (*2000) and Van Heerden *et al, (*2000) studies. Primary data collection was conducted by means of a pilot survey and a financial analysis survey.

1.5.4.1.1 Results from the preceding study

According to Du Preez *et al, (*2000:42) the overall trend in water quality is one of fluctuation, rather than constant deterioration over time. Despite the fluctuation, a slight trend in salinity deterioration over the long-term is also evident in especially the lower reaches of the rivers. As the study area used by Du Preez *et al (*2000) was more extensive, and the analyses conducted for areas that corresponded to the study area of this study were grouped, the water quality data for the individual gauging stations had to be requested from DWAF again and re-analysed.

With the exception of the Olierivier case study farm and the site referred to as Jackson's by Du Preez *et al, (*2000), the soil analyses conducted in the Du Preez *et al, (*2000) study were from outside the study area. Jackson's is also situated within the Olierivier sub-area and was visited during the pilot survey but not selected as a case study farm. The same team that collected and analysed the soil samples for the du Preez *et al, (*2000) study was subcontracted to take samples of the major soil classes on each case study farm. These results appear in **Table 2.7** in chapter 2

1.5.4.1.2 Literature

The main data used from the literature are the crop response to salinity data, which consists of the threshold and gradient values for most crops as originally determined by Maas & Hoffmann (1977) and also used by Maas (1990), François & Maas (1994) and Ayers & Westcot (1985). These threshold and gradient values were determined under very controlled conditions with no soil, drainage and irrigation application variability, and the salinity of the irrigation water applied was set at a constant level by using an exact concentration of sodium and chlorine minerals only, for the entire duration of the crops growth.

1.5.4.1.3 DWAF data base

The first river process data that was obtained was data already processed by Du Preez *et al, (*2000). Chemical water quality data of various sample points was obtained from the DWAF, identified through an inventory of chemical analyses available for hydrological gauging supplied by the DWAF. Du Preez *et al, (*2000) grouped many of these points together to get averages for different river reaches in their study area, which is larger than the area decided on for the purpose of this study. Their results were useful in identifying the area experiencing the worst water quality problems in the lower Vaal River system.

After the study area for this study was specified, the same inventory as used by Du Preez *et al, (*2000) was consulted to ungroup their results for this, a more intensive study of a smaller study area, the OVIB service area.

Water quality data collected and processed by the DWAF for all gauging points in the study area was obtained and analysed. After electronically plotting a map of the study area, this data which included X and Y mapping co-ordinates, was arranged in the proper format to be viewed spatially using WISH, a Windows interpretation System for Hydrogeology (www.uovs.ac.za/igs/software.htm). All readings of the following water quality constituents, pH, EC (mS/m), and TDS, Ca, Mg, Na, K, Alkalinity, Cl, SO_4, Cations, Anions, Balance, F, Al, Fe, Mn and N all measured in mg/l and N measured as mg/l NO_3 were colour coded in WISH according to the DWAF (1993) Water Quality Guidelines so they can easily be identified if the acceptable water quality limits are exceeded. In doing this, electrical conductivity (EC), a measure of irrigation water salinity, was identified as the most problematic water quality constituent for irrigation.

1.5.4.1.4 OVIB water quality readings

The DWAF data was incomplete in some areas and didn't cover all the OVIB sub-areas, so water quality data was obtained from the OVIB. Water samples monitoring for total dissolved salts (TDS) in mg/l were taken regularly from 1992 to 1994 for the study conducted by Moolman and Quibell (1995), and which was obtained from the OVIB. The OVIB has continued taking water quality (TDS) readings every two weeks from the major sampling points used by Moolman and Quibell (1995), which have been combined with the DWAF data for the results and discussion that appears in Chapter 2.

1.5.4.1.5 GWK data

The crop enterprise budgets (CEBs) used in SALMOD model runs have a marked impact on the results. Actual CEBs derived from the case study farmer in each sub-area are used in this study for evaluating the impacts of various management options on a case study farm basis. GWK Ltd. CEBs, set up to be representative of the whole GWK region, were also used in SALMOD runs for all study area sub-areas. What the model does not incorporate when using GWK CEBs is the economically viable size of operation for the production of various crops, and whether or not the farmer has the correct equipment to grow those crops. This is overcome when using the sub-area case study farmers own CEBs, thus CEBs for crops that the farmer does not grow are not incorporated into the model.

1.5.4.2 Primary Data

Primary data on farm sizes, crops grown, crop water use and water quality was obtained from the OVIB office. Results of a pilot survey conducted in the study area gave a good introduction to the magnitude of the water quality problem, an orientation of the study area and an opportunity to get to meet the farmers in the area. Data gathered from the pilot survey was used to identify suitable case study farmers and the types of information that was required from these farmers. The results of the intensive survey together with information from GWK Ltd. provided the price, cost and input data required to set up crop enterprise budgets for each case study farmer and an average crop enterprise budget for the region.

1.5.4.2.1 Pilot survey (Douglas 16 – 18 April 1998)

The perceptions of the farmers were determined by conducting a pilot survey in the study area, the main aim of which was to determine to what extent the farmers are aware of the problem and how they have adapted their practises to the fluctuating water quality levels. The survey indicated that the farmers are very well aware of the problem and those affected have adapted production accordingly. The farmers were however reluctant to apply leaching practises due to high pumping costs and the extra management time required.

Nine farmers were interviewed in the pilot survey, with at least one representative from each sub-area. The survey covered 37% of the total area irrigated in the OVIB service area. Only a small number of farmers in the study area have other farming interests except irrigation farming. Although only 25% of the total area owned by the farmers interviewed is irrigated, being an arid area the livestock that is kept on the land not irrigated is barely of economic significance to the farmers; being used mainly for own consumption, and game for hunting. This is an indication of the reliance of the farmers in the area on irrigation agriculture and thus the importance of ensuring water of an acceptable quality.

A farmer was identified in New Bucklands, situated near Marksdrift (see Figure 4.1) as a case study farmer and an ideal control for the study as irrigation is with unsaline (TDS <200mg/l) Orange River water from out of the Louis Bosman canal. The land is only in its third to fifth year of production and yields are similar to the maximum physiological yields as calculated by Viljoen *et al, (*1992) and as initially used in the model as a basis from which to calculate the potential gains of improved water quality.

The pilot survey also revealed that because of the limits placed by quotas, which are a certain volume per hectare irrigation rights held, farmers are irrigating far less than what they could; where farmers could get two crops per year, because of the implementation of a fixed quota they are only getting an average of approximately 1.3 crops. Farmers prefer to plant a full crop in the winter season, when evapotranspiration isn't as high and thus the negative effect of irrigating with poor quality water is minimized.

Results from the survey clearly indicate that the largest area is planted to wheat, followed by maize and then lucerne.

The main reservations heard from farmers regarding the practise of leaching is that nitrogen fertiliser is an expensive input that farmers do not want to flush away by leaching. As nitrates are applied at various stages during the growing season, the required leachings can be performed before nitrate applications. A pre-season leach could also be sufficient as long as there is enough time between harvesting and planting of the next crop. These practises are however contrary to the model assumptions that a constant leaching fraction is maintained. With good management however the same leaching fraction can be applied over a cropping season at different application rates to coincide with nitrogen applications so as not to waste and pollute.

1.5.4.2.2 Financial analysis survey

The case study farmers identified from the results of the pilot survey were visited and the necessary data accumulated to conduct a financial analysis for each case study farmer. An intensive financial analysis survey was conducted for the 1998/99 and 1999/2000 financial years as the financial year and water year/production season do not coincide. The financial analysis was necessary to verify model results set up using 2000 costs and prices with actual financial results for the same period. The results of this financial analysis appear in Chapter 2 in **Table 2.10** for comparison between the 5 case study farmers.

Once all the data needed was accumulated and ready for implementation in SALMOD a technical meeting was held with some of the members of the project steering committee and irrigation farmers to verify the data.

Chapter 4 provides a more intensive discussion on data formulation and use in this study.

The construction of SALMOD, the simulation and optimisation model used to determine the financial effects of water quality in irrigation, progressed slowly over the course of the project. In the beginning phases SALMOD was constructed using Microsoft Excel spreadsheets for simulating alternative crop enterprise budgets for different irrigation systems, soil types and leaching fractions based on a basic crop enterprise budget. This provided the range of crop gross margins to be used in Microsoft Excels Solver, and later the WhatsBest! optimisation packages, to determine the profit maximising crop combinations for different irrigation water qualities, soil types and irrigation systems (high frequency vs. low frequency irrigation). As the model was refined and more cropping, resource and management options were added the spreadsheet matrix became too cumbersome and large for Excel. At this stage GAMS was studied and the model was converted to GAMS. The GAMS coding in mathematical notation, with a discussion on all input data needed and each equation used in SALMOD, is given in chapter 4.

1.5.4.3 Model runs and validation

Before the final set of results from SALMOD were recorded for writing up of reports, SALMOD was set up and run with each individual case study farmer for validation of the input data and results. For this run with the farmers SALMOD was set up to include GWK Ltd. regional average crop enterprise budgets where the farmers didn’t supply their own enterprise budget for the specific crop. This lead to unrealistic results as the farmers generally had good reasons for leaving a particular crop out. Once SALMOD was set up for the farmers with the crops not grown excluded, the farmers were excited about the results, additional information, management option feasibilities, and the potential total gross margin above specified costs (TGMASC) generated by SALMOD.

1.6. SUMMARY

Following the introduction, Section 1.3 serves as an outline and orientation for the rest of this study. The basic methodology that was followed in conducting this research is presented as an introduction to the relevant chapters that contain a more complete discussion. Section 1.4 lists the data sources used in this research. The data sources used in the collection of secondary data are the OVIB, DWAF, GWK Ltd., the literature study, and the Du Preez *et al, (*2000) and Van Heerden *et al, (*2000) studies. Primary data collection was done by the means of a pilot survey and a financial analysis survey.

1.7. LAYOUT OF THE STUDY

This chapter presents the problem statement and aims of this research followed by a broad overview of the importance of irrigation and of effective salinity management to ensure the sustainability of irrigation: The methodology followed in conducting this research is then given together with the secondary and primary data used, and in conclusion, the potential usefulness of this research at farm, irrigation board and national level is discussed.

Chapter two is a description of the study area and the case study farmers used in the research.

Chapter three is a literature study in which the term water quality is defined and salinity identified as the most important water quality constituent for the study area. An overview of salinity management options and a review of models used in solving salinity problems are presented.

Chapter four is a discussion on the mathematical formulation of SALMOD.

The first part of chapter five lists and discusses the series of results generated by SALMOD under current and parametrically varied results for each of the case study farmers, followed in the second part of the chapter by SALMOD results using Du Preez *et al,* (2000) data predicting irrigation water salinity for 2025.

Chapter six contains the summary, conclusions and recommendations of this research.

CHAPTER 2. THE STUDY AREA

The grass is rich and matted, you cannot see the soil. It holds the rain and mist, and they seep into the ground, feeding the streams in every kloof. It is well-tended, and not too many cattle feed upon it; not too many fires burn it, laying the soil bare. Stand unshod upon it, for the ground is holy, being even as it came from the Creator. Keep it, guard it, care for it, for it keeps men, guards men, cares for men. Destroy it and man is destroyed.

Alan Paton: Cry, The Beloved Country

2.1. INTRODUCTION

The aim of this chapter is to describe and delineate the study area examined for the purpose of this study, namely the area managed by the Orange Vaal Irrigation Board (OVIB). In the first section a short historical overview of water management and control in the study area is given followed by the demarcation of the study area. Water quality and land type characterisation of the study area follows and the chapter ends with a description of each of the case study farms within the study area.

2.2. WATER MANAGEMENT AND CONTROL IN THE STUDY AREA

The initial irrigation plots allocated in the study area (Bucklands and Atherton) were part of a government social-economic scheme after the drought and depression of the 1930’s (DWAF, 1993:14). The sustainability of the soils on which these plots were established for irrigation agriculture was not a primary factor as they were developed mainly for socio-economic purposes.

In 1984 an Irrigation Board was established to manage water allocations in the demarcated area. With the study area being right at the bottom of the Vaal River system, and water usage from the Vaal River prioritised for industrial and residential use in Johannesburg and for mining purposes in the Free State goldfields, times of drought in the upper catchment, often led to water shortages in the study area. A particularly bad drought in 1992 led to the construction of the Louis Bosman Canal in 1994 to transfer Orange River water to the Douglas weir. Together with the increased water security, farmers noticed a marked improvement in crop yields due to the improvement in water quality. Water quality improved dramatically after Orange River water was pumped into the system via the canal.

The reason for the poor water quality along the Lower Vaal River was initially believed to be as a result of industry and mining in the upper reaches of the Vaal River. It has however since been proved by various studies (Du Plessis 1982, Moolman & Quibell 1995 and Nell 1995) that the actual process of irrigation, displaces certain salts in the soil and releases sodium, chloride and other salts into the water while at the same time breaking down the physical structure of the soil. These practises by the irrigation farmers in the middle and upper reaches of the Vaal, Riet and Harts Rivers all contribute to the seasonal water quality fluctuation in the study area. The main problem of concern however is the building up of salts in irrigated soils.

Currently water use is allocated on a per hectare water rights possessed basis and not on a volumetric basis. This does not promote efficiency in irrigation water application, as there is no control on the quantity of irrigation water withdrawn. In the beginning of each irrigation season, farmers submit the proposed area of crops they will be planting to the OVIB, which calculates water usage and charges according to these proposed areas, multiplied by the long-term average evapotranspiration and crop co-efficient for each crop. The OVIB also checks that the proposed areas correlate with the actual area planted later in the season. The only incentive to prevent farmer's from over irrigating and to limit distribution losses is the actual cost pumping. These pumping costs also make farmers reluctant to deliberately "over irrigate" to leach out salts that have built up in the soils from years of irrigating.

2.3. DEMARCATION OF THE STUDY AREA

Spitskop Dam at the bottom end of the Vaal-Harts irrigation scheme, the largest irrigation scheme in South Africa, is identified in Du Preez *et al, (*2000) as one of the water bodies within their study area with the poorest water quality and the greatest potential for rapid further decline, closely followed by the Lower Riet River and then the Lower Vaal River, both of which are situated in the OVIB region. The Spitskop Dam however only serves a very small irrigation community and very little water is released from the Spitskop Dam back into the Vaal River. The OVIB region on the other hand is a very important irrigation region within South Africa and the complex interaction of the hydraulic systems impacting on the area make this a more applicable region to study.

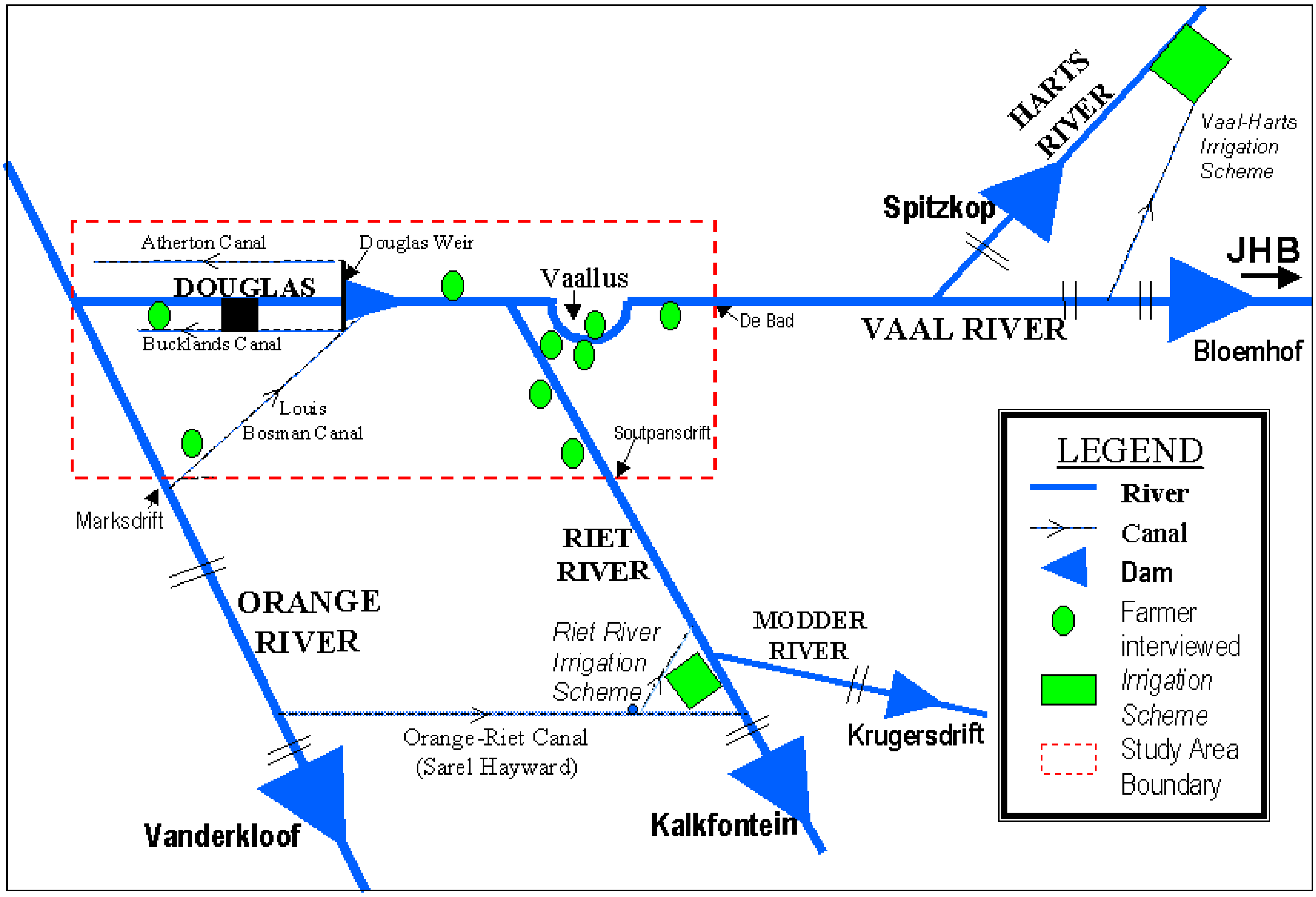


Figure 2.1 A schematic representation of the positioning of the OVIB within the regional hydrology

A schematic representation of the hydrological system impacting upon the study area is shown in Figure 2.1. It can be deducted that the area is highly controlled and has a multitude of factors that interact to determine the water quality in the study area. The high level of control does however create the possibility of ensuring an almost certain annual water quantity through water mixing (Moolman & Quibell, 1995). The accessibility of the water for dilution, the cost of pumping this water and the uncertainty of the real financial benefits of improving the water quality in the study area are factors that make this not a readily practised option.

The OVIB has subdivided its service area into five sub-areas, each receiving a different average water quality as a result of being differently influenced by alternative regional level water management options. Initially there were only four sub-areas as demarcated in the Government Gazette No. 9498, 16 November 1984, but a fifth sub-area was added as new land was developed for irrigation. The soil types in the five sub-areas also differ markedly. The first sub-area, named Olierivier in this study, includes all farmers irrigating out of the Riet River, from the Vaal/Riet confluence to Soutpansdrift, the eastern boundary of the study area. The Second sub-area includes all farmers irrigating from the Vaal River between De Bad, the northern boundary of the study area, and the Douglas Weir. These are predominantly the Vaallus irrigation farmers, but also consist of farmers below the Vaal/Riet confluence, down to the Douglas Weir. The area below the Vaal/Riet confluence is not only influenced by the addition of very poor quality Riet River water, but also by 'pure' Orange River water pumped in via the Louis Bosman Canal. This results in two distinctly different water bodies that do not readily mix. The third and fourth sub-area includes the predominantly smallholding farms irrigating from the Bucklands and Atherton Canals that receive 'mixed' Orange River water. The fifth sub-area comprises newly established farms irrigating with Orange River water out of the Louis Bosman Canal. As these farms are planting on relatively virgin soils (only in their 5th production season) and irrigating with "pure" Orange River water, they provide a good control for this water quality study.

2.4. WATER QUALITY CHARACTERISATION

The seasonality of the EC/TDS fluctuations can be clearly seen in Figure 2.2 for Soutpansdrift where TDS and EC are plotted for ten years from 1990 till 2000. Soutpansdrift directly translated means "salt pans weir " and this is exactly what it is. There are numerous saltpans in the vicinity indicating geologically saline soils and there is a weir at this border between the Riet River irrigation scheme and the OVIB area. All excess water and returnflows from the Riet River irrigation scheme flow into the Lower Riet River arm from which most Olierivier farmers extract their water.

The peaks in irrigation water salinity in Figure 2.2 for each year occur in September or October, which are also the months with the least evapo-transpiration (see Figure 2.7). The drastic improvement in water quality that occurs between December and April is as a result of the onset of the rainfall season in the study area and the catchments in the upper river reaches. A less dramatic increase again occurs from April to August as excess irrigation water that had been applied to irrigate crops seeps through the soil and returns into the river laden with salts.

Figure 2.3 shows the impact of the volume of water flowing over the weir at Soutpansdrift. Flows of over approximately 9 000 000 m^3 per month resulted in a drop in the TDS to below the acceptable level of 600 mg/l. These flows are generally attributed to good rains in the upper reaches of the Riet and its tributaries or large excesses of water pumped from the Orange River via the Orange-Riet (Sarel Hayward) Canal for the Riet River Irrigation Scheme. The fact that the lower volume flows have high TDS concentrations is most probably a result of irrigation returnflows. Note also that most of the peaks in TDS correspond to flows of less than 3 000 000 m^3 per month. Moolman and Quibell (1995:35) suggested in their report that by increasing the flow over the Soutpansdrift weir to $30x10^6$ m^3 per year using Orange River water, reduce the salinity in the Lower Riet River arm to acceptable levels.

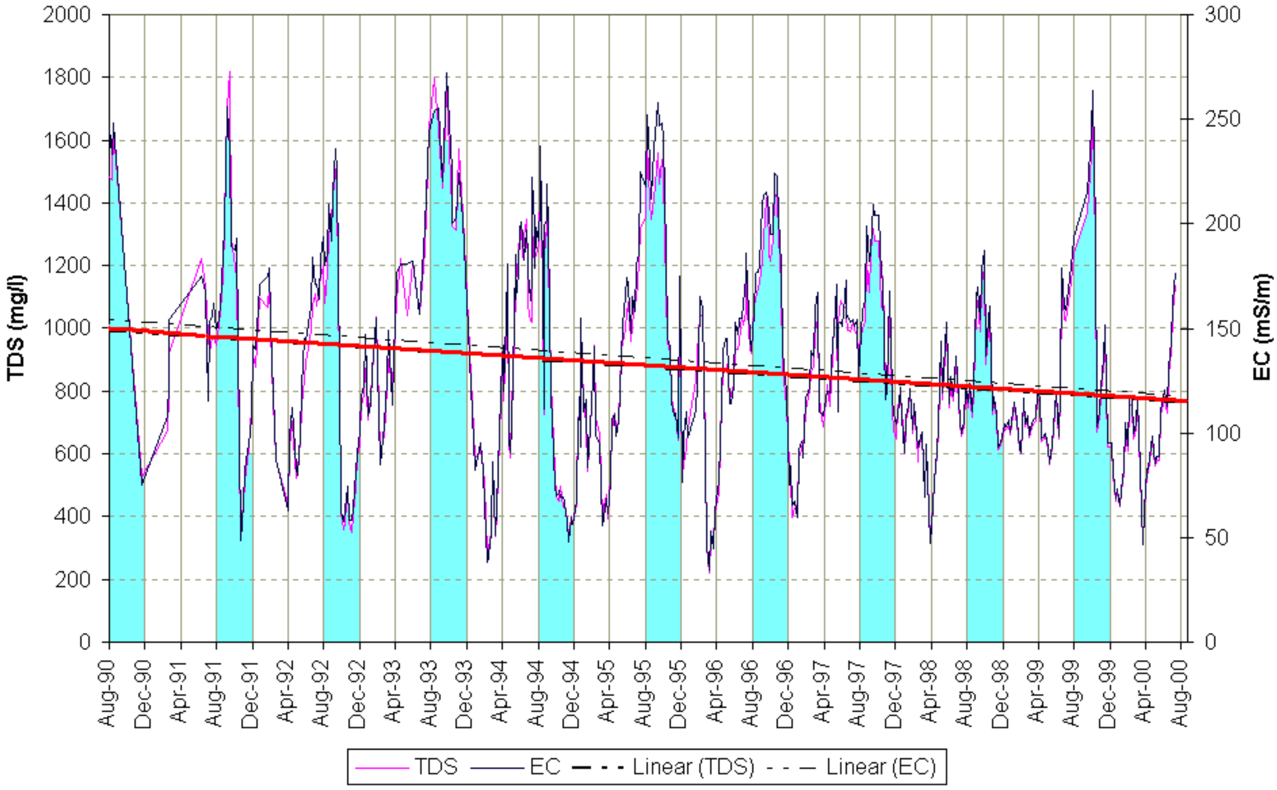


Figure 2.2 Salinity fluctuations measured as EC(mS/m) and TDS(mg/l) at Soutpansdrift on the Riet River, DWAF 1990-1997

Also notable in Figure 2.2 is the declining or improving trend in water quality over the ten years. This could be due to improved irrigation efficiencies brought about by the price-cost squeeze and improved irrigation management resulting in less leaching, or it could be as a result of more Orange River water being transferred into the system and having a dilution effect.

Figure 2.4 is set up for a much longer period than Figure 2.2 to show the impact of completing the Louis Bosman Canal and diverting Orange River water into the Vaal River system at the Douglas Barrage wall. The period from 1990 till 1998 also displays the seasonal trend as observed for Soutpansdrift, but not to as great an extent. From 1977 till 1983 water quality progressively deteriorated due to drought in the region and upper reaches and from little releases of water upstream. Diminishing water quantity (ECiw / TDS) necessitated the building of the Louis Bosman Canal that was completed in 1984. The dramatic improvement in water quality after 1984 is clearly visible in Figure 2.4. Data is missing from 1989 to 1992, but the sharp decrease in water salinity in 1988 is probably attributed to a reduction in the pumping of Orange River water once the dams in the upper reaches of the Vaal and Riet Rivers were full again. There is also a declining / improving trend in water quality at the Douglas Weir over the twenty years for which the data is plotted.

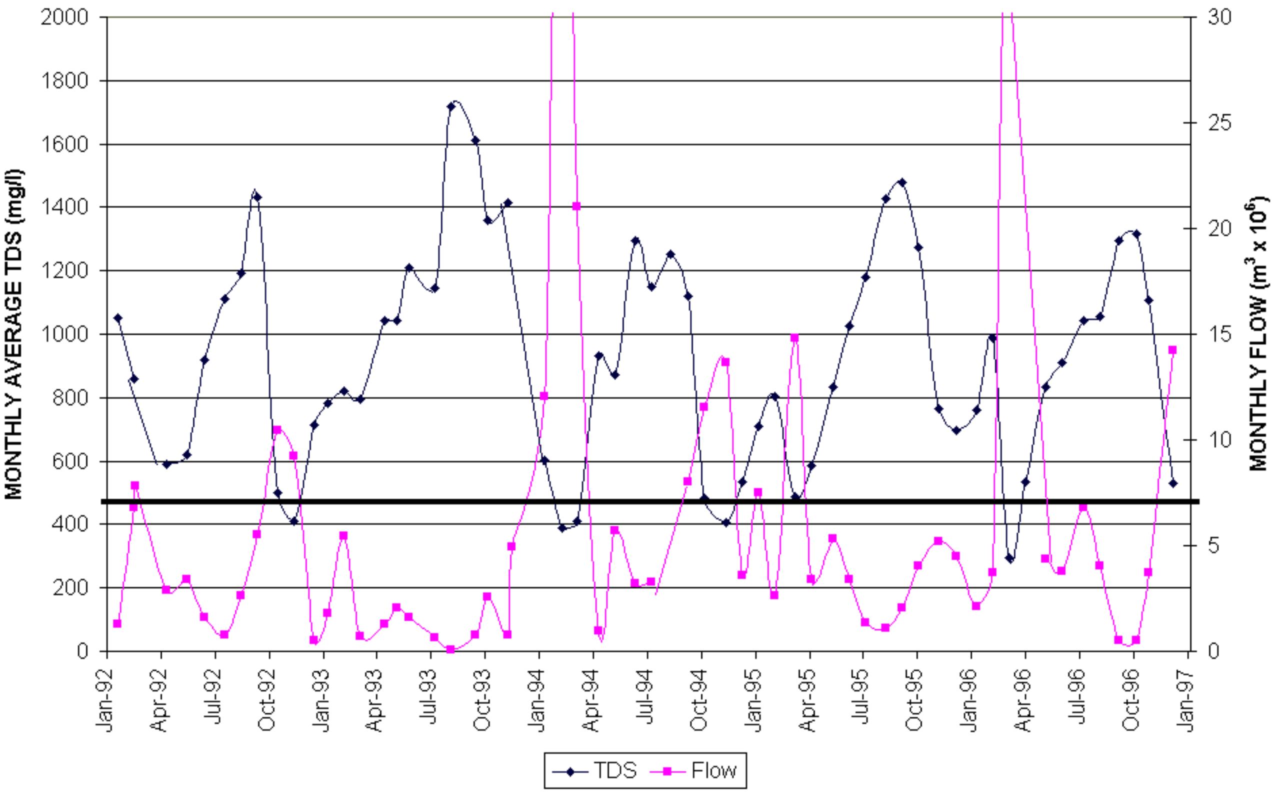


Figure 2.3 The impact of monthly flow (m^3) over the Soutpansdrift weir on salinity (TDS) fluctuations at Soutpansdrift on the Riet River, DWAF 1992-1997

Figure 2.5 displays basically the same data as Figure 2.4 for the period from 1990 till 1998. This data is recorded where the Bucklands canal flows from the Douglas Barrage wall and is therefore very similar to the data recoded at the Barrage wall and also to the Atherton water quality which is diverted from just the other side of the Barrage wall.

A very sharp declining / improving trend can also be observed for the six year period from 1992 to 1998 in Figure 2.5 and is very similar for the Lower Vaal River, from its confluence with the Riet River to the Douglas Barrage, the Bucklands canal and also the Atherton canal.

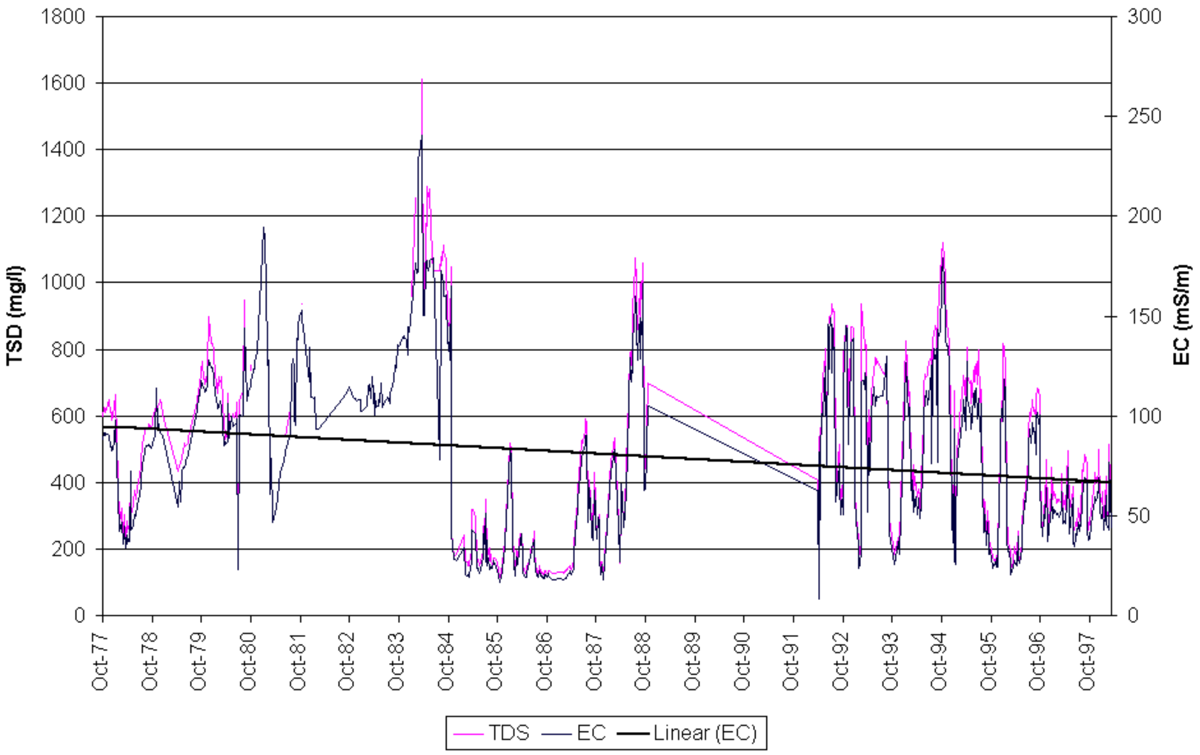


Figure 2.4 **Salinity fluctuations measured as EC(mS/m) and TDS(mg/l) at the Douglas Barrage on the Vaal River, DWAF 1977-1997**

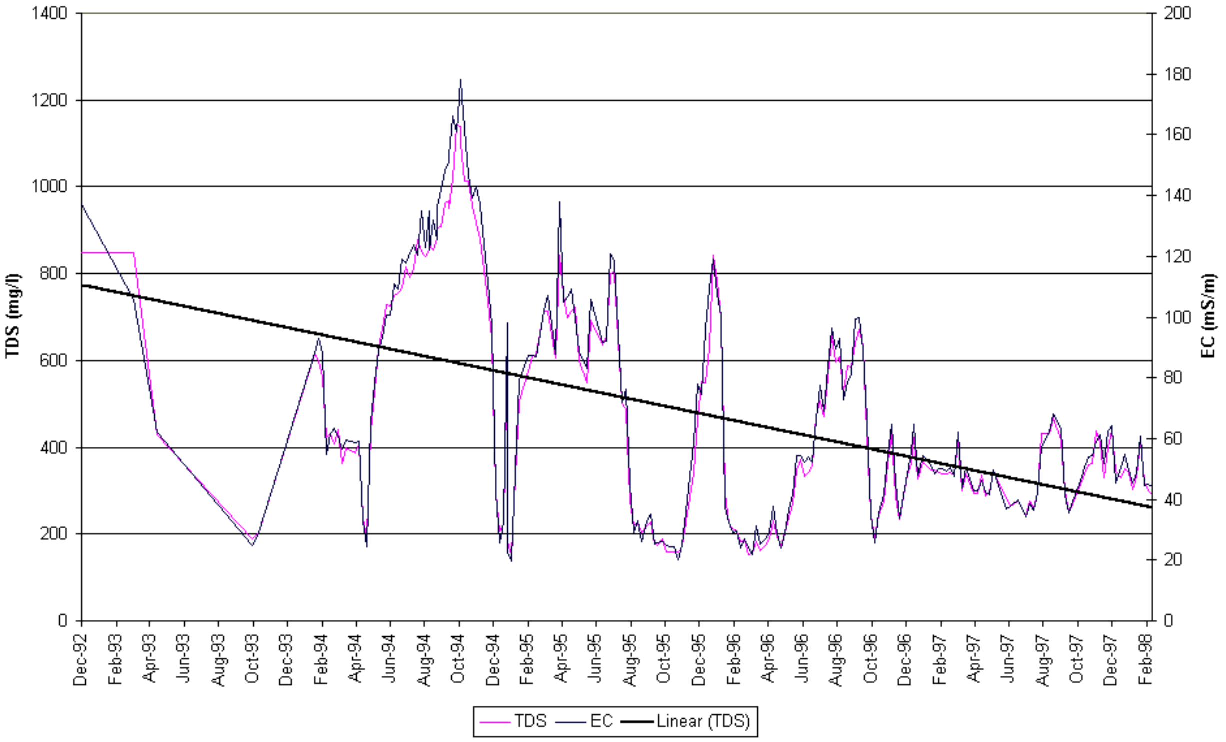


Figure 2.5 **Salinity fluctuations measured as EC(mS/m) and TDS(mg/l) at the Douglas Barrage in the Atherton canal, DWAF 1992-1997**

In Figure 2.6 the monthly average water qualities (EC) for 1998 of the different river reaches in the study are plotted against one another for comparison of the sub-areas. As the DWAF doesn't have gauging stations in all sub-areas of the OVIB, OVIB water quality data is combined with DWAF data in Figure 2.6. At Olierivier (OL) readings are taken by both the OVIB and the DWAF, both of which are plotted in Figure 2.6 for comparison. From January to July the two separate sets of EC readings (OL(DWAF) and OL(OVIB)) are correlated by a narrow range (between 10 and 30 mS/m), with the DWAF readings (OL(DWAF)) being the highest, but from August to December there is no longer a correlation between the readings. The reason for this is unknown.

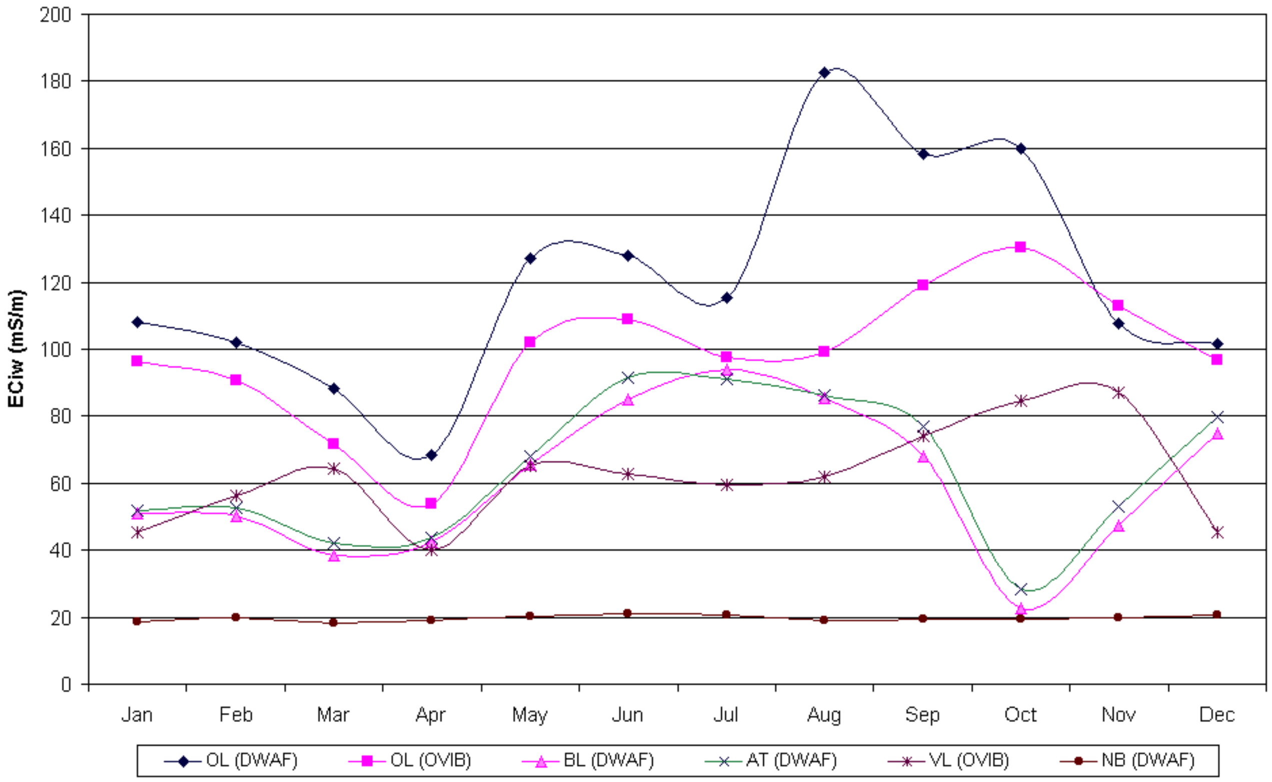


Figure 2.6 Monthly ECiw fluctuation of the OVIB sub-areas, DWAF and OVIB 1998

What Figure 2.6 clearly shows is that Olierivier receives the worst water quality throughout the year and that it is highly variable, whether measured by the OVIB or the DWAF, and that the New Bucklands sub-area constantly receives the best water quality at a very constant EC level of around 20 mS/m. New Bucklands receives its water directly from the Louis Bosman Canal, which diverts Orange River water pumped at Marksdrift to the Douglas Weir (see Figure 2.1). The Lower Vaal River water quality as measured at Vaallus (VL) by the OVIB generally follows a similar pattern as the Lower Riet River water quality at Olierivier (OL) measured by the OVIB, but not to the same magnitude. Water quality in the Atherton (AT) and Bucklands (BL) Canals is very similar as their abstraction points from the source are very close to one another. Their source, the Douglas Weir, which lies below the confluence of the Vaal and the Riet Rivers and where Orange River water pumped via the Louis Bosman Canal, enters the Douglas Weir, is highly influenced by the water quantity and qualities entering it from the various sources. Generally where the Atherton (AT) and Bucklands (BL) water quality is poorer than the Vaal River (VL) water quality level, it is as a result of inflows from the Riet River and where AT and BL water quality is better than VL water quality, Orange River water is being pumped into the weir.

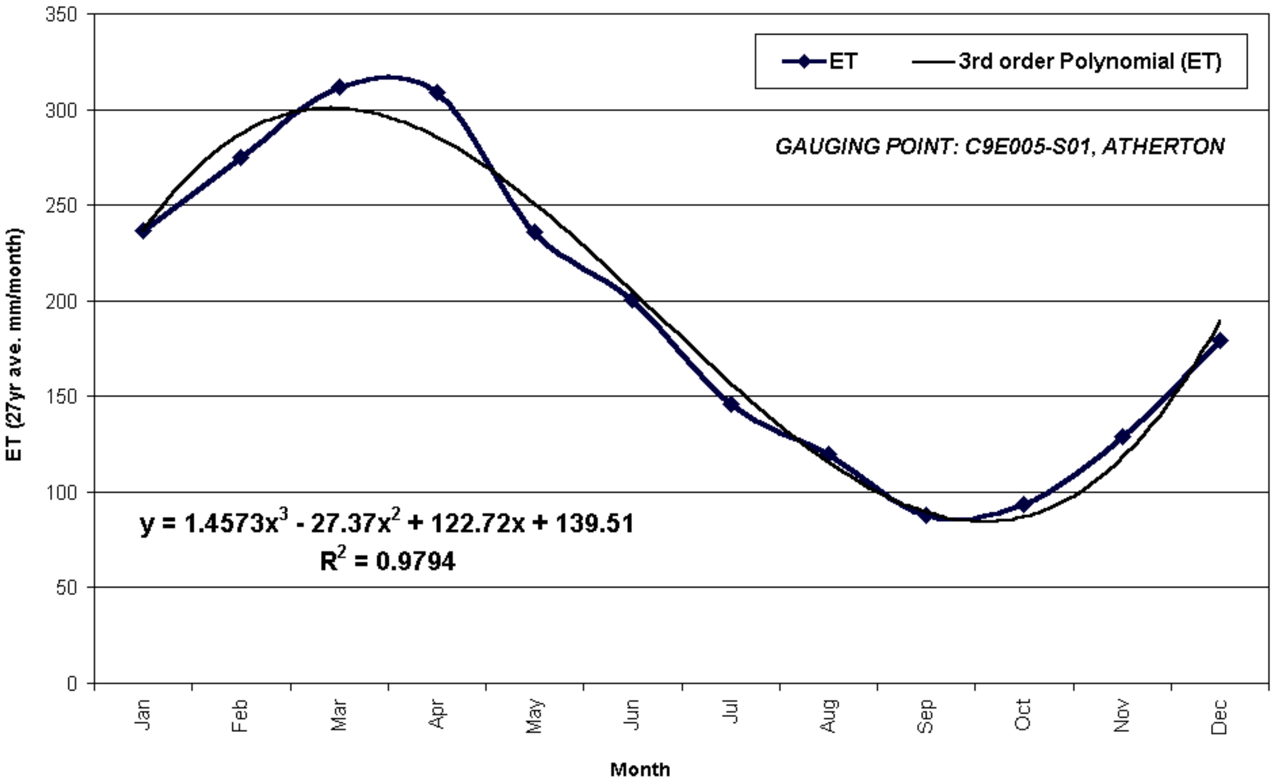


Figure 2.7 Monthly average evapotranspiration in the OVIB, DWAF 1970-1997

Figure 2.7 shows the monthly average evapotranspiration measured at Atherton from 1970 till 1997. These values are used by the OVIB and multiplied by crop specific factors to determine crop water requirements and hence what to charge for water usage. It is clear that in the irrigation season pre-year (July to November) evapotranspiration is at its lowest and for the rest of the year high.

Table 2.1 Long-term monthly average rainfall (mm) at the Douglas weir, DWAF 1986-1998

	86	**87**	**88**	**89**	**90**	**91**	**92**	**93**	**94**	**95**	**96**	**97**	***98***	**Ave.**
Jan	33.5	14	3	75	21	112	4	9	102	100	0	36	*29.4*	**42**
Feb	12.5	87	314	89	55	121	0	94	124	10	46	38	*76.0*	**83**
Mar	34.5	42	119	40	36	108	173	7	23	110	12	133	*70.5*	**70**
Apr	14	19	112	40	57	0	3	21	21	0	36	43	*27.9*	**31**
May	0	0	0	3	15	0	0	0	2	35	0	46	*5.7*	**8**
Jun	4	0	0	1	17.5	44	0	2	1	0	0	16	*3.6*	**7**
Jul	0	16	0	0	0	0	0	2	0	0	22	8	*1.8*	**4**
Aug	4.5	0	0	0	2	0	11	1	0	0	0	0	*7.5*	**2**
Sep	24	33	22	12	0	24	0	0	0	0	6	0	*12.3*	**10**
Oct	7	7	14	0	0	86	4	65	0	4	0	8	*28.4*	**16**
Nov	15	85	30	27	29	26	18	26	49	93	60	0	*29.3*	**38**
Dec	0	37	110	1	39	28	5	31	0	78	73	9	*42.3*	**34**
Total	**149**	**340**	**724**	**288**	**272**	**549**	**218**	**258**	**322**	**430**	**255**	**337**	***335***	**345**

The high evapotranspiration from February to April is offset by good rainfall (see Table 2.1) in these months, resulting in an improvement in water quality (see Figure 2.6), with the exception of the Lower Vaal River. With relatively high evapotranspiration in May and June and little rainfall, a sharp deterioration in water quality takes place and then stabilises until August when wheat, the main crop in the study area starts getting the largest percentage of its water requirement applied. Water quality then continues to deteriorate till November when wheat no longer needs to be irrigated and when it usually starts raining again.

2.5. LAND USE CHARACTERISATION IN THE STUDY AREA

Whereas the previous section focussed on the water resources of the study area and in particular the quality of these resources, this section gives an overview of the number of farmer in each sub-area, their water rights and irrigation areas, the irrigation potential of the soil and the extent of salinisation and waterlogging, followed by a brief discussion on enterprises to be included in the study area and their tolerance to salinity.

Table 2.2 lists the number of farmers served by the OVIB and their numbers and communal water rights owned in each sub-area. Of the 178 farmer members of the OVIB the majority of the members farm in the Atherton sub-area on the smallest average farm size of 11 ha, and possess the third largest hectares of irrigation rights, namely 1341.5 ha. Olierivier that has 23 farm members follows this, but the largest total hectares water right, namely 3124.7 ha, resulting in an average number of hectares per farmer of 135.9. The case study farmer used in Olierivier has 141 ha water rights, which is very close to the sub-area average. Vaallus with 15 members who hold 2659.1 ha irrigation rights communally have the highest average number of water rights per farmer. Bucklands with 11 members holds 349.4 ha water rights with and average of 31.8 ha per farmer and finally the newest irrigation sub-area, New Bucklands has 7 members holding 622.4 ha water rights with an average of 88.9 ha between them. This results in a total of 178 members in the OVIB area and a total of 8097.1 ha of irrigation rights issued with each hectare irrigation right having access to between 9000 and 11000 m^3 of water per year, of which 60% can be used in the pre-year (July to November) and the remaining 40%, together with the unused portion from the pre-year, to be used in the after-year (December to June).

Table 2.2 Orange-Vaal Irrigation Board (OVIB) membership numbers and hectares water rights held in 1998

	Sub-area					**Total / ave. / min / max**
	1	**2**	**3**	**4**	**5**	
	Olierivier	**Vaallus**	**Atherton**	**Bucklands**	**New Bucklands**	
OVIB member numbers:	*23*	*15*	*11*	*122*	*7*	***178***
Member water rights:	3124.7	2659.1	349.4	1341.5	622.4	**8097.1**
Average:	135.9	177.3	31.8	11.0	88.9	***45.5***
Case study farms	141	339	58.4	28.9	100	***133.5***
Mode:	111.1	83.6		2.0	100.0	***2.0***
Standard deviation:	103.6	143.9	30.5	19.0	35.3	***82.2***
Minimum values:	27.0	39.0	1.2	0.1	31.9	***0.1***
Maximum values:	441.3	526.4	93.0	174.1	131.0	***526.4***

The case study farmers used in this study for each sub-area of the OVIB service area were selected *inter alia* according to the hectares water rights held in relation to the sub-area average. The number of water rights possessed by case study farmers is also given in Table 2.2 for comparison with the sub-area average water right, as well as with the mode, standard deviation, minimum and maximum for each sub-area.

Table 2.3 Area (ha) under different irrigation systems in the OVIB region (adapted from Van Heerden, *et al,* 2000)

		IRRIGATION SYSTEM			
Sub-area		**Micro & Drip**	**Sprinkle**	**Flood**	**TOTAL**
1	Olierivier	31	2969	125	**3125**
2	Vaallus	27	1861	771	**2659**
3	Atherton	59	175	115	**349**
4	Bucklands	40	54	1247	**1341**
5	New Bucklands	19	598	0	**617**
TOTAL		***176***	***5657***	***2258***	***8091***
%		2	70	28	100

Table 2.3 indicates that 28% of the OVIB area is flood irrigated and 70% sprinkler irrigated. The trend is towards conversion to centre pivot irrigation, which is a potential problem as it is difficult to leach for salinity management with centre pivot irrigation systems. In other areas where salinity is a problem, flood irrigation on laser-levelled lands seems to be the most efficient and effective. Most of the vineyards in the study region, which predominantly occur in Bucklands and Atherton, are irrigated with micro and drip irrigation systems. The larger farms, which occur in Olierivier, Vaallus, and New Bucklands predominantly have centre pivot irrigation systems. In Atherton, of the 175 hectares under sprinkle irrigation, dragline sprinklers irrigate most.

Table 2.4 Irrigation potential of the irrigable soils in the OVIB region (adapted from Van Heerden, *et al,* 2000)

		IRRIGATION POTENTIAL			
Sub-area		**High (%)**	**Medium (%)**	**Low (%)**	**TOTAL (Ha)**
1	Olierivier	73	14	13	**3125**
2	Vaallus	41	59	0	**2659**
3	Atherton	76	24	0	**349**
4	Bucklands	0	50	50	**1341**
5	New Bucklands	83	16	1	**617**
TOTAL		***51***	***36***	***13***	***8075***

Wiid, J.A. (1999) of GWK Ltd. at Douglas was contacted with regards to irrigation scheduling. He stated that two sources are used to determine irrigation-scheduling data, namely neutron moisture meter readings and weather station evapo-transpiration readings. Farmers who make use of the scheduling service offered by GWK Ltd. also have drainage curves drawn up for their soils. Farmers usually irrigate 12 to 16mm per pivot round (usually weekly) during Ruraflex tariff times from ESCOM to save on electricity. With a heavy irrigation (usually pre-planting or once all soil Nitrogen is used up or just before another Nitrogen application), up to 30mm per ha can be irrigated to leach out salts (i.e. ±50% leaching fraction). According to Du Preez *et al, (*2000:155) the leaching of excess salts from the root zone with centre pivot irrigation proved to be almost impossible because of the high application rates required at the outer circumference of the fields when irrigating more than 30mm per round.

In Olierivier, Atherton and new Bucklands, Table 2.4 indicates that the majority of the soils are high potential irrigation soils, while in Vaallus nearly 60% of the soils are medium potential soils, and in Bucklands 50% medium potential and the other 50% low potential soils.

What is further disturbing is that nearly one quarter (1861) of these hectares are either slightly or severely affected by waterlogging or salinisation as shown in Table 2.5. The largest percentage of affected soils occurs in Vaallus followed by Olierivier.

Table 2.5 Soils affected by salinisation and waterlogging in the OVIB region (adapted from Van Heerden, *et al,* 2000)

		LEVEL OF SALINISATION AND WATERLOGGING		
Sub-area		**Slight[1] (%)**	**Severe[2] (%)**	**TOTAL (ha)**
1	Olierivier	16	4	**625**
2	Vaallus	40	40	**2127**
3	Atherton	5	0	**17**
4	Bucklands	5	3	**107**
5	New Bucklands	0	2	**12**
TOTAL		***13***	***10***	**2888**

[1] Slight salinization and waterlogging is defined as that agricultural production can still take place, but that production potential and/or choice are restricted.

[2] Severe salinization and waterlogging is defined as that agricultural production can no longer take place without special remediation actions such as artificial drainage or gypsum application being applied.

2.5.1. IRRIGATION ENTERPRISES

This section is a motivation for the six crops selected for modelling in this study. Although livestock production and aquaculture are also practised in the study area these are irrelevant for the purposes of his study.

2.5.1.1 Perennial and horticultural crops

Vineyards are perennial and not suited to this seasonal study. Results from the pilot survey indicate no yield reduction from vines takes place as a result of poor water quality according to the farmers interviewed that had vines. There is also little prospect of expansion as the GWK Ltd. wine cellars have their grape delivery quotas filled. As a result, some farmers have started planting olive trees. Mainly olive and also some pecan nut orchards have recently been established as a long-term strategy to reduce the impact of increasing input costs and deteriorating water quality, and in some cases, to keep water tables down.

A farmer interviewed during the pilot survey, who irrigates from the Lower Riet River arm, had to spend a great deal extra on his horticultural tunnel operation because of poor water quality. Not much other intensive horticultural is practised in the study area, though on one farm carrots and beetroots are grown extensively.

2.5.1.2 Annual crops

In Table 2.6 it can be seen that wheat, the major crop in the study area, uses up more than half (4407) of the hectares irrigation rights in the OVIB (8075 ha), followed by maize - 2729 ha, lucerne – 1309 ha, potatoes – 454 ha, etc. The crops included in this study for analysis are wheat, maize, lucerne, potatoes, cotton and groundnuts. Sunflower is not included as only very few farmers grow sunflower. These farmers have a contract to produce sunflowers for seed purposes and are not representative of the region. Irrigated pastures are very variable between farmers as is the livestock component utilising the grazing.

Table 2.6 Cropping composition (ha) of major crops in the OVIB region, 1998 / 1999 production season

Sub-area		**Wheat**	**Maize**	**Lucerne**	**Potatoes**	**Sunflower**	**Cotton**	**Irrigated pastures**	**Vineyards**	**Onions**	**Groundnuts**
1	Olierivier	1 872	1 359	708	227	14	158	40	25	93	90
2	Vaallus	1 551	657	144	197	354	136	128	75	47	
3	Atherton	88	52	116		35		15	50		
4	Bucklands	112	88	310			10	18	25		
5	New Bucklands	783	573	31	30				7	15	40
Total		**4 407**	**2 729**	**1 309**	**454**	**403**	**304**	**202**	**182**	**155**	**130**

Onions is also a crop that is dominated by a few farmers and is not a representative crop of the area. Groundnut production is incorporated in this study as many farmers grow a small area to groundnuts or drybeans. The main constraints for groundnut production are the hectares available of suitable sandy soils and the long time period before groundnuts can be planted on the same soils again. Being a legume groundnuts are also good to include in a crop rotation system, and while conducting the pilot survey several farmers stated that they had a water quality problem particularly with groundnuts, especially when sprinkler irrigated, during the daytime.

The three major crops according to hectares planted remain wheat, maize and lucerne, and in financial terms, potatoes. Wheat is relatively tolerant to saline conditions, while maize and potatoes are equally sensitive to salinity while lucerne is moderately tolerant.

2.6. DESCRIPTION OF THE CASE STUDY FARMS

The aim of this section of the chapter is to describe the case study farms with regards to their soil resource endowments, farming structure and financial positions in 1999.

Previous studies on selecting a representative farmer for a specific study area have dealt extensively with the topic (e.g. Backeberg 1984, Swart 1989, Symington 1993, etc.). In this study case study farmers are selected mainly for the purpose of testing and evaluating the farm level model described in this study. Criteria by which the specific farmers used in this study was selected are:

- the availability of accurate data,
- the source and quality variability of irrigation water,
- the farmers knowledge of irrigation farming in the OVIB region as a whole and
- the hectares irrigation water rights in relation to the other farmers in the sub-area.

Table 2.2 lists the average hectares of water rights held in each sub-area as well as the hectares water rights held by the case study farmers for comparison. Taking all the above points into consideration, the case study farmers are generally close to the average with regards to hectares irrigation rights held.

Table 4.10 shows an example of the sets that irrigation land is divided up into for use in SALMOD to reflect the soil clay percentage, drainage status and the irrigation system used. In the sub-area case study farm descriptions that follow the abbreviations given in brackets correlate with the elements of these sets.

2.6.1. AN ANALYSIS OF THE SOIL RESOURCES OF THE CASE STUDY FARMS

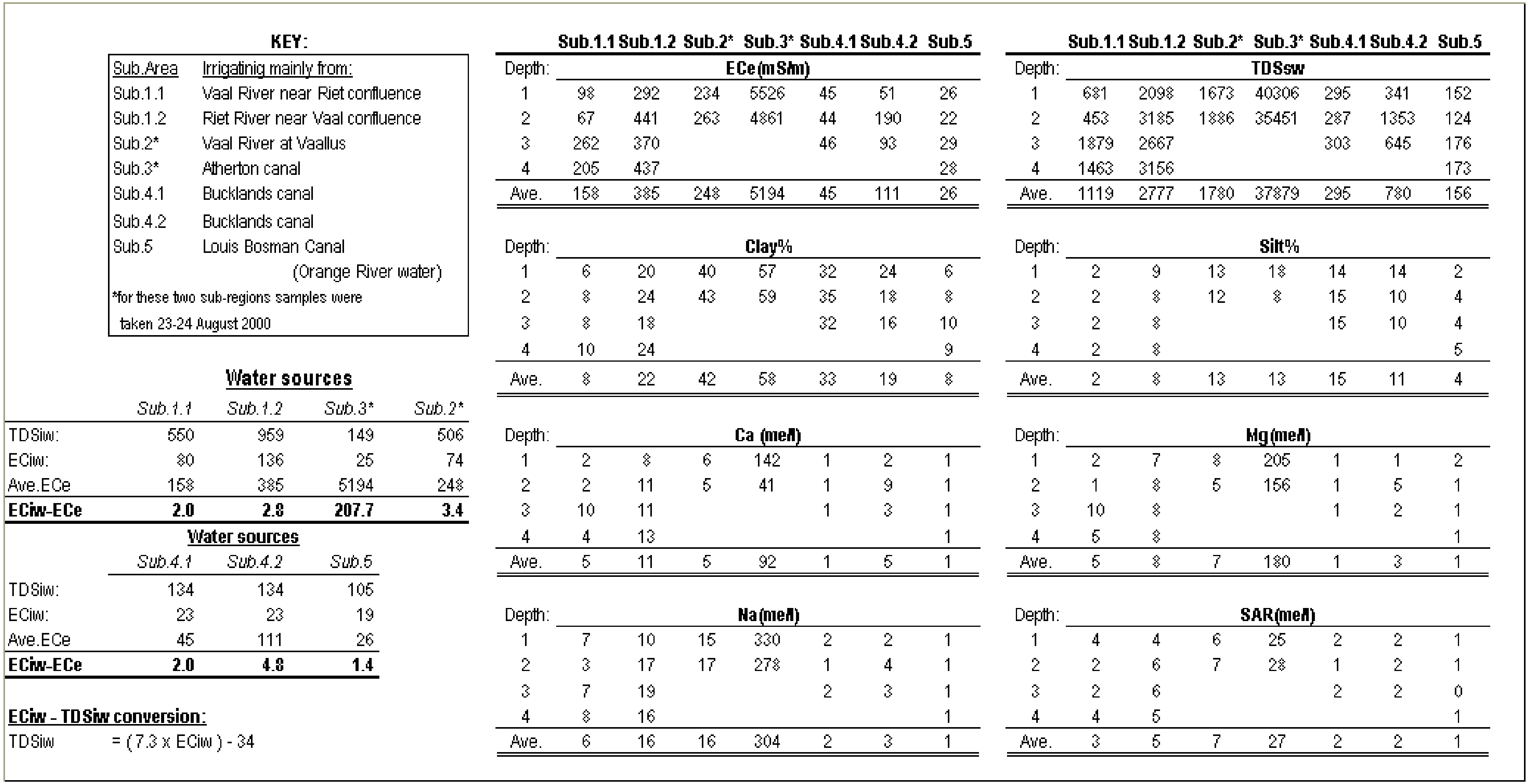
Table 2.7 shows the results of soil samples taken in the study area. The table consists of a key that lists the irrigation extraction points for each sampling point, and a water sources table that displays the electrical conductivity of the irrigation water (ECiw) and the calculated average electrical conductivity of the saturated soil paste (ECe) at each sampling site, which together are used to calculate the ECiw to ECe conversion factors. The table provides ECe, clay and silt%, and Ca, Mg and Na concentrations measured in milli-equivalents per litre (me/l) readings. The total dissolved solids in the irrigation water (TDSiw) is calculated from the ECiw using the following formula:

$$TDSiw = (7.3 \times ECiw) - 34. \qquad \textbf{(2.1)}$$

The sodium adsorption ratio (SAR) is calculated for each sampling point from the Ca, Mg and Na concentration values using the following formula:

$$SAR = Na / \sqrt{(Ca + Mg)/2} \qquad \textbf{(2.2)}$$

Table 2.7 Results of soil samples taken on the case study farms, 2000



KEY:

Sub.Area	Irrigatinig mainly from:
Sub.1.1	Vaal River near Riet confluence
Sub.1.2	Riet River near Vaal confluence
Sub.2*	Vaal River at Vaallus
Sub.3*	Atherton canal
Sub.4.1	Bucklands canal
Sub.4.2	Bucklands canal
Sub.5	Louis Bosman Canal (Orange River water)

*for these two sub-regions samples were taken 23-24 August 2000

Water sources

	Sub.1.1	*Sub.1.2*	*Sub.3**	*Sub.2**
TDSiw:	550	959	149	506
ECiw:	80	136	25	74
Ave.ECe	158	385	5194	248
ECiw-ECe	**2.0**	**2.8**	**207.7**	**3.4**

Water sources

	Sub.4.1	*Sub.4.2*	*Sub.5*
TDSiw:	134	134	105
ECiw:	23	23	19
Ave.ECe	45	111	26
ECiw-ECe	**2.0**	**4.8**	**1.4**

ECiw - TDSiw conversion:

TDSiw = (7.3 x ECiw) - 34

ECe (mS/m)

Depth:	Sub.1.1	Sub.1.2	Sub.2*	Sub.3*	Sub.4.1	Sub.4.2	Sub.5
1	98	292	234	5526	45	51	26
2	67	441	263	4861	44	190	22
3	262	370			46	93	29
4	205	437					28
Ave.	158	385	248	5194	45	111	26

TDSsw

Depth:	Sub.1.1	Sub.1.2	Sub.2*	Sub.3*	Sub.4.1	Sub.4.2	Sub.5
1	681	2098	1673	40306	295	341	152
2	453	3185	1886	35451	287	1353	124
3	1879	2667			303	645	176
4	1463	3156					173
Ave.	1119	2777	1780	37879	295	780	156

Clay%

Depth:	Sub.1.1	Sub.1.2	Sub.2*	Sub.3*	Sub.4.1	Sub.4.2	Sub.5
1	6	20	40	57	32	24	6
2	8	24	43	59	35	18	8
3	8	18			32	16	10
4	10	24					9
Ave.	8	22	42	58	33	19	8

Silt%

Depth:	Sub.1.1	Sub.1.2	Sub.2*	Sub.3*	Sub.4.1	Sub.4.2	Sub.5
1	2	9	13	18	14	14	2
2	2	8	12	8	15	10	4
3	2	8			15	10	4
4	2	8					5
Ave.	2	8	13	13	15	11	4

Ca (me/l)

Depth:	Sub.1.1	Sub.1.2	Sub.2*	Sub.3*	Sub.4.1	Sub.4.2	Sub.5
1	2	8	6	142	1	2	1
2	2	11	5	41	1	9	1
3	10	11			1	3	1
4	4	13					1
Ave.	5	11	5	92	1	5	1

Mg (me/l)

Depth:	Sub.1.1	Sub.1.2	Sub.2*	Sub.3*	Sub.4.1	Sub.4.2	Sub.5
1	2	7	8	205	1	1	2
2	1	8	5	156	1	5	1
3	10	8			1	2	1
4	5	8					1
Ave.	5	8	7	180	1	3	1

Na (me/l)

Depth:	Sub.1.1	Sub.1.2	Sub.2*	Sub.3*	Sub.4.1	Sub.4.2	Sub.5
1	7	10	15	330	2	2	1
2	3	17	17	278	1	4	1
3	7	19			2	3	1
4	8	16					1
Ave.	6	16	16	304	2	3	1

SAR (me/l)

Depth:	Sub.1.1	Sub.1.2	Sub.2*	Sub.3*	Sub.4.1	Sub.4.2	Sub.5
1	4	4	6	25	2	2	1
2	2	6	7	28	1	2	1
3	2	6			2	2	0
4	4	5					1
Ave.	3	5	7	27	2	2	1

2.6.1.1 Sub-area 1 (Olierivier) case study farm

Sub.1.1 and Sub.1.2 represent two sampling points on the Olierivier case study farm, representative of the main soil types on the farm. The samples for Sub.1.1 were taken from the edge of a centre pivot irrigated field from four different depths with 30cm spacing in-between, from depth 1 being the soil surface till depth 4 measuring 1.2 meters below the surface, and similarly so for all the other samples taken. The average soil clay percentage is 8% indicating a loamy sand soil. The field is situated near the confluence of the Vaal and the Riet Rivers, but irrigating with Vaal River water with an ECiw of 80 mS/m. Sampling point Sub.1.2 is also situated near the confluence of the Vaal and the Riet Rivers, but irrigating with Riet River water with an ECiw of 136 mS/m. With an average clay percentage of 22%, Sub.1.2 is a sandy loam soil, bordering on a sandy clay soil. The poor ECiw and high clay percentage result in the ECe being considerably higher (385 mS/m) than Sub.1.1 (158 mS/m). The readings for all the other sub-areas are calculated similarly.

The Olierivier farmer has 100 ha of naturally drained (NDS) loamy sand soils (LMS) that have a clay percentage greater than 15%, and a further 20 ha also on loamy sand soils and centre pivot irrigation (CPI), but with artificial drainage (ADS) installed. 10 ha on sandy loam (SNL) soils are waterlogged (WLS) with 5 ha under centre pivot irrigation and 5 ha flood irrigated (FIS). 30 ha limited drainage (LDS) loamy sand soils are flood irrigated, and a further 40 ha centre pivot irrigated.

2.6.1.2 Sub-area 2 (Vaallus) case study farm

For the Vaallus (Sub.2) and Atherton (Sub.4) case study farmers only one sample was taken at a later date using a soil bore for sample collection instead of a backhactor, so weren't taken to 90 and 120 cm depths. After 60cm the clay was very heavy and the soil bore couldn't go deeper. For Sub.3.1 and Sub.3.2 where the backhactor was used, a water table was detected after 90 cm.

The sampling point for the Vaallus case study farmer, Sub.2 has a high clay percentage of 42% and proportionately high Ca, Mg and Na values resulting in a very high SAR of 7. These soils will be very expensive to drain to remediate and with the high SAR the structure can easily break down causing further impenetrability.

he Vaallus case study farmer has 50 ha of naturally drained (NDS) sandy loam soils (SNL) under centre pivot irrigation (CPI), a further 320 ha also under centre pivots but on sandy clay soils of which 200 ha are naturally drained and the other 120 ha artificially drained (ADS). The 61 ha under drip irrigation (DIS) on the sandy loam naturally drained soils are planted to vineyards, which are not included in this seasonal study.

2.6.1.3 Sub-area 3 (Atherton) case study farm

Sub.4 was measured as an indication of the worst-case scenario possible in the study area; the sample was taken from a portion of the case study farmers' land that has been withdrawn from irrigation. Non-point source irrigation seepage from higher lying neighbouring lands transpire from the specific piece of land, leaving the salts behind. Salts have accumulated to be 207 times greater than the receiving ECiw. Because of the high clay percentage of the soil (58%) it is unfeasible for the farmer to drain and try remediating the soil.

The soil plot sampled in Atherton was a worst-case scenario to show the magnitude of the effects of soil salinisation, however the data recorded in SALMOD is a more representative division than that which appears in the analysis in Table 2.7. The Atherton farmer has 22 flood irrigated (FIS) ha on clayey soils (CLY) with limited drainage.

2.6.1.4 Sub-area 4 (Bucklands) case study farm

The Bucklands sampling point Sub.3.1 has a high clay percentage and the same receiving ECiw and SAR as Sub.3.2 which has a much lower clay percentage yet the ECiw to ECe conversion factor is very good at 2 compared to Sub.3.2 which has a very high factor of 4.8. It was observed when taking the samples that the cracks which form on these clayey soils as they dry out go very deep into the soil, so if allowing the soils to dry out well before irrigating, i.e. low frequency irrigation, a very good infiltration results which seems to have leached out most of the salts. The same irrigation practises and receiving water quality are applied in Sub.3.2, though with the lower clay percentage (19% vs. 33%) doesn't get as much salts leached. Low frequency irrigation is thus a management option on clayey soils if the crop is tolerant to the ECiw applied.

The Bucklands case study farmer indicated that he had only 50 ha of flood irrigated (FIS) clayey soils (CLY), which have a clay percentage of greater than 45% clay, on limited drainage soils (LDS). The analysis in Table 2.7 however shows that the soils are sandy clay (35% - 45% clay) and sandy loam soils (15-25% clay) soils.

2.6.1.5 Sub-area 5 (New Bucklands) case study farm

Sub.5 is the sampling point on the New Bucklands case study farm used as a control in this study. The ECiw of 19 mS/m is the best in the study area and the loamy sand soils with 8% clay are well drained resulting in the lowest ECiw to ECe conversion factor of 1.4. The SAR of 1 is also by far the lowest in the study area.

The New Bucklands case study farmer has 145 ha irrigable land, all on loamy sand soils (LMS) of which 110 ha are centre pivot irrigated (CPI), 30 ha flood irrigated (FIS) and 5 ha drip irrigated (DIS). 100 ha are naturally drained, 22 ha have limited drainage (LDS), 10 ha are artificially drained (ADS) and 10 ha are waterlogged (WLS). Five ha of olive trees are drip irrigated on the stony limited drainage ground, and should essentially also be left out of the seasonal crop analysis.

2.6.2. THE CURRENT FARMING STRUCTURE OF THE 5 CASE STUDY FARMERS

The crop enterprise budgets (CEBs) used in SALMOD for all crops and for each case study farmer appear in Appendix 2. This CEB data, irrigable land division data and the data in Table 2.9 are the only specific case study farm level data required for SALMOD. Table 2.8 provides a description of the table headings in Table 2.9 that lists the individual case study farm data required for SALMOD.

A function is built into SALMOD that calculates that the irrigation area (IA) hectares listed in Table 2.9 have to correspond with the sum of the hectares listed in irrigable land division tables; if not an error message is displayed stating that the areas of irrigated land do not correspond with the soil type, irrigation system and drainage status data. IA shows that all case study farmers have more irrigable land than irrigation rights (IR). The cost of irrigation water (WC) is constant for the whole study area at R0.17/mm/ha irrigation rights (IR). Pumping costs are however vastly different in each sub-area and within each sub-area, depending on where the field is in relation to the water extraction source. For this reason, and because the financial effect of irrigation water quality, and not the effect of pumping costs, is the focus of this study, are the pumping costs set at the

GWK average for the region at R0.56 /mm/ha water rights held. In reality, the New Bucklands and Atherton farmers irrigate directly from out of a passing water distribution canal at a very low cost.

Table 2.8 SET CSF, the case study farmer data set headings description

IA	Total current irrigable area	(ha)
IR	Current irrigation rights per allocated quota	(ha)
WC	Water costs - can be varied for each sub-area	(R per mm)
PC	Pumping costs - will vary within sub-areas	(R per mm)
FC	Non-allocatable annual fixed costs	(R per annum)
MPC	Maximum production capital availability	(R)
MCL	Maximum fixed capital improvement loan availability	(R)
TKWA	Total kilowatts available	(kW)
TLA	Total labourers available	(person)
LABC	Average Labour Costs (\person\ 24 working day month)	(R)

Table 2.9 OVIB individual case study farm data required for SALMOD, 1999

	IA	IR	WC	PC	FC	MPC	MCL	TKWA	TLA	LABC
Units	***ha***	***ha***	***R/mm/ha***	***R/mm/ha***	***R***	***R***	***R***	***kW***	***Men***	***R/month***
OL	200	141	0.17	0.56	561000	300000	600000	280	16	1000
VL	461	339	0.17	0.56	2475015	500000	1000000	720	18	1000
BL	50	58.4	0.17	0.56	38000	100000	200000	46	2	1000
AT	22	28.9	0.17	0.56	130000	150000	300000	120	4	1000
NB	145	100	0.17	0.56	1049109	600000	1200000	300	14	1000
OL,VL,BL,AT & NB are the Olierivier, Vaallus, Bucklands, Atherton and New Bucklands case study farmers										

A full financial analysis was conducted for all the case study farmers to be able to compare their financial solvability, liquidity, profitability and efficiency. The only data from this analysis used in SALMOD however are the crop enterprise budgets and the fixed cost component (FC) calculated for each case study farmer for all income and expenses for all activities excluding the CEB income and expenses of the six crops and management option expenses modelled in SALMOD.

The value in Rands of the maximum production capital (MPC) loan available to the farmers for one production season was obtained when conducting the financial analysis survey. The maximum fixed capital loan (MCL) is calculated as double the MPC loan. This value is used in SALMOD as a constraint to limit the capital expenditure on fixed capital management options.

The total kilowatts available (TKWA) in traction power, the total labour available (TLA) in men and the labour costs (LABC) in Rand per man per month are built into the model as constraints, but not activated for the model runs on which this study is based as the impact of water quality related and not other farm constraints are to be examined.

2.6.3. THE FINANCIAL POSITIONS OF THE 5 CASE STUDY FARMS

Within the top five lines of Table 2.10, the land and water resources available for the five case study farmers are listed, as well as a percentage value which indicates what percentage of the financial analysis data listed is from the six irrigation farming activities modelled in SALMOD alone. The Vaallus case study farmer for example has a total farm size of 3383 ha of which only 461 are irrigated and for which only 314.8 ha water rights are held. Other income is derived from the land not irrigated, but as the farmer keeps separate records for the different farming enterprises, only the irrigation activities data was supplied and therefore the results show 100% of the income is from seasonal irrigation farming alone. The Atherton farmer however is a part time farmer, as is typical in the Atherton and Bucklands sub-areas, and in particular in Bucklands the area referred to in Afrikaans as “Die Erwe”, translated as “the plots”, due to their close proximity to the town of Douglas. The financial data analyses for the Atherton case study farmer included his income from his job in town, his extensive cattle farm and therefore only 53% of the income derived in the statements is from irrigation farming alone. The Bucklands case study farmer’s wife’s income from her private job in town is also included in the statements and thus only 68% of the income derived in the statements is from irrigation farming alone. The basic history of the case study farmers is as follows. The Olierivier farmer has been farming for over 20 years on his farm which is situated right at the confluence of the Vaal and the Riet Rivers, but following the devastation caused to his farm by the 1988 floods is still in a building up phase. The Vaallus farmer has also been farming for over 15 years and is expanding rapidly. The Bucklands farmer has recently started farming, subcontracting his mechanisation and growing flood irrigated lucerne. The Atherton case study farmer farms part-time on an extensive livestock farm and a small irrigation plot that he inherited. A portion of the plot area has been withdrawn from irrigation due to salinisation (see worst case scenario in Table 2.7), and therefore there is an excess of hectares water rights held (28.7) in relation to the area irrigated (22 ha). The New Bucklands farmer had only been farming for 5 years at the date of this analysis, on good virgin irrigation soils and with very good quality irrigation water.

Looking at solvability (Table 2.10), the net capital ratio varies from 5.23 for the Atherton farmer, who is over capitalised having one large tractor and implements for the small area of lands he works, down to 2.24 for the Bucklands farmer, which is the general level for even the larger farmers. The leverage ratio is best for the Atherton case study farmer (0.24), the smallest case study farmer, followed by the largest case study farmer from Vaallus (0.42) and is worst (0.81) for the Bucklands case study farmer, the second smallest case study farm. The own capital ratio is highest for the Atherton case study farmer (80.87%) and second highest for the Olierivier farmer (70.38%), with the other farmers being just over 50%. The solvability of the irrigation farmers is therefore not dependent on the size of the irrigated area.

The norms for liquidity ratios (Table 2.10) are for general farming and could be adjusted lower for the capital-intensive nature of irrigation. The small farms (Bucklands and Atherton) show a current ration greater than 1 while for the larger farms it is around 0.30. The acid test ratio also shows large results for the two small farms and lower results for the larger farms. The low intermediate ratio of the Olierivier farmer reflects the re-build-up phase of his irrigation operation after the floods, and the very high ratio of the Atherton farmer reflects the other sources of income obtained by the farmer.

The results for farm profitability and profitability on own capital show that profitability is a function of farm size and resource endowment. The two small farms, Bucklands and Atherton, have a farm profitability of –4.89% and 1.66% and a profitability on own capital of –53.4% and –6.43% respectively, while the largest farm, the Vaallus case study farm has a farm profitability of 16.77% and profitability on own capital of 23.38%. The New Bucklands farm is half the size of the Olierivier case study farm, yet it achieves a farm profitability of 15.88% and profitability on own capital of 18.62%, which is due to its good resource endowment.

Table 2.10 Financial analysis of the case study farms, March 1998 - February 1999

			Sub-areas:	Olierivier	Vaallus	Bucklands	Atherton	New Bucklands
			Total Farm size (ha):	344	3383	60.4	2035	145
			Irrigable (ha):	200	461	50	22	100
			% Income from irrigation reflected in statements:	97%	100%	68%	53%	83%
			Water rights (ha):	140.3	314.8	58.4	28.7	100
1. SOLVABILITY		**Formula:**	**Norms:**					
a. Net Capital Ratio	=	Total Assets / Total Liabilities	(>2:1)	3.38	2.36	2.24	5.23	2.30
b. Leverage Ratio	=	Total Liabilities / Own Capital (Net worth)	(1:1)	0.42	0.74	0.81	0.24	0.77
c. Own Capital Ratio	=	Own capital / Total Assets * 100	(<50%)	70.38	57.57	55.30	80.87	56.57
2. LIQUIDITY								
a. Current Ratio	=	Current Assets / Current Liabilities	(>2:1)	0.39	0.26	1.28	1.44	0.30
b. Acid Test Ratio	=	Current Assets – Stocks Current Liabilities	(1:1)	0.36	0.26	0.97	0.53	0.23
c. Intermediate Ratio	=	Total Current+ Medium Term Assets Total Current + Medium Term Liabilities	(>4:1)	1.30	2.22	2.24	9.98	2.49
3. PROFITABILITY								
a. Farm Profitability	=	NFI / Ave. Capital use		7.52	16.77	-4.89	1.66	15.88
b. Profitability on Own Capital	=	Net Farm Profit / Ave. Own Capital		3.05	23.38	-53.40	-6.43	18.62
4. EFFICIENCY RATIOS								
a. Capital Turnover Ratio	=	Gross Value of Production Average Total Capital used		0.40	0.51	0.25	0.21	0.34
b. Cost Ratio	=	Total Expenditure Gross Value of Production		0.81	0.67	1.20	0.92	0.53
c. Debt Servicing Ratio	=	Debt servicing (instalment + interest) Gross Value of Production		0.13	0.06	0.40	0.33	0.21

When looking at the efficiency ratios, the capital turnover ratio is definitely correlated to the size of irrigable are possessed, with the smallest farm, Atherton having a ratio of 0.21 and Vaallus the larges, 0.51. The cost ratio shows that the Bucklands farmer doesn't cover his expenditures with his production income alone, and the Atherton farmer barely covers his expenses. The Olierivier farmer value of 0.81 also shows a lot of expenditure. The low cost ratio of 0.53 for the New Bucklands farmer, who has recently started farming, reflects the very good yields obtained on the new ground with very good quality irrigation water. The debt-servicing ratio also reflects farm size and length of time in operation, with the Bucklands and Atherton farmers having a debt serving ratio of 0.40 and 0.33 respectively, followed by the New Bucklands farmer (0.21), the Olierivier farmer (0.13) and a very low 0.06 for the Vaallus farmer, who puts all his profits from his farming operations directly back into his irrigation expenses.

2.7. SUMMARY

2.7.1. OVIB STUDY AREA

The OVIB has a total of 178 irrigation farmer members who hold a total of 8097 ha of irrigation rights. Particularly disturbing is that nearly one quarter (1861) of these hectares are either slightly or severely affected by waterlogging or salinisation and that 49% of the land irrigated is either medium or low potential irrigation land. 28% of the area is flood irrigated and 70% sprinkler irrigated with the trend being conversion to centre pivot irrigation. This is a potential problem as it is difficult to leach for salinity management with centre pivot irrigation systems. The three major crops in the study area are wheat, maize and lucerne and financially, potatoes.

The OVIB service area is subdivided into 5 sub-areas, Olierivier, Vaallus, Atherton, Bucklands and New Bucklands with average hectares water rights possessed ranging from 11 ha in Atherton to 137 ha in Vaallus. Looking at water quality in the different sub-areas Olierivier received by far the poorest irrigation water.

The dilution effect of the Orange River on water quality at the Douglas barrage is clearly evident in Figure 2.4. With the construction of the Louis Bosman canal, the increased incidence of Orange River water mixing with Lower Vaal and Riet River water may be the reason for the declining/improving trend in water quality from 1992 till 1998. With the possibility of a reduction in Orange River supply following the outcome of the Orange River Development Project Replanning Study (DWAF 1998) this trend could be reversed.

2.7.2. CASE STUDY FARMS

The case study farm in the New Bucklands sub-area has the most ideal irrigation water and soil conditions of all the case study farms in the study area and is therefore used as a control in this study, whereas the Atherton farmers soil analysis was taken from an area withdrawn from irrigation due so soil salinity build-up and is used as a worst case scenario. In SALMOD similar conditions as used for the Bucklands study area are used for the Atherton case study farm, to get realistic results for the portion of the farm which is not yet degraded.

The Vaallus case study farmer is in a phase of rapid expansion putting all profits from farming back into the irrigation farm, while the Olierivier farmer is in re-build-up phase after the 1988 floods, which caused major damage to his farm.

In comparing the financial position of the case study farmers in the 5 sub-areas there is a strong correlation of the financial position of the farmers with irrigated farm size and resource endowment. The financial analysis also shows that the Bucklands and Atherton case study farmers need to have an alternative income source for them to survive financially with the current crops planted on the small areas irrigated.

In conclusion, although the hectares of water rights held by the case study farmers are more or less similar to the sub-area averages, the range of farms studied are very diverse with regards to resource endowment and financial position. With data unavailable for the average financial position of farmers in each OVIB sub-area, the author speculates that the financial position of the case study farmers will also reflect the average financial positions of all irrigation farmers for each sub-area. This would allow the results of this study to be extrapolated to sub-area level to determine the economic impact of water quality on the OVIB region as a whole. This is however out of the scope of this study which focuses on the farm level model.

CHAPTER 3. LITERATURE STUDY

The rise and fall of a number of past civilizations have been linked to their ability to sustain irrigated agriculture.
The inability to control salinisation and degradation of irrigated lands are mostly viewed as the main causes for their decline.
South African Water Quality Guidelines DWAF 1993

3.1. INTRODUCTION

With the initial aim of this study being to determine the economic impact of water quality on irrigated agriculture, the term water quality first needed to be defined and understood. In identifying the constituents of water quality and conducting a review of water related literature on the study area, salinisation was identified as the main water quality constituent impacting on the study area. Next the factors that cause or influence salinisation needed to be identified and understood so that the complex interactions between the soil, the water and the crop could be isolated and built into an irrigation salinisation simulation model. The various management options to prevent salinisation from taking place and options to remediate affected soils and water bodies also were researched and where relevant, incorporated into the model to determine the financial feasibility and financially optimal management combinations. Existing models and methodologies to manage irrigation salinisation were also reviewed to conceptualise the methodology and structure of the model to be used to determine the economic impact of water quality on irrigated agriculture in the lower Vaal and Riet Rivers.

As this literature study focuses on aspects relevant to the study area, comments relating the findings of the literature study to the study area, are included.

3.2. THE THEORY AND PRACTISE OF WATER QUALITY

Water quality is a term used to express the suitability of water to sustain various uses or processes. Any particular use or process will have certain requirements for the physical, chemical, or biological characteristics of the water (Bartram & Balance, 1996:9). Water quality is thus a lumped term used to define the state of water and is comprised of different components, each influencing the applicability for an intended use of the specified water body. These components are sedimentation, harmful synthetic organic and inorganic compounds, microorganism contamination, microelement toxicity, heavy metal accumulation, eutrophication and salinity.

Water quality is assessed by relating actual measured concentrations of the constituent being examined to published guidelines. These guidelines link some impact to the user, for example crop yield reduction, for a given concentration range. Although generalised water quality guidelines for South Africa are available (DWAF, 1993), the quality of water required for irrigation depends on the crop being irrigated, the type of irrigation system used and the suitability of the soil for irrigation. Farm management practises such as drainage and gypsum application will also impact on guidelines for irrigation. Moolman & Quibell (1995:11) therefore recommend that site-specific guidelines be formulated.

According to Backeberg *et al, (*1996:22), water quality is becoming of increasing concern to irrigation, both from a supply point of view and with respect to the environmental impacts of irrigation. As the use of the water resources of South Africa intensifies, the general quality of supplies, both surface and ground water declines. The most significant water quality problems facing irrigation are according to the Backeberg, *et al, (*1996:22):

- High sediment loads of surface runoff usually resulting from poor land use and soil conservation practise;
- High salinity resulting from natural sources as well as from the discharge of waste water into river systems;
- Eutrophication of stored water resulting from enrichment by nitrates and phosphates; and
- Raised water temperatures in some isolated cases.

Experience has shown that water quality constituents of concern to irrigation can be subdivided into a number of tiers based on the frequency in which they have been found to determine a waters fitness for use in practise.

a) Potentially toxic ions. Ions are viewed as toxic to plant growth when they cause crop damage or reduced yield at concentrations which are lower than their relative contribution to soil salinity. The ions of primary concern are boron, chloride, and sodium. It is partially concluded that waters impacting upon the study area do not have microelement concentrations of, for example chloride (which mainly affects the quality of crops such as potatoes and tobacco) and boron, so high as to have an impact on the crops grown in the area. According to TAMU AGNEWS (1998) crops grown on soils that have an imbalance of calcium and magnesium may also exhibit toxic symptoms. Sulphate salts affect sensitive crops by limiting the uptake of calcium and increasing the adsorption of sodium and potassium, resulting in a disturbance in the cationic balance within the plant. The bicarbonate ion within the soil solution harms the mineral nutrition of the plant through its effect on the uptake and metabolism of nutrients. High concentrations of potassium may introduce a magnesium deficiency and iron chlorosis. An imbalance of magnesium and potassium may be toxic, but increasing the calcium levels can reduce the effect of both.

b) Trace elements. Trace elements that negatively affect plant growth are also viewed as essentially toxic. The trace elements of heavy metals are easily absorbed by the soil and accumulate within the surface layers, and once absorbed cannot be easily removed.

c) Miscellaneous problems. Other problems associated with the composition of irrigation water are:

- High nitrogen concentrations which cause excessive vegetative growth, lodging, and delayed crop maturity
- High bicarbonate, gypsum or iron concentrations, which can result in unsightly deposits on leaves and fruits
- Chloride at relatively low concentrations affects the quality, but not the yield of tobacco. Most other crops are also affected by high chlorine concentrations.
- The greatest hazard of unusual pH values is the corrosive effect on irrigation equipment.
- Water induced corrosion and encrustation of irrigation equipment.
- A degree of restriction of use due to clogging of sprayers or drippers and/or increased wear on equipment by suspended material and
- Dissolved organic compounds (e.g. herbicides) that can be toxic to plants and soil microorganisms when present in sufficient concentrations.

d) Salinity and Sodicity. As far as water quality constituents are concerned, the salinity and sodicity of water have been found to be the most important factors in determining its fitness for use and are often combined in systems attempting to classify irrigation water quality. Irrigation with saline water induces soil salinity. This causes a reduction in crop yields once the threshold soil salinity is exceeded. By irrigating with sodic water, soil sodicity is induced which results in reduced soil permeability. Salinity and sodicity of water also interact with one another in soil. High irrigation water salinity levels serve to counteract the negative effect that elevated sodicity levels have on soil permeability.

Ragab (2001) states that salinity is of great concern in the irrigated lands of arid and semi-arid zones because of the small contribution of rainfall to leaching and the often-poor quality of irrigation water. It is well established that soil salinity does not reduce crop yield significantly until a threshold level is exceeded. Beyond this threshold, yield decreases almost linearly as salinity increases. To avoid yield loss when salt concentration exceeds the crop tolerance limit, excess salts must be leached below the root zone. In areas where rainfall rate and regime are not adequate to provoke that process, irrigation water must be applied in excess. Therefore, when calculating the irrigation depth, an additional amount of water according to the salinity level should be added for leaching (Oster 1994, and Bresler & Hoffman 1986). The leaching requirement (LR) however is usually defined, assuming a steady state regime.

Gouws *et al, (*1998:8) lists the three water quality components that have a financial impact on crop production as the total salt effect, specific ion toxicity and sodium effect on soil properties. The concentration of dissolved salts however, be it from natural or anthropogenic causes, currently poses the greatest threat within the study area. This study will therefore deal specifically with the economic effects due to salinisation.

The total dissolved solids (TDS) concentration increases in static and slow moving water bodies subject to large scale evaporation, as well as, according to Basson (1997:57), in rivers and river reaches receiving large quantities of effluent, mainly due to salinity build-up which results from the addition of salts through most uses of water. Construction of dams and weirs in a river course for the purpose of water storage, often lead to the problem of salination because, except for increasing the susceptibility to evaporation, also make the water available for use and reuse.

If the TDS concentration in water is high enough the negative effect of irrigating with such waters can be immediate, alternatively salts will accumulate in the soil. A high salt concentration in the soil body creates a physiological drought for the crops planted therein and thus climatic factors are important in salinity management. Sodification can also take place by which calcium and magnesium ions in the clay particles are replaced by sodium ions leading to a breakdown in soil structure making the soil impermeable and impenetrable for germinating seeds.

With regard to the water quality components (sedimentation, harmful synthetic organic and inorganic compounds, micro-organism contamination, microelement toxicity, heavy metal accumulation, eutrophication and salinity) in the study area:

Sedimentation isn’t a problem in the study area because of conscientious soil conservation practises and a low annual precipitation. Although synthetic herbicides and pesticides are used in the study area, and various industrial and mining activities take place upstream in the river system, there have been no reports of concentrations reaching harmful levels within the study area.

Microbiological contamination (e.g. high *E.Coli* count) is also not perceived to be a problem within the study area. It is partially concluded that waters impacting upon the study area of this study do not have microelement concentrations of, for example chloride and boron, so high as to have an impact on the crops grown in the area. Chloride affects certain plants differently. Tobacco for example can produce excellent yields but if the chloride content of the water that it was irrigated with is past a certain threshold level then it is picked up in the grading resulting in financial losses due to the lower grades. Moolman and Quibell (1995:25) identified boron concentrations in excess of the water quality guidelines for poor and medium soils in parts of the study area. While a necessary nutrient, high boron levels cause plant toxicity and concentrations should not exceed a certain plant specific threshold value. Wheat, groundnuts and beans are sensitive to boron while cotton and lucerne are tolerant (DWAF 1996:41).

Stringent water quality standards and point source controls in the industrial areas upstream as well as the mixing of Vaal Barrage and Vaal Dam water to obtain a certain concentration as described by Bath & Quibell (1997:1), have resulted in low enough heavy metal concentrations that significant accumulation in soils doesn't occur. Nitrate pollution isn't either of such a proportion so as to result in large-scale eutrophication. The concentration of dissolved salts however, be it from natural or anthropogenic causes, currently poses the largest threat within the study area.

3.2.1. THE ROLE OF CLIMATE IN WATER QUALITY ASSESSMENT

Climate is a major factor in determining the acceptability of a given water quality. According to Maas (1990) in DWAF (1993:222), crops can tolerate greater salt stress if the weather is cool and humid than if it is hot and dry. Three climatic variables are considered to be of importance in this regard: total precipitation, evaporation demand and seasonality of rainfall.

- *Total precipitation.* The higher the rainfall the lower the irrigation requirements and also therefore the load on irrigation water variables;

- *Evaporation demand.* Crop water requirement usually increases as a ratio of evaporative demand. The higher the evaporative demand, the higher is the crop water requirement and the more irrigation water is required to satisfy this demand;

- *Seasonality of rainfall.* Rain predominantly occurs during either summer or winter in the areas under irrigation in South Africa. Winter rainfall leaches from the soil the salts that accumulated during the summer irrigation season, depending on the quantity of the rain and the ease with which a particular soil is leached. This could provide a practically salt-free topsoil and seedbed for the germination of crops planted in spring. Under summer rainfall conditions it often rains during the period of maximum crop water requirement. Rainfall thus reduces soil salinity in proportion to its share in total water application. The OVIB area however does not receive a winter rainfall, and annual summer precipitation is possibly too low to have a major effect.

It is proposed that climate not be considered in the derivation of general water quality guidelines in DWAF (1993). Ideally, climate should be considered as part of a dynamic model that simulates crop response to climatic factors, irrigation applications and the resultant soil changes. It is however stated in DWAF (1996) that incorporating climatic variables in irrigation water quality assessment is problematic.

3.2.2. THE ROLE OF SOIL IN WATER QUALITY ASSESSMENT

Soil characteristics play an important role in ensuring the success of an irrigation project. Although practically any soil can be irrigated with appropriate management techniques and skills, irrigation soils are mostly selected on the basis of economic viability and the requirement that average management skills and techniques should suffice to irrigate them successfully (DWAF, 1993:223).

The bracketed area **A** shown in Figure 3.1 is the vadose zone that incorporates the root zone. Salt accumulation in this region has the effect on plant growth that affects yield and thus crop returns. Without artificial irrigation drains the salts either accumulate in the vadose zone or are washed into the groundwater which either discharges the saline water back into the river system or which rises into the vadose zone causing waterlogging and heavy secondary salinisation.

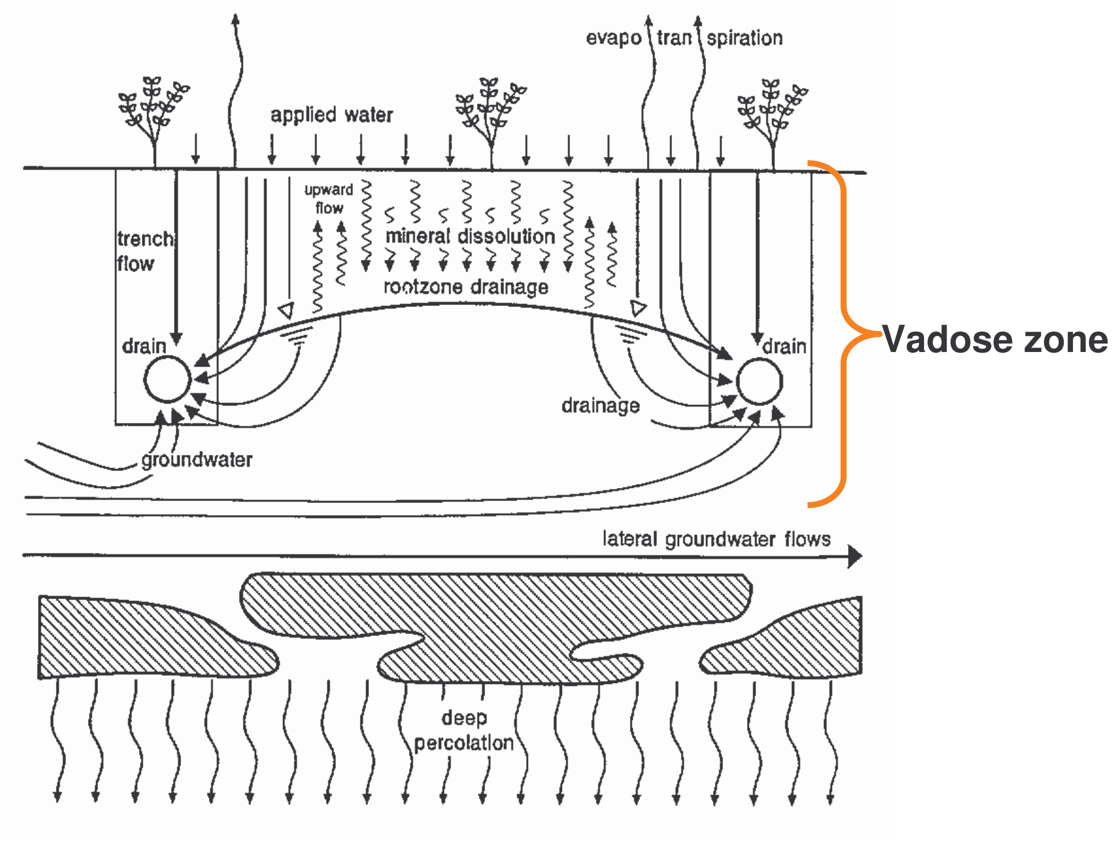


Figure 3.1 A graphical representation of the paths of water movement in an irrigated system (Dinar & Zilberman 1991:54)

Soil properties that according to DWAF (1993) have implications for water quality requirements include:

Susceptibility to sodicity – Although permeability is largely determined by soil texture and mineralogy, the combined effect of exchangeable sodium percentage of the soil and salt concentration of the water are often the most important factors in determining permeability,

Soil pH and free lime – Irrigation water pH, and especially the potential for lime precipitation could, over the long term, determine the pH of an irrigated soil,

Soil texture – Soil texture is one of the primary factors determining permeability and water holding capacity. The presence of clay minerals and organic matter provides soils with an exchange capacity which buffers soils from rapid changes in their chemical composition, and

Soil microbiology – Soil microbial activity plays an important role in the breakdown of potentially harmful organic compounds that may occur in irrigation water. While compounds toxic to microbes may occur in irrigation water they may reduce soil microbial activity.

Moolman & Quibell (1995:11), classified soils for the Riet River according to their suitability for irrigation as follows:

Class 1 – Soils highly suited to irrigation, consisting of soil types that are well drained and that have a 10-25% clay content. There is very little, if any accumulation of salts in these soils and soil water salinity is low. As a result of the good drainage, crops grown on these soils can tolerate higher salt concentrations in the irrigation water.

Class 2 – Soils moderately suited to irrigation, consisting of soil types made up of 15-35% clay with moderate internal drainage and soil water salt concentrations are higher than those of class 1.

Class 3 – Soils poorly suited to irrigation, having poor internal drainage and consisting of 35-55% clay. Salts, therefore, tend to accumulate in these soils and soil water EC is high. The poor drainage will cause crops grown on these soils to display the highest yield loss as a result of salt in the irrigation water.

In TAMU AGNEWS (1998) salt affected soils are classified as saline and/or sodic. Both the electrical conductivity of the saturated soil paste (ECe) and the sodium adsorption ratio (SAR) are commonly used to classify salt effected soils. Salinity and sodicity are two types of salt problems that are very different. Soils may be affected only by salinity or by a combination of both salinity and sodium.

i) **Saline soils** normally have a pH value below 8.5, are relatively low in sodium and contain principally sodium, calcium and magnesium chlorides and sulphates. These compounds cause the white crust that forms on the surface. The compounds which cause saline soils are very soluble in water, therefore leaching is usually very effective in reclaiming these soils. According to Grobler in Aihoon *et al, (*1997:270), soil salinisation (i.e. mineralisation) is a result of accumulated salts – primary chlorides and sulphates of calcium, magnesium, sodium and potassium – in the surface soils of arid and semi-arid regions because of insufficient rainfall to flush them from the upper soil layers. The sources of these salts are the weathering of rocks and minerals (usually, sedimentary and metamorphic rocks of coastal origin), rainfall (in regions that lie close to the sea), groundwater and irrigation. The use of agricultural fertilizers exacerbates this problem. Water salinisation is therefore the result of runoff from the catchment basin of such areas, carrying with it a load of dissolved salts into the rivers into which they run. Groundwater can also become salinised in such areas through deep percolation and may in turn salinise the rivers into which they eventually run.

Salinity Hazard – High concentrations of salt in the soil, as a result of irrigating with water with a high EC_{iw}, can result in a “physiological” drought condition. That is, even though the field appears to have plenty of moisture, the plants wilt because the roots are unable to absorb the water.

ii) **Sodic soils** generally have a pH value between 8.5 and 10. These soils are called “black alkali soils” due to their darkened appearance and smooth, slick looking areas caused by the dispersed condition. In sodic soils sodium has destroyed the permanent structure, which tends to make the soil impervious to water, thus leaching alone will not be effective.

Sodium Hazard – Continued use of water having a high SAR (sodium adsorption ratio) leads to a breakdown in the physical structure of the soil. Sodium is adsorbed and becomes attached to soil particles. The soil then becomes hard and compact when dry and increasingly impervious to water penetration. Fine textured soils, especially those high in clay, are most subject to this action. Certain amendments may be required to maintain soils under high SARs. Calcium and magnesium, if present in the soil in large enough quantities, will counter the effects of the sodium and help maintain good soil properties. Sodium hazard is usually expressed in terms of SAR (sodium adsorption ratio) calculated from the ratio of sodium to calcium and magnesium, which counter the effects of sodium. For waters containing a significant amount of bicarbonate, the adjusted sodium adsorption ratio (SARadj) is sometimes used. Soluble sodium percent (SSP) is also used to evaluate sodium hazard. SSP is defined as the ratio of sodium in epm (equivalents per million) to the total cation epm multiplied by 100. A water with a SSP greater than 60 percent may result in sodium accumulations that will cause a breakdown in the soil’s physical properties (TAMU AGNEWS, 1998).

3.2.3. NORMS, MEASURES AND CONVERSIONS

3.2.3.1 Norms

The norms used by DWAF (1993:17) to categorise the quality of irrigation water into classes of fitness of use are the following:

Crop yield – the effect of irrigation on profitability is the main criterion used to determine the fitness of use of irrigation water,

Soil degradation – sustainability is an important prerequisite of irrigation farming. The fitness of use of irrigation water is largely determined by the degree to which water quality affects the soil degradation and sustainable production,

Management options – crops and soils vary in their sensitivity to the different water quality constituents effecting fitness for use. The degree to which different management options need to be employed to alleviate undesirable effects, affects the fitness for use of irrigation water.

A summary of the exact concentrations and levels used to classify irrigation water can be found in DWAF (1993:65).

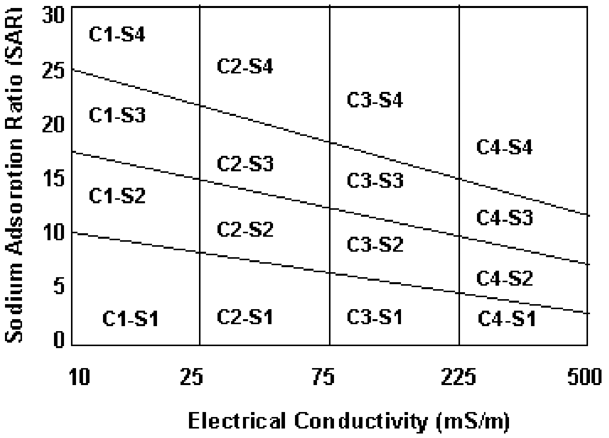
The classification of water in terms of its fitness of use for irrigation according to Van Veelen (1991) in DWAF (1993:18) is as follows:

Class 1 – The water can be used for even the most sensitive crops and soils without any reduction in yield or the need for special management practises.

Class 2 – The water can be used for all but the most sensitive crops and soils, with no reduction in yield or the need for special management practises.

Class 3 – Some yield loss is experienced even though special management practises are implemented, but a reasonable profit is realised.

Class 4 – Yield losses and/or the need for special management practises are such that the economic variability of irrigation is questionable. Certain crops can, however, still be produced in special circumstances or by using special management practises.



Where:

S1 class : Low sodium hazard to soil physical conditions. May harm sensitive crops.

S2 class : Appreciable sodium hazard to fine textured soils.

S3 class : May produce harmful levels of exchangeable sodium in most soils. Require good management.

S4 class : Generally unsatisfactory except at lower salinity levels (where gypsum amelioration is feasible)

C1 class : Suitable for most crops on moist soils.

C2 class : Suitable for moderately salt-tolerant crops without need for special leaching practices.

C3 class : Suitable for soils with restricted drainage. Require crops with good salt tolerance.

C4 class : Suitable only under special conditions.

Figure 3.2 Diagram for the classification of irrigation water quality (DWAF, 1993:244)

Figure 3.2 narrows this classification down for the classification of irrigation water according to the SAR and EC of the irrigation water. This is the same classification system as used by the US Salinity Laboratory and published in the USDA Handbook No.60 (1945).

Crop response is almost as dependent on the way irrigation applications are managed as on the water composition itself. The composition of irrigation water impacts upon crops principally through the changes it induces in soil properties such as soil solution salinity or percentage of exchangeable sodium (DWAF, 1993:211, Appendix 1). In the Vaal River system water quality deteriorates with increased usage pressure and the resulting reduced flow, but improves again with flooding. Water quality displays seasonal or cyclical fluctuations but does not actually progressively worsen over time, it is however expected that the irrigability of the soils can be affected as salts accumulate in the soils, and this in turn impacts on the sustainability of crop production. According to Du Preez *et al, (*2000:42) the overall trend in water quality is one of fluctuation, rather than increase over time. Despite the fluctuation, a slight trend in water quality deterioration is also evident in especially the lower reaches of the rivers.

3.2.3.2 Measures

Irrigation water salinity is measured as TDS (total dissolved solids) or EC (electrical conductivity).

- TDS is sometimes referred to as the total salinity and is measured or expressed in parts per million (ppm) or in the equivalent units of milligrams per litre or mg/l (1mg/l = 1ppm). TDS(lb/ac-ft) = TDS(mg/l) X 2.72.
- EC is a measure of electrical current and is reported in mmhos/cm, µmhos/cm or dS/m (1dS/m = 1mmhos/cm = 1000µmhos/cm).

  Subscripts are used with the symbol EC to identify the source of the sample:

  - EC_{iw} is the electrical conductivity of the irrigation water.
  - EC_e is the electrical conductivity of the soil as measured in a soil sample (saturated extract) taken from the root zone.
  - EC_d is used to determine the salinity of the drainage water that leaches below the root zone.

3.2.3.3 Conversions

Various TDS to EC (and *vice versa*) conversions are published in the water quality literature, but these are usually very vague and / or site specific.

EC is an indirect measure of the concentration of the total dissolved solids in solution – the greater the concentration of salts in solution the greater the ability to conduct an electrical current. EC (mS/m) is measured more easily than TDS (mg/l or ppm) and thus used more widely in databases storing water quality data. EC is related to TDS by multiplying EC by a factor of between 6 and 7 depending on the composition of dissolved salts (DWAF, 1993:31-35).

Marshall & Jones (1997) use electrical conductivity measured in deci-Siemens per meter (dS/m) as a measure of soil salinity. Milli-Siemens per meter (mS/m) is however most commonly used and will be used in this analysis. In the study by Marshall & Jones (1997) the TDS to EC conversion used was 650mg/l = 1mmohs/cm where 1dS/m = 1mmhos/cm.

3.3. THE IMPACT OF SALINITY ON IRRIGATED AGRICULTURE

By way of introduction to the impact of salinity on irrigated agriculture over time, two quotations:

> “ Irrigation has been an important base for agriculture in Mesopotamia (what is now Iraq and part of Iran) for 6000 years. But Mesopotamia is very different from Egypt. Mesopotamia has low rainfall, and is supplied with surface water by only two major rivers, the Tigris and the Euphrates. Although they are much smaller than of the Nile, they have much more dramatic spring floods, from snowmelt in the highlands of Anatolia, and they carry more silt. Furthermore, the plains of Mesopotamia are very flat, and poorly drained, so that the region has always had persistent problems with poor soil, drought, catastrophic flooding, silting, and soil salinity.
>
> Mesopotamia has had times of successful irrigation, and times of silt and salinity crises: the latter around 2000 BC, 1100 BC, and after 1200 AD. The first crisis may have been caused by water politics. In any irrigation system, the farmers most downstream are those most likely to be short of water in a dry year, or to receive the most polluted water. In Sumeria, the city of Lagash was rather far downstream in the canal system based on the Euphrates. Apparently

> Entemanna of Lagash decided that he would instead cut a canal to tap Tigris water, but the addition of poor-quality water led to rapid salinisation of the soil." **R Cowen** **www-geology.ucdavis.edu/faculty.html (2001)**

> " The Aral Sea will disappear by the year 2010, leaving behind an ecological and social desert. Massive irrigation projects in the region have reduced the Aral Sea to less than 40% of its original volume and more than tripled its salinity. More than 80% of animals once found in the region have disappeared. Increasing wind erosion has covered agricultural land with salt deposits from the newly exposed seabed, and both daily and annual temperature ranges are increasing significantly. As a final injustice, draining the Aral Sea has changed the regional climate sufficiently so that it can no longer support the vital irrigated cotton crop for which the sea was originally sacrificed. " **Perry and Vanderklein**

The accumulation of salts in soils and the frequently accompanying problem of drainage have plagued irrigated agriculture for centuries. Such accumulation results when plants transpire pure water leaving behind most of the salts in the soil solution; over time salts may concentrate to such an extent that they hinder germination, seedling, and vegetative growth, and consequently the yield and quality of crops (ASCE, 1990:13).

The ways in which a society manages water quality is a telling reflection of political, cultural, and economic processes within that society (Perry & Vanderklein, 1996, p.1). Backeberg, *et al, (*1996:iii) states that practically all government water schemes (in South Africa) were built for socio-economic objectives; economic viability criteria were not accorded much importance. Cost recovery (even operational and maintenance) was usually not required for state expenditure on government irrigation schemes. Large capital subsidies were paid to irrigation boards and private irrigators in certain areas. Although project design was technically sound (soil/water/crop interactions), long-term social and environmental sustainability was not the order of the day then and therefore not considered.

According to Backeberg, *et al, (*1996:i), approximately 40 000 small-scale farmers, 15 000 medium-to-large-scale farmers, 120 000 permanent workers, and an unknown number of seasonal workers are involved in irrigation farming, which consumes approximately 51% of South Africa's water on some 1,3 million ha and contributes 25 to 30 % of South Africa's agricultural output. From these figures the importance of irrigation farming to the South African economy is evident. If water quality degradation, and the accompanying environmental impacts, were to jeopardize the irrigation industry the socio-economic consequences could be disastrous for South Africa.

Although the impacts of irrigating with water of a poor quality along the Lower Riet and Vaal Rivers may not be felt directly (i.e. the quality of the water is not so bad so as to influence the crop directly or else the crop is tolerant to the quality of the water applied), the problem is that water of a poor quality deposits a salt load onto the soil, which slowly builds up and jeopardizes the sustainability of the specific production practise. At a certain level of salt accumulation it will become economically feasible (depending on the soil type and depth) to over irrigate to leach out salts, yet this eventually results in soils becoming waterlogged and underground drainage becomes necessary. The water quality problem now becomes an observable externality because returnflows to rivers are now direct, less filtration takes place and fertilizers and chemicals supplement the water applied to the crops irrigated. The practise in California and Australia is that these agricultural returnflows have to be managed on the farm or be strictly controlled with heavy fines for exceeding fixed limits.

3.4. MANAGEMENT OPTIONS TO IMPROVE WATER QUALITY

One of the aims of this study was to investigate various management options for the improvement of water quality. Although the main water quality constituent identified as problematic in the study area is salinisation, management options for other constituents will also be mentioned in the discussion to follow. After an introduction, the water quality management options discussed are grouped into farm, regional and national level water quality management options.

3.4.1. INTRODUCTION

It is stated in DWAF (1993:221) that both the physical and chemical water quality constituents and properties can be manipulated in order to improve the quality of water for irrigation. Filtration removes particles that would otherwise clog drippers; pH is adjusted to acceptable levels or to decrease the adjustable sodium adsorption ratio and bicarbonate concentrations (lowering a low pH), or to precipitate heavy metals (raising a low pH). Adding agricultural gypsum increases the calcium-to-sodium ratio in order to decrease the sodicity hazard. Addition of a chelating agent prevents the oxidation of iron, which causes precipitation problems or rust-like blemishes on fruit. An improved composition can also be achieved by mixing with other water sources, as has also been proposed by Moolman & Quibell (1995) for the improvement of water quality in the Lower Vaal River near Douglas.

DWAF (1993:221) further states the following problem associated with water quality amelioration: Although it is technologically possible to ameliorate the quality of practically any water until it is suitable for an intended use, it is seldom economically justifiable. Other undesirable compounds could also be introduced during the amelioration process. It is generally however not the responsibility of the irrigator to remove undesirable constituents added to the river source by a previous user.

According to O'Keeffe *et al, (*in Aihoon *et al,* 1997) salinisation is a particularly intractable problem; the only known remedies are dilution with less saline water or reverse osmosis to remove dissolved salts, which is a very expensive process. The solution to water quality degradation is therefore prevention and not cure.

3.4.2. FARM LEVEL WATER QUALITY MANAGEMENT OPTIONS

With regards to water quality management in general, Cooper & Keim (1996) list the following management practises that can be implemented by farmers as water quality protection practises: integrated pest management, legume crediting, manure testing, split application of nitrogen and soil moisture testing for accurate irrigation scheduling. Appendix 1 of DWAF (1993:211) also lists the role of on-farm irrigation management practises and other considerations in determining water quality guidelines.

With regards to salinity in particular, Lee & Howitt (1996:41) state that applying more irrigation water, installing drainage systems, and planting salt-tolerant crops are among the alternatives available to farmers for mitigating the effects of rising water salinity levels, but when all the feasible alternatives are exhausted cropland can and has gone out of production.

Numerous management practises exist for handling salinity and drainage problems in irrigated agriculture. They include: modifying crop rotations, changing the volume and timing of irrigation water, investing in improved irrigation systems, installing subsurface drainage systems, reusing drainage water, and treating or disposing of water collected in subsurface drains. (ASCE 1990:530)

Different on-farm management strategies for irrigation can produce a large range of soil salinity or soil sodicity values. These different on-farm management practises have been found to play a major role in the quality of water that can be used for irrigation. The following are important in irrigation management.

3.4.2.1 Understanding the effects of water quality on plants and crop yields

Yield reductions of different crops vary for different levels of soil salinity as measured by the ECe under normal growing conditions. Plants usually have a certain threshold value up to which no yield reduction is experienced but as that threshold value is exceeded there is a steady reduction on yield as ECe deteriorates (Maas and Hoffman, 1977, Ayers and Westcot, 1985).

Certain crops are also susceptible to foliar injury from spray irrigation with water containing sodium and chloride. Irrigating with the same water quality, but at night, instead of during the day can reduce the level of foliar injury.

3.4.2.2 Leaching for salinity management

ASCE (1990:414) lists alternative leaching methods, namely: continuous ponding, intermittent ponding, sprinkling, alternative row or border leaching and surface flushing.

Leaching is the basic management tool for controlling salinity. Water is applied in excess of the total amount used by the crop and lost to evaporation. The strategy is to keep the salts in solution and flush them below the root zone. The amount of water needed is referred to as the leaching requirement or leaching fraction. According to TAMU AGNEWS (1998) the time interval between leaching does not appear to be critical provided that crop tolerances are not exceeded. Hence, leaching can be applied by applying extra water with every irrigation, every few irrigations, once yearly, or even every few years depending on the severity of the salinity problem and salt tolerance of the crop.

The leaching fraction is commonly calculated using the following relationship:

$$LF = EC_{iw} / EC_e \qquad \textbf{(3.1)}$$

Where:

LF (leaching fraction) is the fraction of applied irrigation water that must be leached through the root zone

EC_{iw} is the electric conductivity of irrigation water

EC_e is the electrical conductivity of the soil at the bottom of the root zone

The leaching requirement is thus based on the electrical conductivity of the irrigation water and that of the drainage water at the bottom of the root zone.

Managing soil salinity by increasing the leaching fraction poses several problems. These arise from the fact that, in order to increase the leaching fraction, larger volumes of irrigation water are required. For example, to satisfy a leaching fraction of 0.1 (10%) for a crop with an evapotranspiration requirement of 1 000 mm, a total of 1 111 mm irrigation water needs to be applied. According to DWAF (1993:213) the following problems arise from this:

- the cost to acquire, distribute and apply the additional volume of water will be high;
- the infrastructure on most existing irrigation schemes would be unable to cope with a significant increase in water allocation;
- the possibility of irrigating a smaller area in order to increase the volume of water available for leaching per unit area, is not attractive;
- total income would be reduced while the expense per unit area would increase;
- To prevent probable water logging following water applications for an increased leaching fraction, artificial drainage will probably have to be installed.
- The increased throughput of water could reduce the aeration of the soil profile to such a degree that secondary problems such as root rot may arise.

Depending upon the mechanisms associated with irrigation return flow (e.g. the displacement of saline ground water bodies or leaching of saline geological strata), increased leaching fractions could promote the salinisation of rivers by mobilizing the salt sources and leaching them into river systems. This has already been identified as a threat in the Vaalharts irrigation scheme by Herold & Bailey (1996) and will result in potentially drastic down stream effects on the study area of this research.

3.4.2.3 Subsurface drainage

Shallow water tables complicate salinity management since water may actually move upward into the root zone, carrying with it dissolved salts. Crops through evapotranspiration then extract soil-water and the salts are left behind. Shallow water tables also contribute to the salinity problem by restricting the downward leaching of salts through the soil profile. Installation of a subsurface drainage system is about the only solution available for this situation. Proper spacing and depth of the subsurface drains maintain the water level at an optimal level.

Herold & Bailey (1996) mentioned the following problem with regard to artificial drainage; besides the tremendous cost implications, the problem when soils reach saturation levels within the root zone and when subsurface drains are installed, is that the returnflows back into the river are greater and with it increased salinity pollution for down stream users.

3.4.2.4 Seed placement

Obtaining a satisfactory stand is often a problem when furrow irrigating with saline water. Growers sometimes compensate for poor germination by planting two or thee times as much seed as is normally required. However, planting procedures can be adjusted to lower the salinity in the soil around the germinating seeds. Good salinity control is often achieved with a combination of suitable practises, bed shapes and irrigation water management. Where seed germination or young plants are sensitive to salinisation, seeds must be placed away from the area where salts accumulate. In furrow irrigated soils or when planting in raised rows, seeds should be placed on the shoulders above the water line. When irrigating with drip emitters or micro sprinklers salts tend to move outward and upward (Rhoades *et al,* 1992:99).

3.4.2.5 Irrigation systems as a management option

The appropriate irrigation system is often determined by the soil properties, rather than irrigation water quality. The interaction between soil properties and water quality however determines the most appropriate irrigation system. This consideration influences the cost-benefit relationship. Where high frequency is needed to keep the soil profile wet, drip and sprinkler irrigation are more suitable than flood systems as they are easier to manipulate and control and thus improve water use efficiency (Rhoades *et al,* 1992:103).

It is imperative when installing an expensive irrigation system such as a centre pivot irrigation system that the delivery capacity not only meets the crop requirement, but also the potential leaching requirement and importantly also be matched to the infiltrability of the soil. The larger the centre pivot irrigation system is, the greater the volume per second that needs to be delivered at the edges of the system. These very high delivery rates should not exceed the rate at which the water can infiltrate into the soil. Irrigating on slopes exacerbates this problem and runoff damage can occur (Du Preez *et al,* 2000:155).

3.4.2.6 Management of production inputs and resources

One environmental benefit derived from use of land is its “sink value” i.e. its ability to accumulate and neutralise the hazardous effects of some fund pollutants deposited on it from natural and anthropogenic (i.e. stemming from human production and consumption activities) sources. The sink value of land results from microbial activities and natural reactions that detoxify hazardous substances. Intensification of farming, especially by applying more fertilizer, manure or pesticides per unit of land, increases the level of pollution. Conversely if the land area is increased for production while all other farming inputs, such as the quantities of fertilizers applied are held constant, the level of pollution should decrease. The quantities of pollution emitted from this land should decrease accordingly. Unfortunately sink value does not apply to all pollution situations involving land (Aihoon *et al,* 1997:276). This is the case with stock pollutants as opposed to fund pollutants (Tietenberg, 1992:361).

In Aihoon (1994:181) the following hypotheses were proved: The functional relationship existing between the quantities of salt(s) emitted, as the dependent variable and the area of land cultivated, as the independent variable is either positive or negative, depending on the main source of the salt(s). If the salt is mainly anthropogenic in source, the relationship is negative, and if the salt is mainly geologic in source, then the relationship is positive. Aihoon (1994) further established that agricultural activities have an effect on the emission of chlorides in the Loskop Valley, but the main source of chlorides in the valley is the land, and that agricultural practises in the Loskop Valley result in the materialisation of surface water, such that the quantities of salts (minerals) emitted into the Olifants River draining the Loskop Valley are a function of the area of land cultivated to crops; the amount of rainfall received; and the quantities of fertilizer applied to crops on the land. From these quantities which Aihoon (1994) determined he calculated elasticity’s which are: 2.57 for land (i.e. a 1% increase(decrease) in the total land area cultivated to tobacco leads to a decrease(increase) of 2.57% in the emission of total dissolved salts); between 2.07 and 2.65 for rainfall (i.e. a 1% change in rainfall induces a change in the same direction of between 2.07 and 2.65 % in the emission into the river); and 2.93 for fertilizer (i.e. a 1% increase in the annual total quantity of fertilizer (tons) applied to crops leads to an increase of 2.93 % in the total quantity of dissolved salts emitted to the river).

Rainfall in the study area - the lower Vaal River - is relatively low in comparison with the Loskop Valley with the result that it probably will not have as large an elasticity as that of the Loskop study area, however rainfall in the Vaal, Modder and Riet River catchment areas will have an effect, but only if the storage capacity in the various dams in these rivers are exceeded. In Moolman & Quibell (1995:5) it is stated that when these schemes (Orange-Riet and Douglas Weir) were first planned it was first envisaged that occasional floods would wash these salts (built up as a result of irrigation returnflows) from the system. But this does not often occur as the dams along these rivers store most of the rainfall runoff from their catchment areas, most of the time. Furthermore saline water has a higher density than fresh water so when flooding events occur the fresh water washes “over” the saline water, so proper flushing does not take place.

Rainfall is an uncontrollable variable, but land area cultivated and the fertilizer application rate can be varied to improve the quality of irrigation returnflows. Therefore to reduce the effect of agriculture on water quality and in doing so improve the quality of water used for irrigation, farmers could either extensify land use and/or reduce the amount of fertilizer applied.

3.4.2.7 Other salinity management techniques

Techniques for controlling salinity that require relatively minor changes are more frequent irrigations, selection of more salt-tolerant crops, additional leaching, pre-plant irrigation, bed forming and seed placement. Alternatives that require significant changes in management are changing the irrigation method, altering the water supply, land levelling, modifying the soil profile, and installing subsurface drainage. A brief explanation on some of these techniques follows:

More frequent irrigations - Salt concentrations increase in the soil as the crop extracts soil water. Typically, salt concentrations are lowest following irrigation and higher just before the next irrigation. Increasing irrigation frequency maintains more constant moisture content in the soil. Through implementing higher frequency irrigation, more salts are kept in solution, which aids the leaching process. In Heynike (1987), it states that under high frequency irrigation the soil is not allowed to dry-out, which retards the effects of high salt concentrations in the crop root zone. Such a system could maintain high crop yields, but to attain this advantage, additional irrigation equipment and management ingenuity is required as well as a water source that must always be available. With proper placement, drip irrigation is very effective at flushing salts, and water can be applied almost continuously. Both sprinkler and drip provide more control and flexibility in scheduling irrigation than furrow systems.

Pre-plant irrigations - Salts often accumulate near the soil surface during fallow periods, particularly when water tables are high or when off-season rainfall is below normal. Under these conditions, seed germination and seedling growth can be seriously reduced unless the soil is leached before planting.

Residue management - Exposed soils have higher evaporation rates than those covered by residues. Leaving crop residues behind between harvest and planting will thus reduce evaporation, fewer salts will accumulate and rainfall will be more effective in providing for leaching.

Changing irrigation method - Surface irrigation methods such as flood, basin, furrow and border are usually not sufficiently flexible to permit changes in the frequency of irrigation or the depth of water applied per irrigation. Irrigating more frequently using these systems will improve water availability to the crop but will also waste water and increase the incidence of waterlogging. Converting to surge furrow irrigation may be the solution to many furrow systems. Otherwise a sprinkler or drip system may be required.

Chemical amendments - Chemical amendments such as gypsum applications, lime applied in conjunction with organic material, or sulphur-containing amendments are only effective on sodium-affected soils. Amendments are ineffective for saline soil conditions and will often exacerbate the existing salinity problem. The choice of an amendment for a particular situation will depend upon its relative effectiveness judged from its improvement of soil properties and crop growth, the availability of the amendment, the relative costs involved, handling and application difficulties, and time allowed and required for the amendment to react in the soil to effectively replace adsorbed sodium (Rhoades *et al,* 1992:101).

3.4.3. IRRIGATION BOARD / WATER USERS ASSOCIATION LEVEL WATER QUALITY MANAGEMENT OPTIONS

Moolman & Quibell (1995) discuss the possibility of utilizing excess capacity in the Orange/Riet canal to dilute the salt saturated water trapped by the Douglas weir in the Lower Riet River. This however doesn't improve salinity in the lower Vaal and Vaallus irrigation area, upstream from where the Vaal converges with the Riet. Excess water will have to be released from either the Bloemhof or Spitskop Dam. The water quality of the water released from the Bloemhof Dam is far better than that of the Spitskop Dam (Du Preez, *et al,* 2000), though Spitskop has more capacity to release water. Rough calculations by Moolman & Quibell (1995) show that the benefits exceed the costs, but as water becomes scarcer and more expensive or drought conditions persist this option is not feasible. Furthermore Orange River water could be diverted into the Vaal River system if further phases of the Lesotho Highlands Water Project are implemented (DWAF, 1998). After being used and reused as it passes through Gauteng the quality of this water could be questionable.

Any open water delivery system is subject to evaporation, which leads to higher salt concentrations in the water. The salinity content of irrigation water can thus increase during the entire time water is transported through irrigation canals or stored in reservoirs. Replacing irrigation ditches with pipe systems will help stabilize salinity levels, increasing the amount of water available for leaching, as well as improve water use efficiency by reducing the water lost to canal seepage.

3.4.4. NATIONAL LEVEL WATER QUALITY MANAGEMENT OPTIONS

Irrigation farming is known, together with urban, industrial and mining effluents, to be a major contributor to salinisation of South African rivers. The DWAF has had some success in tracing industrial, urban and mining effluents entering water bodies to their sources, but not so for agricultural effluents. While the DWAF pursues the 'polluter pays' principle with other polluters, it has not been possible to do so with agricultural polluters. The main reasons according to Aihoon *et al, (*1997:269) are:

- Agricultural pollution is non-point source, rendering liability allocation difficult;

- The quantification of pollution and the assessment of the costs of pollution damage is time consuming and expensive;
- Agricultural pollution involves a large number of producers that are geographically dispersed; and
- The political influence of South African farmers has made past governments reluctant to initiate policies that affect their incomes negatively.

While the irrigation water quota is based on the number of hectares of irrigation rights a farmer posses, as is the practise in the study area, and not volumetrically based, there will be little control over irrigation returnflows and no incentive for the installation of irrigation drainage.

It is the authors' personal experiences that in Australia and California in the USA, irrigation water returnflows are managed intensively and are not allowed to re-enter the source of the irrigation water by law. The irrigators in Australia pump their returnflows into evaporation basins or practise serial biological concentration (SBC) whereby returnflows from a sensitive crop are used to irrigate a more tolerant crop. In the Coachella valley in California the irrigation water management authority monitors the irrigation returnflows of individual farmers and manages the returnflows collectively.

3.5. A REVIEW OF PREVIOUS AGRICULTURAL SALINITY MODELLING WORK

Numerous mathematical models have been developed for agricultural salinity management. Linear programming (LP) models were generally used in the early stages of salinity research (Moore *et al,* 1974, Gardner & Young 1988, Johnson *et al,* 1991, Dandy & Crawly 1992, Marshall & Jones 1997, etc.) These models however most closely resemble the type of problems to be addressed in this research. More recently the focus has been on dynamic linear programming (DLP) models (Dinar *et al,* 1993, etc.) and stochastic and dynamic programming models (Feinerman & Yaron 1983, Dinar *et al,* 1986, Knapp 1992, Feinerman 1994, etc.).

The dynamic linear programming (DLP) models constructed either optimised only one crop on one soil type or were more regional hydraulic management optimisation models, as were the stochastic and dynamic programming models. These models if conducted for crops required data from tightly controlled experimental data specifically set up for the model and would not work with the South African water quality data limitations as identified by Du Preez *et al, (*2000:154).

The generalised algebraic modelling system (GAMS) (GAMS Development Corporation, www.gams.com) was identified as the ideal programming platform for building the salinity and drainage management model required for this research. Other water quality management models constructed using GAMS are by Lee and Howitt (1996) which is used for modelling regional agricultural production and salinity control alternatives within a water quality policy analysis framework, and Percia *et al,* (1997) which is used to determine the optimal operation of a regional system with diverse water quality sources. Both these models however optimise regional system operations and not farm level financial returns.

Coupling or integrating these models with a geographical information system (GIS) to create spatial optimisation models (Rhoades *et al,* 1999, Johnston 1994, Bende 1997, Engel *et al,* 1993, Negahban *et al,* 1996, Wolff-Piggott 1994) was identified as the latest trend and reinforced by DWAF(1996) (see paragraph 3.5.1, ii) but would fall beyond the scope and budget of this research.

Ragab (2001) proposes transient models that use the basic flow equation of water and solute to compute the soil water and solute contents as a function of time and depth of inundation. These models use a root extraction term added to the flow equations that relate the soil water salinity level and the crop yield. A sink term in these models accounts for the osmotic potential. The theory of a transient model is that when the osmotic and matrix potential exceed a critical level, transpiration ceases. These models do not account for crop salt tolerance and are thus not reliant on the Maas and Hoffmann (1977) type crop threshold and gradient values. Data limitations and expertise would also limit the use of this type of model in this research.

Most of the models mentioned above are a combination of two or more separate models, usually a simulation model and an optimisation model (Johnson *et al,* 1991,). The proposed methodology aimed at integrating the results generated from different models to create a holistic water quality management tool, makes use of both optimisation and simulation techniques. Negahban *et al, (*1997), defines an optimisation technique as “a tool which can sift through the numerous combinations of local choices to pick those which, when combined, will produce an optimum plan which best meets regional goals within the constraints imposed on combinations of activities.” The use of both optimisation and simulation is motivated in ASCE (1990:530); “One approach to select the best management practise is to simulate alternative management policies using crop-water production functions and then choose the best according to some criterion. Another approach is to formulate a dynamic optimisation problem and then solve it with the appropriate algorithms. The simulation approach allows construction of a detailed physical chemical and biological processes model but does not optimise beyond simple enumeration or trial and error. Dynamic optimisation finds the best management practise under specific conditions, but computational considerations usually limit model complexity. The two approaches may be combined for some applications. First, the various options are screened with an optimisation model, and then one or more simulation models are used to evaluate the selected options.”

3.5.1. LIMITATIONS OF PREVIOUS SALINITY MODELS

To determine the impact of various natural or artificial (e.g. policy mechanism) scenarios on existing schemes to provide answers to assist in increasing the economic efficiency and sustainability of the irrigation industry as a whole, the full dynamics and interactions between irrigation water quality and the soil salinity status on crop yields over irrigated time would need to be incorporated into a model. Blackwell, *et al.*(2000) however states that current USDA Salinity Laboratory evidence suggests these interactions are far more complex than originally thought, and that Rhoades, the doyen of soil/plant/salinity interactions, contends that no one has succeeded in combining all the refinements necessary to overcome the inherent problems of relatively simple salt balance models and geophysical sensors, to address the enormous field variability of infiltration and leaching rates. Blackwell, *et al.*(2000) further state that current literature and research on salinity management in irrigation agriculture also fails to capture the stochastic nature of inter-seasonal irrigation water quality as well as the cumulative economic and sustainability effects of irrigating with stochastic water quality levels. This is reinforced by Ragab (2001) and DWAF(1996), of which the latter stated that further limitations for setting criteria for salinity include:

(i) The need to make assumptions about the relationship between soil saturation extract salinity (for which yield response data is available) and soil solution salinity.

(ii) The deviation of the salinity of the soil saturation extract from the mean soil profile salinity, to which crops would respond.

(iii) The criteria for crop salt tolerance do not consider differences in crop tolerance during different growth stages

Ragab (2001) states that there is a need for more process-oriented dynamic models that integrate the various factors affecting the crop growth (which he backs up quoting Van Aelst *et al,* 1988 and Ragab *et al,* 1990) instead of simple statistical models describing the Crop-Water-Yield-Function relationships.

3.5.2. THE WEAKNESSES OF THE YIELD PERCENTAGE (YP) METHODOLOGY

The key formula of the YP methodology determines the leaching requirement (LR) percentage over a fixed range of targeted yield percentages. The formula as used in Ayers & Westcot, (1985:26) is as follows:

$$LR_{c,yp} = A\_EC\_CW_c / (5*(TRSH_{c,yp} - A\_EC\_CW_c)) \tag{3.2}$$

where: $TRSH_{c,yp}$ is a matrix of the ECe limits for each crop ($_c$) at which no crop yield reduction will be observed below the specific yield percentage ($_{yp}$) as water quality deteriorates (Maas & Hoffman, 1977), adapted to be a function of the expected yield percentage, and

$A\_EC\_CW_c$ is the average electrical conductivity of the crop water.

The shortfall of the YP methodology is that it assumes the ECiw to ECe conversion factor constant over all soil types, drainage statuses and irrigation systems used. This is not the case in practise and is better captured in the leaching fraction (LF) methodology used in Chapter 4. The YP methodology can be used in conjunction with the LF methodology because it calculates the exact leaching fraction required for a specific yield percentage target, while the LF methodology calculates the actual percentage of optimal yield attainable (yield percentage) for a specific fixed leaching fraction.

3.6. A SYNTHESIS OF THE LITERATURE STUDY

In this literature study, the term water quality is defined and broken down into its various constituents. The main water quality constituent impacting on the study area was identified as salinity. The fluctuation of irrigation water salinity is the immediate problem impacting on irrigation agriculture directly, but the deposition of salts on irrigated soils will have very little or no effect until it has accumulated to exceed the threshold level for the particular crop.

The importance of effective, water efficient, well managed and environmentally sound leaching was also identified and various leachate management options touched on. The building of an on-farm storage dam to manage irrigation returnflows was identified as an option to include in the model.

Various farm level management options were selected for the management, prevention and remediation of water quality problems and were assumed to be implemented and therefore not built directly into the model, except for the two major capital-intensive options, namely the installation of underground drainage and the conversion of an irrigation system. The proposed national policy option of imposing restrictions on the volume of returnflows allowed is incorporated in SALMOD at the farm level by determining the feasibility of building an on-farm storage dam to contain returnflows that exceed the limit proposed.

Finally, from the essence of a literature study conducted to identify existing models and methodologies used to simulate and optimise for water quality management in irrigation agriculture it was concluded that a simulation model and LP optimisation model would be constructed using GAMS to determine the economic effects of not only poor, but fluctuating irrigation water salinity in the study area.

The limitations and voids in previous work was also addressed in the literature study and it was decided to attempt to attempt to address these voids while heeding to the statement by Blackwell, *et al,* (2000) that no one has yet succeeded in combining all the refinements necessary to overcome the inherent problems of relatively simple salt balance models.

To achieve this two key mathematical equations were identified, the yield percentage (YP) equation as used by Ayers & Westcot (1985), (of which the weaknesses are listed in this chapter) and the leaching fraction (LF) equation by Maas and Hoffmann (1977) on which the rest of this study is based.

CHAPTER 4. SALINITY AND LEACHING MODEL FOR OPTIMAL IRRIGATION DEVELOPMENT (SALMOD): FORMULATION AND USE

"Farming looks mighty easy when your plough is a pencil and you're a thousand miles from the corn field"

Dwight D. Eisenhower

4.1. INTRODUCTION

The main aim in constructing SALMOD (Salinity And Leaching Model for Optimal irrigation Development) was to determine the financial magnitude of the salinity problem in different reaches of the Lower Vaal and Riet Rivers. This was necessary to identify the most appropriate stewardship actions, and to justify the cost of these actions to the farmers, water user authorities and policy makers.

To determine the financial magnitude of the water quality problem on irrigation, the *status quo* first had to be simulated as close a possible and the interactions between the irrigation water, the soil and certain management options understood. Then, using this framework various model constants were changed to test the impact of various scenarios.

Weighted average electrical conductivity data had to be constructed due to the fluctuating irrigation salinity levels in the study area over the growth period of the crops planted. The methodology derived in this study to calculate the average electrical conductivity, weighted according to monthly irrigation water requirements and effective rainfall, is demonstrated in this chapter.

SALMOD is constructed using GAMS 2.50 (GAMS Development Corporation, www.gams.com) coding in two sections. See Figure 4.1 for a schematic representation of SALMOD. Contrary to ASCE (1990:530) the simulation section of SALMOD precedes the optimisation section. The simulation section determines the range of gross margins and water requirements for all possible combinations of six crops, four soil types, four soil drainage status' and three irrigation system combinations for various leaching fractions, resulting in approximately 1700 crop combination activities to choose from in the optimisation section of SALMOD.

As a point of departure some of the assumptions and limitations of SALMOD are briefly discussed, followed by a section on data requirements, thereafter the layout of the rest of this chapter will follow the structure as depicted in Figure 4.1.

4.2. MODEL ASSUMPTIONS AND LIMITATIONS

In constructing a mathematical model, the main factors impacting the problem being analysed need to be identified, isolated and built into the model so that the model is as close a representation of the reality as possible. In reality however, a far greater multitude of factors interact to affect an outcome being analysed than could be integrated into a model. A model cannot simulate an outcome in reality with 100% accuracy, and as such is only a representation of what could happen. The use of a model is to try to understand why a certain outcome occurs, to predict the possible magnitude of alternative scenarios and to identify the main factors responsible for the problem.

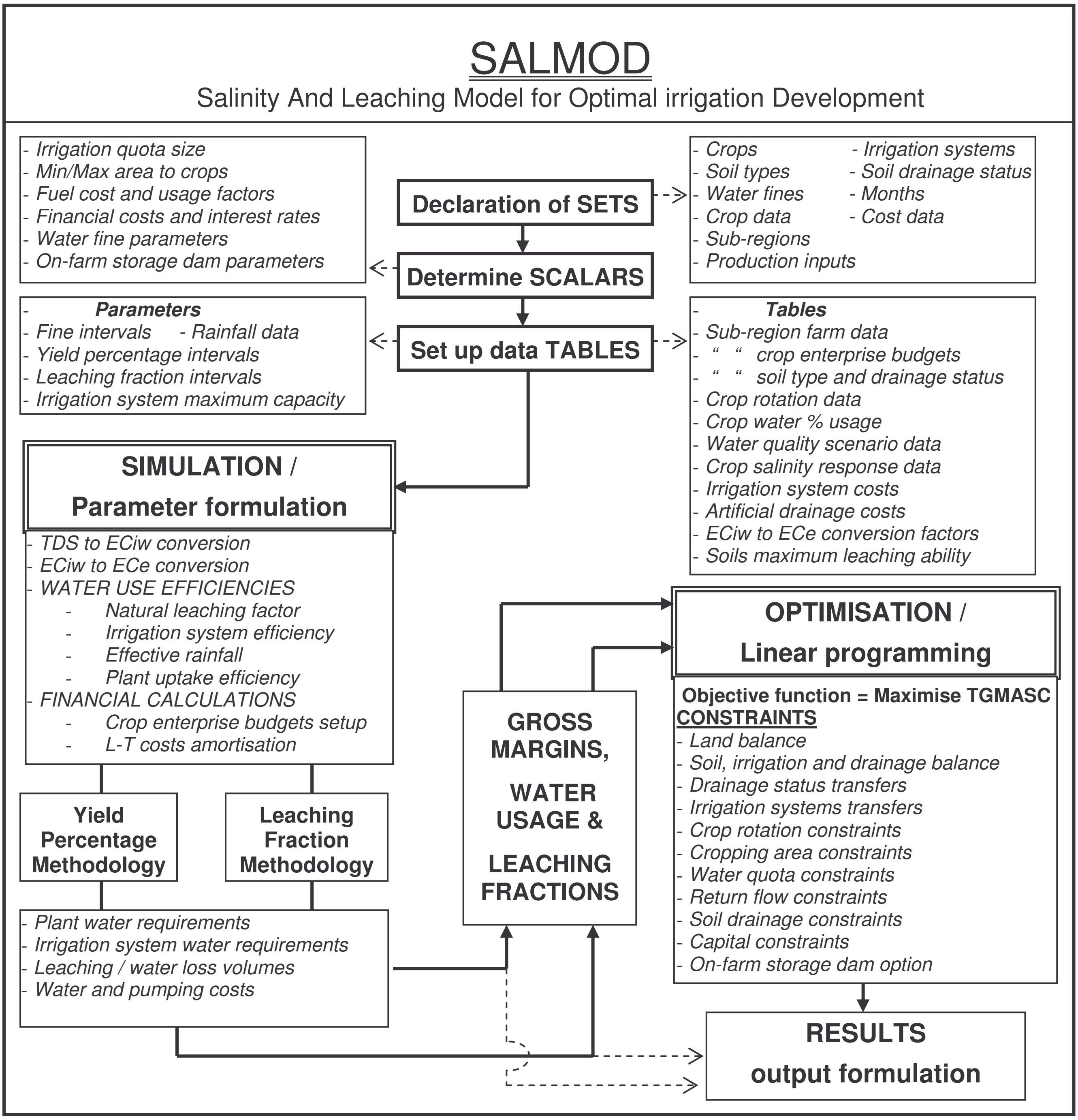


Figure 4.1 A schematic representation of SALMOD

Various assumptions are therefore needed. SALMOD for instance is set up so that the total kilowatt-hours available (traction component of the farm) can be constraining, but was not activated for the model runs discussed in this study, leading to assumption 1.

Assumption 1: Case study farmers are assumed to have sufficient kilowatt-hours available to perform the mechanisation tasks required in the SALMOD optimal cropping combination results.

This puts the sub-area case study farmers on an equal footing for sub-area comparison. The same holds for labour requirements:

Assumption 2: Case study farmers are assumed to have sufficient labour hours available to perform the labour tasks required in the SALMOD optimal cropping combination results.

Further assumptions and limitation of SALMOD will be mentioned in their relevant contexts in the discussion to follow in this chapter and a full list of the assumptions is compiled in the summary end of this chapter.

4.3. SALMOD DATA REQUIREMENTS

The aim of this section is to describe the manipulation and derivation of the data required for the operation of SALMOD. SALMOD specific data requirements are the model constants, value judgement data, maximum physiological crop yield data and weighted average electrical conductivity data. The SALMOD abbreviations for various terms are given in brackets in a different font.

4.3.1. SALMOD CONSTRAINTS

A list of all the model constant values, together with the model abbreviation and description is given in Table 4.7. The values for the irrigation quota, allowable pre- and after-year water use percentage and the fine increment were provided by the OVIB. The rest of the scalars in Table 4.7 are value judgement data based on the surveys conducted.

4.3.2. VALUE JUDGEMENT DATA

Value judgement data is generally data that doesn't formally exist and that could be measured *in situ*, but of which people who work in the situation where the data is used have a good indication. This data is gathered not by a formal survey, but by personal discussion and later verified with others who are also familiar with the data required. In this study all the value judgement data was verified at a technical meeting held with some members of the Steering Committee of this project.

Due to the immense variability in biological/natural systems when dealing with grouped averages, an acceptable average or representative value has to be determined for use in the model. The ECe variability within an irrigated field varies immensely, both across the surface area of the field and in soil depth. This variability could be captured when measured very intensively at a specific field level. These results will however not be similar to any other field in the world, thus the need for value judgements that are acceptable and widely applicable.

The value judgement data used in SALMOD include the following:

- The maximum leaching fraction ability of the 3 main types of irrigation systems,
- The maximum leaching ability / infiltrability of the soil types and drainage classes modelled in this study,
- Irrigation drainage cost on the soil types modelled in this study,
- Aggregate irrigation system transfer costs,

- Irrigation system plant water uptake efficiencies and
- Irrigation water to soil saturation extract electrical conductivity conversions.

4.3.2.1 Maximum irrigation system leaching ability

The irrigation systems maximum leaching capacity (`Parameter ISMLF(IS)`) is important to include in SALMOD as a constraint so that the leaching fractions calculated for the soil are not too high for the water delivery capacity of the irrigation system. The irrigation system maximum leaching fraction value judgement values used in SALMOD are 60% for flood irrigation systems (`FIS`), 20% for centre pivot and sprinkler irrigation systems (`CPI`) and 15% for drip irrigation systems (`DIS`) and were verified with Du Preez (2000) and Van Staden (2001).

4.3.2.2 Maximum soil leaching ability

The table listing the maximum fractions that different soils can be leached, classified according to clay percentage (vertical axis) and soil drainage status (horizontal axis), is listed in Table 4.11. Naturally drained `(NDS)` loamy soils `(LMS)` for example have a maximum leaching capacity of 50% `(0.50)`, which indicates that 50% more water than the plant water requirement can be given for leaching purposes. This percentage value decreases as the clay content of the soil increases and as the drainage status of the soil changes. The table was set up so that artificially drained soils have a 5% higher drainage factor and that limited drainage soils have a smaller maximum leaching percentage than naturally drained soils. Giving waterlogged soils (`WLS`) a value of 0%, results in the model producing an infeasible answer because of division by zero, therefore WLS get a value of 5%. The author set up the range in this table with verification by Du Preez (2000) and Van Staden (2001).

4.3.2.3 Artificial drainage installation costs

A rough approximation of the costs of underground drainage for various soil types according to Du Randt (2000) is given as parameter `ADTC(S)`. These costs can range from R15 000 per hectare on loamy sand soils to R25 000 per hectare on clayey soils and are the costs of getting a contractor to come and install the drainage. A farmer could do it for less himself with his own mechanisation and labour. These costs are for the whole field drained with fixed spacing, based on the average clay content of the field, and are the costs of converting waterlogged soils into artificially drained soils. These total system costs are accounted for in the fixed costs capital constraint equation, and are annualised by multiplying them by an amortisation factor to be accounted for in the production capital constraint equation. A waterlogged soils drainage factor (scalar `WLSDF`) of 10% is multiplied by the annualised drainage costs (`ADC`) for converting waterlogged soils to artificially drained soils, to determine the annualised costs of converting waterlogged soils to only limited drainage soils (`WSDC`). It is assumed that only the worst 10% of the field needs to be drained. If however the model calculates that it is feasible to convert limited drainage soils to fully drained artificially drained soils, then the costs of this are calculated by subtracting the WSDF from ADC. This is shown in mathematical formulation in equation 4.22, which is a sub-equation of the objective function of SALMOD.

4.3.2.4 Aggregate irrigation system transfer costs

One possible management option in SALMOD is to determine whether it is feasible to replace the current irrigation system with one that is either more efficient or able to leach better. Table 4.13 provides the data required for this operation; total irrigation system costs `(TSC)` in Rand per hectare, the salvage value `(SALV)` of the irrigation system after its expected life `(LIFE)` and the annual maintenance costs `(MAINT)` for flood `(FIS)`, centre pivot `(CPI)` and drip irrigation `(DIS)` systems. This table was set up with and verified by Van Staden (2000)

4.3.2.5 Irrigation system plant water uptake efficiencies

Irrigation system plant water uptake efficiencies are not to be confused with the 65%, 75% and 85% efficiencies for flood, sprinkler and drip irrigation systems respectively, which are the norms for, from withdrawal to reaching the soil surface, for irrigation system efficiencies and are the figures that the irrigation system design engineers work with. Plant water uptake efficiencies are the efficiency of different irrigation systems at getting the water applied to the field, to be taken up by the plant. Besides the crop spacing and leaf canopy percentage, a major factor in determining the plant water uptake efficiency is the irrigation frequency and duration. Flood irrigation has the lowest efficiency of 90% because the water is applied in large volumes at a time and then there is a long period before irrigating again. Also where the water is applied and stands the longest, there are losses below the vadose zone. Drip irrigation systems on the other hand have a lower application rate and very even distribution, resulting in 99% plant water uptake efficiency. For plant water uptake efficiency losses, i.e. losses from between delivery to the soil surface till the water is actually absorbed by the plant, De Wet (2000) suggests 10%, 5% and 1% for flood, sprinkler and drip irrigation systems respectively. This corresponds with the 90%, 95% and 99% values inputted in SALMOD table `IR_EF(C,IS)` for all crops.

4.3.2.6 Irrigation water to soil saturation extract electrical conductivity conversions

Table 4.18 shows the ECiw to ECe conversion factors used in SALMOD. With a leaching fraction of 25% (LF25) on loamy sand, naturally drained soils (LMS.NDS) for example the ECiw to ECe conversion factor of 1.00 indicates that system is in equilibrium. A conversion factor of 10 is used for waterlogged soils to force the model to reject these soils for crop production because it is assumed that crops won't grow in waterlogged soils. Note also that naturally (NDS) and artificially (ADS) drained soils have the same values. The values in Table 4.18 were set up using the case study farmer soil sample analysis data in Table 2.7.

4.3.3. MAXIMUM PHYSIOLOGICAL CROP YIELDS

Table 4.1 The derivation of the maximum crop yields (ton/ha) to be used as a guideline in SALMOD

CROP	Max. Physiological Yield:	Yields used in SALMOD	Farmer's average max. expected yields	Orange river control yields	***Technical meeting values***
Maize	12	14	12.7	12	***15***
Wheat	7	7	7.7	7	***8.5***
Lucerne	25	20.4	21.8		***30***
Groundnuts	4	3.4	4.3	3.5	***4.5***
Potatoes		45	57.0		***60***
Onions		50	50.0		
Cotton	5	5	4.5		
Sunflower		4	1.6		
	Viljoen *et al*, *(1992)*	GWK CEBs	Sub-area survey	New-Bucklands farmer	***Technical meeting 29-30 July 1999***

The technical meeting values of Table 4.1 were not used in SALMOD for this study because they are the maximum physiological yields attainable under perfect conditions, while for this study actual 1998 conditions are to be simulated. Each sub-area farmer's actual crop yields for 1998 were used and as a guide, the GWK Ltd. values were also included in SALMOD. These maximum physiological yields can however be used in SALMOD when wanting to compare the optimal attainable results between the 5 sub-areas.

4.3.4. PHYSIOLOGICAL GROWTH STAGE MODEL

Work was done with Dudley (2000), formerly from the Centre for Water Policy Research, University of New England in Australia, to develop a dynamic programming (DP) model to determine the optimal leaching requirements over different plant physiological growth stages, with varying plant salt tolerances at different physiological growth stages and fluctuating irrigation water quality. Fictitious, yet value judgment data was used; however the accumulative nature of the problem was unsuited for DP application. Where DP chooses the optimal path using the branch and bounds method, the input data that was generated was transferred into a simulation model PG5SM (Physiological Growth Stage Soil Salinity Sensitivity Simulation Model) using GAMS and run for all possible outcomes. An algorithm at the end chose the outcome with the highest returns and mapped the path taken to achieve this. The results from this model are not scientifically tested and therefore not included in this study, but the model developed, although simple, provides a basis for modelling the varying crop tolerance to salinity for the different physiological growth stages of the crop. This is particularly useful as in the study area irrigation water salinity fluctuates markedly over the lifespan of the crop planted. This effect is partially built into SALMOD in the following section by calculating a weighted average salinity for each crop, depending on the monthly average salinity of the irrigation water, the monthly volume of irrigation water required and monthly average rainfall, or part thereof, that the crop is in the soil.

4.3.5. WEIGHTED AVERAGE ELECTRICAL CONDUCTIVITY

From the various methodologies suggested on how the average EC can be determined over a season with fluctuating receiving water qualities, the most suitable method was identified as the average EC weighted for irrigation water volume and quality and rainfall volume and quality. A worked example of the process followed in deriving the weighted average electrical conductivity (EC) of the water used by the plant (i.e. irrigation water and rainfall) is shown in Table 4.2.

Crop specific data required in this hypothetical example is the potential yield, total crop water requirement, threshold and gradient. For SALMOD the potential crop yields were verified in a technical meeting, the total crop water requirement was obtained from the OVIB and the threshold and gradient values taken form Maas & Hoffmann (1977). The values used in this example are a potential yield of 1000 kg/ha, a total crop water requirement of 1000 mm/ha, an ECe threshold value of 200 mS/m and a yield decline with increasing ECe gradient value of 0.7 %/mS/m.

Other data required are the monthly ECe reading of the irrigated soil, the monthly percentage requirements of the total crop water requirement and the monthly rainfall. As the salinity of the irrigation water is usually measured as TDS in ppm or mg/l the TDS of the irrigation water (iw) first has to be converted to ECiw. The following formula was used in this study:

$$EC_{iw} = 0.1572 \times TDS_{iw} - 2.2295 \qquad (4.1)$$

ECe is then derived form ECiw by multiplying ECiw by a factor of 2. The monthly percentage crop water requirements used in SALMOD was obtained form Van Heerden *et al, (*2000) and monthly rainfall from the DWAF for the gauging point at Atherton. These values are shown in Table 4.2. The TDSiw for the months of July to December, assuming these are the months that the hypothetical crop is in the ground, appear on the left in the table, together with the conversion to ECiw and ECe.

The monthly water requirement percentage (MW) is converted to a monthly water volume (MWV) required by the crop and multiplied by the monthly average ECe. The sum of the products of MWV and ECe over all months that the crop is in the ground is then divided by the total water requirement to give the average ECe weighted for irrigation water requirements alone. Pure rainfall however also contributes salinity dilution and leaching, but because of overlaps of irrigation events and rainfall, runoff and deep percolation, not all rainfall is utilised by the crop, or for leaching purposes. For this reason, only effective rainfall (ER) is accounted for. According to Van Heerden (2000), citing "*the Green book*", ER is calculated by subtracting 20 from the monthly average rainfall and dividing the result by 2. Monthly ER is then multiplied by the EC of rainwater (ECr) assumed to be 1mS/m, and added to the monthly ECe weighted for water to give the results in the right hand side of Table 4.2.

The sum of the products of MWV and ECe plus the sum of the products of ER and ECr over all months that the crop is in the ground is then divided by the sum of the total crop water requirement and effective rainfall to give the average ECe weighted for irrigation water requirements (MWV) and effective rainfall (ER).

Table 4.2 A hypothetical example of the determination of the average ECe to which a plant is subjected over its growing season, weighted according to monthly crop water requirements (MW) and effective rainfall (ER)

Crop yield (kg):	**1000**	Rainfall EC (ECr) (mS/m):	**1**
Crop water requirement (mm):	**1000**	ECiw to ECe conversion factor:	**2**
Threshold (mS/m):	**200**	TDSiw to ECiw conversion factor (CF):	**y = 0.1572x - 2.2295**
Gradient (%/mS/m):	**0.7**	Effective rainfall (ER) formula:	**= (Rainfall - 20) / 2**

	TDSiw (ppm or mg/l)	**ECiw (mS/m)**	**ECe (mS/m)**	**Monthly Water (%)**	**Monthly water volume (mm)**	**ECe weighted for water**	**Rainfall (mm)**	**Effective rainfall (mm)**	**Ave. ECe weighted for water & ER**
MONTH	**TDS**	**TDS x CF2**	**ECiw x 2**	**MW**	**MWV**	**ECe x WV**	**Rain**	$\frac{\textbf{Rain - 20}}{\textbf{2}}$	**ECe x (MWV+ (ER x ECr)**
Jul	**626**	96	192.2	**0.029**	29	5575	**1.8**	0	5574.8
Aug	**691**	106	212.7	**0.075**	75	15955	**7.5**	0	15954.5
Sep	**762**	118	235.2	**0.206**	206	48445	**12.3**	0	48444.9
Oct	**747**	115	230.3	**0.347**	347	79911	**28.4**	4.2	79915.0
Nov	**713**	110	219.6	**0.343**	343	75308	**29.6**	4.8	75312.9
Dec	**595**	91	182.5	**0.000**	0	0	**42.3**	11.15	11.2
TOTALS:				**1.000**	**1000**	**225193**	**121.9**	**20.15**	**225213.4**
Averages:	*689.7*	*106.0*	***212.1***	***Weighted:***		***225.2***	***Weighted:***		***220.8***

The average ECe weighted for irrigation water requirement and effective rainfall, calculated in Table 4.2 as 220.8 mS/m, is inputted into the equation 4.2, together with the crop threshold and gradient as calculated by

Maas & Hoffmann (1977) to give the percentage of maximum yield obtainable under the average ECe conditions.

$$Y = (100 - Gradient \cdot (Ave.ECe - Threshold))/100 \qquad (4.2)$$

Where Y is the fraction of maximum yield obtainable under average ECe ($Ave.ECe$) and $Gradient$ and $Threshold$ are the crop specific values as determined by Maas & Hoffmann (1977).

The yield fraction (Y) worked out using average ECe weighted for monthly water requirements (MWV) alone calculated as 225.2 mS/m is 0.82 resulting in a 823.6 kg/ha yield if the maximum yield is 1000kg/ha, while the yield fraction (Y) worked out using average ECe weighted for monthly water requirements (MWV) and effective rainfall (ER) calculates as 220.8 mS/m is 0.85 resulting in a 854.6 kg/ha yield if the maximum yield is 1000kg/ha, a 3.6% improvement.

Table 4.3 lists the limitations and resulting assumptions for which the average ECe is calculated. Although very simple, this methodology is more applicable to conditions of rapidly fluctuation irrigation water salinities, as is the case in the study area, than simply using an average ECe value held constant over the growing season of the crop planted.

Table 4.3 The limitations and resulting assumptions for the methodology used to calculate average ECe

Data:	Limitation:	Assumptions:
TDSiw to ECiw conversion factor:	Different depending on origin	Same origin throughout season
ECiw to ECe conversion factor:	Depends on soil type and drainage status	Cropping unit homogeneous and stays the same for whole season
Effective rainfall values:	Monthly totals, doesn't take intensity / distribution into account	Equal distribution and intensity and runoff / wastage factor of 20 (Van Heerden, 2000)
Threshold and Gradient values:	Don't make provision for different salt sensitivities at different physiological stages of growth.	Constant for whole season (Information limitation)

4.4. THE MODEL SETS

The first step in setting up a model in GAMS is the declaration of the model sets and sub-sets. No values are assigned in sets and sub-sets, just the table column and row headings under which the data is to be entered. The sets used in SALMOD are shown in Table 4.4 and Table 4.5. The sets in Table 4.4 are self-explanatory, but where very cryptic abbreviations are used these sets are explained in more detail than under the description heading in the table. Table 4.5 contains a description of each element within the sets.

Table 4.4[2] The sets used in SALMOD to classify data with set, description and elements

SET	DESCRIPTION	ELEMENTS
C	Crops modelled	WHEAT,MAIZE,GRNDNUT,POTATO,COTTON,LUCERNE
F	Water overuse fine levels	WF1,WF2,WF3,WF4,WFPY
T	Time periods (monthly)	JAN,FEB,MAR,APR,MAY,JUN,JUL,AUG,SEP,OCT,NOV,DEC
CROPDAT	Crop data	WREQ_PRE,WREQ_AFT,TRSH,GRAD
COSTDAT	Cost data	PRICE,MEY,HC,FVC,MASC,FUEL,MAINT
PLD	Production loan data	AMT,TRM,INT
IO	Outputs of Inputs&Outputs	WHEAT,MAIZE,GRNDNUT,POTATO,COTTON,LUCERNE
LF	Leaching fraction	LF0,LF5,LF10,LF15,LF20,LF25

Set `CROPDAT` (Table 4.4) contains the element headers for basic data needed for each crop. `WREQ_PRE` is the crop water requirement in the pre-year and `WREQ_AFT` the crop water requirement in the after-year, `TRSH` is the threshold salinity level up to which no reduction in yield occurs and `GRAD` the gradient at which crop yield declines after the threshold value has been exceeded as water quality declines.

Set `COSTDAT` is used in simplifying the crop enterprise budgets, `PRICE` is the market price of the outputs, `MEY` the maximum expected yield for a crop, `HC` the harvesting costs which are yield dependent, `FVC` are the variable costs of the grouped inputs that are not dependent on irrigation volume, pumping and crop yield. The farmer enters his fuel and maintenance data into the CEBs table for comparison, but `FUEL` and `MAINTENANCE` are calculated internally in SALMOD.

Set `PLD` contains the element headers for data needed to calculate a production loan. `AMT` is the initial amount of the production loan, `TRM` the term of the loan in years and `INT` the annual interest rate.

Table 4.5 The sets used in SALMOD to classify data accordingly, with set description, elements and element description columns

SET	SET DESCRIPTION	ELEMENTS	ELEMENT DESCRIPTION
S	Soils classified according to clay %	LMS	LOAMY SAND SOILS <15% CLAY
		SNL	SANDY LOAM SOILS 15-25% CLAY
		SNC	SANDY CLAY SOILS 25-45% CLAY
		CLY	CLAY SOILS >45% CLAY
DS	Soil drainage status	NDS	NATURALLY DRAINED SOILS
		ADS	ARTIFICIALLY DRAINED SOILS
		LDS	LIMITED DRAINAGE NATURALLY DRAINED SOIL
		WLS	WATERLOGGED SOILS
IS	Type of Irrigation system	FIS	FLOOD IRRIGATION SYSTEM
		CPI	CENTRE PIVOT IRRIGATION SYSTEM
		DIS	DRIP IRRIGATION SYSTEM
IO	Inputs and Outputs (Inputs only - outputs listed in Table 4.4 above)	PRICE	PRICE OF PRODUCT IN RANDS PER TON
		YIELD	YIELD OF PRODUCT IN TONS PER HECTARE
		SEED	SEED COSTS IN RANDS PER HECTARE
		FERT	FERTILIZER COSTS RANDS PER HECTARE

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[2] All tables printed in the `Courier New` font are tables taken directly out of SALMOD

		HERB	HERBICIDE COSTS IN RANDS PER HECTARE
		PEST	PESTICIDE COSTS IN RANDS PER HECTARE
		INSUR	INSURANCE COSTS IN RANDS PER HECTARE
		HARV	HARVESTING COSTS IN RANDS PER TON
		INT	INTEREST ON PRODUCTION CAPITAL
		WAT	WATER COSTS IN RANDS PER HECTARE
		ELEC	ELECTRICITY PUMPING COSTS IN R PER HA
		LABOR	LABOUR COSTS IN RANDS PER HECTARE
		MHLR	MAN-HOURS OF LABOUR REQUIRED
		FUEL	FUEL AND LUBRICATION IN RANDS PER HA
		KWHR	KILOWATT HOURS REQUIRED PER HECTARE
		MAINT	MAINTENANCE AND REPAIRS COSTS IN R/HA
		CAP	CAPITAL GOODS REPAYMENTS
SR	OVIB Sub-area names	OL	OLIERIVIER (1)
		VL	VAALLUS (2)
		AT	ATHERTON (3)
		BL	BUCKLANDS (4)
		NB	NEW BUCKLANDS (5)
		GWK	GWK Ltd. REGIONAL DATA
CSF	Case study farmer data set		SEE Table 4.8

4.4.1. MODEL SUBSETS

The subsets shown in Table 4.6 are used when only a part of a set is being referred to. Subset `PL` for example only refers to those elements of set `IO` that are used in the calculation of the production loan.

Table 4.6 The subsets used in SALMOD with set, description and elements

SUBSETS	SET	DESCRIPTION	ELEMENTS
NODRIP	C	Can't drip irrigate these crops	WHEAT,MAIZE,LUCERNE
LMYS	S	Loamy sand only	LMS
NOTLMS	S	Not loamy sand	SNL,SNC,CLY
NPDS	DS	No potatoes on drainage state	WLS,LDS
FPY	F	Pre-year fine	WFPY
FAY	F	After-year fine tiers	WF1,WF2,WF3,WF4
PY	T	Pre-year	JUL,AUG,SEP,OCT,NOV
AY	T	After-year	DEC,JAN,FEB,MAR,APR,MAY,JUN
SUMMER	T	Summer months	NOV,DEC,JAN,FEB,MAR,APR
WINTER	T	Winter months	MAY,JUN,JUL,AUG,SEP,OCT
PL	IO	Production loan required for:	SEED,FERT,HERB,PEST,INSUR,INT

4.5. SALMOD SCALARS (CONSTANTS)

The scalars used in SALMOD, and depicted in Table 4.7, are applicable to all sub-area case study farmers and remain constant for a complete model run. The only value that is changed for comparing two different scenarios is `MAXRF`, the maximum volume of irrigation return flows allowed, which is set at 1000 when return flows are not constraining and at 100 in this study to constrain return flows. These values can be updated when modelling a specific farmer run or scenario run.

Table 4.7 Scalars/constant values used in SALMOD, 2000

SCALARS	**DESCRIPTION**	**UNIT**	**VALUE**
IQ	Irrigation quota size	mm/ha/yr	1100
PYWU	Allowable pre-year water use	%fraction	0.6
AYWU	Allowable after-year water use	%fraction	0.4
WFI	Water overuse fine increment	mm/ha	100
MAXPOT	Maximum area to plant to potatoes	%fraction	0.05
MAXGN	Maximum area to plant to groundnuts	%fraction	0.25
WLSDF	Waterlogged soils drainage factor	%	0.1
FP	Fuel price	R/litre	3.7
FLR	Fuel cost: lubrication cost ratio	%	0.01
FMR	Fuel cost: maintenance cost ratio	%	0.05
LPKWH	Litres per kilowatt-hour	Litres	0.35
SUMLH	*Summer labour hours (working hours per day)*	*Hrs*	*10*
WINLH	*Winter labour hours (working hours per day)*	*Hrs*	*8*
WDPM	*Working days per month*	*Days*	*25*
LTT	Long term loan term for drainage/irrigation system	Years	10
LTI	Long term loan annual interest rate	%	0.15
PCI	Production capital interest rate	%	0.17
ECRW	Electrical conductivity of rain water	mS/m	1
FORCE	A constant used to eliminate an option if to high		-0.001
NZERO	A very small constant used when dividing by 0		0.00001
COFSD	Total cost of 1 on-farm storage dam	R	30000
VOFSD	Total volume of 1 on-farm storage dam (50x50x3m)	mm/ha	750
EVAPY	Evaporation - surface water	mm/ha/dam/yr	575
MAXRF	Max return-flows allowed/ha water right	mm/ha	100

4.6. MODEL TABLES AND PARAMETERS

When the elements of two or more sets are arranged in table or matrix format then this is referred to as a table in GAMS. A parameter is a one-dimensional array of values assigned to the elements of a set. The set references of a table or parameter follow the table or parameter name in brackets. The tables in SALMOD into which the setup data is inputted are grouped into the following categories and discussed in this order:

- Farm data including soil type and drainage data
- Financial data including crop enterprise budgets, irrigation system and artificial drainage costs
- Crop rotation, crop water usage and rainfall data
- Water quality scenario data and ECiw to ECe conversion factors

Using matrix algebra, table coefficients are manipulated mathematically to create new tables in the simulation section of SALMOD. The three main tables produced in the simulation section of SALMOD to be transferred into the optimisation section are a table of gross margins, water usages and leaching fraction volumes for all possible crop, resource and management combinations, and for both methodologies.

4.6.1. FARM DATA

Table 4.8 is a list of the elements of set `CSF` and contains the descriptions of the column headings inTable 4.9. This set is separate from the sets listed in Table 4.4 as it is applicable to `TABLE CSFD(SR,CSF)` only.

Table 4.8 Set `CSF` for SALMOD `TABLE CSFD(SR,CSF)`, the case study farmer data set

ELEMENT	**DESCRIPTION**	**UNIT**
IA	Total current Irrigable Area	Ha
IR	Current Irrigation Rights per allocated quota	Ha
WC	Water Costs - CAN BE VARIED FOR EACH SUB-AREA	R per mm
PC	Pumping Costs - will vary within sub-area	R per mm
FC	Case study farm non-allocatable annual Fixed Costs	R per yr
MPC	Maximum Production Capital availability	R
MCL	Maximum fixed Capital improvement Loan availability	R
TKWA	Total Kilowatts Available	KW
TLA	Total Labourers Available	person
LABC	Average Labour Costs (/person/24 working day month)	R

In Table 4.9 separate values are filled in for the different sub-areas' case study farmers. SALMOD is constructed that the data from all the sub-area case study farmers are in the model and that with minimal changes the same model can solve for a different farmer under a different scenario. SALMOD is constructed in this way that for the proposed next stage of this project it can be further developed to solve for all sub-areas under one scenario and extrapolate each sub-area to calculate the economic impact for the whole OVIB service region. Currently SALMOD is only a farm level management tool.

Assumption 3: The fixed costs (FC) in Table 4.9 assume all farming income and expenses from all other activities not modelled in SALMOD remain constant.

Table 4.9 `CSFD(SR,CSF)`, OVIB sub-area land and cost data, 2000

	IA	**IR**	**WC**	**PC**	**FC**	**MPC**	**MCL**	**TKWA**	**TLA**	**LABC**
Units	***ha***	***ha***	***R/mm/ha***	***R/mm/ha***	***R***	***R***	***R***	***kW***	***Men***	***R/month***
OL	200	141	0.17	0.56	561000	300000	600000	280	16	1000
VL	461	339	0.17	0.56	2475015	500000	1000000	720	18	1000
BL	50	58.4	0.17	0.56	38000	100000	200000	46	2	1000
AT	22	28.9	0.17	0.56	130000	150000	300000	120	4	1000
NB	145	100	0.17	0.56	1049109	600000	1200000	300	14	1000

Farm specific soil type, drainage class and irrigation system are specified in the SALMOD `TABLE SOIL_D(S,IS,DS,SR)`. In Table 4.10 this is only shown for the Olierivier case study farm. For a full discussion of the soil type, drainage class and irrigation system sub-division for each case-study farm see chapter 2. The model will not solve if the sum of the values in Table 4.10 do not equal the farm size as specified in the in `TABLE CSFD(SR,CSF)` under `CSF` element `IA` (irrigation area) for `SR` (sub-area) element `OL` (Olierivier) which is 200 (see Table 4.9).

Table 4.10 `SOIL_D(S,IS,DS,SR)`, farm specific soil type, drainage class and irrigation system, Olierivier case study farm, 2000

	NDS.OL	ADS.OL	WLS.OL	LDS.OL
LMS.FIS				30
LMS.CPI	100	20		40
LMS.DIS				
SNL.FIS			5	
SNL.CPI			5	
SNL.DIS				
SNC.FIS				
SNC.CPI				
SNC.DIS				
CLY.FIS				
CLY.CPI				
CLY.DIS				

Table 4.11 `MLFS(S,DS)`, maximum fractions that the soils in table `SOIL_DATA` can be leached, 2000

	NDS	**ADS**	**WLS**	**LDS**
LMS	0.50	0.55	0.05	0.35
SNL	0.35	0.40	0.05	0.25
SNC	0.25	0.30	0.05	0.20
CLY	0.15	0.20	0.05	0.10

Table 4.11 shows the maximum fractions that the soils class and drainage status combinations can be leached according to value judgements as verified by Van Staden (2000) and Du Preez (2000). Naturally drained `(NDS)` loamy soils `(LMS)` in Table 4.11 for example have a maximum leaching capacity of 50% `(0.50)`. This means that up to 50% extra water over and above the plant water requirement can be applied to the specific soil body without causing waterlogging problems over a production season.

As SALMOD was set up to model 1998 conditions specifically the month elements of parameter `RAIN(T)` were assigned 1998 average monthly rainfall data as measured at the Douglas Weir by the DWAF. Long-term average monthly rainfall data can however also be inputted for parameter `RAIN(T)`.

4.6.2. <u>FINANCIAL DATA</u>

Table 4.12 lists the CEBs for wheat only for the various sub-area case study farms as well as the GWK Ltd. CEB. The CEBs for the other crops used in this study appear in Appendix 1. Additional crops can be added with ease into SALMOD if a wider spectrum of crops is to be analysed. Enterprise budgets need to be filled in for all crops that each farmer grows, or has the capacity to grow. Farm values for `WAT and ELEC` are filled in for comparison, but are calculated separately in the model, as they are a function of the actual volume of water used. With yield reduction management options, harvesting costs are recalculated to reflect the reduced yield. SALMOD summarises the CEB table shown in Table 4.12, grouping all cost components that are not dependent on water volume and yield, and works out the production loan interest on these using the following loan terms: wheat – 6, maize – 6, groundnuts – 9, potatoes – 5, cotton – 7 and lucerne – 3 months.

Assumption 4: All farmers make use of the production loan facility in full when planting the crop and repay the loan in full one month after harvest.

Table 4.12 `EBTable(IO,C,SR)`, Crop Enterprise Budgets* (CEBs) of the OVIB sub-areas and GWK for wheat (other crops in set C ommitted), 2000

	WHEAT.OL	**WHEAT.VL**	**WHEAT.AT**	**WHEAT.BL**	**WHEAT.NB**	**WHEAT.GWK**
PRICE	1072	1022	1060	0	918	780
YIELD	5	6	10	0	7	7
SEED	483	108	1900	0	247	237
FERT	950	1388	1300	0	1072	1214
HERB	158	98	300	0	6	212
PEST	0	5	0	0	0	302
INSUR	125	98	520	0	0	154
HARV	97	1	52	0	52	45
MHLR	16	16	16	0	16	16
KWHR	343	343	343	0	343	343
WAT	74	82	211	0	121	150
ELEC	245	123	253	0	198	345
CAP	87	51	211	0	97	0
FUEL	142	286	390	0	119	246
MAINT	393	530	172	0	279	51
LABOR	507	504	597	0	446	30

* All units are in **R/ha** except harvesting costs (HARV) which are in **R/ton**

Assumption 5: It is assumed that farmers plan for the maximum physiological yield. All crop establishment costs remain static under different water quality scenarios, however harvesting and irrigation costs vary with different water qualities and leaching fractions.

The Soil Protection Unit of the Department of Agriculture at Silverton compiled standard drainage cost norms, which were used in the past to calculate subsidies. Currently however, subsidies are virtually non-existent and besides the clay % of the soil there are many other factors that determine drainage costs (Du Randt 2000). A rough approximation of the per hectare costs of underground drainage for various soil types, parameter `ADTC(S), are` according to Du Randt (2000) as follows: Loamy sand `(LMS)` – R15 000, Sandy loam `(SNL)` – R17 000, Sandy clay `(SNC)` – R20 000 and Clay `(CLY)` – R25 000 per hectare.

Table 4.13 Irrigation system transfer cost data, Van Staden (2000)

	TSC	**SALV**	**MAINT**	**LIFE**
Units	*R/ha*	*% of TSC*	*R/Ha/Yr*	*YRS*
FIS	500	0.6	10	100
CPI	5000	0.1	100	20
DIS	8000	0.03	500	5

One possible management option in SALMOD is to determine whether it is feasible to replace the current irrigation system with one that is either more efficient or able to leach better. Paragraph 4.3.2.4 mentions the data required for this operation (see Table 4.13); total irrigation system costs `(TSC)` in Rand per hectare, the salvage value `(SALV)` of the irrigation system after it's expected life `(LIFE)` and the annual maintenance costs `(MAINT)` for flood `(FIS)`, centre pivot `(CPI)` and drip irrigation `(DIS)` systems.

4.6.3. CROP DATA

Table 4.14 `LAND(T,C)`, monthly land requirements (fraction of 1) of the crops modelled in SALMOD

	WHEAT	**MAIZE**	**GROUNDNUT**	**POTATO**	**COTTON**	**LUCERNE**
JAN		1	1	1	1	1
FEB		1	1	1	1	1
MAR		1	1	1	1	1
APR		1	1	1	1	1
MAY		1	1	1		1
JUN	0.5	0.5				1
JUL	1					1
AUG	1					1
SEP	1		0.5		0.5	1
OCT	1		1		1	1
NOV	1		1		1	1
DEC	0.25	0.75	1		1	1

The crop rotation systems practised by a specific case study farmer are incorporated into SALMOD with Table 4.14. This table `LAND(T,C)` is used in the optimisation section of SALMOD as a constraint to ensure that the area planted to crops in any one month does not exceed the irrigable area of the specific farmer being modelled. The value of 0.5 for wheat in June `(JUN)` indicates that wheat gets planted in the second half of the month of June, then the values of 1 for July `(JUL)` to November `(NOV)` indicate that wheat will be on the specific lands for 100% of those months. The value of 0.25 in December indicates that harvesting is finished by the end of the first quarter of December `(DEC)`.

Table 4.15 shows the monthly percentages according to Van Heerden *et al* (2000), of the total irrigation water requirement of the crops included in SALMOD. A check is performed in SALMOD to ensure that all the percentages add up to 100. If not, an error message is displayed and the model will not run.

Table 4.15 `WAT_PER(T,C)`, **monthly percentages of the total irrigation water requirement of the crops included in SALMOD, Van Heerden *et al,* 2000**

	WHEAT	MAIZE	POTATO	COTTON	GRNDNUT	LUCERNE
Jan		24.6	13.0	33.7	35.7	17.4
Feb		31.4	13.8	17.5	19.2	8.1
Mar		30.1	29.4	14.8	9.5	8.4
Apr		9.9	27.3	4.2	3.6	7.9
May			16.5		0.9	5.5
Jun						
Jul	2.9					
Aug	7.5					5.5
Sep	20.6					8.3
Oct	34.7			3.2	2.6	11.5
Nov	34.3			8.3	5.2	13.7
Dec		4.0		18.3	23.3	13.7

Table 4.16 `CROP_DATA (C, CROPDAT)`, **pre-year** `(WREQ_PRE)` **and after-year** `(WREQ_AFT)` **water requirements (Bruwer, 2000) and the thresholds** `(TRSH)` **and gradients** `(GRAD)` **(Maas, & Hoffman, 1977) of each crop modelled in SALMOD**

	WREQ_PRE	WREQ_AFT	TRSH	GRAD
Units	*mm/PreYr*	*mm/AftYr*	*mS/m*	*%/mS/m*
WHEAT	660	0	600	0.071
MAIZE	0	700	170	0.12
GRNDNUT	0	590	320	0.29
POTATO	0	580	170	0.12
COTTON	220	680	770	0.052
LUCERNE	479	791	200	0.073

Table 4.16 indicates the pre- `(WREQ_PRE)` and aft- `(WREQ_AFT)` year water requirements as determined by Bruwer (2000) for each crop as well as the threshold `(TRSH)` and gradient `(GRAD)` values according to Maas & Hoffman (1977) for each crop.

SALMOD table `IR_EF(C,IS)`, not presented here, lists the efficiency of different irrigation systems at getting the water applied to the field to be taken up by the plant. A major factor in determining the plant water uptake efficiency is the irrigation frequency and duration. Flood irrigation (`FIS`) has the lowest efficiency of 90% because water is applied in large volumes at a time and where the water is applied and stands the longest, there are losses below the root zone. Centre pivot irrigation systems `(CPI)` also apply large volumes of water on the perimeter of the pivot as compared to the centre, but are more efficient than Flood with an efficiency of 95%. Drip irrigation systems (`DIS`) on the other hand have a lower application rate and very even distribution, resulting in 99% plant water uptake efficiency. Different crops, depending on their planting density and root structure can also influence plant water uptake efficiency, and for this reason Table `IR_EF(C,IS)` is set up that the efficiencies can vary depending on the crop planted (set `C`), but for this study all crops have been given the same value due to a lack of information to differentiate between the crops.

4.6.4. WATER QUALITY DATA

The monthly water quality data for 1998 for each of the 5 OVIB sub-areas is given in Table 4.17. OVIB data was only available for Olierivier `(OL)` and Vaallus `(VL)` and for the other 3 sub-areas only DWAF data was available. This data was therefore combined in Table 4.17. From the data it is clear that OL by far has the poorest water quality and NB the best. BL and AT readings are very closely correlated as they get water from the same source. For a more in-depth discussion on the irrigation water salinity impacting on the sub-areas see Chapter 2.

Table 4.17 Monthly average ECiw (mS/m) for the OVIB sub-areas, 1998

	OL	**BL**	**AT**	**VL**	**NB**
Best '98	*OVIB*	*DWAF*	*DWAF*	*OVIB*	*DWAF*
Jan	96	51	52	45	19
Feb	91	50	52	56	20
Mar	72	38	42	64	18
Apr	54	43	44	40	19
May	102	65	68	65	20
Jun	109	85	91	63	21
Jul	97	94	91	59	20
Aug	99	86	86	62	19
Sep	119	68	77	74	19
Oct	130	23	28	84	20
Nov	113	47	53	87	20
Dec	97	75	80	45	20

Table 4.18 `SWCF(S,DS,LF)` ECiw to ECe conversion factors based on results of soil samples taken on the case study farms in the OVIB, 2000

	LF0	**LF5**	**LF10**	**LF15**	**LF20**	**LF25**
LMS.NDS	2.35	2.30	2.20	1.60	1.10	1.00
LMS.ADS	2.35	2.30	2.20	1.60	1.10	1.00
LMS.LDS	6.00	4.50	3.60	3.20	2.90	2.50
LMS.WLS	10.00	10.00	10.00	10.00	10.00	10.00
SNL.NDS	2.75	2.60	2.40	1.80	1.60	1.40
SNL.ADS	2.75	2.60	2.40	1.80	1.60	1.40
SNL.LDS	6.25	4.75	4.00	3.50	3.20	2.75
SNL.WLS	10.00	10.00	10.00	10.00	10.00	10.00
SNC.NDS	3.35	3.30	3.20	2.80	2.10	1.80
SNC.ADS	3.35	3.30	3.20	2.80	2.10	1.80
SNC.LDS	6.50	5.35	4.60	3.90	3.30	2.85
SNC.WLS	10.00	10.00	10.00	10.00	10.00	10.00
CLY.NDS	4.35	4.30	4.20	3.80	3.10	1.80
CLY.ADS	4.35	4.30	4.20	3.80	3.10	1.80
CLY.LDS	7.00	5.75	5.40	4.60	4.10	3.55
CLY.WLS	10.00	10.00	10.00	10.00	10.00	10.00

Table 4.18 shows the ECiw to ECe conversion factors used in SALMOD. With a leaching fraction of 25% `(LF25)` on loamy sand naturally drained soils `(LMS.NDS)` for example the ECiw to ECe conversion factor of

1.00 indicates that the system is in equilibrium. A conversion factor of 10 is used for waterlogged soils to force the model to reject these soils for crop production, as crops are assumed not to grow in waterlogged soils. Note also that naturally `(NDS)` and artificially `(ADS)` drained soils have the same values.

4.6.5. PARAMETERS

The range over which the leaching fraction intervals (`LFV(LF)`) span in SALMOD can be varied. For this study the values were set in SALMOD ranging from 0 to 0.25 (leaching fraction of 0% to 25%) for `LF0` to `LF25`.

The after-year water overuse fine `(FAY)` tiers are calculated as percentages of the scalar `WC` (water costs) of R0.17 /mm/ha (which equals 1.7c /m^3), to pay extra when more water is required than the irrigation quota allows. If for example a farmer has a water quota for 100 ha at 1 100 mm/ha/yr and requires 130 000 mm in a year, he uses 20 000 mm / 100ha = 200 mm/ha more water than he is entitled to. At the tier interval of 100 mm/ha, his water bill would come to 110 000mm x 17c = R18 700 plus 20 000 mm x 17c = R3 400 for the extra water at the normal rate, plus 10 000 mm x (17c x 50%) = R850 for the first tier of the water fine plus 10 000mm x (17c x 100%) = R1 700 for the second tier of the water fine equalling a total water bill of R24 650, of which the extra water costs R5 950. This is however only true if all the excess water was required in the after-year. If all the extra water was required in the pre-year, the fine would have been 20 000mm x R1.00 = R20 000. SALMOD is constructed that only four tiers of extra water at 100 mm/ha water right are allowed in the after-year `(FAY)` and only one tier in the pre-year `(FPY)`.

Assumption 6: It is assumed in SALMOD that all farmers have access to their full allocated water quota as well as an additional four tiers at 100 mm/ha water right possessed in the after-year `(FAY)` at the block rate tariff and one tier in the pre-year `(FPY)` at the fixed tariff, although in reality the extra water is only available on request and availability from the OVIB.

The parameter `ISMLF(IS)` indicates the maximum leaching fraction that an irrigation system can deliver. Value judgement according to Van Staden (2000) is that a flood irrigation system `(FIS)` has a maximum leaching fraction capacity of 60%, a centre pivot irrigation system `(CIS)`, 20% and a drip irrigation system `(DIS)`, 15%. In the optimisation section of SALMOD, any crop / resource / management combination activity requiring a leaching fraction greater than these and those specified in Table 4.11 is eliminated from entering the optimal solution.

4.7. SALMOD SIMULATION

The data defined in the previous paragraphs list the input data structure and format required to set up SALMOD in GAMS. This section describes the manipulation of the input data that takes place in the simulation section of SALMOD, also programmed in GAMS. The final output from the simulation section of SALMOD to be used in the optimisation section of SALMOD (see Figure 4.1) are a range of gross margins, water usage volumes and leaching fractions required for all crop, soil, drainage status, irrigation system and leaching fraction combinations.

4.7.1. TDS TO EC CONVERSION

The electrical conductivity of the irrigation water (ECiw) is measured in milli-Siemens per meter (mS/m) and is usually a derived value from a total dissolved solids (TDS) reading, measured in milligrams per litre (mg/l) or parts per million (ppm). Using a JENCO model 113 salinity meter (Bruwer, 2000), the OVIB takes TDS readings every 2 weeks throughout the OVIB service area. A calibration fluid is used to calibrate the meter at 0.774gr. The salt concentration results displayed by the meter are in units of ppm (parts per million). Figure 4.2 shows the relationship between EC and TDS using DWAF data. With the intercept forced through zero, EC can be derived from TDS, with a coefficient of determination (R^2) of 97%, by dividing by a factor of 6.425. In Figure 2.2 to Figure 2.5, where TDS and EC readings are taken independently of each other by the DWAF, TDS and EC plotted on different vertical axes display a very close correlation.

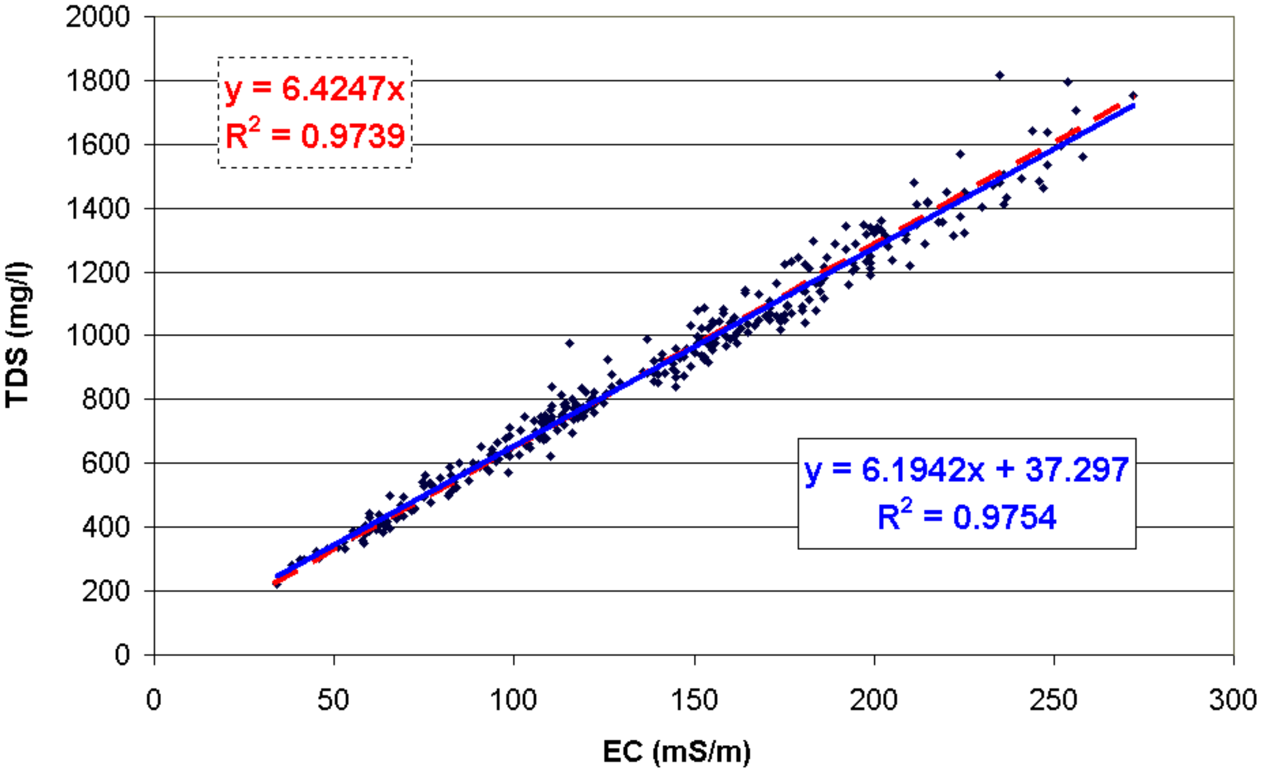


Figure 4.2 The relationship between EC and TDS of irrigation water at Soutpansdrift on the Riet River in the OVIB area, DWAF 1990-1998

4.7.2. IRRIGATION WATER QUALITY TO SOIL WATER QUALITY CONVERSION

Once irrigation water quality has been converted from TDS to ECiw, the electrical conductivity of the saturated soil extract (ECe) needs to be derived to determine the impact on the receiving crop. This leads to Assumption 7, that SALMOD only accounts for the effects of water quality on crop yield through the soil water, and not for the leaf wetting effect of overhead irrigation applications of saline water, scorching the crops leaves.

Assumption 7: It is assumed in SALMOD that farmers manage the leaf scorching effect of sprinkler irrigation on sensitive crops sufficiently so as not to affect crop yield.

Converting ECiw to ECe is done using the factors in Table 4.18. ECe is dependent on the soil type, soil drainage status and the amount that a soil is leached. ECiw to ECe conversion factors are only used in the LF methodology of SALMOD. For the LF methodology the electrical conductivity of the irrigation water (ECiw) first has to be converted to the electrical conductivity of the saturated soil paste (ECe) using the following formula:

$$ECe_{c,s,ds,lf} = A\_EC\_CW_c \,.\, WCF_{s,ds,lf} \tag{4.3}$$

where: $A\_EC\_CW_c$ is the average EC of the crop water, weighted according to monthly volumes demanded at monthly ECiw values for each crop ($_c$) and the dilution effect of rainwater

$WCF_{s,ds,lf}$ is the water conversion factor from ECiw to ECe and is a three dimensional matrix of soil type ($_s$), soil drainage status ($_{ds}$) and leaching fraction($_{lf}$).

This formula is the closest representation to calculate the effect of fluctuating irrigation water quality possible with the limited data available. See Table 4.2 for the derivation of the average seasonal ECe.

4.7.3. WATER USE EFFICIENCIES

Not all water extracted from a water source for the purpose of irrigation is utilised by the crop being irrigated. There are distribution losses in getting the water to the crop, irrigation system losses where irrigation water is applied unevenly and runoff or evaporation occurs, and there is deep percolation losses where water penetrates into the soil till beyond the vadose (root) zone (Van Staden, 2000).

4.7.3.1 Natural leaching factor

An argument against having a zero leaching fraction option in SALMOD is that if no leaching takes place, salt carried by the irrigation water accumulate in the soil and can reach harmful concentrations over time (Du Plessis, 2000). Farmers interviewed in the study region who have been irrigating for over 50 years say they do not actively practise leaching as a management option. If no leaching took place these soils would surely be badly salinised. A certain amount of accidental/natural leaching therefore has to take place. In SALMOD the natural leaching factor is calculated as the sum of the minimum of any excess rainwater over and above the monthly crop irrigation water requirement for each crop and zero divided by the sum of the pre-year and after-year crop water requirement.

Assumption 8: Farmers manage their irrigation scheduling to account for all effective rainfall.

The formula used to calculate the natural leaching factor (NLF) for each crop (C) is:

$$NLF_c = - \sum_t(\min(MC\_IW\_R_{t,c} - (RAIN_t \,.\, LAND_{t,c})),0) \,/\, SUM\_WR_c \tag{4.4}$$

where:

$MC\_IW\_R_{t,c}$ is the monthly (t) crop irrigation water requirement for each crop (c)

$RAIN_t$ is the expected monthly rainfall

$LAND_{t,c}$ is the land use pattern of each of the crops (see Table 4.14)

SUM_WR_c is the sum of the pre-year and the after-year water requirements

4.7.3.2 Effective Rainfall

Table 4.2 shows how effective rainfall is used to contribute towards the determination of the average weighted ECe over a production season with fluctuating irrigation water quality levels, which is used to calculate the expected yield. Effective rainfall is calculated according to Van Heerden, *et al, (*2000) as the monthly rainfall minus 20mm divided by 2. Table 4.2 is discussed in more detail in the beginning of this chapter.

4.7.3.3 Irrigation system efficiency and leaching fraction capacity

The amount of drainage resulting from irrigation is a factor of the soils water holding capacity or infiltrability (De Wet, 2000). Furthermore 65%, 75% and 85% efficiencies for flood, sprinkler and drip irrigation systems respectively are norms for, from withdrawal till reaching the soil surface. These are the figures that the irrigation engineers work with.

Furthermore, there is also the irrigation systems maximum leaching capacity. This is important to include in SALMOD as a constraint so that the leaching fractions calculated for the soil are not too high for the water delivery capacity of the irrigation system. The irrigation system maximum leaching fraction value judgement values (`Parameter ISMLF(IS)`) used in SALMOD are 60% for flood irrigation systems (`FIS`), 20% for centre pivot and sprinkler irrigation systems (`CPI`) and 15% for drip irrigation systems (`DIS`).

4.7.3.4 Plant uptake from the soil efficiency

For plant water uptake efficiency losses, i.e. losses from between delivery to the soil surface till the water is actually absorbed by the plant, De Wet (2000) uses the following value judgements: 10%, 5% and 1% for flood, sprinkler and drip irrigation systems respectively. This corresponds with the 90%, 95% and 99% values in used in SALMOD in table `IR_EF(C,IS)` to indicate the crop/irrigation system soil water use efficiency.

4.7.4. FINANCIAL CALCULATIONS

The financial calculations performed in SALMOD are all for a fixed period in time and are based on 1998 prices. The main groups of financial calculations that get performed in the simulation section of SALMOD are the setting up of a range of condensed CEBs based on the CEBs entered in Table 4.12 for the calculation of the gross margin above specified costs (GMASC) to be used in the optimisation section, and the amortisation of long term costs.

4.7.4.1 Crop enterprise budgets setup

The yield in tons and the crop price and harvesting costs in R/ton are transferred directly from the farmer CEBs entered in Table 4.12 into the condensed CEBs set up in SALMOD called `CCDAT(COSTDAT,C,SR)`. The other input cost coefficients, excluding fuel and maintenance cost, and water and pumping costs, are grouped together as fixed variable costs (FVC) for use in SALMOD as they are not affected by yield and irrigation water volumes.

Fuel and lubrication ($FUEL$), and maintenance ($MAINT$) costs are recalculated in SALMOD to be a function of the crop kilowatt-hour requirements ($KWHR$) entered in Table 4.12.

$$FUEL = (KWHR . LPKWH . FP) + (KWHR . LPKWH . FP . FLR) \tag{4.5}$$

This kilowatt-hour requirement ($KWHR$) multiplied by the litres per kilowatt-hour scalar ($LPKWH$) of 0.35, multiplied by the fuel price (FP) gives the total fuel costs for each crop. This fuel cost multiplied by the fuel to lubrication cost ratio (FLR) of 0.01 to include lubrication costs, gives the fuel and lubrication cost.

$$MAINT = KWHR . LPKWH . FP . FMR \tag{4.6}$$

Maintainance costs ($MAINT$) are calculated by multiplying the fuel price discussed for equation 4.5 by the fuel to maintenance cost ration (FMR) of 0.05.

$$\begin{aligned} FVC = &(PL + FUEL + MAINT) \\ &+ ((PL + FUEL + MAINT)* PCI . (PCLT/12)) \end{aligned} \tag{4.7}$$

The interest component of the variable costs is calculated in the second line of equation 4.7 for the sum of element coefficients of sub-set PL (production loan), fuel ($FUEL$) and maintenance ($MAINT$) costs, using the production capital loan term parameter values ($PCLT$) for each crop (`c`) and the production capital interest rate (PCI).

4.7.4.2 Long-term cost amortisation

An amortisation factor is a factor used to determine the annual repayments of a loan over a given number of years at a fixed interest rate. An amortisation factor is calculated as follows:

$$AF = (LTI.(1+LTI)^{LTT}) / (1+LTI)^{LTT} -1 \tag{4.8}$$

Where:

LTI is the fixed long-term interest rate (%/yr)

LTT is the long-term loan term (yrs)

The annualised costs of installing artificial drainage (ADC) and building an on-farm storage dam ($AOFSC$) are determined by multiplying the total cost by the amortisation factor described in equation 4.8, for example:

$$ADC \text{ or } AOFSC = ADTC \text{ or } COFSD . AF \tag{4.9}$$

Where:

ADC is the annualised drainage costs (R/yr). This value is worked out for all soil types of set S.

$AOFSC$ is the annualised on-farm storage costs (R/yr)

$ADTC$ is the artificial drainage total costs (R)

$COFSD$ is the cost of an on-farm storage dam as specified in scalars Table 4.7 (R)

Calculating the annual costs of replacing an irrigation system however is not as simple because parts of the old system can be used. Depending on the change, there is usually a salvage value for the old system and annual maintenance costs also need to be taken into account. When looking at three irrigation systems, there are 6 options for change: ***ATCFC, ATCFD, ATCCD, ATCCF, ATCDC, ATCDF,*** where ***ATCFC*** for instance is the annualised transfer costs from flood to centre pivot irrigation.

The formula used in calculating the ***ATCFC*** is for example:

$$ATCFC = (TSC_{cpi} - (TSC_{fis} . SALV_{fis})).AF + MAINT_{cpi} \tag{4.10}$$

Where:

TSC_{cpi} is the total system costs of a centre pivot irrigation system (R)

TSC_{fis} is the total system costs of a flood irrigation system (R)

$SALV_{fis}$ is the salvage value factor of a flood irrigation system (R)

$MAINT_{cpi}$ is the maintenance cost of a centre pivot irrigation system (R/yr)

All these costs come from Table 4.13, `STC(IS,*);` irrigation system transfer cost.

4.8. THE FIXED INTERVAL LEACHING FRACTION (LF) EQUATION

The LF formula determines the relative yield (***RY***) percentage of maximum physiological yield over a fixed range of leaching fractions. The ***RY*** for each crop ($_c$) is a function of the soil type, drainage status of the soil and leaching fraction implemented. The matrix of ECe values is then used in the LF methodology as follows:

$$RY_{c,s,ds,lf} = ((100 - GRAD_c)*(ECe_{c,s,ds,lf} - TRSH_c))/100 \tag{4.11}$$

where:

$TRSH_c$ is the ECe limit for each crop ($_c$) at which no crop yield reductions will be observed if water quality deteriorates as determined by Maas & Hoffman (1977). The threshold ECe value in Figure 4.3 is where the crop function first deviates from 100% relative yield percentage. For maize for example, it is just over 300mS/m.

$GRAD_c$ is the gradient for each crop ($_c$), after the threshold has been reached, at which yield declines as ECe deteriorates (determined by Maas & Hoffman, 1977). The gradient is the slope of the crop function depicted in Figure 4.3. The gradient for groundnuts (`GRNDNUT`) has the steepest slope and cotton the flattest.

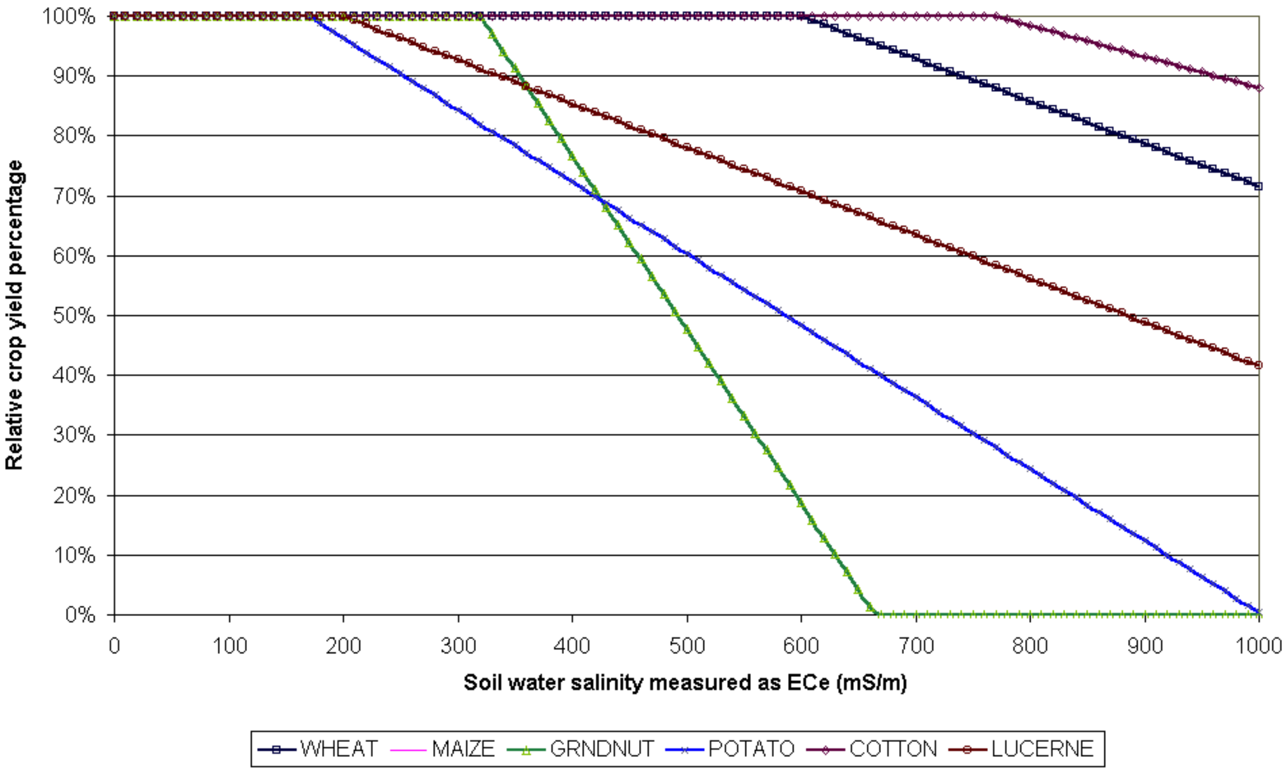


Figure 4.3 A figure depicting the threshold (mS/m) and gradient (%/mS/ha) of the six crops modelled in SALMOD, as determined by Maas and Hoffman (1977) (NOTE: Maize and potato have the same threshold and gradient values)

4.8.1. WATER USAGE AND LEACHING VOLUMES

In SALMOD a distinction is made between the plant water requirement and the irrigation water requirement. Both the plant water requirement and the irrigation water requirement are greater than the physiologically optimal plant water needs because of efficiency losses in getting the water to the plants' roots as discussed under section 4.7.3. The equation to determine the total pre-year plant water requirements ($PPWRl_{c,lf}$) in mm/ha for all crops ($_c$) and leaching fractions ($_{lf}$), is calculated as follows:

$$PPWRl_{c,lf} = SPYIWR_c / (1 - LFV_{lf}) \qquad \textbf{(4.12)}$$

where:

LFV_{lf} are the predetermined fixed leaching fraction values

The pre-year irrigation water requirement ($PIWR_{c,is}$) is the volume of water that needs to be applied to ensure the crop receives the physiologically optimal volume of water. It is no longer a function of the leaching ability of the soil as indicated in the previous two equations, but of the crop ($_c$) and irrigation system ($_{is}$), and is calculated as follows:

$$PIWR_{c,is} = SPYIWR_c \,/\, IR\_EF_{c,is} \tag{4.13}$$

where:

$IR\_EF_{c,is}$ are the irrigation system plant water use efficiencies as defined in paragraph 4.3.2.5.

The after-year irrigation water requirement ($AIWR_{c,is}$) for crop (c) using irrigation system (is), is calculated the same as in Equation 4.13.

The following formula to determine the pre-year irrigation demand ($PIDl_{c,s,ds,is,lf}$) for the leaching fraction methodology (lf) for all crops (c), on soils (s), with different drainage status (ds), using irrigation system (is) and for leaching fraction (lf), chooses the maximum of the pre-year irrigation water requirement ($PIWR_{c,is}$) or the pre-year plant water requirement ($PPWRl_{c,lf}$) to transfer to the optimisation section of SALMOD:

$$PIDl_{c,s,ds,is,lf} = MAX\ (PIWR_{c,is}\ ,\ PPWRl_{c,lf}) \tag{4.14}$$

The after-year irrigation demand ($AIDl$) is calculated in the same way as equation 4.14.

The pre-year water loss ($PWLl$) is the difference between the actual volume of water applied in the pre-year to the crop and the volume effectively utilised by the crop. This is the value that provides an indication of how much water leaches from a field. The pre-year water losses are calculated as the maximum difference between either the irrigation water requirement ($PIWR$) and the plant water requirement ($PPWR$), or the plant water requirement ($PPWR$) and the optimal physiological water requirements ($SPYIWR$).

$$PWLl_{c,s,ds,is,lf} = MAX\ (\ (PIWR_{C,IS} - PPWRl_{C,LF})\ ,\ (PPWRl_{C,LF} - SPYIWR_C)\ ) \tag{4.15}$$

The after-year irrigation water loss ($AWLl$) is calculated in the same way as equation in 4.15.

Once $PIDl$ and $AIDl$ have been assigned the highest values from either plant or irrigation water requirements, the leaching fraction requirements ($LFRl$) are calculated as the sum of the pre- and aft- year water loss divided by the sum of the pre- and aft- year irrigation demands as in the formula for the leaching fraction methodology:

$$LFRl_{c,s,ds,is,lf} = (\ PWLl_{c,s,ds,is,lf} + AWLl_{c,s,ds,is,lf}\ )\ /\ (\ PIDl_{c,s,ds,is,lf} + AIDl_{c,s,ds,is,lf}\ ) \tag{4.16}$$

It might seem erroneous that a leaching fraction requirement be calculated for a methodology using predetermined fixed leaching rates. However, with irrigation system and plant water inefficiencies, a fraction more water can be leached than expected when applying a fixed leaching rate. This actual leaching rate that results from applying a specific leaching fraction is what is used in calculating irrigation returnflows and in eliminating cropping combinations in the optimisation section which require a larger leaching requirement than either the irrigation system can deliver or can infiltrate the soil.

The final data required from the SALMOD simulation section for the optimisation section is the water and electricity costs associated with the pre- and aft- year irrigation demand. The pre-year water and electricity costs ($PWEC_{c,s,ds,is,lf}$) for example are calculated as follows:

$$PWEC_{c,s,ds,is,lf} = PID_{c,s,ds,is,lf} \;.\; (WC + PC) \tag{4.17}$$

where:

WC is the water costs (R/mm) from Table 4.9 for a specific sub-area, and

PC is the water pumping costs (R/mm) from Table 4.9 for a specific sub-area

4.9. GROSS MARGIN

The final step of the simulation section is the setting up of the range of crop/resource combination gross margins above specified costs ($GMASC_{c,s,ds,lf}$) to be transferred as the decision variable coefficients (GM_i) into the optimisation section of SALMOD.

$$GMASC_{c,s,ds,lf} = PRICE_c \;.\; MEY_c \;.\; RY_{c,s,ds,lf} - FVC_c - HC_c \;.\; RY_{c,s,ds,lf} \tag{4.18}$$

Where: $PRICE_c$ is a vector of selling prices for each crop ($_c$)

MEY_c is a vector of the maximum expected yield of each crop ($_c$)

FVC_c is a vector of the variable per hectare costs for each crop ($_c$) excluding the water tariff and pumping costs

HC_c is a vector of the per ton harvesting costs of each crop ($_c$) dependent on the calculated relative yield (RY)

As can be seen in Equation 4.18 the specified costs only include the fixed variable costs (FVC) and harvesting costs. The FVC used in the calculation of the GMASCs include fuel and maintenance costs. Water and pumping costs are calculated separately and also used in the optimisation section of the model, and are only brought together with the specified crop enterprise costs in the calculation of maximum farm level net revenue, the objective of the optimisation section.

4.10. MATHEMATICAL FORMULATION FOR LINEAR PROGRAMMING (LP)

The structure of a linear programming problem in its most basic form is as follows:

Maximize
$$\pi = \sum^{n}_{i=1} GM_i \,.\, X_i \tag{4.19}$$

Subject to
$$\sum^{n}_{i=1} A_{ij} \,.\, X_i \;\geq \,,\; \leq \; or \; = \; R_j \qquad (i = 1, 2, \ldots , n) \tag{4.20}$$

and $$X_i \geq 0 \qquad (j = 1, 2, \dots, m) \qquad \mathbf{(4.21)}$$

where: π is profit

GM_i is the per hectare gross margin of variable i

X_i is the level of activity i (i = 1 to n)

A_{ij} is the matrix of coefficients linking variable i to constraint j

R_j is the values of constraint j

The objective function (4.19) is to maximise profit (π) by choosing the optimal level of X from the range of choice variables X_i $(i = 1 \text{ to } n)$ multiplied by the objective function coefficients, GM_i $(i = 1 \text{ to } n)$ which is a set of constants. In SALMOD these constants are calculated in the simulation section of the model. In equation 4.20 the technical coefficient (A_{ij}) and constraints (R_j) are specified. The levels of these constraints, R_j are also constants. The coefficients of the choice variables (X_i) in the constraint are denoted by A_{ij}. Since there are m constraints in n variables, the coefficients A_{ij} form a rectangular matrix with an m x n dimension. Equation 4.21 is the non-negativity constraint of the choice variables. The variables used in SALMOD are described in Table 4.19 that lists the variable names followed by the set dimensions in brackets.

SET	***ACTIVITY***	***TOTAL***
	6 Crop types	
C	WHEAT, MAIZE, GROUNDNUT, POTATO, COTTON, LUCERNE	**6**
	↓	
S	**4 Soil Types**	**x**
	LMS, SLM, SNC, CLY	**4**
	↓	
DC	**4 Soil drainage classes**	**X**
	NDS, ADS, LDS, WLS	**4**
	↓	
IS	**3 Irrigation System Types**	**X**
	FIS, CPI, DIS	**3**
	↓	
LF	**6 Leaching Fractions**	**X**
	LF0 to LF25	**6**
		= 1728

Figure 4.4 A flow diagram showing the dimensions of ACTIVITY, the main choice variable of SALMOD

Figure 4.4 shows the magnitude of the main choice variable in SALMOD. Variable $\text{ACTIVITY}_{\text{C,S,DC,IS,LF}}$. generates 1728 possibilities from which an optimal combination has to be chosen. The leaching fraction intervals of 5% for the leaching fraction methodology can be changed in SALMOD if a finer range is required. Only the leaching fraction methodology will be discussed in this chapter.

Based on the matrix version of the mathematical equations 4.19 to 4.21, Table 4.20 shows a schematic representation (as determined by GAMSCHK, McCarl, 1998) of SALMOD without fixed capital management options.

Table 4.19 The variables used for the SALMOD optimisation section

VARIABLE NAME (SETS)	***DESCRIPTION***
NR[*]	Net Revenue
ACTIVITY(C,S,DS,IS,LF)	Ha of crop C to grow on S, DS, IS and LF (ha)
FINES(F)	Water overuse fines charged at step interval F (mm)
TRANS_P2A	Pre-Year water not used transferred to After-year
NPSD	Non-Point Source Discharge counter (mm)
OFS[**]	On-farm Storage management option (dams)
TRANS_W2L(S,IS)	Soil Transfer - WL to limited drained soils (ha)
TRANS_W2A(S,IS)	Soil Transfer - WL to artificially drained soils (ha)
TRANS_L2A(S,IS)	Soil Transfer - Limited artificially drained soils
TRANS_F2C(S,DS)	Irrigation system transfer. Flood to Centre Pivot (ha)
TRANS_F2D(S,DS)	Irrigation system transfer. Flood to a Drip System (ha)
TRANS_C2F(S,DS)	Irrigation system transfer. Centre Pivot to Flood (ha)
TRANS_C2D(S,DS)	Irrigation system transfer. Centre Pivot to a Drip (ha)
TRANS_D2F(S,DS)	Irrigation system transfer. Drip to Centre Pivot (ha)
TRANS_D2C(S,DS)	Irrigation system transfer. Drip to Flood (ha)

[*] NR is the only Free Variable (i.e. can be +or-). The rest are positive variables.

Table 4.20 A schematic representation of the structure of the optimisation (LP) section of the SALMOD without management options with constraint description

		VARIABLES								CONSTRAINT DESCRIPTION
		NR	**Y**	**P2A**	**X**	**NPSD**	**OFS**	**Sign**	**RHS**	***NR***=*TGMASC(**π**)*, ***Y***=*Water Fines Decision variable*, ***P2A***=*Water transfer, pre-year to after-year*, ***X***=*cropping decision variables*, ***NPSD***=*Non-point source discharge counter*, ***OFS***=*On-farm storage*, ***RHS***=*Right hand side (**R_j**)*
	OBJN	**+**	**+**		**m**		**+**	**=**	**0**	**Objective Function**
CONSTRAINTS	LAND_BAL				+			<=	+	Land Balance
	ROTATION$_T$				+			<=	+	To check only 1 crop planted per ha at any time
	PotCons				+			<=	+	Max potato Constraint
	PotDS				+			=	0	Plant potatoes only on well drained soils
	PotIS				+			=	0	No Potatoes under flood Irrigation Systems
	WhtMax				+			<=	+	Max. ha of wheat that can be planted
	GNMax$_{GN}$				+			<=	+	Max. ha of groundnuts that can be planted
	GnSand$_{GN}$				+			<=	0	Plant groundnuts only on loamy sand soils
	GnDS$_{GN}$				+			<=	0	Plant groundnuts only on well drained soils
	DRIP_CONS				+			=	0	Limits crops not grown under drip irrigation
	MAX_QUOTA		–		+			<=	+	Maximum water quota constraint
	PY_QUOTA		–	+	+			<=	+	Maximum pre-year withdrawals
	AY_QUOTA		–	–	+			<=	+	Maximum after-year withdrawals
	RFC				–	+	+	=	0	Irrigation Returnflows Counter
	MRF				+		–	<=	+	Maximum Returnflows allowed constrainer
	SDC$_{C,S,DS,IS,lf}$				m			<=	0	Soil Drainage Constraint
	PCC		+		+		+	<=	+	Production Capital Constraint
	FCLC						+	<=	+	Fixed Capital Loan Constraint
Variable Type:		***u***	***+***	***+***	***+***	***+***	***+***			*m = mixed values (+&-), u = free variable (+ or -)*

4.10.1. THE OBJECTIVE FUNCTION

For the purpose of this study some abbreviations and simplifications have been used when converting the formulas discussed from GAMS coding into mathematical format. Table 4.21 gives a guide to these changes and provides a description for the mathematical notation symbols.

Table 4.21 A key used in converting GAMS coding into mathematical notation or *vice versa*

GAMS coding	Mathematical notation	Comment
(sum(	$\sum$	Summation symbol used
*	.	Multiplication symbol used
NR	***TGMASC***	The objective function is to maximise NR/TGMASC
ACTIVITY	***X***	Cropping combination activity decision variable
GMASC	***GM***	Coefficient of decision variable X
FINES	***Y***	Fine volume decision variable
CSFD(SR,"PC")	***PC***	Pumping Costs varied for case study farmers
CSFD(SR,"WC")	***WC***	Water Costs constant for all case study farmers
(C,S,DS,IS,LF)	$_{c,s,ds,is,lf}$	Cropping combination activity identifiers
(FAY)	$_{a}$	After-year fine interval identifier
(FPY)	$_{p}$	Pre-year fine interval identifier
(S,IS)	$_{s,is}$	Soil type / irrigation system identifiers
(S,DS)	$_{s,ds}$	Soil type / drainage status identifiers
(S)	$_{s}$	Soil type identifier
wlds	$_{wlds}$	Waterlogged drainage status – subset of set DS
dti	$_{dti}$	Drip type irrigation – subset of set IS
fti	$_{fti}$	Flood type irrigation – subset of set IS
gn	$_{gn}$	Groundnuts – subset of set C
luc	$_{luc}$	Lucerne – subset of set C
pot	$_{pot}$	Potatoes – subset of set C
wht	$_{wht}$	Wheat – subset of set C
Npds	$_{npds}$	Non-potatoes drainage status – subset of set DS
Nlms	$_{nlms}$	Not loamy sand – subset of set S
Nodrip	$_{nodrip}$	Not drip irrigable – subset of set C
tsc	$_{tsc}$	Total irrig. system costs from table ISTC(IS,*)

The objective function is:

$$
\begin{aligned}
&\mathbf{Max\ TGMASC} = \\
&\quad \textstyle\sum_{c,s,ds,is,lf} GM_{c,s,ds,is,lf} \,.\, X_{c,s,ds,is,lf} \;- \\
&\quad \textstyle\sum_{c,s,ds,is,lf} PID_{c,s,ds,is,lf} \,.\, X_{c,s,ds,is,lf} \,.\, (WC + PC) \;- \\
&\quad \textstyle\sum_{c,s,ds,is,lf} AID_{c,s,ds,is,lf} \,.\, X_{c,s,ds,is,lf} \,.\, (WC + PC) \;- \\
&\quad \textstyle\sum_{p} Y_p \,.\, FRPY_p - \sum_{p} Y_p \,.\, PC \;- \\
&\quad \textstyle\sum_{a} (WC+(FRAY_a . WC)) \,.\, Y_a - \sum_{a} Y_a \,.\, PC \;- \\
&\quad \textstyle\sum_{s,i} W2L_{s,i} \,.\, WSDC_s - \sum_{s,i} L2A_{s,i} \,.\, (ADC_s - WSDC_s) - \sum_{s,i} W2A_{s,i} \,.ADC_s \;- \\
&\quad \textstyle\sum_{s,d} F2C_{s,d} \,.\, ATCFC - \sum_{s,d} F2D_{s,d} \,.\, ATCFD - \sum_{s,d} C2F_{s,d} \,.\, ATCCF \;- \\
&\quad \textstyle\sum_{s,d} C2D_{s,d} \,.\, ATCCD - \sum_{s,d} D2F_{s,d} \,.\, ATCDF - \sum_{s,d} D2C_{s,d} \,.\, ATCDC \;- \\
&\quad (OFS \,.\, AOFSC)
\end{aligned}
\tag{4.22}
$$

The objective function of SALMOD is to maximise the total gross margin above specified costs (***TGMASC***).

This TGMASC is calculated as in equation 4.22 as:

~ the sum of the gross margin (***GM***) above specified costs for each individual crop, soil, drainage status, irrigation system and leaching fraction (***c,s,ds,is,lf***) option multiplied by the decision variable ***X*** (which is the number of ha) for each ***c,s,ds,is,lf*** option.

~ minus the pre-year water and pumping costs calculated as the sum of the pre-year irrigation demand (***PID***) for all ***c,s,ds,is,lf*** options multiplied by the decision variable ***X*** (ha) for each ***c,s,ds,is,lf*** option and the constant water cost (***WC***) and pumping cost (***PC***).

~ minus the after-year water and pumping costs calculated as the sum of the after-year irrigation demand (***AID***) for all ***c,s,ds,is,lf*** options multiplied by the decision variable ***X*** (ha) for each *c,s,ds,is,lf* option and the constant water cost (***WC***) and pumping cost (***PC***).

~ minus the pre-year costs of water used exceeding the irrigation quota and its pumping costs, calculated as the sum of the decision variable ***Y*** (which is the number of mm/ha) multiplied by the fixed rate fine for water overuse in the pre-year (***FRPY***) and also minus the sum of ***Y*** (mm/ha) multiplied by the pumping costs (***PC***) of the water.

~ minus the after-year costs of water used exceeding the irrigation quota and its pumping costs, calculated as the sum of the decision variable ***Y*** (mm/ha) for the range of fine intervals for the after-year multiplied by the stepped percentage of the water cost (***WC***) fine for water overuse in the after-year (***FRAY***) and also minus the sum of ***Y*** (mm/ha) multiplied by the pumping costs (***PC***) of the water. The quota includes excess unused water from the pre-year quota transferred to the after-year.

~ minus the sum of each of the range of artificial drainage installation options.

> The cost of artificial drainage to convert from waterlogged soils to limited drainage soils (***W2L***) is calculated by multiplying the sum of all hectares converted from waterlogged to limited drainage soils for the range of soil types and irrigation systems (***s,is***) by the annualised waterlogged soils drainage costs (***WSDC***) for all soil types (***s***). The ***WSDC*** is determined as a factor (***WLSDF*** which = 10%, see scalars) of ***ADC.***
>
> The cost of artificial drainage to convert from limited drainage soils to fully drained artificially drained soils (***L2A***) is calculated by multiplying the sum of all hectares converted from limited drainage soils to fully drained artificially drained soils for the range of soil types and irrigation systems (***s,is***), by the annualised drainage costs (***ADC***) for all soil types (***s***) minus the waterlogged soils drainage costs (***WSDC***) for all soil types (***s***).
>
> The cost of artificial drainage to convert from waterlogged soils to fully drained artificially drained soils (***W2A***) is calculated by multiplying the sum of all hectares converted from waterlogged soils to fully drained artificially drained soils for the range of soil types and irrigation systems (***s,is***) by the annualised drainage costs (***ADC***) for all soil types (***s***).

- ~ minus the sum of each of the range of the irrigation system transfer options (***_2_***) for the range of soil types and drainage classes (***s,ds***) multiplied by the annualised transfer costs (***ATC _ _***) for the specific system transfer combination. Taking the first option for example, the number of hectares converted from flood to centre pivot (***F2C***) over range of soil types and drainage classes (***s,ds***) is multiplied by the annualised transfer costs of converting from a flood to a centre pivot irrigation system (***ATCFC***). The abbreviations used in the formula are as follows: ***F*** for flood, ***C*** for centre pivot and ***D*** for drip irrigation systems.
- ~ minus the non-integer number of on-farm storage dams of a predetermined size to construct (***OFS***) multiplied by the annualised on-farm storage dam costs (***AOFSC***).

4.10.2. MODEL CONSTRAINTS

Maximising the objective function is subject to various constraints. Each of the equation names in Table 4.20 and Table 4.22 is the name of a mathematical equation of a model constraint. In the discussion to follow these equations will be grouped under the following categories: land, crop, water and financial constraints.

Table 4.22 A description of the fixed capital management equations used in SALMOD, 2000

Equation (set)	*Description*
SIDBal***WF***(S,IS,DS)	Soil, irrigation and drainage status balance on waterlogged soils (W) that are flood irrigated (F).
WC,WD,LF,LC,LD,AF	W=Waterlogged, L=Limited, A=Artificial & N=Natural drainage
AC,AD,NF,NC,ND	C=Centre pivot, F=Flood & D=Drip irrigation systems
DST***_WF***(S,IS,DS)	Drainage status transfer on waterlogged soils (W) that are flood irrigated (F).
WC,WD,LF,LC,LD,AF	W=Waterlogged, L=Limited, A=Artificial & N=Natural drainage
AC,AD,NF,NC,ND	C=Centre pivot, F=Flood & D=Drip irrigation systems
IST***_WF***(S,IS,DS)	Irrigation system transfer on waterlogged soils (W) that are flood irrigated (F).
WC,WD,LF,LC,LD,AF	W=Waterlogged, L=Limited, A=Artificial & N=Natural drainage
AC,AD,NF,NC,ND	C=Centre pivot, F=Flood & D=Drip irrigation systems

An advantage of using GAMS above most other LP packages is that the right hand side (RHS) of the constraint equation doesn't have to be a single value; it can be a mathematical formula. This makes formulating and reading the formula easier, eliminating errors made when transferring the formula body to the left hand side of the equation. GAMS automatically does this and the formula transformation can be viewed in the .LST file generated when a GAMS problem is run.

4.10.2.1 Land constraints

$$LAND\_BAL \qquad \sum_{c,s,ds,is,lf} X_{c,s,ds,is,lf} \leq IA\ .\ 2 \qquad \textbf{(4.23)}$$

The land balance equation (***LAND_BAL***) is to ensure that the sum of hectares of all the crops calculated for inclusion in the optimal solution does not exceed the irrigated area (IA) multiplied by two. The irrigated area is multiplied by two because there are generally two crops grown per season (i.e. double cropping). This equation becomes redundant with the inclusion of the crop rotation equation ($ROTATION_t$), but is useful as the shadow price of ***LAND_BAL*** indicates the shadow value of irrigable land.

$$\begin{aligned} SIDBalWF_{s,fti,wlds} \quad & \textstyle\sum_{c,lf} \; X_{c,s,wlds,fti,lf} + W2L_{s,fti} + W2A_{s,fti} \\ & + F2C_{s,wlds} + F2D_{s,wlds} - C2F_{s,wlds} - D2F_{s,wlds} \;\leq\; SOIL\_DATA_{s,fti,wlds} \qquad \textbf{(4.24)} \end{aligned}$$

Equation 4.24 represents the first of the range of soil, irrigation and drainage status balance equations (***SIDBal_*** _). The equation is repeated for ***WC, WD, LF, LC, LD, AF, AC, AD, NF, NC*** and ***NF*** in the place of ***WF***. The first letters in these terms; ***W, L, A*** and ***N*** represent the soil drainage statuses; Waterlogged, Limited drainage, Artificially drained and Naturally drained respectively. The second letters in these terms; ***F, C*** and ***D*** represent the irrigation system type, namely; Flood, Centre pivot, and Drip respectively. This lettering is applicable to Equations 4.25 and 4.26 as well.

$$\begin{aligned} DST\_WF_{s,fti,wlds} \quad & \textstyle\sum_{c,lf} \; X_{c,s,wlds,fti,lf} + W2L_{s,fti} + W2A_{s,fti} \\ & + F2C_{s,wlds} + F2D_{s,wlds} - C2F_{s,wlds} - D2F_{s,wlds} \;\leq\; SOIL\_DATA_{s,fti,wlds} \qquad \textbf{(4.25)} \end{aligned}$$

Equation 4.25 represents the first of the range of soil drainage status transfer equations. Equation 4.25 specifically is for transferring the soils drainage status from waterlogged to limited drainage on flood-irrigated fields.

$$\begin{aligned} IST\_WF_{s,fti,wlds} \quad & \textstyle\sum_{c,lf} \; X_{c,s,wlds,fti,lf} + W2L_{s,fti} + W2A_{s,fti} \\ & + F2C_{s,wlds} + F2D_{s,wlds} - C2F_{s,wlds} - D2F_{s,wlds} \leq SOIL\_DATA_{s,fti,wlds} \qquad \textbf{(4.26)} \end{aligned}$$

Equation 4.26 represents the first of the range of irrigation system transfer equations for all soil drainage status types. Equation 4.26 is the column for adding to and subtracting from the current hectareage on waterlogged soils under flood irrigation, to maintain the correct irrigation system balance on all soil drainage status types.

4.10.2.2 Crop constraints

$$ROTATION_t \qquad \textstyle\sum_{c,s,ds,is,lf} \; X_{c,s,ds,is,lf} \; . \; LAND_{t,c} \qquad \leq IA \qquad \textbf{(4.27)}$$

The crop rotation constraint ($ROTATION_t$) makes sure that in any one month ($_t$), the total area in ha planted to all crops does not exceed the total irrigable area (IA).

$$\begin{aligned} PotCons \qquad & \textstyle\sum_{pot,s,ds,is,lf} \; X_{pot,s,ds,is,lf} \leq MAXPOT \; . \; \sum_{s,is,ds} \\ & SOIL\_DATA_{s,is,ds} - \textstyle\sum_{s,is,npds} SOIL\_DATA_{s,is,npds} + \sum_{s,is} \; L2A_{s,is} \\ & + W2A_{s,is} + \textstyle\sum_{s,ds} F2C_{s,ds} + F2D_{s,ds} \; - \; \sum_{s,ds} \; C2F_{s,ds} \; - \; D2F_{s,ds} \qquad \textbf{(4.28)} \end{aligned}$$

$$PotDS \qquad \sum_{pot,s,npds,is,lf} X_{pot,s,npds,is,lf} = 0 \qquad (4.29)$$

$$PotIS \qquad \sum_{pot,s,ds,fti,lf} X_{pot,s,ds,fti,lf} = 0 \qquad (4.30)$$

Equations 4.28 to 4.30 are to limit the total hectares planted to potatoes ($\sum_{pot,s,ds,fti,lf} X_{pot,s,ds,fti,lf}$) on soils suitable for growing potatoes to the adjustable percentage fraction ***MAXPOT***. Equation 4.29, the soil drainage status constraint for potatoes (***PotDS***) prohibits potatoes from being planted on soils with a drainage status not suitable for potatoes ($_{npds}$) and equation 4.30 prevents potatoes from being planted under flood irrigation.

$$WhtMax \qquad \sum_{wht,s,ds,is,lf} X_{wht,s,ds,is,lf} \leq IR \qquad (4.31)$$

Equation 4.31 is a constraint on wheat – it limits the number of hectares allocated for wheat production in the optimal solution to the area of irrigable land available (***IR***).

$$GnSand_{gn} \qquad \sum_{notlms,ds,is,lf} X_{gn,notlms,ds,is,lf} \leq 0 \qquad (4.32)$$

$$GnDS_{gn} \qquad \sum_{s,npds,is,lf} X_{gn,s,npds,is,lf} \leq 0 \qquad (4.33)$$

$$GnMax_{gn} \qquad \sum_{s,ds,is,lf} X_{gn,s,ds,is,lf} \leq IR \, . \, MAXGN \qquad (4.34)$$

Equations 4.32 to 4.34 are used to limit the area planted to Groundnuts ($GnMax_{gn}$) and to prevent groundnuts from being planted on unsuitable soils ($GnSand_{gn}$) i.e. soils that are not loamy sand soils ($_{notlms}$) and from planting groundnuts on soils with insufficient drainage ($_{npds}$) i.e. either soils that are waterlogged or that have limited drainage.

$$MinLuc\_WF_{s,fti,wlds} \qquad \sum_{luc,lf} X_{luc,s,wlds,fti,lf} + W2L_{s,fti} + W2A_{s,fti} + F2C_{s,wlds} + F2D_{s,wlds} - C2F_{s,wlds} - D2F_{s,wlds} \geq SOIL\_DATA_{s,fti,wlds} . LUCMIN_{s,fti,wlds} \qquad (4.35)$$

Equation 4.35 was not included in the SALMOD model run of which the results are discussed in this document, but the formula is explained in case it needs to be used. Equation $MinLuc\_WF_{s,fti,wlds}$ is the first in a range of equations that put (force) a minimum value on the hectares to be planted to lucerne. The range includes a separate equation for each irrigation system and soil drainage status used. The sum of all hectares planted to lucerne ($_{luc}$) for a specific irrigation system and soil drainage status ($\sum_{luc,lf} X_{luc,s,wlds,fti,lf}$) plus all hectares converted to, and minus all hectares converted from, the specific drainage status' and irrigation systems, must be greater than the actual amount of that specific soil drainage status under the specific irrigation system ($SOIL\_DATA_{s,fti,wlds}$) multiplied by the minimum area of lucerne to plant factor ($LUCMIN_{s,fti,wlds}$).

$$DRIP\_CONS \qquad \sum_{nodrip,s,ds,dti,lf} X_{nodrip,s,ds,dti,lf} = 0 \tag{4.36}$$

The drip irrigation system constraint ***DRIP_CONS*** is used in SALMOD to prevent crops that cannot be grown on a commercial scale under drip irrigation ($_{nodrip}$) from being selected in the model.

4.10.2.3 Water constraints

$$PYFineInt_{fpy} \qquad FINES_{fpy} \leq WFI \,.\, IR \tag{4.37}$$

$$AYFineInt_{fay} \qquad FINES_{fay} \leq WFI \,.\, IR \tag{4.38}$$

Equations 4.37 and 4.38 are not used in GAMS because in GAMS the upper bounds (***UP***) on the fine intervals (***F***) are set using the following coding: ***FINES.UP(F) = WFI . IR*** where ***WFI*** is a scalar for the water fine interval, set at 100 mm/ha per annum and ***IR*** the irrigation rights also in mm/ha per annum allocated to the farmer.

$$MAX\_QUOTA \qquad \sum_{c,s,ds,is,lf} PID_{c,s,ds,is,lf} \,.\, X_{c,s,ds,is,lf} + \sum_{c,s,ds,is,lf} AID_{c,s,ds,is,lf} \; X_{c,s,ds,is,lf} - \sum_{fpy} FINES_{fpy} - \sum_{fay} FINES_{fay} \leq IR \,.\, IQ \tag{4.39}$$

The maximum quota (***MAX_QUOTA***) constraint (equation 4.39) is put into SALMOD to prevent water use (which is the sum of the pre- and after-year irrigation water demand {***PID and AID***} and fines {$FINES_{fpy\&fay}$}) from exceeding the irrigation rights (***IR***) in hectares multiplied by the irrigation quota (***IQ***) in mm/ha

$$PY\_QUOTA \qquad \sum_{c,s,ds,is,lf} PID_{c,s,ds,is,lf} \; X_{c,s,ds,is,lf} - \sum_{fpy} FINES_{fpy} + P2A \leq IR \,.\, IQ \,.\, PYWU \tag{4.40}$$

$$AY\_QUOTA \qquad \sum_{c,s,ds,is,lf} AID_{c,s,ds,is,lf} \,.\, X_{c,s,ds,is,lf} - \sum_{fay} FINES_{fay} - P2A \leq IR \,.\, IQ \tag{4.41}$$

Equations 4.40 and 4.41 are seasonal water use controls, where the pre-year water quota constraint (***PY_QUOTA***) limits the sum of the irrigation water demanded in the pre-year (***PID***) for all *c,s,ds,is,lf* combinations multiplied by the decision variable ($X_{c,s,ds,is,lf}$) and the unused water in the pre-year to be transferred to the after-year (***P2A***) to the irrigation rights (***IR***) multiplied by the irrigation quota (***IQ***) multiplied by the pre-year water use fraction (***PYWU***) and the sum of the excess water used in the pre-year ($FINES_{fpy}$). The after-year water quota constraint (***AY_QUOTA***) is calculated similarly except it is not multiplied by the after-year water use fraction (***AYWU***) because the (***MAX_QUOTA***) constraint (equation 4.39) will prevent water use in the after-year from exceeding the farmers total irrigation quota multiplied by the after-year water use fraction (***AYWU***).

$$RFC \qquad \sum_{c,s,ds,is,lf} PWL_{c,s,ds,is,lf} \,.\, X_{c,s,ds,is,lf} + \sum_{c,s,ds,is,lf} AWL_{c,s,ds,is,lf} \,.\, X_{c,s,ds,is,lf} - VOFSD.OFS - EVAPY.OFS = NPSD \tag{4.42}$$

The returnflows counter (***RFC***) is not a constraint, but just a formula used to calculate the sum of non-point source discharge (***NPSD***) that is not intercepted by the volume of one on-farm storage dam (***VOFSD***) multiplied by the optimal number of on-farm storage dams (***OFS***) to be built and the annual evaporation that takes place off these dams (***EVAPY.OFS***).

$$\begin{aligned} MRF \qquad & \textstyle\sum_{c,s,ds,is,lf} PWL_{c,s,ds,is,lf} \cdot X_{c,s,ds,is,lf} + \sum_{c,s,ds,is,lf} AWL_{c,s,ds,is,lf} \cdot X_{c,s,ds,is,lf} \\ & - VOFSD.OFS \ - EVAPY.OFS \qquad \le \ MAXRF.IR \end{aligned} \qquad \textbf{(4.43)}$$

The maximum returnflows constraint ***(MRF)*** is calculated the same as equation 4.42 except that it doesn't count the returnflows, but limits the volume returnflows to the maximum returnflows allowed (***MAXRF***) multiplied by the farmers hectares of irrigation rights (***IR***).

$$SDC_{c,s,ds,is,lf} \qquad LFR_{c,s,ds,is,lf} \cdot X_{c,s,ds,is,lf} \qquad \le (MLF_{s,ds,is} - NLF_c) \cdot X_{c,s,ds,is,lf} \qquad \textbf{(4.44)}$$

The soil drainage constraint (***SDC***) for each possible ***c,s,ds,is,lf*** combination in equation 4.44 is used in SALMOD to prevent the model from selecting crops for which the leaching fraction requirement (***LFR***) is greater than the maximum leaching fraction allowed (***MLF***) for each soil, drainages status and irrigation system combination ($_{s,ds,is}$) minus the natural leaching fraction (***NLF***) of the crop ($_c$).

In the simulation section of SALMOD parameter $MLF_{s,ds,is}$ is assigned the minimum of the soils maximum leaching capacity as shown in Table 4.11 and the irrigation systems maximum leaching capacity as inputted in table `IR_EF(C,IS)`. Any crop / water / management option that requires or results in more leaching taking place than the MLF value will be eliminated from consideration in the optimisation section of SALMOD.

4.10.2.4 Financial constraints

The two financial constraints are limits that are placed on the production capital allowed by the case study farmer and a limit to the total capital the farmer may loan for long-term fixed capital improvements. Production capital includes seasonal input costs and interest, the annualised cost of the management options, water costs, pumping costs and water fines while fixed capital includes the total capital costs of the management options.

$$\begin{aligned} PCC \qquad & \textstyle\sum_{c,s,ds,is,lf} AMT_c \cdot X_{c,s,ds,is,lf} \\ & + \textstyle\sum_{c,s,ds,is,lf} PID_{c,s,ds,is,lf} \cdot X_{c,s,ds,is,lf} \cdot (WC + PC) \\ & + \textstyle\sum_{c,s,ds,is,lf} AID_{c,s,ds,is,lf} \cdot X_{c,s,ds,is,lf} \cdot (WC + PC) \\ & + \textstyle\sum_{fay} FINES_{fay} \cdot (WC + FRAY_{fay} \cdot WC) + \sum_{fpy} FINES_{fpy} \cdot FRPY_{fpy} \\ & + \textstyle\sum_{fay} FINES_{fay} \cdot PC + \sum_{fpy} FINES_{fpy} \cdot PC \\ & + \textstyle\sum_{s,is} W2L_{s,is} \cdot WSDC_s + \sum_{s,is} L2A_{s,is} \cdot (ADC_s - WSDC_s) + \sum_{s,is} W2A_{s,is} \cdot ADC_s \\ & + \textstyle\sum_{s,ds} (F2C,F2D,C2F,C2D,D2F,D2C)_{s,ds} \cdot ATC(FC,FD,CF,CD,DF,DC) \\ & + OFS \cdot AOFSC \qquad \le MPC \end{aligned} \qquad \textbf{(4.45)}$$

The production capital constraint (PCC) limits the:

- amount of production capital required per hectare for each crop (AMT_c) multiplied by the optimal hectares to be planted ($X_{c,s,ds,is,lf}$) for each *c,s,ds,is,lf* combination
- plus the water (WC) and pumping costs (PC) of the pre- (PID) and after-year (AID) irrigation water demanded multiplied by the optimal hectares to be planted ($X_{c,s,ds,is,lf}$) for each *c,s,ds,is,lf* combination
- plus the sum of the after-year water overuse fine volumes ($FINES_{fay}$) multiplied by the fine rate for after-year water overuse ($FRAY_{fay}$) which is a fraction of the water costs (WC)
- plus the sum of the pre-year water overuse fine volumes ($FINES_{fpy}$) multiplied by the fixed fine rate for pre-year water overuse ($FRPY_{fpy}$)
- plus the volume of pre- and after-year water overuse fines ($FINES_{fpy\ \&}\ FINES_{fay}$) multiplied by the pumping costs of this extra water
- plus the annualised costs of the drainage status conversion management options
- plus the annualised transfer costs (ATC) of the irrigation systems
- plus the annualised costs of building an on-farm storage dam ($AOFSC$) multiplied by the on-farm storage dam decision variable (OFS)

to be smaller than the fixed maximum production capital constraint value (MPC).

$$
\begin{aligned}
FCLC \qquad & \textstyle\sum_{s,is} W2L_{s,is} \,.\, (ADTC_s \,.\, WLSDF) \\
& + \textstyle\sum_{s,is} L2A_{s,is} \,.\, (ADTC_s - (ADTC_s \,.\, WLSDF)) \ + \textstyle\sum_{s,is} W2A_{s,is} \,.\, ADTC_s)) \\
& + \textstyle\sum_{s,ds} (F2C,F2D,C2F,C2D,D2F,D2C)_{s,ds} \,.\, ISTC_{is,tsc} \\
& + OFS \,.\, COFSD \qquad\qquad\qquad \leq MCL \qquad (4.46)
\end{aligned}
$$

The fixed capital loan constraint ($FCLC$) limits the maximum amount of fixed capital that can be loaned using a long-term loan, to be smaller than MCL. That is:

- the sum of hectares to be converted from waterlogged to limited drainage soils ($W2L$) for each soil type and irrigation system combination ($_{s,is}$) multiplied by the full artificial drainage transfer costs ($ADTC$) for the different soil types ($_s$) and the waterlogged soils drainage factor ($WLSDF$),
- plus the sum of hectares to be converted from limited drainage soils to artificially drained soils ($L2A$) for each soil type and irrigation system combination ($_{s,is}$) multiplied by the full artificial drainage transfer costs ($ADTC$) for the different soil types ($_s$) minus the full artificial drainage transfer costs ($ADTC$) multiplied by the waterlogged soils drainage factor ($WLSDF$),
- plus the sum of hectares to be converted from waterlogged to artificially drained soils ($W2A$) for each soil type and irrigation system combination ($_{s,is}$) multiplied by the full artificial drainage transfer costs ($ADTC$) for the different soil types ($_s$).

- plus the sum of hectares of irrigation system combinations that need to be transferred (***F2C,F2D,C2F,C2D,D2F or D2C***) for each soil and drainage status combination ($_{s,ds}$) multiplied by the irrigation system transfer costs (***ISTC***) for each irrigation system ($_{is}$) combination.
- plus the costs of building an on-farm storage dam (***COFSD***) multiplied by the on-farm storage dam decision variable (***OFS***).
- Must be smaller than or equal to ***MCL.***

4.11. A DESCRIPTION OF SALMOD OUTPUT FILES

GAMS/Minos 5.6 by Murtagh, *et al, (*1996) was used as the GAMS linear programming (LP) optimisation solver to generate the results discussed in this section. SALMOD was also run using the GAMS/BDMLP 1.1 solver by Brooke *et al, (*1994) to see if the model was stable when using other solvers and virtually the same results were generated, proving SALMOD stable using at least these two solvers.

Each SALMOD run generates three output files; the automatic GAMS listing (.LST extension) file that contains all the results of the model run and two separate pre-programmed files that extract the information required from the bulky listing file. These consist of a farm level and a water quality scenario (/parametric) file. Examples of these two files generated by SALMOD are depicted in Text Boxes 4.1 to 4.3.

4.11.1. OUTPUT TABLES

The results of the calculations performed in SALMOD to get the data in the right format for linear programming optimisation, appear as output tables in the GAMS listing (.LST) files, created whenever SALMOD is run.

4.11.2. OUTPUT FILE EXPLANATION

Text Boxes 4.1 to 4.3 below contain the output files as generated by SALMOD of a model run for case study farm 1 (Olierivier), with returnflows constrained to 100 millimetres per hectare of irrigation rights and all possible management options activated except the minimum area to lucerne option. The results displayed in these text boxes are only examples to illustrate the condensed SALMOD output files generated by the programmer. This run was set up to use the parametric water quality range of the OVIB 1998 ECiw values. Text Boxes 4.1 and 4.2 come from the same output file.

The acronym Smflf.prn stands for SALMOD (Sm) farm level output (f) using the leaching fraction methodology (lf) and is saved as a .prn file that is a type of text file. When the ‘no management options’ (nmo) version of SALMOD is run, Text Box 4.2 is excluded as it displays the results of incorporating the fixed capital management options.

Text Box 4.3 is derived from the output file Smplf.prn, where the ‘p’ indicates a parametric run. The farm level output uses the last column of ECiw values in the scenario range, and is thus the result of the last linear programming (LP) optimisation run in the parametric section of the model. As can be seen in Text Box 4.3, the column on the far right of the table displays the results of the EC98 scenario, where actual 1998 monthly ECiw values are used. The model is set up in this way so that the farm level results show in detail what the case study farm is and could be doing to optimise TGMASC under current (1998) water quality conditions. The parametric model run then shows, in a summarised version, the impact of improving and deteriorating water qualities on TGMASC, crop composition and the shadow price of water overuse fines.

The bracketed sections A, B and C in Text Box 4.1 indicate the basic model variables that distinguish one case study farmer from another. In Section A the ratio of irrigation rights (141 ha) to irrigable area (200 ha) is important to determine whether irrigable land or irrigation water quota will become constraining. If irrigable area exceeds irrigation rights than water is generally constraining. The question is whether it is feasible to use extra water at the stepped fine structure rate, and how much? As the fine is linked to the standard price of the water (R0.17 /mm/ha per annum) and the pumping costs of the water (R0.56 /mm/ha per annum) these are also shown under section A in the output.

Section B shows the monthly average irrigation water quality (ECiw) measured in milli-Siemens per meter (mS/m) of the scenario for which the results are set up.

Section C list the division of the irrigable area (200 ha) according to soil type (loamy sand (LMS) 190 ha, sandy loam (SNL) 10 ha and sandy clay (SNC) and clay (CLY) both zero ha), irrigation system (flood (FIS) 35 ha, centre pivot (CPI) 165 ha and drip (DIS) zero ha) and soil drainage status classification (naturally drained (NDS) 100 ha, artificially drained (ADS) 20 ha, limited drainage (LDS) 70 ha and waterlogged soils 10 ha).

Sections D, E and F in Text Box 4.1 display the actual model results. To the left of the bracket marked D is the per hectare gross margin (R) above specified costs (GMASC) of each of the crops resource combination to be incorporated into the optimal solution. The soil type (Soil), soil drainage status (Class), irrigation system (Irrig), leaching fraction required (LF) expected yield factor (Yield) and hectares to plant of the specific resource combination (HECTARES) are also given for each crop resource combination. By way of illustration, the first 2 crop resource combinations under section D in Text Box 4.1 will be explained:

- 40 ha of wheat, planted on loamy-sand soils (LMS) that have a limited drainage status (LDS) under a centre pivot irrigation system (CPI) and leached at 5% (LF5) will yield 100% of the expected maximum yield and give a GMASC of R2 890.00 per hectare for the specific water quality scenario modelled.
- 23,8 ha of maize, planted on loamy-sand soils (LMS) that have a limited drainage status (LDS) under a flood irrigation system (FIS) and leached at 15% (LF15) will yield 97% of the expected maximum yield and give a GMASC of R3 315.00 per hectare for the specific water quality scenario modelled.

To the right of the bracket marked D is the total pre-year (PYwater) and after-year (AYwater) irrigation water requirements in mm/ha (divide by 10 for m^3) for the total hectares to plant to each crop resource combination. At the bottom of section D, in the row starting with “Total water used (mm):” is firstly the sum of all water used (225 600 mm) then the sum of the total pre-year water requirements (95 756 mm) and lastly the sum of the total after-year water requirements (129 844 mm). In the next row, ”Unused trans. from Pre- to After-year:” is the volume of unused water rights from the pre-year that can be transferred to be used in the after-year (11 404 mm) at normal rates.

In Section E the total water costs and the total water overuse fines and their duals are calculated. For the example in Text Box 4.1 the total water costs to be paid to the OVIB is R38 352 plus R35 673 for using extra water and the total electricity costs to pump that water is R126 336. The interpretation of the dual value (shadow price) is given in the following chapter where the results are discussed.

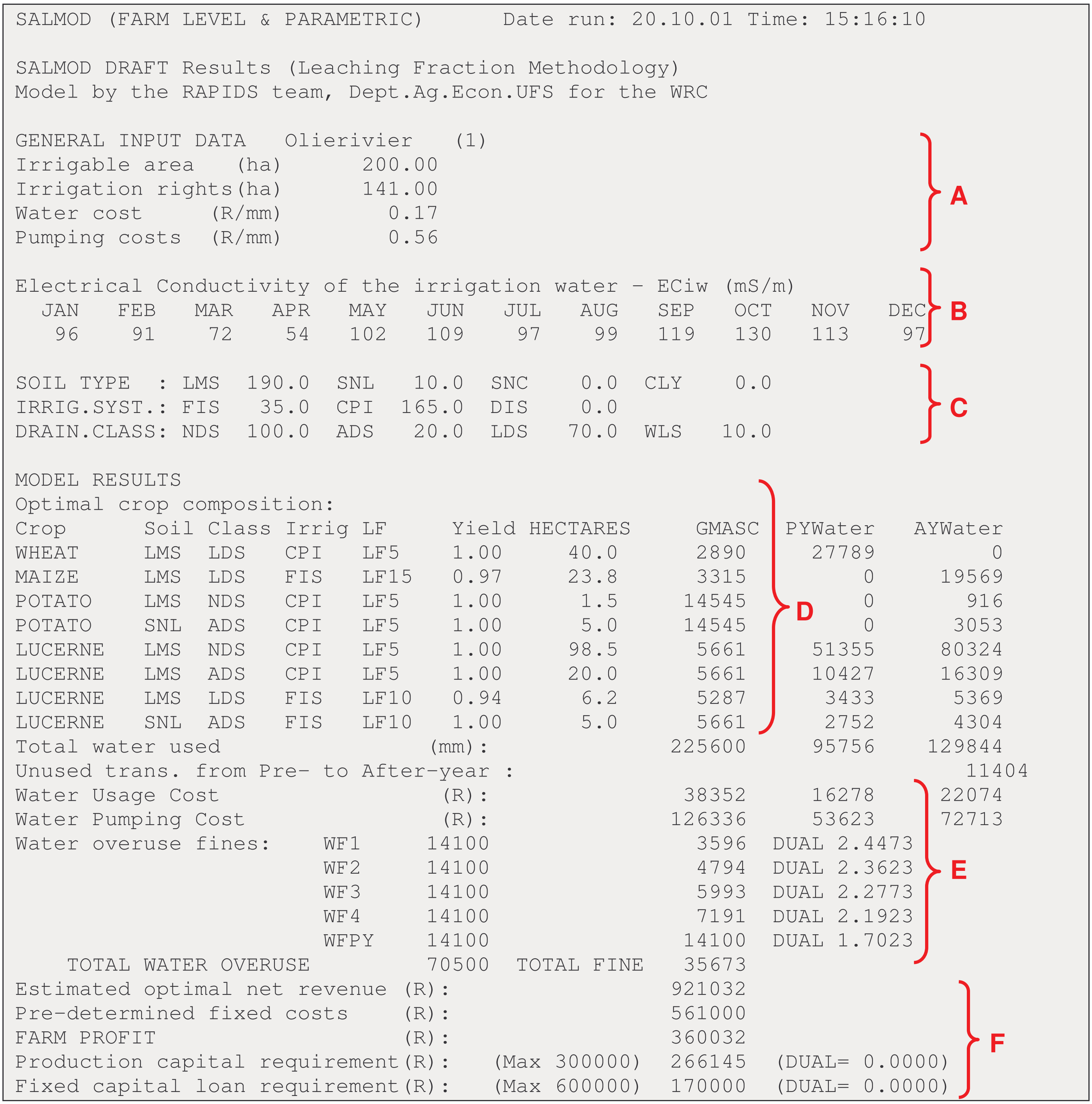
The farm level TGMASC (FARM PROFIT) is shown in Section F. It is the difference between the estimated optimal net revenue and the pre-determined fixed costs. The production and fixed capital loan limit, requirement and dual are also given in the farm level results. For this example neither production nor fixed capital requirements are constraining and therefore the dual values are zero.

The encircled area G in Text Box 4.2 shows the only management option found feasible in the model run is the installation of artificial drainage to convert 10 ha of waterlogged sandy-loam soils, 5 of which are flood irrigated and 5 ha under centre pivot, to fully artificially drained soils (WL-AD option).

Since there are no values in the irrigation system transfer options, the model run shows that at 30% deterioration in water quality the current irrigation systems suffice or else it is not financially feasible to replace them.

The last line in Text Box 4.2 shows whether it is feasible to build an on-farm storage dam under current water quality conditions and with return-flow limiting restrictions in place. The value in the text box indicates that when using the leaching fraction methodology no dams need to be built to manage irrigation returnflows.

Text Box 4.1 An example of a SALMOD farm level output report file (Management options follow in Text Box 4.2)



```
SALMOD (FARM LEVEL & PARAMETRIC)      Date run: 20.10.01 Time: 15:16:10

SALMOD DRAFT Results (Leaching Fraction Methodology)
Model by the RAPIDS team, Dept.Ag.Econ.UFS for the WRC

GENERAL INPUT DATA   Olierivier   (1)
Irrigable area   (ha)      200.00
Irrigation rights(ha)      141.00
Water cost     (R/mm)        0.17
Pumping costs  (R/mm)        0.56

Electrical Conductivity of the irrigation water - ECiw (mS/m)
  JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP   OCT   NOV   DEC
   96    91    72    54   102   109    97    99   119   130   113    97

SOIL TYPE  : LMS  190.0  SNL   10.0  SNC    0.0  CLY    0.0
IRRIG.SYST.: FIS   35.0  CPI  165.0  DIS    0.0
DRAIN.CLASS: NDS  100.0  ADS   20.0  LDS   70.0  WLS   10.0

MODEL RESULTS
Optimal crop composition:
Crop      Soil Class Irrig LF     Yield HECTARES     GMASC  PYWater   AYWater
WHEAT     LMS  LDS   CPI   LF5    1.00      40.0      2890     27789         0
MAIZE     LMS  LDS   FIS   LF15   0.97      23.8      3315         0     19569
POTATO    LMS  NDS   CPI   LF5    1.00       1.5     14545         0       916
POTATO    SNL  ADS   CPI   LF5    1.00       5.0     14545         0      3053
LUCERNE   LMS  NDS   CPI   LF5    1.00      98.5      5661     51355     80324
LUCERNE   LMS  ADS   CPI   LF5    1.00      20.0      5661     10427     16309
LUCERNE   LMS  LDS   FIS   LF10   0.94       6.2      5287      3433      5369
LUCERNE   SNL  ADS   FIS   LF10   1.00       5.0      5661      2752      4304
Total water used                (mm):               225600     95756    129844
Unused trans. from Pre- to After-year :                                   11404
Water Usage Cost                 (R):                38352     16278     22074
Water Pumping Cost               (R):               126336     53623     72713
Water overuse fines:    WF1     14100                 3596  DUAL 2.4473
                        WF2     14100                 4794  DUAL 2.3623
                        WF3     14100                 5993  DUAL 2.2773
                        WF4     14100                 7191  DUAL 2.1923
                        WFPY    14100                14100  DUAL 1.7023
    TOTAL WATER OVERUSE         70500  TOTAL FINE   35673
Estimated optimal net revenue (R):                 921032
Pre-determined fixed costs    (R):                 561000
FARM PROFIT                   (R):                 360032
Production capital requirement(R):   (Max 300000)  266145  (DUAL= 0.0000)
Fixed capital loan requirement(R):   (Max 600000)  170000  (DUAL= 0.0000)
```

Soil type: LMS – Loamy Sand, SNL – Sandy loam, SNC – Sandy clay & CLY – Clay
Irrigation System: FIS – Flood irrigation system CPI – Centre pivot irrigation & DIS – Drip irrigation system
Soil drainage status: NDS – Naturally drained soils, ADS – Artificially drained soils, LDS – Limited drainage soils, & WLS – waterlogged soils
Leaching fraction (LF): LF5, LF10, LF15 – Leaching fraction of 5,10 & 15% respectively
Water overuse fines (mm/ha): WF1 to WF4 – stepped after-year(AY) fine & WFPY – flat rate pre-year (PY) fine

Text Box 4.2 Management option output results for a SALMOD farm level run for the leaching fraction methodology (follows Text Box 4.1)

```
MANAGEMENT OPTIONS:
Soil Trans.WL-LD    LMS     SNL     SNC     CLY
FIS                 0.00    0.00    0.00    0.00
CPI                 0.00    0.00    0.00    0.00
DIS                 0.00    0.00    0.00    0.00
Soil Trans.WL-AD    LMS     SNL     SNC     CLY
FIS                 0.00    5.00    0.00    0.00
CPI                 0.00    5.00 G  0.00    0.00
DIS                 0.00    0.00    0.00    0.00
Soil Trans.LD-AD    LMS     SNL     SNC     CLY
FIS                 0.00    0.00    0.00    0.00
CPI                 0.00    0.00    0.00    0.00
DIS                 0.00    0.00    0.00    0.00

Irrig.Syst.Trans.F-C    LMS     SNL     SNC     CLY
NDS                     0.00    0.00    0.00    0.00
ADS                     0.00    0.00    0.00    0.00
LDS                     0.00    0.00    0.00    0.00
WLS                     0.00    0.00    0.00    0.00
Irrig.Syst.Trans.F-D    LMS     SNL     SNC     CLY
NDS                     0.00    0.00    0.00    0.00
ADS                     0.00    0.00    0.00    0.00
LDS                     0.00    0.00    0.00    0.00
WLS                     0.00    0.00    0.00    0.00
Irrig.Syst.Trans.C-D    LMS     SNL     SNC     CLY
NDS                     0.00    0.00    0.00    0.00
ADS                     0.00    0.00    0.00    0.00
LDS                     0.00    0.00    0.00    0.00
WLS                     0.00    0.00    0.00    0.00
Irrig.Syst.Trans.C-F    LMS     SNL     SNC     CLY
NDS                     0.00    0.00    0.00    0.00
ADS                     0.00    0.00    0.00    0.00
LDS                     0.00    0.00    0.00    0.00
WLS                     0.00    0.00    0.00    0.00
Irrig.Syst.Trans.D-C    LMS     SNL     SNC     CLY
NDS                     0.00    0.00    0.00    0.00
ADS                     0.00    0.00    0.00    0.00
LDS                     0.00    0.00    0.00    0.00
WLS                     0.00    0.00    0.00    0.00
Irrig.Syst.Trans.D-F    LMS     SNL     SNC     CLY
NDS                     0.00    0.00    0.00    0.00
ADS                     0.00    0.00    0.00    0.00
LDS                     0.00    0.00    0.00    0.00
WLS                     0.00    0.00    0.00    0.00

Number of On-Farm Storage dams (50x50x3m) required:  0.0
```

Soil type:	LMS – Loamy Sand, SNL – Sandy Loam, SNC – Sandy Clay & CLY – Clay
Irrigation System:	FIS – Flood Irrigation System CPI – Centre Pivot Irrigation & DIS – Drip Irrigation System
Soil drainage status:	NDS – Naturally Drained Soils, ADS – Artificially Drained Soils, LDS – Limited Drainage Soils,& WLS – Waterlogged Soils
Irrig.Syst.Trans.:	Irrigation system transfer from: F-C – Flood to Centre pivot, F-D – Flood to Drip, C-D – Centre pivot to Drip, C-F Centre pivot to Flood, D-F Drip to Flood & D-C – Drip to Centre pivot
Soil Trans.:	Soil drainage status transfer from: WL-LD – Waterlogged to Limited Drainage, WL-AD – Waterlogged to Artificially Drained & LD-AD – Limited Drainage to Artificially Drained.

Text Box 4.3 Parametric results output file of a SALMOD run with the leaching fraction methodology

```
SALMOD DRAFT Results (Leaching Fractions Methodology - PARAMETRIC ANALYSIS)
Model by the RAPIDS team, Dept.Ag.Econ.UFS for the WRC

PARAMETRIC MODEL RUN FOR:           Olierivier   (1)

                      MN3     MN2     MN1     PL1     PL2     PL3    EC98
Total Gross Margin   944662  940281  930268  859563  767948  605052  921032
Total Water Fine      35673   35673   35673   35673   35673   21573   35673
Returnflows          13673   14100   14100   14100   14100   14100   14030
(Shadow prices)        0.00    0.13    0.58    3.79    4.51    3.83    0.00

OPTIMAL CROP COMPOSITION
WHEAT                  0.00    0.00    0.00   53.51   46.98    0.00   40.00
MAIZE                 66.27   67.28   67.28    9.99    0.00    0.00   23.76
GRNDNUT                0.00    0.00    0.00    0.00    0.00    0.00    0.00
POTATO                 6.50    6.50    6.50    6.50    6.50    6.50    6.50
COTTON                 0.00    0.00    0.00    0.00    0.00    0.00    0.00
LUCERNE              127.23  126.22  126.22  130.00  138.36  152.46  129.74

WATER FINE SHADOW VALUES
WFPY                 1.8302  1.6475  1.6289  1.5808  1.0689 -0.0933  1.7023
WF1                  2.5752  2.3925  2.3739  1.5355  1.2743  0.6517  2.4473
WF2                  2.4902  2.3075  2.2889  1.4505  1.1893  0.5667  2.3623
WF3                  2.4052  2.2225  2.2039  1.3655  1.1043  0.4817  2.2773
WF4                  2.3202  2.1375  2.1189  1.2805  1.0193  0.3967  2.1923
```

4.12. SUMMARY (SALMOD ASSUMPTIONS AND LIMITATIONS)

In summary the assumptions of SALMOD are listed together with the page reference where the assumption is listed in context with the relevant programming, followed by further limitations of SALMOD.

Assumption 1: Case study farmers are assumed to have sufficient kilowatt-hours available to perform the mechanisation tasks required in the SALMOD optimal cropping combination results..................................55

Assumption 2: Case study farmers are assumed to have sufficient labour hours available to perform the labour tasks required in the SALMOD optimal cropping combination results. 55

Assumption 3: The fixed costs (FC) in Table 4.9 assume all farming income and expenses from all other activities not modelled in SALMOD remain constant. 64

Assumption 4: All farmers make use of the production loan facility in full when planting the crop and repay the loan in full one month after harvest. 66

Assumption 5: It is assumed that farmers plan for the maximum physiological yield. All crop establishment costs remain static under different water quality scenarios, however harvesting and irrigation costs vary with different water qualities and leaching fractions. 66

Assumption 6: It is assumed in SALMOD that all farmers have access to their full allocated water quota as well as an additional four tiers at 100 mm/ha water right possessed in the after-year `(FAY)` at the block rate tariff and one tier in the pre-year `(FPY)` at the fixed tariff, although in reality the extra water is only available on request and availability from the OVIB. 70

Assumption 7: It is assumed in SALMOD that farmers manage the leaf scorching effect of sprinkler irrigation on sensitive crops sufficiently so as not to affect crop yield. 71

Assumption 8: Farmers manage their irrigation scheduling to account for all effective rainfall. 72

Further limitations of SALMOD are that:

- SALMOD is set up to take only the 6 main crops in the study area into account but could easily be expanded to include more crops.
- SALMOD is dynamic only in the sense that annual crops are modelled for two production seasons, namely the irrigation pre-year and after-year, but not dynamic in that perennial crops such as orchards and vines can be incorporated and modelled over a number of years.
- The threshold and gradient values used in SALMOD may be outdated, but are used because other data doesn't exist.
- A farm level model like SALMOD can never account for the massive in field variability of salinity distribution, soil types, depths and infiltrability. The SWAGMAN suite of models developed by the CSIRO in Australia overcomes this problem by having different models focussing on different size dimensions.

SALMOD is however sufficient for the purpose that it was built for, namely to determine the farm-level financial impact of poor and fluctuating irrigation water quality. The key component of SALMOD, developed by the author, is the derivation of the average crop ECe weighted for rainfall and monthly crop water requirements demonstrated in paragraph 4.3.5. The monthly crop water requirements take into consideration fluctuating salinity levels, the clay percentage and drainage status of the soil, the irrigation system used (accounting for irrigation inefficiencies) and leaching fraction required for effective salinity control. The average crop ECe is then inputted into equation 4.2 that uses crop salinity thresholds and gradients as determined by Maas and Hoffmann (1977) to calculate the resulting crop yields. It is based on these yield reductions that SALMOD calculates the farm level financial impact of irrigation water salinity. To reduce these impacts SALMOD uses linear programming to incorporate the annualised costs of short and long-term management options to maximise the total gross margin above specified costs (TGMASC) of the farm. If it is financially feasible for the farmer to implement the long-term management options this will be taken into consideration in the calculation of the TGMASC, if not, SALMOD generates a shadow price that indicates by how much the price of the management option needs to be reduced for feasible implementation. This provides an indication to policy makers of the magnitude of subsidy requirements.

CHAPTER 5. **SALMOD RESULTS**

"The whole land will be a burning waste of salt and sulphur - nothing planted, nothing sprouting, no vegetation sprouting on it..."

Deuteronomy 29:13

5.1. INTRODUCTION

The aim of this chapter is to convey the results generated by SALMOD and to interpret these results pertaining mainly to the farm level economic impacts and possible management options for poor and fluctuating irrigation water salinity.

The results generated by SALMOD provide the following:

- The maximum attainable farm level total gross margin above specified costs (TGMASC) under various water quality and management scenarios.
- The optimal combination of leaching fraction and yield reduction management options to implement in order to attain the maximum farm level TGMASC over a production year.
- The identification of the main factors of production constraining attainment of optimal TGMASC.
- What farmers in the OVIB region can indirectly afford to pay for irrigation water of various qualities (salinities) in a free water market system.
- What the impact of various management scenarios and constraints will be on the dual or shadow value of irrigation water.
- How the crop composition in each sub-area is expected to change as water quality changes.
- What the impact of restricting irrigation returnflows would be on the TGMASC of the various case study farms.

For all water quality and parameter change scenario runs, SALMOD is run with and without fixed capital management options (the latter, no management options, is abbreviated to "nmo" in this study) to show the financial impact of the fixed capital management options as compared to the *status quo*.

The management options tested with SALMOD for this study are as follows:

- Model implicit management options that determine the optimal combination of yield percentages and leaching fractions to use to maximise the objective function.
- Model explicit management options that test the impact on the objective function of constraining the total farm irrigation returnflows allowed, production capital and the leaching ability of centre pivot irrigation systems and "forcing" a minimum area to plant to lucerne.

- Fixed capital improvement management options that entail the enhancement of the drainage status of irrigated soils, a possible change in the irrigation systems used to irrigate the crops and the option of constructing on-farm storage if irrigation returnflows were to be constrained.

The water quality data set used in this chapter to display the impact of possible water quality changes is a table comprising 10% interval parametric changes from the actual monthly water quality readings taken by OVIB for 1998. As the most interesting results are obtained for the Olierivier case study farm, they are described first and in greater depth, followed more briefly by the Vaallus, Bucklands, Atherton and then the New Bucklands case study farm results. The chapter concludes with a comparison of the economic impact of water quality changes between sub-areas. In the second section of this chapter a second water quality data set is used to display the possible impact of water quality changes predicted for the year 2020 based on a wider range of water qualities of the different river trajectories in the study area as predicted by Du Preez *et al, (*2000).

5.2. MANAGEMENT OPTIONS

5.2.1. MODEL IMPLICIT (AUTOMATIC) MANAGEMENT OPTIONS

5.2.1.1 Adjusting leaching fractions and expected yield percentage

The choices of leaching fraction to implement and the related yield reduction to accept as water quality deteriorates, are calculated implicitly in SALMOD. With the objective function of the model being to maximise farm level total gross margin above specified costs (TGMASC), SALMOD automatically calculates the optimal crop enterprise composition at certain leaching fractions and yield percentages subject to various constraints with all other farm level management options assumed optimal.

The calculated yield percentages for a fixed range of leaching fractions are shown in the output results. In Text Box 4.1 for example, the optimal crop composition calculated using the fixed leaching fraction intervals (LF0 to LF25 = leaching fraction of 0% to 25% in 5% intervals) includes *inter alia,* wheat with a 5% leaching fraction yielding 100% of it's maximum yield potential, and maize with a 15% leaching fraction yielding 97% of it's maximum yield potential under the water quality conditions modelled.

5.2.2. MODEL EXPLICIT (USER CONTROLLED) MANAGEMENT OPTIONS

The following management options are not implicitly built into the model, but instead are operator adjustments to the model input data in response to identified constraints to give a sensitivity analysis or test the response to TGMASC of a specific variable.

5.2.2.1 Minimum lucerne area constraint

A management option to plant a minimum area to lucerne is built into the model. This option was not activated for the model runs on which this study is based as it was found to reflect unrealistic results when compared to what the case study farmers are actually doing. The reason for including this management option in the model was that optimal management capabilities to ensure long-term farming sustainability are assumed in the model. Planting 5 years of lucerne after 7 years of grain cropping to maintain soil productivity is considered a sustainable practise and would require a minimum of approximately 5% of irrigable area being planted to lucerne each year.

5.2.2.2 Maximum returnflows constraint

Constraining the maximum volume of returnflows in SALMOD shows what the effects of implementing a policy that limits the total amount of returnflows allowed would be for a case study farm. In SALMOD the maximum returnflows are limited at 100mm/ha irrigation quota per year for the returnflows constrained (Rfc) results.

5.2.2.3 Centre pivot irrigation system maximum leaching ability

As mention was made in the Du Preez *et al, (*2000:155) report of the inability of centre pivot irrigation systems to leach effectively, the effect of increasing the extra delivery capacity of the irrigation system is also investigated. The infiltration ability of the soil is taken into consideration and with fixed capital management options the impact of installing artificial drainage can be analysed.

5.2.2.4 Production capital constraint

The availability of production capital plays an important role in optimal enterprise composition, farming practises, and thus farm profit. Production capital was found to be most constraining for some case study farms - freeing the production capital constraint showed a vast improvement in TGMASC till the water quota became constraining.

5.2.2.5 Changing the tariff of irrigation water

When changing the tariff of the irrigation water used, SALMOD results show the impact on optimal TGMASC, crop composition, returnflows, water fine shadow values, etc. The effects of this regional level management option are shown in the discussion to follow.

5.2.3. FIXED CAPITAL IMPROVEMENT MANAGEMENT OPTIONS

The management options that are discussed in this section refer to capital improvements that are only brought into the optimal SALMOD solution if the resulting increase in TGMASC is greater than their annualised costs[3].

5.2.3.1 Soil drainage status improvement

SALMOD makes provision for the installation of artificial drainage (AD) to convert waterlogged (WL) soils to fully drained artificially drained soils (WL-AD option). Other soil drainage status improvement options are to only partially convert waterlogged soils to limited drainage (LD) artificially drained soils (WL-LD option), and to convert limited drainage soils to fully drained artificially drained soils by installing additional underground artificial drainage (LD-AD option). For the WL-LD option it is assumed that artificial drainage is only installed on the worst 10% of the waterlogged area, and that this is sufficient to drain the worst of the water away. For the WL-AD option the whole waterlogged area gets artificial drainage installed if selected as management option.

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[3] The tax deductions and possible subsidies allowed for with these fixed capital improvement options are not accounted for in SALMOD and so the impact on the TGMASC is actually under-estimated.

5.2.3.2 Change of irrigation system

SALMOD also test the feasibility of converting one irrigation system to another. Particularly under poor water quality conditions, where it is more feasible to leach than to accept a lower yield, and where the soils drainage status will not restrict a certain amount of leaching, the existing irrigation system might not have the capacity to over irrigate to leach sufficiently. In this instance it might be feasible to replace the existing irrigation system with a system that has a higher water delivery rate. This problem was identified by Du Preez *et al, (*2000:155) "Leaching of excess salts from the root zone with centre pivot irrigation systems proved to be almost impossible in the study area." SALMOD can identify the threshold water quality at which an irrigation system needs to be replaced to meet the leaching requirements of the crop.

5.2.3.3 On-farm storage/evaporation dam construction

This management option is only considered in SALMOD when returnflows are constrained. This would be the result of regional or national policy restricting the amount of returnflows allowed back into rivers from irrigated land to protect the water source, underlying ground water and downstream users from agricultural contaminants and leached minerals. The model does not only account for point source agricultural returnflows, but all excess water applied to the crop. The return flow volume restriction is attached to the farmers' irrigation water quota.

The dimensions of the earthen storage dam were set in the SALMOD runs for this study to be 50 x 50 x 3 meters, which gives a storage capacity of 7 500m^3 of water, and amounts to a total cost of R30 000, annualised as R5 977 over a period of 10 years. The option of building a storage dam is not included in the model as an integer option, thus a fraction of a dam can also be calculated. The total construction cost is constrained in SALMOD by a maximum capital costs constraint, while the annualised repayment costs are constrained by the maximum production costs constraint. Income generating uses of the dam, such as aquaculture, are not accounted for in the calculation of the costs of the dam.

5.3. PARAMETRIC RESULTS BASED ON OVIB 1998 EC$_{iw}$ DATA

For each sub-area case study farm, SALMOD is run at actual 1998 monthly ECiw values of the water source metering point closest to the farm to depict the farm-level results (taking Olierivier – OL – as an example) of the *status quo* (OLnmo), with fixed capital management options (OL), returnflows constrained (OLrfc) and *status quo* with returnflows constrained (OLnmoRfc).

The actual 1998 monthly average ECiw value is varied parametrically by 10, 20 and 30% positively (PL1, PL2 and PL3) and negatively (Mn1, Mn2 and Mn3) to show the results of 10% incremental improvements and deteriorations of the irrigation water quality.

When looking at the parametrically varied results of the 10-yr average irrigation water quality at Soutpansdrift, depicted in Figure 5.1, they fall within the 10-year minimum and maximum ECiw range. In October and November however the full spectrum of the potential range in ECiw is not completely covered. For this reason, SALMOD results based on predicted ECiw values calculated by Du Preez *et al, (*2000) are discussed later in this chapter. These values cover the full spectrum of possible water quality fluctuations in the OVIB region.

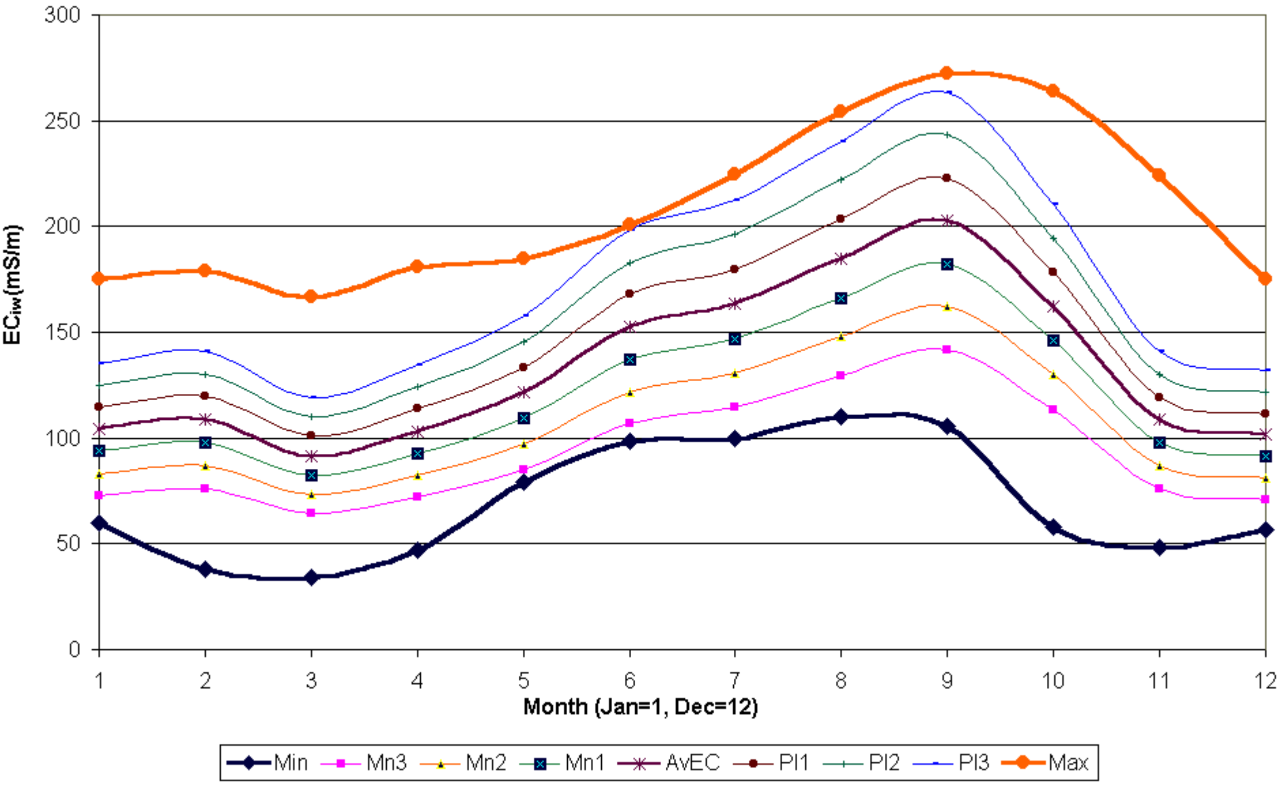

Figure 5.1 10-yr monthly average ECiw (mS/m) measured by the OVIB at Soutpansdrift varied 10% incrementally between the 10-yr min., and max. ECiw for use in parametric SALMOD model runs.

Following is the parametric results of each of the OVIB sub-areas, Olierivier explained in full and the other four sub-areas listing only main findings.

5.3.1. SUB-AREA 1 RESULTS: OLIERIVIER

Table 5.1 Olierivier case study farm basic model input data, 2000

GENERAL INPUT DATA	
Irrigable area (ha)	200
Irrigation rights(ha)	141
Water cost (R/mm/ha)	0.17
Pumping costs (R/mm/ha)	0.56
Pre-determined fixed costs(R)	561 000

The general input data required in SALMOD to define the Olierivier case study farm is displayed in Table 5.1 to Table 5.3. A more detailed description of each of the case study farmers can be found in Chapter 2. The farm consists of 200 ha of irrigable land of which there is only an irrigation quota for 141 ha. The irrigation water cost with which SALMOD is run, is the 1998 OVIB tariff set for the area, namely R0.17 per millimetre per hectare (mm/ha). The pumping cost used however is the average pumping cost determined in the pilot survey conducted in the area. These tariffs are fixed in all the scenarios run (for all the other case study farms as well) but can be changed to reflect the impact of a change in the tariff of irrigation water or the cost of pumping the water. The pre-determined fixed cost for the Olierivier case study farmer is R561 000. To determine annual net farm profit/loss this value is subtracted from the TGMASC value generated by SALMOD.

Table 5.2 The division of the Olierivier case study farm irrigable area into soil type, irrigation system used and the drainage status of the soil (ha), 2000

SOIL TYPE :	LMS	190	SNL	10	SNC	0	CLY	0
IRRIG.SYST.:	FIS	35	CPI	165	DIS	0		
DRAIN.CLASS:	NDS	100	ADS	20	LDS	70	WLS	10

The soil type is a function of the clay percentage of the soil. Of the 200 ha irrigable soil (Table 5.2), the Olierivier case study farmer has 190 ha loamy sand (LMS) and the remaining 10 ha are sandy loam (SNL). 165 ha are under a centre pivot irrigation system (CPI) while the remaining 35 ha are flood irrigated (FIS). 100 ha of the irrigable area have sufficient natural drainage (NDS), 70 ha have limited drainage (LDS), 20 ha are artificially drained (ADS) and the remaining 10 ha are waterlogged (WLS).

Table 5.3 Olierivier 1998 monthly average ECiw (mS/m) (source: OVIB)

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
96	91	72	54	102	109	97	99	119	130	113	97

The monthly average electrical conductivity of the irrigation water (ECiw), measured in milli-Siemens per meter (mS/m), is depicted in Table 5.3. The annual average of these monthly average ECiw values measured by OVIB through the year in 1998 (OL98) is 98.25 mS/m and is used in Table 5.4 to set up a range of water qualities incrementally varied at positive and negative intervals of 10%. This range of water qualities is later broadened when SALMOD is run for predicted water qualities determined by Du Preez *et al, (*2000:18).

Table 5.4 The annual average ECiw varied parametrically from the 1998 OVIB reading for Olierivier

	Mn3	Mn2	Mn1	**OL98**	PL1	PL2	PL3
Parametric range	-30%	-20%	-10%	OL98	+10%	+20%	+30%
Annual Average ECiw (mS/m)	***68.8***	***78.6***	***88.4***	***98.3***	***108.1***	***117.9***	***127.7***

Table 5.5 shows the change in TGMASC, water fine and returnflows over the parametric range of water quality variations. With a 30% deterioration in ECiw form the 1998 average level, TGMASC is only reduced by 6.27%, but unconstrained returnflows increase by 19.25%. An improvement in the ECiw form the 1998 average level, results in a TGMASC improvement of only 3.5%, and a reduction in returnflows by 20.42%. The total water fine remains unchanged as the volume of additional water is fully utilised. The dual values are zero because returnflows are not constrained.

Table 5.5 Percentage change in TGMASC (R), total fine (R) and returnflows (mm/ha) from the OVIB 1998 ECiw results for a parametric run with no management options, Olierivier case study farm (2000)

	MN3	MN2	MN1	**EC98**	PL1	PL2	PL3
Total Gross Margin	3.50%	2.50%	1.17%	**662 706**	-1.13%	-3.59%	-6.27%
Total Water Fine	0.00%	0.00%	0.00%	**35 673**	0.00%	0.00%	0.00%
Return Flows	-20.42%	-20.42%	0.00%	**104.7**	6.55%	6.55%	19.25%
Returnflows duals	0 %	0 %	0 %	**0**	0 %	0 %	0 %

Table 5.6 shows the change in optimal crop composition over ECiw varied parametrically. Area planted to lucerne is slightly reduced as EC deteriorates (MN3 through to PL3) with the area planted to potatoes and maize remaining unchanged. Wheat and groundnuts are left out of the optimal cropping combination over the whole range of ECiw. Using the Olierivier case study farmers own CEBs, SALMOD is set up to choose only between wheat, maize, groundnuts, potato and lucerne.

Table 5.6 Optimal crop composition (ha) for a parametric run with no management options using OVIB 1998 ECiw values as basis, Olierivier case study farm (2000)

	MN3	MN2	MN1	**EC98**	PL1	PL2	PL3
WHEAT							
MAIZE	25.1	25.1	25.1	25.1	25.1	25.1	25.1
GROUNDNUT							
POTATO	6.0	6.0	6.0	6.0	6.0	6.0	6.0
LUCERNE	151.4	151.4	149.5	149.5	148.6	148.6	146.7

In Table 5.7 it can be seen how the productive value of irrigation water decreases as the water quality deteriorates. In all water after-year fine rows (WF1-4) the shadow price decreases from left to right. The pre-year water fine row (WFPY) however doesn't show this trend as excess water from the pre-year is transferred to the after-year. The EC98 value of 0.59 for the pre-year indicates that if 1 extra mm per hectare of the pre-year irrigation overuse volume were allowed, that the farmers TGMASC could increase by up to 59 cents per hectare. Similarly if 1 more mm per hectare of the fourth tier of the after-year irrigation overuse volume were allowed, that the farmers TGMASC could increase by up to 1.22 cents.

Table 5.7 Change in water fine shadow values (R) from the OVIB 1998 ECiw results for a parametric run with no management options, Olierivier case study farm (2000)

	MN3	MN2	MN1	**EC98**	PL1	PL2	PL3
WFPY	0.73	0.56	0.55	**0.59**	0.60	0.60	0.60
WF1	1.74	1.59	1.55	**1.54**	1.52	1.50	1.47
WF2	1.62	1.47	1.43	**1.44**	1.42	1.40	1.37
WF3	1.51	1.36	1.32	**1.33**	1.31	1.30	1.27
WF4	1.39	1.24	1.20	**1.22**	1.21	1.19	1.17

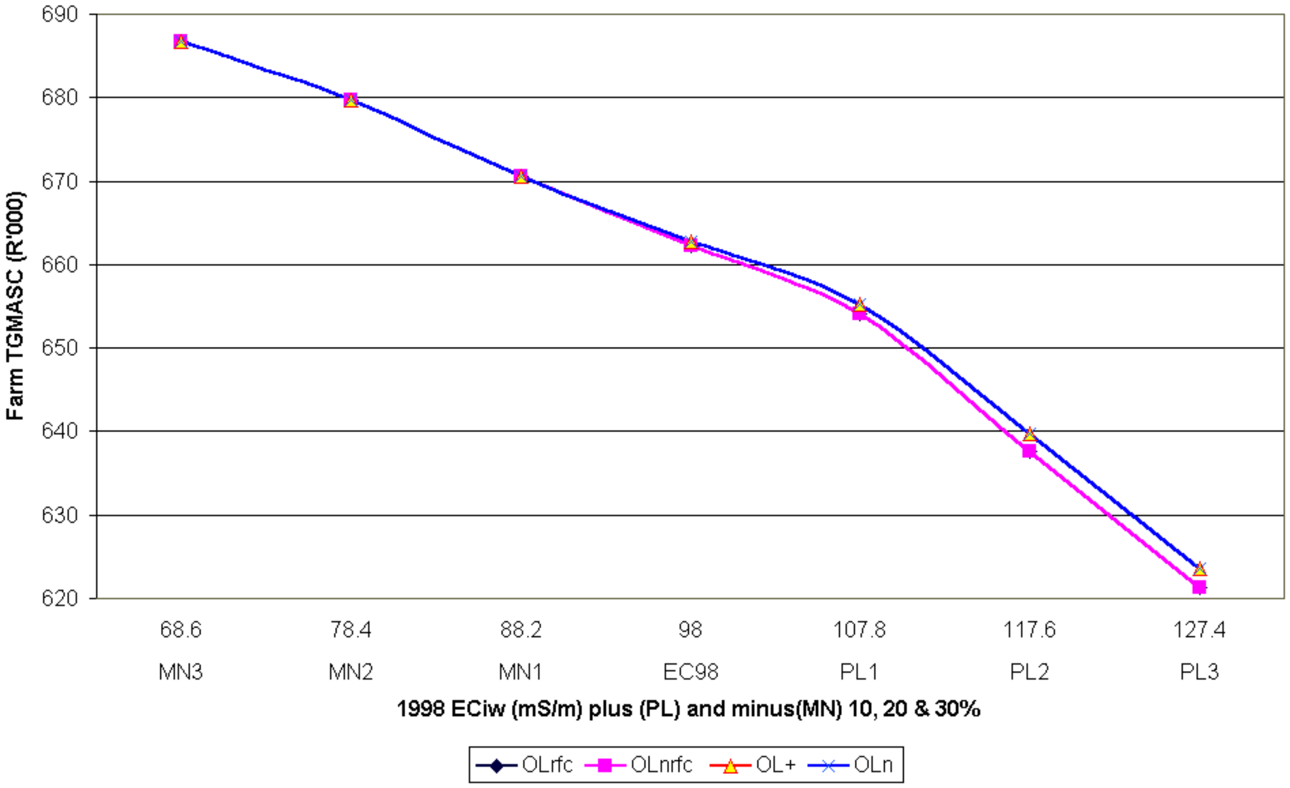

Figure 5.2 TGMASC for the Olierivier case study farm using OVIB 1998 ECiw readings varied parametrically, with and without returnflows constrained (rfc) and fixed capital management options implemented (n = no management options), 2000

Figure 5.2 shows the maximum attainable TGMASC for the Olierivier case study farm at the 1998 ECiw varied parametrically for various scenarios. Constraining irrigation returnflows only has an effect if ECiw deteriorates worse than the 1998 level as can be seen by the OL+ and OLn and OLrfc and OLnrfc lines splitting after EC98. Over the 30% plus and minus 1998 ECiw range no fixed capital management options are feasible to be implemented, shown by the OLrfc and OLnrfc line running together over the whole ECiw range in Figure 5.2.

For a water quality deterioration of 30%, Table 5.8 shows a 6.7% reduction from the attainable TGMASC modelled under 1998 ECiw conditions with and without management options implemented and returnflows constrained (rows OLnrfc and Olrfc and column PL3). A 6.3% reduction in TGMASC is obtained under the same ECiw conditions if returnflows are not constrained, with and without fixed capital management options (rows OL+ and OLn and column PL3). The impact of constraining irrigation returnflows only starts to have an effect once water quality deteriorates till below 1998 ECiw levels. Over the range for ECiw of 68 to 128 mS/m no fixed capital management options are feasible to implement.

Table 5.9 indicates that the volume of the irrigation quota is constraining. At the current water tariff and stepped water overuse fine structure, all 4 levels of the after-year fine (WF1-4) and the full pre-year fine (WFPY) volumes are fully utilised. This is true for all incremental water quality scenarios that the model was run at for Olierivier. This is partially because more irrigable land is available (200 ha) than water rights (141 ha) to irrigate all the land.

Table 5.8 TGMASC (R/farm) for parametrically changed ECiw 1998 values for the Olierivier case study farmer, 2000

	MN3	*MN2*	*MN1*	***EC98***	*PL1*	*PL2*	*PL3*
Ave.Annual ECiw (mS/m)	***68.6***	***78.4***	***88.2***	***98***	***107.8***	***117.6***	***127.4***
OLn	3.5%	2.5%	1.2%	**662706**	-1.1%	-3.6%	-6.3%
OL+	3.5%	2.5%	1.2%	0.0%	-1.1%	-3.6%	-6.3%
OLnrfc	3.5%	2.5%	1.2%	-0.1%	-1.3%	-3.9%	-6.7%
OLrfc	3.5%	2.5%	1.2%	-0.1%	-1.3%	-3.9%	-6.7%

Table 5.9 Water overuse volumes, fines (Cost) and shadow price (Dual) results for the Olierivier case study farm using 1998 OVIB ECiw data, 2000

Stepped tariff	Volume (mm)	Cost (R)	Dual (R)
WF1	14100	3596	1.54
WF2	14100	4794	1.44
WF3	14100	5993	1.33
WF4	14100	7191	1.22
WFPY	14100	14100	0.59

The dual of the first after-year fine tier (R1.54) indicates that for every 1 extra millimetre per hectare of water rights available at that specific charge rate (R0.17 + R0.17 x 50% / mm/ha) an extra R1.54 could be added to the TGMASC. This indicates that for every 26.5 cents that the farmer currently pays for the 1st tier of water overuse, he makes 154 cents gross, and thus indirectly could afford to pay up to 154 cents per millimetre per hectare for that water. As water quality however changes (see Table 5.4) the dual prices for irrigation water change quite markedly.

5.3.1.1 The impact of changing the tariff of irrigation water for Olierivier

Table 5.10 shows the change in the water fine rates as the water tariff (`WC`) is increased from R0.17 /mm/ha to R0.68 /mm/ha. SALMOD was run over this range of consecutive tariff increases to show the impact of water tariffs on the sub-area case study farmers TGMASC. The results in Table 5.10 are derived by changing only the water tariff (`WC`). This results in only the after-year (December to June) fine rates (`WF1-WF4`) being adjusted accordingly as they are derived from the water tariff. The fixed pre-year (July to November) water fine rate (`WFPY`) was kept constant at R1 /mm/ha for all water tariffs.

Table 5.10 The water fine tariff structure for the OVIB in response to increases in the tariff of water (`WC`)

		Water tariff (R/mm/ha)							
Water tariff		***0.17***	***0.1785***	***0.187***	***0.2125***	***0.255***	***0.34***	***0.51***	***0.68***
% change		***0%***	***5%***	***10%***	***25%***	***50%***	***100%***	***200%***	***300%***
WFPY	***fixed***	1	1	1	1	1	1	1	1
WF1	***150%***	0.255	0.268	0.281	0.319	0.383	0.510	0.765	1.020
WF2	***200%***	0.340	0.357	0.374	0.425	0.510	0.680	1.020	1.360
WF3	***250%***	0.425	0.446	0.468	0.531	0.638	0.850	1.275	1.700
WF4	***300%***	0.510	0.536	0.561	0.638	0.765	1.020	1.530	2.040

Table 5.11 shows the impact of increasing the tariff of irrigation water on TGMASC, water fine costs, returnflows, the optimal crop composition and the shadow prices of the water fines as the water tariff is increased from R0.17 /mm/ha to R0.68 /mm/ha. In Table 5.11 we see that the full volume of pre-year extra water allowed, subject to the pre-year water fine (WFPY), remains fully utilized as the water tariff is increased (indicated by positive shadow values) because the pre-year water fine is not linked to the water tariff, as are the after-year stepped fines. Negative after-year water fine shadow values show the decrease in fine / water tariff needed before that tier of extra water can be used profitably on the farm.

Table 5.11 The impact of a change in irrigation water tariffs on TGMASC, total excess water use fine, returnflows, crop composition and water fine shadow values for 1998 OVIB ECiw data for the Olierivier case study farm, 2000

WATER TARIFF INCREASE	**0%**	**5%**	**10%**	**25%**	**50%**	**100%**	**200%**	**300%**
Total Gross Margin (R)	***662706***	-0.6%	-1.2%	-2.9%	-5.8%	-12.1%	-21.7%	-28.5%
Total Water Fine (R)	***35673***	3.0%	6.0%	15.1%	30.2%	32.9%	10.1%	-47.9%
Return Flows (mm)	***14757***	0.0%	0.0%	0.0%	0.0%	-6.5%	-19.1%	-35.2%
OPTIMAL CROP COMPOSITION (ha)								
WHEAT	0	0	0	0	0	0	0	0
MAIZE	25.09	23.00	20.91	14.62	4.15	0.00	1.39	22.56
GROUNDNUT	0	0	0	0	0	0	0	0
POTATO	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
COTTON	0	0	0	0	0	0	0	0
LUCERNE	149.45	150.60	151.76	155.22	160.99	156.46	142.53	114.00
WATER FINE SHADOW VALUES (R)								
WFPY	0.59	0.58	0.57	0.53	0.48	0.03	0.15	0.03
WF1	1.54	1.52	1.49	1.41	1.27	0.73	0.45	0.00
WF2	1.44	1.40	1.37	1.27	1.11	0.48	0.13	-0.40
WF3	1.33	1.29	1.25	1.13	0.94	0.24	-0.20	-0.90
WF4	1.22	1.17	1.13	1.00	0.78	0.00	-0.50	****

As the water tariff and the water overuse fine costs are included as production costs in SALMOD, it was observed in the farm-level results (not shown here) that the increasing cost of water causes production capital to become constraining. Increasing the tariff of irrigation water results in less returnflows, but only after a 100% increase in the cost of irrigation water, at which rate it is no longer viable to use all the extra water.

Increasing the tariff of irrigation water is therefore not a sustainable irrigation policy to reduce agricultural returnflows, as it provides a disincentive to leach that will lead to the continued building up of salts in the vadose zone. It is also important to note that this analysis was only conducted for the Olierivier case study farmer as none of the case study farms in the other sub-areas use more than the volume of the extra water of the first tier made available in the model under ECiw scenarios run for this study.

5.3.2. SUB-AREA 2 RESULTS: VAALLUS

Table 5.12 Vaallus case study farm basic model input data, 2000

GENERAL INPUT DATA	
Irrigable area (ha)	461
Irrigation rights (ha)	339
Water cost (R/mm/ha)	0.17
Pumping costs (R/mm/ha)	0.56
Pre-determined fixed costs(R)	2 475 015

The general input data required in SALMOD to define the Vaallus case study farm is displayed in Table 5.12 to Table 5.14. The farm consists of 461 ha of irrigable land of which there is only an irrigation quota for 339 ha. The pre-determined fixed cost for the Vaallus case study farmer is R2 475 015.

Table 5.13 The division of the Vaallus case study farm irrigable area into soil type, irrigation system used and the drainage status of the soil (ha), 2000

SOIL TYPE:	LMS	0	SNL	111	SNC	320	CLY	30
IRRIG.SYST.	FIS	30	CPI	370	DIS	61		
DRAIN.CLASS:	NDS	311	ADS	120	LDS	30	WLS	0

Of the 461 ha irrigable soil (Table 4.12), the Vaallus case study farmer has 111 ha sandy loam (SNL), 320 ha sandy clay (SNC) and the remaining 30 ha are clayey (CLY). 30 ha of vines are drip irrigated[4], 370 ha are under centre pivot irrigation system (CPI) while the remaining 30 ha are flood irrigated (FIS). 311 ha of the irrigable area have sufficient natural drainage (NDS), 30 ha have limited drainage (LDS), 120 ha are artificially drained (ADS) and no land is waterlogged (WLS). These values are shown in Table 5.13.

Table 5.14 Vaallus 1998 monthly average ECiw (mS/m) (source: OVIB)

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
45	56	64	40	65	63	59	62	74	84	87	45

The monthly average electrical conductivity of the irrigation water (ECiw), measured in milli-Siemens per meter (mS/m), is depicted in Table 5.14. The annual average of these monthly average ECiw values measured by OVIB through the year in 1998 (VL98) is 62 mS/m and is used in Table 5.15 to set up a range of water qualities incrementally varied at positive and negative intervals of 10%. Note that these Vaallus irrigation water quality values are much lower than for Olierivier (Table 5.3), indicating that the 10% increment used for calculating the parametric range, won't be as wide as for Olierivier.

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[4] SALMOD doesn't have an option to include vines in the choice of crops, so this area should actually be left out

Table 5.15 The annual average ECiw varied parametrically from the 1998 OVIB reading for Vaallus, 2000

	Mn3	Mn2	Mn1	**VL98**	PL1	PL2	PL3
Parametric range	-30%	-20%	-10%	VL98	+10%	+20%	+30%
Annual Average ECiw (mS/m)	43.4	49.6	55.8	62	68.2	74.4	80.6

The *status quo* results for the Vaallus case study farm using OVIB 1998 ECiw readings are a TGMASC of R 2 158 249, and zero shadow values for both the total water fine and returnflows (only 48.6 mm/ha returnflows are generated). Varying EC98 over the parametric range results in no changes in the TGMASC, water fine and returnflows. The dual values are zero because returnflows are not constrained.

There is no change in optimal crop composition over EC98 varied parametrically for the Vaallus case study farm. Maize (35.14 ha) and lucerne (368.75 ha) remain the optimal crops to produce over the parametric range. Using the Vaallus case study farmer CEBs, SALMOD is set up to choose only between wheat, maize, potatoes and cotton.

The results show zero shadow values for all pre-year (WFPY) and after-year (WF1-4) extra water required over and above the allocated irrigation rights. This shows that it is not feasible for this case study farmer to exceed his irrigation water allocation of 11000 m^3 per hectare for 399 hectares even though he has additional irrigable land.

The maximum attainable TGMASC for the Vaallus case study farm at the 1998 ECiw varied parametrically in 10% intervals from –30% to +30% for various scenarios do not vary over the range of ECiw from 43 to 81 mS/m.

No management options are feasible for implementation over this range and constraining returnflows also makes no difference to the Vaallus case study farm TGMASC.

The impacts of constraining irrigation returnflows only starts to have an effect once water quality deteriorates till levels outside of the parametric range modelled above, but captured in the model runs in the following section based on Du Preez *et al* (2000) predictions. With production capital being a major constraint for the Vaallus farm and the small parametric range of VL ECiw compared to OL ECiw there is no change in VL TGMASC over the whole range of scenarios (see Table 5.8**).**

No extra irrigation water is needed for the optimal solution, over and above the irrigation water quota. It is not feasible for the Vaallus farmer to use any extra water in the pre-year (WFPY) and in the after-year (WF1-4).

With all 461 ha irrigable area being planted and a water quota of only 339 ha, SALMOD results show that no extra water is required. This indicates that another constraint is limiting the volume of extra water needed. The limiting constraint is identified as the production capital constraint. See Table 5.16 and the accompanying discussion for the notable impact of un-constraining production capital for the Vaallus region. The SALMOD farm level output results (not included in this study) show the dual value resulting from constraining production capital at R500 000 is 3.6431. This means that for every R1 more production capital allowed, TGMASC could be increased by R 3.64.

For the Vaallus case study farmer, the substantial impact of releasing the production capital constraint is shown in Table 5.16. With production capital capacity increased three-fold (PC3) a 55.1% (EC98-VLnPC3) increase in TGMASC was realised from the 1998 ECiw level (EC98) with and without management options (n) and return-flows constraining (c), but production capital remained constraining. At this level the full irrigable area was used, maize was expanded to 400 hectares, potatoes were included in the optimal crop composition at 19 hectares and cotton was reduced form 368 hectares to only 42 hectares. Increasing the production capital constraint four-fold (PC4) production capital was no longer constraining but only a small improvement in TGMASC (EC98 - VLnPC4) resulted. Allowing fixed capital management options to be implemented improved TGMASC by only a further 2.2% (EC98 - VLPC4).

Table 5.16 The percentage change in TGMASC from the *status quo* when increasing the production capital constraint for 1998 OVIB ECiw data, Vaallus case study farm, 2000

	MN3	**MN2**	**MN1**	**EC98**	**PL1**	**PL2**	**PL3**
	-30%	*-20%*	*-10%*	*0%*	*10%*	*20%*	*30%*
	43	*50*	*56*	*62*	*68*	*74*	*81*
VL (n / c / cn)	0.0%	0.0%	0.0%	**2 158 249**	0.0%	0.0%	0.0%
VLcnPC3	55.3%	55.3%	55.2%	55.1%	55.0%	54.9%	54.7%
VLnPC4 (c)	55.7%	55.6%	55.5%	55.4%	55.3%	55.2%	55.0%
VLPC4 (c)	57.9%	57.8%	57.7%	57.6%	57.5%	57.4%	57.3%

5.3.3. SUB-AREA 3 RESULTS: ATHERTON

The general input data required in SALMOD to define the Atherton case study farm is displayed in Table 5.17 to Table 5.19. The farm consists of 22 ha of irrigable land of which there is an irrigation quota for 28.9 ha. The pre-determined fixed cost for the Atherton case study farmer is R130 000.

Table 5.17 Atherton case study farm basic model input data, 2000

GENERAL INPUT DATA	
Irrigable area (ha)	22
Irrigation rights (ha)	28.9
Water cost (R/mm/ha)	0.17
Pumping costs (R/mm/ha)	0.56
Pre-determined fixed costs(R)	130 000

Table 5.18 The division of the Atherton case study farm irrigable area into soil type, irrigation system used and the drainage status of the soil (ha), 2000

SOIL TYPE:	LMS	0	SNL	0	SNC	0	CLY	22
IRRIG.SYST.:	FIS	22	CPI	0	DIS	0		
DRAIN.CLASS:	NDS	0	ADS	0	LDS	22	WLS	0

All 22 ha of the Atherton farm irrigable land are clayey (CLY), flood irrigated (FIS) and have limited drainage (LDS).

Table 5.19 Monthly average ECiw (mS/m) Atherton, 1998 (source: OVIB)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ECiw	52	52	42	44	68	91	91	86	77	28	53	80

The monthly average electrical conductivity of the irrigation water (ECiw), measured in milli-Siemens per meter (mS/m), is depicted in Table 5.19. These values are used to set up a range of water qualities incrementally varied at positive and negative intervals of 10%. Note that these Atherton ECiw values are much lower than for Olierivier (Table 5.3).

Table 5.20 The annual average ECiw varied parametrically from the 1998 OVIB reading for Atherton

	Mn3	Mn2	Mn1	**AT98**	PL1	PL2	PL3
Parametric range	-30%	-20%	-10%	AT98	+10%	+20%	+30%
Annual Average ECiw (mS/m)	44.6	50.9	57.3	**63.7**	70.0	76.4	82.8

Table 5.20 lists the parametric ECiw values base on the average ECiw for 1998 for Atherton. The results for Atherton using OVIB 1998 ECiw readings remain unchanging over the parametric range giving a TGMASC of R102 786, zero water fine and returnflow shadow values, and a returnflow volume of 849 mm/ha. The dual values are zero because returnflows are not constrained.

The optimal crop composition over ECiw remains unchanged over the parametric range of ECiw, ranging from 44 mS/m to 88 mS/m. 22 ha of wheat remains the optimal crop to plant as water quality deteriorates from MN3 through to PL3. Wheat monoculture is however an unsustainable practise over the long-term. Using the Atherton case study CEBs, SALMOD is set up to choose between maize, wheat and lucerne only.

The Atherton case-study farmer possess 28 ha irrigation allocations, but only irrigates 22 ha and therefore has enough irrigation water for the area irrigated. The shadow values for the maximum water quota are all zero because the water quota is not binding. Negative and meaningless (****) shadow values are a result of no extra irrigation water being required over and above the irrigation water quota allocated. The negative values indicate the reduction in TGMASC as a result of forcing one unit of the specific fine tier. Over the parametric range of ECiw these shadow values remain unchanged at -R0.80, -R0.90 and -R1.00 for the water fine tiers (WF) 1 to 3, and meaningless (****) for the pre-year water fine (WFPY) and water fine tier 4.

Constraining returnflows to 100 mm/ha of irrigation allocation has no effect on the optimal TGMASC results for Atherton.

5.3.4. SUB-AREA 4 RESULTS: BUCKLANDS

Table 5.21 Bucklands case study farm basic model input data, 2000

GENERAL INPUT DATA	
Irrigable area (ha)	50
Irrigation rights (ha)	58.4
Water cost (R/mm/ha)	0.17
Pumping costs (R/mm/ha)	0.56
Pre-determined fixed costs(R)	38 000

The general input data required in SALMOD to define the Bucklands case study farm is displayed in Table 5.21 to Table 5.23. The farm consists of 50 ha of irrigable land for which there is an irrigation quota of 58.4 ha. The pre-determined fixed cost for the Bucklands case study farmer are R38 000.

Table 5.22 The division of the Bucklands case study farm irrigable area into soil type, irrigation system used and the drainage status of the soil (ha), 2000

SOIL TYPE:	LMS	0	SNL	0	SNC	0	CLY	50
IRRIG.SYST.	FIS	50	CPI	0	DIS	0		
DRAIN.CLASS:	NDS	0	ADS	0	LDS	50	WLS	0

All 50 ha of the Bucklands farm irrigable land are clayey (CLY), flood irrigated (FIS) and have limited drainage (LDS).

Table 5.23 Monthly average ECiw (mS/m) for Bucklands, 1998 (source: OVIB)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ECiw	51	50	38	43	65	85	94	86	68	23	47	75

The monthly average electrical conductivity of the irrigation water (ECiw), measured in milli-Siemens per meter (mS/m), is depicted in Table 5.23 The annual average of these monthly average ECiw values measured by OVIB in 1998 (BL98) is 60.42 mS/m and is used in Table 5.24 to set up a range of water qualities incrementally varied at positive and negative intervals of 10%. Note that these Bucklands values are much lower than for Olierivier and very similar to the Atherton values.

Table 5.24 The annual average ECiw varied parametrically from the 1998 OVIB reading for Bucklands

	Mn3	Mn2	Mn1	**BL98**	PL1	PL2	PL3
Parametric range	-30%	-20%	-10%	BL98	+10%	+20%	+30%
Annual Average ECiw (mS/m)	42.29	48.33	54.38	**60.42**	66.46	72.50	78.54

Table 5.24 to Table 5.27 display the *status quo* results for Bucklands using OVIB 1998 ECiw readings. Table 5.25 shows the percentage change in TGMASC, water fine and returnflows over the parametric range. The dual values are zero because returnflows are not constrained.

Table 5.25 Percentage change in TGMASC (R), total fine (R) and returnflows (mm) from the OVIB 1998 ECiw results with no management options for the Bucklands case study farm, 2000

	MN3	MN2	MN1	**EC98**	PL1	PL2	PL3
Total Gross Margin	7.01%	7.01%	4.18%	**86 905**	-4.56%	-9.55%	-15.04%
Total Water Fine	0.00%	0.00%	0.00%	**56**	0.00%	0.00%	0.00%
Returnflows	0.00%	0.00%	0.00%	**3 393**	0.00%	0.00%	0.00%
Dual	0.00%	0.00%	0.00%	**0**	0.00%	0.00%	0.00%

The parametric model runs shows that at all levels of ECiw tested, 45.68 hectares of lucerne is grown. Using the Bucklands case study farmer CEBs, SALMOD is set up to only grow lucerne. If however GWK Ltd. CEBs are used, lucerne remains the optimal crop till water quality level PL2 where it gets replaced with cotton.

Table 5.26 shows simulated ECe over the parametric range. The farm level results (SMF.prn) show that at EC98 a yield of 97% of the maximum yield for Lucerne is achieved using a 5% leaching fraction (LF5). As the water fine and returnflows shown in Table 5.25 do not change over the parametric range, the salinity threshold and gradient are the only reasons for this decline in TGMASC. Lucerne's salinity threshold lies at 200 mS/m and it's gradient is 0.073, explaining the same TGMASC for MN3 and MN2 and then a linear decline in yield after the threshold has been exceeded. This can be seen in Table 5.26 for the leaching fraction of 5% where for MN3 and MN2 the simulated ECe is lower than the threshold.

Table 5.26 SALMOD simulated ECe (mS/m) values for Lucerne planted on Clayey (CLY), limited drainage soils (LDS), 2001

	MN3	***MN2***	***MN1***	***EC98***	***PL1***	***PL2***	***PL3***
LF0	206	236	265	294	323	353	382
LF5	**169**	**193**	**218**	**242**	**266**	**290**	**314**
LF10	159	182	204	227	249	272	295
LF15	136	155	174	193	212	232	251

The water overuse fine shadow values in Table 5.27 are the same across all levels of ECiw because there is no change in the optimal crop composition and no fixed capital management options are implemented. Negative values in the pre-year (WFPY) and for water fine tiers 2 to 4 (WF2 to WF4) indicate that it is not feasible to use extra water at the specified tariffs. Only a part of WF1 is used, indicated by the zero shadow value. The Maximum quota shadow values however correspond with the TGMASC to the decline in ECiw and the response of the crop (lucerne) to the specific ECiw.

Table 5.27 Maximum water allocation and water overuse fine shadow values (R/mm/ha) for OVIB 1998 ECiw results, with no fixed capital management options implemented for the Bucklands case study farm, 2000

	MN3	MN2	MN1	**EC98**	PL1	PL2	PL3
Max Quota	1.03	1.03	1.02	1	0.98	0.96	0.94
WFPY	-0.9	-0.9	-0.9	-0.9	-0.9	-0.9	-0.9
WF1	0	0	0	0	0	0	0
WF2	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
WF3	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
WF4	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3

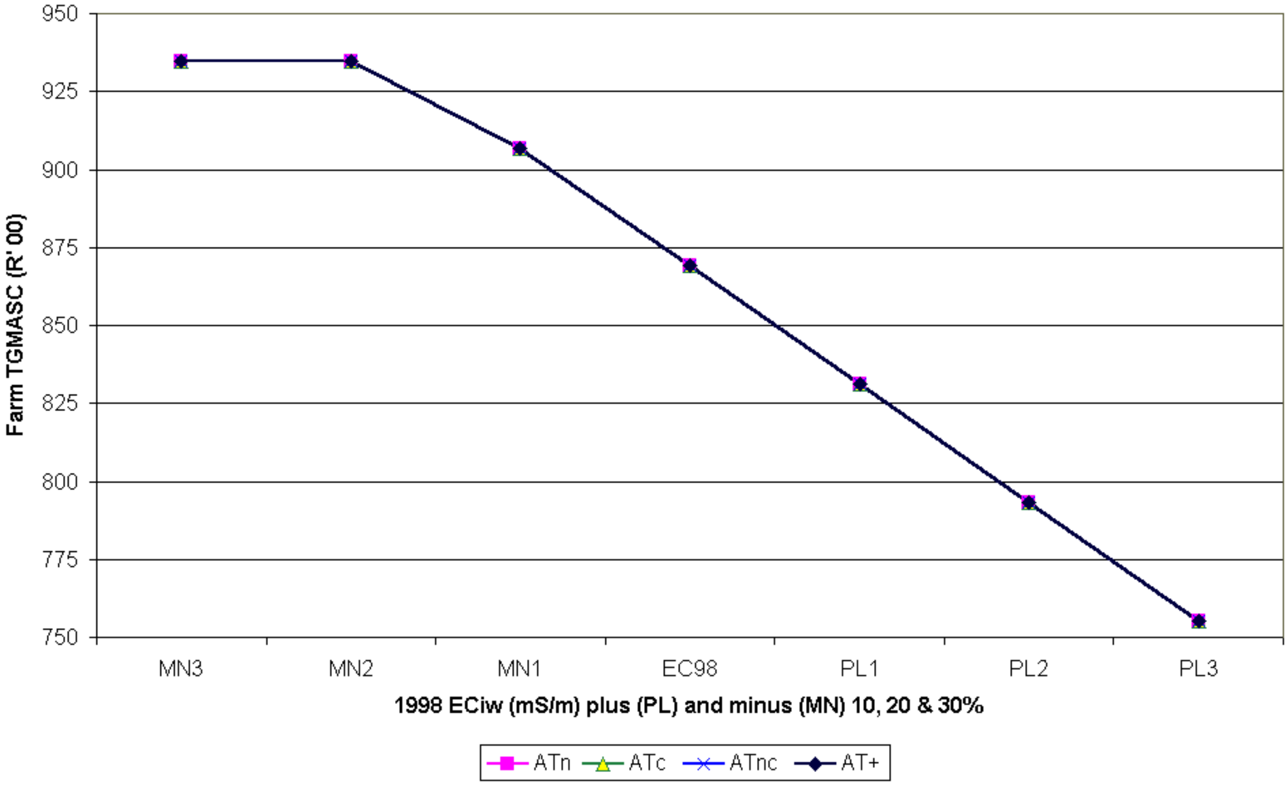

Figure 5.3 TGMASC for the Bucklands case study farm using OVIB 1998 ECiw readings varied parametrically, with and without fixed capital management options implemented, and with and without returnflows constraining, 2000

Figure 5.3 shows the TGMASC for the Bucklands case study farm, using farmer CEBs. At all levels of ECiw only lucerne is grown, as lucerne is all the farmer indicated he grows. When using GWK Ltd. CEBs (see Table 5.28), lucerne remained in the optimal crop composition, but wheat was also added. Using GWK Ltd. CEBs and incorporating wheat resulted in a 62% improvement in TGMASC for EC98 and resulted in a lesser decline as ECiw deteriorated. Constraining returnflows had no effect on the optimal TGMASC.

Table 5.28 TGMASC (R/farm) for parametrically changed 1998 OVIB ECiw values for the Bucklands case study farm, 2000

	MN3	MN2	MN1	**EC98**	PL1	PL2	PL3
AT+	93455	93455	90692	86905	83117	79330	75543
ATn	93455	93455	90692	86905	83117	79330	75543
ATc	93455	93455	90692	86905	83117	79330	75543
ATnc	93455	93455	90692	86905	83117	79330	75543
ATnGWK	148688	148688	145362	140804	136245	131686	127128

AT = Atherton, + = with L-T capital management options, n = no L-T management options, c = return-flows constrained & GWK = using GWK Ltd. crop enterprise budgets.

5.3.5. SUB-AREA 5 RESULTS: NEW BUCKLANDS

Table 5.29 New-Bucklands case study farm basic model input data, 2000

GENERAL INPUT DATA	
Irrigable area (ha)	145
Irrigation rights (ha)	100
Water cost (R/mm)	0.17
Pumping costs (R/mm)	0.56
Pre-determined fixed costs(R)	1 049 109

The general input data required in SALMOD to define the New-Bucklands case study farm is displayed in Table 5.29 to Table 5.31. The farm consists of 145 ha of irrigable land of which there is an irrigation quota of 100 ha. The pre-determined fixed cost for the New-Bucklands case study farmer is R1 049 000.

Table 5.30 The division of the New-Bucklands case study farm irrigable area into soil type, irrigation system used and the drainage status of the soil (ha), 2000

SOIL TYPE:	LMS	145	SNL	0	SNC	0	CLY	0
IRRIG.SYST.	FIS	30	CPI	110	DIS	5		
DRAIN.CLASS:	NDS	100	ADS	10	LDS	25	WLS	10

According to Table 5.30 all 145 ha of the New-Bucklands farm irrigable land consists of loamy sand (LMS), 30 ha are flood irrigated (FIS), 110 ha centre pivot irrigated (CPI) and the remaining 5 ha drip irrigated. 100 ha have sufficient natural drainage, 10 ha are artificially drained, 25 ha have limited drainage (LDS) and the remaining 10 ha are waterlogged.

Table 5.31 New-Bucklands 1998 monthly average ECiw (mS/m) (source: OVIB)

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
19	20	18	19	20	21	20	19	19	20	20	20

The monthly average electrical conductivity of the irrigation water (ECiw), measured in milli-Siemens per meter (mS/m), is depicted in Table 5.31. The annual average of these monthly average ECiw values measured by OVIB in 1998 (NB98) is 19.58 mS/m and is used in Table 5.32 to set up a range of water qualities incrementally varied at positive and negative intervals of 10%. Note that these New-Bucklands values are much lower than for any of the other sub-areas above as Orange River water of a very good quality is used.

Table 5.32 The annual average ECiw varied parametrically from the 1998 OVIB reading for New-Bucklands

	Mn3	Mn2	Mn1	**EC98**	PL1	PL2	PL3
Parametric range	-30%	-20%	-10%	EC98	+10%	+20%	+30%
Annual Average ECiw (mS/m)	13.71	15.67	17.63	**19.58**	21.54	23.50	25.46

The *status quo* results for New-Bucklands using OVIB 1998 ECiw readings are a TGMASC of R 877 463, zero water fine and returnflow shadow values and a returnflow volume of 56.08 mm/ha. These results show a zero percentage change over the parametric range from the EC98 values. The percentage changes are zero because of the good quality water being used and being a low number the percentage change is also small. The dual values are zero because returnflows are not constrained.

130 ha of maize remain the optimal crop to plant as water quality deteriorates from MN3 through to PL3. SALMOD is set up for New-Bucklands to choose between wheat, maize, groundnuts and lucerne.

As the Orange River water quality used at New-Bucklands is very good over the whole parametric range, the shadow values remain unchanged at -R0.80, -R0.90 and -R1.00 for the water fine tiers (WF) 1 to 3, and meaningless (****) for the pre-year water fine (WFPY) and water fine tier 4, indicating that no extra water is required for the optimal crop composition. These water fine shadow value results are the same as for the Atherton case study farm.

When applying Olierivier water quality to the New Bucklands case study farm to test the impact of poor water quality on a good resource base and CEBs with a high gross margin, maize remained the optimal crop with 130 hectares being planted. Where fixed capital management options are applied it is financially feasible for the New-Bucklands case study farmer to partially convert 10 hectares of waterlogged soils into limited drainage soils. It is also feasible to convert the 5 hectares under drip irrigation into flood irrigation, making a total of 15 extra hectares available for maize production. Using Olierivier ECiw with no fixed capital management options, the water overuse fine shadow values remain unchanged, however if fixed capital management options are implemented some water from the 1st tier of overuse is used resulting in a zero shadow value.

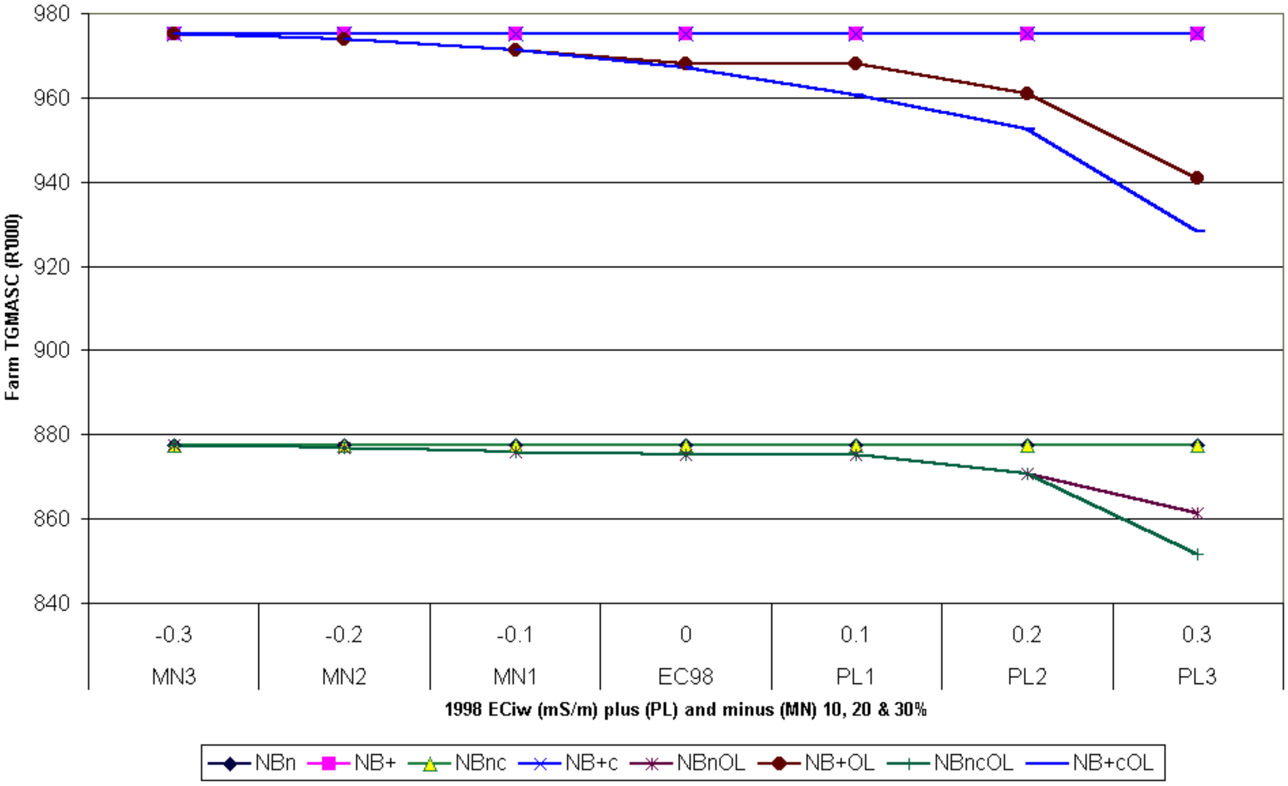

Figure 5.4 TGMASC for the New-Bucklands case study farm using Orange River and Riet River (OL) OVIB 1998 ECiw readings varied parametrically, with and without fixed capital management options implemented, 2000

Figure 5.4 shows the maximum attainable TGMASC for the New-Bucklands case study farm, using farmer CEBs, with 1998 ECiw varied parametrically, under both current Orange River (NB..) and possible Riet River (NB..OL) water quality conditions. Using Orange River water quality, constraining returnflows has no effect on the optimal TGMASC results (straight lines NBn & NBnc and NB+ & NB+c). Implementing fixed capital management options however (NB+ and NB+c) results in a 10% improvement from the *status quo* (NBn) as can be seen in Table 5.33 (EC98-NB+). The letter c in brackets (c) after NBn and NB+ indicate that he results are the same with and without returnflows constraining.

Table 5.33 Percentage change in TGMASC (R/farm) using 1998 OVIB Orange River and lower Riet River (OL) ECiw values for the New-Bucklands (NB) case study farm, 2000

	MN3	*MN2*	*MN1*	***EC98***	*PL1*	*PL2*	*PL3*
NBn (c)	0.00%	0.00%	0.00%	**877463**	0.00%	0.00%	0.00%
NB+ (c)	10.01%	10.01%	10.01%	10.01%	10.01%	10.01%	10.01%
NBnOL	0.00%	-0.08%	-0.16%	-0.26%	-0.27%	-0.78%	-1.88%
NB+OL	10.01%	9.90%	9.65%	9.36%	9.35%	8.69%	6.74%
NBncOL	0.00%	-0.08%	-0.16%	-0.26%	-0.27%	-0.78%	-3.02%
NB+cOL	10.01%	9.90%	9.65%	9.26%	8.66%	7.89%	5.48%

Applying poorer Lower Riet River (Olierivier case study farm) ECiw to the New-Bucklands case study farm model results in a decrease in TGMASC over the parametric range, with a greater decreasing trend observed where return flows are constraining. The magnitude between where fixed capital management options are implemented and not implemented remains similar.

Even when using as low as 1998 Riet River (Olierivier) water quality (see Table 5.3 and Table 5.4), the same optimal TGMASC is obtained at New-Bucklands under MN3 conditions. Only when the low water quality starts to exceed the MN2 Olierivier ECiw levels do we start to see a drop in the TGMASC for the New-Bucklands case study farm.

Table 5.34 Fixed capital management options (Ha soil class and irrigation system transfer) brought into the optimal solution using 1998 OVIB ECiw for the New-Bucklands case study farm, 2000

Soil Trans. WL-LD	LMS	SNL	SNC	CLY
FIS	10	0	0	0
Irrig.Syst.Trans. D-F	LMS	SNL	SNC	CLY
LDS	5	0	0	0

The management options determined by SALMOD to realise the optimal TGMASC for the 1998 ECiw scenario are shown in Table 5.34. SALMOD calculates that installing artificial drainage to convert 10 ha of waterlogged sandy-loam soils to limited drainage artificially drained soils (Soil Trans. WL-LD) and converting 5 ha of drip irrigation on the limited drainage soils (LDS) to flood irrigation (Irrig.Syst.Trans. D-F) will bring about a 10% (see Table 5.33) increase in TGMASC after the annualised costs of these options are deducted. The option of converting the area under drip irrigation is however not feasible in reality because a permanent crop, olives is irrigated under the drip irrigation for which provision isn’t made in SALMOD. The reason for incorporating this land under drip irrigation in the model is to see if drip irrigation is economically/physically suitable for the crops modelled and soil and drainage combinations included. With drip irrigation also being a far more efficient irrigation system, it would replace less efficient irrigation systems if the value of water savings (at the specific tariff of irrigation water used) exceeded the value of leaching (and thus indirectly “wastage”) to flush out excess salts in the soil profile. The results in Table 5.34 confirm that at the current tariff for irrigation water, even under very good water quality conditions, it is better to have an irrigation system that has leaching capacity than a system that saves water. In South Africa where severe water shortages are predicted by 2020, pricing irrigation water incorrectly can convey the wrong signals to irrigators. Unfortunately as water quantity decreases water quality also deteriorates giving rise to a leaching paradox, i.e. as water quantity decreases due to increased demand for water, water quality deteriorates, necessitating more leaching which in turn exacerbates the water quality problem, and decreases water use efficiency.

With current ECiw conditions for the New-Bucklands case study farm and not implementing any fixed capital management options it is not feasible for the New-Bucklands farmer to use any extra water as only maize is included in the optimal crop composition. With 145 ha of irrigable land and an irrigation water quota of 100 ha, this is sufficient for only one seasonal crop per year. Planting maize year after year however is not a sustainable practise, thus the option of running SALMOD with a minimum lucerne area constraint. Furthermore, the New-Bucklands case study farmer does produce other high value crops such as onions that are not included in

SALMOD as options. The beneficial effects of legumes on follow up crops in a crop rotation system are also not implicitly included in SALMOD, thus a possible reason for not including groundnuts, a crop that is produced successfully by the farmer.

5.4. A SUMMARY OF THE PARAMETRIC RESULTS

What the automatic leaching fraction and yield percentage management option results show are that at current water tariffs, the economic impact of accepting a reduction in yield is greater than the cost of applying extra water to leach accumulated salts from the soil to attain a better yield. At current water tariffs SALMOD results indicate that the maximum yield is selected with as much leaching as required subject to the drainage status constraint of the specific soil. Where the drainage status of soils is constraining, a reduction in yield is accepted in the optimal solution.

In summary, the main factors affecting the results are the following:

- The maximum returnflows allowed constraint
- The production capital constraint
- The minimum lucerne constraint
- The leaching ability of centre pivot irrigation systems

Results for the New-Bucklands case study farm, where it was feasible to implement certain fixed capital management options because the vast majority of the resource base (soils) are very good, indicated that at the current tariff for irrigation water, even under very good water quality conditions, it is better to have an irrigation system that has leaching capacity than a system that saves water. This is recommended because leaching promotes soil sustainability. Leaching however creates downstream externalities in an open system and irrigation water quality degradation in a closed system if the leachate is not contained and managed.

Using 1998 ECiw levels and up to a 30% reduction in ECiw, in none of the case study farm model runs was it feasible to construct on-farm storage dams where leaching was constrained. Except for the New-Bucklands case study farm, it was also not feasible to implement any fixed capital management options. The criteria for feasibility of implementing fixed capital management options (installing artificial drainage, changing the irrigation system and building on farm storage) depends on the quality of the resource base, namely soil drainage status and quality, and the magnitude of the gross margins of the CEBs supplied by the case study farmers. Within the narrow parametric range, irrigation water quality does not influence the decision of implementing fixed capital management options as was shown with the New-Bucklands case study farm results.

It is also clear from the results that where irrigation water quota area allocations exceed the total irrigable area, irrigation water quantity is generally sufficient and the shadow prices of water overuse fines are lower than where the irrigable area far exceeds irrigation water quota area allocations. Furthermore, even with the high electricity costs of pumping irrigation water, SALMOD results for the Olierivier case study farm show that the productive value of the extra water exceeds the stepped fines charged for exceeding water quota allocations.

When conducting the farm level survey, the impression gained was that where the irrigable area far exceeded the irrigation quota, it was a cheaper alternative to move the irrigation system to new land than to remediate old land. Irrigable land without water rights can be purchased for R7000 per ha (2000) while the cost of installing artificial drainage could exceed R15000 per hectare. The purchase of additional land was however not an option included in the model. This practise is however unsustainable and environmentally unfriendly.

The subsidisation of the costs of artificial drainage on farms (implemented in SALMOD by leaving the costs of drainage installation out of the objective function and production capital constraints), results in an increase in the volumes of returnflows when return flow volumes aren't constrained, clearly indicating that this course of action could actually further exacerbate the water quality problem. Subsidising irrigation drainage thus has to be implemented together with return flow constraining/effective management policy.

By implementing policy constraining returnflows, water quality will be improved and prevented from deteriorating further. Under these improved water qualities the returnflows from the resulting optimal crop composition will be less than the maximum specified in the constraint, making the returnflows constraint unnecessary once farmers are using and managing their on-farm storage dams properly; but this constraint is initially required to get farmers to install drainage and build on-farm storage dams.

The scenario runs also show that when production capital is constraining or limited, the capital will rather be used for production inputs than for implementing long-term capital improvements.

The results clearly indicate that the benefits from leaching more as water quality deteriorates, to obtain a 100% yield, outweigh the costs of leaching, up until returnflows become constraining.

Maize and potatoes have the same sensitivity and gradient and are the most sensitive crops to salinity of the 6 crops modelled in SALMOD. With potatoes by far being the highest value crop included in SALMOD, it is included in OL, VL and NB (AT and BL do not have potatoes as an option in their CEBs) under all water quality situations, taking up the best soils. Maize is also included in most optimal crop enterprise selections. Although according to pilot survey data, GWK Ltd. statistics and OVIB data wheat is the major crop grown in the study area, SALMOD shows that Atherton is the only sub-area case study farm where wheat is the most feasible crop choice. Cotton is only included in the Vaallus sub-area case study farm optimal crop selection, which is realistic.

5.5. SALMOD RESULTS FOR FUTURE IRRIGATION WATER SALINITY PREDICTIONS

Besides a general gradual deterioration in irrigation water quality throughout the OVIB area as captured in the preceding parametric analysis, a possible water quality scenario to occur is for water to be diverted from the headlands of the Orange River System into the Vaal River System via the Lesotho Highlands Water Project. This could result in their being less water available to the OVIB region via the Orange River, but this could be supplemented with more water from the Vaal River system. The Bucklands, Atherton and New Bucklands sub-areas, which currently receive predominantly Orange River water via the Louis Bosman Canal, would then receive more Vaal River water with the associated decrease in water quality. There could also be less Orange River water entering the lower Riet River via the Sarel Hayward Canal resulting in a more rapid water quality deterioration in the Lower Riet River.

With this in mind the results displayed in this section are based on a second salinity data set for the year 2020 predicted by Du Preez *et al,* 2000.

To show the upper and lower extremes of the economic effects of water quality fluctuations/deterioration, the 2020 predictions from the report by Du Preez *et al, (*2000:18) for the lower Harts River segment (H2), middle Orange River segment (O2) Lower Riet River segment (R3) and Lower Vaal River segment (V4) will be used in the following analysis.

In this analysis the same set of water quality ranges (ECiw) are applied to each sub-area to obtain the parametric results, while for the farm level results the Du Preez *et al*, (2000:18) annual long-term average ECiw is applied for each sub-area. For the New Bucklands, Bucklands, Atherton and Vaallus sub-area farm level model runs Lower Vaal River (V4) 2020 predicted ECiw values are used while for Olierivier Lower Riet River (R3) 2020 predicted ECiw values are used. The full spectrum of predictions are run for each sub-area with Olierivier (O4) following the Olierivier OVIB ECiw monthly pattern (see Figure 5.5) and the other sub-areas the Vaallus monthly water quality pattern (see Figure 5.8).

As the Du Preez *et al, (2000)* report only predicts annual ECiw values, 1998 OVIB monthly EC readings for the lower Riet River (R3) are modified in Figure 5.5 to reflect the annual averages predicted, to be used in the Olierivier SALMOD model runs, and 1998 OVIB monthly EC readings for the lower Vaal River (V4) are modified in Figure 5.8 to reflect the annual averages predicted, to be used in the Bucklands (BL), Atherton (AT), New-Bucklands (NB) and Vaallus (VL) SALMOD model runs.

5.5.1. SUB-AREA 1 RESULTS: OLIERIVIER

The monthly ECiw values in Figure 5.5 are the result of adjusting 1998 monthly average Vaallus ECiw readings to equal the annual predicted average ECiw of the various water quality scenarios determined by Du Preez *et al, (*2000). This is done so that the predicted average annual ECiw can be transformed into monthly water quality fluctuations. The values in Figure 5.5 are used in SALMOD to generate the results depicted in Figure 5.6.

What can be seen in either Table 5.35 or graphically in Figure 5.6 is that as ECiw improves (<136mS/m) from the Riet River segment 3 long-term (R3LT) value calculated by Du Preez *et al, (*2000:18), the same percentage increase in TGMASC from the *status quo* takes place; whether returnflows are constrained or not and whether fixed capital management options are implemented or not (OL=OLc=OLn=OLnc for O2Pre+, OL98, R3Pre- and R3LT). At the R3LT ECiw level constraining return-flows has a marginal impact on TGMASC. However, as ECiw deteriorates beyond R3Pre+ the negative impact on TGMASC can be lessened only marginally (approximately 4% - difference between OLsn and OLs+) for H2Pre by applying management options when return flow restrictions are not imposed. With return-flow constraints imposed fixed capital management options are not feasible to implement at the worst-case scenario salinity levels of the Harts River (H2Pre).

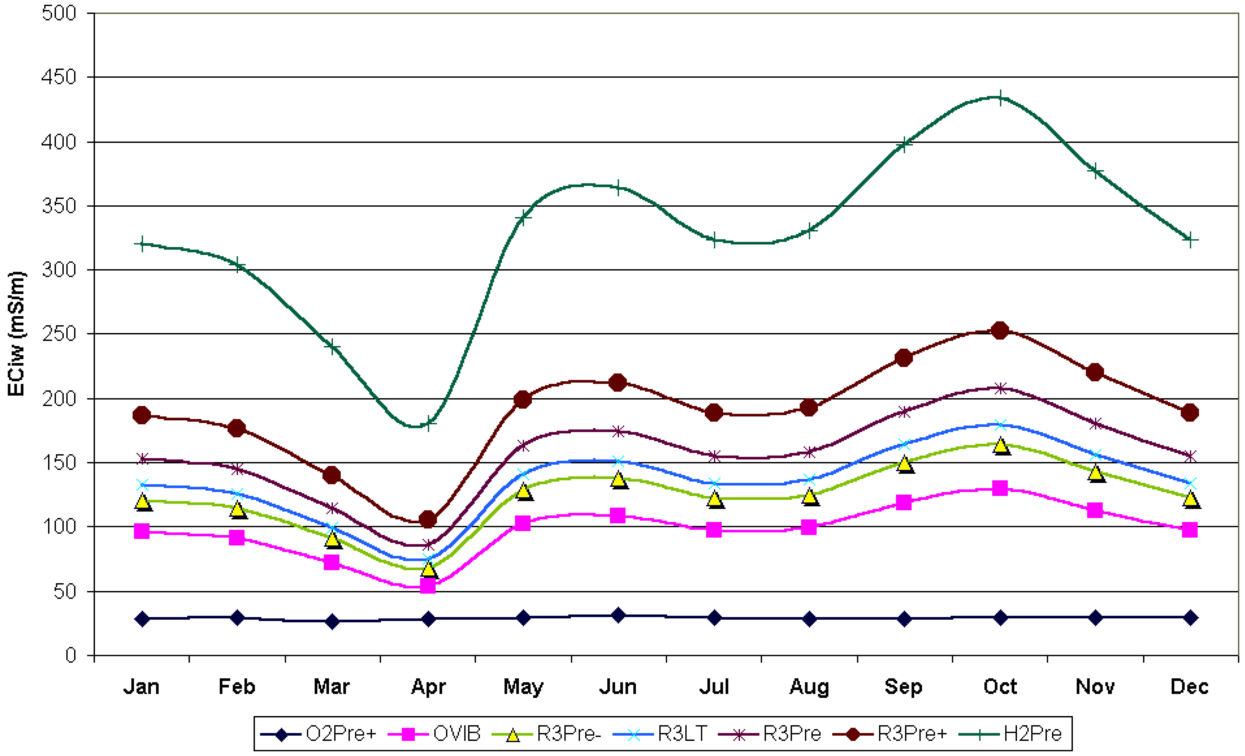

Figure 5.5 2020 predicted annual ECiw values based on OVIB 1998 monthly ECiw fluctuations for Olierivier.

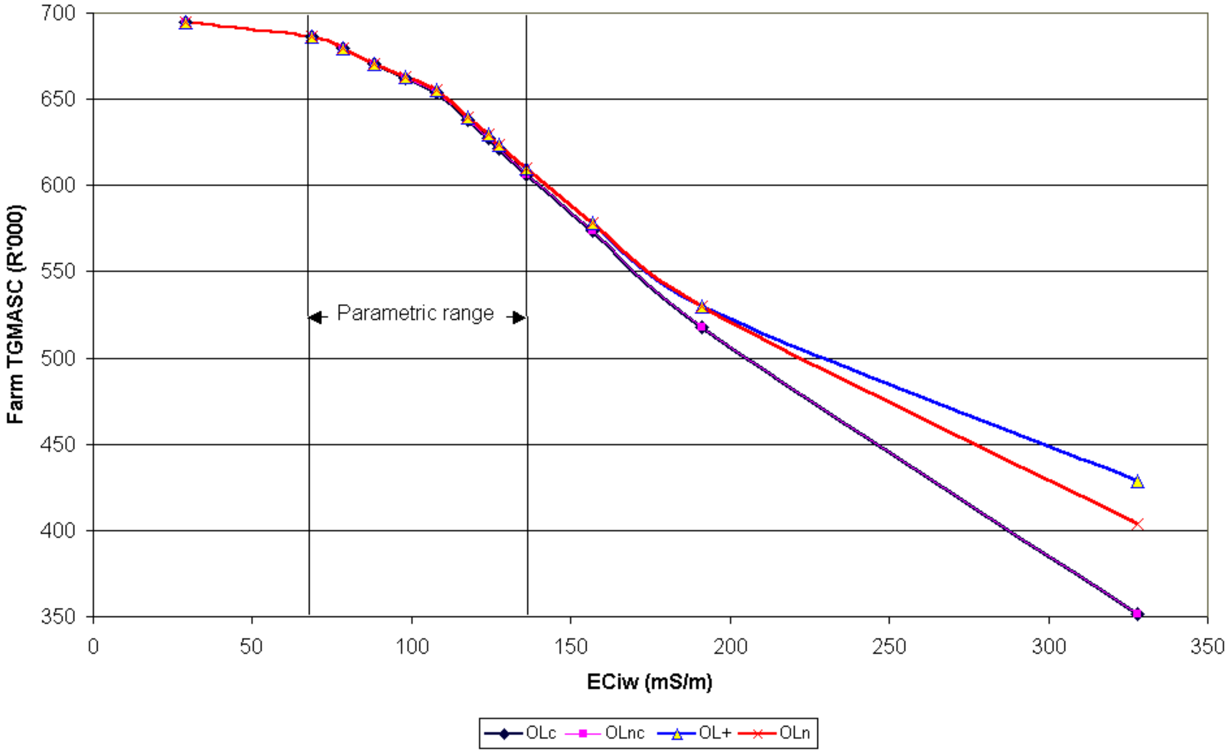

Figure 5.6 The impact on the Olierivier case study farm TGMASC (R'000) of predicted ECiw (mS/m) scenarios with (+) and without (n) fixed capital management options and with (c) and without returnflows constrained

Table 5.35 The percentage change in Olierivier TGMASC from the *status quo* for returnflows restricted, with and without management options (for DuPreez *et al,* 2000 R3 water quality scenarios)

	O2Pre+	OL98	R3Pre-	**R3LT**	R3Pre	R3Pre+	H2Pre
Ave.ECiw(mS/m)	***29.0***	***98.3***	***124.0***	***136.0***	***157.0***	***191.0***	***328.0***
OLsn	13.92%	8.66%	3.26%	**609874**	-5.21%	-13.13%	-33.85%
OLs+	13.92%	8.66%	3.26%	0.00%	-5.21%	-13.13%	-29.66%
OLsnc	13.92%	8.60%	2.84%	-0.57%	-5.87%	-15.04%	-42.39%
OLs+c	13.92%	8.60%	2.84%	-0.57%	-5.87%	-15.04%	-42.39%

The dual values determined in Table 5.36 for the return flow constraint show what the impact on TGMASC would be if the constraint were to be relaxed by one unit, or inversely, the cost to the farmer of constraining return-flows by one further unit. The higher dual value when fixed capital management options are implemented (OL+c) indicate that by implementing these management options, a far greater value per mm/ha water used can be obtained under poor water quality conditions.

Table 5.36 Dual prices (R/mm/ha) of the return flow constraint for Olierivier using DuPreez *et al,* 2000 R3 water qualities

	O2Pre+	OL98	R3Pre-	**R3LT**	R3Pre	R3Pre+	H2Pre
Ave.ECiw(mS/m)	***29.0***	***98.3***	***124.0***	***136.0***	***157.0***	***191.0***	***328.0***
Dual (OLnc)	0	0	0.05	0.6	1.14	1.69	1.31
Dual (OL+c)	0	0.6	1.91	1.52	3.85	4.17	3.43

The impact on TGMASC of changing the excess delivery capacity of the centre pivot irrigation system is shown in Table 5.37. Decreasing the excess delivery capacity from 20% to 10% results in the greatest decrease in TGMASC when return-flows are constrained (c) and no fixed capital management options (n) implemented (OLS n c CP1). These impacts are greatest for the worst-case scenario, H2Pre, results. There is no improvement from the *status quo* in TGMASC when increasing the excess delivery capacity of the centre pivot irrigation system from 20% to 30% except for H2Pre whether fixed capital management options are included or not (n and +) and only with return-flows not constraining. With return-flows constraining (*OLS n and + c CP3)* increasing the excess delivery capacity of the centre pivot irrigation system from 20% to 30% resulted in a marginal improvement (0.4%) of just over R2 000.

It must however be noted that a serious factor in increasing the delivery capacity of a centre pivot irrigation system is the infiltrability of the irrigated soils. Without proper infiltration the high deliveries that have to be given at the edge of the field can result in runoff and waterlogging, rendering leaching ineffective. A further limitation of centre pivot irrigation systems when using poor quality irrigation water is that foliar wetting takes place that can causes an additional salinity damage known as scorching, especially when irrigating germinating legumes and cotton. This is a factor not taken into consideration in SALMOD, as accurate information to incorporate this is unavailable. As scorching can be limited by good management, optimal management practices are assumed.

Table 5.37 The percentage change in Olierivier TGMASC from the *OLS n CP2* scenario values subject to centre pivot leaching ability changes using DuPreez *et al, (*2000:18) R3 water quality scenarios

	O2Pre+	*OVIB*	*R3Pre-*	***R3LT***	*R3Pre*	*R3Pre+*	*H2Pre*
OLS n&+ CP3	13.9%	8.7%	3.3%	0.0%	-5.2%	-13.1%	-26.8%
OLS + CP2	13.9%	8.7%	3.3%	0.0%	-5.2%	-13.1%	-29.7%
OLS n CP2	13.9%	8.7%	3.3%	**609 874**	-5.2%	-13.1%	-33.8%
OLS n&+ c CP3	13.9%	8.6%	2.8%	-0.6%	-5.9%	-15.0%	-42.0%
OLS n&+ c CP2	13.9%	8.6%	2.8%	-0.6%	-5.9%	-15.0%	-42.4%
OLS + c CP1	13.9%	8.5%	2.6%	-0.8%	-6.3%	-16.0%	-44.4%
OLS n c CP1	13.9%	8.5%	2.6%	-0.9%	-6.7%	-16.4%	-46.3%

With returnflows constrained the impact of the ability of centre pivot irrigation systems to deliver excess capacity to leach is reduced, as there is an incentive to reduce returnflows. The impact is largely offset by the implementation of fixed capital management options as can be seen when comparing the OLS n c CP1 and OLS + c CP1 rows.

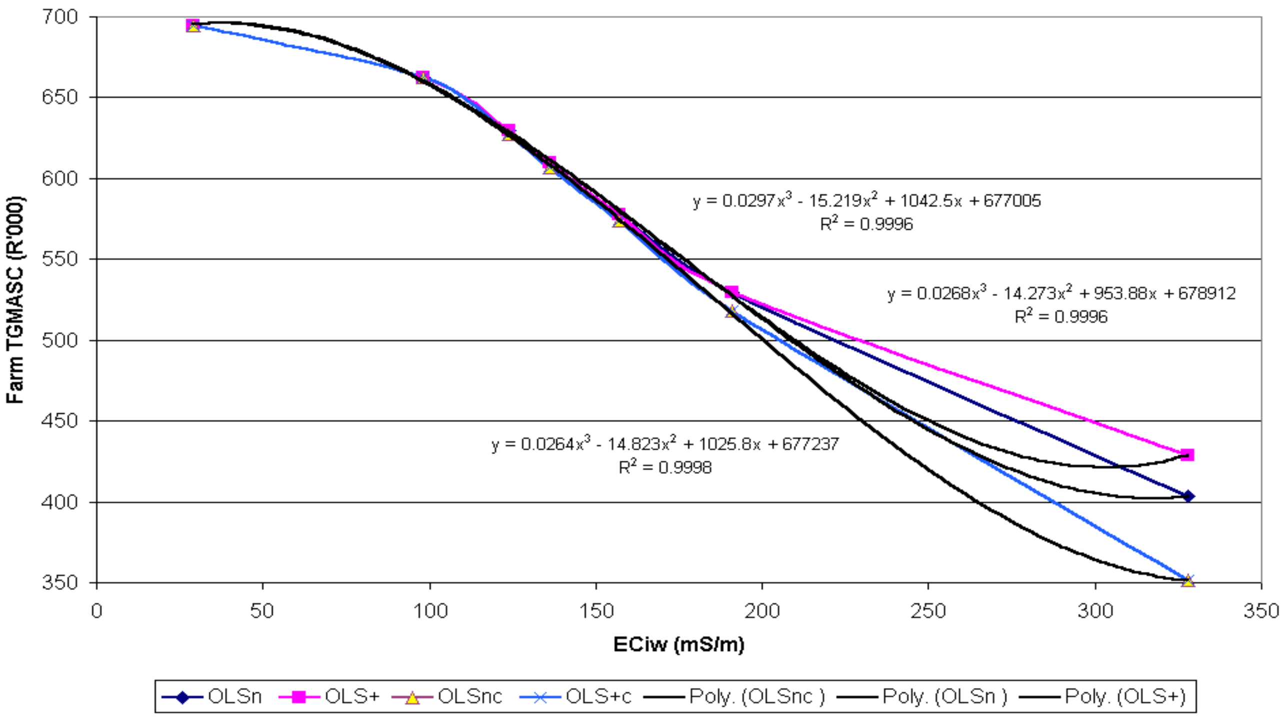

Figure 5.7 Third order polynomial functions of the effect of ECiw on TGMASC for the Olierivier case study farm with and without management options and with and without returnflows constrained

Third order polynomial functions 5.1 to 5.3, were derived for Olierivier to predict the effect of ECiw on TGMASC and which can be used in macro area and policy formulation models (see also Figure 5.7). It must be noted that these functions are only useful for the ranges specified above as going beyond the range will result in distorted values as the 3rd order polynomial function reaches a turning point and then proceeds in the opposite direction.

The bottom turning points for OLSn and OLS+ are reached within the end of the range resulting in positive gradients at H2Pre (328 mS/m).

$$OL+ \qquad y = 0.0297x^3 - 15.219x^2 + 1042.5x + 677005 \qquad (R^2 = 0.9996) \tag{5.1}$$

$$OLn \qquad y = 0.0268x^3 - 14.273x^2 + 953.88x + 678912 \qquad (R^2 = 0.9996) \tag{5.2}$$

$$OL+c = OLnc \qquad y = 0.0264x^3 - 14.823x^2 + 1025.8x + 677237 \qquad (R^2 = 0.9998) \tag{5.3}$$

Where: y is the TGMASC (in R'000) attainable under average water quality (ECiw) situation x.

The monthly water quality fluctuations follow the actual OVIB monthly average water quality fluctuations readings taken at Olierivier for 1998 as depicted in Figure 5.5.

5.5.2. SUB-AREA 2 RESULTS: VAALLUS

The monthly ECiw values in Figure 5.8 are the result of adjusting 1998 monthly average Vaallus ECiw readings to equal the annual predicted average ECiw of the various water quality scenarios determined by Du Preez *et al, (*2000). This is done so that the predicted average annual ECiw can be transformed into monthly water quality fluctuations.

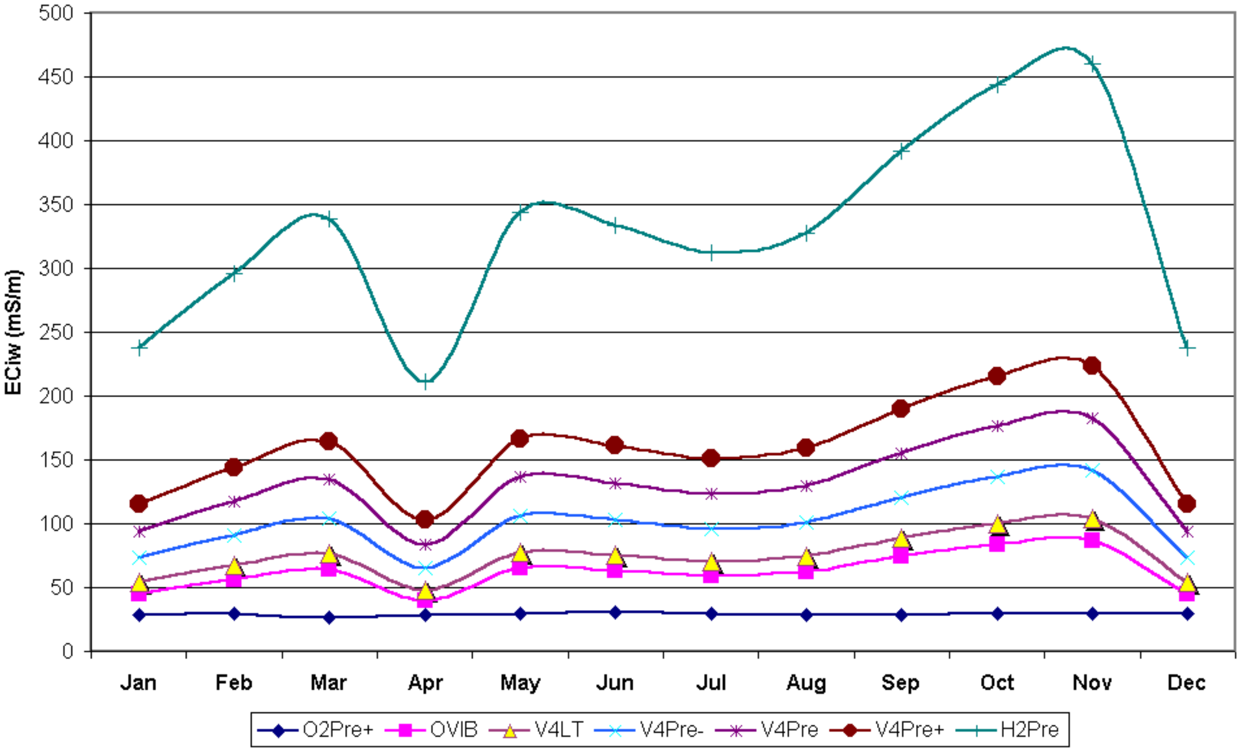

Figure 5.8 2020 predicted annual ECiw values based on OVIB 1998 monthly ECiw fluctuations for Vaallus.

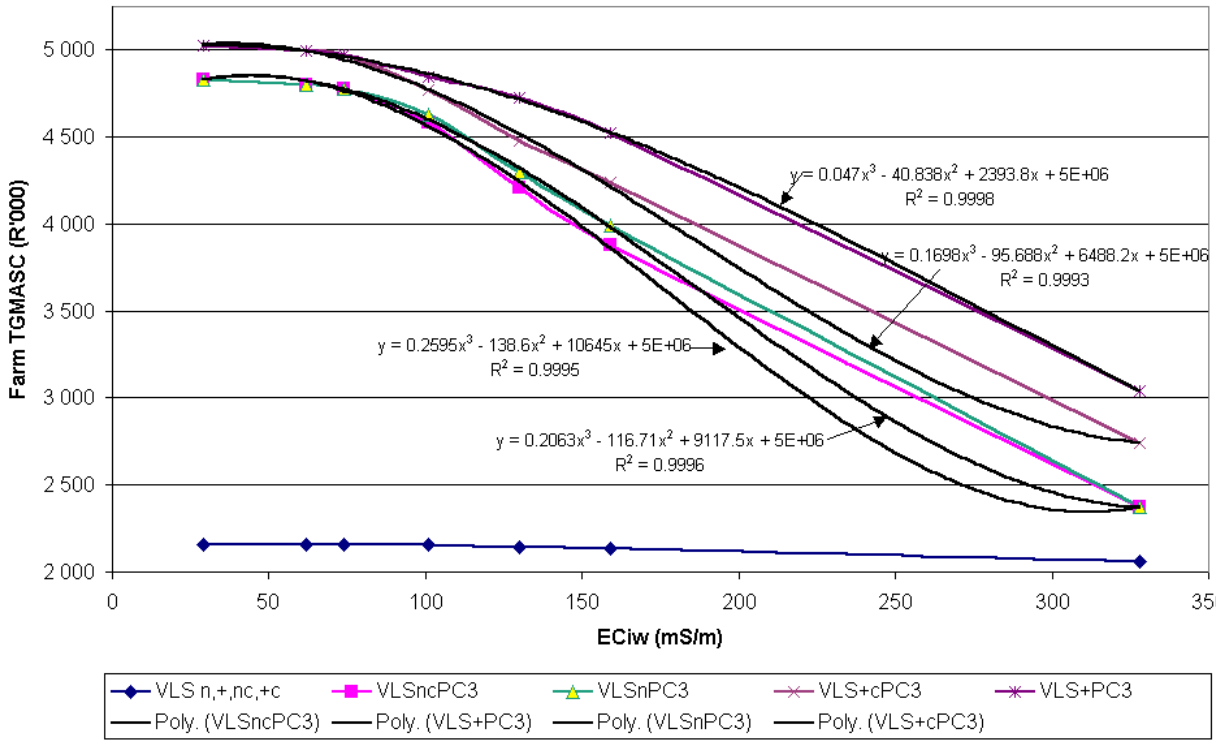

Figure 5.9 Third order polynomial functions of the effect of ECiw on TGMASC for the Vaallus case study farm, with production capital unconstrained, with and without management options and, with and without returnflows constrained

Third order polynomial functions (5.4 to 5.7) were derived for Vaallus and graphed in Figure 5.9 to predict the effect of ECiw on TGMASC with production capital unconstrained:

VLS+PC3 $y = 0.047x3 - 40.838x2 + 2393.8x + 5E+06 \quad R^2 = 0.9998$ **(5.4)**

VLScPC3 $y = 0.1698x3 - 95.688x2 + 6488.2x + 5E+06 \quad R^2 = 0.9995$ **(5.5)**

VLSnPC3 $y = 0.2063x3 - 116.71x2 + 9117.5x + 5E+06 \quad R^2 = 0.9996$ **(5.6)**

VLSncPC3 $y = 0.2595x3 - 138.6x2 + 10645x + 5E+06 \quad R^2 = 0.9995$ **(5.7)**

Where: y is the TGMASC (in R'000) attainable under average water quality (ECiw) situation x.

The monthly water quality fluctuations follow the actual OVIB monthly average water quality fluctuations readings taken at Vaallus for 1998 as depicted in Figure 5.8. The impact of relaxing the production capital constraint (increasing it three-fold) results in a far greater impact under good ECiw values (124% improvement for O2Pre+) than under poor ECiw values (only 10% for H2Pre).

As Du Preez *et al*, 2000 only provide future scenario results for the lower Vaal River as a whole and not for the specific sub-areas used in this study, this analysis is not conducted for the sub-areas, Bucklands, Atherton and New Bucklands. The impact of Du Preez *et al*, 2000 scenarios for the Lower Vaal River on the TGMASC of these sub-areas are show in the following section.

5.5.3. OVIB SUB-AREA COMPARISON

The impact of different predicted irrigation water qualities on the sub-area case study farms TGMASC is compared in Table 5. For all sub-area model runs returnflows are not constraining and fixed capital management options are not implemented so as to compare the optimal results for the case study farms for each sub-area under their current conditions, and not their potential optimal conditions.

Table 5.38 The percentage change in sub-area TGMASC (R) for the predicted ECiw values determined by Du Preez *et al,* and with no fixed capital management options *(*2000:18)*)*

	O2Pre+	***OVIB***	***V4LT***	***V4Pre-***	***V4***	***V4Pre+***	***H2Pre***
NB	0.06%	0.06%	**876 963**	-0.20%	-1.99%	-3.18%	-33.49%
BL	30.06%	12.01%	**71 856**	-26.72%	-55.25%	-84.13%	-100.00%
AT	0.00%	0.00%	**102 786**	-9.92%	-38.72%	-57.61%	-100.00%
VL	0.00%	0.00%	**2 158 249**	0.00%	-0.61%	-1.01%	-4.51%
OL-V4	1.60%	1.09%	**683 796**	-3.42%	-9.28%	-15.84%	-40.79%
OL-R3	13.92%	8.66%	3.26%	**609 874**	-5.21%	-13.13%	-33.85%
VL-R3	0.62%	0.62%	0.00%	**2 144 990**	-0.21%	-1.29%	-3.92%
	O2Pre+	***OVIB***	***R3Pre-***	***R3LT***	***R3Pre***	***R3Pre+***	***H2Pre***

Table 5. shows that under the worst-case water quality scenario (H2Pre) the Bucklands(BL) and Atherton(AT) case study farms will experience a 100% reduction in TGMASC from the V4LT value. The farm least affected by the H2Pre water quality scenario is the Vaallus (VL) farm, experiencing only a 4.51% reduction in TGMASC. The BL and AT farms are the smallest and the VL farm the largest. The reason however is not only farm size, but also natural resource endowment and most importantly the choice of crops to be grown. BL and AT farms are set in SALMOD to produce only lucerne and lucerne and wheat respectively, whereas the VL farm also has the option of including cotton, which is moderately tolerant to saline conditions. Similarly, as the BL farmer can only grow lucerne the impact on TGMASC of an improvement of irrigation water quality to O2Pre+ levels results in the largest (30.06%) potential increase.

What rows OL-V4 shows is the impact of the Vaal River segment 4 (V4) monthly water quality fluctuation patterns applied to the Olierivier case study farm. The same annual average water quality predictions are just applied to different monthly water quality fluctuation patterns, resulting in an approximately 12.12% TGMASC improvement when using the Vaallus 1998 monthly ECiw pattern instead of the Olierivier ECiw pattern for Olierivier case study farm, while using the Riet River segment 3 (R3) monthly water quality fluctuation patterns for the Vaallus case study farm results in only a 0.61% reduction in TGMASC.

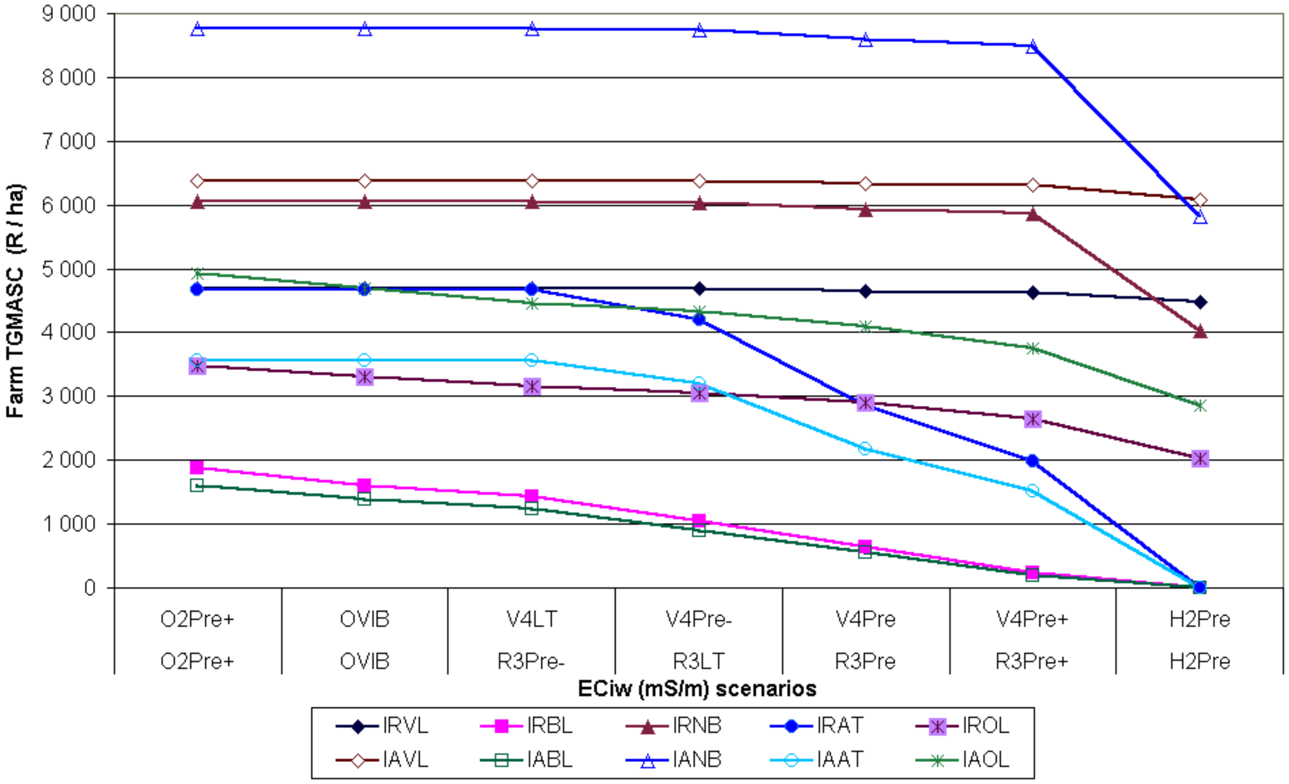

Figure 5.10 TGMASC per hectare irrigable area (IA) and per hectare irrigation rights (IR) held for irrigation water salinity scenarios as determined by Du Preez et al, (2000)

Figure 5.10 compares the 5 case study farms on a TGMASC per hectare irrigable area (IA..) and TGMASC per hectare irrigation water rights (IR..) basis. Case study farmers who have more hectares irrigation water rights (IR) than hectares irrigable land area (IA) will show better results on a per hectare irrigable land area (IA) basis.

On a per hectare irrigation water rights held basis (IR..), the New Bucklands case study farmer (IRNB) shows the best results, closely followed by the Vaallus case study farmer (IRVL) with TGMASC R6051-R4042 and R4682-R4470 respectively for the ECiw range of 20 to 160 mS/m. The Atherton case study farmer (IR-AT) does better than the Bucklands case study farmer (IRL) although holding half the hectares water right, and also does better than the Olierivier case study farmer (IROL) until V4Pre/R3Pre after which IR-AT quickly approaches zero at H2Pre. The Olierivier case study farmer (IROL) follows with much lower TGMASC results of between R2017 and R2434 for the ECiw range of 20 to 160 mS/m. Between an ECiw of 20 and 100 mS/m, TGMASC is around R4 600 for IR-AT but falls sharply after 100 mS/m and is zero at 328 mS/m (H2Pre). Between an ECiw of 20 and 100 mS/m, TGMASC gradually declines from around R1800 to nearly R1 000 for IR-BL and continues almost linearly till nearly R1 000 at and ECiw is 150 mS/m and is then zero at 328 mS/m.

On a per hectare irrigable area basis (IA..), TGMASC for IANB and IAVL are very similar at just below R8 000 with ECiw between 20 and 160 mS/m, but at the worst case ECiw, IAVL outperforms IANB. IAAT TGMASC also outperforms IAOL TGMASC at and ECiw between 29 and 101 mS/m, but as ECiw deteriorates IAAT TGMASC drops fast and reaches zero at 328 mS/m. IAOL TGMASC drops gradually from just below R5 000 at 29 mS/m till just above R3 000 at 328 mS/m. IABL TGMASC is only slightly better than IABL for an ECiw of 29 to 159 ES/m but also reaches zero at 328 mS/m.

Of significance in Figure 5.10 is that on the two small farms, AT and BL, TGMASC drops more rapidly than on the larger farms, and at the ECiw worst-case scenario level of 328 mS/m these two small farms have a TGMASC of zero, while the larger farms are not as dramatically affected. One of the reasons for this is the limited crop choice that the smaller farmers currently plant.

5.5.4. A SUMMARY OF SALMOD RESULTS USING PREDICTED SALINITY LEVELS FOR 2020

The impact of implementing the worst-case scenario of receiving the predicted Harts River water salinity from Spitskop Dam (328 mS/m) results in a major drop in TGMASC for all scenarios from the Lower Riet long-term average water salinity (136 mS/m).

Constraining production capital can have a large effect on TGMASC under ideal water salinity conditions, but as water salinity deteriorates the impact becomes less, while the impact of constraining irrigation returnflows on TGMASC increases as water quality decrease.

The third order polynomial functions derived for the Olierivier case study farmer for both return-flow and management options, and for the Vaallus case study farmer with both management, return-flow and production capital options, should prove useful in predicting the financial effect on the Olierivier and Vaallus case study farmers under any irrigation water salinity level within the analysed range.

Farming profitability of small farmers drops more rapidly than for larger farms, and by ECiw levels of 328 mS/m the smaller farms go out of production, while the larger farms are not as dramatically affected. One of the reasons for this is the limited crop choice that the smaller farmers currently plant due to management, labour and mechanisation constraints, and their generally poor resource endowment.

CHAPTER 6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Swarms of living creatures will live wherever the river flows. There will be large numbers of fish, because this water follows there and makes the salt water fresh; so where the river flows everything will live.

Ezekiel 47:8-10

6.1. SUMMARY

In the Lower Vaal and Riet Rivers, changing irrigation water quality has raised concern about the long-term sustainability of irrigation due to reduced crop yields of some crops and even the withdrawal of other crops in some regions.

The main aim of this study is to develop and apply models to determine the long-term financial and economic viability of irrigation farming in the Lower Vaal and Riet Rivers, with specific aims to: evaluate the relationship between changing water quality, soil conditions and crop production; determine the impact on yield, crop choice, agronomic and water management practises, expected income and costs; develop models for typical farms in different river reaches, and apply these models to test the outcome of alternative scenarios regarding internal water quality management practises and external policy measures.

This study proceeded as follows to achieve these aims; the term water quality was first defined to identify the key problematic constituent in the Lower Vaal and Riet Rivers. The study area was delineated as the OVIB service area. A pilot survey was conducted to determine the magnitude and distribution of the problem and to identify case study farmers. Once identified, financial data was collected from *inter alia* the case study farmers and inputted into SALMOD which was developed to simulate crop enterprise gross margins under a range of resource conditions and to maximise total farm gross margin above specified costs (TGMASC) by determining the optimal crop and management combinations subject to the resource constraints.

The term water quality was defined as a broad term used that encompasses a range of constituents that can modify a volume of water resulting in a change in its utility value. In the Lower Vaal and Riet Rivers the primary water quality constituent of concern impacting the financial status of irrigation farms was identified as salinity.

A study by Du Preez *et al, (*2000) identified the Spitskop Dam below the Vaal-Harts irrigation scheme as one of the water bodies within the Lower Vaal and Riet Rivers with the highest salinity levels and the greatest potential for further rapid decline, it was closely followed by the Lower Riet River and then the Lower Vaal River, both of which are situated in the OVIB region. As the Spitskop Dam only serves a very small irrigation community and very little water is released from the Spitskop Dam back into the Vaal River, the OVIB region was chosen as the study area as it is a very important irrigation region within South Africa and the complex interaction of the hydraulic systems impacting on the area make it a more applicable region.

The diversion of Orange River water into the Lower Vaal and Riet Rivers has a major effect on improving the salinity in the study area. With the possibility of a reduction in Orange River supply following the outcome of the Orange River Development Project Replanning Study (DWAF 1998) this crucial dilution effect could be reduced.

The OVIB has 178 irrigation farmer members communally holding 8097 ha of irrigation rights of which nearly one quarter (1861 ha) are either slightly or severely affected by waterlogging or salinisation. 49% of the land irrigated is either medium or low potential irrigation land, 28% of the area is flood irrigated and 70% sprinkler irrigated with the trend being conversion to centre pivot irrigation (Van Heerden *et al*, 2000).

Five case study farmers were selected, one from each of the different sub-areas of the OVIB. The case study farmers were representative of their sub-areas with regards to the hectares of irrigation water rights held, and jointly, also sufficiently representative of the OVIB region.

With the contradicting aims of improved water use efficiency and increased leaching for salinity management, the importance of a financial optimisation model was evident to solve the apparent paradox between saving water due to it's scarcity value and "wasting" water to leach out salts that build up in soils through the process of irrigation.

SALMOD was constructed using GAMS and consists of a simulation and optimisation section that calculate the optimal crop enterprise, management and resource use combination that maximises farm returns under different water quality, management and policy scenarios.

The management options built into SALMOD are the appropriate leaching fraction to implement, and crop yield to accept for the optimal crop / resource combination calculated. The fixed capital management options included in SALMOD are the installation of artificial drainage, the change of irrigation system and the building of on-farm storage / evaporation dams for return-flow management.

Useful third order polynomial functions were derived from the results generated by SALMOD to determine the financial impact on the variable cost component of irrigation water salinity for OVIB sub-areas.

The shadow prices for irrigation water of different qualities indicate what farmers can afford to pay for irrigation water of different qualities.

6.2. CONCLUSIONS

Irrigation water quality and particularly salinity, reaches levels in the Lower Vaal and Riet River that are harmful to certain crops irrigated. Saline irrigation water however irrigated onto soils is transpired as pure water leaving the salts behind in the soil. These salts accumulate over the long term and reach levels rendering soils sub-optimal for crop production. A way to manage salt build up in soils is to apply excess irrigation water to leach the accumulated salts out of the soils. Results from SALMOD show that it is feasible to leach. To leach however, soils have to have sufficient infiltrability and irrigation systems with extra excess capacity to irrigate sufficient water to cover the plant water requirements and the leaching fraction.

The option of installing artificial drainage in waterlogged and limited drainage fields is a fixed capital management option built into SALMOD. For the New-Bucklands case-study farm where water quality isn't a problem, results show that the installation of artificial drainage on waterlogged soils is feasible while for the Olierivier case study farmer where water quality is worst in the study area draining waterlogged soils is infeasible.

The increased point-source returnflows generated by the installation of artificial drainage needs to be managed, so as not to cause externalities to other farmers extracting irrigation water from where the returnflows re-enter the water source. Another fixed capital management option was built into SALMOD to manage irrigation returnflows, namely the construction of on-farm storage / evaporation dams. Results however also showed that with irrigation water returnflows constrained it was infeasible for case-study farmers to construct the on-farm storage dams. Financial losses incurred from not exceeding the maximum return-flow levels allowed were less than the financial gains from being able to continue to leach for optimal crop production minus the annualised costs of constructing on-farm storage dams.

The % reduction in TGMASC from the long-term average ECiw (74 mS/m) to the worst expected Vaal River ECiw as predicted by Du Preez *et al, (*2000) for 2020 (159 mS/m), is 84 and 58% for the small farmers from Bucklands and Atherton respectively, between 13 and 16% for the Olierivier farmer, depending on whether the Vaal River of the Riet River has the major impact, 1% for the large and financially strong Vaallus farmer and 3% for the small yet resource strong New Bucklands farmer (see Table 5.38). These results clearly show that the small and resource poor farmers will be the most affected by irrigation water salinity deterioration.

Scenario results from SALMOD further show that:

- Leaching is financially viable for all case study farmers
- Accepting lower yields on soils with insufficient leaching capacity is also financially viable
- For farmers with limited area of well drained soils it can be financially viable to install artificial drainage
- The option of building on-farm storage dams when returnflows are constrained to 100 mm per hectare water rights held, is financially infeasible for all case-study farms and for all scenarios
- It is not financially viable for farmers to replace their current irrigation systems with more efficient systems, but in some instances with systems that can apply a greater leaching fraction
- At the worst-case scenario salinity conditions, farmers with below 60 ha water rights, and who don’t grow cotton, will go out of production.

SALMOD has proved to be a valuable farm level salinity management tool. SALMOD is also potentially useful at regional and national level for determining the farm level financial impacts of various water quality and quantity scenarios where the farmers are affected by irrigation water salinity.

6.3. RECOMMENDATIONS

6.3.1. POLICY CONSIDERATIONS

6.3.1.1 Reinstate subsidisation of irrigation drainage

No irrigation system is sustainable without sufficient drainage. Unless natural drainage till below the root zone is sufficient and water tables aren't rising, artificial drainage has to be installed. Quoting Du Preez *et al, (*2000:154) "Results from these estimations (Szabolcs model) indicate that all the undrained soils will, due to excessive salt accumulation, become unsuitable for irrigation by approximately the year 2050." To reinforce this, Brady & Weil (1996:307) state, "If the irrigation system does not provide good internal drainage, soil salinity can increase to intolerable levels, as can the exchangeable sodium level. The latter engenders chemical and physical problems that, if not corrected, will render a soil virtually useless as a habitat for plants."

Subsidising irrigation drainage on it's own however, will lead to the exacerbation of the water quality problem, especially in closed hydraulic system such as in the Lower Vaal and Riet Rivers, because of the greater mobilisation of salts in the system facilitated through the artificial drainage.

A major advantage of managing / monitoring an irrigation systems with irrigation drainage is that, what was a non-point / diffuse pollution source is now a point-source pollution problem that can be measured, monitored, and controlled and accordingly a possibility of imposing waste discharge charge (WDC) system.

6.3.1.2 Consider putting constraints on returnflows

Subsidising irrigation drainage will lead to an increase in irrigation returnflows that in turn will increase the salinity levels in the rivers they flow into if controls aren't placed on irrigation returnflows. The environment is also not protected from the agricultural chemicals and salts that these returnflows would deposit into the river if not managed. Coupled with artificial drainage subsidisation there therefore has to be a constraint on agricultural returnflows and possibly also the subsidisation and promotion of on-farm management practises to manage irrigation returnflows.

Putting a limit on the volume of irrigation returnflows allowed might solve the river water quality problem but soil salinisation will proceed because the incentive for leaching is removed.

A waste discharge charge (WDC) system can only be effective where return-flows are point source – A model such a SALMOD can simulate the contribution of an irrigation practise to non-point source pollution, but the results will always be sceptical and untrustworthy to the perpetrator.

6.3.1.3 Consider subsidisation of on-farm storage/evaporation ponds

In the US and Australia there are stringent controls on irrigation returnflows from being allowed to re-enter the water source. There are either canals that transport the irrigation returnflows to irrigation scheme managed evaporation basins or wetlands, or the farmers have their own evaporation ponds and / or practise serial biological concentration (SBC). In SBC the saline returnflows from a salt sensitive crop are used to irrigate a moderately tolerant crop, and the even more saline returnflows from this crop are used to irrigate salt tolerant crops (halophytes) or woodlots or are used for aquaculture. This promotes greater water use efficiency, but requires large capital expenditure and management expertise.

By implementing a policy to constrain returnflows, river and groundwater water quality will be improved and prevented from deteriorating further. Under these improved water quality conditions the returnflows from the resulting optimal crop compositions could be less than the maximum specified in the constraint, making the returnflows constraint no longer necessary once farmers are using and managing their on-farm storage dams properly. This constraint is however initially required to get farmers to install drainage and build on-farm storage dams. Constraining irrigation returnflows must be coupled with the incentives of artificial drainage subsidisation and on-farm storage dam subsidisation.

6.3.2. PROVISION OF LASER LEVELLING AND SOIL SALINITY MAPPING SERVICES

The Provision of laser levelling and soil salinity mapping services needn’t be state supplied, but entrepreneurial opportunity exists in supplying these services. The Orange Vaal Water Users Association or GWK Ltd. could provide the service or put out a tender.

Although the model didn’t show it was feasible to change the irrigation system for any case study farmers under any salinity scenario, it must be brought to the attention of irrigation system designers to make provision in new centre pivot irrigation systems for greater application capacities for the provision for sufficient irrigation leaching. This was identified as a problem in the study area in the Du Preez *et al, (*2000) report.

What wasn’t taken into account in SALMOD was the leaf wetting effects of sprinkler type irrigation systems. High concentrations for certain inorganic salts in the irrigation water can cause leaf scorching.

Although laser levelling and salinity mapping were not studied implicitly in this study, the latest literature and trends in salinity management reveal that these salinity management options are being widely used.

Laser levelling for flood irrigation could provide a cheaper, and very nearly as efficient method of irrigation as centre pivot irrigation without the leaf wetting effect and much greater capacities to leach. The installation of artificial drainage is also easier on a laser-levelled field.

Soil salinity mapping is conducted using a global positioning system (GPS) linked to an electrical conductivity field meter such as the Geonics EM-38 meter. The vehicle on which these instruments are mounted traverses the field taking regular bulk soil electrical conductivity (ECa) readings. These spatial readings are statistically processed to provide soil salinity contours. A soil sample is then taken from each contour grouping and analysed to get the ECa and ECe correlation. Soil salinity mapping provides infield identification of problem areas so that with remediation only the problem areas need to be managed and with regular soil salinity readings the effectiveness of a leaching management strategy on salinity control can be gauged.

6.3.3. FURTHER RESEARCH NEEDS / SHORTCOMINGS OF THIS STUDY

The purpose of the National Water Act (39 of 1998) is to ensure that the Nation’s water resources are protected, used, developed, conserved, managed and controlled, to *inter alia* promote the efficient, sustainable and beneficial use of water. Further research to ensure the financial sustainability of irrigation schemes in South Africa is essential to ensure national food security and employment in some otherwise barren area of the country. It has been predicted that by the year 2025 South Africa will be the only surplus food producer in the whole of Sub-Saharan Africa, thus making the stability of food supply made possible by irrigated agriculture a stabilising force not only in South Africa but also in most of the rest of Africa. Declining water quality levels in most of our rivers however threaten the productive use of this water for food production.

With irrigation being the largest user of water, micro research that can contribute to more efficient water use and better water quality management is essential to maintain our most valuable resource and the agriculture it supports. However, macro research is also needed to place into perspective the national benefit of improving water use efficiency and better water quality management and the costs of not doing so, and to guide the public policy making process in the right direction. Furthermore, macro research takes into consideration the secondary economic, socio-economic and environmental effects that stem from the results of the micro research.

The dynamics of water -use, -pollution and -control are so tightly interwoven by a multitude of external factors that the traditional style of mono-disciplinary research is no longer suited to achieve overall satisfactory results (McKinney et al. 2000). To proactively manage and implement policy to anticipate problems and sustainably introduce change, the correct research tools are necessary.

By understanding the full dynamics and interactions between irrigation water quality and the soil salinity status on crop yield over irrigated time, mistakes made in the past by choosing unsustainable irrigation sites can be prevented. Furthermore the impact of various natural or artificial (e.g. policy mechanism) scenarios on existing schemes could be more accurately modelled, leading to increased economic efficiency and sustainability of the irrigation industry as a whole. However "current USDA Salinity Laboratory evidence suggests these interactions are far more complex than originally thought. …. Rhoades, the doyen of soil/plant/salinity interactions, contends that no one has succeeded in combining all the refinements necessary to overcome the inherent problems of relatively simple salt balance models and geophysical sensors, to address the enormous field variability of infiltration and leaching rates" (Blackwell, et al. 2000).

Current literature and research on salinity management in irrigation agriculture also fails to capture the stochastic nature of inter-seasonal irrigation water quality as well as the cumulative economic and sustainability effects of irrigating with stochastic water quality levels. "Further limitations for setting criteria for salinity include: (i) the need to make assumptions about the relationship between soil saturation extract salinity (for which yield response data is available) and soil solution salinity. (ii) the deviation of the salinity of the soil saturation extract from the mean soil profile salinity, to which crops would respond. (iii) The criteria for crop salt tolerance do not consider differences in crop tolerance during different growth stages" (DWAF, 1996).

The water quality problem set out to be studied was initially perceived with the main variable being the water quality changes of in stream irrigation water. DWAF data recorded over many years was studied and incorporated into models, but the essence of the problem remained unresolved. This being the indirect and long-term accumulation effects of irrigation water carried constituents within irrigated soils and their underlying water tables, and the effects of the resulting returnflows from these soils and groundwater on downstream irrigation water quality.

Salinity, is the term used to represent a group of these constituents, namely the inorganic salts, comprising mainly Sodium (Na) and Chloride (Cl). Sodicity, usually coupled with salinity is measured by the ability of

Sodium to displace Calcium (Ca) and Magnesium (Mg) in soils, leading to a degradation of soil structure and an accumulation of sodium that is non-beneficial to plant growth. The only way to remediate these soils is to “flush” out the accumulated salts through leaching and to displace the sodium with calcium sources. However “leaching to maintain an acceptable salt balance in the root zone is often considered by non-specialists as wasteful, especially as irrigation engineers and scientists appear to be to be in doubt about the required leaching rates and the efficiency of the leaching practise” (Kijne, J.W. et al. 1998).

And also, “if the irrigation systems do not provide good internal drainage, soil salinity can increase to intolerable levels, as can the exchangeable sodium levels. The latter engenders chemical and physical problems that, if not corrected, will render the soil virtually useless as a habitat for plants” (Brady & Weil, 1996).

Currently, degraded returnflows from 3 major irrigation schemes comprising ± 60 000 ha all come together at the Douglas weir. Presently, of the main focuses of the Orange River Project are to: “provide irrigation water to areas in the Riet River catchment, as well as water to alleviate water quality problems in the Vaal River at Douglas”. Obviously, a large transfer of water from the upper reaches of the Orange River (due to the Orange River Replanning Project) will have a significant influence on the water availability further downstream and therefore influence the supply (and salt dilution) capabilities of the Orange River Project.” (DWAF 1998).

Concerning land redistribution, areas within the study area are earmarked for resettlement of historically disadvantaged individuals. To avoid making mistakes of the past and designing irrigation schemes in areas that might not be economically and environmentally sustainable, a thorough understanding of potentially land degrading processes such as salinisation, sodification, waterlogging etc. is essential.

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APPENDIX 1. SUB-AREA CASE STUDY FARMER CROP ENTERPRISE BUDGETS USED IN SALMOD, 1999

Wheat	**OL**	**VL**	**AT**	**BL**	**NB**	**GWK**	**Ave**	**Combud**
PRICE	1072	1022	1060	0	918	780	1018	650
YIELD	5	6	10	0	7	7	7	8
SEED	483	108	1900	0	247	237	685	182
FERT	950	1388	1300	0	1072	1214	1177	1045
HERB	158	98	300	0	6	61	141	27
PEST	0	5	0	0	0	408	5	36
INSUR	125	98	520	0	0	180	248	0
HARV	97	1	52	0	52	63	69	93
MHLR	16	16	16	0	16	16	16	16
KWHR	343	343	343	0	343	343	343	343
WAT	74	82	211	0	121	111	122	72
ELEC	245	123	253	0	198	345	205	597
CAP	87	51	211	0	97	0	111	178
FUEL	142	286	390	0	119	150	234	346
MAINT	393	530	172	0	279	51	343	0
LABOR	507	504	597	0	446	86	514	92

Maize	**OL**	**VL**	**AT**	**BL**	**NB**	**GWK**	**Ave**	**Combud**
PRICE	599	1253	570	0	895	580	829	650
YIELD	9	11	9	0	11	12	10	8
SEED	255	790	2000	0	219	411	816	182
FERT	1039	302	3250	0	1149	1346	1435	1045
HERB	0	294	750	0	6	321	350	27
PEST	0	200	0	0	0	71	200	0
INSUR	0	401	625	0	0	209	513	0
HARV	0	0	69	0	52	72	64	93
MHLR	40	40	40	40	40	40	40	40
KWHR	329	329	329	329	329	329	329	329
WAT	121	330	228	0	95	128	194	72
ELEC	399	499	273	0	157	398	332	597
CAP	130	77	126	0	97	0	107	0
FUEL	212	429	234	0	119	236	249	150
MAINT	589	795	103	0	279	0	442	51
LABOR	760	757	358	0	446	75	580	86

*** Where: PRICE=price(R/t), YIELD=yield(t/ha), SEED=seed costs (R/ha), FERT=fertilizer costs(R/ha), HERB=herbicide costs(R/ha), PEST=pesticide costs(R/ha), INSUR=insurance costs(R/ha), HARV=harvesting costs (R/t), MHLR=Max.hours of labour required, KWHR=kilowatt hours required, WAT=water costs (R/ha), ELEC=electricity costs (R/ha) ,CAP=capital cost(R/ha), FUEL=fuel costs(R/ha), MAINT=maintenance costs (R/ha) and LABOR=labour costs (R/ha)**

Groundnuts	**OL**	**VL**	**AT**	**BL**	**NB**	**GWK**	**Ave**	**Combud**
PRICE	2167	0	0	0	864	0	1516	0
YIELD	2	0	0	0	3	0	3	0
SEED	1200	0	0	0	383	0	792	0
FERT	1333	0	0	0	849	0	1091	0
HERB	67	0	0	0	6	0	36	0
PEST	0	0	0	0	0	0	0	0
INSUR	0	0	0	0	0	0	0	0
HARV	67	0	0	0	52	0	63	0
MHLR	312	0	0	0	312	0	312	0
KWHR	343	0	0	0	343	0	343	0
WAT	102	0	0	0	82	0	92	0
ELEC	336	0	0	0	135	0	235	0
CAP	260	0	0	0	145	0	203	0
FUEL	425	0	0	0	179	0	302	0
MAINT	1178	0	0	0	419	0	798	0
LABOR	1521	0	0	0	669	0	1095	0

Potato	**OL**	**VL**	**AT**	**BL**	**NB**	**GWK**	**Ave**	**Combud**
PRICE	633	955	0	0	0	0	794	1125
YIELD	30	45	0	0	0	0	38	28
SEED	1500	0	0	0	0	0	1500	0
FERT	1000	17257	0	0	0	0	9129	0
HERB	700	0	0	0	0	0	700	0
PEST	0	0	0	0	0	0	0	0
INSUR	0	0	0	0	0	0	0	0
HARV	283	0	0	0	0	0	227	54
MHLR	424	424	0	0	0	0	424	424
KWHR	500	0	0	0	0	0	500	500
WAT	141	0	0	0	0	0	141	0
ELEC	466	0	0	0	0	0	466	0
CAP	521	307	0	0	0	0	414	178
FUEL	849	1717	0	0	0	0	1283	346
MAINT	2356	3179	0	0	0	0	2768	0
LABOR	3041	3026	0	0	0	0	3034	92

*** Where: PRICE=price(R/t), YIELD=yield(t/ha), SEED=seed costs (R/ha), FERT=fertilizer costs(R/ha), HERB=herbicide costs(R/ha), PEST=pesticide costs(R/ha), INSUR=insurance costs(R/ha), HARV=harvesting costs (R/t), MHLR=Max.hours of labour required, KWHR=kilowatt hours required, WAT=water costs (R/ha), ELEC=electricity costs (R/ha) ,CAP=capital cost(R/ha), FUEL=fuel costs(R/ha), MAINT=maintenance costs (R/ha) and LABOR=labour costs (R/ha)**

Cotton	**OL**	**VL**	**AT**	**BL**	**NB**	**GWK**	**Ave**	**Combud**
PRICE	0	2631	0	0	0	0	2631	0
YIELD	0	3	0	0	0	0	3	0
SEED	0	102	0	0	0	0	102	0
FERT	0	158	0	0	0	0	158	0
HERB	0	0	0	0	0	0	0	0
PEST	0	71	0	0	0	0	71	0
INSUR	0	0	0	0	0	0	0	0
HARV	0	501	0	0	0	0	501	0
MHLR	0	216	0	0	0	0	216	0
KWHR	0	329	0	0	0	0	329	0
WAT	0	173	0	0	0	0	173	0
ELEC	0	262	0	0	0	0	262	0
CAP	0	153	0	0	0	0	153	0
FUEL	0	859	0	0	0	0	859	0
MAINT	0	1590	0	0	0	0	1590	0
LABOR	0	1513	0	0	0	0	1513	0

Lucerne	**OL**	**VL**	**AT**	**BL**	**NB**	**GWK**	**Ave**	**Combud**
PRICE	413	0	393	375	115	0	324	0
YIELD	15	15	17	15	19	0	16	0
SEED	0	0	130	210	116	0	152	0
FERT	0	0	228	690	861	0	593	0
HERB	0	0	0	188	6	0	97	0
PEST	0	0	0	0	0	0	0	0
INSUR	0	0	0	0	0	0	0	0
HARV	0	0	0	60	0	0	56	0
MHLR	56	0	56	56	56	0	56	0
KWHR	357	0	357	357	357	0	357	0
WAT	186	0	398	196	82	0	216	0
ELEC	617	0	477	132	136	0	340	0
CAP	260	0	506	0	193	0	320	0
FUEL	425	0	937	653	239	0	563	0
MAINT	1178	0	412	0	558	0	716	0
LABOR	1521	0	1433	2683	892	0	1632	0

*** Where: PRICE=price(R/t), YIELD=yield(t/ha), SEED=seed costs (R/ha), FERT=fertilizer costs(R/ha), HERB=herbicide costs(R/ha), PEST=pesticide costs(R/ha), INSUR=insurance costs(R/ha), HARV=harvesting costs (R/t), MHLR=Max.hours of labour required, KWHR=kilowatt hours required, WAT=water costs (R/ha), ELEC=electricity costs (R/ha) ,CAP=capital cost(R/ha), FUEL=fuel costs(R/ha), MAINT=maintenance costs (R/ha) and LABOR=labour costs (R/ha)**

APPENDIX 2. LIST OF SALMOD ABBREVIATIONS

Abbreviation	***Ref***	***Key***	***Explanation***
ADDS(DS)	DS	SS	Individual soil drainage status
ADS	DS	SE	Artificially drained soils
AMT	PLD	SE	Amount
APR	T	SE	April
AT	SR	SE	Atherton (3)
AUG	T	SE	August
AY(T)	T	SS	After-Year
AYWU		SC	Allowable After-year water use (%fraction)
BL	SR	SE	Bucklands (4)
C		S	Main annual Crops produced in the study area
CAP	IO	SE	CAPITAL GOODS repayments
CLY	S	SE	Clay soils >45% Clay
COFSD		SC	Total cost of 1 on-farm storage dam (R)
COSTDAT		S	Cost Data
COTTON	C	SE	Cotton
CPI	IS	SE	Centre Pivot Irrigation System
CROP_DATA(C,*)	C,*	T	A table heading for crop data required in SALMOD
CROPDAT		S	Crop Data
CSF		S	Case study farmer data set
CSFD(SR,CSF)	SR,CSF	T	Sub-area land and cost data
CTI(IS)	IS	SS	Individual irrigation system
DEC	T	SE	December
DIS	IS	SE	DRIP Irrigation System
DS		S	Soil drainage status
DTI(IS)	IS	SS	Individual irrigation system
EBTable(IO,C,SR)		T	Enterprise budget table for OVIB region
ECRW		SC	Electrical conductivity of rain water (mS per m)
ELEC	IO	SE	Electricity pumping costs in R per ha
EVAPY		SC	Evaporation - surface water (ha-mm\dam\yr)
F		S	Water Fines
FAY(F)	F	SS	After-Year fines
FC		SE	Sub-area representative farm non-allocatable annual fixed costs (R per annum)
FEB	T	SE	February
FERT	IO	SE	Fertilizer costs in R per ha
FIS	IS	SE	Flood Irrigation System
FLR		SC	Fuel cost:lubrication cost ratio (%)
FMR		SC	Fuel cost: maintenance cost ratio (%)
FORCE		SC	A constant used to eliminate an option if too high
FP		SC	Fuel price (R \ litre)
FPY(F)	F	SS	Pre-year Fines
FRAY(FAY)		P	After-year stepped fine (% of normal R per mm added to mm water

			overused in each step
FRPY(FPY)		P	Fixed Pre-year fine (R per mm) water overused
FTI(IS)	IS	SS	Individual irrigation system
FUEL	IO	SE	Fuel and lubrication costs calculated from farmer data
fuel	COSTDAT	SE	Fuel costs according to kWh
FVC	COSTDAT	SE	Fixed variable costs
GN(C)	C	SS	Individual Crop
GRAD	CROPDAT	SE	Gradient
GRNDNUT	C	SE	Groundnut
GWK	SR	SE	Regional budgets
HARV	IO	SE	Harvesting costs in R/ha
HC	COSTDAT	SE	Model calculated harvesting costs
HERB	IO	SE	Herbicide costs in R/ha
IA		SE	Total current irrigable area (ha)
INSUR	IO	SE	Insurance costs in R/ha
INT	COSTDAT	SE	Interest
INT	IO	SE	Interest on production capital
IO		S	Inputs and Outputs
IQ		SC	Irrigation Quota size (ha-mm per annum per ha)
IR		SE	Current irrigation rights per allocated quota (ha)
IS		S	Type of Irrigation system
JAN	T	SE	January
JUL	T	SE	July
KWHR	IO	SE	Kilowatt hours required
LABC		SE	Average Labour Costs (\person\ 24 working day month)(R)
LABOR	IO	SE	Labour costs
LDDS(DS)	DS	SS	Individual soil drainage status
LDS	DS	SE	Limited drainage soil
LF		S	Leaching fractions
LF0	LF	SE	Leaching fraction, set at 0%
LF10	LF	SE	Leaching fraction, set at 10%
LF15	LF	SE	Leaching fraction, set at 15%
LF20	LF	SE	Leaching fraction, set at 20%
LF25	LF	SE	Leaching fraction, set at 25%
LF5	LF	SE	Leaching fraction, set at 5%
LFV(LF)		P	Assigning values to leaching fraction variable names
LMS	S	SE	Loamy Sand soils <15% Clay
LMYS(S)	S	SS	Loamy sand only
LPKWH		SC	Litres per kilowatt-hour (litres)
LTI		SC	Long Term loan annual Interest rate (%)
LTT		SC	Long Term loan term for drainage/irrigation (years)
LUC(C)	C	SS	Individual Crop
LUCERNE	C	SE	Lucerne
MAINT	IO	SE	Maintenance and repairs
MAINT	COSTDAT	SE	Maintenance
MAIZE	C	SE	Maize

MAR	T	SE	March
MASC	COSTDAT	SE	Margin above specified costs
MAXGN		SC	Maximum area to plant to groundnuts (%fraction)
MAXPOT		SC	Maximum area to plant to potatoes (%fraction)
MAXRF		SC	Max. returnflows allowed\ha water right (ha-mm)
MAY	T	SE	May
MCL		SE	Maximum Capital Improvement loan availability (R)
MEY	COSTDAT	SE	Maximum expected yield
MHLR	IO	SE	Man-hours of labour required
MPC		SE	Maximum Production Capital availability (R)
NB	SR	SE	New Bucklands(5)
NDDS(DS)	DS	SS	Individual soil drainage status
NDS	DS	SE	Naturally drained soils
NODRIP(C)	C	SS	Can't drip irrigate Irrigation
NOTLMS(S)	S	SS	Not loamy sand
NOV	T	SE	November
NPDS(DS)	DS	SS	No potatoes to be drained non these drainage status'
NZERO		SC	A very small constant used when dividing by 0
OCT	T	SE	October
OL	SR	SE	Olierivier (1)
PC		SE	Pumping costs - will vary within sub-area (R per mm)
PCI		SC	Production capital interest rate (%)
PEST	IO	SE	Pesticide costs in R per ha
PL(IO)	IO	SS	Production loan
PLD		S	Production loan data
POT(C)	C	SS	Individual Crop
POTATO	C	SE	Potato crop
PRICE	IO	SE	Price of product in R per ton
PRICE	COSTDAT	SE	Price (A new table is set up using the price from IO)
PY(T)	T	SS	Pre-year
PYWU		SC	Allowable pre-year water use (%fraction)
S		S	Soils classified according to clay %
SEED	IO	SE	Seed costs in R per ha
SEP	T	SE	September
SNC	S	SE	Sandy Clay soils 25-45% Clay
SNL	S	SE	Sandy Loam soils 15-25% Clay
SOIL_D(S,IS,DS,SR)		T	Farm specific soil types
SR	SR	S	OVIB Sub-area names
SUMLH		SC	Summer labour hours (working hours per day)(hrs)
SUMMER(T)	T	SS	Summer
T		S	Time periods
TKWA		SE	Total kilowatts available (kW)
TLA		SE	Total labourers available (person)
TRM	PLD	SE	The loan term in Production Loan Data
TRSH	CROPDAT	SE	The that salinity threshold for the different crops according to Maas & Hoffman

TRSH_FNCT(C,*)		T	y = - V1 x + V2 * = V1, V2
VL	SR	SE	Vaallus (2)
VOFSD		SC	Total volume of 1 OFS dam (50x50x3m) (ha-mm)
WAT	IO	SE	Water costs in R per ha
WC		SE	Water costs (R/mm)
WDPM		SC	Working days per month (days)
WF1	F	SE	The first tier of the water fine
WF2	F	SE	The second tier of the water fine
WF3	F	SE	The third tier of the water fine
WF4	F	SE	The fourth tier of the water fine
WFI		SC	Water overuse fine increment mm per annum per ha)
WFPY	F	SE	The only tier of water overuse allowed in the pre-year
WHEAT	C	SE	Wheat crop
WHT(C)	C	SS	Individual Crop
WINLH		SC	Winter labour hours (working hours per day)(hrs)
WINTER(T)		SS	Winter
WLDS(DS)	DS	SS	Individual soil drainage status
WLS		SE	Waterlogged soils
WLSDF		SC	Waterlogged Soils Drainage Factor (%)
WREQ_AFT		SE	Water requirement in the after-year
WREQ_PRE		SE	Water requirement in the pre-year
YIELD		SE	Yield of product in ton per ha
YP		S	Expected Yield percentages
YP1	YP	SE	Yield % (adjustable) for this study set at 100%
YP2	YP	SE	Yield % (adjustable) for this study set at 98%
YP3	YP	SE	Yield % (adjustable) for this study set at 95%
YP4	YP	SE	Yield % (adjustable) for this study set at 90%
YP5	YP	SE	Yield % (adjustable) for this study set at 83%
YP6	YP	SE	Yield % (adjustable) for this study set at 75%
YPER(YP)		P	Assigning values to Yield% variable names

APPENDIX 3. SALMOD SCHEMATIC LAYOUT WITH MANAGEMENT OPTIONS

	NR	**Y**	**P2A**	**W2L**	**W2A**	**L2A**	**F2C**	**F2D**	**C2F**	**C2D**	**D2F**	**D2C**	**X**	**NPSD C**	**OFSD**	**Sign**	**RHS**
OBJN	+	+		+	+	+	+	+	+	+	+	+	m		+	=	0
LAND_BAL													+			<=	+
SIDBalWF				+	+		+	+	−		−		+			<=	+
SIDBalWC				+	+		−		+	+		−	+			<=	+
SIDBalWD				+	+			−		−	+	+	+			<=	0
SIDBalLF				−		+	+	+	−		−		+			<=	+
SIDBalLC				−		+	−		+	+		−	+			<=	+
SIDBalLD				−		+		−		−	+	+	+			<=	0
SIDBalAF					−	−	+	+	−		−		+			<=	0
SIDBalAC					−	−	−		+	+		−	+			<=	+
SIDBalAD					−	−		−		−	+	+	+			<=	0
SIDBalNF							+	+	−		−		+			<=	0
SIDBalNC							−		+	+		−	+			<=	+
SIDBalND								−		−	+	+	+			<=	0
DST_WF				+	+		+	+	−		−		+			<=	+
DST_WC				+	+		−		+	+		−	+			<=	+
DST_WD				+	+			+		+	−	−	+			<=	0
DST_LF				−		+	+	+	−		−		+			<=	+
DST_LC				−		+	+	+	−		−		+			<=	+
DST_LD				−		+	+	+	−		−		+			<=	0
DST_AF					−	−	+	+	−		−		+			<=	0
DST_AC					−	−	−		+	+		−	+			<=	+
DST_AD					−	−		−		−	+	+	+			<=	0
DST_NF							+	+	−		−		+			<=	0
DST_NC							−		+	+		−	+			<=	+
DST_ND								−		−	+	+	+			<=	0
IST_WF				+	+		+	+	−		−		+			<=	+
IST_WC				+	+		−		+	+		−	+			<=	+
IST_WD				+	+			−		−	+	+	+			<=	0
IST_LF				−		+	+	+	−		−		+			<=	+
IST_LC				−		+	−		+	+		−	+			<=	+
IST_LD				−		+		−		−	+	+	+			<=	0
IST_AF					−	−	+	+	−		−		+			<=	0
IST_AC					−	−	−		+	+		−	+			<=	+
IST_AD					−	−		−		−	+	+	+			<=	0
IST_NF							+	+	−		−		+			<=	0
IST_NC							−		+	+		−	+			<=	+
IST_ND								−		−	+	+	+			<=	0
ROTATION													+			<=	+
PotCons					−	−	−	−	+		−		+			<=	+
PotDS													+			=	0
PotIS													+			=	0
WhtMax													+			<=	+
GNMax													+			<=	+
GnSand													+			<=	0
GnDS													+			<=	0
DRIP_CONS													+			=	0
MAX_QUOTA		−											+			<=	+
PY_QUOTA		−	+										+			<=	+
AY_QUOTA		−	−										+			<=	+
RFC													−	+	+	=	0
MRF													+		−	<=	+
SDC													m			<=	0
PCC		+		+	+	+	+	+	+	+	+	+	+		+	<=	+
FCLC				+	+	+	+	+	+	+	+	+			+	<=	+
Variable Type	***u***	***+***	***+***	***+***	***+***	***+***	***+***		***+***	***+***	***+***	***+***	***+***	***+***	***+***		

APPENDIX 4. SALMOD FARM-LEVEL RESULTS WITH FIXED CAPITAL MANAGEMENT OPTIONS INCLUDED AND RETURNFLOWS CONSTRAINED

A4.1. SUB-AREA 1: OLIERIVIER

A4.2. SUB-AREA 2: VAALLUS

A4.3. SUB-AREA 3: ATHERTON

A4.4. SUB-AREA 4: BUCKLANDS

A4.5. SUB-AREA 5: NEW BUCKLANDS

NOTE: The results displayed in Chapter 5 are the *status quo* results and do not have returnflows constrained – these results have returnflows constrained and will therefore be different to those displayed in Chapter 5.

The results for each sub-area consist of two files: firstly, the farm level results for the long-term water quality to which the particular case-study farm is exposed, followed by the water quality scenario/range file where the results are displayed of the impact of water quality predictions according to Du Preez *et al*, 2000.

A4.1. SUB-AREA 1: OLIERIVIER

```
SALMOD (FARM LEVEL)               Date run: 21.05.02 Time: 08:47:43

SALMOD Results
Model by the RAPIDS team, Dept.Ag.Econ.UFS for the WRC

GENERAL INPUT DATA   Olierivier   (1)
Irrigable area   (ha)      200.00
Irrigation rights(ha)      141.00
Water cost     (R/mm)        0.17
Pumping costs  (R/mm)        0.56

Electrical Conductivity of the irrigation water - ECiw (mS/m)
  JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP   OCT   NOV   DEC
   94   117   134    84   136   132   124   130   155   176   182    94

SOIL TYPE  : LMS  190.0  SNL   10.0  SNC    0.0  CLY    0.0
IRRIG.SYST.: FIS   35.0  CPI  165.0  DIS    0.0
DRAIN.CLASS: NDS  100.0  ADS   20.0  LDS   70.0  WLS   10.0

MODEL RESULTS
Optimal crop composition:
Crop      Soil Class Irrig LF     Yield HECTARES     GMASC  PYWater   AYWater
WHEAT     LMS  LDS   CPI   LF5    0.97     19.0      2333     13168         0
MAIZE     LMS  LDS   CPI   LF15   0.87      0.0      2822         0        31
POTATO    LMS  ADS   CPI   LF5    0.98      6.0      6177         0      3663
LUCERNE   LMS  NDS   CPI   LF5    0.96    100.0      5126     52137     81547
LUCERNE   LMS  ADS   CPI   LF5    0.96     14.0      5126      7299     11417
LUCERNE   LMS  LDS   FIS   LF10   0.86     30.0      4522     16510     25823
LUCERNE   LMS  LDS   CPI   LF10   0.86      9.9      4522      5462      8543
Total water used                (mm):              225600     94576    131024
Water shadow price,Max,pre-&aft-year:                2.26      0.00      0.00
Unused trans. from Pre- to Aft-year :                                   12584
Water Usage Cost                 (R):               69040     16078     52962
Water Pumping Cost               (R):              126336     52962     73374
Water overuse fines:    WF1     14100                3596  DUAL 1.3769
                        WF2     14100                4794  DUAL 1.2847
                        WF3     14100                5993  DUAL 1.1926
                        WF4     14100                7191  DUAL 1.1004
                        WFPY    14100               14100  DUAL 0.5692
    TOTAL WATER OVERUSE         70500  TOTAL FINE   35673
Estimated optimal net revenue (R):                 606390
Pre-determined fixed costs    (R):                 561000
FARM PROFIT                   (R):                  45390
Production capital requirement(R):   (Max 300000)  300000  (DUAL= 0.0840)
Fixed capital loan requirement(R):   (Max 600000)       0  (DUAL= 0.0000)

MANAGEMENT OPTIONS:
Soil Trans.WL-LD   LMS     SNL     SNC     CLY
FIS                0.00    0.00    0.00    0.00
CPI                0.00    0.00    0.00    0.00
DIS                0.00    0.00    0.00    0.00

Soil Trans.WL-AD   LMS     SNL     SNC     CLY
FIS                0.00    0.00    0.00    0.00
CPI                0.00    0.00    0.00    0.00
DIS                0.00    0.00    0.00    0.00
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```
Soil Trans.LD-AD   LMS     SNL     SNC     CLY
FIS                0.00    0.00    0.00    0.00
CPI                0.00    0.00    0.00    0.00
DIS                0.00    0.00    0.00    0.00


Irrig.Syst.Trans.F-C   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.F-D   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.C-D   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.C-F   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.D-C   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.D-F   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Number of On-Farm Storage dams (50x50x3m) required:  0.0   (Dual -4470.49 )
```

```
SALMOD (PARAMETRIC/RANGE)                 Date run: 21.05.02 Time: 08:47:43

SALMOD Results
Model by the RAPIDS team, Dept.Ag.Econ.UFS for the WRC

PARAMETRIC MODEL RUN FOR:            Olierivier   (1)

                          R3Pre  O2Pre+    OVIB  R3Pre-  R3Pre+   H2Pre    R3LT
Total Gross Margin  (R) 574057  694766  662312  627204  518143  351356  606390
Total Water Fine    (R)  25226   35673   35673   35673   25055    1851   35673
Return Flows       (mm)  14100   12158   14100   14100   14100   14100   14100
Returnflows duals   (R)   3.85    0.00    0.60    1.91    4.17    3.43    1.52
Production capital  (R) 300000  300000  300000  300000  300000  147666  300000
Prod. capital dual  (R)   0.15    0.34    0.28    0.14    0.02    0.00    0.08
Fixed capital       (R)      0       0       0       0       0       0       0
Fixed capital dual  (R)   0.00    0.00    0.00    0.00    0.00    0.00    0.00

WATER QUOTA SHADOW VALUE
Max Quota                 1.80    2.89    2.53    2.28    1.55    0.82    2.26
Pre-year Quota            0.00    0.00    0.00    0.00    0.04    0.00    0.00
After-year Quota          0.00    0.00    0.00    0.00    0.00    0.00    0.00

WATER FINE SHADOW VALUES
WFPY                      0.00    0.81    0.53    0.50    0.00    -0.7    0.57
WF1                       0.86    1.80    1.48    1.35    0.72    0.00    1.38
WF2                       0.76    1.69    1.38    1.25    0.63    -0.1    1.28
WF3                       0.66    1.58    1.27    1.16    0.54    -0.2    1.19
WF4                       0.56    1.46    1.16    1.06    0.46    -0.3    1.10

OPTIMAL CROP COMPOSITION
WHEAT                    31.72    0.00    0.00   18.91   31.93    0.00   18.95
MAIZE                     0.00   25.06   25.09    0.10    0.00    0.00    0.04
GRNDNUT                   0.00    0.00    0.00    0.00    0.00    0.00    0.00
POTATO                    6.00    6.00    6.00    6.00    6.00    6.00    6.00
COTTON                    0.00    0.00    0.00    0.00    0.00    0.00    0.00
LUCERNE                 139.08  151.51  149.97  153.92  138.84  114.00  153.92
```

A4.2. SUB-AREA 2: VAALLUS

```
SALMOD (FARM LEVEL)                 Date run: 21.05.02 Time: 09:02:00

SALMOD Results
Model by the RAPIDS team, Dept.Ag.Econ.UFS for the WRC

GENERAL INPUT DATA   Vaallus      (2)
Irrigable area   (ha)      461.00
Irrigation rights(ha)      339.00
Water cost     (R/mm)        0.17
Pumping costs  (R/mm)        0.56

Electrical Conductivity of the irrigation water - ECiw (mS/m)
  JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP   OCT   NOV   DEC
   94   117   134    84   136   132   124   130   155   176   182    94

SOIL TYPE  : LMS    0.0  SNL  111.0  SNC  320.0  CLY   30.0
IRRIG.SYST.: FIS   30.0  CPI  370.0  DIS   61.0
DRAIN.CLASS: NDS  311.0  ADS  120.0  LDS   30.0  WLS    0.0

MODEL RESULTS
Optimal crop composition:
Crop      Soil Class Irrig LF     Yield HECTARES     GMASC  PYWater   AYWater
MAIZE     SNL  NDS   CPI   LF0    1.00      22.9     11137         0     16867
MAIZE     SNC  NDS   CPI   LF0    1.00      12.3     11137         0      9026
COTTON    SNL  NDS   DIS   LF0    1.00      61.0      5530      6377     49077
COTTON    SNC  NDS   CPI   LF0    1.00     187.7      5530     20455    157413
COTTON    SNC  ADS   CPI   LF0    1.00     120.0      5530     13074    100611
Total water used                (mm):              372900     39906    332994
Water shadow price,Max,pre-&aft-year:                0.88      0.00      0.00
Unused trans. from Pre- to Aft-year :                                       0
Water Usage Cost                 (R):               29131      6784     22347
Water Pumping Cost               (R):              208824     22347    186477
Water overuse fines:    WF1         0                   0  DUAL -0.E+1
                        WF2         0                   0  DUAL -0.E+1
                        WF3         0                   0  DUAL -0.E+1
                        WF4         0                   0  DUAL -0.E+1
                        WFPY        0                   0  DUAL -1.E+1
    TOTAL WATER OVERUSE             0  TOTAL FINE       0
Estimated optimal net revenue (R):                2158249
Pre-determined fixed costs    (R):                2475015
FARM PROFIT                   (R):                -316766
Production capital requirement(R):   (Max 500000)  500000  (DUAL= 3.6431)
Fixed capital loan requirement(R):   (Max1000000)       0  (DUAL= 0.0000)

MANAGEMENT OPTIONS:
Soil Trans.WL-LD   LMS     SNL     SNC     CLY
FIS                0.00    0.00    0.00    0.00
CPI                0.00    0.00    0.00    0.00
DIS                0.00    0.00    0.00    0.00

Soil Trans.WL-AD   LMS     SNL     SNC     CLY
FIS                0.00    0.00    0.00    0.00
CPI                0.00    0.00    0.00    0.00
DIS                0.00    0.00    0.00    0.00


Soil Trans.LD-AD   LMS     SNL     SNC     CLY
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FIS                0.00    0.00    0.00    0.00
CPI                0.00    0.00    0.00    0.00
DIS                0.00    0.00    0.00    0.00

Irrig.Syst.Trans.F-C   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.F-D   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.C-D   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.C-F   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.D-C   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.D-F   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00


Number of On-Farm Storage dams (50x50x3m) required:  0.0   (Dual -2.78E+4 )
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SALMOD (PARAMETRIC/RANGE)                 Date run: 21.05.02 Time: 09:02:00

SALMOD Results
Model by the RAPIDS team, Dept.Ag.Econ.UFS for the WRC

PARAMETRIC MODEL RUN FOR:           Vaallus      (2)

                        O2Pre+    OVIB  V4Pre-      V4  V4Pre+   H2Pre    V4LT
Total Gross Margin  (R)2158249 2158249 2158249 2144990 2136448 2061128 2158249
Total Water Fine    (R)      0       0       0       0       0    8434       0
Return Flows       (mm)  16427   16427   16427   19380   19380   18140   16427
Returnflows duals   (R)   0.00    0.00    0.00    0.00    0.00    0.00    0.00
Production capital  (R) 500000  500000  500000  500000  500000  500000  500000
Prod. capital dual  (R)   3.64    3.64    3.64    3.44    3.31    2.00    3.64
Fixed capital       (R)      0       0       0       0       0     158       0
Fixed capital dual  (R)   0.00    0.00    0.00    0.00    0.00    0.00    0.00

WATER QUOTA SHADOW VALUE
Max Quota                 0.88    0.88    0.88    1.11    1.26    2.44    0.88
Pre-year Quota            0.00    0.00    0.00    0.00    0.00    0.00    0.00
After-year Quota          0.00    0.00    0.00    0.00    0.00    0.00    0.00

WATER FINE SHADOW VALUES
WFPY                      ****    ****    ****    ****    ****    ****    ****
WF1                       ****    ****    ****    ****    ****    0.00    ****
WF2                       ****    ****    ****    ****    ****    -0.2    ****
WF3                       ****    ****    ****    ****    ****    -0.5    ****
WF4                       ****    ****    ****    ****    ****    -0.8    ****

OPTIMAL CROP COMPOSITION
WHEAT                     0.00    0.00    0.00    0.00    0.00    0.00    0.00
MAIZE                    35.14   35.14   35.14   35.85   35.85    0.32   35.14
GRNDNUT                   0.00    0.00    0.00    0.00    0.00    0.00    0.00
POTATO                    0.00    0.00    0.00    0.00    0.00    0.00    0.00
COTTON                  368.75  368.75  368.75  364.91  364.91  430.68  368.75
LUCERNE                   0.00    0.00    0.00    0.00    0.00    0.00    0.00
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A4.3. SUB-AREA 3: ATHERTON

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SALMOD (FARM LEVEL)                 Date run: 21.05.02 Time: 09:08:37

SALMOD Results
Model by the RAPIDS team, Dept.Ag.Econ.UFS for the WRC

GENERAL INPUT DATA   Atherton     (3)
Irrigable area   (ha)       22.00
Irrigation rights(ha)       28.90
Water cost     (R/mm)        0.17
Pumping costs  (R/mm)        0.56

Electrical Conductivity of the irrigation water - ECiw (mS/m)
  JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP   OCT   NOV   DEC
   94   117   134    84   136   132   124   130   155   176   182    94

SOIL TYPE  : LMS    0.0  SNL    0.0  SNC    0.0  CLY   22.0
IRRIG.SYST.: FIS   22.0  CPI    0.0  DIS    0.0
DRAIN.CLASS: NDS    0.0  ADS    0.0  LDS   22.0  WLS    0.0

MODEL RESULTS
Optimal crop composition:
Crop      Soil Class Irrig LF     Yield HECTARES     GMASC  PYWater   AYWater
WHEAT     CLY  LDS   FIS   LF5    1.00      22.0      5207     16133         0
Total water used              (mm):                16133     16133         0
Water shadow price,Max,pre-&aft-year:                0.00      0.00      0.00
Unused trans. from Pre- to Aft-year :                                      0
Water Usage Cost               (R):                11777      2743      9035
Water Pumping Cost             (R):                 9035      9035         0
Water overuse fines:    WF1         0                   0  DUAL -0.815
                        WF2         0                   0  DUAL -0.900
                        WF3         0                   0  DUAL -0.985
                        WF4         0                   0  DUAL -0.E+1
                        WFPY        0                   0  DUAL -0.E+1
    TOTAL WATER OVERUSE             0  TOTAL FINE       0
Estimated optimal net revenue (R):                 102786
Pre-determined fixed costs    (R):                 130000
FARM PROFIT                   (R):                 -27214
Production capital requirement(R):   (Max 150000)  108615  (DUAL= 0.0000)
Fixed capital loan requirement(R):   (Max 300000)       0  (DUAL= 0.0000)

MANAGEMENT OPTIONS:
Soil Trans.WL-LD   LMS     SNL     SNC     CLY
FIS                0.00    0.00    0.00    0.00
CPI                0.00    0.00    0.00    0.00
DIS                0.00    0.00    0.00    0.00

Soil Trans.WL-AD   LMS     SNL     SNC     CLY
FIS                0.00    0.00    0.00    0.00
CPI                0.00    0.00    0.00    0.00
DIS                0.00    0.00    0.00    0.00

Soil Trans.LD-AD   LMS     SNL     SNC     CLY
FIS                0.00    0.00    0.00    0.00
CPI                0.00    0.00    0.00    0.00
DIS                0.00    0.00    0.00    0.00

Irrig.Syst.Trans.F-C   LMS     SNL     SNC     CLY
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NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.F-D   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.C-D   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.C-F   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.D-C   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.D-F   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00


Number of On-Farm Storage dams (50x50x3m) required:  0.0   (Dual -5977.56 )
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SALMOD (PARAMETRIC/RANGE)                  Date run: 21.05.02 Time: 09:08:37

SALMOD Results
Model by the RAPIDS team, Dept.Ag.Econ.UFS for the WRC

PARAMETRIC MODEL RUN FOR:            Atherton     (3)

                         O2Pre+    OVIB  V4Pre-      V4  V4Pre+   H2Pre    V4LT
Total Gross Margin   (R) 102786  102786   92590   62984   43571       0  102786
Total Water Fine     (R)      0       0       0       0       0       0       0
Return Flows        (mm)    849     849     849     849    1634       0     849
Returnflows duals    (R)   0.00    0.00    0.00    0.00    0.00    0.00    0.00
Production capital   (R) 108615  108615  108615  108615   31331       0  108615
Prod. capital dual   (R)   0.00    0.00    0.00    0.00    0.00    0.00    0.00
Fixed capital        (R)      0       0       0       0       0       0       0
Fixed capital dual   (R)   0.00    0.00    0.00    0.00    0.00    0.00    0.00

WATER QUOTA SHADOW VALUE
Max Quota                  0.00    0.00    0.00    0.00    0.00    0.00    0.00
Pre-year Quota             0.00    0.00    0.00    0.00    0.00    0.00    0.00
After-year Quota           0.00    0.00    0.00    0.00    0.00    0.00    0.00

WATER FINE SHADOW VALUES
WFPY                       ****    ****    ****    ****    ****    ****    ****
WF1                        -0.8    -0.8    -0.8    -0.8    -0.8    -0.8    -0.8
WF2                        -0.9    -0.9    -0.9    -0.9    -0.9    -0.9    -0.9
WF3                        -1.0    -1.0    -1.0    -1.0    -1.0    -1.0    -1.0
WF4                        ****    ****    ****    ****    ****    ****    ****

OPTIMAL CROP COMPOSITION
WHEAT                     22.00   22.00   22.00   22.00    0.00    0.00   22.00
MAIZE                      0.00    0.00    0.00    0.00    0.00    0.00    0.00
GRNDNUT                    0.00    0.00    0.00    0.00    0.00    0.00    0.00
POTATO                     0.00    0.00    0.00    0.00    0.00    0.00    0.00
COTTON                     0.00    0.00    0.00    0.00    0.00    0.00    0.00
LUCERNE                    0.00    0.00    0.00    0.00   22.00    0.00    0.00
```

A4.4. SUB-AREA 4: BUCKLANDS

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SALMOD (FARM LEVEL)                 Date run: 21.05.02 Time: 09:11:12

SALMOD Results
Model by the RAPIDS team, Dept.Ag.Econ.UFS for the WRC

GENERAL INPUT DATA   Bucklands    (4)
Irrigable area   (ha)        50.00
Irrigation rights(ha)        58.40
Water cost     (R/mm)         0.17
Pumping costs  (R/mm)         0.56

Electrical Conductivity of the irrigation water - ECiw (mS/m)
  JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP   OCT   NOV   DEC
   94   117   134    84   136   132   124   130   155   176   182    94

SOIL TYPE  : LMS    0.0  SNL    0.0  SNC    0.0  CLY   50.0
IRRIG.SYST.: FIS   50.0  CPI    0.0  DIS    0.0
DRAIN.CLASS: NDS    0.0  ADS    0.0  LDS   50.0  WLS    0.0

MODEL RESULTS
Optimal crop composition:
Crop      Soil Class Irrig LF     Yield HECTARES     GMASC  PYWater   AYWater
LUCERNE   CLY  LDS   FIS   LF5    0.90     50.0       2607     27517     43039
Total water used                 (mm):               70556     27517     43039
Water shadow price,Max,pre-&aft-year:                 0.90      0.00      0.00
Unused trans. from Pre- to Aft-year :                                        0
Water Usage Cost                  (R):               20087      4678     15409
Water Pumping Cost                (R):               39511     15409     24102
Water overuse fines:    WF1      5840                 1489  DUAL 0.0850
                        WF2       476                  162  DUAL 0.0000
                        WF3         0                    0  DUAL -0.085
                        WF4         0                    0  DUAL -0.170
                        WFPY        0                    0  DUAL -0.660
    TOTAL WATER OVERUSE          6316  TOTAL FINE    1651
Estimated optimal net revenue (R):                   73659
Pre-determined fixed costs    (R):                   38000
FARM PROFIT                   (R):                   35659
Production capital requirement(R):   (Max 200000)  114447  (DUAL= 0.0000)
Fixed capital loan requirement(R):   (Max 300000)       0  (DUAL= 0.0000)

MANAGEMENT OPTIONS:
Soil Trans.WL-LD   LMS     SNL     SNC     CLY
FIS                0.00    0.00    0.00    0.00
CPI                0.00    0.00    0.00    0.00
DIS                0.00    0.00    0.00    0.00

Soil Trans.WL-AD   LMS     SNL     SNC     CLY
FIS                0.00    0.00    0.00    0.00
CPI                0.00    0.00    0.00    0.00
DIS                0.00    0.00    0.00    0.00

Soil Trans.LD-AD   LMS     SNL     SNC     CLY
FIS                0.00    0.00    0.00    0.00
CPI                0.00    0.00    0.00    0.00
DIS                0.00    0.00    0.00    0.00
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Irrig.Syst.Trans.F-C   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.F-D   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.C-D   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.C-F   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.D-C   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.D-F   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00


Number of On-Farm Storage dams (50x50x3m) required:  0.0   (Dual -5977.56 )
```

```
SALMOD (PARAMETRIC/RANGE)                 Date run: 21.05.02 Time: 09:11:12

SALMOD Results
Model by the RAPIDS team, Dept.Ag.Econ.UFS for the WRC

PARAMETRIC MODEL RUN FOR:           Bucklands    (4)

                        O2Pre+    OVIB  V4Pre-      V4  V4Pre+   H2Pre    V4LT
Total Gross Margin  (R)  97301   83106   52685   32157   11401       0   73659
Total Water Fine    (R)   1651    1651    1489       0       0       0    1651
Return Flows       (mm)   3713    3713    3688    3381    3381       0    3713
Returnflows duals   (R)   0.00    0.00    0.00    0.00    0.00    0.00    0.00
Production capital  (R) 114447  114447  113282   99479   99479       0  114447
Prod. capital dual  (R)   0.00    0.00    0.00    0.00    0.00    0.00    0.00
Fixed capital       (R)      0       0       0       0       0       0       0
Fixed capital dual  (R)   0.00    0.00    0.00    0.00    0.00    0.00    0.00

WATER QUOTA SHADOW VALUE
Max Quota                 0.90    0.90    0.82    0.50    0.18    0.00    0.90
Pre-year Quota            0.00    0.00    0.00    0.00    0.00    0.00    0.00
After-year Quota          0.00    0.00    0.00    0.00    0.00    0.00    0.00

WATER FINE SHADOW VALUES
WFPY                      -0.7    -0.7    -0.7    ****    ****    ****    -0.7
WF1                       0.09    0.09    0.00    -0.3    -0.6    -0.8    0.09
WF2                       0.00    0.00    -0.1    -0.4    -0.7    -0.9    0.00
WF3                       -0.1    -0.1    -0.2    -0.5    -0.8    -1.0    -0.1
WF4                       -0.2    -0.2    -0.2    -0.6    -0.9    ****    -0.2

OPTIMAL CROP COMPOSITION
WHEAT                     0.00    0.00    0.00    0.00    0.00    0.00    0.00
MAIZE                     0.00    0.00    0.00    0.00    0.00    0.00    0.00
GRNDNUT                   0.00    0.00    0.00    0.00    0.00    0.00    0.00
POTATO                    0.00    0.00    0.00    0.00    0.00    0.00    0.00
COTTON                    0.00    0.00    0.00    0.00    0.00    0.00    0.00
LUCERNE                  50.00   50.00   49.66   45.52   45.52    0.00   50.00
```

A4.5. SUB-AREA 5: NEW BUCKLANDS

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SALMOD (FARM LEVEL)                Date run: 09.06.02 Time: 22:40:46

SALMOD Results
Model by the RAPIDS team, Dept.Ag.Econ.UFS for the WRC

GENERAL INPUT DATA   New Bucklands(5)
Irrigable area   (ha)      145.00
Irrigation rights(ha)      100.00
Water cost      (R/mm)        0.17
Pumping costs  (R/mm)         0.56

Electrical Conductivity of the irrigation water - ECiw (mS/m)
  JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP   OCT   NOV   DEC
   94   117   134    84   136   132   124   130   155   176   182    94

SOIL TYPE  : LMS  145.0  SNL    0.0  SNC    0.0  CLY    0.0
IRRIG.SYST.: FIS   30.0  CPI  110.0  DIS    5.0
DRAIN.CLASS: NDS  100.0  ADS   10.0  LDS   25.0  WLS   10.0

MODEL RESULTS
Optimal crop composition:
Crop      Soil Class Irrig LF     Yield HECTARES     GMASC  PYWater   AYWater
MAIZE     LMS  NDS   CPI   LF0    1.00    100.0       7292        0     73684
MAIZE     LMS  ADS   CPI   LF0    1.00     10.0       7292        0      7368
MAIZE     LMS  LDS   FIS   LF10   1.00     35.0       7267        0     27222
Total water used              (mm):             108275        0    108275
Water shadow price,Max,pre-&aft-year:             0.00      0.00      0.00
Unused trans. from Pre- to Aft-year :                                    0
Water Usage Cost                (R):                 0        0         0
Water Pumping Cost              (R):             60634        0     60634
Water overuse fines:    WF1         0                0  DUAL -0.815
                        WF2         0                0  DUAL -0.900
                        WF3         0                0  DUAL -0.985
                        WF4         0                0  DUAL -0.E+1
                        WFPY        0                0  DUAL -0.E+1
    TOTAL WATER OVERUSE             0  TOTAL FINE    0
Estimated optimal net revenue (R):              974156
Pre-determined fixed costs    (R):             1049109
FARM PROFIT                   (R):              -74953
Production capital requirement(R):   (Max 600000)  304069  (DUAL= 0.0000)
Fixed capital loan requirement(R):   (Max1200000)   17500  (DUAL= 0.0000)

MANAGEMENT OPTIONS:
Soil Trans.WL-LD   LMS     SNL     SNC     CLY
FIS              10.00    0.00    0.00    0.00
CPI               0.00    0.00    0.00    0.00
DIS               0.00    0.00    0.00    0.00

Soil Trans.WL-AD   LMS     SNL     SNC     CLY
FIS               0.00    0.00    0.00    0.00
CPI               0.00    0.00    0.00    0.00
DIS               0.00    0.00    0.00    0.00

Soil Trans.LD-AD   LMS     SNL     SNC     CLY
FIS               0.00    0.00    0.00    0.00
CPI               0.00    0.00    0.00    0.00
DIS               0.00    0.00    0.00    0.00
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Irrig.Syst.Trans.F-C   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.F-D   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.C-D   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.C-F   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.D-C   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    0.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Irrig.Syst.Trans.D-F   LMS     SNL     SNC     CLY
NDS                    0.00    0.00    0.00    0.00
ADS                    0.00    0.00    0.00    0.00
LDS                    5.00    0.00    0.00    0.00
WLS                    0.00    0.00    0.00    0.00

Number of On-Farm Storage dams (50x50x3m) required:  0.0   (Dual -5977.56 )
```

```
SALMOD (PARAMETRIC/RANGE)                 Date run: 09.06.02 Time: 22:40:46

SALMOD Results
Model by the RAPIDS team, Dept.Ag.Econ.UFS for the WRC

PARAMETRIC MODEL RUN FOR:           New Bucklands(5)

                        O2Pre+    OVIB  V4Pre-      V4  V4Pre+   H2Pre    V4LT
Total Gross Margin  (R) 975031  975031  963524  915847  866446  682135  974156
Total Water Fine    (R)      0       0     382     383    3657    4888       0
Return Flows       (mm)   5485    6775   10000   10000   10000   10000    6775
Returnflows duals   (R)   0.00    0.00    2.67    4.39    4.51    4.51    0.00
Production capital  (R) 304069  304069  307646  307646  379115  496594  304069
Prod. capital dual  (R)   0.00    0.00    0.00    0.00    0.00    0.00    0.00
Fixed capital       (R)  17500   17500   17500   17500  283649  893113   17500
Fixed capital dual  (R)   0.00    0.00    0.00    0.00    0.00    0.00    0.00

WATER QUOTA SHADOW VALUE
Max Quota                 0.00    0.00    0.82    0.82    0.90    0.90    0.00
Pre-year Quota            0.00    0.00    0.00    0.00    0.00    0.00    0.00
After-year Quota          0.00    0.00    0.00    0.00    0.00    0.00    0.00

WATER FINE SHADOW VALUES
WFPY                      ****    ****    -0.7    -0.7    -0.7    -0.7    ****
WF1                       -0.8    -0.8    0.00    0.00    0.08    0.08    -0.8
WF2                       -0.9    -0.9    -0.1    -0.1    0.00    0.00    -0.9
WF3                       -1.0    -1.0    -0.2    -0.2    -0.1    -0.1    -1.0
WF4                       ****    ****    -0.3    -0.3    -0.2    -0.2    ****

OPTIMAL CROP COMPOSITION
WHEAT                     0.00    0.00    0.00    0.00    0.00    0.00    0.00
MAIZE                   145.00  145.00  145.00  145.00  145.00  145.00  145.00
GRNDNUT                   0.00    0.00    0.00    0.00    0.00    0.00    0.00
POTATO                    0.00    0.00    0.00    0.00    0.00    0.00    0.00
COTTON                    0.00    0.00    0.00    0.00    0.00    0.00    0.00
LUCERNE                   0.00    0.00    0.00    0.00    0.00    0.00    0.00
```

APPENDIX 5. GAMS CODING FOR SALMOD

```
$Title SALMOD Salinity and Leaching Model for Optimal irrigation Management
$ontext
  A LP model to determine the optimal crop enterprise combination when
  irrigating with changing water salinities on non-uniform soil types.

  Developed by R.J. Armour, Department of Agricultural Economics,
  University of the Orange Free State, South Africa.
  Project funded by the Water Research Commission.

  (Farm level model run for "NB")
       OL = Olierivier case study farm
       VL = Vaallus case study farm
       AT = Atherton case study farm
       BL = Bucklands case study farm
       NB = New Bucklands case study farm
$offtext
$offlisting
$offinclude
$offsymlist

OPTION BRatio=0;
OPTION LimCol=0;
OPTION LimRow=0;

*   ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
*   ~~~~DECLARATION OF SETS (Leave unchanged for all farmers)~~~~~~~~~~~~
*   ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

SETS
   C         Main annual Crops produced in the study area
                             /WHEAT,MAIZE,GRNDNUT,POTATO,COTTON,LUCERNE/
   S         Soils clasified according to clay %
                             /LMS   Loamy Sand soils <15%    Clay
                              SNL   Sandy Loam soils  15-25% Clay
                              SNC   Sandy Clay soils  25-45% Clay
                              CLY   Clay soils          >45% Clay/
   DS        Soil drainage status
                             /NDS   Naturally drained soils
                              ADS   Artificially drained soils
                              LDS   Limited drainage naturally drained soil
                              WLS   Waterlogged soils /
   IS        Type of Irrigation system
                             /FIS   Flood Irrigation System
                              CPI   Center Pivot Irrigation System
                              DIS   DRIP Irrigation System /
   F         Water Fines     /WF1,WF2,WF3,WF4,WFPY/
   T         Time periods    /JAN,FEB,MAR,APR,MAY,JUN,JUL,AUG,SEP,OCT,NOV,DEC/
   CROPDAT   Crop Data       /WREQ_PRE,WREQ_AFT,TRSH,GRAD/
   COSTDAT   Cost Data       /PRICE,MEY,HC,FVC,MASC,FUEL,MAINT /
   IO        Inputs and Outputs
                             /WHEAT,MAIZE,GRNDNUT,POTATO,COTTON,LUCERNE
                              PRICE   PRICE OF PRODUCT IN RANDS PER TON
                              YIELD   YIELD OF PRODUCT IN TONS PER HECTARE
                              SEED    SEED COSTS IN RANDS PER HECTARE
                              FERT    FERTILIZER COSTS RANDS PER HECTARE
                              HERB    HERBICIDE COSTS IN R PER HA
                              PEST    PESTICIDE COSTS IN R PER HA
                              INSUR   INSURANCE COSTS IN RANDS PER HECTARE
                              HARV    HARVESTING COSTS IN RANDS PER TON
```

```
                              INT     INTEREST ON PRODUCTION CAPITAL
                              WAT     WATER COSTS IN RANDS PER HECTARE
                              ELEC    ELECTRICITY PUMPING COSTS IN R PER HA
                              LABOR   Labour costs
                              MHLR    Man-hours of labour required
                              FUEL    Fuel and lubrication
                              KWHR    Kilowat hours required
                              MAINT   Maintainance and repairs
                              CAP     CAPITAL GOODS repayments  /
   SR OVIB Sub-Region NAMES  /OL  Olierivier   (1)
                              VL  Vaallus      (2)
                              AT  Atherton     (3)
                              BL  Bucklands    (4)
                              NB  New Bucklands(5)
                              GWK Regional budgets /
   PLD Production loan data  /AMT,TRM,INT/

*SUBSETS
   POT(C)    Ind.Crop         /POTATO/
   LUC(C)    Ind.Crop         /LUCERNE/
   WHT(C)    Ind.Crop         /WHEAT/
   GN(C)     Ind.Crop         /GRNDNUT/
   NODRIP(C) Can'T DRIP Irri  /WHEAT,MAIZE,LUCERNE/
   LMYS(S)   Loamy sand only  /LMS/
   NOTLMS(S) Not loamy sand   /SNL,SNC,CLY/
   NPDS(DS)  NoPotDrain.state /WLS,LDS/
   WLDS(DS)  Ind.Drain.state  /WLS/
   LDDS(DS)  Ind.Drain.state  /LDS/
   ADDS(DS)  Ind.Drain.state  /ADS/
   NDDS(DS)  Ind.Drain.state  /NDS/
   DTI(IS)   Ind.Irrig.Sys.   /DIS/
   CTI(IS)   Ind.Irrig.Sys.   /CPI/
   FTI(IS)   Ind.Irrig.Sys.   /FIS/
   FPY(F)    PreYear Fines    /WFPY/
   FAY(F)    AftYear Fines    /WF1,WF2,WF3,WF4/
   PY(T)     PreYear          /JUL,AUG,SEP,OCT,NOV/
   AY(T)     AftYear          /DEC,JAN,FEB,MAR,APR,MAY,JUN/
   SUMMER(T) Summer           /NOV,DEC,JAN,FEB,MAR,APR/
   WINTER(T) Winter           /MAY,JUN,JUL,AUG,SEP,OCT/
   PL(IO)    Prod. Loan       /SEED,FERT,HERB,PEST,INSUR,INT/    ;
*   ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
*   ~~~CONSTANTS DEFINED (Change values between backslashes /......./ )       .
*   ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
SCALARS
*   ~~~~~~~~~~~~~~~~~~~  REGIONAL / FARM SPECIFIC DATA    ~~~~~~~~~~~~~~~~~~~~~
   IQ     Irrigation Quota size    (ha-mm per anum per ha) /    1100.00 /
*  1mm/ha = 10cubic meters       in cubic meters = 11000.00 - this constant can
*            also be changed to test the effect of quota size changes on TGMASC
   MAXPOT Maximum area to plant to potatoes    (%fraction) /       0.05 /
   MAXGN  Maximum area to plant to groundnuts  (%fraction) /       0.25 /
   WLSDF  Waterlogged Soils Drainage Factor            (%) /       0.10 /
*   ~~~~~~~~~~~~~~~~~~~  MOSTLY CONSTANT FOR ALL FARMERS ~~~~~~~~~~~~~~~~~~~~~~
   FP     Fuel price                           (R \ liter) /       3.70 /
   FLR    Fuel cost:Lubrication cost ratio             (%) /       0.01 /
   FMR    Fuel cost:Maintainance cost ratio            (%) /       0.05 /
   LPKWH  Liters per kilowatt-hour                (liters) /       0.35 /
   SUMLH  Summer labour hours (working hours per day)(hrs) /      10.00 /
   WINLH  Winter labour hours (working hours per day)(hrs) /       8.00 /
   WDPM   Working days per month                    (days) /      25.00 /
   LTT    Long Term loan Term for drainage\irig.   (years) /      10.00 /
   LTI    Long Term loan annual Interest rate          (%) /       0.15 /
   PCI    Production capital interst rate              (%) /       0.17 /
   PYWU   Allowable PreYear water use          (%fraction) /       0.60 /
```

```
   AYWU   Allowable AftYear water use          (%fraction) /       0.40 /
   WFI    Water overuse fine increment(mm per anum per ha) /     100.00 /
   ECRW   Electrical conductivity of rain water (mS per m) /       1.00 /
   FORCE  A constant used to eliminate OPTION'cause too hi /     -0.001 /
   NZERO  A very small constant used when dividing by 0    /    0.00001 /
*~~~~~~~  SCENARIO DATA ~~~~~~~~~~~~~   To free RF constraint~~ADD EXTRA 0~~~~~
   MAXRF  Max. return flows allowed\ha water right (ha-mm) /     100.00 /
   COFSD  Total cost of 1 on-farm storage dam          (R) /   30000.00 /
   VOFSD  Total volume of 1 OFS dam (50x50x3m)     (ha-mm) /     750.00 /
   EVAPY  Evaporation - surface water       (ha-mm\dam\yr) /     575.00 / ;

SET   CSF    Case study farmer data set
/IA    Total current irrigable area                                       (ha)
 IR    Current irrigation rights per allocated quota                      (ha)
 WC    Water costs - CAN BE VARIED FOR EACH SUB-REGION              (R per mm)
 PC    Pumping costs - will vary within sub-region                  (R per mm)
 FC    Sub-regional representative farm nonalloc.anual fixed costs(R per anum)
 MPC   Maximum Production Capital  availability                            (R)
 MCL   Maximum Capital Improvement loan availability                       (R)
 TKWA  Total killowatts available                                         (kW)
 TLA   Total labourers avalable                                       (person)
 LABC  Average Labour Costs (\person\ 24 working day month)               (R)/;

TABLE CSFD(SR,CSF) Sub-region land and cost data
*CS Farm ha  ha R\mm\ha R\mm\ha   R      R       R   kW   Man  R\month
         IA  IR      WC      PC       FC      MPC      MCL  TKWA  TLA  LABC
OL      200 141   0.17   0.56  561000  300000  600000   280   16  1000
VL      461 339   0.17   0.56 2475015  500000 1000000   720   18  1000
BL       50  58.4 0.17   0.56   38000  100000  200000    46    2  1000
AT       22  28.9 0.17   0.56  130000  150000  300000   120    4  1000
NB      145 100   0.17   0.56 1049109  600000 1200000   300   14  1000 ;
*   ~~~~~~~~~~~~~~~~~~~~~~~  E N D   S C A L A R S ~~~~~~~~~~~~~~~~~~~~~~~~~~~~

* See origional table at the end
TABLE EBTable(IO,C,SR) Enterprize budget table for OVIB region
*   Farm values for WAT & ELEC are filled in for comparison, but are calculated
*   seperately in model. Model values are used in the model calculations.
*   NB All values are per ha except harvesting costs which are per ton
          WHEAT.OL    WHEAT.VL    WHEAT.AT    WHEAT.BL    WHEAT.NB    WHEAT.GWK
PRICE         1072        1022        1060           0         918          780
YIELD            5           6          10           0           7            7
SEED           483         108        1900           0         247          237
FERT           950        1388        1300           0        1072         1214
HERB           158          98         300           0           6          212
PEST             0           5           0           0           0          302
INSUR          125          98         520           0           0          154
HARV            97           1          52           0          52           45
MHLR            16          16          16           0          16           16
KWHR           343         343         343           0         343          343
WAT             74          82         211           0         121          150
ELEC           245         123         253           0         198          345
CAP             87          51         211           0          97            0
FUEL           142         286         390           0         119          246
MAINT          393         530         172           0         279           51
LABOR          507         504         597           0         446           30
+         MAIZE.OL    MAIZE.VL    MAIZE.AT    MAIZE.BL    MAIZE.NB    MAIZE.GWK
PRICE          599        1253         570           0         895          580
YIELD            9          11           9           0          11          9.5
SEED           255         790        2000           0         219          411
FERT          1039         302        3250           0        1149         1346
HERB             0         294         750           0           6          321
PEST             0         200           0           0           0           71
INSUR            0         401         625           0           0          165
```

```
HARV             0           0          69           0          52           50
MHLR            40          40          40           0          40           40
KWHR           329         329         329           0         329          329
WAT            121         330         228           0          95          180
ELEC           399         499         273           0         157          413
CAP            130          77         126           0          97            0
FUEL           212         429         234           0         119          236
MAINT          589         795         103           0         279            0
LABOR          760         757         358           0         446           75
+       GRNDNUT.OL  GRNDNUT.VL  GRNDNUT.AT  GRNDNUT.BL  GRNDNUT.NB  GRNDNUT.GWK
PRICE         2167           0           0           0         864         2414
YIELD            2           0           0           0           3            3
SEED          1200           0           0           0         383          675
FERT          1333           0           0           0         849          725
HERB            67           0           0           0           6          295
PEST             0           0           0           0           0          396
INSUR            0           0           0           0           0          217
HARV            67           0           0           0          52          340
MHLR           312           0           0           0         312          312
KWHR           343           0           0           0         343          343
WAT            102           0           0           0          82          128
ELEC           336           0           0           0         135          307
CAP            260           0           0           0         145          203
FUEL           425           0           0           0         179          246
MAINT         1178           0           0           0         419          798
LABOR         1521           0           0           0         669           90
+        POTATO.OL   POTATO.VL   POTATO.AT   POTATO.BL   POTATO.NB   POTATO.GWK
PRICE          633         955           0           0           0          950
YIELD           30          45           0           0           0           35
SEED          1500           0           0           0           0         6800
FERT          1000       17257           0           0           0         2710
HERB           700           0           0           0           0            0
PEST             0           0           0           0           0         2760
INSUR            0           0           0           0           0            0
HARV           283          63           0           0           0           63
MHLR           424         424           0           0           0          424
KWHR           500         500           0           0           0          500
WAT            141           0           0           0           0          144
ELEC           466           0           0           0           0          318
CAP            521         307           0           0           0          296
FUEL           849        1717           0           0           0          359
MAINT         2356        3179           0           0           0         2768
LABOR         3041        3026           0           0           0          795
+        COTTON.OL   COTTON.VL   COTTON.AT   COTTON.BL   COTTON.NB   COTTON.GWK
PRICE            0        2631           0           0           0         2057
YIELD            0           3           0           0           0          3.4
SEED             0         102           0           0           0          141
FERT             0         158           0           0           0         1022
HERB             0           0           0           0           0          299
PEST             0          71           0           0           0          496
INSUR            0           0           0           0           0          902
HARV             0         501           0           0           0          333
MHLR             0         216           0           0           0          216
KWHR             0         329           0           0           0          329
WAT              0         173           0           0           0          212
ELEC             0         262           0           0           0          468
CAP              0         153           0           0           0          153
FUEL             0         859           0           0           0          236
MAINT            0        1590           0           0           0            0
LABOR            0        1513           0           0           0          405
+       LUCERNE.OL  LUCERNE.VL  LUCERNE.AT  LUCERNE.BL  LUCERNE.NB  LUCERNE.GWK
PRICE          413           0         393         375         115          345
YIELD           15           0          17          15          19           18
```

```
SEED             0           0         130         210         116          91
FERT             0           0         228         690         861         680
HERB             0           0           0         188           6         264
PEST             0           0           0           0           0          15
INSUR            0           0           0           0           0           0
HARV            23           0          23          60          32          23
MHLR            56           0          56          56          56          56
KWHR           357           0         357         357         357         357
WAT            186           0         398         196          82         299
ELEC           617           0         477         132         136         702
CAP            260           0         506           0         193         192
FUEL           425           0         937         653         239         240
MAINT         1178           0         412           0         558         274
LABOR         1521           0        1433        2683         892         120
;
TABLE  SOIL_D(S,IS,DS,SR) Farm specific soil types
* The model will not solve if the SUM of the values in this table do not equal
* the farm size as specified in the SCALAR IA.
* The full martix is given for OL only-for VL, AT, BL & NB on necessary fields
          NDS.OL  ADS.OL  WLS.OL  LDS.OL
LMS.FIS                            30
LMS.CPI    100     20              40
LMS.DIS
SNL.FIS                      5
SNL.CPI                      5
SNL.DIS
SNC.FIS
SNC.CPI
SNC.DIS
CLY.FIS
CLY.CPI
CLY.DIS
+         NDS.VL  ADS.VL  WLS.VL  LDS.VL
SNL.CPI     50
SNL.DIS     61
SNC.CPI     200     120
CLY.FIS                              30
+         NDS.AT  ADS.AT  WLS.AT  LDS.AT
CLY.FIS                             22
+         NDS.BL  ADS.BL  WLS.BL  LDS.BL
CLY.FIS                             50
+         NDS.NB  ADS.NB  WLS.NB  LDS.NB
LMS.FIS                     10        20
LMS.CPI     100     10
LMS.DIS                                5

********************************* FIXED DATA ***********************************
SET         LF       Leaching fract. /LF0,LF5,LF10,LF15,LF20,LF25/;
PARAMETER   LFV(LF)  Assigning values to leaching fraction varuable names
         / LF0    0.00
           LF5    0.05
           LF10   0.10
           LF15   0.15
           LF20   0.20
           LF25   0.25    /;
PARAMETER   FRPY(FPY)  Fixed PreYear fine (R per mm) water overused
         / WFPY   1.00 /;
PARAMETER   FRAY(FAY)  AftYear stepped fine (% of normal R per mm added
         / WF1    0.50
           WF2    1.00
           WF3    1.50
           WF4    2.00  /;
TABLE TRSH_FNCT(C,*) y = - V1 x + V2
```

```
                           V1         V2
             WHEAT      1400.00   2000.00
             MAIZE       843.17   1011.50
             GRNDNUT     344.49    663.79
             POTATO      843.17   1011.50
             COTTON     1874.00   2658.30
             LUCERNE    1356.80   1558.50  ;
TABLE        CROP_DATA    (C, *)
          WREQ_PRE   WREQ_AFT   TRSH    GRAD
*        mm/PreYr   mm/AftYr   mS/m  %/mS/m
WHEAT          660          0    600   0.071
MAIZE            0        700    170    0.12
GRNDNUT          0        590    320    0.29
POTATO           0        580    170    0.12
COTTON         220        680    770   0.052
LUCERNE        479        791    200   0.073   ;


* ---------------------------- EC SCENARIO DATA  ------------------------------
TABLE  MAveECiw(T,SR) Here farm specfic data needs to be filled in.(EC in mS\m)
              OL      BL      AT      VL      NB
*Best '98   OVIB    DWAF    DWAF    OVIB    DWAF
Jan           96      51      52      45      19
Feb           91      50      52      56      20
Mar           72      38      42      64      18
Apr           54      43      44      40      19
May          102      65      68      65      20
Jun          109      85      91      63      21
Jul           97      94      91      59      20
Aug           99      86      86      62      19
Sep          119      68      77      74      19
Oct          130      23      28      84      20
Nov          113      47      53      87      20
Dec           97      75      80      45      20
*Ave:         98.3    60.4    63.7    62.0    19.6

*************************************************************************
PARAM
*   -----------------------   SET   PARAMETRIC   RANGES   -------------------------
PARAM
*************************************************************************
PARAM
SET EC Electrical Conductivity Parameters /MN3,MN2,MN1,PL1,PL2,PL3,EC98/;
PARAMETER PP(EC) Parameter percentage
           /MN3  -0.3
            MN2  -0.2
            MN1  -0.1
            EC98  0.0
            PL1   0.1
            PL2   0.2
            PL3   0.3 /;

PARAMETER RAIN(T) Rainfall doesn't vary significantly to have seperate values
          / JAN   29.4
            FEB   76.0
            MAR   70.5
            APR   27.9
            MAY    5.7
            JUN    3.6
            JUL    1.8
            AUG    7.5
            SEP   12.3
            OCT   28.4
```

```
            NOV   29.3
            DEC   42.3 /;
***************** VALUE JUDGEMENT / CALIBRATION DATA **************************
PARAMETER PCLT(C) Production Capital Loan Term (months)
        / WHEAT      6
          MAIZE      6
          GRNDNUT    9
          POTATO     5
          COTTON     7
          LUCERNE    3  /  ;
PARAMETER ADTC(S)   The total per ha cost of installing artificial drainage on
        / LMS    15000
          SNL    17000
          SNC    20000
          CLY    25000 / ;
Parameter ISMLF(IS)  The Irrigation system max.% leaching capacity
        / FIS   0.60
          CPI   0.20
          DIS   0.15  /;
TABLE   ISTC(IS,*) Irrigation system transfer costs
               TSC    SALV    MAINT   LIFE  MINHA     MAXHA     INTRVL
*      R/ha  % of TSC R/Ha/Yr   YRS    HA        HA        HA
       FIS     500    0.60      10    100      1        50         1
       CPI    5000    0.10     100     20     20        80        10
       DIS    8000    0.03     500      5      0.5      10         0.25   ;

TABLE  IR_EF(C,IS) Plant irrigation water use efficiencies
*           of different types of irrigation systems(IS) on different crops (C)
*           Can be different for various crops depending on planting density.
                     FIS   CPI   DIS
       WHEAT        0.90  0.95  0.99
       MAIZE        0.90  0.95  0.99
       GRNDNUT      0.90  0.95  0.99
       POTATO       0.90  0.95  0.99
       COTTON       0.90  0.95  0.99
       LUCERNE      0.90  0.95  0.99  ;

TABLE  MLFS(S, DS)  The max.% that soils in table SOIL_DATA can be leached
                  NDS   ADS   WLS    LDS
       LMS       0.50  0.55  0.05   0.35
       SNL       0.35  0.40  0.05   0.25
       SNC       0.25  0.30  0.05   0.20
       CLY       0.15  0.20  0.05   0.10

TABLE  SWCF(S,DS,LF)  The EC_IW to ECe conversion factor.
*Determined by farm specific in field measurements(Controled Dept.Soil Science)
             LF0     LF5    LF10    LF15    LF20    LF25
LMS.NDS      2.35    2.30    2.20    1.60    1.10    1.00
LMS.ADS      2.35    2.30    2.20    1.60    1.10    1.00
LMS.LDS      6.00    4.50    3.60    3.20    2.90    2.50
LMS.WLS     10.00   10.00   10.00   10.00   10.00   10.00
SNL.NDS      2.75    2.60    2.40    1.80    1.60    1.40
SNL.ADS      2.75    2.60    2.40    1.80    1.60    1.40
SNL.LDS      6.25    4.75    4.00    3.50    3.20    2.75
SNL.WLS     10.00   10.00   10.00   10.00   10.00   10.00
SNC.NDS      3.35    3.30    3.20    2.80    2.10    1.80
SNC.ADS      3.35    3.30    3.20    2.80    2.10    1.80
SNC.LDS      6.50    5.35    4.60    3.90    3.30    2.85
SNC.WLS     10.00   10.00   10.00   10.00   10.00   10.00
CLY.NDS      4.35    4.30    4.20    3.80    3.10    1.80
CLY.ADS      4.35    4.30    4.20    3.80    3.10    1.80
CLY.LDS      7.00    5.75    5.40    4.60    4.10    3.55
CLY.WLS     10.00   10.00   10.00   10.00   10.00   10.00  ;
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TABLE  LAND(T,C)  Crop LAND req. per month (1 month is 1 - 1 week is 0.25 etc.)
    WHEAT MAIZE GRNDNUT POTATO COTTON LUCERNE
JAN        1         1       1     1       1
FEB        1         1       1     1       1
MAR        1         1       1     1       1
APR        1         1       1     1       1
MAY        1         1       1             1
JUN  0.5   0.5                             1
JUL  1                                     1
AUG  1                                     1
SEP  1               0.5          0.5      1
OCT  1               1             1       1
NOV  1               1             1       1
DEC  0.25  0.75      1             1       1;

TABLE  KWHDIST(T,C)  Crop kWH distribution per month in % (NB sum crop must=1)
    WHEAT MAIZE  GRNDNUT  POTATO COTTON LUCERNE
JAN        0.1               0.2         0.1
FEB        0.1               0.1  0.05   0.1
MAR        0.05              0.1  0.1    0.2
APR                  0.2     0.2  0.25   0.1
MAY                  0.2     0.4         0.1
JUN  0.5   0.25
JUL  0.1
AUG  0.1
SEP  0.05            0.4          0.5    0.1
OCT                  0.1          0.05   0.1
NOV                  0.1          0.05   0.1
DEC  0.25  0.5                           0.1;

TABLE  LABDIST(T,C)  Labour distribution per month in % (NB sum crop must=1)
    WHEAT MAIZE  GRNDNUT  POTATO COTTON LUCERNE
JAN        0.1               0.2         0.1
FEB        0.1               0.1  0.05   0.1
MAR        0.05              0.1  0.1    0.2
APR                  0.2     0.2  0.25   0.1
MAY                  0.2     0.4         0.1
JUN  0.5   0.25
JUL  0.1
AUG  0.1
SEP  0.05            0.4          0.5    0.1
OCT                  0.1          0.05   0.1
NOV                  0.1          0.05   0.1
DEC  0.25  0.5                           0.1;

TABLE WAT_PER(T,C)  %water requirement per crop
     Wheat  Maize Potato Cotton   GRNDNUT  Lucerne
Jan         0.246  0.130  0.337     0.357    0.174
Feb         0.314  0.138  0.175     0.192    0.081
Mar         0.301  0.294  0.148     0.095    0.084
Apr         0.099  0.273  0.042     0.036    0.079
May                0.165            0.009    0.055
Jun
Jul  0.029
Aug  0.075                                   0.055
Sep  0.206                                   0.083
Oct  0.347                0.032     0.026    0.115
Nov  0.343                0.083     0.052    0.137
Dec         0.040         0.183     0.233    0.137  ;

*   ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
*                        PARAMETER DEFINITION SECTION
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*   ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
PARAMETERS
   VARCOSTS(C,SR)       Variable costs                                   (R\ha)
   CCDAT(COSTDAT,C,SR)  Sub-regional crop cost data set                  (R\ha)
   CROP_COST(COSTDAT,C) Farm crop cost data-Marg.AboveSpec.Costs-(Wat+Elec&Int)
   SOIL_DATA(S,IS,DS)   Sub-regional specific data set from table SOIL_D   (ha)
   PLOAN(PLD,C,SR)      Production Loan required                         (R\ha)
   WATCHK(C)            Checks that SUM of %'S in Table WAT_PER = 1
   kWHDCHK(C)           Checks that SUM of %'S in Table kWHDIST = 1
   LABCHK(C)            Checks that SUM of %'S in Table LABDIST = 1
   SOILCHK              Checks that values in table SOIL_DATA add up to IA
   PARAM(T,EC)          EC Parameter generator (See table MAveECiw)      (mS\m)
   COUNT(C)             Formulation Loop counter
   SOILD(S,IS,DS)       Equates Table SOIL_DATA to 1                       (ha)
   ST_COUNT(S)          Counts # of Ha'S to Soil Type S                    (ha)
   IS_COUNT(IS)         Counts # of Ha'S under Irrigation System IS        (ha)
   DS_COUNT(DS)         Counts # of Ha'S that are Drainage Status DS       (ha)
   STAC(S,DS)           Counts Ha'S to SoilType S and Drainage status DS   (ha)
   ADC(S)               Annual Artificial Drainage costs on SoilType S   (R\ha)
   WSDC(S)              Annual Artificial Drainage Costs on WL Soils     (R\ha)
   AOFSC                Annualised On-Farm Storage costs                    (R)
   ATCFC                Annualised Transfer Cost - Flood to Center Pivot (R\ha)
   ATCFD                Annualised Transfer Cost - Flood to Drip Irrigat (R\ha)
   ATCCD                Annualised Transfer Cost - Center Pivot to Drip  (R\ha)
   ATCCF                Annualised Transfer Cost - Center Pivot to Flood (R\ha)
   ATCDC                Annualised Transfer Cost - Drip to Center Pivot  (R\ha)
   ATCDF                Annualised Transfer Cost - Drip to Flood irrigat (R\ha)
   TDS_IW               Total Disolved Solids - irrigation water         (mg\l)
   EC_IW                Electical Conductivity - irrigation water        (mS\m)
   ECe(C,S,DS,LF)       EC - soil saturation extract                     (mS\m)
   A_TDS_IW             Annual average TDS_IW              (see Table MAveECiw)
   A_EC_IW              Annual average EC_IW            (derived from A_TDS_IW)
   M_TDS_IW(T)          Monthly Average TDS_IW             (see Table MAveECiw)
   M_EC_IW(T)           Monthly Average  EC_IW             (see Table MAveECiw)
   LAND_ONE(T,C)        Equates fractions in Table LAND_ONE to 1
   CA_EC_IW(C)          Crop Average EC_IW over months crop in soil      (mS\m)
   SUM_CW(C)            Total water applied to crop (Rainfall accntd for)  (mm)
   SUM_WR(C)            SUM of ppre&Aftyear Irrig.wat.req.(Tab.CROP_DATA)  (mm)
   SUM_TCWR             Checks if Tab.s LAND & WAT_PER are correct
   SPYIWR(C)            SUM of PRE-year irrig.water requ.(after rain)      (mm)
   SAYIWR(C)            SUM of AFT-year irrig.water requ.(after rain)      (mm)
   MRAIN(T)             Monthly Rainfall (from table MONTH_DATA)           (mm)
   A_EC_CW(C)           Average EC of Irrig. + Rain Water on Crops       (mS\m)
   MC_IW_R(T,C)         Monthly crop irrigation requirement     7       (mm\ha)
   MC_W_R(T,C)          Monthly crop Irrig.+Rain water applied          (mm\ha)
   MA_EC_CW(T,C)        Monthly ave. EC of crop water applied            (mS\m)
   NLF(C)               Natural leaching factor                             (%)
   RCY(C,S,DS,LF)       Relative Crop Yield                   (Max = 1 or 100%)
   RY(C,S,DS,LF)        Transision equation for RCY          (not limited to 1)
   MLF(S,DS,IS)         Min. of soil & irrig. system max. leaching capacity (%)
   PPWR(C,LF)           Total PreYear Plant Water Requirement LF        (mm\ha)
   APWR(C,LF)           Total AftYear Plant Water Requirement LF        (mm\ha)
   PIWR(C,IS)           Total PreYear Irrigation Water Requirement      (mm\ha)
   AIWR(C,IS)           Total AftYear Irrigation Water Requirement      (mm\ha)
   LFR(C,S,DS,IS,LF)    Leaching fraction requirements                  (mm\ha)
   PID(C,S,DS,IS,LF)    PreYear Irrigation Depth                        (mm\ha)
   AID(C,S,DS,IS,LF)    AftYear Irrigation Depth                        (mm\ha)
   PWL(C,S,DS,IS,LF)    PreYear Water Loss (irrig.effic. + leaching)    (mm\ha)
   AWL(C,S,DS,IS,LF)    AftYear Water Loss (irrig.effic. + leaching)    (mm\ha)
   PWEC(C,S,DS,IS,LF)   PreYear Water+Electricity costs of PID              (R)
   AWEC(C,S,DS,IS,LF)   AftYear Water+Electricity costs of AID              (R)
   FINE_AY(FAY)         Determines volume of each AftYear Fine increment   (mm)
   GMASC(C,S,DS,IS,LF)  Gross Margin Above Specified Costs -(wat.+elec.) (R\ha)
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   I                    A variable value
;
*  ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
*  ~~~~~~~~~~~~~~~~~~~~ PARAMETER FORMULATION SECTION ~~~~~~~~~~~~~~~~~~~~~~~~~
*  ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

* -- Setting up table CROP_COST --
  CCDAT("PRICE",C,SR)=EBTable("PRICE",C,SR);
  CCDAT("MEY"  ,C,SR)=EBTable("YIELD",C,SR);
  CCDAT("HC"   ,C,SR)=EBTable("HARV" ,C,SR);
  CCDAT("FUEL" ,C,SR)=(EBTable("KWHR" ,C,SR)*LPKWH*FP)
                     +(EBTable("KWHR" ,C,SR)*LPKWH*FP)*FLR;
  CCDAT("MAINT",C,SR)=(EBTable("KWHR" ,C,SR)*LPKWH*FP)*FMR;
  VARCOSTS(C,SR)=
           SUM(PL, EBTable(PL,C,SR))+CCDAT("FUEL",C,SR)+CCDAT("MAINT",C,SR)
        +((SUM(PL, EBTable(PL,C,SR))+CCDAT("FUEL",C,SR)+CCDAT("MAINT",C,SR))
          *PCI*(PCLT(C)/12));
  CCDAT("FVC"  ,C,SR)= VARCOSTS(C,SR);
  CCDAT("MASC" ,C,SR)= (CCDAT("PRICE",C,SR)*CCDAT("MEY",C,SR))
                      -(CCDAT("HC",C,SR)   *CCDAT("MEY",C,SR))
                      - CCDAT("FVC",C,SR);
* -- Calculating the production loan required per ha in "NB" --          GWK---
* -- using either GWK CEBs or case study farm CEBs                       GWK---
  CROP_COST(COSTDAT,C)=CCDAT(COSTDAT,C,"NB");
  PLOAN   ("AMT",C,"NB")= SUM(PL, EBTable(PL,C,"NB"))
                        + CCDAT("FUEL" ,C,"NB")+CCDAT("MAINT",C,"NB");
  PLOAN   ("TRM",C,"NB")= PCLT(C);
  PLOAN   ("INT",C,"NB")= PLOAN("AMT",C,"NB")*PCI*(PCLT(C)/12);
  EBTable("INT",C,"NB")= PLOAN("INT",C,"NB");
*End of GWK CEBs                                                         GWK---
* -- Calculating the production loan required per ha in all the sub-regions ---
  PLOAN   ("AMT",C,SR)= SUM(PL, EBTable(PL,C,SR));
  PLOAN   ("TRM",C,SR)= PCLT(C);
  PLOAN   ("INT",C,SR)= PLOAN("AMT",C,SR)*PCI*(PCLT(C)/12);
  EBTable("INT",C,SR)= PLOAN("INT",C,SR);

* -- Setting up table SOIL_DATA --
SOIL_DATA(S,IS,DS)=SOIL_D(S,IS,DS,"NB");

*CHECKS MONTHLY WATER USAGE% PER CROP = 1 & SUM OF SOIL TYPES AND CLASSES=IA
*---------------------------------------------------------------------------
  WATCHK (C)=SUM((T),       WAT_PER(T,C)      );
  kWHDCHK(C)=SUM((T),       kWHDIST(T,C)      );
  LABCHK (C)=SUM((T),       LABDIST(T,C)      );
  SOILCHK   =SUM((S,IS,DS), SOIL_DATA(S,IS,DS));
LOOP (C,
   abort$(round(WATCHK(C),2) <> 1)
      "Crop monthly water usage %s must add up to 1"
   abort$(round(kWHDCHK(C),2) <> 1)
      "kW hour usage %s must add up to 1"
   abort$(round(LABCHK(C),2) <> 1)
      " Labour usage %s must add up to 1"
      );
abort$(round(SOILCHK,0)<>CSFD("NB","IA"))
      "Areas in table SOIL_DATA must add up to scalar IA";

ST_COUNT(S)=0; IS_COUNT(IS)=0; DS_COUNT(DS)=0; STAC(S,DS)=0;
LOOP ((S,IS,DS),
   If (SOIL_DATA(S,IS,DS)>0,
       SOILD(S,IS,DS)=SOIL_DATA(S,IS,DS)/SOIL_DATA(S,IS,DS);
       ST_COUNT(S)=ST_COUNT(S)+SOIL_DATA(S,IS,DS);
       IS_COUNT(IS)=IS_COUNT(IS)+SOIL_DATA(S,IS,DS);
       DS_COUNT(DS)=DS_COUNT(DS)+SOIL_DATA(S,IS,DS);
```

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       STAC(S,DS)=STAC(S,DS)+SOIL_DATA(S,IS,DS);
   Else
       SOILD(S,IS,DS)=0;    ));

*---------------------- DRAINAGE COSTS ANUALIZED -------------------------------
 ADC(S)=ADTC(S)*( (LTI*(1+LTI)**LTT) / (((1+LTI)**LTT)-1) );
 WSDC(S)=ADC(S) * WLSDF;
*-------------------- ON-FARM STORAGE DAM COST ANUALIZED -----------------------
 AOFSC=COFSD *( (LTI*(1+LTI)**LTT) / (((1+LTI)**LTT)-1) );

*---------------------- IRRIGATION SYSTEM COSTS ANUALIZED ----------------------
 ATCFC=((ISTC("CPI","TSC")-(ISTC("FIS","TSC")*ISTC("FIS","SALV")))
      *( (LTI*(1+LTI)**LTT) / (((1+LTI)**LTT)-1) ))+ISTC("CPI","MAINT");
 ATCFD=((ISTC("DIS","TSC")-(ISTC("FIS","TSC")*ISTC("FIS","SALV")))
      *( (LTI*(1+LTI)**LTT) / (((1+LTI)**LTT)-1) ))+ISTC("DIS","MAINT");
 ATCCD=((ISTC("DIS","TSC")-(ISTC("CPI","TSC")*ISTC("CPI","SALV")))
      *( (LTI*(1+LTI)**LTT) / (((1+LTI)**LTT)-1) ))+ISTC("DIS","MAINT");
 ATCCF=((ISTC("FIS","TSC")-(ISTC("CPI","TSC")*ISTC("CPI","SALV")))
      *( (LTI*(1+LTI)**LTT) / (((1+LTI)**LTT)-1) ))+ISTC("FIS","MAINT");
 ATCDC=((ISTC("CPI","TSC")-(ISTC("DIS","TSC")*ISTC("DIS","SALV")))
      *( (LTI*(1+LTI)**LTT) / (((1+LTI)**LTT)-1) ))+ISTC("CPI","MAINT");
 ATCDF=((ISTC("FIS","TSC")-(ISTC("DIS","TSC")*ISTC("DIS","SALV")))
      *( (LTI*(1+LTI)**LTT) / (((1+LTI)**LTT)-1) ))+ISTC("FIS","MAINT");

* -------------------- CALCULATING THE THRESHOLD % FROM TABLE TRSH_FNCT -------
TRSH_PER(C,YP)=-TRSH_FNCT(C,"V1")*YPER(YP)+TRSH_FNCT(C,"V2");

*  --------------------- WATER REQUITEMENT PARAMETERS -------------------------
   SUM_WR(C)=CROP_DATA(C,"WREQ_PRE")+CROP_DATA(C,"WREQ_AFT");
   MC_IW_R(T,C)  = WAT_PER(T,C)*SUM_WR(C);
   MC_W_R(T,C)   = MC_IW_R(T,C)+(RAIN(T)*LAND(T,C));
   SUM_CW(C)     = SUM(T, MC_W_R(T,C));

*  --------To determine the natural leaching factor (NLF) that does occur------
   NLF(C)= (-(SUM(T, MIN((MC_IW_R(T,C)-(RAIN(T)*LAND(T,C))),0)))) / SUM_WR(C);
   SPYIWR(C) = SUM( (PY), MC_IW_R(PY,C));
   SAYIWR(C) = SUM( (AY), MC_IW_R(AY,C));
   MLF(S,DS,IS)=MIN(ISMLF(IS),MLFS(S,DS));
   PARAM(T,EC)=MAveECiw(T,"NB")+(MAveECiw(T,"NB")*PP(EC));

*   ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
*   ~~~~~~~~~~~~~~~~~~~~~~~OPTIMIZATION SECTION ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
*   ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

FREE VARIABLES
  NR                   Net Revenue
POSITIVE VARIABLES
  FINES(F)              Water overuse steps F-different FINES are charged (mm)
  TRANS_P2A             Pre-Year water not used transfered to Aft-Year    (mm)
  TRANS_W2L(S,IS)       Soil Transfer - WL to Ltd.drained soils           (ha)
  TRANS_W2A(S,IS)       Soil Transfer - WL to Artific.drained soils       (ha)
  TRANS_L2A(S,IS)       Soil Transfer - Ltd. to Artific.drained soils     (ha)
  TRANS_F2C(S,DS)       Irrigation system transfer. Flood to Center Pivot (ha)
  TRANS_F2D(S,DS)       Irrigation system transfer. Flood to a Drip System(ha)
  TRANS_C2F(S,DS)       Irrigation system transfer. Center Pivot to Flood (ha)
  TRANS_C2D(S,DS)       Irrigation system transfer. Center Pivot to a Drip(ha)
  TRANS_D2F(S,DS)       Irrigation system transfer. Drip to Center Pivot  (ha)
  TRANS_D2C(S,DS)       Irrigation system transfer. Drip to Flood         (ha)
  ACTIVITY(C,S,DS,IS,LF) Ha'S of crop C to grow on S DS IS YP             (ha)
  NPSD                 Non-Point Source Discharge counter                 (mm)
  OFS                  On Farm Storage management OPTION
EQUATIONS
  LAND_BAL          LAND Balance
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  SIDBalWF(S,IS,DS) Soil Irrigation and Drainage status Balance - WL\FLOOD
  SIDBalWC(S,IS,DS) Soil Irrigation and Drainage status Balance - WL\CP
  SIDBalWD(S,IS,DS) Soil Irrigation and Drainage status Balance - WL\
  SIDBalLF(S,IS,DS) Soil Irrigation and Drainage status Balance - LD\FLOOD
  SIDBalLC(S,IS,DS) Soil Irrigation and Drainage status Balance - LD\CP
  SIDBalLD(S,IS,DS) Soil Irrigation and Drainage status Balance - LD\DRIP
  SIDBalAF(S,IS,DS) Soil Irrigation and Drainage status Balance - AD\FLOOD
  SIDBalAC(S,IS,DS) Soil Irrigation and Drainage status Balance - AD\CP
  SIDBalAD(S,IS,DS) Soil Irrigation and Drainage status Balance - AD\DRIP
  SIDBalNF(S,IS,DS) Soil Irrigation and Drainage status Balance - ND\FLOOD
  SIDBalNC(S,IS,DS) Soil Irrigation and Drainage status Balance - AD\CP
  SIDBalND(S,IS,DS) Soil Irrigation and Drainage status Balance - AD\DRIP
  DST_WF(S,IS,DS)   Soil transfer from waterlogged to limited drainage - Flood
  DST_WC(S,IS,DS)   Soil transfer from waterlogged to limited drainage - CP
  DST_WD(S,IS,DS)   Soil transfer from waterlogged to limited drainage - Drip
  DST_LF(S,IS,DS)   Soil transfer from waterlogged to limited drainage - Flood
  DST_LC(S,IS,DS)   Soil transfer from waterlogged to limited drainage - CP
  DST_LD(S,IS,DS)   Soil transfer from waterlogged to limited drainage - Drip
  DST_AF(S,IS,DS)   Soil transfer from ltd. drainage to artif. drainage-Flood
  DST_AC(S,IS,DS)   Soil transfer from ltd. drainage to artif. drainage-CP
  DST_AD(S,IS,DS)   Soil transfer from ltd. drainage to artif. drainage-Drip
  DST_NF(S,IS,DS)   Soil transfer from nat. drainage to artif. drainage-Flood
  DST_NC(S,IS,DS)   Soil transfer from nat. drainage to artif. drainage-CP
  DST_ND(S,IS,DS)   Soil transfer from nat. drainage to artif. drainage-Drip
  IST_WF(S,IS,DS)   Irrigation system transfer. Waterlogged - Flood
  IST_WC(S,IS,DS)   Irrigation system transfer. Waterlogged - Center Pivot
  IST_WD(S,IS,DS)   Irrigation system transfer. Waterlogged - Drip
  IST_LF(S,IS,DS)   Irrigation system transfer. Limited drainage - Flood
  IST_LC(S,IS,DS)   Irrigation system transfer. Limited drainage-Center Pivot
  IST_LD(S,IS,DS)   Irrigation system transfer. Limited drainage - Drip
  IST_AF(S,IS,DS)   Irrigation system transfer. Artificially drained - Flood
  IST_AC(S,IS,DS)   Irrigation system transfer. Artif. drained - Center Pivot
  IST_AD(S,IS,DS)   Irrigation system transfer. Artificially drained - Drip
  IST_NF(S,IS,DS)   Irrigation system transfer. Naturally drained - Flood
  IST_NC(S,IS,DS)   Irrigation system transfer. Naturally drained-Center Pivot
  IST_ND(S,IS,DS)   Irrigation system transfer. Naturally drained - Drip
  ROTATION(T)       To make sure only 1 crop planted per ha in any season
  PotCons           POTATO Constraint
  PotDS             No Potatoes on soils not naturally or Artificially drained
  PotIS             No Potatoes under flood Irrigation Systems  WhtMax
  WhtMax            Max. WHEAT that can be planted
  GNMax(GN)         Max. ha's of GROUNDNUTS that can be planted
  GnSand(GN)        Groundnuts only to be planted on LOAMY SAND type soils
  GnDS(GN)          Constraining groundnuts to only be grown on sandy soils
  DRIP_CONS         Limits crops that canm be grown under DRIP Irrigation
  MAX_QUOTA         Maximum water quotq constraint
  PY_QUOTA          Max PreYear withdrawls
  AY_QUOTA          Max AftYear withdrawls
  RFC               Irrigation water Return Flows Counter
  MRF               Maximum Return Flows allowed constrainer
  SDC(C,S,DS,IS,LF) Soil Drainage Constraint
  PCC               Production Capital Constraint
  FCLC              Fixed Capital Loan Constraint
  OBJN              Objective Function             ;

* ~~~~~~~~~~~~~~~~~~~ EQUATIONS   I M P L E M E N T A T I O N ~~~~~~~~~~~~~~~~~
*------------------------------ L A N D  constraints --------------------------
LAND_BAL..             SUM((C,S,DS,IS,LF), ACTIVITY(C,S,DS,IS,LF))
                                        =l= CSFD("NB","IA")*2;
SIDBalWF(S,FTI,WLDS).. SUM((C,LF), ACTIVITY(C,S,WLDS,FTI,LF))
                              +TRANS_W2L(S,FTI) +TRANS_W2A(S,FTI)
                              +TRANS_F2C(S,WLDS)+TRANS_F2D(S,WLDS)
                              -TRANS_C2F(S,WLDS)-TRANS_D2F(S,WLDS)
```

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                              =l= SOIL_DATA(S,FTI,WLDS);
SIDBalWC(S,CTI,WLDS)..                      "
SIDBalWD(S,DTI,WLDS)..                      "
SIDBalLF(S,FTI,LDDS)..                      "
SIDBalLC(S,CTI,LDDS)..                      "
SIDBalLD(S,DTI,LDDS)..                      "
SIDBalAF(S,FTI,ADDS)..                      "
SIDBalAC(S,CTI,ADDS)..                      "
SIDBalAD(S,DTI,ADDS)..                      "
SIDBalNF(S,FTI,NDDS)..                      "
SIDBalNC(S,CTI,NDDS)..                      "
SIDBalND(S,DTI,NDDS)..                      "

DST_WF(S,FTI,WLDS).. SUM((C,LF), ACTIVITY(C,S,WLDS,FTI,LF))
                                  +TRANS_W2L(S,FTI) +TRANS_W2A(S,FTI)
                                  +TRANS_F2C(S,WLDS)+TRANS_F2D(S,WLDS)
                                  -TRANS_C2F(S,WLDS)-TRANS_D2F(S,WLDS)
                                  =l= SOIL_DATA(S,FTI,WLDS);
DST_WC(S,CTI,WLDS)..                        "
DST_WD(S,DTI,WLDS)..                        "
DST_LF(S,FTI,LDDS)..                        "
DST_LC(S,CTI,LDDS)..                        "
DST_LD(S,DTI,LDDS)..                        "
DST_AF(S,FTI,ADDS)..                        "
DST_AC(S,CTI,ADDS)..                        "
DST_AD(S,DTI,ADDS)..                        "
DST_NF(S,FTI,NDDS)..                        "
DST_NC(S,CTI,NDDS)..                        "
DST_ND(S,DTI,NDDS)..                        "

IST_WF(S,FTI,WLDS).. SUM((C,LF), ACTIVITY(C,S,WLDS,FTI,LF))
                              +TRANS_W2L(S,FTI) +TRANS_W2A(S,FTI)
                              +TRANS_F2C(S,WLDS)+TRANS_F2D(S,WLDS)
                              -TRANS_C2F(S,WLDS)-TRANS_D2F(S,WLDS)
                              =l= SOIL_DATA(S,FTI,WLDS);
IST_WC(S,CTI,WLDS)..                       "
IST_WD(S,DTI,WLDS)..                       "
IST_LF(S,FTI,LDDS)..                       "
IST_LC(S,CTI,LDDS)..                       "
IST_LD(S,DTI,LDDS)..                       "
IST_AF(S,FTI,ADDS)..                       "
IST_AC(S,CTI,ADDS)..                       "
IST_AD(S,DTI,ADDS)..                       "
IST_NF(S,FTI,NDDS)..                       "
IST_NC(S,CTI,NDDS)..                       "
IST_ND(S,DTI,NDDS)..                       "

*-------------------- C R O P   R O T A T I O N  Constraints ------------------
ROTATION(T)..    SUM((C,S,DS,IS,LF), ACTIVITY(C,S,DS,IS,LF)*LAND(T,C))
                                      =l=CSFD("NB","IA") ;
PotCons..        SUM((POT,S,DS,IS,LF), ACTIVITY(POT,S,DS,IS,LF))=l= MAXPOT
                *(SUM((S,IS,DS),   SOIL_DATA(S,IS,DS))
                 -SUM((S,IS,NPDS), SOIL_DATA(S,IS,NPDS))
                + SUM((S,IS), TRANS_L2A(S,IS) + TRANS_W2A(S,IS) )
                + SUM((S,DS), TRANS_F2C(S,DS) + TRANS_F2D(S,DS) )
                - SUM((S,DS), TRANS_C2F(S,DS) - TRANS_D2F(S,DS) ) );
PotDS..          SUM((POT,S,NPDS,IS ,LF), ACTIVITY(POT,S,NPDS,IS ,LF)) =e=0;
PotIS..          SUM((POT,S,  DS,FTI,LF), ACTIVITY(POT,S,  DS,FTI,LF)) =e=0;
WhtMax..         SUM((WHT,S,DS,IS,LF),     ACTIVITY(WHT,S,DS,IS,LF))
                                           =l=CSFD("NB","IR") ;
GnSand(GN)..    SUM((NOTLMS,DS,IS,LF),   ACTIVITY(GN,NOTLMS,DS ,IS,LF))=l=0;
GnDS(GN)..      SUM((S,NPDS,DS,IS,LF),   ACTIVITY(GN,S     ,NPDS,IS,LF))=l=0;
GnMax(GN)..     SUM((S,DS,IS,LF),        ACTIVITY(GN,S,DS,IS,LF))
```

```
* -----------------  W A T E R   U S E  &  F I N E  Constraints ---------------
DRIP_CONS..   SUM((NODRIP,S,DS,DTI,LF), ACTIVITY(NODRIP,S,DS,DTI,LF))=e= 0;
MAX_QUOTA..  (SUM((C,S,DS,IS,LF), PID(C,S,DS,IS,LF)*ACTIVITY(C,S,DS,IS,LF)))
            +(SUM((C,S,DS,IS,LF), AID(C,S,DS,IS,LF)*ACTIVITY(C,S,DS,IS,LF)))
            -(SUM(FPY, FINES(FPY)))
            -(SUM(FAY, FINES(FAY)))            =l= CSFD("NB","IR")*IQ;
PY_QUOTA..   (SUM((C,S,DS,IS,LF), PID(C,S,DS,IS,LF)*ACTIVITY(C,S,DS,IS,LF)))
            -(SUM(FPY, FINES(FPY)))+ TRANS_P2A =l= CSFD("NB","IR")*IQ*PYWU;
AY_QUOTA..   (SUM((C,S,DS,IS,LF), AID(C,S,DS,IS,LF)*ACTIVITY(C,S,DS,IS,LF)))
            -(SUM(FAY, FINES(FAY)))- TRANS_P2A =l= CSFD("NB","IR")*IQ ;
RFC.. NPSD=e=(SUM((C,S,DS,IS,LF), PWL(C,S,DS,IS,LF)*ACTIVITY(C,S,DS,IS,LF))
            )+(SUM((C,S,DS,IS,LF), AWL(C,S,DS,IS,LF)*ACTIVITY(C,S,DS,IS,LF))
            )- (VOFSD*OFS)
             - (EVAPY*OFS);
MRF..       (SUM((C,S,DS,IS,LF), PWL(C,S,DS,IS,LF)*ACTIVITY(C,S,DS,IS,LF)))+
            (SUM((C,S,DS,IS,LF), AWL(C,S,DS,IS,LF)*ACTIVITY(C,S,DS,IS,LF)))
            - (VOFSD*OFS)
            - (EVAPY*OFS)
              =L= MAXRF*CSFD("NB","IR") ;
SDC(C,S,DS,IS,LF).. LFR(C,S,DS,IS,LF)*ACTIVITY(C,S,DS,IS,LF)
                     =l= (MLF(S,DS,IS)-NLF(C))*ACTIVITY(C,S,DS,IS,LF);

* -------------------- F I N A N C I A L  Constraints  ------------------------
PCC..   +(SUM((C,S,DS,IS,LF), PLOAN("AMT",C,"NB")*ACTIVITY(C,S,DS,IS,LF)))
         +(SUM((C,S,DS,IS,LF), PID(C,S,DS,IS,LF)*ACTIVITY(C,S,DS,IS,LF)))
                                         *(CSFD("NB","WC")+CSFD("NB","PC"))
         +(SUM((C,S,DS,IS,LF), AID(C,S,DS,IS,LF)*ACTIVITY(C,S,DS,IS,LF)))
                                         *(CSFD("NB","WC")+CSFD("NB","PC"))
         +(SUM(FAY, FINES(FAY)*(CSFD("NB","WC")+(FRAY(FAY)*CSFD("NB","WC")))))
         +(SUM(FPY, FINES(FPY)*FRPY(FPY)))
         +(SUM(FAY, FINES(FAY)*CSFD("NB","PC")))
         +(SUM(FPY, FINES(FPY)*CSFD("NB","PC")))
         +(SUM((S,IS), TRANS_W2L(S,IS) * WSDC(S)))
         +(SUM((S,IS), TRANS_L2A(S,IS) *(ADC(S)-WSDC(S))))
         +(SUM((S,IS), TRANS_W2A(S,IS) * ADC(S)))
         +(SUM((S,DS), TRANS_F2C(S,DS))* ATCFC)
         +(SUM((S,DS), TRANS_F2D(S,DS))* ATCFD)
         +(SUM((S,DS), TRANS_C2F(S,DS))* ATCCF)
         +(SUM((S,DS), TRANS_C2D(S,DS))* ATCCD)
         +(SUM((S,DS), TRANS_D2F(S,DS))* ATCDF)
         +(SUM((S,DS), TRANS_D2C(S,DS))* ATCDC)
         + (OFS * AOFSC)
          =l= CSFD("NB","MPC");
*~Production capital includes the anualised cost of management options, water ~
*~costs & fines while:                                                         ~
*~Fixed capital includes the total capital costs of the management options    ~

FCLC..          (OFS * COFSD)
                +(SUM((S,IS), TRANS_W2L(S,IS) *(ADTC(S)*WLSDF)))
                +(SUM((S,IS), TRANS_L2A(S,IS) *(ADTC(S)-(ADTC(S)*WLSDF))))
                +(SUM((S,IS), TRANS_W2A(S,IS) * ADTC(S)))
                +(SUM((S,DS), TRANS_F2C(S,DS))* ISTC("CPI","TSC"))
                +(SUM((S,DS), TRANS_F2D(S,DS))* ISTC("DIS","TSC"))
                +(SUM((S,DS), TRANS_C2F(S,DS))* ISTC("FIS","TSC"))
                +(SUM((S,DS), TRANS_C2D(S,DS))* ISTC("DIS","TSC"))
                +(SUM((S,DS), TRANS_D2F(S,DS))* ISTC("FIS","TSC"))
                +(SUM((S,DS), TRANS_D2C(S,DS))* ISTC("CPI","TSC"))
                =l= CSFD("NB","MCL");

OBJN.. NR=e=(SUM((C,S,DS,IS,LF), GMASC(C,S,DS,IS,LF)*ACTIVITY(C,S,DS,IS,LF)
         ))-(SUM((C,S,DS,IS,LF), PID(C,S,DS,IS,LF)*ACTIVITY(C,S,DS,IS,LF)))
                                         *(CSFD("NB","WC")+CSFD("NB","PC"))
```

```
           -(SUM((C,S,DS,IS,LF), AID(C,S,DS,IS,LF)*ACTIVITY(C,S,DS,IS,LF)))
                                         *(CSFD("NB","WC")+CSFD("NB","PC"))
          -(SUM(FAY, (CSFD("NB","WC")+(FRAY(FAY)*CSFD("NB","WC")))*FINES(FAY)))
          -(SUM(FPY, FINES(FPY)*FRPY(FPY)))
          -(SUM(FAY, FINES(FAY)*CSFD("NB","PC")))
          -(SUM(FPY, FINES(FPY)*CSFD("NB","PC")))
          -(SUM((S,IS), TRANS_W2L(S,IS) * WSDC(S)))
          -(SUM((S,IS), TRANS_L2A(S,IS) *(ADC(S)-WSDC(S))))
          -(SUM((S,IS), TRANS_W2A(S,IS) * ADC(S)))
          -(SUM((S,DS), TRANS_F2C(S,DS))* ATCFC)
          -(SUM((S,DS), TRANS_F2D(S,DS))* ATCFD)
          -(SUM((S,DS), TRANS_C2F(S,DS))* ATCCF)
          -(SUM((S,DS), TRANS_C2D(S,DS))* ATCCD)
          -(SUM((S,DS), TRANS_D2F(S,DS))* ATCDF)
          -(SUM((S,DS), TRANS_D2C(S,DS))* ATCDC)
          -(OFS * AOFSC) ;

Model SMLF /ALL/ ;
  SMLF.workspace = 12;
  FINES.UP(F) = WFI*CSFD("NB","IR");

*     ------- P A R A M E R T I C A L   R E S U L T S ------------------------
SET    ITEMS   / X   Ha's Crop Produced
                 TF  Total Water Fine    (R)
                 RF  Return Flows       (mm)
                 QDm Max Quota dual     (ha)
                 QDp Pre-year Quota dual(ha)
                 QDa Aft-year Quota dual(ha)
                 PC  Production capital  (R)
                 PCd Prod. capital dual  (R)
                 FC  Fixed capital       (R)
                 FCd Fixed capital dual  (R)
                 TGM Total Gross Margin  (R) /;
PARAMETER
         TGMRESULT(ITEMS,EC)  Total gross margin for each level of WQ
         TFRESULT(ITEMS,EC)   Total Fines for each level of Water quality
         FSPPY(FPY,EC)        Fine Shadow Prices for the Pre-Year
         FSPAY(FAY,EC)        Fine Shadow Prices for the Aft-Year
         RFRESULT(ITEMS,EC)   Total Leaching for each level of Water quality
         RFDUAL(ITEMS,EC)     Returnflow constraints dual
         QUOTAmDUAL(ITEMS,EC) Maximum water quota dual values
         QUOTApDUAL(ITEMS,EC) Pre-year water quota dual values
         QUOTAaDUAL(ITEMS,EC) Aft-year water quota dual values
         ProdCap(ITEMS,EC)    Production capital requirements
         PCDual(ITEMS,EC)     Production capital dual values
         FixdCap(ITEMS,EC)    Fixed capital requirements
         FCDual(ITEMS,EC)     Fixed capital dual values
         XRESULT(C,EC)        Optimal crop composition for each level of WQ ;

* ------------------------------------------------------------------------------
* -------------------- S T A R T   O F   E C   L O O P ------------------------
LOOP (EC,
      M_EC_IW(T)=PARAM(T,EC);
      MA_EC_CW(T,C) = ((M_EC_IW(T)*MC_IW_R(T,C))+(RAIN(T)*LAND(T,C)*ECRW))
                      /((MC_IW_R(T,C)+(RAIN(T)*LAND(T,C))+nzero));
      A_EC_CW(C)    = (SUM(T, M_EC_IW(T)*MC_IW_R(T,C) + RAIN(T)*LAND(T,C)*ECRW))
                     /(SUM_CW(C));
*     ------------------------------------------------------------------------
*     *************** CORE FORMULA OF THE LF MODEL ***************************
*     ------------------------------------------------------------------------

*     -------------WHERE SOIL WATER CONVERSION FACTORS ARE USED ---------------
*     --Effect of rainfall taken into account in the calculation of A_EC_CW(C)-
```

```
        ECe(C,S,DS,LF) = A_EC_CW(C) * SWCF(S,DS,LF);

*       ---------------CALCULATION OF REALTIVE CROP YIELD--------------------------
*       -----------Not taking leaf burm factor into account-----------------------
        RY(C,S,DS,LF)=(100-CROP_DATA(C,"GRAD")*(ECe(C,S,DS,LF)
                           -CROP_DATA(C,"TRSH")))/100;
        RY(C,S,DS,LF)=MIN(1,RY(C,S,DS,LF));
        RY(C,S,DS,LF)=MAX(0,RY(C,S,DS,LF));

*       ---- Crop\Irrigation Water and wastage calculations-----------------------
        PPWR(C,LF)=SPYIWR(C)/(1-LFV(LF));
        APWR(C,LF)=SAYIWR(C)/(1-LFV(LF));
        PIWR(C,IS)=SPYIWR(C)/IR_EF(C,IS);
        AIWR(C,IS)=SAYIWR(C)/IR_EF(C,IS);

*       -ASSIGNING PID\AID THE HIGHEST VALE - PLANT OR IRRIG. WATER REQUIREMENT--
        PID(C,S,DS,IS,LF)=MAX(PIWR(C,IS),PPWR(C,LF) );
        PWL(C,S,DS,IS,LF)=MAX((PIWR(C,IS)-PPWR(C,LF)),(PPWR(C,LF)-SPYIWR(C)));
        AID(C,S,DS,IS,LF)=MAX(AIWR(C,IS),APWR(C,LF) );
        AWL(C,S,DS,IS,LF)=MAX((AIWR(C,IS)-APWR(C,LF)),(APWR(C,LF)-SAYIWR(C)));
        LFR(C,S,DS,IS,LF)=(PWL(C,S,DS,IS,LF)+AWL(C,S,DS,IS,LF))
                          /(PID(C,S,DS,IS,LF)+AID(C,S,DS,IS,LF));

*       --------------- CALCULATING WATER AND PUMPING COSTS ---------------------
        PWEC(C,S,DS,IS,LF)=PID(C,S,DS,IS,LF)*(CSFD("NB","WC")+CSFD("NB","PC"));
        AWEC(C,S,DS,IS,LF)=AID(C,S,DS,IS,LF)*(CSFD("NB","WC")+CSFD("NB","PC"));

*       ----------------------- CALCULATING THE GROSS MARGIN ---------------------
    GMASC(C,S,DS,IS,LF)=(CROP_COST("PRICE",C)*CROP_COST("MEY",C)*RY(C,S,DS,LF))
                       -(CROP_COST("hc"  ,C)*CROP_COST("MEY",C)*RY(C,S,DS,LF))
                       - CROP_COST("fvc" ,C);
        SMLF.solprint = 0.;
        Solve SMLF using LP maximizing NR;
     TGMRESULT("TGM",EC)=NR.L;
     TFRESULT("TF",EC)=SUM((FAY), (CSFD("NB","WC")+(FRAY(FAY)*CSFD("NB","WC")))
                       *FINES.L(FAY))+SUM((FPY), FINES.L(FPY)*FRPY(FPY));
     FSPPY(FPY,EC)=FINES.M(FPY);
     FSPAY(FAY,EC)=FINES.M(FAY);
     RFRESULT("RF",EC)=NPSD.l;
     RFDUAL("RF",EC)=MRF.m;
     QUOTAmDUAL("QDm",EC)=MAX_QUOTA.m;
     QUOTApDUAL("QDp",EC)=PY_QUOTA.m;
     QUOTAaDUAL("QDa",EC)=AY_QUOTA.m;
     ProdCap("PC",EC)=PCC.l;
     PCdual("PCd",EC)=PCC.m;
     FixdCap("FC",EC)=FCLC.l;
     FCDual("FCd",EC)=FCLC.m;
     XRESULT(C,EC)=SUM((S,DS,IS,LF), ACTIVITY.l(C,S,DS,IS,LF));                );
* ------------------------ E N D   O F   E C   L O O P -----------------------
* ----------------------------------------------------------------------------

* ------------------------------ S T A R T -----------------------------------
* -------------------------- PARAMETRIC RESULTS ------------------------------
    FILE SMP /C:\SALMOD\nb\SMPOL.prn/ ;
    PUT  SMP ;
    PUTTL SYSTEM.TITLE '      Date run: ',SYSTEM.DATE, ' Time: ', SYSTEM.TIME //;
    PUT
    'SALMOD DRAFT Results (Leaching Fractions Methodology - PARAMETRIC ANALYSIS)'
   /'Model by the RAPIDS team, Dept.Ag.Econ.UFS for the WRC' //
    'PARAMETRIC MODEL RUN FOR:              ', SR.te("NB")       //;
    I=19; LOOP (EC, I=I+8; PUT @I, EC.tl;                         );      PUT /;
    I=18; LOOP (EC, I=I+8; PUT @I, PP(EC):5:2;                    );      PUT /;
    PUT  ITEMS.te("TGM");
```

```
  I=16; LOOP (EC,I=I+8;  PUT @I, TGMRESULT("TGM",EC):7:0;   );      PUT /;
  PUT  ITEMS.te("TF");
  I=16; LOOP (EC, I=I+8; PUT @I, TFRESULT ("TF" ,EC):7:0;   );      PUT /;
  PUT  ITEMS.te("RF");
  I=16; LOOP (EC, I=I+8; PUT @I, RFRESULT ("RF" ,EC):7:0;   );      PUT /;
  PUT  'Returnflows duals   (R)';
  I=19; LOOP (EC, I=I+8; PUT @I, RFDUAL   ("RF" ,EC):4:2;   );      PUT /;
  PUT  ITEMS.te("PC");
  I=16; LOOP (EC, I=I+8; PUT @I, ProdCap  ("PC" ,EC):7:0;   );      PUT /;
  PUT  ITEMS.te("PCd");
  I=19; LOOP (EC, I=I+8; PUT @I, PCDUAL   ("PCd",EC):4:2;   );      PUT /;
  PUT  ITEMS.te("FC");
  I=16; LOOP (EC, I=I+8; PUT @I, FixdCap  ("FC" ,EC):7:0;   );      PUT /;
  PUT  ITEMS.te("FCd");
  I=19; LOOP (EC, I=I+8; PUT @I, FCDUAL   ("FCd",EC):4:2;   );      PUT /;
  PUT /, 'WATER QUOTA SHADOW VALUE' /;
  PUT 'Max Quota'; I=19;
  LOOP (EC, I=I+8; PUT @I, QUOTAmDUAL("QDm",EC):4:2           );    PUT /;
  PUT 'Pre-year Quota'; I=19;
  LOOP (EC, I=I+8; PUT @I, QUOTApDUAL("QDp",EC):4:2           );    PUT /;
  PUT 'After-year Quota'; I=19;
  LOOP (EC, I=I+8; PUT @I, QUOTAaDUAL("QDa",EC):4:2           );    PUT /;
  PUT /, 'WATER FINE SHADOW VALUES' / ;
  LOOP (FPY,  PUT FPY.tl;   I=19;
      LOOP (EC, I=I+8; PUT @I, FSPPY(FPY,EC):4:2           );       PUT /;  );
  LOOP (FAY,  PUT FAY.tl;   I=19;
      LOOP (EC, I=I+8; PUT @I, FSPAY(FAY,EC):4:2           );       PUT /;  );
  PUT /, 'OPTIMAL CROP COMPOSITION' / ;
  LOOP (C,  PUT C.tl;  I=16;
       LOOP (EC, I=I+8; PUT @I, XRESULT  (C   ,EC):7:2;    );       PUT /; );
* -------------------------- PARAMETRIC RESULTS --------------------------------
* -------------------------------- E N D ---------------------------------------

*------------------ F A R M   L E V E L   R E S U L T S -----------------------
*---------------- YIELD PERCENTAGE MODEL OUTPUT FILE GENERATOR -----------------
Parameter
   PWU(C,S,DS,IS,LF)     Pre-year water usage per crop system
   AWU(C,S,DS,IS,LF)     Pre-year water usage per crop system
   TPWU                  Total Pre-year water use
   TAWU                  Total Aft-year water use
   TWU                   Total water use
   TPWUC                 Total Pre-year water use cost
   TAWUC                 Total Aft-year water use cost
   TPWPC                 Total Pre-year water pumping cost
   TAWPC                 Total Aft-year water pumping cost
   TWUC                  Total water use cost
   TWPC                  Total water pumping cost
   TWOF                  Total water overuse fine
   FVAL(F)               Value of each fine increment
   TFVAL                 Total value of the fines
   GNW                   Growth in net worth   ;
file SMF /C:\SALMOD\nb\SMFOL.prn/;
PUT  SMF ;
PUTTL SYSTEM.TITLE '      Date run: ', SYSTEM.DATE, ' Time: ', SYSTEM.TIME //;
PUT 'SALMOD DRAFT Results (Leaching Fraction Methodology)'/
    'Model by the RAPIDS team, Dept.Ag.Econ.UFS for the WRC'//
    'GENERAL INPUT DATA   ', SR.te("NB")      /
    'Irrigable area   (ha)',  CSFD("NB","IA") /
    'Irrigation rights(ha)',  CSFD("NB","IR") /
    'Water cost     (R/mm)',  CSFD("NB","WC") /
    'Pumping costs  (R/mm)',  CSFD("NB","PC") //
    'Electrical Conductivity of the irrigation water - ECiw (mS/m)' /;
I=3; LOOP (T, PUT @I, T.tl;                 I=I+6;)     PUT /;
```

```
I=1; LOOP (T, PUT @I, MAveECiw(T,"NB"):5:0; I=I+6; )     PUT //;
PUT'SOIL TYPE  :'; I=14; LOOP (S,  PUT @I, S.tl;  I=I+4;
                                   PUT @I, ST_COUNT(S):6:1;  I=I+8; );PUT /;
PUT'IRRIG.SYST.:'; I=14; LOOP (IS, PUT @I, IS.tl; I=I+4;
                                   PUT @I, IS_COUNT(IS):6:1; I=I+8; );PUT /;
PUT'DRAIN.CLASS:'; I=14; LOOP (DS, PUT @I, DS.tl; I=I+4;
                                   PUT @I, DS_COUNT(DS):6:1; I=I+8; );PUT //;
PUT 'MODEL RESULTS'/ ;
PUT 'Optimal crop composition:'/
    'Crop'@11'Soil'@16'Class'@22'Irrig'@28'LF'@35'Yield%'@40' HECTARES'
    @50'    GMASC'@60' PYWater'@70' AYWater' /;
LOOP ((C,S,DS,IS,LF),
       PWU(C,S,DS,IS,LF)=PID(C,S,DS,IS,LF)*ACTIVITY.l(C,S,DS,IS,LF);
       AWU(C,S,DS,IS,LF)=AID(C,S,DS,IS,LF)*ACTIVITY.l(C,S,DS,IS,LF);
   if (ACTIVITY.l(C,S,DS,IS,LF)>0,
     PUT C.tl, @11, S.tl, @16, DS.tl, @22, IS.tl, @28, LF.tl,
       @35,  RY(C,S,DS,LF):4:2
       @40,  ACTIVITY.l(C,S,DS,IS,LF):8:1
       @50,  GMASC(C,S,DS,IS,LF):8:0
       @60,  PWU(C,S,DS,IS,LF):8:0
       @70,  AWU(C,S,DS,IS,LF):8:0 /                                   ) );
  TPWU=SUM((C,S,DS,IS,LF), PWU(C,S,DS,IS,LF));
  TAWU=SUM((C,S,DS,IS,LF), AWU(C,S,DS,IS,LF));
  TWU=TPWU+TAWU;
  TPWUC=TPWU*CSFD("NB","WC");
  TPWPC=TPWU*CSFD("NB","PC");
  TAWUC=TPWU*CSFD("NB","PC");
  TAWPC=TAWU*CSFD("NB","PC");
  TWUC=TAWUC+TPWUC;
  TWPC=TAWPC+TPWPC;
  PUT 'Total water used                (mm):', @50, TWU:8:0  @60, TPWU:8:0,
                                               @70, TAWU:8:0  /
      'Water shadow price,Max,pre-&aft-year:'  @50, Max_Quota.m:8:2
                                               @60, PY_Quota.m:8:2
                                               @70  AY_Quota.m:8:2 /
      'Unused trans. from Pre- to Aft-year :'  @70, TRANS_P2A.l:8:0 /
      'Water Usage Cost                 (R):', @50, TWUC:8:0 @60, TPWUC:8:0,
                                               @70, TAWUC:8:0 /
      'Water Pumping Cost               (R):', @50, TWPC:8:0 @60, TPWPC:8:0,
                                               @70, TAWPC:8:0 / ;
PUT   'Water overuse fines:' ;
  FVAL(FAY)=(CSFD("NB","WC")+(FRAY(FAY)*CSFD("NB","WC")))*FINES.L(FAY);
  FVAL(FPY)=FINES.L(FPY)*FRPY(FPY);
  TFVAL=SUM(F, FVAL(F));
LOOP (F,
PUT @25, F.tl,
    @30, FINES.l(F):8:0,
    @50, FVAL(F):8:0,
    @60, 'DUAL', @65, FINES.m(F):6:7     /      );
  TWOF=SUM(F, FINES.l(F));
PUT @5, 'TOTAL WATER OVERUSE',
    @30, TWOF:8:0,
    @40, 'TOTAL FINE',
    @50, TFVAL:8:0            / ;
 GNW=NR.l-CSFD("NB","FC");
PUT 'Estimated optimal net revenue (R):', @50, NR.l:8:0 /
    'Pre-determined fixed costs    (R):', @50, CSFD("NB","FC"):8:0 /
    'FARM PROFIT                   (R):', @50, GNW:8:0 /
    'Production capital requirement(R):', @50, PCC.l:8:0,
                            @38,  '(Max', CSFD("NB","MPC"):7:0, ')',
                            @60,'(DUAL=', @67, PCC.m:6:7,      ')' /
    'Fixed capital loan requirement(R):', @50, FCLC.l:8:0,
                            @38,  '(Max', CSFD("NB","MCL"):7:0, ')',
```

```
                            @60,'(DUAL=', @67, FCLC.m:6:7,     ')' // ;
PUT  'MANAGEMENT OPTIONS:' /;
PUT  'Soil Trans.WL-LD';  I=12;  LOOP (S, I=I+8; PUT @I, S.tl; ); PUT /;
LOOP (IS, I=1; PUT @I, IS.tl;
      I=8; LOOP (S, I=I+8; PUT @I, TRANS_W2L.L(S,IS):8:2; ); PUT /; ); PUT /;
PUT  'Soil Trans.WL-AD';  I=12;  LOOP (S, I=I+8; PUT @I, S.tl; ); PUT /;
LOOP (IS, I=1; PUT @I, IS.tl;
      I=8; LOOP (S, I=I+8; PUT @I, TRANS_W2A.L(S,IS):8:2; ); PUT /; ); PUT /;
PUT  'Soil Trans.LD-AD';  I=12;  LOOP (S, I=I+8; PUT @I, S.tl; ); PUT /;
LOOP (IS, I=1; PUT @I, IS.tl;
      I=8; LOOP (S, I=I+8; PUT @I, TRANS_L2A.L(S,IS):8:2; ); PUT /; ); PUT //;
PUT  'Irrig.Syst.Trans.F-C'; I=16; LOOP (S, I=I+8; PUT @I, S.tl; ); PUT /;
LOOP (DS, I=1; PUT @I, DS.tl;
      I=12; LOOP (S, I=I+8; PUT @I, TRANS_F2C.L(S,DS):8:2; ); PUT /; ); PUT /;
PUT  'Irrig.Syst.Trans.F-D'; I=16; LOOP (S, I=I+8; PUT @I, S.tl; ); PUT /;
LOOP (DS, I=1; PUT @I, DS.tl;
      I=12; LOOP (S, I=I+8; PUT @I, TRANS_F2D.L(S,DS):8:2; ); PUT /; ); PUT /;
PUT  'Irrig.Syst.Trans.C-D'; I=16; LOOP (S, I=I+8; PUT @I, S.tl; ); PUT /;
LOOP (DS, I=1; PUT @I, DS.tl;
      I=12; LOOP (S, I=I+8; PUT @I, TRANS_C2D.L(S,DS):8:2; ); PUT /; ); PUT /;
PUT  'Irrig.Syst.Trans.C-F'; I=16; LOOP (S, I=I+8; PUT @I, S.tl; ); PUT /;
LOOP (DS, I=1; PUT @I, DS.tl;
      I=12; LOOP (S, I=I+8; PUT @I, TRANS_C2F.L(S,DS):8:2; ); PUT /; ); PUT /;
PUT  'Irrig.Syst.Trans.D-C'; I=16; LOOP (S, I=I+8; PUT @I, S.tl; ); PUT /;
LOOP (DS, I=1; PUT @I, DS.tl;
      I=12; LOOP (S, I=I+8; PUT @I, TRANS_D2C.L(S,DS):8:2; ); PUT /; ); PUT /;
PUT  'Irrig.Syst.Trans.D-F'; I=16; LOOP (S, I=I+8; PUT @I, S.tl; ); PUT /;
LOOP (DS, I=1; PUT @I, DS.tl;
      I=12; LOOP (S, I=I+8; PUT @I, TRANS_D2F.L(S,DS):8:2; ); PUT /; );PUT //;
PUT 'Number of On-Farm Storage dams (50x50x3m) required: ',
    OFS.l:4:1 PUT @60, '(Dual ', OFS.m:8:2, ' )';
* ---------------- F A R M   L E V E L   R E S U L T S ------------------------
* -------------------------------   E N D   ----------------------------------
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SUMMARY

Keywords: *Economic impact, irrigation agriculture, irrigation water salinity, soil salinisation, linear programming optimisation, farm level model, SALMOD, Farm level management options, policy guidelines, Lower Vaal and Riet Rivers.*

In the Lower Vaal and Riet Rivers, changing irrigation water quality has raised concern about the long-term sustainability of irrigation due to reduced yields of certain crops and the withdrawal of some very profitable crops.

The main aim of this study is to develop and apply models to determine the long-term financial and economic viability of irrigation farming in the Lower Vaal and Riet Rivers, with specific aims to: evaluate the relationship between changing water quality, soil conditions and crop production; determine the impact on yield, crop choice, agronomic and water management practises, expected income and costs; develop models for typical farms in different river reaches, and apply these models to test the outcome of alternative scenarios regarding internal water quality management practises and external policy measures.

Five case study farmers were selected, one from each of the different sub-areas of the OVIB study area. The case study farmers were representative of their sub-areas with regards to the hectares of irrigation water rights held, and jointly, also sufficiently representative of the OVIB region.

With the contradicting aims of improved water use efficiency and increased leaching for salinity management, the importance of a financial optimisation model was evident to solve the apparent paradox between saving water due to it's scarcity value and "wasting" water to leach out salts that build up in soils through the process of irrigation.

SALMOD was constructed using GAMS and consists of a simulation and optimisation section that calculate the optimal crop enterprise, management and resource use combination that maximises farm returns under different water quality, management and policy scenarios.

The management options built into SALMOD are the appropriate leaching fraction to implement and crop yield to accept for the optimal crop / resource combination calculated. The fixed capital management options included in SALMOD are the installation of artificial drainage, the change of irrigation system and the building of on-farm storage / evaporation dams for return-flow management.

The % reduction in TGMASC from the long-term average ECiw (74 mS/m) to the worst expected Vaal River ECiw as predicted by Du Preez *et al, (*2000) for 2020 (159 mS/m), is 84% and 58% for the small farmers from Bucklands and Atherton respectively, between 13% and 16% for the Olierivier farmer, depending on whether the Vaal River of the Riet River has the major impact, 1% for the large and financially strong Vaallus farmer and 3% for the small yet resource strong New Bucklands farmer (see Table 5.38). These results clearly show that the small and resource poor farmers will be the most affected by irrigation water salinity deterioration.

Scenario results from SALMOD further show that:

- Leaching is financially viable for all case study farmers

- Accepting lower yields on soils with insufficient leaching capacity is also financially viable
- For farmers with limited area of well drained soils it can be financially viable to install artificial drainage
- The option of building on-farm storage dams when returnflows are constrained to 100 mm per hectare water rights held, is financially infeasible for all case-study farms and for all scenarios
- It is not financially viable for farmers to replace their current irrigation systems with more efficient water saving systems, but in some instances to replace them with systems that can apply a greater leaching fraction
- At the worst-case scenario salinity conditions, farmers with below 60 ha water rights, and who don't grow cotton, will go out of production.

SALMOD has proved to be a valuable farm level salinity management tool. SALMOD is also potentially useful at regional and national level for determining the farm level financial impacts of various water quality and quantity scenarios where the farmers are affected by irrigation water salinity.

OPSOMMING

Sleutel woorde: *Ekonomiese impak, besproeiingslandbou, besproeiingswaterversouting, grondversouting, lineêre programmering optimalisering, plaasvlakmodel, SALMOD, plaasvlakbestuursopsies, beleidsriglyne, Benede Vaal- en Rietriviere.*

In die Benede Vaal- en Rietriviere het veranderende besproeiingswaterkwaliteit bekommernis veroorsaak oor die langtermyn volhoubaarheid van besproeiing weens verlaagde opbrengste van sekere gewasse asook die staking van verbouing van baie winsgewende gewasse.

Die hoofdoel van die studie is om modelle te ontwerp en toe te pas om die langtermyn finansiële en ekonomiese volhoubaarheid van besproeiingslandbou in die Benede Vaal- en Rietriviere te bepaal, met verdere spesifieke doelwitte om: die verhoudinge te bepaal tussen veranderende waterversouting, grondomstandighede en gewasproduksie; die impak te bepaal op opbrengs, gewaskeuses, agronomiese en waterbestuurspraktyke en verwagte inkomste en uitgawes; modelle te ontwikkel vir tipiese plase in die verskillende riviertrajekte, en om die modelle toe te pas om die uitkomste te toets van alternatiwe scenarios van toepassing op interne waterkwaliteitsbestuurspraktyke en eskterne beleidsmaatreëls.

Vyf gevallestudie boerderye was geselekteer, een vir elk van die verskillende sub-gebiede van die Oranje-Vaal Besproeingsraad (OVIB) gebied. Die gevallestudieboerderye is verteenwoordigend van die sub-gebiede met betrekking tot die hektare besproeiingswaterregte toegeken, en gesamentlik ook voldoende verteenwoodigend van die OVIB ondersoekgebied.

Met die teenstrydige doelwitte van verhoogde waterverbruiksdoeltreffendheid en toenemende belangrikheid van loging vir vesoutingsbestuur, is die belangrikheid van ‘n finansiële optimaliseringsmodel duidelik, naamlik om die paradoks tussen waterbesparing weens die skaarsheidwaarde daarvan en watervermorsing om die soute wat deur die proses van besproeiing in die grond opgebou het, op te los en uit te loog.

SALMOD is in GAMS opgestel en bestaan uit ‘n simulasie- en optimaliseringsafdeling wat die optimale gewasamestelling, bestuurs en hulpbron verbruikskombinasies bepaal wat plaasinkomstes maksimaliseer onder verskillende water kwaliteit , bestuurs- en beleidscenarios.

Die bestuurskeuse wat in SALMOD ingebou is, is om die toepaslikste logingsfraksie te gebruik, en verlaagde gewasopbrengs te aanvaar om die optimale gewas- / hulpbronsamestelling te bepaal. Die vaste kapitaal bestuurskeuses wat in SALMOD ingebou is, is die installering van kunsmatige dreinering, die verandering van besproeiingstelsels en die bou van ‘n plaas opgaar / verdampingsdam vir terugvloeibestuur.

Die persentasie afname in totale bruto marge bo gespesifiseerde kostes (TGMASC) vanaf die langtermyn gemiddelde elektriese geleiding van die besproeiingswater (ECiw = 74 mS/m) na die slegste verwagte Vaal Rivier ECiw soos beraam deur Du Preez *et al, (*2000) vir 2020 (159 mS/m), is 84% en 58% vir die klein boerderye van Bucklands en Atherton, tussen 13% en 16% vir die Olierivierboerdery, afhangende van of die Vaalrivier of die Rietrivier die hoof impak het, 1% vir die groot en finansieel sterk Vaallusboerdery en 3% vir die klein maar hulpbron-sterk New Bucklandsboerdery (sien **Table 5.38**). Die resultate wys duidelik dat die klein en hulpbronarm boerderye die meeste geaffekteer word deur besproeiingswaterversouting.

Scenario resultate van SALMOD wys verder dat:

- Loging finansieel uitvoerbaar is vir al die gevallestudieboerderye
- Die aanvaarding van ‘n verlaagde opbrengs op gronde met onvoldoende logingskapasiteit ook finansieel uitvoerbaar is
- Vir boerderye met onvoldoende goed gedreineerde gronde kan dit finansieel lonend wees om kunsmatige dreinering te installeer
- Die opsie om ‘n opgaardam op die plaas te bou as besproeiingsterugvloei watervolumes tot 100 mm per hektaar waterregte toegeken, beperk is, is finansieel nie lonend vir al die gevallestudieboerderye en vir alle scenarios nie
- Dit is nie finansieel uitvoerbaar vir boerderye om hulle huidige besproeiingsstelsels met ‘n meer doetreffende waterbesparingsstelsel te vervang nie, maar wel in sommige gevalle met ‘n stelsel wat ‘n groter logingsfraksie kan toedien
- Vir die slegste geval versoutingscenario-omstandighede, sal boerderye met minder as 60 ha waterregte toegeken, en wat nie katoen kan plant nie, uit produksie gaan.

SALMOD is ‘n nuttige plaasvlak versoutingsbestuurhulpmiddel. Ook is dit potensieel waardevol op gebieds- en nasionale vlak vir die bepaling van plaasvlak finansiële impakte van verskillende water kwaliteit and kwantiteit scenarios waar boerderye geaffekteer word deur besproeiingswatervesouting.