INTEGRATED MODELLING FOR SUSTAINABLE MANAGEMENT OF SALINITY IN THE LOWER VAAL AND RIET RIVER IRRIGATION AREAS

By

Robert Jack Armour

Student Number 1992282846

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Department of Agricultural Economics

University of the Free State

Bloemfontein

Promotor: **Prof. M.F. VILJOEN**
University of the Free State

Co-promotor: **Prof. K.W. EASTER**
University of Minesota

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I declare that this dissertation hereby submitted by me for the Ph.D. degree in Agricultural Economics at the University of the Free State is my own independent work, conducted under the guidance and supervision of a project reference group (or steering committee) and a study leader and co-study leader, and has not previously been submitted by me at any other university / faculty.

....	13 September 2007
ROBERT JACK ARMOUR	DATE

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ACRONYMS, TERMS AND DEFINITIONS

DWAF Department of Water Affairs and Forestry

GFI Gross Farm Income

GWK The old Griqualand West Co-operative, now GWK Pty. Ltd.

IVRS Integrated Vaal River System

OR-WUA Orange-Riet WUA

OV-WUA Orange-Vaal WUA

SALMOD Salinity And Leaching Model for Optimal irrigation Development (developed in Armour & Viljoen 2002)

VRSAU Vaal River System Analysis Update

WMP Water Management Plan

WRC Water Research Commission

WRPM Water Resources Planning Model (funded by DWAF and administrated by WRP Consultants, Pretoria)

WRYM Water Resource Yield Model

WUA Water Users Association

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.

TDS Total dissolved solids (mg/l)

SAR Sodium adsorption ratio

CU The concentration of salts in the upper zone, measured TDS in mg/l

CUe The saturated extract concentration of salts in the upper zone, (TDS in mg/l)

ECiw Electrical conductivity of the irrigation water (measured in mS/m)

ECe Electrical conductivity of the saturated soil extract (measured in mS/m)

HE Monthly effective water volume (mm) holding capacity in the upper zone (HU) and lower zone (HL)

DEFINITIONS

SMsim Salinity simulation Model. The acronym used when referring to the integrated micro-economic model.

WRPM Water Resources Planning Model. Developed for the DWAF, it is the hydrology model that generates the stochastic hydrology sequences used in SMsim.

ISIM **Integrated Salinity Impact Model.** The acronym used when referring to the regional economic irrigation simulation model developed by the macro-economic project team of UrbanEcon, which uses *inter alia* SMsim results as inputs.

ISEW **Index for Sustainable Economic Welfare.** The weighted index of the Social, Environmental and Economic Welfare impacts used to compare different scenarios at regional level using ISIM data as input.

CEB **Crop Enterprise Budget**. The CEBs set up in this thesis 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 thesis 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 SMsim the TGMASC is generated at per hectare level and extrapolated to sub-WUA, irrigation block, WUA and regional levels. It is the difference between Gross Farm Income (GFI) and the specified allocatable production input costs, including water, electricity, an interest component and harvesting costs, as well as the annualised capital repayment costs of management options modelled for various scenarios. As each farming situation varies with regards to the fixed cost component of production (including depreciation), all annual non-allocatable costs are not included in the calculations in SMsim.

SPATIAL DEFINITION TERMS

WUA level – or, **Scheme level** refers to the OV- and OR-WUAs specifically.

sub-WUA level – or, **Sub-Scheme level** refers to internal divisions within the Scheme/WUA based on water source, and managed differently by the WUA.

Irrigation Block – is the specific term used in the WRPM to define a hydrology block made up of one or more sub-WUA level areas. The following four irrigation blocks are referred to in this thesis:

RloR – The Lower Riet River sub-WUA of the OR-WUA

Rscm – The Riet River Scheme sub-WUA of the OR-WUA (including Canal and Ritchie sub-WUAs)

Rszg – The Scholtzburg sub-WUA of the OR-WUA

Vall – All the Sub-WUA's of the OV-WUA

Regional level – used in the Macro-economic regional model to demarcate the municipal areas (local government areas) as economic units through which the particular river reaches under analysis flow (i.e. incorporating the area managed by both the OV- and OR-WUAs).

Study area – the study area referred to in this thesis encompasses all of the above.

ENGLISH SUMMARY

Abstract:

This thesis is the culmination of salinity economics research conducted for the South African Water Research Commission. The contribution of this thesis to science is not only in the field of Agricultural Economics, but also in other fields involved in irrigation salinisation research. It integrates the diverse mono-disciplinary spatial and temporal dimensions of the various disciplines of hydrology, agronomy, soil science and agricultural- and macro-economics, into an economic base model, to test scenarios and evaluate the economic, social and environmental sustainability of irrigated areas subject to salinisation.

Problem Statement and the Study Area:

Salinisation of irrigation schemes has become a problem in various schemes in South Africa. One such area that experiences salinisation problems selected for this research is the Lower Vaal and Lower Riet irrigation areas, upstream from where these two rivers converge and flow into the Orange River.

By understanding the dynamics and interactions between irrigation water quality and the soil salinity status on crop yield over time, mistakes made in the past by choosing unsustainable irrigation sites and practices can be prevented in the future. Furthermore the impact of various natural or artificial (e.g. policy mechanism) scenarios on existing schemes can be more accurately modelled, leading to increased economic efficiency and sustainability of the irrigation industry, together with its primary and secondary linkages, as a whole.

Aims:

The overall aim of the WRC study on which this thesis is based was to develop and integrate multi-dimensional models for sustainable management of water quantity and quality in the Orange-Vaal-Riet (OVR) convergence system.

More specifically the following sub-objectives had to be addressed:

1. To better understand the polluting chemical processes and interactions in and in-between the plant and surface-, vadose zone- and ground- water, to achieve efficient and sustainable water quality management
2. To develop new economic models at both,
   a. Micro level, namely dynamic long term simulation models, and at
   b. Macro level, using a regional dynamic Input / Output model[1]
3. To integrate these new economic models with models from the other disciplines of:
   a. Hydrology[2] (incorporating a salt mass balance and flow), and
   b. Agronomy (crop growth in the presence of salinity model)
4. To determine and prioritise best management practices at:

[1] The macro economic level (/ regional economic) part of the WRC study was conducted by the economic consultancy firm Urban-Econ

[2] The generation of stochastic hydrology data was conducted by the firm WRP consultants and funded by the DWAF

   a. Micro level, (i.e. per hectare and irrigation block level) and at

   b. Regional level.

5. Through a better understanding of the multi-dimensional interactions, to enhance water use efficiency as the quantity and quality of water available for agriculture inevitably decreases

6. To develop policy guidelines to ensure social, environmental and economic sustainability

7. To achieve all these aims based on using the complex OVR convergence system as a study area, but developing a method and models that can be applied elsewhere with relative ease.

This thesis however only covers the micro-economic aspect of the WRC project conducted by the author, and how it is driven by the hydrological and bio-physical processes and how it links and translates to the macro-economic (regional) impact.

Model:

The economic base model of the integrated model uses hydrology and biophysical data and algorithms as input into the monthly time-step, per hectare Crop Enterprise Budget based, MSExcel simulation model (SMsim) to generate the base data. The resulting stochastic and spatially differentiated data set of per hectare total gross margin above specified costs data is then converted to sub-WUA, WUA, combined WUA and regional area level data for comparison and interpretation at these various levels and for input into the macro-economic regional level model (ISIM) and the index for socio-economic welfare (ISEW) for sustainability evaluation between alternative scenarios.

Results:

The results of this thesis *inter alia* show that the installation of irrigation drainage to facilitate leaching is a far better option than planting more salt tolerant crops. In the WRC project on which this thesis is based the results of a macro-economic analysis based on the micro-economic results from this thesis show that although at sub-WUA level it may not be financially feasible to install drainage in some sub-WUA areas, the secondary and regional socio-economic and environmental impacts justify the spending of government grants for drainage installation as the secondary benefits on the regional economy exceed the costs of the drains.

AFRIKAANSE OPSOMMING

Uittreksel:

Hierdie tesis is die kulminasie van navorsing oor die ekonomie van versouting gedoen vir die Suid Afrikaanse Waternavorsingskommissie (WNK). Die bydrae van die tesis tot die wetenskap is nie net op die terrein van Landbouekonomie nie, maar ook op ander terreine betrokke by navorsing oor versouting van besproeiing. Dit integreer diverse mono-disiplinêre ruimtelike en tyds dimensies van die verskillende disiplines van hidrologie, agronomie, grondkunde en landbou- en makro-ekonomie, in 'n ekonomiese basis model, om scenarios te toets en die ekonomiese-, sosiale- en omgewingsvolhoubaarheid van besproeiingsgebiede wat deur vesouting geaffekteer word te evalueer.

Probleemsteling en Ondersoekgebied:

Die vesouting van verskeie besproeiingskemas het 'n problem in Suid Afrika geword. Een sodanige gebied wat versouting ervaar en wat vir die doeleindes van die navorsing gekies is, is die Benede-Vaal en -Rietrivier besproeiingsgebiede, stroomop van waar die twee riviere bymekaar kom en in die Oranjerivier vloei.

Deur die dinamika en interaksies tussen besproeiingswaterkwalitiet en die grond se vesoutingstatus op gewas opbrengs oor tyd te verstaan, kan foute van die verlede soos die keuse van onvolhoubaare besproeiingsgebiede en praktyke vehoed word. Verder kan die impakte van verskeie natuurlike en kunsmatige (b.v. beleidsmeganismes) scenarios op huidige skemas meer akuraat gemodeleer word, wat kan lei tot toenemende ekonomiese doeltreffendheid van die besproeiingsindustrie, met sy primêre en sekondêre koppelinge.

Doelstelling:

Die oorhoofse doelstelling van die studie waarop die tesis gebaseer is was om multi-dimensionele modelle te ontwikkel en te integreer vir die volhoubare bestuur van water-kwantiteit en -kwalitiet in die Oranje-Vaal-Riet (OVR) samevloeiings.

Meer spesifiek, was die volgende sub-doelstellings aangepak:

1. Om die besoedelende chemiese prosesse en interaksies tussen en binne in die plant en oppervlakte-, wortelsone- en grond- water beter te verstaan, om doeltreffende en volhoubare waterkwaliteit te bestuur
2. Om nuwe ekonomiese modele te ontwikkel op beide,
   a. Mikro vlak, naamlik dinamiese langtermyn simulasiemodelle, en
   b. Makro vlak, deur die gebruik van 'n streeksvlak dinamiese Inset / Uitsel model[1]
3. Om die nuwe ekonomiese modelle te integreer met modelle van die ander dissiplines, naamlik:
   a. Hidrologie[2] (deur die inkorporering van 'n soutmassabalans en vloei), en
   b. Agronomie (gewasgroei in die teenwoodigheid van soute)

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[1] Die makro ekonomiese vlak (streeksvlak) gedeelte van die WNK studie was gedoen deur die makro-ekonomiese konsultante Urban-Econ

[2] Die generering van stogastiese hidrologie data was deur die firma WRP konsultante gedoen en deur die DWW&B befonds

4. Om die beste bestuurspraktyke te bepaal en prioritiseer op:
    a. Mikro vlak, (d.i. per hektaar en besproeiingsblok vlak) en op
    b. Streek vlak
5. Deur die multi-dimensionele interaksies beter te verstaan, kan waterverbruiksdoeltreffendheid verbeter soos wat die kwantiteit en kwaliteit van die water beskikbaar vir landbou doeleindes verminder
6. Om beleidsmaatreëls te ontwikkel om sosiale-, omgewings- en ekonomiese-volhoubarheid te bevorder
7. Om die doelstellings te bereik deur die gebruik van die komplekse OVR samevloeiingstelsel as studiegebied, maar om die metodiek en modelle so te onkwikkel dat hulle met relatiewe gemak op ander gebiede toegepas kan word.

Die tesis dek net die mikro-ekonomiese aspekte van die WNK projek wat deur die skrywer self nagevors is, en hoe die aspekte deur die hidrologiese en bio-fisiese prosesse gedryf word, asook die koppeling met die makro-ekonomiese (streeksvlak) impakte.

Die Model:

Die ekonomiesebasis model van die geintegreerde model gebruik hidrologiese en bio-fisiese data en algoritmes as insette op 'n maandelikse-tydskaal-per-hektaar-gewasbegroting-gebaseerde-MSExcel-simulasie-model (SMsim) om die basis data te genereer. Die stogastiese en ruimptelik gedifferensieerde uitkomsdata stel van per hektaar Totale Bruto Marge Bo Gespesifieseerde Koste (TBMBGK) word dan omgeskakel na sub-Waterverbruikersvereniging (sub-WVV), WVV, gesamentlikke WVV en streeksvlak data vir vegelyking en interpretasie op die verskillende vlakke, en as insette binne in die makro-ekonomiese streeksvlak model (ISIM) en die Indeks vir Sosio-Ekonomiese Welvaart (ISEW) om volhoubaarheid van alternatiewe scenarios te bepaal.

Resultate:

Die resultate van die tesis wys onder andere dat die installering van besproeiingsdreinering om loging te fasiliteer 'n heelwat beter opsie is as om meer sout-verdraagsame gewasse te plant. In die WNK verslag waarop die tesis gebaseer is, het die resultate van die makro-ekonomiese analiese wat gebaseer is op die mikro-ekonomiese resultate van die tesis gewys dat alhoewel dit op sub-WVV vlak dalk nie finansieël die moeite werd is om dreinering in sekere sub-WVV gebiede te installeer nie, dit wel op groter gebiedsvlak geregverdig kan word. Dit is omdat die voordele van die sekondêre en streeksvlak sosio-ekonomiese en omgewingsimpakte heelwat groter is as die koste van dreinering.

CHAPTER 1 INTRODUCTION

Faced with the choice between changing one's mind and proving that there is no need to do so,
almost everyone gets busy on the proof.
John Kenneth Galbraith

1.1 INTRODUCTION

The purpose of this introductory chapter is the following:

- to sketch the background situation leading to the identification of the research on which this thesis is based,
- to state the problem and specific sub-problems stemming from the background overview,
- to present the aims of the research on which this thesis is based,
- to briefly introduce the methods followed, and
- to map / lay out the rest of this thesis for the reader.

1.2 BACKGROUND

The purpose of the National Water Act (39 of 1998) which gets its mandate from (amongst others) Section 24 of the Bill of Rights in the Constitution, 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. To achieve this, ongoing research on the different aspects mentioned is needed. Further research to ensure the sustainability of irrigation schemes in South Africa is thus essential to ensure national food security and employment in some otherwise barren areas 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 (Winpenny, 2002). At the same time however it is also predicted by a recent World Bank study (Seckeler *et al.*, 1999) that water scarcity in South Africa will increase drastically in the nearby future moving its status from somewhere between 2005 and 2040 from a water scarce to a water stressed country. Together with increasing water scarcity, declining water quality levels in most of our rivers will further threaten the productive use of this water for food production.

With irrigation being the largest user of water, field-, farm- and Water Users Association -level 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 which it supports, and also to release water for other sectors of the economy. However, macro-level 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), as well as 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.* 1999). To proactively manage and implement policy to anticipate problems, and sustainably introduce change, the best information obtained from comprehensive multi-disciplinary research is needed.

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 and practices can be prevented. Furthermore the impact of various natural or artificial (e.g. policy mechanism) scenarios on existing schemes can 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. DWAF, 1996 mentioned the following in this respect: "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."

The research project on which this thesis is based, followed on a previous study by Armour and Viljoen (2002) entitled "The Economic Effects of Changing Water Quality on Irrigated Agriculture in the Lower Vaal and Riet Rivers". The water quality problem set out to be studied in this project was 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.

In the research project on which this thesis is based, the proposed macro-level research to determine impacts at regional level followed on an Urban-Econ study (Gouws *et al.*, 1998) that was successfully completed using economic simulation modelling to identify and quantify the economic impacts of salinity in the Middle Vaal River System. The input/output analysis technique was used as the simulation model and various applications of the model were used to determine the results.

The research project on which this thesis is based therefore essentially consisted of two separate projects, but it was deemed necessary for synergy and the achievement of optimal project results that the micro and macro level models be linked. Also, for Urban-Econ to extend the scope of their previous salinity research downstream and for the WRC to enhance the static model in Armour and Viljoen (2002) by developing an integrated dynamic model for the area, the complex Orange-Vaal-Riet convergence system was selected the study area for the project. Degraded returnflows from 3 major irrigation schemes comprising ± 60 000 hectares all come together within the proposed study area where the dilution effect of Orange River water is critical. The area is also a main economic force in the Northern Cape with strong agriculturally based industry such as GWK Pty. Ltd., many strong farmers reliant on irrigation and further irrigation potential for previously disadvantaged farmers. Isolated from other crop farming areas the area is strategically located for the production of a large portion of the countries seed, further stressing the importance of irrigation in this area and thus the large negative effects of proposed water transfers away from the area.

Concerning land redistribution, there are areas within the study area that are earmarked for resettlement of historically disadvantaged individuals. To avoid making mistakes of the past and designing irrigation schemes in areas which might not be economically and environmentally sustainable, a thorough understanding of potentially land degrading processes such as salinisation, sodification, water-logging etc. is essential.

The research project on which this thesis is based proposes to address the current void in existing research and within a multidisciplinary framework, aims to better understand the dynamic interactions between the hydrology, bio-physical and socio-economics of irrigated agriculture in the Orange-Vaal-Riet convergence system. The objective is to determine the current trends, private-, social- and regional- impacts, externalities, and the long-term sustainability of current and proposed irrigation practices. With these interactions better understood the impact of various policy measures and management practices at farm, WUA, inter-WUA and at a regional level will be able to be modelled to determine the potential impacts on the sustainability of irrigated agriculture, communities and the eco-system of the Lower Vaal, Riet and Middle Orange River systems.

The resulting models are used to monitor the economic impact of changing water quality, simulated over time, and the method followed in developing these models can be applied with the necessary modifications to other river reaches.

As the research project on which this thesis is based was a team effort, only the portions thereof conducted by the author of this thesis are incorporated into this document as his original work, with citation of the WRC project Viljoen *et al.* (2006) where work by the other authors is used in this thesis.

1.3 PROBLEM STATEMENT

The main problem for investigation in this thesis is the serious threat to the long-term sustainability of irrigation in the Orange-Vaal-Riet convergence system posed by salinisation, and the serious impact that this can have on the economics of the study area as a whole. Various policy and management options have been identified in previous studies, but an inter-disciplinary approach is required to test the applicability and sustainability of these options, posing its own set of problems.

1.3.1 SUB-PROBLEMS

1.3.1.1 Interdisciplinary model integration for effective soil salinity impacts interpretation

The short-term economic impact of irrigation water quality fluctuation in the Lover Vaal and Riet Rivers was quantified in a study by Armour and Viljoen (2002), but the build-up of salts in the soil was identified as a potential long-term problem. The integration of this build-up of salts in the soil over time together with the hydrology of the study area, the biophysical interactions that relate soil salinity to crop yield, and the economic impact of changing crop yields due to salinity, form the basis of investigation for this study.

1.3.1.2 Deciding on additional leaching versus switching to salt tolerant crops as the best salinity management option

The application of additional irrigation water for leaching is required to wash salts out that have built up in the soils over time, however where soil type or topography does not allow for natural drainage from the soil, either salt tolerant crops need to be planted or expensive artificial drainage installation is required. Whether farmers can survive planting salt tolerant crops or whether they can afford to pay for the additional drainage, and what grant assistance policy may be required are the second and third sub-problems analysed in this study

1.3.1.3 Internalising the downstream impacts of additional leaching and drainage

Downstream externalities from point and non-point source drainage as a result of additional leaching needs to be quantified, together with the impact of the additional leaching on downstream farmers, so that effective policy decisions as to who pays for remediation action, and at what cost to effectively internalise the costs of leaching, can be made.

1.3.1.4 Quantifying the importance of salinisation at a regional level

As salts, mobilised through leaching and drainage, migrate, a solution to one farmer may be a problem to another. Furthermore, a solution for farmers in general in an area, may have serious repercussions on employment / the environment / other secondary industries either supplying inputs to irrigation agriculture or be involved in further benefaction of the produce from irrigated agriculture. Therefore, the analysis at a regional level is required to holistically assess the salinity problem.

1.3.2 HYPOTHESES / PROCEDURE

The hypotheses / procedural steps that follow tie up with the sub-problems identified in the preceding paragraph and each one is followed by a relevant research question. The sequence of hypotheses determines the procedural steps followed.

- Soil / plant / atmosphere interactions and salt balance models can be successfully incorporated into economic models to effectively interpret soil salinity at micro and regional levels.

  The research question is which soil / plant / atmosphere and salt balance models can be successfully incorporated into what type of economic models and how these would effectively interpret soil salinity at micro and regional levels?

- In low rainfall areas, the inevitable salinisation of soils irrigated with poor quality water can be managed sustainably through either increased leaching, or shifting to more salt tolerant crops.

  The research question is which management option of leaching or shifting to more salt tolerant crops is the more financially feasible and environmentally sustainable option?

- Through the application of correct policy and management interventions, the downstream externalities associated with additional leaching and drainage can be internalized with a positive net regional benefit.

The research question is which policy and management interventions are required and what institutional framework needs to be in put in place?

- Irrigation agriculture is essential for sustainable regional social economic welfare in the study area.

  The research question is how would one go about determining regional social economic welfare, to what extent does irrigation agriculture contribute and what impact does salinisation therefore have on regional social economic welfare?

1.4 AIMS

The overall aim of the WRC project on which this thesis is based was the development and integration of multi-dimensional models for the sustainable management of water quantity and quality in the Orange-Vaal-Riet convergence system. To achieve this, the following sub aims were identified:

1. To better understand the polluting chemical processes and interactions in and in-between the plant and surface-, vadose zone- and ground- water, to achieve efficient and sustainable water quality management
2. To develop new economic models at both,
   1. Micro level, namely dynamic long term simulation[1] models, and at
   2. Macro level, using regional dynamic Input / Output model[2]
3. To integrate these new economic models with models from the other disciplines[3] of:
   a. Hydrology[4] (incorporating a salt mass balance and flow), and
   b. Agronomy (crop growth in the presence of salinity model)
4. To determine and prioritise best management practices at:
   a. Micro level, (i.e. per hectare and irrigation block level) and at
   b. Regional level[2].
5. Through a better understanding of the multi-dimensional interactions, to enhance water use efficiency as the quantity and quality of water available for agriculture inevitably decreases
6. To develop policy guidelines to ensure social, environmental and economic sustainability
7. To achieve all these aims based on using the complex Orange-Vaal-Riet convergence system as a study area, but developing the method followed and models so that they can be applied elsewhere with relative ease.

[1] The initial aims stated that an optimization model would be used, but this aim was changed at a Reference Group meeting to a simulation approach.

[2] The macro economic (/ regional economic) level part of the WRC study was conducted by the economic consultancy firm Urban-Econ and can be found in the WRC report by Armour *et al.* 2006.

[3] The initial aims also included the integration of vadose zone (unsaturated root zone) chemical balance models and groundwater (saturated - below water table) models. The incorporation of the WRPM as the hydrology model fulfilled both there requirements to a certain degree.

[4] The generation of stochastic hydrology data was conducted by the firm WRP consultants and funded by the DWAF

1.5 APPROACH / METHOD FOLLOWED

The approach followed consisted of the following steps:

- Study area and research orientation and planning
- Multi-dimensional background research and literature study
- The formulation of an integrated conceptual framework
- Model design and testing
- Data collection and processing
- Model runs, validation and the analysis of the data
- Formulation of management and policy recommendations

Throughout the duration of the WRC project, reports were prepared for each of these steps for presentation and discussion at the WRC project reference group meetings. The final WRC report (Viljoen *et al.*, 2006) was completed and submitted in August 2006.

1.5.1 ORIENTATION

The following actions were carried out in the initial orientation phase of this research:

- The classification of land-uses and economic activities according to generally acceptable systems (integrating an economic classification system with a hydrological system),
- The delineation of the study area, and
- The identification and sourcing of background information.

1.5.2 MULTI-DIMENSIONAL BACKGROUND RESEARCH (LITERATURE STUDY)

The purpose of this step was to undertake a detailed specialist evaluation of the multi-dimensional components underlying the integrated modelling. The research undertaken during this step was aimed at understanding and identifying relevant applicable models, obtaining an indication of the type of base / setup data required, compiling profiles, identifying trends and identifying the main problem areas.

A combination of study area specific information gleaned from existing reports and documents was used in compiling a description of the study area in Chapter 2. Chapter 3 is a comprehensive literature study of all perceived aspects related to the specific salinity problem in the study area. Results from the literature study in Chapter 3 lead to the interdisciplinary (hydrology, soil science, agronomy, micro- and macro economics) review of the proposed sub-models and their integration with the other disciplines in Chapter 4. The discipline specific bio-physical interrelations relevant to the salinisation process are reviewed in Chapter 5, and the linkage from the micro-economic model to the macro-economic model is discussed in the end of Chapter 6.

1.5.3 INTEGRATED CONCEPTUAL FRAMEWORK

The purpose of this step was to develop an integrated conceptual framework that provides a reference framework for the salinity modelling. This framework guided the design and the development of the model. The first action was to conceptualise the problem and express it as a functional relationship (i.e. the objective function). Such a relationship is the first move towards economic modelling as it represents the base formula for the model. In finalising the framework, the data needs of the model were identified providing the specifications for the data gathering actions. A conceptualisation workshop was held with key role-players and technical experts to finalise the conceptual and generic modelling approach of the study.

1.5.4 MODEL DESIGN

1.5.4.1 Regional hydrology model (WRPM) results

The Water Resources Planning Model (WRPM) results provide stochastic water quality and quantity predictions for the various river reaches and irrigation blocks in the study area for the various scenarios tested based on approximately 70 years of historical data. Results from the WRPM as produced by WRP consultants indicate the changes in hydrology, irrigation block upper and lower soil layers and return flow impacts of the management options tested in the various scenarios. These results should prove useful for farmers, WUA managers and policy planners.

1.5.4.2 Regional Input / Output model, ISIM (Integrated Salinity Impact Model)

In the WRC report (Viljoen *et al*,. 2006) Urban-Econ compiled a detailed layout and explanation of the regional economic model (ISIM) developed for this study, taking the irrigation block level TGMASC results to regional level and incorporating the forward and backward linkages on the regional economy through the use of Input / Output tables. An index for socio-economic welfare (ISEW) is also calculated as an indication of the long-term economic, environmental and social sustainability of the various options analysed.

The regional economic model, ISIM, through the use of an elaborate input/output matrix, determines the secondary effects on other sectors of the regional economy and the environment and job creation of various policies / management options modelled and provides a potential method for input/output analysis modelling of other river reaches. Through the use of the index for socio-economic welfare (ISEW) different policy and management options can be compared, taking the environmental, social and secondary economic implication into consideration. This is an important tool for water policy makers, local government and regional planners.

1.5.5 DATA COLLECTION

The purpose of this step is to undertake primary and secondary data gathering exercises to obtain data for each of the functional relationships as specified in the model. The data gathering exercises are thus aimed at obtaining data in accordance with the user requirement specifications of model. The data collection included selected surveys and sampling as well as interviews with specialists and key role-players. The information obtained by means of the data gathering exercises is computerised for inclusion in the model.

1.5.6 ANALYSIS

The purpose of this step is to analyse and transform the data to be used in the model. The data gathered during the data collection step is computerised, analysed and utilised in the model framework developed during integrated conceptual framework formulation step. An integral part of this analysis is to undertake sectoral and technical evaluations which provide the necessary background for interpreting the data. The results of the analysis are used to determine the nature and extent of water quantity and quality impacts at both micro (per hectare level to irrigation block level) and macro (study area) level.

1.5.7 MANAGEMENT POLICY RECOMMENDATIONS

The purpose of this final step is to utilise and interpret results from the preceding steps to formulate strategic guidelines for micro and regional level management and policy formulation. Although the regional level model was set up and run by Urban Econ, the interpretation of the results for regional level management and policy formulation is conducted by the author, under the guidance of the macro-economic team.

Recommendations are formulated based on the integrated economic, biophysical and hydrologic modelling results. These include the following: policy recommendations, modelling applications suggestions, pricing options, water resource allocation options, pro-active intervention focus areas, applications of research findings, policy guidelines, governance and intervention, and a sectoral focus of interventions.

1.6 SUMMARY

In summary, this chapter sketched:

- The background situation leading to the identification of this research in view of the National Water Act and in context of food security in Southern Africa, sketching the potential threat of salinisation in South Africa.
- The problem statement stemming from the background overview, stressed the multidisciplinary approach needed to capture the dynamic nature of the salinisation problem. The main problem for investigation in this thesis was identified as the serious threat to the long-term sustainability of irrigation in the Orange-Vaal-Riet convergence system posed by salinisation, and the serious impact that this can have on the economy of the study area as a whole.
- The sub aims of the main aim were formulated into hypotheses / procedural steps, each with leading questions.
- The approach / method followed in conducting this thesis is briefly discussed, explaining the connection with the greater research project from which this thesis is based.

The final paragraph of this chapter that follows, maps the layout of the rest of this thesis for the reader.

1.7 THESIS LAYOUT

The rest of this thesis consists of the following:

- Chapter 2, sketches the spatial and temporal delineation and main characteristics of the study area.
- Chapter 3, a literature study, which is the theoretical grounding of this thesis
- Chapter 4, also an introductory chapter in a sense, formulating and mapping out the integrated conceptual framework of the research that follows, briefly introducing other chapters and integrating them as a whole.
- Chapter 5, explains the various bio-physical components and sub-models, including the hydrology model, that are incorporated into the economic models.
- Chapter 6, is a detailed layout and explanation of the micro-economic model (SMsim) developed for this study, calculating per hectare crop enterprise budgets (CEBs) and taking these to irrigation block level total

gross margin above specified cost (TGMASC) level results for analysis of the economic impact of salinisation.

- Chapter 7 motivates, sketches and discusses the various scenarios modelled.
- Chapter 8 is the presentation and discussion of the micro-economic level model results, including reference to the hydrology model results and regional economic model results.
- Chapter 9 is a discussion on, and implications of the results for management and policy decisions.
- Chapter 10 summarises the thesis, lists the overall conclusions and provides a synthesis of the work done in this study, leading to important lessons learnt and further research needs.

Three appendices are included, namely:

- Appendix 1 is a detailed description of the physical process followed in compiling, setting up, running, transferring and interpreting data to operate SMsim.
- Appendix 2 lists complete crop enterprise budgets, the basis of SMsim, for all 20 crops incorporated in the model.
- Appendix 3 is a summary of the mathematical formulation of SMsim as described in full in Chapters 5 and 7.

CHAPTER 2 A DESCRIPTION OF THE STUDY AREA

"The Riet-Modder catchment is a 'feast or famine' catchment with only 8 years in 50 being 'average' years"

Van Veele (2004)

"The river, like blue veins on the map, is the life blood sustaining the agriculture on which the region depends."

Bosman (1997)

2.1 INTRODUCTION

The aim of this chapter is to describe the study area of this thesis, highlighting only of the main characteristics relevant for this report. Aspects addressed include:

- the study area in general, defined by geography, topography, climate, and economic activity
- the Water User Associations (WUAs) that fall within the study area,
- and the irrigation blocks that are made up of sub-WUAs areas, and are the spatial level at which the majority of analysis of this thesis takes place.

The physical boundaries and characteristics of the various hierarchical levels (per hectare up to regional level) modelled in this study, are compiled from biophysical, hydrologic, economic and political boundaries that further differentiate areas within the study area.

As this study is based on hydrology model data, the significance of the different hydrology dynamics between irrigation blocks, and how these dimensions are to be captured in this study, are discussed in the final paragraph before the summary in this chapter.

2.2 GEOGRAPHY

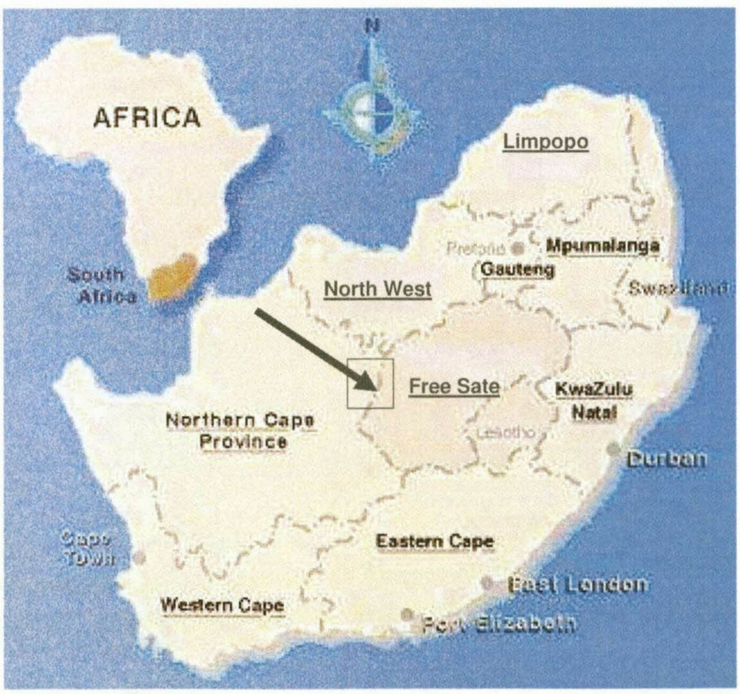


Figure 2.1 shows the placement of the study area in South Africa. The study area spans two provinces, namely the Northern Cape and Free State. The provinces are sub-divided into district municipalities as discussed in Chapter 7, where the selection of the relevant regional municipalities for delineation of boundaries for regional economic analysis in this study is described.

Figure 2.1. The position of the study area within South Africa

2.3 TOPOGRAPHY

Douglas, the main town in the OV-WUA is positioned 1030 meters (3263 ft) above sea level at the following GPS coordinates 29°03'16.85" S, 23°46'41.64" E (Google Earth, 2006).

Jacobsdal, the main town of the OR-WUA is positioned 1140 meters (3791 ft) above sea level at the following GPS coordinates 29°13'05.71" S, 24°48'48.41" E (Google Earth, 2006).

The topography of the area is typical Kalahari plains with small hills. Large salt pans have formed in the troughs and often hill tops and higher lying areas are covered in deep red soil. Limestone layers are also exposed in places, which can cause impermeable layers and can *inter alia* lead to water-logging.

2.3.1 HYDROLOGY

Shown in Figure 2.2, the study area falls within 3 major river catchments in South Africa, namely the Upper Orange, Lower Orange and Lower Vaal River catchments. Also shown in Figure 2.2 are the transfers from the Upper Orange River catchment via the Orange-Vaal and Orange-Riet canals into the Lower Vaal catchments.

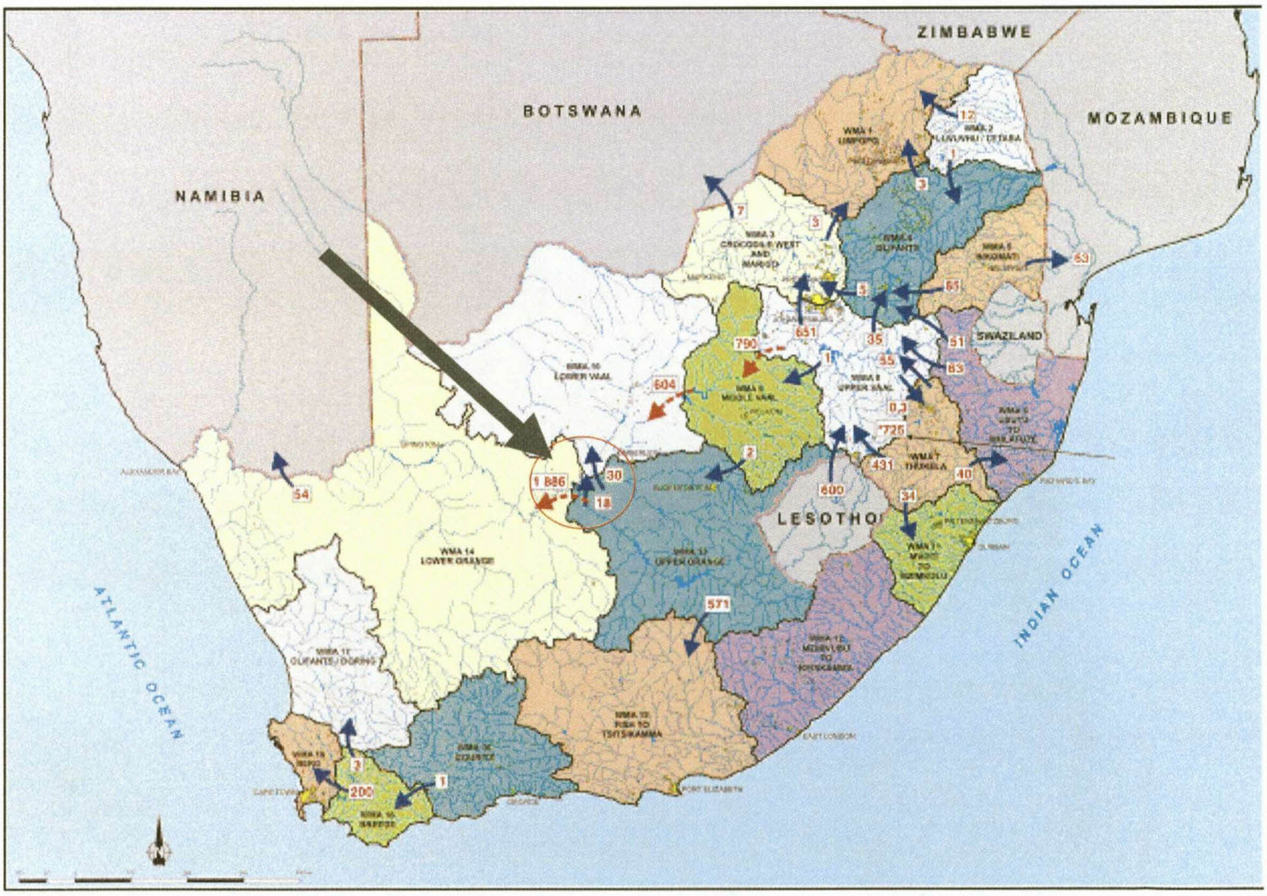


Figure 2.2 River catchments and inter-basin transfers of South Africa (Ninham Shand, 2004)

Figure 2.3 shows the generalised mean annual precipitation isohyets in millimetres after, seasonal rainfall zones and the main two rivers of South Africa in relation to the study area, positioned at the confluence of the Orange and Vaal Rivers. Deduced from Figure 2.3, the study area lies in an arid summer rainfall region receiving approximately 325 mm of rain annually. Also indicated, and of particular significance to this study, is that the Orange River headwaters are in the sparsely populated Maloti Mountains of Lesotho, receiving pure snowmelt and rainfall, resulting in a good irrigation water quality downstream. The Vaal River on the other hand has its headwaters in the densely urbanized, mining and industrial hub of South Africa around Johannesburg, receiving potentially polluted returnflows that could contribute to poorer irrigation water quality (du Preez, *et al.* 2000). The water quality is however effectively managed at the Vaal barrage long before reaching the study area. The returnflows from the Vaal-Harts WUA, situated upstream of the study area, collect in the Spitskop Dam in the Harts River tributary to the Vaal River, where salts have been concentrated over time. Spitskop Dam releases can have an impact on the salinity of Vaal river water entering the study area. Although levels of dissolved salts elevate as one moves downstream, the main cause of soil salinisation is as a result of the process of irrigation itself (Volschenk *et al.*, 2005), releasing latent salts accumulated in the soils in the low rainfall areas as depicted in Figure 2.3.

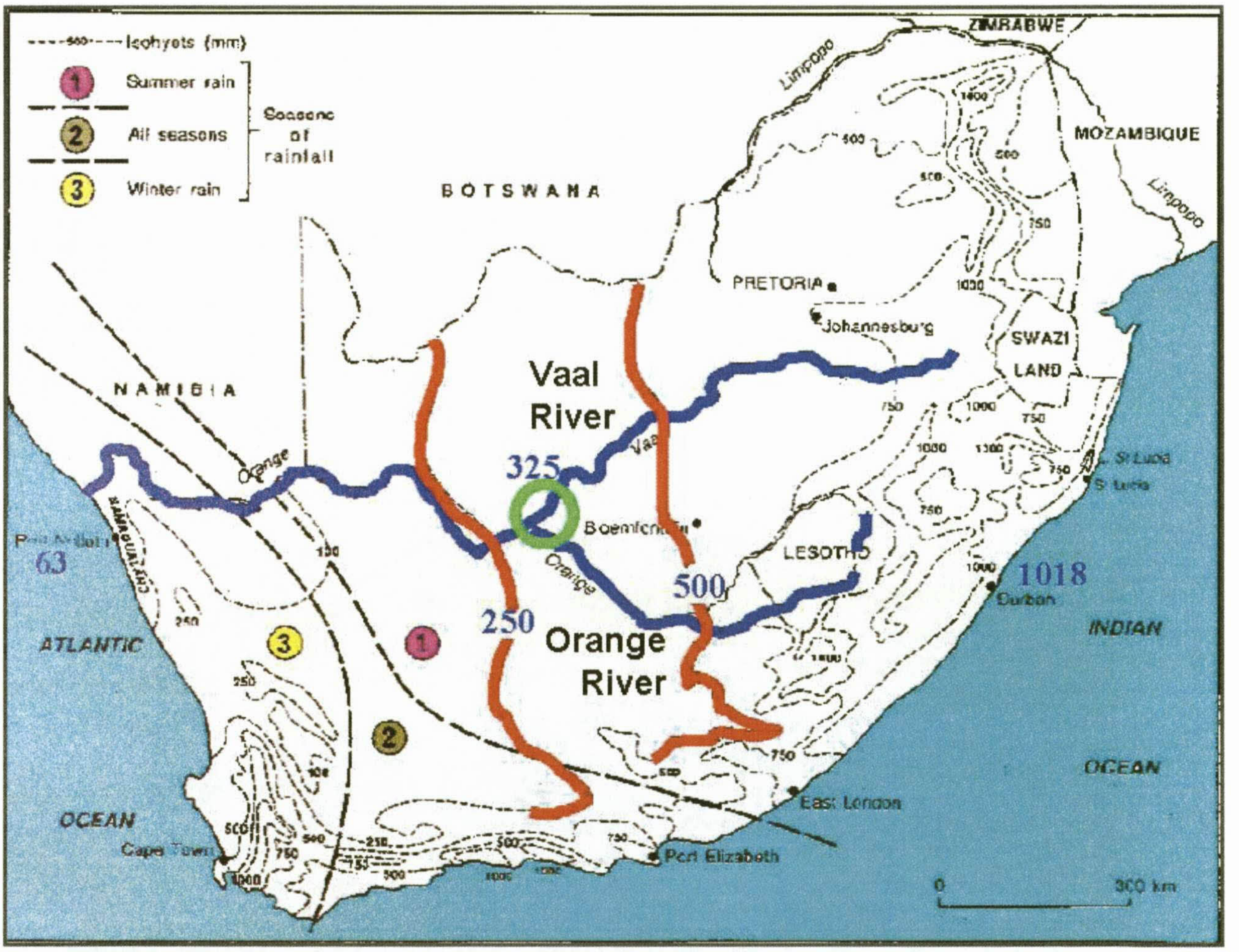


Figure 2.3 Generalised mean annual precipitation (mm) isohyet, seasonal rainfall zones and the main two rivers of South Africa in relation to the study area at the confluence of the Orange and Vaal Rivers

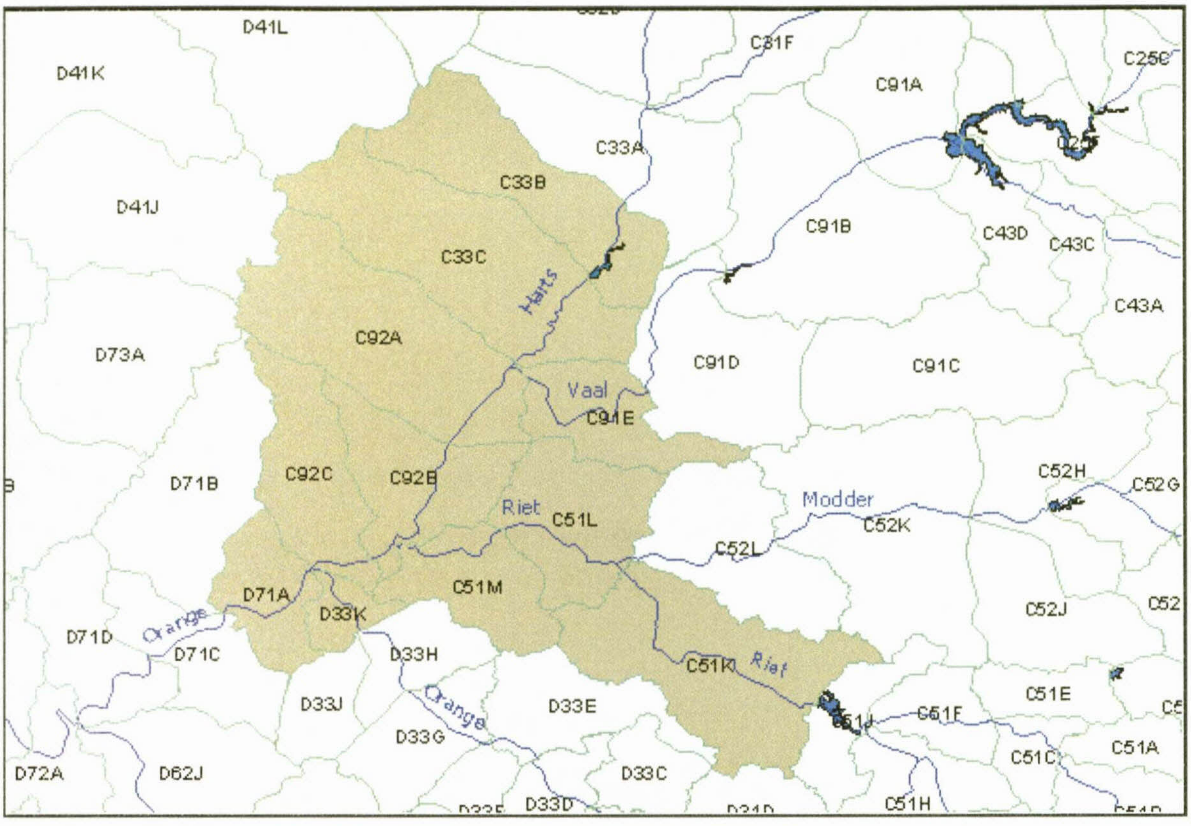


Figure 2.4. Quaternary catchments falling in the study area

Figure 2.4 shows the all the quaternary catchments falling within the study area. The hydrology model selected for use in this study will make use of these quaternary catchments areas data in calculating runoff, catchments size, etc.

2.4 CLIMATE

Rainfall - Figure 2.3 shows that the study area lies between the 250 mm and 500 mm isohyet and in a summer rainfall season region. Historical mean annual precipitation at the town of Douglas, in the OV-WUA is 355 mm per annum, and at Jacobsdal in the OR-WUA 366 mm per annum. Summer rainfall occurs mainly from November to March.

Evapo-transpiration - Figure 2.5 shows the reference evaporation (mm) for Douglas and the Riet River scheme using the Douglas jail data set. With evapo-transpiration reaching 2000 mm per annum, and a rainfall of only 300 to 400 mm per year, the need for a large volume of irrigation to grow crops is evident.

Temperature – temperatures often exceed 40°C at midday in the hot summer months from December for February, with frost occurring in the winter months, limiting the choice of certain high value crops and the duration others can be planted.

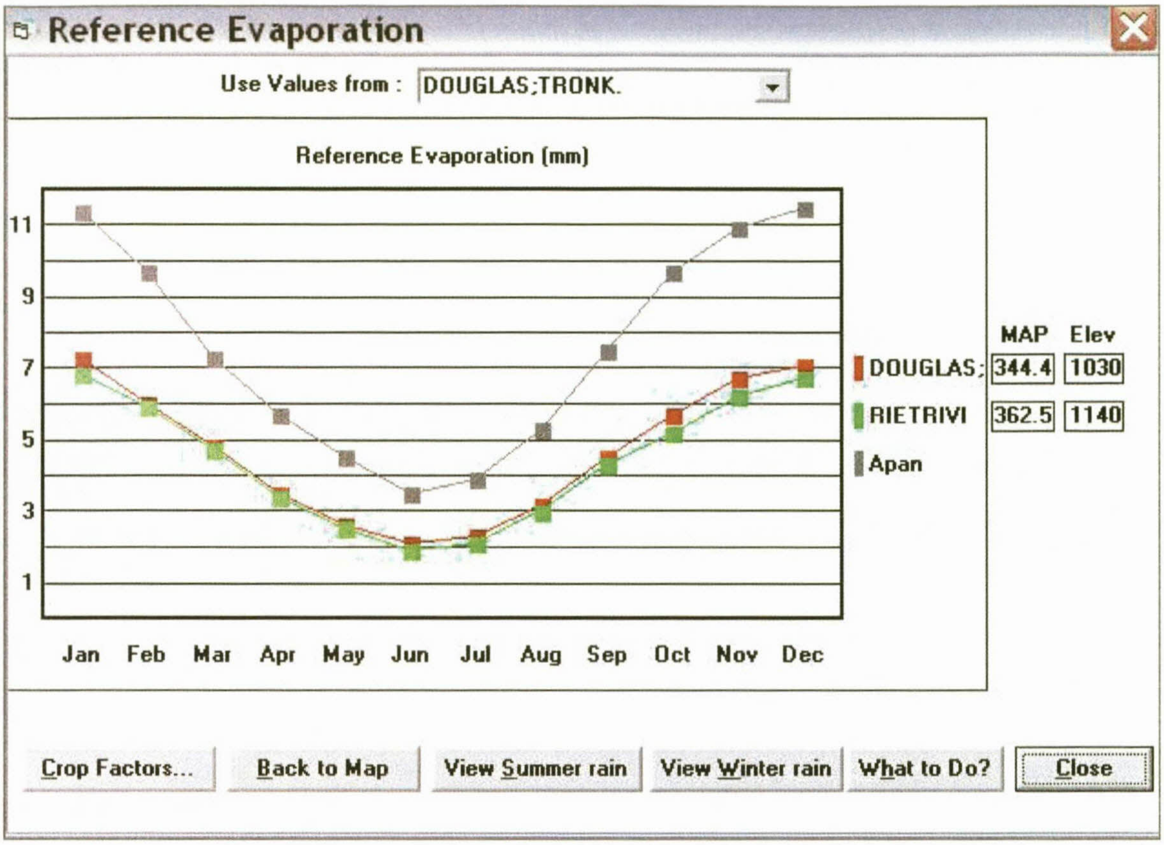


Figure 2.5. Screen from SAPWAT showing the reference Evaporation (mm) at the Douglas jail.

2.5 DEMARCATION OF THE STUDY AREA

2.5.1 REGIONAL DELINEATION

This study does not look at the impacts at national and provincial level, but focuses on the regional level enclosed by the municipal boundaries that overlap the hydrology demarcation of the study area. The outer perimeters of the total study area under investigation follow both administrative and hydrologic borders. The administrative boundaries used in the regional analysis of this study are the boundaries of the municipalities shown in Figure 2.10. The quaternary catchments covered in this study are shown in Figure 2.4. The study area boundaries are also indicated schematically in Figure 2.6 and Figure 2.8.

Hydrologically, the study area falls within these boundaries;

- Vaal River, downstream of the Bloemhof Dam to the confluence with the Orange River
- Orange River, the Orange-Riet and Orange-Vaal Canal extraction points downstream of the Vanderkloof Dam to the Orange-Vaal Confluence where the returnflows of the study area re-enter the Orange River
- Riet River, downstream of the Kalkfontein Dam to the confluence with the Vaal River

This encompasses the Orange-Vaal (OV-WUA) and Orange-Riet (OR-WUA) Water Users Associations (WUAs).

2.5.2 WUA DELINEATION

Figure 2.8 is a schematic diagram of the regional hydrology and some external factors that impact on the salinisation of the study area, also showing the position of the WUAs in the regional geography and in relation to one another.

Shown in Figure 2.6 is that:

- the OV-WUA lies directly downstream of the OR-WUA along the Riet River
- Besides OR-WUA returnflows, the OV-WUA is also subject to the Vaal-Harts WUA returnflows when released from Spitskop dam into the Vaal river upstream
- The Orange-Vaal and Orange-Riet extraction canals that pump Orange River water to the Vaal and Riet WUAs respectively
- Canal, Scheme, Scholtzburg and Lower Riet are the sub-WUAs[1] of the OR-WUA
- Olierivier, Vaallus, Atherton, Bucklands and New Bucklands are the sub-WUAs of the OV-WUA
- Besides irrigation agriculture there are also water demands from mining, municipalities, and for the environmental reserve
- The Oppermansgronde (800ha) is also indicated in Figure 2.6 as a planned future sub-WUA of the OR-WUA for the previously disadvantaged community living there. The area has deep red sandy soils with high irrigation potential and its development will promote equity in irrigation water use in the Free State province. Although good quality Orange River irrigation water may be received via the Orange Riet Canal, good natural drainage alone may not be sufficient for the effective leaching of salts that may accumulate over time from the soil.

[1] Ritchie is not shown in Figure 2.6 as a sub-WUA

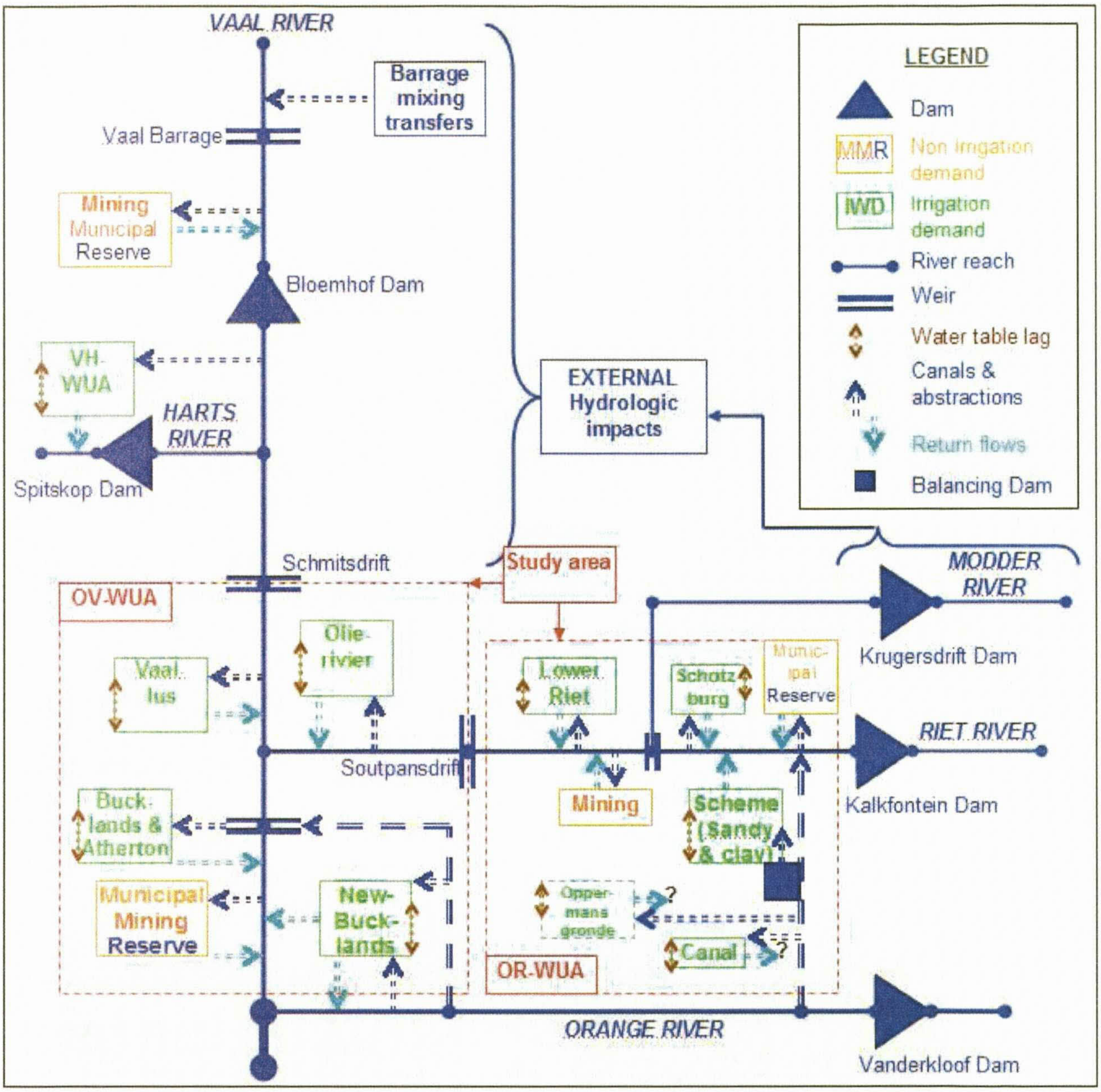


Figure 2.6. A schematic diagram of the regional hydrology impacting on the WUAs that make up the study area

2.5.2.1 Orange-Riet WUA

The Orange-Riet WUA is divided into 5 sub-WUAs, as shown in Table 2.1, covering a total area of 61 771,3 hectares on which 371 irrigators farm:

- The ***Riet River Scheme sub-WUA*** makes up 48% of the OR-WUA irrigated area, with 50% of the 371 irrigators in the OR-WUA farming on an average farm size of 43.5 hectares.

- The ***Orange Riet Canal sub-WUA*** is the newest sub-WUA, formed after completion of the Canal in 1987. The area comprises 3970 hectares (24% of the WUA area), with 44 farmers irrigating on an average farm size of 90.2 hectares per farmer, the largest average farm size in the WUA.
- Developed in 1932 as small holder irrigation plots, the ***Ritchie sub-WUA*** is the smallest, comprising 96.8 hectares (1% of WUA area) on which 75 irrigators farm (20% of the WUA irrigators) on an average of 1.3 hectares.
- The ***Scholtzburg sub-WUA*** comprising 721.6 hectares (4% of the WUA area) is the second smallest sub-WUA in the OR-WUA and smallest irrigation block analysed in this study.
- The ***Lower Riet sub-WUA*** of the OR-WUA comprises 3937.9 hectares irrigated lands, (23% of the OR-WUA total) occupied by 51 irrigators (14% of the OR-WUA irrigators) with an average farm size, the second larges in the OR-WUA, of 77.2 hectares.

The three sub-WUAs, namely the Scheme, Canal and Ritchie sub-WUA, are joined as one irrigation block (***Rscm***) for the purposes of this study, whereas Scholtzburg (***Rszg***) and the Lower Riet (***RloR***) sub-WUAs are analysed as such.

Table 2.1. Sub-WUAs of the Orange-Riet WUA (Source: Ninham Shand, 2004)

Sub-WUA	*Irrigation Block*	*Irrigated Area (ha)*	*% of total area*	*Irrigators*	*% of irrigators*	*Average irrigated area (ha)*
Orange-Riet Canal	***Rscm***	3 970.0	*24*	44	*12*	90.2
Ritchie	***Rscm***	96.8	*1*	75	*20*	1.3
Riet River Scheme	***Rscm***	8 045.0	*48*	185	*50*	43.5
Scholtzburg	***Rszg***	721.6	*4*	16	*4*	45.1
Lower Riet	***RloR***	3 937.9	*23*	51	*14*	77.2
TOTAL		**16 771.3**	***100***	**371**	***100***	**45.2**
Irrigation Block						
Rscm (Riet scheme)		12 111.8	*72*	304	*82*	135.0
Rszg (Riet Scholtzburg)		721.6	*4*	16	*4*	45.1
RloR (Riet Lower Riet)		3 937.9	*24*	51	*14*	77.2
TOTAL		**16 771.3**	***100***	**371**	***100***	**257.3**

2.5.2.2 Orange-Vaal WUA

The Orange-Vaal WUA comprised in 2005 of five sub-WUAs with the development of a sixth sub-WUA taking place. The sixth area extracts irrigation water directly from the Orange River and is therefore excluded from this study. Shown roughly in Figure 2.8 is the spatial layout of Olierivier, Vaallus, Bucklands (Erwe) and Atherton. New Bucklands is the area indicated in Figure 2.8 as OV Canal.

- The ***Vaallus sub-WUA*** irrigates predominantly with Vaal River water and Spitskop dam releases while there is overflow over the Schmidtsdrift weir (the Vaal River boundary of the OV-WUA). Otherwise Orange River water pumped into the Douglas weir builds up and "flows upstream" to feed Vaallus. Vaallus constitutes 33% of the OV-WUAs irrigated area, farmed by 15 (9%) of the farmers on the largest average farm size of 177 ha (Table 2.2).

- ***Olierivier sub-WUA*** receives all the OR-WUA returnflows from over the Soutpansdrift weir, as well as Orange River water possibly mixed with some Vaal River water at the Douglas weir that pushed upstream when the flow over the Soutpandsdrift weir is low. Olierivier also constitutes 33% of the OV-WUAs irrigated area, farmed by 24 (14%) of the farmers on an average farm size of 112 ha.
- ***Bucklands sub-WUA*** (also called "*die erwe*" or "the plots") and ***Atherton sub-WUA*** both receive Douglas weir water, but Atherton is situated mainly along earthen canals to the west of the Vaal River, and Bucklands along a concrete canal that runs east of the Vaal River. Returnflows from both these sub-WUAs flow back into the Vaal River affecting only farmers irrigating directly out of the river below the Douglas weir, thereafter it is diluted with low TDS Orange River water at the confluence of the Vaal with the Orange River. Bucklands constitutes 17% of the OV-WUAs irrigated area, farmed by 110 (63%) of the farmers on an average farm size of 32 ha. Atherton constitutes only 4% of the OV-WUAs irrigated area, farmed by 10 (6%) of the farmers on an average farm size of 12 ha.
- ***New Bucklands sub-WUA*** consists of farmers irrigating out of the Orange Riet Canal. There are only 7 irrigators (4% of the total) irrigating 13% of the total WUA area (Table 2.2). The average irrigated area is 150 hectares, the second largest of all OV-WUA sub-WUAs after Vaallus.
- The ***"Samevloei" sub-WUA*** (or confluence) is the newest sub-WUA, but which is not included in this study as it falls with in the hydrology boundaries of the Orange River catchment. There are 9 irrigators in this sub-WUA with an average farm size of nearly 75 hectares each.

All these sub-WUA combined make up the Orange-Vaal WUA irrigation block, ***Vall***.

Table 2.2. Sub-WUAs of the Orange-Vaal WUA (Source: CSIR, 2004)

Sub-WUA	*Irrigation block*	*Irrigable area (ha)*	*Irrigation rights (ha)*	*% of scheduled area*	*Irrigators*	*% of irrigators*	*Average irrigated area (ha)*
Olierivier	**Vall**	2 702	2 683	*33*	24	*14*	112
Vaallus	**Vall**	2 778	2 659	*33*	15	*9*	177
Atherton	**Vall**	349	349	*4*	11	*6*	32
Bucklands ("Erwe")	**Vall**	1 271	1 340	*17*	110	*63*	12
New Bucklands	**Vall**	1 876	1 049	*13*	7	*4*	150
Confluence ("Samevloei")		673	0	*0*	9	*5*	*75*
Total		**9 649**	**8 081**	***100***	**176**	***100***	**46**
Irrigation Block							
Vall (All Orange-Vaal sub-WUA's)		**8 976**	**8 080**	**100**	**167**	**96**	**48**

Table 2.3 gives an indication of irrigation potential (according to van Heerden *et al.* 2001) in the sub-WUA areas of the OV-WUA. It shows that Bucklands has no high potential irrigation soil and that Atherton with only 349 ha is the smallest sub-WUA, justify joining these two sub-WUA as one for the purpose of analysis. Olierivier, with the largest hectarage irrigated (3125 ha) thus has two case study farmers, namely one situated south of the Riet River with predominantly heavy soils and one to the north of the Riet River, farming on predominantly sandy soils.

Table 2.3. Irrigation potential of the irrigable soils in the OV-WUA region (adapted from Van Heerden *et al.* 2001)

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

2.5.2.3 Interactions between WUAs

The following interaction between WUAs are taken into consideration in this study:

- Potential externalities to downstream WUAs
- Potential impacts downstream of the study area
- Irrigation water transfers within and in-between WUAs

The externalities from upstream water sources, namely the Kalkfontein and Vaal Harts WUAs, are implicitly taken into consideration in the water resources planning model (WRPM) used to model the hydrology of the study area and are assumed to remain the same as in the past. Irrigation water transfers within and in-between schemes are also assumed the same as set up in the past in the WRPM. It is noted that additional pumping of good quality Orange River water has already been approved to dilute the poor Lower-Riet irrigation water quality, but this has not been included in this study, although the motivation / reinforcement of this WUA level management option is mentioned in the conclusion. Although irrigation water quality is improved, salts found inherently in the soil still need to be removed to prevent soil salinisation.

2.5.3 IRRIGATION BLOCK DELINEATION

For the purposes of micro hydrology level modelling, four irrigation blocks were identified through the WRPM (Water Resources Planning Model) in the two WUAs consisting of one or more sub-WUAs, to represent the main receiving water quality areas within the Orange-Vaal-Riet-Modder confluence area, namely:

- the Riet River Scheme, Orange Riet Canal and Ritchie sub-WUAs of the OR-WUA combined, ***Rscm***, all receiving Orange river water directly from the Orange Riet Canal,
- the Scholtzburg sub-WUA of the OR-WUA, ***Rszg***, lying mainly at the confluence of the Modder and Riet Rivers, but receiving a large portion of Orange River water diluting the tail ends of the Riet and Modder Rivers upstream,
- the Lower Riet River sub-WUA of the OR-WUA, ***RloR,*** from Ritchie to Soutpansdrift, mainly receiving Riet Scheme and Scholtzburg returnflows, and

- the whole Orange Vaal WUA, ***Vall***, receiving Vaal River system excess spillage and a large portion of Orange River water pumped via the Orange-Vaal and Orange-Riet Canals, with the latter carrying the returnflows of the whole OR-WUA.

Figure 2.7 shows schematically the placement of the irrigation blocks in relation with one another, and to the Orange, Vaal, Riet and Modder Rivers. Farm boundaries are also shown as the shaded areas within the irrigation blocks, with the darker shaded predominantly round dots within the farm boundaries indicating the placement of Centre pivot irrigation systems. Clearly centre pivot irrigation is the predominant form of irrigation and most irrigation lands lie close to the water source, be it a river or canal.

In the discussions on the two WUAs in Paragraph 2.5.2 reference has already been made to the basic delineation of the irrigation blocks. Figure 2.7 also shows where the irrigation blocks lie in relation to each other, and the river reaches and canals that serve them.

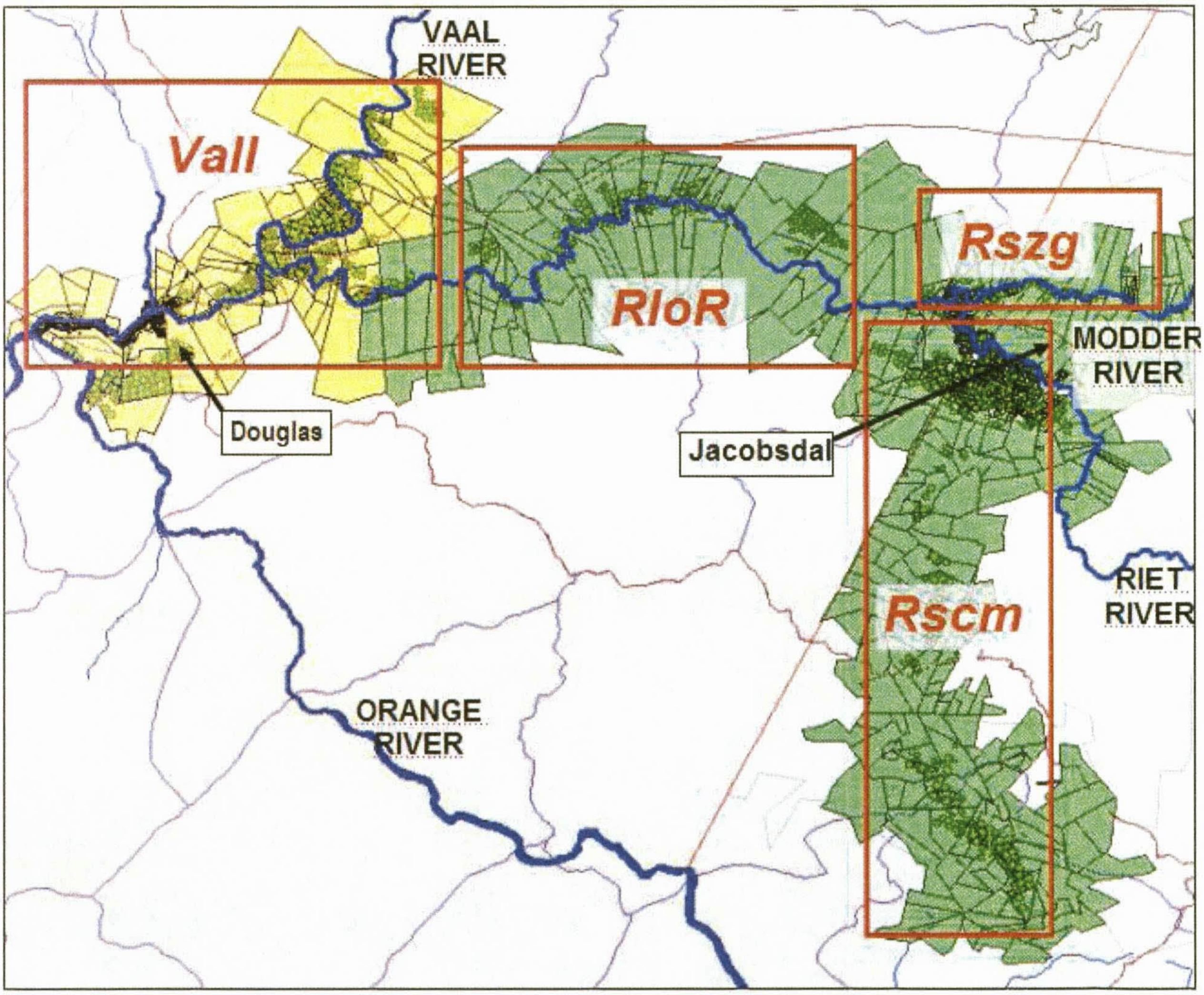


Figure 2.7. An indication of the layout of the irrigation blocks (OV-WUA farms, *Vall*, coloured Yellow and OR-WUA farms, RloR, Rszg and Rscm, coloured green).

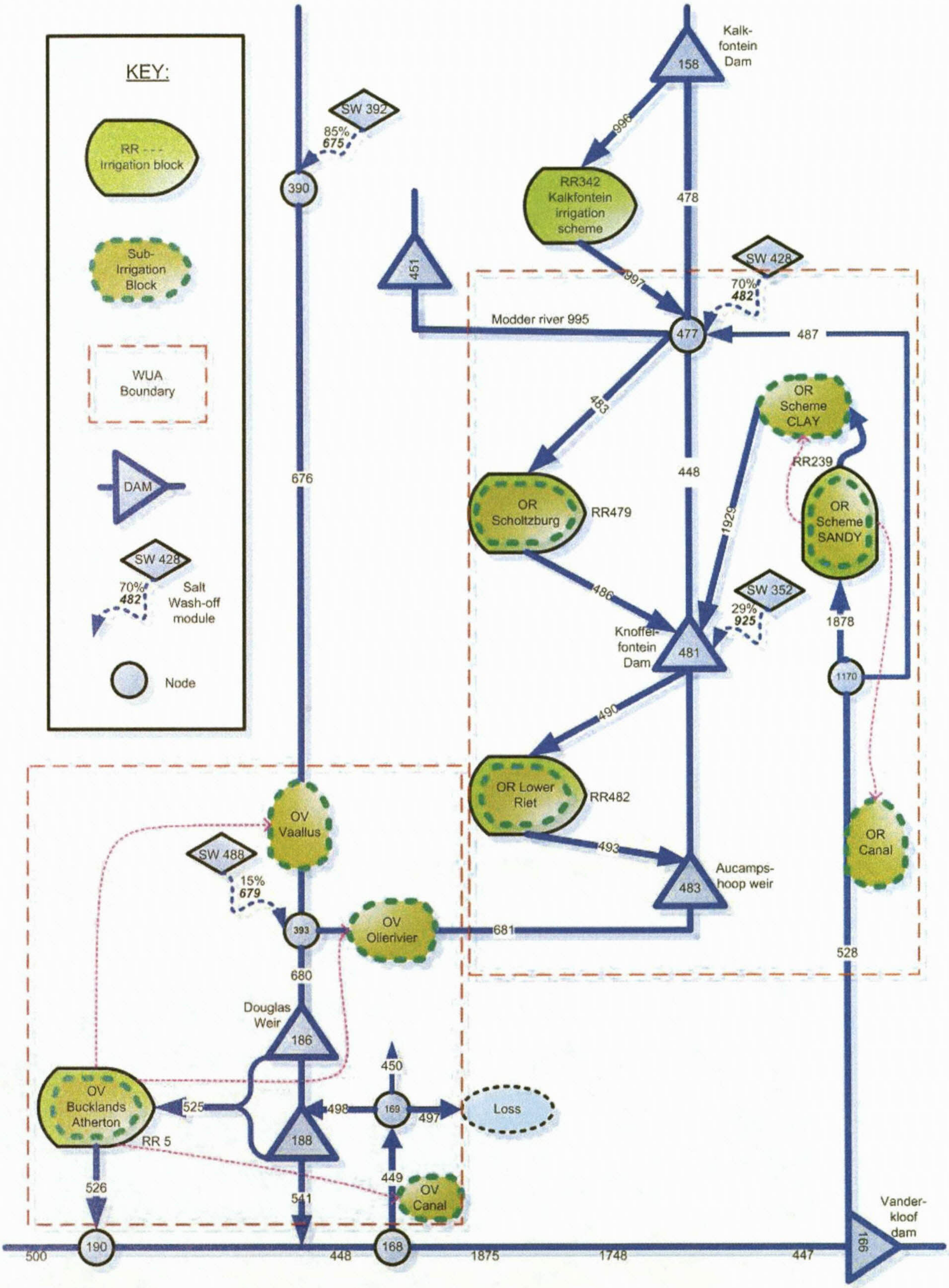


Figure 2.8. A simplified diagram of the hydrology setup of the study area, indicating channels, nodes, irrigation blocks, WUAs and sub-WUAs.

Figure 2.8 is a simplified schematic diagram of the hydrology setup of the study area. For the complete channel and node diagram produced by WRP Consultants, of the WRPM setup applicable to the study area, see Viljoen *et al.*(2006). The irrigation blocks modelled in this study are the ones in the figure with solid perimeter lines, and these include the WUA sub-WUA connected to them with the dotted lines indicated with dashed perimeter lines.

The four irrigation blocks predominantly analysed in this study therefore are:

- OR Scheme Sandy, which includes OR Scheme Clay and OR Canal
- OR Scholtzburg
- OR Lower Riet
- OV Bucklands and Atherton, and which includes OV Vaallus, OV Olierivier and OV Canal (farmers irrigating directly from the Orange River in the OV WUA are not included in this study)

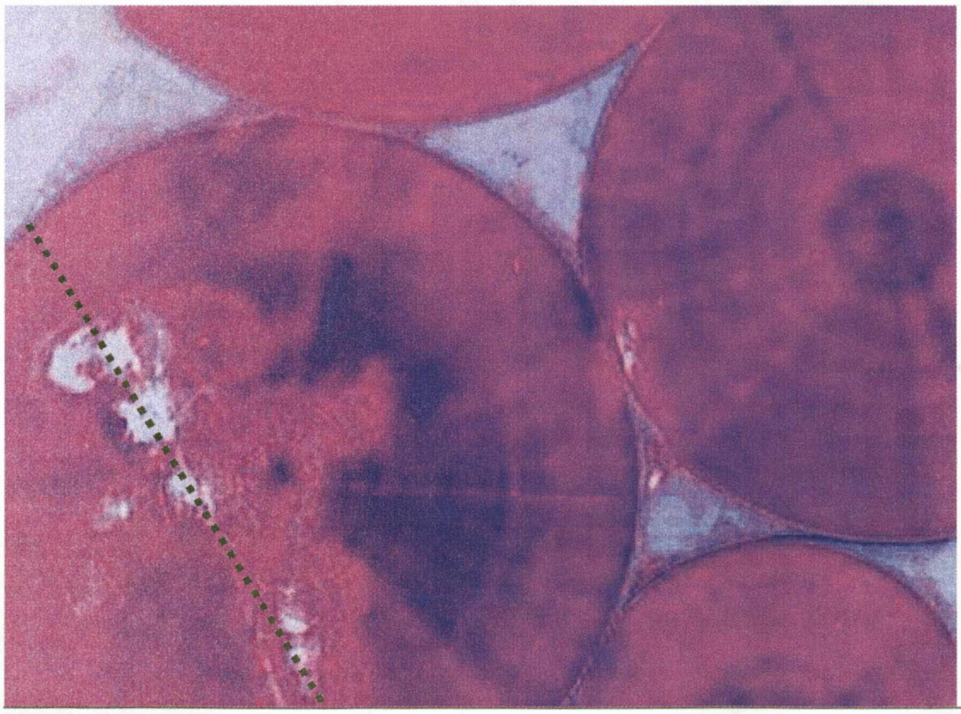
Table 2.4 lists the water allocations (ha) and total annual water quota supplied (million m^3) to give an indication of the water volume allocated in each irrigation block.

Table 2.4. Scheduled areas and quotas as used in the model for the irrigation blocks in the study area (2005)

	WUA		Irrigation blocks (*WRPM codes*)		Scheduled areas (*ha*)	Quota (*m^3/ha*)	Annual allocation (*mil.m^3*)
1	Orange-Vaal WUA	1.1	***Vall***	***(RR5)***	10 014	11 000[1]	110.15
	Orange-Vaal WUA	**TOTAL**			**10 014**		**110.15**
2	Orange-Riet WUA	2.1	***Rscm***	***(RR239)***	12 335	11 000	135.69
		2.2	***Rszg***	***(RR479)***	641	11 000	7.05
		2.3	***RloR***	***(RR482)***	3 853	11 000	42.38
	Orange-Riet WUA	**TOTAL**			**16 829**		**185.12**
	STUDY AREA TOTAL				***26 843***		***295.27***

[1] Technically the water quota for Orange-Vaal WUA farmers for 2005 was 10 000 m^3/ha but to compensate for poorer water quality the farmers are allowed to use 11 000 m^3/ha without being penalised, and therefore 11 000 m^3/ha is used. This also allows for easier comparison between irrigation blocks.

2.5.4 PER HECTARE DELINEATION



The discussion that follows on Figure 2.9 is hypothetical, aimed at illustrating the enormous in-field variability in soil salinisation and possible remediation actions.

Figure 2.9. An inverted colour spectral imagery view (aerial photo) of a salt affected centre pivot land (courtesy GWK, 2002)

Figure 2.9 is an aerial view of an irrigation field under centre pivot in the study area (2001) affected by salinisation. The white areas clearly show salinisation and the darkest areas show good crop growth. The areas in-between are where crop growth occurs, but where the effect of salinisation is not yet clearly visible to the naked eye. If the field is 40 hectares, then roughly 10 hectares has near optimal crop growth, 5 hectares no growth and the rest in-between. The purpose of this illustration is to show that salinity is not clearly constrained in a certain land, but that the in field variability in soil salinity values is large, making the determination of a starting point soil salinity value very difficult. Salinity sampling only at the edge of the field may be misleading. Inter-field level specific remediation therefore needs to be applied.

In Figure 2.9, the installation of one straight sub surface drain, depending of the slope of the field along the dashed line drawn in the diagram, may suffice to sufficiently leach out the salts accumulated. The dashed line may also represent a dip in the field where salts have accumulated, causing water logging problems which exacerbate the impacts of salinity, though salinity doesn't have as great an effect on crop yields under wet conditions than under dry conditions. The dashed line may also represent a peak in the field where salts have migrated to along the moisture gradient of the field, or may represent an underground soil bank that has a significantly different texture from the rest of the field.

The discussion on Figure 2.9 highlights the need of field specific solutions for isolated serious salinisation problems, e.g. salinity mapping and/or precision farming solutions. These however fall out of the scope of this study which models at irrigation block level (50 to 300 times larger than this picture) where the average soil salinity, derived from a hydrology salt balance model for an irrigation block is used.

2.6 HYDROLOGY DYNAMICS

As this study is based on hydrology model data, the significance of the different hydrology dynamics between irrigation blocks, and how these dimensions are to be captured in this study, are discussed under the following headings:

- Source and salt concentration of irrigation water
- Wet and dry rainfall cycles
- Flooding events
- Changes in policy regarding water allocation and water use charges
- Economic / political boundaries

The WUAs and corresponding irrigation blocks are essentially defined according to hydrology boundaries. The micro-economic level of analysis of this study takes place at per hectare level (a standard agricultural economic unit for farm level analysis) and is extrapolated to irrigation block level. Further analysis combines irrigation blocks into WUAs, and WUAs into the regional unit of analysis for the whole study area.

2.6.1 SOURCE OF IRRIGATION WATER AND SALT CONCENTRATION

The irrigation blocks are differentiated mainly according to their source of irrigation water.

- the Riet River Scheme, ***Rscm***, gets predominantly Orange river water directly from the Orange Riet Canal,

- the Schotzburg sub-WUA, ***Rszg***, receives a large portion of good quality Orange River water that dilutes the tail end outflows of the Riet and Modder Rivers upstream,
- the Lower Riet River sub-WUA ***RloR,*** mainly receives Riet Scheme and Scholtzburg returnflows together with additional Orange River water pumped for dilution along the Lower Riet section of the OV-WUA, and
- the Orange Vaal WUA, ***Vall***, receives a large portion of Orange River water pumped via the Orange-Vaal and Orange-Riet Canals, but the latter carrying the returnflows of the whole OR-WUA.

  Hydrology model results discussed in Chapter 9 show the highly stochastic nature of especially the ***RloR*** and ***Vall*** irrigation block that receive water from a number of different sources.

2.6.2 <u>WET AND DRY RAINFALL CYCLES</u>

Besides annual wet and dry cycles, there are longer term wet (flood) and dry (drought) cycles of between 6 and 8 years. To accommodate this in this study the time frame of analysis in the hydrology model is 25 years and 15 years in the economic model. Only the first 15 years of output data from the hydrology model is fed into the economic model, with the last 5 years of hydrology data only used to analyse longer term trends to help explain economic data. As the Water Resource Planning Model (WRPM) used for stochastic hydrology forecasting in this study, runs for the entire Integrated Vaal River System (IVRS), which includes several major sub-catchments upstream such as the Upper Vaal, Vaal Barrage, Middle Vaal, Lower Vaal, Riet-Modder, Komati, Usutu, Tugela and Upper and Lower Orange, different rainfall cycles in these catchments upstream result in different wet and dry cycles in the different irrigation blocks.

2.6.3 <u>FLOODING EVENTS</u>

One of the questions often asked in extension exercises with the farmers in the study area is, if salts build up in soils over time, then why are some of the oldest irrigated lands (irrigated for over 70 years!) not already totally salinised? The answer to this is, besides unintentional leaching from "inefficient" irrigation practices, the occasional high rainfall event (a few months in a row of above average high rainfall) or flood (very high rainfall over a very short period of time) has washed out the salts in the soil. As these events are very important to the soil salinity dynamics and resulting economic impacts through crop yield (particularly examined in this study), they are accounted for by running 100 stochastic sequences of possible monthly hydrology events for 25 years for each irrigation block and for each scenario examined in this study.

From cumulative economic results based on all 100 stochastic sequences, a worst case (0.05 percentile), best case (0.95 percentile) and most probable (0.50 percentile) sequences are selected for further analysis. The best case sequence (in respect to soil salinity build-up) will include more high rainfall events than the worst case sequence. In the economic analysis of this study the economic costs due to damages from flooding are not included.

2.6.4 CHANGES IN POLICY REGARDING WATER ALLOCATION AND WATER USE CHARGES[1]

Not implicitly taken into account in this study, yet important to mention are factors that influence / impact on the water quality received in the study area. These factors are *inter alia*:

- the improvement of water distribution and use efficiency as currently promoted
- the implementation of the environmental reserve in river reaches, and
- policy changes in the mining industry on discharge

The improvement of water distribution and use efficiency as currently promoted by the DWAFs "more crop per drop" slogan (together with minimum wage labour policy) has resulted in the expansion of centre pivot irrigation systems. This, together with the dramatic improvement in irrigation scheduling due to GWK's irrigation scheduling service using SAPWAT and Neutron moisture meters, have made irrigation farmers in the study area far more efficient, thus less over irrigation takes place resulting in less unintentional leaching or drainage and therefore a faster accumulation of salt in the soil if provision isn't deliberately made in irrigation planning for additional water for leaching. This positive increasing efficiency trend has also seen an increase in soil salinity over the last few years (Du Preez *et al.* 2000). National water policy principles such as the waste discharge charge system (WDCS) and polluter pays principle (PPP) could have further made farmers reluctant to leach and even to install additional irrigation drains that make a non-point source pollution (NPS) problem a point source pollution problem that is easier to trace and to fine the perpetrator.

A study is currently being conducted on the Spitskop dam (DWAF) by WRP consultants examining the effect of different releases from Spitskop dam on *inter alia* algae downstream. Depending on the results of this study, an increase in Spitskop dam releases may further increase the salinity in the Lower Vaal River.

Increased Spitskop dam releases could also be implemented to maintain the environmental reserve requirement in the Lower Vaal River - this can have a trade-off of increased salinity loads.

Mining policy on mine water decantering could also influence irrigation water quality in the Lower Vaal River.

Changes in water use charges[1] (up to a 35% increase modelled by Greengrowth Strategies cc, 2003) could also have an impact on hydrology dynamics. Due to the increase in the cost of water for irrigation, farmers will either be forced to become more efficient on existing crops (exacerbating salinity build-up if leaching and drainage isn't practiced) and / or plant higher value crops. The financial benefit from paying for additional water to leach to attain a better yield will be less, resulting in possibly less leaching, lower yields and weaker financial returns.

2.6.5 ECONOMIC / POLITICAL BOUNDARIES

Local municipality boundaries form the economic / political boundaries of the study area and are the main unit of modelling for the regional economic input/output model developed by Urban-Econ. Output from the micro economic model, which contains economic data at the irrigation block level, is combined to feed into the regional economic model. For a finer delineation of the regional economy modelled in the WRC study see Viljoen *et*

[1] Where the term "water use charges" is used, it refers to the lumped term comprising of all the water use charges including: the water volume charge, water management cost, use of water works costs, and where applicable, the waste discharge charge.

al.(2006). Figure 2.10 shows the local municipal areas in the study area and Figure 2.4 shows the quaternary catchments falling in the study area.

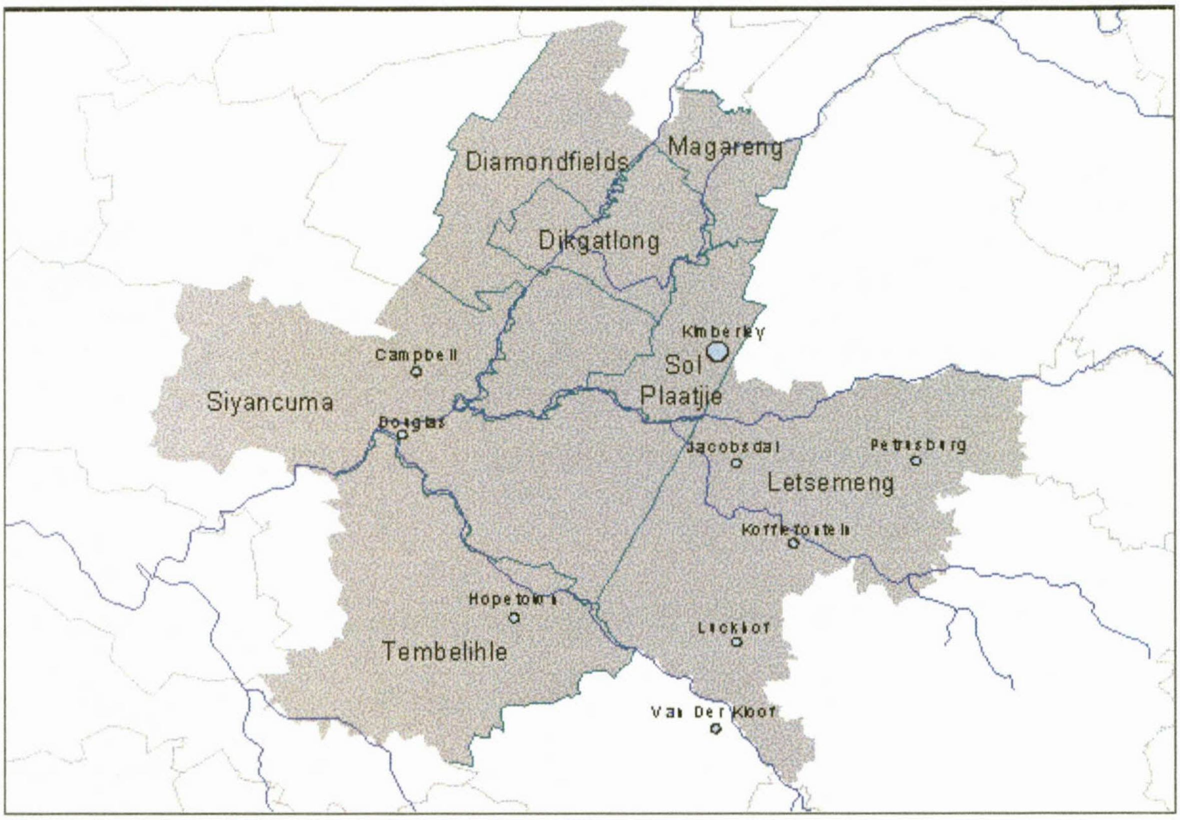


Figure 2.10. Local municipal areas in the study area

2.7 ECONOMIC ACTIVITIES

2.7.1 COMPOSITION OF GGP

A complete description of the regional economy of the study area appears in Viljoen *et al.* (2006). This brief overview merely aims to sketch the level of economic activity and relation between economic sectors. In Figure 2.11 the relatively small direct contribution to gross geographical product (GGP) by agriculture in relation to mining, trade, transport, finance, services and government is shown. A large portion of these sectors' GGP however are generated in Kimberley, see Figure 2.12, the main centre of the Northern Cape, that falls within the Sol Plaatjie district municipality that borders on the Riet River at Jacobsdal. Away from Kimberley, agriculture is expected to be a dominant sector in the otherwise barren country side. Agriculture and people employed in agriculture are major contributors to the trade, transport, finance and services sectors.

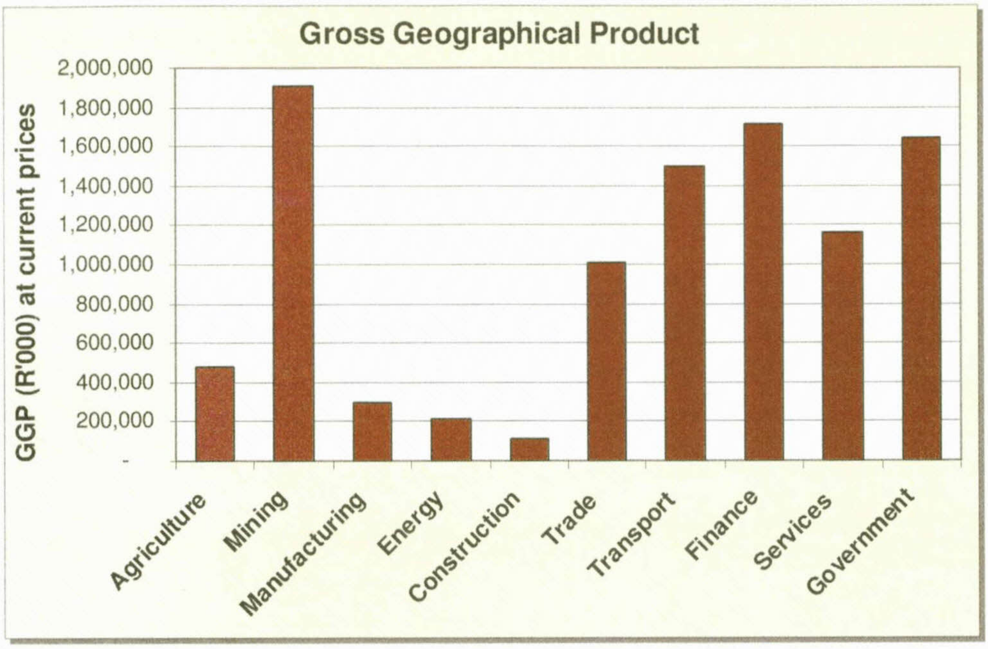


Figure 2.11. Gross Geographical Product (R'000) of the study area by economic sector, 2005 (Urban-Econ)

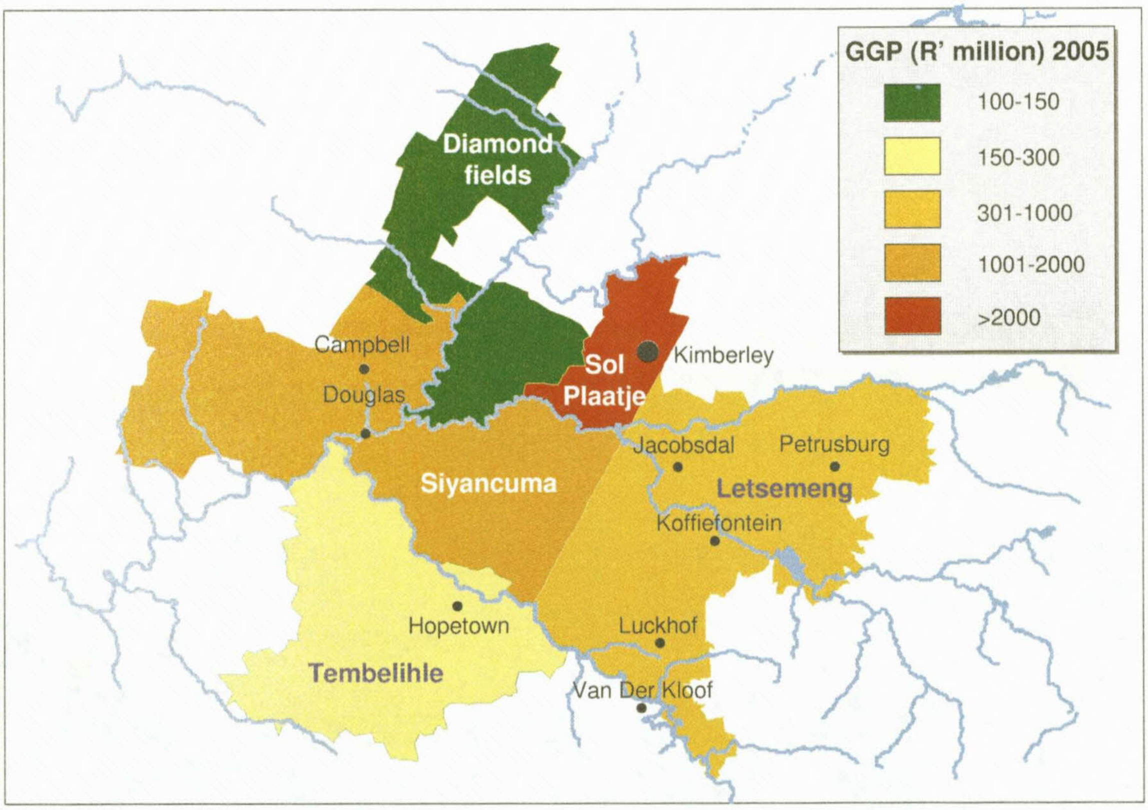


Figure 2.12. Gross Geographical Product (R'000) per local municipal area in the study area, 2005 (Urban-Econ)

2.7.2 AGRICULTURE

As irrigation is the major agricultural contributor to the economic activity of the sudy area, only this sub-sector is focussed on, although extensive livestock and game farming also contribute to agricultural GGP.

Table 2.5. Area (ha) under different irrigation systems in the OR-WUA (Ninham Shand, 2004)

Irrigation Block	Sub-WUA	Total area in ha	Centre Pivot %	Flood Irrigation %	Sprinkler Irrigation %	Micro-jet Irrigation %
RScm	Orange-Riet	3 970.0	95	0	5	0
	Riet River	8 045.0	60	20	19	1
RSzg	Scholtzburg	721.6	70	20	10	0
RloR	Lower Riet	3 937.9	70	20	10	0
	Ritchie	96.8	0	75	25	0

Table 2.5 shows that the centre pivot irrigation system is the predominant irrigation system in the OR-WUA region followed by flood. Flood irrigation is only dominant in the Ritchie sub-WUA region.

Table 2.6. Area (ha) under different irrigation systems in the OV-WUA region (adapted from Van Heerden *et al.* 2001)

Irrigation Block	Sub-WUA	Micro and Drip	Sprinkler	Flood	TOTAL
Vall	Olierivier	31	2969	125	**3125**
	Vaallus	27	1861	771	**2659**
	Bucklands and Atherton	99	229	1362	**1690**
	New Bucklands	19	598	0	**617**
	TOTAL	***176***	***5657***	***2258***	***8091***
	%	2	70	28	100

From Table 2.6 it is clear that sprinkler (which includes centre pivot and drag line) irrigation is the main type of irrigation practiced in the OV-WUA region. This is also evident in Figure 2.7 or from any aerial of satellite photo of the area. Also evident from the air are large white salt pans where salts accumulate and wash off into the system, a possible cause of salinisation in the area. Table 2.7 shows that in the year 2001, 23% of the land in the OV-WUA region was already slightly (13%) or severely (10%) affected by salinisation.

Table 2.7. Soils affected by salinisation and water logging in the OV-WUA region (adapted from Van Heerden *et al.* 2001)

Irrigation Block	Sub-WUA	LEVEL OF SALINISATION AND WATER LOGGING		TOTAL (ha)
		Slight[1] (%)	Severe[2] (%)	
Vall	Olierivier	16	4	**625**
	Vaallus	40	40	**2127**
	Atherton and Bucklands	10	3	**124**
	New Bucklands	0	2	**12**
	TOTAL	***13***	***10***	**2888**

[1] Slight salinisation and water logging is defined as that agricultural production can still take place, but that production potential and/or choice are restricted.
[2] Severe salinisation and water logging is defined as that agricultural production can no longer take place without special remediation actions such as artificial drainage or gypsum being applied.

On the farm land not utilised for irrigation most farmers keep cattle, sheep and/or goats extensively as the carrying capacity of the natural grazing is over 15 hectares per livestock unit. Many farmers also keep game. The economic contribution of game and livestock farming is however not factored into the micro economic analysis of this study and kept constant for the macro economic level of analysis.

2.7.3 INFRASTRUCTURE

The study area has a good road and rail network, however the long distance from the main cities in South Africa is a large constraint for high value, fresh market crop choices. GWK Pty. Ltd. Is the agricultural company that has evolved from the old GWK co-operative. GWK has taken over and further developed an extensive network of *inter alia*, grain handling, storage and value adding infrastructure, a wine press and cellar (a capacity constraint to the further expansion of vineyards for wine grapes), etc. A cotton gin within the study area closed down in 2005, placing a constraint on the production of cotton.

2.8 SUMMARY

In summary, the main characteristics of the study area are:

- it spans over two provinces, namely the Free State and Northern Cape provinces
- it falls within and impacts various municipal / local government management areas (see **Figure 2.10**)
- it covers the confluence of the two major rivers in South Africa, namely the Orange and the Vaal Rivers, and receives returnflows from the Harts, Riet and Modder Rivers.
- it is impacted by various quaternary catchments and different water management areas (see **Figure 2.4**)
- it falls within an arid / low rainfall area with average annual rainfall of less than 370 millimetres and evapo-transpiration exceeding 2000 mm
- the municipal (i.e. economic zone) boundaries are quite different from the quaternary catchment (i.e. hydrology) boundaries posing a challenge to model integration
- a major economic driver of the regional economy is irrigated agriculture
- possible future water reform and redistribution away from the study area, and from irrigated agricultural use within the area, could negatively impact the overall long term sustainability of the area
- the long distance from the major urban centres in South Africa limits the type of crops that can be grown in the area, limiting the water use efficiency / productivity attainable, and
- according to Van Veele (2004), "the Riet-Modder catchment is a "feast or famine" catchment with only 8 years in 50 being 'average' years". This statement can be applied to the rest of the study area as the runoff from the Riet-Modder catchment is a large contributor to the salt loads in the study area.

In short, the area is not suited to dry-land agriculture except extensive grazing, and is reliant on the stability that irrigated agriculture brings for socio economic sustainability. However, increasing pressure on the use of water for irrigation, together with degrading irrigated soils due to salinity, is placing increasing financial pressure on farmers, and hence on the regional economy.

CHAPTER 3 A LITERATURE REVIEW OF INTEGRATED SALINISATION MODELLING

The world we live in is integrated, complex and dynamic. We disaggregate it, creating specialist disciplines and reductionist thinking that advances our understanding. While doing so we have deliberately ignored its connectedness, perhaps hoping that someone else will reconstruct the connections. It should not come as a surprise to discover that the environmental problems, the critical threats, we face will not find solution until we commit to integrated learning and action.

Charles M Breen (2006)

The success of water quality models will not necessarily be due to "bigness" and complexity but rather to increases in understanding, which can contribute to building consensus in water quality management decision-making

Thomann (1998)

3.1 INTRODUCTION

The aim of this chapter is to give an overview of the relevant literature reviewed to formulate a methodology to address the overall aim of this thesis, namely, the development and integration of multi-dimensional models for the sustainable management of water quantity and quality in the Orange-Vaal-Riet convergence system. The main problem identified for investigation is the serious threat to the long-term sustainability of irrigation in the system posed by salinisation, and the serious impact that this can have on the economy of the study area as a whole. Various policy and management options are identified in previous studies, but an inter-disciplinary approach is required to test the applicability and sustainability of these options, posing its own set of problems. In this literature review therefore, proposals for the method to achieve this within the project parameters are included at the end of some paragraphs and are printed in *italics*.

This introductory section starts with a brief historical overview of incidences of salinisation in the past and an overview of the current extent of salinisation, globally, in South Africa and in the study area, followed by a brief history of salinisation modelling in South Africa. Subsequent paragraphs investigate the literature regarding the original project aims to formulate a theoretical basis for the salinisation modelling method applied in this study. The main paragraph headings of this literature study relate to, and follow the same sequence of the main project aims as set out in Chapter 1.

In Paragraph 3.2 salinisation is first defined followed by a review of salinity interactions in and between the surface-, vadose zone- and ground- water, and the plant. Relevant micro- and macro- economic models are discussed in Paragraph 3.3 followed by a discussion of the integration of the economic models with the applicable hydrology and agronomy models in Paragraph 3.4.

Paragraph 3.5 looks at the best management practices (BMPs) at per hectare, per irrigation block and at a regional level, followed by a_motivation as to why multi-dimensional interventions enhance water-use efficiency in Paragraph 3.6. This leads to policy guidelines in Paragraph 3.7 and a study area specific literature review in Paragraph 3.8.

To conclude the chapter, Paragraph 3.8.2 lays out the method derived from the preceding literature study, introducing the integrated conceptual framework (the topic of the following chapter) and the data requirements (Paragraph 3.8.3) for the method proposed. Paragraph 3.8.4 is also included to address part of the final project aims, and is a short discussion on the ease of application of the method selected to other irrigation areas.

3.1.1 AN HISTORICAL OVERVIEW OF SALINISATION

"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" DWAF (1993). Cowen (2002) and Khan *et al.* (2006) speak of the Ancient Mesopotamian and Egyptian civilizations:

Irrigation has been important for agricultural production in Mesopotamia (parts of present day Iraq and Iran) for 6000 years. The region has low rainfall and is supplied with surface water by two major rivers, the Tigris and the Euphrates. The plains of Mesopotamia have always had problems with poor drainage of soils, drought, catastrophic flooding, silting, and soil salinity. Although Mesopotamia is very flat, the bed of the Euphrates is higher than that of the Tigris, resulting in flooding events of the Euphrates sometimes finding their way across plains that separate them into the Tigris. Engineers took advantage of this gradient as soon as irrigation schemes became large enough by using the Euphrates water as the supply and the Tigris channel as a drain (Khan *et al.,* 2006). This situation is incidentally very similar to that of the Vaal-Harts irrigation scheme in South Africa where irrigation water is supplied by the Vaal River and the drainage discharged into the parallel flowing Harts River that lies at a lower gradient (Herold and Bailey, 1996).

The main engineering problems of the earlier civilisations were water storage, flood control and maintenance of canals. The salinity problem was more subtle, not fully appreciated, and could not be overcome by the knowledge and skills available at the time. It was difficult to drain water from fields, and there was always a tendency for salt to accumulate in the soil (Khan *et al.,* 2006).

Furthermore the problems of irrigated agriculture in Mesopotamia according to Khan *et al.* (2006) are summarised as:

- <u>Silting of canals:</u> silt built up quickly in the canal beds, threatening to block them
- <u>Soil salinity:</u> recorded evidence around 2000 B.C., 1100 B.C., and after 1200 A.D.
- <u>Water politics</u> arising from tension between upstream and downstream users. In Sumeria, the city of Lagash was far downstream in the Euphrates canal system. The governor of Lagash apparently decided that he would dig a canal to tap Tigris water rather than rely on water from the Euphrates, but the addition of poor-quality water from the Tigris led to rapid salinisation of the soil.
- <u>Over exploitation of resources:</u> after the wave of Moslem expansion overtook Mesopotamia, the Abassid Caliphate was based in Baghdad from 762 A.D. until its demise in 1258. Existing irrigation schemes were renovated and greatly extended in very large projects. Abassid engineers drew water from the Euphrates at five separate points, and led it in parallel canals across the plains, watering a huge area south of Baghdad. This system provided the basis for the enormously rich culture of Baghdad, which is still remembered in

legends (Scheherezade, the Caliph of Baghdad, and the Arabian nights) as well as history. But the scheme required a high level of physical maintenance, and there was increasing salinisation in the south.

- Institutional failure: as the central government began to fail in the 12th century (mostly from overspending), the canals became silt-choked, the irrigation system deteriorated, and the lands became more salinised. The deathblow to the system was aided by nature: massive floods about 1200 A.D. shifted the courses of both the Tigris and the Euphrates, cutting off most of the water supply to the Nahrwan canal and wrecking the whole system. The Abbasids were too weak (or bankrupt) by then to institute repairs, and the agricultural system collapsed. By the time the Mongols under Hulagu devastated Iraq and Baghdad in 1258 A.D., they conquered a society that occupied wasteland. Iraq has remained a desert for more than 600 years.

Perry and Vanderklein (1996) document the more recent ecological disaster due to salinisation of the Aral Sea, and Postel (1999) questions whether the current irrigation miracle can last.

To learn from history and not let it repeat itself, a holistic approach is required that should not just look at salinisation in isolation, but also take note *inter alia* in the case of South Africa, of the following:

- the contribution to salinisation from the irrigation canals (leakages and distribution losses),
- the effectiveness of drainage and waste water removal canals (including maintenance costs),
- the impact of current politics (e.g. Land Reform and AgriBEE),
- the impact of activity in the study area on Orange River water downstream shared with Namibia,
- the impact of the Lesotho Highland Water Project on the Orange River water quality used in the study area,
- unsustainable and exploitative irrigation practices (set aside without remediation of degraded lands),
- the institutional capacity of government to implement and enforce the legislation that they have promulgated, which is widely recognised as the most comprehensive in the world (Saleth and Dinar, 1999).

3.1.2 THE CURRENT EXTENT OF SALINISATION

3.1.2.1 The Global Extent of Salinisation

Poor irrigation practices accompanied by inadequate drainage have often damages soils through over-saturation and salt build-up. It is estimated that on a global scale there are about 20-30 million hectares of irrigated lands severely affected by salinity. An additional 60-80 million hectares are affected to some extent by water-logging and salinity (FAO 1996). Of the 60-80 million hectares affected globally, about 10 million hectares of agricultural land is lost annually due to salinisation (Khan *et al.*, 2006), of which about 1.5 million hectares is in irrigated areas. Schwabe *et al.* (2006) confirm this stating that one-third of the 260 million hectares of irrigated land worldwide (land that provides 40% of global food production) is affected by salinisation and "is in need of drainage".

3.1.2.2 The Importance, Extent and Potential Threat of Salinisation in South Africa

Johnson (1994) warned that "most of the irrigation schemes in South Africa are affected to some degree by soil salinity. This accumulation of salts in the soil is normally associated with waterlogging that occurs primarily in the poorly- drained regions of the landscape. Salinisation usually develops insidiously over many years, and can present a serious threat to the long-term viability of an irrigation scheme. There is a need therefore to monitor trends in soil salinity levels on irrigation schemes." Not heading to this warning by Johnson (1994) made over 10 years ago, there is currently still no soil salinity monitoring process initiated and thus no reliable data on soil salinity trends.

In a 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." They will not be able to meet water needs in the year 2025." Water use efficiency in irrigation agriculture will thus also become crucial as per capita demand for water increase in South Africa (Basson, *et. al.*, 1997). Currently irrigation agriculture is by far the largest user of stored water, using 53% (Backeberg *et. al.,* 1996). With total water demand predicted by Seckler *et al.* (1999) to exceed supply before 2020, industry and urban users are going to be competing strongly for this most valuable resource. This all makes motivating the additional water required to drain irrigation fields to manage salinity difficult, necessitating a thorough investigation.

The current price-cost squeeze experienced by farmers, due to *inter alia* fuel price increases and the increasing cost of labour, further jeopardise the economic sustainability of irrigation agriculture, an industry so crucial for the economies of many rural areas, and of particular importance for the Orange-Vaal and Orange-Riet WUAs areas that fall within the complex Orange-Vaal-Riet convergence system study area of this thesis.

The further manifestation of the very real threat of salinisation to the fragile irrigation industry should therefore be averted. What is necessary to avert salinisation is good irrigation drainage to leach the salts out of the soils (ARC-ILI-1997, ASCE-1990, Ayers and Westcot-1985, Dinar and Zilberman-1991, Gardner and Young-1988, Hillel and Feinerman-2000, Khan *et al.*-2006, Kijne *et al.*-1998, Knapp-1992, Lee and Howitt-1996, Letey *et al.*-1995, Maas and Hoffman-1977, Moolman and Quibell-1995, Prathapar *et al.*-1997, Ragab-2000, Rhoades *et al.*-1992, Van Coller-2006, Van der Merwe-2005, Volschenk *et al.* 2005 and Young-1996). However of the 1.3 million hectares of irrigated land in South Africa, a large percentage does still require irrigation drainage due to salinisation, water-logging or a combination of both to remain productive (Van Coller, 2006). Irrigation farmers in the Orange-Vaal WUA who are already experiencing salinisation or water-logging have already lost potential income and would generally not be in the financial position to afford costly irrigation drainage (Armour and Viljoen, 2002b), thus requiring some form of financial assistance to ensure the sustainability of this important food growing sector for our country.

3.1.2.3 The Extent of Salinisation in the Study Area

The salinisation problem in the study area is of a long-term and cyclical nature (Armour and Viljoen 2002). According to Van Veele (2004), the Riet-Modder catchment is a "feast or famine" catchment with only 8 years in 50 being "average" years. Also according to Van Veele (2004) additional pumping of 5 million m^3 from the Orange-Riet(OR) WUA to the Orange-Vaal(OV) WUA has been approved by DWAF to flush and dilute the tailwaters of the OR–WUA that enter the OV-WUA. From a total irrigation area of 12 556 ha in the Orange-Vaal Water Users Association alone, 23% is either slightly (13%) or severely (10%) affected by salinity problems (van Heerden, *et al.* 2001).

Previous research conducted in the area, namely to determine the nature and extent of the salinity problem and how to effectively address it has provided some answers (Armour and Viljoen 2002b, Du Preez *et al.* 2000, Moolman and Quibel 1998 and Allen and Herold 1988). New research was however necessary to integrate existing multidisciplinary research and to address the unsolved questions regarding the dynamic long-term economic impact of salinity on farm, water user association and regional level in the study area, and the economic and environmental effects of different strategies to address the problem on the different levels of decision making.

3.1.3 A BRIEF HISTORY OF SALINISATION -RESEARCH AND -MODELLING IN SOUTH AFRICA

This is by no means a complete history of all salinisation related research and modelling conducted in South Africa. This historical review focuses on work specifically related to the study area or to modelling approaches of possible relevance to the study area. The research is listed in chronological order with linkages to research upon which it builds; giving a very brief overview of the work done by the authors listed.

Du Plessis and Van Der Merwe (1970) already reported on the reclaiming of saline-alkali soils in the Riet River Irrigation Scheme, indicating that salinisation and water-logging have been problems in the OR-WUA for at least thirty years. Realising the necessity of irrigation drainage, Backeberg (1981) determined the economic feasibility of drainage in the Pongola Government Water Scheme dividing soils into saline, sodic and saline-sodic, and further dividing these into different clay percentage classes and for each determining the drainage spacing and costs. From this and the Gross Margins (GMs) of the predominant crops grown on each soil class, the derived Net Present Values (NPVs) of a series of payments to repay the drainage installation was calculated. The number of years was calculated to repay the loan and the soil classes ranked according to the rate of loan servicing.

In response to fears of water pollution from the "Witwatersrand" in the upper and middle reaches of the Vaal River, Du Plessis (1982) conducted a study on the working of worsening water quality on the yields of crops along the lower Vaal River.

Allen and Herold (1988) developed through the Vaal River System Analysis, a water quality modelling component for the DWAF suite of models that simulates South Africa's whole network of water.

DISA (Daily Irrigation System Analysis) was initially developed for the DWAF in 1990 (Görgens *et al.* 2000) to predict the impact of irrigation development from the Greater Brandvlei Dam supply area on river flow and salinity returnflow impacts on the Breede River. Görgens *et al.* (1993) looked into the applicability of hydrodynamic reservoir models for water quality management of stratified water bodies in South Africa using DISA. Wolff-Piggott (1994) coupled a geographical information system to the DISA catchment hydrological models, fulfilling an important future trend of integrated models as confirmed by McKinney *et al.* (1999).

Johnson (1994) evaluated the four-electrode and electromagnetic induction techniques of soil salinity measurement. He warned that salinisation usually develops insidiously over many years and can present a serious threat to the long-term viability of an irrigation scheme, and that there is a serious need to monitor trends in soil salinity levels on irrigation schemes.

The application of the DISA model in 1995 on Vaalharts confirmed that about 80% of the total dissolved salts (TDS) load in the incoming irrigation water is retained in deep groundwater bodies underneath the Vaalharts Scheme.

Moolman and Quibel (1995) conducted a study for the DWAF on the river water salinity problems at the Douglas Weir and Lower Riet River, concluding that additional transfers from the Orange River were necessary to dilute and flush the water in the Lower Riet River and Vaal Barrage.

Aihoon *et al.*(1997) wrote a paper on the agricultural salinisation in the Olifants River at the Loskop Valley in Mpumalanga which followed a study on pollution insurance for the agricultural sector in Loskop Valley. His work, through the calculation of elasticity's for dissolved salts, provides insight into the process of salinisation and the externalities it imposes and provides useful policy interventions.

Gouws *et al.* (1998) quantified the impact of salinisation on South Africa's water resources with special reference to economic effects, concluding that water quality does impose a substantial cost to the South African economy.

Du Preez *et al.* (2000) examined the effects of the river water quality on irrigation farming along the lower Vaal River, looking specifically at the impact on soils and crops. Their work concluded that irrigation did lead to a build-up of salts in the soil, but not to such an extent as to have major yield impacts. Their analysis compared currently irrigated soils to virgin (un-irrigated) soil profiles nearby.

Urban-Econ (2001) led a multi industry analysis to determine the macro-economic cost effects of salinity in the Middle Vaal River catchment, concluding *inter alia* that no immediate (annual) economic effects are felt by agriculture at river water TDS levels of below 600 mg/l.

SALMOD (Salinity and Leaching Model), developed by Armour & Viljoen (2002) in close parallel with du Preez *et al.*(2000) was a short term farm level financial model that optimised farm level cropping choice for one production season based on future knowledge of the irrigation water salinity. Viljoen *et al.*(2006) was proposed to be an extension of this work, spatially - to regional level, temporally - to a dynamic long term model, and incorporating detailed hydrology, soil and plant dynamics and interactions. McKinney *et al.*(1999) however warned that "extending the short-term model into a long-term model with a large number of time periods and more complex structures will lead to complex technical difficulties for mathematical modelling." This was realised and a completely new approach to expanding SALMOD therefore needed to be developed to meet the project aims.

The integration of different disciplinary models was part of the WRC long term strategy as explained in Backeberg *et al.* (1996). Benade *et al.* (2002) developed an integrated information system for irrigation water management using the WAS (Water Accounting System by Benade in Benade *et al.*, 2002), SWB (Soil Water Balance by Annandale and Jovanovic in Benade *et al.*, 2002) and RiskMan (financial Risk Management by Meiring and Crous in Benade *et al.*, 2002) computer models. However water quality was not considered in this integrated suite of models, only water quantity.

ACRUsalinity was developed by Teweldebrhan (2003) based on the object-oriented version of ACRU (Agro-hydrological Modelling System by Schulze, 2002), using its objects and structure, and interacting salinity processes with the hydrological processes of ACRU. *ACRUsalinity* was successfully validated and verified in the Upper Mkomazi Catchment in Kwa-Zulu Natal.

Ellington *et al.* (2003) quantified the impact of irrigation on the aquifer underlying the Vaalharts irrigation scheme, looking at the water table rise, groundwater discharges into the Hart River and the rate and levels of salt accumulation underneath the Vaalharts irrigation scheme. This study was conducted in response to the Herold and Bailey (1996) study that calculated a long-term salt balance of the Vaal-Harts irrigation scheme. Their warning was that salt was being added to Vaalharts at a faster rate than was infiltrating to the Harts River. Ellington *et al.*'s (2003) explanation of this was that the salts aren't necessarily building up underneath the scheme, but in the riverbanks just before flowing into the Harts River. Occasional heavy rainfall events and flooding have repeatedly washed these salts out, and because of high river flows and the resulting dilution effect, the salts didn't rise to observable levels in the river.

This study builds on the previous research that was conducted in South Africa, integrating its relevant parts to effectively model salinisation at regional level to guide policy making and irrigation practices towards sustainable water quantity and quality management.

3.2 SALINISATION PROCESSES AND INTERACTIONS

This paragraph aims to review literature relevant to the first WRC project aim, namely, to better understand the polluting chemical processes and interactions in and between the plant and surface-, vadose zone- and ground-water, to achieve efficient and sustainable water quality management.

With the greatest threat to the sustainability of irrigated agriculture in arid and semi-arid areas being water-logging and salinisation which render soils less suitable for crops grown therein (Ringler 2001, Postel 1999, Rosegrant *et al.* 2002, Khan *et al.* 2000, Kijne 1998, etc.), the understanding of the salinisation process and the drainage response to address water-logging and salinisation is focussed on. Kijne *et al.* (1998) provide a comprehensive review of the causes of irrigation-induces salinity.

By way of introduction, this paragraph proceeds with a definition and the delineation of the term salinisation as used in this thesis, and then examines the salinity interactions in and between soil and surface-, vadose zone- and ground- water, and the salinity interactions in and between the water available in the soil for plant uptake and it's effect on plant yield. The section concludes with a discussion on the incorporation of the saline water-plant-yield interactions into a financial model for eventual reporting of the economic effects of salinisation.

3.2.1 SALINISATION DEFINED

Salinisation is defined as the building up / concentration of salts (primary chlorides and sulphates of calcium, magnesium, sodium and potassium) in soils (Aihoon *et al.,* 1997:270). When occurring in the vadose (root) zone of soils, salinisation renders the soil less suitable for the normal growth of the current vegetation growing in the soils. Salinisation is usually coupled with rising / fluctuating water tables, or water flow / flux in soils which mobilise the salts in the soils to concentrate them at a certain point/level which becomes salinised.

Due to the concentration of salts being proportional to the water content of a body of soil, for the purposes of standardisation and comparability, salinisation is measured as the concentration of salts (Total Dissolved Solids, TDS) in a saturated extract of a soil sample in either milligrams per litre (mg/l) or parts per million (ppm, where mg/l=ppm). Salinisation also influences the electrical conductivity (EC) of a body of soil, measured in milli-Siemens per metre (mS/m), and for the same reasons as above, the saturated EC (ECe) is used for soils. ECe is an indirect measure of the concentration of the total dissolved salts (TDS) in solution. EC is related to TDS by multiplying by a factor of between 6 and 7 depending on the composition of dissolved salts (DWAF 1993:31-35).

Although dryland salinisation occurs, the focus of this thesis is on irrigation salinisation, whereby the process of irrigation mobilises the salts to accumulate in the vadose zone. 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 the irrigation water used. Salinisation can however be reversed / controlled with a properly designed drainage system that leaches salts out of the soils. This process however can lead to externalities whereby downstream farmers are negatively influenced by the leaching practice. The new Waste Discharge Charge System (DWAF 2006) to be implemented in South Africa may place serious limits on the volumes and way farmers are allowed to leach.

An alternative to leaching to control lower levels of salinisation is to accept the process and change the crops grown to crops that can tolerate higher levels of salinisation, such as barley, sugar beet and cotton (Maas and Hoffman, 1977). Halophytes are the genre of plants that can tolerate exceptionally high levels of salinisation in the soil (Benes *et al.*, 1999). Drainage and leaching versus planting tolerant crops are two salinisation management options that would need to be further evaluated in this thesis as the author was not able to find a financial comparison in the literature of these two options.

Falling out of the scope of this study, but still important to note for holistic salinity management are the following other salinity interactions:

- Sodium (Na) mobilised in the soil can result in a Sodium Absorption Ratio (SAR) that can break down soil structure, preventing effective water infiltration and uptake by the plant. It is important when evaluating the irrigation potential of soils and the irrigation water applied to look at both the salinity and SAR and the relation between the two (Sumner and Naidu, 1998).
- Overhead sprinkling can cause salt phytotoxicity (salt burn) if the following salt levels are exceeded in the irrigation water: Chloride 100ppm, Sodium 70ppm and Boron 1ppm (McEachern, 2000).

3.2.2 <u>SALINITY INTERACTIONS IN AND BETWEEN THE SURFACE-, VADOSE ZONE- AND GROUND-WATER</u>

A thorough understanding of the hydrological cycle and water movement and water chemistry trough the soil is required to model the salinity interactions in and between the surface-, vadose zone- and ground- water. This is required to determine the salinity interactions in and between the plant and plant available water in the soil, so as to determine the salinity interactions in and between the crop and the financial considerations thereof to successfully model the economic impacts of salinisation.

Saturated and unsaturated groundwater chemistry and soil science models / model components (algorithms) will need to be identified that can provide input into a long term dynamic model that covers numerous catchments, or parts thereof. The physical basis for integrated water quality management includes the dynamics of soil moisture and salt movement in the root zone, which is generally described by the Richard's equation (McKinney *et al.*, 1999).

The level of detail however required and the point specificity of the models used to simulate these relationships needs to be compared with the scope and scale of the envisaged area of study (or meaningful sub-parts thereof) and a compromise reached as to an applicable level of detail required for the integrated model (Van Genuchten, 2003).

3.2.3 SALINITY INTERACTIONS IN AND BETWEEN THE PLANT AND AVAILABLE WATER IN THE SOIL

In Letey *et al.* (1985), the relationship between crop yield and the seasonal amount of applied water (crop-water production function) is required to determine optimum irrigation management. The Letey *et al.* (1985) model is developed for the computation of crop-water production functions with saline irrigation waters, and combines three relationships: yield and evapotranspiration, yield and average root zone salinity, and average root zone salinity and leaching fraction to allow for plant growth adjustment, and therefore evapotranspiration adjustment, to root zone salinity.

SAPWAT by Van Heerden *et al.* (2002) is a South African irrigation scheduling model that uses a database of nationwide reference transpiration values to determine crop and area specific crop factors derived according to Green (1985) to indicate the monthly crop water requirements depending on crop growth stage and planting date. This data is necessary in the determination of monthly crop water requirements in the different WUAs. Furthermore, the

Maas & Hoffmann (1977) equation is extensively used to determine the plants relation to salinity in the soil water it takes up. Each crop has a specific salinity threshold value up to which 100% yield can be achieved, but once exceeded, yield is reduced by a linear gradient value. Both SAPWAT and the Maas and Hoffman equations are used to simulate the interaction between the soil water and the plant and are discussed in depth in Chapter 5.

3.2.4 SALINITY INTERACTIONS IN AND BETWEEN THE CROP AND THE FINANCIAL CONSIDERATIONS THEREOF

If through the understanding and modelling of the soil-crop-atmosphere interactions, a reduction in crop yield due to salinity can be obtained (e.g. by using the Maas and Hoffman, 1977 equation), then the financial implications can be calculated using a crop enterprise budget (CEB) as in Knapp, 1992. The soil-crop interaction model will however have to be aggregated from per plant / point in field level to per hectare level, as this is the spatial unit at which CEBs are determined and for which data is available (Victoria *et al.*, 2005).

Per hectare level CEB data can easily be extrapolated to field, farm and regional level, provided that the aggregation of the soil physical properties for which the soil plant interactions were calculated, as well as the plant atmosphere interactions, remains the same. Otherwise groupings need to be made of areas with similar properties, and the appropriate variations need to be made in the CEBs (i.e. yield and input requirement and cost changes) as was done in Armour and Viljoen, 2002. When setting up CEBs across farm/financial borders then they are set up to total gross margin above specified costs (TGMASC) level, accounting only for the variable costs of production (Armour and Viljoen, 2002). The farm level fixed costs component is not included as this varies considerably from farmer to farmer depending on the level and rate at which fixed capital investments such as land and loose capital investments such as tractors, implements and irrigation systems are paid off. From a purely physical resource endowment perspective, a typical / representative farm can be identified, however when incorporating the capital basis of a farming enterprise and the financial implications thereof, a typical / representative farm is far more difficult to identify, and a case study farmer is used.

3.2.4.1 Demand curve and elasticity for water quality

According to Hall *et al.* (1994), developer of the IMMS spatial equilibrium model designed to simulate the competitive market equilibrium of the southern Murray-Darling basin, the prices of farm products have a key influence on the position of the demand curve, which for farming enterprises is usually simulated by using a farm sector enterprise model (i.e. CEBs).

The shape of the demand curve determines whether price-elasticity of demand (i.e. the % change in water quantity or quality demanded divided by a percentage change in the price) is high or low. Inelastic demand for water quantity or quality indicates relatively high value, because users do not adjust their water consumption pattern and quality preferences when the water price changes (Thomas 2001). Elastic demand indicates lower value in use of water because users are able and willing to give up more of their water consumption or water quality requirements if the water price increases. Aihoon (1997) calculated the elasticity's for dissolved salts in the Olifants River in South Africa, providing insight into the process of salinisation, the externalities imposed and useful information for policy interventions.

When high farm product prices are achieved for a crop, the demand for water is "inelastic" with respect to water price. In other words, the quantity of water required by farmers is relatively insensitive to the price of the water, and the value of water to the users is high. On the other hand, low farm product prices can produce a shift in the water demand curve: for example, if maize prices are low farmers may shift to wheat, and much less water will be used as wheat is a winter crop with a lower total water requirement. Water demand also is influenced by production possibilities. For example, the increasing shift from irrigated maize to irrigated pasture with the decrease in the maize price in the 2004/5 production year. Here demand is price-elastic, and the value of the water to the producers is relatively low. Irrigation blocks producing mainly bulk commodity, low value crops have low marginal product values for water, whereas the irrigation blocks producing a portion of higher value crops and orchards have high marginal product values for water.

3.3 ECONOMIC MODELS FOR EFFICIENT AND SUSTAINABLE WATER QUALITY MANAGEMENT FOR SALINISATION CONTROL

The purpose of this paragraph is to introduce the second WRC project aim by investigating the literature to guide the development of the new economic models, both at micro and macro level, to sustainably model various scenarios to aid in the selection of the best management options and policy interventions for sustainable salinisation management. As this thesis focuses on the micro-economic model, a more comprehensive literature review on the macro economic component can be found in Viljoen *et al.*, 2006.

Numerous agricultural and resource economists have developed salinity related models – Dinar, Knapp and Zilberman in Letey *et al.* (1985), Dinar and Knapp (1986), Dinar and Zilberman (1991), Dinar (1993), Lee and Howitt (1996), Madden in Prathapar *et al.* (1997) and Khan *et al.* (2000), Feinerman and Yaron in Feinerman and Yaron (1983), Feinerman (1994), Hillel and Feinerman (2000), Tsur in Tsur, Shani, and Zemel (2004), Young in Gardner and Young (1988), Booker and Young (1994) and Young (1996), etc. to mention a few.

McKinney *et al.* (1999) who reviewed and proposed future directions for modelling water resource management at the basin level give a very comprehensive literature review of the progression of the economic modelling of salinity. Wichelns (1999) also gives a review of economic models of water-logging and salinisation in arid regions, citing *inter alia* Afzal (1996), Amer (1996) and Chaudery and Young (1990).

Conradie and Hoag (2004) give a review of mathematical programming models that calculate the values of irrigation water. Among these are models that incorporate a salinity dimension into the calculation of the value of water (Afzal et al.1992, Lefkoff and Gorelick 1990, Gardner and Young 1988 and Booker and Young 1994). According to Young (1996) most applications of mathematical programming for the analysis of water use in agricultural production have been in a partial equilibrium, deterministic, static framework. However according to McKinney *et al.*(1999), extensions to these approaches are now extensively being used.

Numerous mathematical models have been developed for the micro-economic management of irrigation salinisation; 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.), yet these models however most closely resemble the type of problems to be addressed in this research. Afzar (1992) developed a LP model to optimise the use of different quality waters. In a situation of poor-quality ground water and limited good-quality canal water, the model decides how much land to put under each crop and how much ground water to abstract and apply to each crop in each time period. The objective function is to maximize net returns, a function of crop yield, which is in itself a function of irrigation water applied. The objective function thus involves the maximising of a function that includes the product of two variables, crop area and amount of ground water applied. To overcome the difficulties of nonlinearity, a number of irrigation strategies were identified for each crop; each strategy has a corresponding yield level, which becomes a coefficient in the objective function rather than a variable.

Gardner and Young (1988) designed one of a series of linear programming models to test policy options for the Colorado River. The model compares the efficiency and cost effectiveness of irrigation equipment subsidies to effluent taxes and price increases for irrigation water. The model maximises net revenue across five crops (lucerne, barley, maize, pasture and dry beans) and four irrigation technologies (siphon tubes, gated pipes, ported ditch and 'cablegation') used at different labour intensities with and without lined ditches. Land retirement is also an option. Crop mix is exogenously constrained to the long-term average plus and minus one standard deviation. Parameters for crop activities come from extension service reports while irrigation extension specialists supplied irrigation parameters.

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 are the stochastic and dynamic programming models. These models, developed for crop / area optimisation, required data from tightly controlled experiments specifically setup for the models, and would not work in South African because of the water quality data limitations identified by Du Preez *et al.* *(*2000:154).

The Generalised Algebraic Modelling System (GAMS) (GAMS Development Corporation, www.gams.com) was successfully used in Armour and Viljoen (2002) and initially identified as the ideal optimisation programming platform for building the salinity and drainage management model required for this research. Louw and Van Schalkwyk, 2000 and Grove and Oosthuizen, 2001 have also extensively used GAMS for water related economic optimisation models in South Africa. Other water quality management models constructed using GAMS are by Lee and Howitt (1996), used for modelling regional agricultural production and salinity control alternatives within a water quality policy analysis framework, Percia *et al,* (1997), 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 cropping and management decisions.

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 practice 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 practice 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."

Coupling or integrating these models with a Geographical Information System (GIS) to create spatial optimisation and simulation models as referred to in Engel *et al.* (1993), Wolff-Piggott (1994), Johnston (1994), Bende (1997), Negahban *et al.* (1996) and Rhoades *et al.* (1999) was identified as the latest trend, and reinforced in DWAF(1996) but lies beyond the scope of this thesis.

3.3.1 MICRO ECONOMIC MODELS

In deciding on which approach to follow for the development of a new micro-economic model for specifically the study area identified, a first step would be the identification of the limitations of previous salinity models. A review of literature on the demand curve of and elasticity for water quality also reveals a possible approach to better understand the economics and salinity linkages to effectively capture these in the new economic model.

3.3.1.1 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 state 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), with the latter stating 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.

3.3.2 MACRO ECONOMIC MODELS

For the full discussion on the background literature for the macro-economic model see Viljoen *et al.*, 2002.

Macro-economic modelling is required to incorporate the secondary impacts of changes simulated by the micro-economic model. Economic and job creation impacts, that changes in production output have on the manufacturing, service and transport sectors play a large role in guiding informed political decision making that can impact on levels of primary production. Providing grants to improve water use, management and distribution efficiency, not justified through purely financial benefit-cost analysis, can often be justified when the secondary impacts on the economy, job creation and environmental benefits are included in the analysis (Tietenberg 2006).

Gouws *et al.* (1998) used economic simulation modelling, using the input/output analysis technique to identify and quantify the economic impacts of salinity in the Middle Vaal River System. The macro-economic project team, Urban Econ, decided to use the same method in the Lower Vaal River System, incorporating the Lower Riet River. For their motivation of the method of macro-economic analysis used see Viljoen *et al.* (2006).

3.4 THE INTEGRATION OF ECONOMIC MODELS WITH MODELS FROM OTHER DISCIPLINES

The aim of this paragraph is to review literature that relates to the third WRC project aim, namely, to integrate economic models with models from the other disciplines, particularly hydrology, and agronomy models. The first section is a motivation for a multi-disciplinary approach. Thereafter the lessons learnt from the integration of multidimensional models are discussed, followed by a review of applicable mono disciplinary models and there level of integratability. The final two sections deal with economic-hydrology interactions and with the economic-agronomic interactions specifically.

3.4.1 MULTI-DISCIPLINARY MOTIVATION

At the outset of this thesis, the challenges cited by preceding authors of the integrated modelling approach required for the economic interpretation of irrigation salinity over larger areas than the farm field are listed.

As a motivation for multidisciplinary research McKinney *et al.*(1999) state that "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." Blackwell, *et al.* (2000) however warns that "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." Furthermore Antle and Stoorvogel (2003) state that "it seems unlikely that a general, integrated model applicable to many different production systems will be available in the foreseeable future, nor will data adequate to support such a model be available."

In the foreword to their book, Quaddus and Siddique (2004), state that "Taking account of the fact that sustainable development planning is multidisciplinary by nature, the contributors concede that a single exemplary model does not exist. The aims of the stakeholders, along with preferences and priorities surrounding the planned objectives determine the ways and means of sustainable development planning". Although irrigation agriculture is a very small component of overall development planning, the nature of it fitting into the bigger sustainable development picture makes it multidisciplinary as the linkages and interactions need to be understood and facilitated. To proactively manage and implement policy to anticipate problems, and sustainably introduce change, the best information obtained from comprehensive multi-disciplinary research is needed. Botes (2004) further state that "research in a team context is still one of the best ways to ensure that you include a multiplicity of views, thereby enhancing the validity and relevance of your research attempts."

In Figure 3.1 Victoria *et al.* (2005) demonstrate a multidisciplinary integration of the ISRAEG field scale agricultural model with the PROPAGAR (/SAGBAH) basin scale multi sector model. They conclude that the multi-scale analysis allows for the improvement of knowledge on processes relative to water use, a better understanding of spatial and temporal variations and effective simulation with historical data for different scenarios.

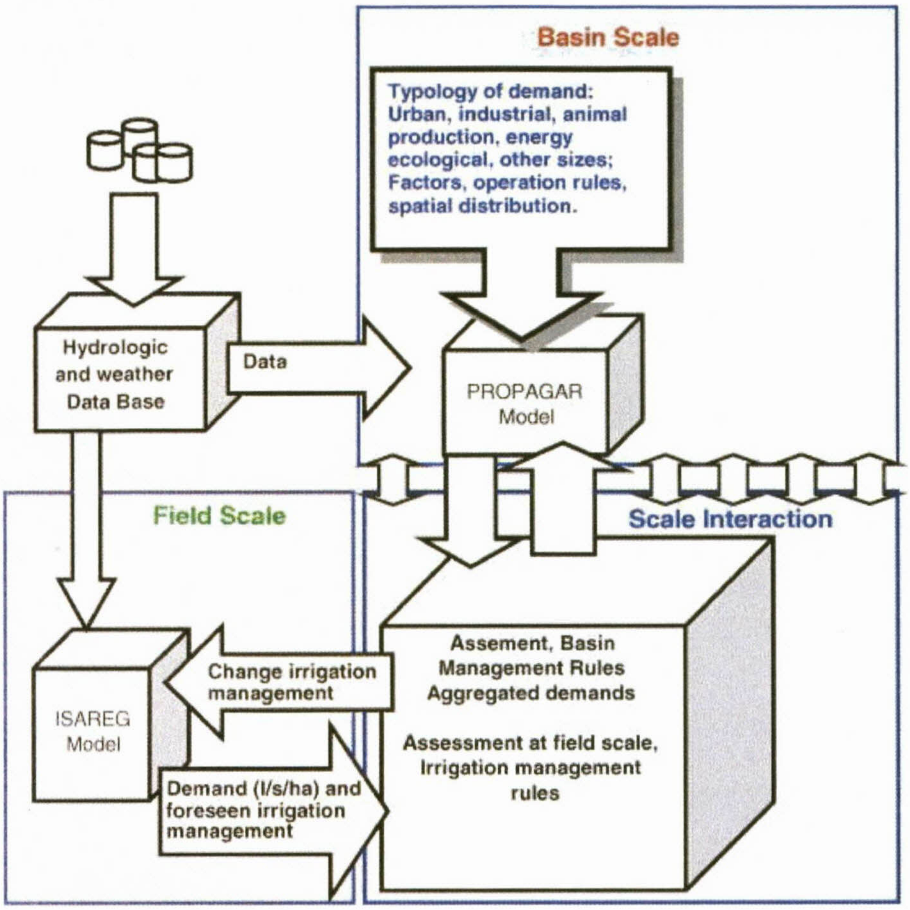


Figure 3.1. Schematic of the integration of the ISRAEG field scale model to the PROPAGAR basin scale model according to Victoria *et al.* (2005), showing model & scale integration

In a South African context, Benade *et al.* (2002) developed an integrated information system for irrigation water quantity management using the Water Accounting System (WAS), Soil Water Balance (SWB) model by Annandale *et al.*(2005) and the RiskMan computer model by by Meiring and Crous in Benade *et al.*, 2002.

McKinney *et al.*(1999) in their review of and proposal for the future direction of water resources management modelling, conclude that integrated modelling is essential and that it is at the river basin level that hydrologic, agronomic and economic relationships can be integrated into a comprehensive modelling framework. They also conclude that integrated basin-scale modelling will further improve the modelling and understanding of the tradeoffs of water policy options for better water resources management decisions.

To conduct integrated research, applicable mono-disciplinary models first need to be identified, together with their existing interdisciplinary linkages and / or possibility of effective integration with a clear vision on the aims and outcome of the expected integrated model. The various means of integrating different types of models also needs to be reviewed so that the right approach is followed.

3.4.2 <u>REVIEW OF INTEGRATION OF MULTI-DIMENSIONAL SALINISATION MODELS</u>

Ringler (2001:17) lists the many challenges to the integrated modelling of economic and hydrologic components. Among others she lists that water resources management and allocation studies have generally been dominated by hydrologic analyses from an engineering perspective, while economic and policy analyses studies usually solely focussed on profit maximisation of water used for the different sectors. This makes information exchange difficult due to differences in the simulation and optimisation modelling techniques. Spatial units also differ, with economic analyses focussing on political and administrative boundaries, and the hydrologic approach referring to the river systems. Time intervals and temporal horizons also differ, and insufficient and inadequate data can also be further constraints to integrating economic and hydrologic model components (Ringler, 2001 and McKinney *et al.*,1999). According to Antle & Stoorvogel (2003) "It seem unlikely that a general, integrated model applicable to many different production systems will be available in the foreseeable future, nor will data adequate to support such a model be available"

Van Genuchten (2003) suggests that the best possible model / algorithm of the soil salinisation process to integrate into an economic model depends on how simple or complex the user wants to make the model. It depends on the expertise available, and what type of applications the user is mostly interested in, with the data issue also important. However, even for more complicated problems (e.g., 2D flow/transport with salinity interactions) there is often some guidance on the parameters. Van Genuchten (2003) further states that there is a range of models one could construct or use:

- Solute transport only, with steady-state flow
- A tipping bucket type model that simply routes water downward according to field capacity and surface irrigation rates and ET (or root water uptake). TETRANS is a good example (http://www.ussl.ars.usda.gov/models/modelsmenu.htm), and WATSUIT includes salinity/sodicity
- A 1D Richards equation type model for variably-saturated flow, and considering total salinity only. HYDRUS could also be a good starting point, or the more sophisticated HYDRUS-1D and HYDRUS-2D models
- Same as above, but increasingly complex flow and transport features, such as lots of soil or geochemistry to account for precipitation / dissolution, cation exchange, etc, such as the UNSATCHEM model

Van Genuchten (2003) goes on to state that to be really competitive, these types of modelling efforts are becoming quickly more than just one-man efforts. Heeding to this warning and not having personal or local expertise in setting up and running these models, none of them are selected. Furthermore, WRPM gives a satisfactory indication of vadose zone salt mass and water volume for the scale of modelling required.

SWAGMAN (Salt, Water and Groundwater Management models), a suite of Australian models developed by the CSIRO to facilitate the problems of rising water tables and salinisation in irrigation areas (Godwin *et al.* 2000), are set up at different scales and for different purposes to address different classes of salinity problems, but all on the same programming platform with integrability as an objective:

- *SWAGMAN Whatif* is a teaching tool to help farmers understand irrigation, water tables and salt.
- *SWAGMAN Destiny* simulates crop responses to salt and water-logging at a point in the field scale
- *SWAGMAN Farm* ensures the optimum mix of crops to minimise recharge and maximise farm level profits. In Khan *et al.* 2000, *SWAGMAN Farm* is used in a farm scale hydrologic economic optimisation model to manage waterlogging and salinity in irrigation areas. Khan 2001, use *SWAGMAN Farm* to develop policies aimed at sustainable development of rice farming systems, highlighting the importance of considering groundwater discharge and recharge zones in and around an irrigation area.

- *SWAGMAN options* optimises crops at a multiple field level to determine optimum policy decisions such as restrictions on area planted to rice (which had a large influence in raising water tables). SWAGMAN Options was used by Prathapar *et al.* (1999), to identify profitable land uses that minimize water table rise and salinisation.
- *SWAGSIM* links irrigation and crops to groundwater response through an unsaturated flow to a spatially distributed shallow water-table dynamic model.
- *SWAGMAN Basin* is a supply and use balance model for a entire river basin to represent variations of flows in the river and its impact on irrigation areas.
- *SWAGMAN Futures* integrates hydrology with economics on a regional scale using a non-linear optimisation algorithm to investigate the effect of potential changes in cropping patterns, drainage management, water trading and water reforms on the future of an irrigation area for effective policy formulation.

The application of the SWAGMAN suite of models was examined, but not found practical, nor one hundred percent suitable for South African conditions due to the strong focus on groundwater and water tables, and the multi-disciplinary team that would be required to set up and calibrate the SWAGMAN models for South African conditions in the study area. The approach and methods used however were studied and learned from and to a degree incorporated into this thesis.

Another research group, the Integrated Catchment Assessment and Management Centre (iCAM) of the Australian National University, has as one of their three main research themes, *Model Integration and Evaluation: Sensitivity, Uncertainty and Scale Assessment* (iCAM, 2006). This centre recognises the crucial need for thorough analysis of large simulation models that integrate hydrological, water-quality, landuse and socioeconomic aspects of resource management. iCAM (2006) states that for such models to be useful in predicting the effects of management actions, the sensitivity of predictions to uncertainties affecting them must be well understood and quantified as far as possible. Assessment of sensitivity and uncertainty is closely associated with the selection of model structure and estimation of the model parameters. These in turn are strongly influenced by the spatio-temporal scale of the problem and of the data available for model calibration. The benefits and dangers of spatial and temporal aggregation are major concerns in model development and testing (iCAM, 2006). The existence of the iCAM centre indicates the complication of integrated modelling, and the need to be aware of the dangers thereof, requiring careful planning in the choice of modelling approach and integration processes, and being thorough in the interpretation of the results, listing their sensitivity to main variables.

To aid in the development and integration of models, a static versus a dynamic timeframe needs to be decided on and whether a simulation or an optimisation modelling approach will be followed, or a combination of these. For integration, it needs to be decided whether a compartment versus integrated modelling approach will be followed. These choices and potential combinations are discussed in the following paragraphs.

3.4.2.1 Static versus dynamic modelling

See paragraph 3.3 for a full review of various static and dynamic salinisation models. This paragraph provides insight as to the applicability of dynamic programming for salinisation modelling based on a theoretical description by Kamien and Swartz (1981). They prove that the optimal action in the short run (i.e. static) need not be optimal in the long run (i.e. dynamic). They therefore studied various economics and management science problems from a long run, dynamic perspective. A problem becomes truly dynamic if the production level affects not only current profit but also profit in a later period (Kamien and Swartz, 1981). For example, current profit may depend on both current and past output due to costs of changing the production rate. In the salinisation problem context, current crop yields (and hence profit) depend on both the current and past levels of leaching applied (with associated drainage cost implications) to control the fluctuating rate of salinisation in the soil. Randomly occurring natural floods also contribute towards the salt mobilisation dynamics in the soil.

The dynamic optimisation techniques of calculus of variations and of optimal control theory are used to solve planning problems in continuous time according to Kamien and Swartz (1981), who further state that the solution to a continuous time dynamic problem is a continuous function (or set of functions), indicating the optimal path to be followed by the variables through time or space. Note the use of wording by Kamien and Swartz (1981); "time or space" and not "time and space". The problem with salinisation is that it builds up over time and over space, and fluctuates within three-dimensional space (within the soil layers) depending on the levels of production (irrigation water requirement) and management interventions (leaching and drainage) in current time, which are dependent on what has been done in the past. This poses a potential threat to using dynamic optimisation for salinisation modelling. The alternative is therefore the use of a simulation approach to capture the dynamic nature of salinisation modelling.

3.4.2.2 Simulation versus optimisation modelling

Negahban *et al.*(1997) define optimisation 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 by ASCE (1990:530); "One approach to select the best management practice 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 practice 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."

A distinguishing feature of simulation models as opposed to optimisation models is their ability to assess performance over the long term (McKinney, 1999). As the process of salinisation is clearly a long term process, a simulation approach will have to be used.

3.4.2.3 Compartmental versus integrated modelling approaches

McKinney *et al.* (1999) reviews the state of the art of modelling approaches to integrated water resources management at the river basin scale, with particular focus on the potential of coupled economic-hydrologic models, and concludes with directions for future modelling exercises. According to McKinney *et al.* (1999) integrated economic-hydrologic models can be classified into those with a compartment modelling approach and those with a holistic approach. Under the compartmental approach there is a loose connection between the economic and hydrologic components, i.e. only output data is transferred between components. Each sub-model can be very complex, but the analysis is often difficult due to the loose connection between the components. Under the holistic approach McKinney *et al.* (1999) explain that there is one single unit with both components tightly connected to a consistent model, and an integrated analytical framework is provided. However they further state, the hydrologic side if often considerably simplified due to model solving complexities.

Heeding to this statement by McKinney et al. (1999) it was proposed for the integrated economic-hydrologic model, that a hydrology model supply input data for the economic model in a compartment modelling approach instead of trying to holistically integrate a grossly simplified hydrology component into an economic optimisation model. Other less complex bio-physical models (i.e. plant yield response to salinisation models) can be holistically integrated into the economic model, instead of modelling in a compartmental approach.

3.4.3 THE IDENTIFICATION AND INTEGRABILITY OF APPROPRIATE MONO-DISCIPLINARY MODELS

3.4.3.1 Hydrology Models

Table 3.1. Summary table of the attributes of models used by DWAF in DWAF (2001)

Model	Calibration or physically based	Operational hydrology	Water quantity modelling	System yield	Individual water availability	Water quality modelling	Finest temporal scale	Spatial scale	Trans-parency and credibility	Applicable to SA conditions	User friendly	Model under develop-ment
WSAM	C	Limited	Yes	No	No	No	Annual	Catchment	Low	Yes	Yes	Yes
WRSM90	C	No	Yes	No	No	No	Monthly	Catchment	Low	Yes	Yes	No
WRYM	C	Yes	Yes	Yes	No	Limited	Monthly	System	Low	Yes	No	No
WRPM	C	Yes	Yes	Yes	No	Limited	Monthly	System	Low	Yes	No	No
MIKE-BASIN	C	Yes	Yes	Yes	?	No	Daily	Catchment	Low	Some recent develop-ments	Yes	Yes
ACRU	P	UD	Yes	UD	UD	Limited	Daily	Catchment	High	Yes	No	Yes
HSPF	C	Yes	Yes	Yes	?	Yes	Sub-daily	Catchment	Medium	No	No	Yes
VTI	C	No	Yes	No	No	No	Sub-daily		Low	Yes	No	
PRMS	P	No	Yes	No	No	No	Monthly	Catchment		No		
SWAT	P	No	Yes			Limited	Daily	Catchment	High	No	Yes	
SAPWAT	C	No	Yes					Farm level		Yes	Yes	

UD = Under development

Table 3.1 lists the attributes of water quantity modelling models currently used by DWAF in South Africa. This matrix together with a brief overview of some of the models reviewed in greater detail helped with the decision of the hydrology model to use in this study.

The models used by DWAF in South Africa for water quality modelling can be divided into five types, viz. simple process models, detailed process models, system analysis models, daily reservoir hydrodynamics models and sub-daily river hydrodynamics models (DWAF, 2001). Applicable for this study are only the simple process and system analysis models. Of these ACRU, DISA and the WRPM were investigated for application to this study. A short description of each, and the sub-models, WQT and WRYM of the WRPM follow, categorised according (DWAF 2001) as either simple process or system analysis models:

Simple process models

Hydrosalinity Model (WQT) – monthly: This is a *coarse-scaled* model for *salinity* production and transport in *large multi-use catchments*, specially designed to be driven by the same natural flows that drive the Water Resources Yield Model (WRYM) and Water Resources Planning Model (WRPM) as system analysis models. WQT is used to determine salinity parameters, which are then input into the WRPM model for multiple stochastic optimisation runs in large river systems (DWAF 2001).

ACRU – daily: This is a *fine-scaled* model for *sediment and phosphate* production from *individual small catchments* with a limited range of agricultural land-uses. It is driven by daily rainfall and uses soil-moisture budgeting according to a discretisation based on soil texture classes and agricultural practices. It is recommended to investigate localised impacts of land-use and their related management options (DWAF 2001). ACRU is according to Hallows and Pott (2006), the most advanced Hydrological model in SA. ACRUsalinity (Teweldebrhan, 2003) is a hydro-salinity module for ACRU that vastly improves the salinity modelling component of ACRU. The process objects in *ACRUSalinity* according to Teweldebrhan (2003) are grouped into six packages that conduct:

- the initial salt load determination in subsurface components and a reservoir
- determination of wet atmospheric deposition and salt input from irrigation water
- subsurface salt balance, salt generation and salt movement
- surface flow salt balance and salt movement
- reservoir salt budgeting and salt routing, and
- channel-reach salt balancing and, in the case of distributed hydrosalinity modelling, salt transfer between sub-catchments.

ACRUsalinity was also evaluated for possible use to generate the hydrology data for the WRC study in which this thesis is based, but proved too data and manpower intensive, and would achieve far more than was required for the WRC project.

The ACRU model has been designed to be a multi-level model with a hierarchy of alternatives possible in many of its routines depending on the level of input data available. The ACRU model is physically processed base, with inputs being defined explicitly in terms of land and water use information. The information is hence transparent and allows for stakeholder understanding, interaction and query. The parameters are locally developed and are suited to South African conditions. The new water quality and systems operation components being introduced into the model allow for more flexibility. The system does not however include the stochastic runoff generation and many of the components still need to be developed (DWAF, 2001).

Pott and Creemers (2000) used ACRU results, formulated into GAMS coding (Brooke *et al.*, 1994), to determine the land use pattern changes and resulting economic effects of changes in water quantity with financial results reported within a cost-benefit analytical framework. They commented that ACRU is very data intensive and process based (i.e. basically a big water accounting model).

DISA – daily: This is a fine-scaled model for salinity production and transport through formalised irrigation schemes and allows operation of supply reservoirs, river channel transport, diversion devices, primary and secondary canals, balancing dams, artificial drainage, groundwater variability and a wide range of irrigation practices. It is driven by daily rainfall and uses soil-moisture budgeting according to a discretisation based on soil texture classes, location on the landscape, and agricultural practices. It is recommended as support for any of the other models to assess irrigation impacts of large or multi-offtake irrigation schemes, or to examine management options for salinity control (DWAF 2001).

System analysis models

The following two models are used to optimise the allocation of water on a monthly basis throughout a large multi-use river system, according to a penalty structure, for a given time horizon of water demands and allowing stochastic variation (DWAF 2001).

WRYM: This model is used to calculate the long-term yield from a specific flow series, to examine operating rules or to develop yield-reliability curves (DWAF 2001).

WRPM: Based on WRYM and using WQT for the salinity mass balance and runoff component, WRPM allows various sub-systems to support each other during deficit periods and is used as a planning tool to explore augmentation or restriction strategies (DWAF 2001).

As ACRU and DISA are daily time-step models that require levels of detail outside of the scope of this study to set up and calibrate for the study area, they are impractical to use. HSPF, the only model in Table 3.1 with detailed water quality modelling exacerbates this problem as it requires sub-daily data. WRPM alternatively, although a system wide model, is monthly based and does limited salinity modelling through incorporation of WQT. It was already set up for the study area, but required further refinement (additional nodes and channels and associated setup data) to be relevant at sub-WUA level, of which some had already been proposed by DWAF.

The initial aims of the WRC project included the integration of vadose zone (unsaturated root zone) chemical balance models and groundwater (saturated - below water table) models. The incorporation of the WRPM as the hydrology model fulfils both these requirements to a certain degree as WRPM has the ability to generate stochastic hydrology data using basic salt wash-off and balance and groundwater flow models (Van Rooyen *et al.*, 2004).

As in ACRU, The MIKE BASIN model by DHI (2006) also needs generated pre process flows to run. The time step used can vary from daily to monthly, depending on the type of simulation required. The operating rules are explicitly defined attaching certain operating conditions to reservoir or river levels and not through the penalty structure system of the WRYM and WRPM. Stochastic flow generation operations are available and have been derived for South African conditions. The model setup is relatively easy with the GIS linked system with a GUI (Graphic User Interface). User-friendly GUIs make pre and post processing far quicker and user friendly. The explicitly defined operating rules make the system more transparent than the WRYM and WRPM. The speed of processing also makes this system an attractive alternative. However, the purchasing costs are extremely high and could prove prohibitively expensive (DWAF, 2001).

3.4.3.2 Agronomy Models Incorporating Salinisation

Ragab (2000) in his SALTMED model incorporates the Penman-Monteith (evapo-transpiration) and Richards (transient-state soil water flow) equations with Cardon and Letey's (1992b) plant water uptake model in the presence of salts. Although this approach is very well suited to accurate real time modelling, it is more suited to single crop static models and is very data intensive for the dynamic inter-disciplinary model. SWB (Annandale *et al.*, 2005) use a similar approach and is therefore not deemed suitable for incorporation into the inter-disciplinary model developed for the WRC project at the scope and scale intended.

The Maas and Hoffman (1977) salinity-yield equation, using crop threshold and gradient values is far less data intensive than the transient models proposed by Ragab (2001), and applicable to any crop for which crop threshold and gradient values have been determined. The main data used from the literature is 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 and updated by Ayers & Westcot (1985), Maas (1990) and François & Maas (1994). 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 set at a constant level by using an exact concentration of sodium and chlorine minerals only for the entire duration of crops growth.

Maas *et al.* (1983) also looked at the salt sensitivity of maize at various growth stages, an approach with merit as there are large changes in the crop salinity threshold and gradient values as crop growth progresses from germination to vegetative growth to reproductive growth to seed set and finally at drying off. This level of detail in modelling crop yield response to salinity may prove too fine for incorporation in regional economic models, and furthermore threshold and gradient values at different growth stages for the other crops besides maize may not be available.

As maize is the major crop grown in the study area, reference to Beltrão and Ben Asher (1997) is necessary. The CERES-maize model they used is a site specific, single crop, one season model, therefore not suitable for this study, but the results are of importance for the study area, and for guiding further research. Beltrão and Ben Asher (1997) used the CERES-maize simulation model in order to predict corn yields as a function of water salinity under several environmental, agro technical, and plant characteristics. A model is presented in which the wilting point is a function of the soil salt content. At high salinity, the water content at wilting point is higher than at low salinity, resulting in an insufficient amount of available water and, therefore, a reduced yield. Simulation results showed that nitrogen fertilisation increases the salinity threshold value and the yield sensitivity (rate of yield reduction per unit of salinity). Results also showed that if the soil is not leached, a heavier soil texture has a higher salinity threshold value. If the soil is leached, the soil texture has no influence on the salinity threshold value and the yield is less sensitive to salinity in sandy soils.

The proven Maas and Hoffman (1977) approach is therefore recommended together with its assumptions and limitations. The major limitation in preceding work was the conversion of irrigation water salinity (ECiw) to saturated soil paste salinity (ECe) by using a rough "rule of thumb" factor of 2. As the WRPM produces an irrigation block level water and salt balance, this is no longer a limitation and ECe can be derived by multiplying the soil salt concentration (mg/l) in the upper layer (CU) by the soil water content (HE) in the upper layer (mm) and dividing by upper layer soil saturation factor (HSU) – see Figure 5.2.

3.4.3.3 Soil Science Models

SAPWAT (van Heerden *et al.* 2000) is an irrigation scheduling models based on atmospheres-soil-plant water dynamics. This model does not implicitly contain a salinity modelling component, but automatically includes a 10% drainage factor to account for "sufficient" leaching for salinisation control.

According to Oosterbaan (2000), "most of the computer models available for water and solute transport in the soil are based on the Richards differential equation for the movement of water in unsaturated soil in combination with a differential salinity dispersion equation. The models require inputs of soil characteristics like the relation between unsaturated soil moisture content, water tension, hydraulic conductivity and dispersivity. These relations vary to a great extent from place to place and are not easy to measure. The models use short time steps and need at least a daily data base of hydrologic phenomena. Altogether this makes model application to a fairly large project the job of a team of specialists with ample facilities."

Feddes *et al.* (2004) further state that "heterogeneity of soil properties further limits the capability of prediction." Also "practical and reliable transfer from plot to regional scale, without losing the actual physical behaviour of the system, has not been made so far". This has serious implications for the analysis, validity and consequence of the resulting policy measures formulated.

Ultimately, the soil must be leached to sustain crop production. Managing irrigation to maximize crop production under conditions were water use is minimized and salt accumulates in soils requires an understanding of the interactions among climate, soils, water and the plant. Feddes *et al.* (2004) suggest that mechanism-based hydro-chemical models are attractive tools for designing irrigation systems, evaluating water and salt management options, and testing our understanding of the soil-water-plant-atmosphere system. They go on to say that the algorithms for computing water uptake and plant response to water deficit and excessive salinity have been neglected by modellers. Feddes *et al.* (2004) propose that the main objective be to modify the root-sink term in a mechanism-based hydro-chemical model to account for matric stress via a Darcy function and osmotic stress via an exponential Maas-Hoffman response, and in a parallel modelling effort, to add a salt uptake term for predicting the effects of salt accumulation on yield and water use.

3.4.3.4 Groundwater Salinisation Models

Bell and Klinje (2000) developed the Salinity and Landuse Simulation Analysis (SALSA) model, an integrated economic, hydrology and geo-hydrology simulation model to guide decisions about priorities for public investment in salinity control in various river basins in Australia. The integration of bio-physical hydrology and geo-hydrology relationships within an economic framework provided a tool for better understanding and illustration of the tradeoffs involved with salinity management where changes in the surface vegetation has had tremendous repercussions, raising saline water-tables to levels that impact surface crops and vegetation and river salinity. This is however not the situation in South Africa and will not be further pursued.

Oosterbaan (2000) developed SALTMOD for the prediction of general trends in soil moisture, ground water and drainage salinity, the depth to the water-table and the drainage discharge volumes from irrigated lands; using different (geo)hydrological conditions, varying water management options, including the use of groundwater for irrigation, and several crop rotation schedules. Besides being written in dated Fortran coding, the model manual provides a good overview of the salinity plant interactions, clearly demonstrating the mathematics involved.

SALTMOD however, is also more suited to areas with groundwater- and fluctuating water-table- problems, and also too data intensive for easy integration into an economic model.

Ellington *et al.*(2004) conducted a study to determine the impact of irrigation on the aquifer underlying the Vaalharts irrigation scheme heeding to the warnings of Herald and Bailey (1996) who implied Vaalharts was sitting on a salinity time bomb. Discussion with Ellington *et al.*(2004) revealed that integration of a groundwater model into the economic-hydrologic model proposed would not be feasible due to a longer time frame required from groundwater modelling and very specific data needs for the groundwater modelling not available for the selected study area and not budgeted for to acquire. Furthermore, within Vaalharts and the proposed study area, the pumping of groundwater for supplementary irrigation is not practiced and therefore further excluding the applicability of inclusion of a geo-hydrology model component.

The Institute for Groundwater Studies (IGS), the institute where Ellington *et al.*(2004) work, have however developed an Interpretation System for Hydrogeologists (WISH). WISH, which incorporates a Geographical Interpretation System (GIS) can possibly be useful as a visual representation in three-dimensions of water carried salts / pollutants in the soils.

3.4.3.5 Financial / Economic Models

Based on the input/output analysis technique used by Gouws *et al.* (1998), the macro-economic team for the WRC project on which this thesis is based, together with close cooperation from the author, developed an interface between the micro-economic model and the new input/output analysis model. A bio-physical linkage between the micro-economic and the macro-economic model was also added. Together these make up the Index for Socio-Economic Welfare (ISEW), used as a means to compare modelled scenarios on a weighted scale bases for social, environmental and economic outcomes combined. A full description of the input-output technique and multipliers used by the Urban-Econon project team who set up and conducted the macro-economic analysis for the WRC project can be found in Viljoen *et al.* (2006). For a discussion on the calculation of the ISEW see Paragraph **5.6** and the results in Paragraph **8.8.2**.

3.4.4 HYDROLOGY MODEL SELECTION FOR INCORPORATION INTO THE ECONOMIC MODEL

Numerous references have already been given about the importance of the Economic-Hydrology model interactions, difficulties and importance. The following factors are a motivation for the use of the WRPM:

Temporal dimensions – the monthly time-step of the WRPM fits in well with financial modelling. Daily hydrology data would not contribute significantly to the scale and scope of modelling required for the WRC project on which this thesis is based. Rapid fluctuations in the hydrology are acknowledged as having an effect on the impact of salinisation on crop yields and hence economic returns. Clear assumptions therefore need to be made regarding optimal inter monthly management to counter the effect of these fluctuations.

Scale dimensions – the author initially divided the OV and OR WUA into four sub-WUAs each, based on the source of the irrigation water and soil properties. The WRPM however only accommodates 3 sub-WUAs in the OR WUA and lumps the whole OV WUA together as one irrigation block. Where scale discrepancies occurred, the economic model was adjusted spatially, but the same hydrology results assumed.

Data availability – the WRPM is already setup and calibrated for the study area, although only for larger irrigation blocks than initially required for the economic models. Additional sub-WUA hydrology data can be used to refine the economic sub-WUA data. Various crop factors as input into the WRPM are spatially available from the SAPWAT model (van Heerden *et al.*, 2000).

Support team & costs – WRP consultants were able to make someone available to set up and run the WRPM model as they were already mandated by the DWAF to refine the Lower Riet section of the model.

Salt mass balance component – the WRPM does include salt mass balance components, though the channel and node mass balances, salt wash-off modules, and upper and lower soil zone salt mass calculations, all be it quite rough.

Feedback loops – although WRPM can not be fully integrated into the new economic models, WRP consultants could change the initial setup values to reflect various scenarios, and generate any number of stochastic sequences of hydrology results for these setup values to account for a full range of possible events.

A full discussion on the WRPM model as used or the WRC project can be found in Viljoen *et al.* (2006), and the hydrology model linkages can be found in Paragraph **5.5**.

3.4.5 AGRONOMY MODEL SELECTION FOR INCORPORATION INTO THE ECONOMIC MODEL

References to crop growth (agronomy) in the presence of salinity models and their linkage to economic models have already been made. To financially interpret the change in crop yield subject to salinity, the decision to use the Maas & Hoffman equation in this study was made after weighing up the following factors:

Temporal dimensions – the crop specific cropping season time-step of the ECe component of the Maas & Hoffman equation can be calculated by weighted monthly crop water requirement with the monthly ECe data produced in the WRPM. The assumptions are discussed in full in Paragraph **5.4**. Crop enterprise budgets (CEBs) compiled for the economic model are also crop seasonal models and therefore merge well temporally with the Maas & Hoffman equation requirements.

Scale dimensions – Although the Maas & Hoffman equation can apply to a scale of a point in the field due to the spatial heterogeneity of soil salinisation, it will be used in the model at per hectare level and extrapolated to irrigation block level, where the area planted to a specific crop in the whole irrigation block is assumed homogeneous in soil salinity and irrigation water application.

Data availability – The crop factor data required as input into the WRPM is spatially available from the SAPWAT (van Heerden *et al.*, 2000) model, differentiating between the OV-WUA and the OR-WUA. Maximum expected crop yield data is obtainable from the COMBUDS, GWK study group data and can be verified with expert panel opinion.

Support team & costs – As the Maas & Hoffman equation is just a function that is incorporated into the economic model, there is no cost involved and no support team required.

Salt mass balance component – To get the ECe value required for the Maas and Hoffmann equation to relate salinity into economic terms, the salt mass balance results from the WRPM are converted to a saturated TDS values by accounting for full soil saturation capacity. The TDSe however has to be converted to ECe to calculate the impact on yield; Du Preez *et al.* (2000) did this by dividing TDS by a constant of 6.5 as used in.

Feedback loops – as the Maas and Hoffmann equation is a function built into the model and isn't a separate model that has to be linked, what ever permutations are run, they will be subject to the Maas and Hoffmann equation.

A full discussion on setting up of the salinity-yield functions using the Maas and Hoffmann equation can be found in Paragraph **5.4**.

3.5 A REVIEW OF BEST PRACTICES FOR SALINISATION MANAGEMENT

This section is a literature review to contribute towards achieving the fourth WRC project aim, namely to determine and prioritise best management practices. On a scale level, the following per hectare, irrigation block and regional level best management practices (BMP's) are discussed:

- At a per hectare level, the main options of leaching and changing crop choice are reviewed.
- At an irrigation block level, storage structures, dilution and the controlled release option are reviewed.
- At a regional level, holistic management is reviewed.

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.

Kijne *et al.* (1998) in their paper on "*How to manage salinity in irrigated lands: A selective review with particular reference to irrigation in developing countries*", provide a comprehensive review of the causes of irrigation-induced salinity, particularly in developing countries, together with a discussion on several remedial management actions, categorized as engineering, agronomic, policy-level and system-level approaches.

3.5.1 PER HECTARE LEVEL BEST MANAGEMENT PRACTICES

3.5.1.1 Leaching

Leaching is the process of applying water over and above the requirements of the plants irrigated. It is a management practice used to "flush" a certain amount of accumulated salts out of the root zone to maintain an acceptable salt balance. This practice is often considered by non-specialists as wasteful, especially as irrigation engineers and scientists appear to be in doubt about the required leaching rates and the efficiency of the leaching practice (Kijne *et al.*, 1998).

To leach effectively, soils should have a good infiltration rate till beyond the root zone. In heavy soils and where waterlogging occurs artificial drainage is required. The heavier the soils, the more expensive the costs of installing the artificial drainage. Thus the benefits of leaching need to be quantified to be able to justify the capital expenses involved.

Furthermore, leachate flows back into the river or groundwater carrying high concentrations of salts, further degrading the water source and creating secondary costs through externalities for downstream users. The apparent paradox (Armour and Viljoen 2002) however is that without leaching salts (those inherently found in soil or those deposited by irrigating with poor water quality) out of the soil, salts build up, degrading the soil to levels that can no longer support viable crop production. Improper leachate management results in downstream water degradation, rendering it less suitable for other uses (including the environment), can cause water tables to rise, flushes out expensive nitrogen applied to the fields and may carry with it other polluting agricultural chemicals.

The importance of irrigation agriculture has been stressed and that leaching is essential for its long-term sustainability (Kijne *et al.*, 1998). To leach however, effective drainage needs to be in place. In the past, the government subsidized the installation of artificial drainage, however currently only the planning phase is provided as a service to farmers where problems are identified by the few remaining qualified extension officers. Subsidizing drainage should create the incentive to leach more and lead to improved irrigation sustainability.

As water is an increasingly scarce renewable resource with growing competing demands (Basson, *et. al.*, 1997), with resulting increasing water costs, there is a drive for irrigation efficiency to conserve water. As water costs therefore increase, a threshold is reached where it may possibly be better to accept a reduced yield due to salinisation and not leach with relatively expensive water, or convert to crops that are not sensitive to the current levels of salinisation.

3.5.1.2 Change crop choice

This management option involves changing from the current crop mix that is being affected by salinisation to a more salt tolerant crop mix.

In Maas and Hoffmann (1977) crops have been classified according to their relative salt tolerance. Subsequent literature (Maas at al., 1983, Ayers and Westcot, 1985, Maas, 1990, Francois and Maas, 1994) however cites the development and / or discovery of new cultivars / varieties of crops, changing the relative salt tolerance of the specific crop. Ehlers *et al.* (2006) have also recently obtained new indications of the salinity threshold and values of certain crops under South African conditions.

In extreme salt conditions, halophytes (salt tolerant crops) can be planted. There have been a number of studies identifying the salt tolerance physiological properties of halophytes (Benes *et al.* 1999) but limited research has been conducted on the financial feasibility of growing halophytes commercially. *Atriplex Spp.* (salt bush), *Salicornia* and other halophytes, and even *Paspalum spp* (siltgrass) to an extent, have been recognised for their value as a salt resistant grazing crops, as well as their potential of removing salts from the soil to reclaim the soil (Le Houérou, 1992, Oster and Kaffka, 1999). These extremes crops however fall outside of the scope of this research.

3.5.1.3 Other Best Management Practices

The management of various other conditions under which a crop is grown can also influence the salinity tolerance of the crop, namely *inter alia*:

- Cooler weather (resulting in reduced evaporation) results in greater salt tolerance (Rhodes *et al.*, 1992)
- Sprinkler irrigation at night prevents the salts that precipitate on the leaves causing sun scorching (McEachern, 2000)
- Ridging rows and planting half way up results in the salts migrating to the top of the ridge and away from the root zone (Rhodes *et al.*, 1992)
- Higher frequency irrigation prevents the plants from experiencing water stress and thus reduced levels of sensitivity to salts (Rhodes *et al.*, 1992).

Only the management options of installing drainage and changing crop choice are selected for analysis in this study as they have financially significant impacts, requiring capital investment and large changes in cash flow. These other conditions are therefore assumed in this study to be managed at levels that will not affect crop yield.

3.5.2 IRRIGATION BLOCK LEVEL BEST MANAGEMENT PRACTICES

Besides assuming that irrigation blocks are the summation of a number of homogenous farms grouped together, there are a number of combined infrastructure services that serve all the individual farms collectively. Using the benefit-cost analysis technique, Backeberg (1981) calculated net present values over a range of discount rates to determine the most cost effective combination of soil types and levels of salinisation and water-logging, to prioritise investment infrastructure for efficient budget allocation. A similar approach could be applied to the collective infrastructure best management practices for irrigation blocks within the study area, namely:

- **Cut-off drains:** to prevent saline water intrusion into the irrigation block. This can be from either surface or groundwater runoff / seepage from nearby salt pans or higher lying irrigation fields.
- **Drainage collection and control:** using a network of drains that collect the irrigation field drainage water for controlled management and release.
- **Return-flow storage dams / evaporation ponds and controlled releases:** these are options for controlled storage of irrigation returnflows that could fit in with DWAF's new Waste Discharge Charge System (WDCS) where irrigation point-source returnflows may be considered polluted and should no longer be "dumped" back into the river to create a negative externality to downstream water users without paying a charge (DWAF, 2003 and DWAF, 2006).

3.5.3 REGIONAL LEVEL BEST MANAGEMENT PRACTICES

Regional level best management practices are basically policy interventions or public programs aimed at reducing the extent of problem areas. These may include *inter alia* the construction of regional drainage systems as discussed by Amer (1996) in Wichelns (1999) as an expensive exercise requiring a great amount of regional co-ordination, especially in areas with many small farmers. In this section sustainability grants and the role and responsibility of the state based on existing Acts and Bills is discussed.

3.5.3.1 Sustainability grants

Following the recent (July 2006) World Trade Organisation negotiations deadlock over subsidies, import tariffs, quotas, and other direct farmer support to protect local farmers, any form of support to farmers for the installation of irrigation drainage or conversion to perennial/tolerant crops will need to be done as a "Green Box" sustainability grant. In order to qualify for a "Green Box" grant according to Amani, 2004, the subsidy must not distort trade, or at most cause minimal distortion. A sustainability grant does not distort agricultural product pricing by either supporting farmers' input costs or imposing tariffs and quotas on imports that inflate local market prices. A sustainability grant includes environmental protection and protects the natural resource base and enables higher levels of production for generations to come.

Gardner and Young (1988) concluded that the most cost-effective way to reduce saline return-flows was by subsidising irrigation hardware (i.e. drains). They calculated that salt loads could be reduced by about 10% with a fourfold price increase of water at a social cost of $4.49 per ton salt removed, by taxing salt directly ($1.10 /t salt removed) or by subsidising irrigation hardware ($0.40 /t salt removed).

3.5.3.2 Acts and Bills

The following South African national Bills and Acts *inter alia* point to the necessity of government's role and responsibility in managing salinisation:

- The Bill of Rights in the Constitution of South Africa – emphasises the right to have the environment protected, for the benefit of present and future generations, through legislative and other measures that:
  1.1.1 prevent pollution and ecological degradation;
  1.1.2 promote conservation; and
  1.1.3 secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development.
- The National Water Act (39 of 1998) aims that water resources are protected, used, developed, conserved, managed and controlled, to inter alia promote the efficient, sustainable and beneficial use of water,
- The Conservation of Agricultural Resources Act (43 of 1993) provides for the conservation of natural agricultural resources by maintaining the production potential of land, and
- The draft Sustainable Utilization of Agricultural Resources Bill (Draft 11 created 25 May 2004) pertinently refers to standards and control measures for the prevention or control of the water-logging or salinisation of agricultural land.

3.6 MULTI-DIMENSIONAL INTERVENTIONS FOR ENHANCED WATER USE EFFICIENCY

A literature review on the fifth WRC project aim, which relates to a better understanding of the multi-dimensional interactions to enhance water use efficiency as the quantity and quality of water available for agriculture inevitably decreases, is conducted in this section.

Easter and Liu (2005) define efficiency in water use as maximising society's benefits over time from the water and technology available, and in practical terms, as increasing the value of crop output per unit of water consumed through evapotranspiration by the plants. The second part of this definition however doesn't include the distribution losses in getting the water to the plant, irrigation system inefficiencies, and the leaching and remediation actions and inputs that may be required to render soils in a better state for more efficient crop water uptake.

Janmaat (2005) states that enhancing the economic efficiency of water use may unfortunately conflict with some measures of sustainability. Economic efficiency occurs when the marginal cost of a change has increased to the point where it equals the marginal benefit. For economic efficiency, actions which cause soil degradation should be contained only if the costs resulting from this degradation come to exceed the benefits. Janmaat (2005) points out that the economically efficient water use pattern frequently coincides with higher levels of soil degradation. To those accustomed to considering physical measures of sustainability, market-based reforms could appear to be failures, hence the use of the index for socio-economic welfare (ISEW) in this study.

A slogan often used by the South African DWAF is "more crop per drop", urging irrigation efficiency. Irrigation leaching however requires intentional "over-irrigation" to flush salts out of the soils. The challenge is to identify a methodology to efficiently leach while maintaining water use efficiency. The financially optimal level of leaching is the point where the marginal private costs of leaching equal the marginal private benefits thereof. However due to the downstream externalities imposed by leaching the social cost also have to be considered. Furthermore, increased economic benefits and increased job creation brought about through increased leaching and drainage will also have to be considered and weighed up with the social costs. If however all downstream farmers have adequate drainage and also leach, then the social costs may not be that great. While some climate and management aspects are common to semi-arid regions, the detailed mechanisms and options to secure ecological sustainability and economic viability may vary considerably from case to case (Khan *et al.*, 2006).

While "wasting" water through leaching, and water use efficiency may seem an apparent paradox (Armour and Viljoen, 2002), it must be emphasised that striving for leaching is essential for the sustainable maintenance of production and therefore needs to be done in an as efficient manner as possible. Excessive leaching leads to rising water tables and down -gradient and -stream externalities. Although essentially, leaching is a non-consumptive use of the water, it does however render the water less suitable for downstream consumption, and hence also needs to be administered as efficiently as possible. Indications from DWAF are that water allocations are so close to the maximum water delivery of a catchment that on-farm storage options to prevent irrigation returnflows further polluting a river, may result in insufficient water to meet quota obligations. Reporting of financial/economic results therefore need to be expanded by introducing a water use efficiency dimension by dividing the financial/economic results with the volume of water required to achieve the results.

A move away from area based water pricing to volumetric water pricing is essential to manage and control leaching and point and non-point pollution problems (Easter and Liu, 2005, Tsur and Dinar, 1997 and Janmaat, 2005). For optimal water pricing the price should be set to the marginal cost of providing the water, which requires accurate measurement of the water through meters (Easter and Liu, 2005).

Theoretical analysis in Schwabe *et al.* (2006) suggests that economic efficiency requires the acknowledgement of the non-separability between water use and land value. Shadow prices generated from an optimisation modelling approach provide the land value of the water rights associated with the land. As an optimisation approach was not applied in the WRC project, land values were not modelled, but this citation is included to make readers aware of this crucial link.

3.7 POLICY GUIDELINES FOR SOCIAL, ENVIRONMENTAL AND ECONOMIC SUSTAINABILITY

Review in this section of salinity literature on policies to ensure social, environmental and economic sustainability, is necessary for the sixth WRC project aim, namely: to develop policy guidelines to ensure social, environmental and economic sustainability.

The objectives of externality policy application according to Hillel and Feinerman (2000) and Tietenberg (2006) are to reduce the deviation of competitive outcomes from socially optimal ones with policy instruments aimed at providing incentives for individual farmers to align their private self interests with societal socio-economic and environmental goals.

As a very good indication of the situation in South Africa the following two quotes from FAO (2003) serve as an introduction (and warning) for the formulation of proposed policy guidelines:

> *"Applying concepts such as the 'polluter pays' principle, cost recovery and cost sharing may prove unrealistic, impractical or politically disastrous to governments in countries where millions of people are poor and small-scale farmers are trying to make a living on marginal lands. A common concern in developing countries is how agricultural production in marginal areas can fulfil its primary function without depleting the natural resource base. For these reasons, developing appropriate technologies, assigning individual or common property rights, and the promotion of alternative employment outside the agricultural sector will be key strategies." (FAO, 2003)*

> *"The prospects for the future are clear. Agriculture will have to respond to changing patterns of demand for food and combat food insecurity and poverty amongst marginalized communities. In so doing, agriculture will have to compete for scarce water with other users and reduce pressure on the water environment. Agriculture policies and investments will therefore need to become much more strategic. They will have to unlock the potential of agricultural water management practices to raise productivity, spread equitable access to water, and conserve the natural productivity of the water resource base." (FAO, 2003)*

Khan *et al.* (2006) express the need for applicable policy in a slightly different way. They state that there is a need to quantify regional-water quality trends, downstream environmental impacts and the trade-off between yield reduction and direct regional groundwater use (*and build-up*) by crops in these systems. It is possible to can maintain the productive function of any area by providing adequate drainage and salt export facilities, which however have high energy and capital requirements. The most cost-effective option may be to increase water-use efficiency and reduce negative impacts on the environment, thereby reducing the associated costs of maintaining the natural capital budget. There is a need according to Khan *et al.* (2006) to radically rethink sustainability of food production, rational pricing and sharing of water and commodities to justify investment that will maintain and enhance ecosystem function within irrigated catchments. Schwabe *et al.* (2006) further address this on a micro scale and introduce and discuss a system of drainage water charges, marketable permits and land retirement as policy options to address drainage water management for salinity mitigation in a regional optimisation model.

Janmaat (2005) speaks of the many barriers to implementing environmental taxes in irrigated agriculture of which the most substantial of these is the fact that volumetric water pricing is not commonly practiced. This is also particularly relevant in the study area. Volumetric pricing is typically not used because the distribution infrastructure does not support delivery of precise volumes, and where water can be measured, farmers are quick to override/tamper with formal metering systems (Van der Stoep, 2000). The common substitute is area-based pricing, where farmers are levied for water based on the area they plant to each crop as is the practice by the OV and OR WUAs (Ninham Shand, 2004 and CSIR, 2004). This however results in the marginal cost for additional water for leaching to be constant, and little incentive to conserve water as the only additional direct cost to the farmer of over-irrigating are the pumping costs.

The adoption of a Pigouvian tax to correct an irrigation externality is proposed by Janmaat (2005), but this is not practically implementable in the absence of volumetric water pricing. The establishment of clear property rights over water, and markets where such rights can be exchanged is a prerequisite. Once such institutions (i.e. water markets) are in place, then taxes and subsidies become feasible instruments in the effort to control soil degradation.

With competition for water expected to continue increasing as stated in FAO (2003) above, Dudley (1992), Janmaat (2005) and Niewoudt and Armitage (2004) states that it may be more appropriate to emphasize the establishment and enforcement of tradable property rights for water (i.e. water markets) - held by institutions (WUA or even Sub-WUA level) or individuals (farmers) - than to make huge investments in dealing with salinity and waterlogging externalities (i.e. through the Waste Discharge Charge System). Until tradable property rights in water (i.e. water markets) are widely accepted, along with the right of the authority to assess levies, environmental taxes are unlikely to be of much use (Janmaat, 2005).

Under the current Waste Discharge Charge System (WDCS), irrigation water dischargers do not currently require registrations and, therefore, cannot be charged under the WDCS for irrigation returnflows (DWAF, 2006), whether point or diffuse source. For the categories that are charged for point source discharges, financial support in the form of seed funding from the Incentive Charge revenue is available, where reducing waste load at source is economically efficient but institutional or financial (sunk capital) barriers prevent expenditure. Seed funding is granted based on an application that clearly details the measures to be taken, costs involved and anticipated reductions in discharge load (DWAF, 2006). If/when the WDCS does become applicable to point sources on farms, farmers could possibly apply for this funding to build drainage canals or on-farm returnflow storage dams to capture saline returnflows, only to release back into the river during sufficiently high flow events. Alternatively an efficient level of irrigation returnflows needs to be determined and just so many tradable discharge rights be issued. (Legras and Lefran, 2006)

In conclusion, to view the policy objective holistically, Easter and Liu (2005) advise that successful cost recovery for an efficient irrigation system will have the appropriate mix of technology, management, policy, and institutional arrangements that facilitate transparent and efficient service delivery and increase farmer's willingness to pay and to use limited water resources more efficiently. Added to this, water trade and discharge markets also need to be in place for efficient water use management and policy implementation (Janmaat, 2005 and Bell 2002).

To aid in the development of policy guidelines for social, environmental and economic sustainability an Index for Socio-Economic Welfare (ISEW) is proposed to be used as a means to compare modelled scenarios on a weighted scale bases for societal, environmental and economic outcomes combined, to identify the best policy simulations / scenarios.

3.8 THE APPLICATION OF A METHOD TO ADDRESS THE PROBLEM IN THE COMPLEX ORANGE-VAAL-RIET CONVERGENCE SYSTEM STUDY AREA

Reviewed in this section is literature to address the final aim of this research, namely, to achieve the project aims based on using the complex Orange-Vaal-Riet (OVR) convergence system as a study area, but developing the method followed and models so that they can be applied elsewhere with relative ease. This section therefore starts off by identifying the factors that cause salinisation in the study area. A discussion on the method proposed to address salinisation in the study area follows, as well as a roundup of data needs for applying the method in the study area and potential sources for this data. The section concludes with a paragraph on the application of the method followed to other areas.

3.8.1 IDENTIFICATION OF THE FACTORS CAUSING SALINISATION

3.8.1.1 River Water Quality

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 practices such as drainage and gypsum application will *inter alia* impact on guidelines for irrigation water quality (Moolman & Quibell, 1995:11). In Volschenk *et al.* (2005) soil salinisation along the Lower Orange River is analysed, and its concluded that the river water is not the factor causing salinisation, but the mobilisation of the salts already in the soil.

3.8.1.2 Point and Diffuse Sources

Upstream irrigation agriculture contributes to point- and diffuse- source river salinisation (Moolman and Quibell 1995). Irrigation with good quality water can dissolve salts already in the soil and mobilise them to contribute to river salinisation. Irrigating with poor quality water further concentrates the salts when they return to the river, however, this does not necessarily change the mass of salts returned to the river. The contribution of fertilisation to salinity is negligibly small and can therefore be ignored (Du Preez *et al.*, 2000).

3.8.1.3 Surface Runoff

Salt wash-off modules (see Figure 2.8) in the WRPM (Van Rooyen *et al.*, 2004) account for the surface runoff in the hydrology model and included a salinisation component that measures the combined upstream salt load to a particular node (see Figure 5.2, SNAT – Natural Salt Recharge, and SLOAD – Applied Salt Load). Looking at Figure 3.2, a satellite aerial view of the study area (Google earth, 2006) one can clearly see the salt pans in the area, showing up as vast bright white expanses. There are also old names given to places such as "*Soutpansdrift*", translated into english meaning Salt Pan Crossing, "*Brakpan*" etc. indicating that surface salinity naturally occurs in the area and has been around for a long time, where rainfall runoff accumulates and evaporates leaving behind the concentrated salts.

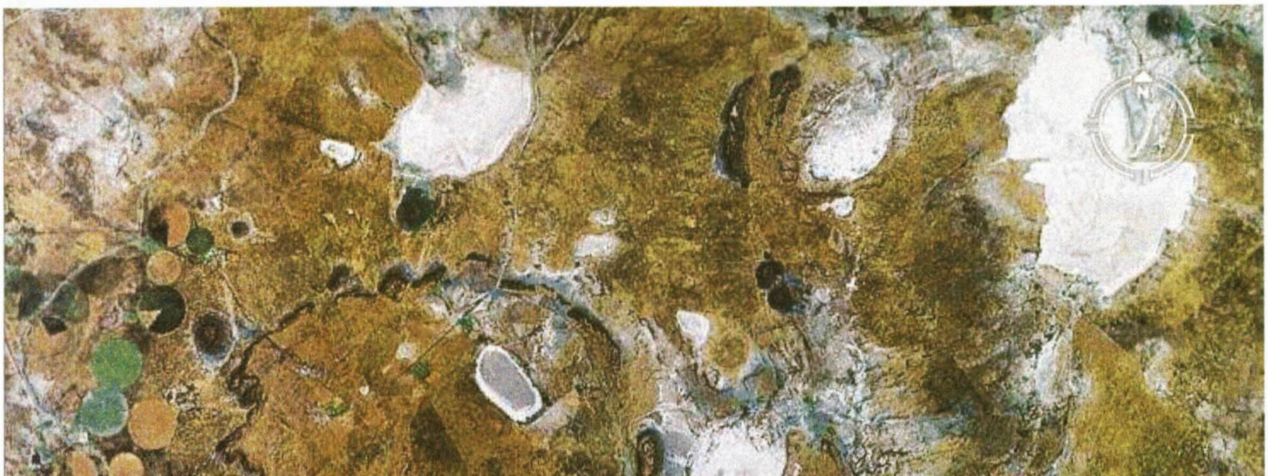


Figure 3.2. A Google Earth (2006) Image of some salt pans (e.g. Gannapan and other lighter areas) situated near irrigated lands that lie along the Orange Riet Canal (copied 11 September 2006, Picture centre co-ordinates Lat. 29° 37' 23.39" Long. 24° 41' 21.62", Alt. 22.22m)

3.8.1.4 Soil Mineralization

A high salt concentration in a soil body creates a physiological drought for the crops planted therein. Sodification can also take place, which results in a breakdown in soil structure; it makes the soil impermeable and impenetrable for germinating seeds. The sodium adsorption ratio (SAR) is a measure of sodification and is determined by the division of the sodium concentration by the square root of the half the sum of the calcium and magnesium concentrations in a specified water body (DWAF 1993:37-40).

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

Where: SAR is the Sodium adsorption ratio

Na, Ca and Mg are the sodium, calcium and magnesium concentrations in a saturated soil extract

Before sodic soils can be effectively leached to wash out salts, soil remediation may first have to take place using gypsum or lime so that water can freely flow through the soil profile (USDA, 1969).

3.8.1.5 Irrigation System

Flood irrigation systems have the best ability to flush salts out of the soil to facilitate effective leaching if sufficient drainage is present and the soils aren't too heavy (Du Preez *et al.*, 2000). Very heavy soils can also be effectively leached by applying low frequency irrigation and allowing cracking and salt migration to the surface as the soils dry out, and then flooding to wash the salts deep into the cracks again (Armour & Viljoen, 2002). The type of crop grown however has too suite low frequency irrigation. Flood systems are however the least efficient irrigation systems (60-70% efficient) according to Van Heerden *et al.* (2001), but large improvements are achieved with laser levelling.

Dripper type irrigation systems are the most efficient (80+%), but do not have the ability to apply a large volume of water to successfully leach salts. High frequency irrigation (constantly keeping the soil profile wet) with drippers keeps the saline barrier at the edge of the wetted area and away from the root zone. If however there is an irrigation system breakdown or water shortage and the soils dry out these salts may migrate into the root zone causing plant damage (Du Preez *et al.,* 2000).

Centre pivot type sprinkler irrigation systems are the most popular for extensive irrigation in the study area (see Table 2.5 and Table 2.6) as deducted from data by van Heerden *et al.* (2001). 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.

If using a sprinkler type irrigation system, a high enough TDS concentration of the irrigation water can cause foliar damage from contact, especially together with sunlight. Irrigating at night can reduce this leaf scorch (McEachern, 2000).

3.8.1.6 Insufficient drainage and salt accumulation

A result of insufficient drainage is salt accumulation. According to Hillel and Feinerman (2000), adequate drainage – natural or artificial – is imperative to maintain the irrigated land in equilibrium with the surrounding environment over time. Tying up with the point on irrigation system above, even if the soil is well drained but additional water is not applied to leach out salts due to irrigation system inability, then salts will also accumulate.

3.8.2 THE METHOD PROPOSED TO ADDRESS SALINISATION IN THE STUDY AREA

Based on the literature reviewed in this chapter, an integrated framework methodology is proposed to address the dynamic problem of salinisation in the study area, and this is discussed in detail in Chapter 4. Concluded from the literature study, this section aims to briefly delineate the spatial and temporal dimensions of the model, as well as to introduce the hydrology, bio-physical and macro-economic linkages of the micro economic model of irrigated production under salinisation conditions.

At a spatial level the integrated model is made up of per hectare level cropping units, combined to sub-WUA level units. One or more Sub-WUAs combine to make up an irrigation block, consistent with the irrigation blocks delineated in the WRPM. Groupings of one or more irrigation blocks forms a WUA, and the two WUAs together form the study area for the micro-economic model, which is the core model of this thesis. As an extension of the micro economic model, the macro-economic model includes the municipal managerial (i.e. political) boundaries that the study area (the two WUAs) overlaps with.

The sequence of modelling proceeds as follows; an irrigation block level stochastic data generating hydrology model, WRPM, provides hydrology input into a per hectare level biophysical (SAPWAT, Maas & Hoffman equation) model that results in a per hectare economic interpretation (in SMsim). The per hectare level model is extrapolated to a sub-WUA level micro economic model (in SMsim), which combined together form the micro economic irrigation agriculture sector model (in SMsim). These results are inputted into a regional level macro-economic model (ISIM) through input–output analysis multiplier tables.

Temporally the model is based on monthly biophysical data generated over a period of 15 years. This data is converted into crop specific yield data and converted into annual (2005 basis year) micro economic data. The annual micro economic data is converted to annual macro economic data which is added cumulatively to produce the 15 year cumulative total values to compare scenarios.

The Hydrology model selected is the WRPM as it runs at a catchment level and is already set up and calibrated for an area that covers the study area (as opposed to ACRU and DISA). A minor modification to the WRPM model output data is that the soil salinity concentration data needs to be converted to saturated salinity data, and this can be done using the WRPM soil moisture content data provided.

As biophysical models linking soil salinity to the economic model through yield, SAPWAT and the Maas & Hoffman (1977) equation are selected. SAPWAT is used to determine the monthly crop water requirements to convert monthly saturated soil salinity data from WRPM into crop specific weighted average soil salinities to be applied to the Maas & Hoffman (1977) equation to determine the impact on yield.

The micro-economic model was initially proposed as a dynamic linear programming optimisation model. However, due to the large number of decision variables and exponentially increasing possible spatial solutions, a stochastic simulation approach was decided on.

3.8.3 DATA REQUIREMENTS AND POTENTIAL SOURCES OF DATA

Followed by a brief introduction as to the importance and types of data required, this section lists the hydrology-, agronomy- and soil science- bio-physical data requirements, the financial data requirements and model set-up and calibration data requirements.

Kijne *et al.* (1998) state that to address the economic and policy impacts of land degradation, reliable data and information on the rate of degradation and on the associated costs of prevention and reclamation are required. They further state that the models to predict the economic impacts of salinity control measures need information on the expected impacts of water scarcity and salinity on crop yields, but that all the information required is not available at present. This is to even a greater extent the case in South Africa. To address this however, current research on deficit irrigation under the influence of salinity is being conducted in Israel by Shani (2006), but results are not yet forthcoming.

From a scientific standpoint, according to Stirzaker *et al.* (2004), more information is better, because each technique gives a different slant on the problem under study. For the farmer however, relatively simple information can improve management decisions. The case study by Stirzaker *et al.* (2004) showed that a greater volume of information or greater attention to accuracy increases the cost and complexity of monitoring without necessarily significantly impacting the final management decisions. Keeping this in mind, the specific needs and requests of farmers, extension officers and WUA staff were obtained.

3.8.3.1 Bio-physical data - hydrology

For the study area specific crop-water-requirement data, required as input into the hydrology model, WRPM, crop factors obtained from SAPWAT (van Heerden, 2001) can be used. Benade *et al.* (2002) have Water Accounting System (WAS) data for the Orange-Riet WUA.

3.8.3.2 Bio-physical data – agronomic / soil science

As a measure of the specific monthly crop water requirements in the OVR convergence system, crop factors obtained from SAPWAT (van Heerden, 2001) can be used.

Not heeding to Johnson (1994) who warned that that there is a need to monitor trends in soil salinity levels on irrigation schemes, no data could be found on soil salinity. Fertiliser company soil analysis data will have to be used to derive the soil salt dynamics over time. A starting point soil salinity level is required for different soil types. If data cannot be found comparable / relative starting point values will have to be created using export opinion and deductive reasoning.

Maximum expected (/ planned for) crop yields will also have to be decided on at technical and expert panel meetings.

3.8.3.3 Financial data

As the farm level financial situation from one farmer to the next varies considerably, it is very difficult to include the financial position of a farmer from the criteria for selection of a representative / typical farm. It is therefore decided to model at a Total Gross Margin Above Specified Cost (TGMASC) level. It will therefore not be necessary to conduct representative / typical farm level financial surveys.

Financial data that has direct implication on the management options tested will be included in the model. The costs of drainage installation for the effective level of leaching required for different soil conditions will have to be calculated, possibly using the benefit cost analysis method in Backeberg (1981). The establishment costs of changes in cropping patterns from the status quo to either more salt tolerant or higher value more salt sensitive crops will also need to be calculated. This can be done using GWK crop enterprise budget data and the National Department of Agriculture's (NDA) Computerised Budgeting System (COMBUDS).

3.8.3.4 Model setup and calibration data

Surveys and expert opinion will have to be used to obtain the additional model setup data required, and to test the model parameters for calibration and verification.

3.8.3.5 Existing data sources for the Orange-Vaal-Riet convergence

GWK Pty. Ltd., the main input supplier, extension and marketing agribusiness in the study area has comprehensive crop enterprise budget data. The data makes distinction between the sub-WUAs (irrigation blocks) depending on the average distance of the sub-WUAs from the trade depots, silos and other agricultural services (e.g. aerial crop spraying).

The Orange-Vaal and Orange-Riet WUA's are both pilot WUA's used in a study to formulate guidelines for the compilation of integrated Water Management Plans (WMP) as required under the National Water Act (Article 22(1) of the National Water Act of 1998 (Act 36 of 1998)). Copies of these documents (Ninham Shand, 2004 and CSIR, 2004) provide valuable institutional and operation information. The WUA's also have member databases that contain the farmers' water entitlements, cropping areas requested to plant and cropped area verifications for the last 5 years.

3.8.4 APPLICATION OF THE METHOD FOLLOWED TO OTHER AREAS

Using the WRPM as a hydrology basis, the method proposed in this study can be replicated to anywhere in the Orange and Vaal River Catchments as the WRPM is set up for these main catchments of South Africa. As in the case with this study, certain refinements had to be made to the Orange-Riet WUA area setup and further refinements are proposed for the Orange-Vaal WUA area setup. These refinements can currently only be conducted by WRP Consultants who operate the databases and model for DWAF. Any hydrology (ACRUsalinity, SWB, DISA, etc) or soil water model from which a spatially connected monthly saturated soil salinity extract (ECe) value can be obtained could also be used.

The nationally setup crop factors required as irrigation block inputs for the WRPM can be accessed via the SAPWAT (Van Heerden 2002) software package. Irrigation block level crop enterprise budget (CEB) and crop price data, the main inputs into the micro-economic model, have to be updated, depending on the base year and study area selected. This information is readily available through the National Department of Agriculture's COMBUD database, and can be further refined using farmer study group data or CEBs from the local agribusinesses, banks and / or agricultural consultants.

Regarding the macro economic model, only the input-output tables and multipliers will have to be updated to the specific region where the model is being adapted for. This data is generally available, but for correct incorporation and interpretation macro economists would have to be consulted.

The addition of a user-friendly interface that would facilitate the model setup and data input by an experienced programmer would facilitate the ease of adaptation of the basic model framework to other areas; however this is outside of the scope of the work for this study.

3.9 SYNTHESIS / SUMMARY

In this chapter a broad literature study is undertaken, including an interdisciplinary evaluation of the multi-dimensional components required for effective integrated salinisation modelling. A better understanding of the interdisciplinary nature of the problem is achieved and the following models / methodologies have been identified:

- WRPM to simulate stochastic hydrology sequences and importantly, linked soil salinity values,
- The Maas and Hoffmann equation to translate saturated soil salinity values into reduced crop yield,
- CEB simulation analysis to interpret the reduced yield in per hectare-, sub-WUA-, WUA- and Regional-TGMASC terms,
- A link to macro-economic models for input / output analysis, to interpret the socio-economic changes in agriculture at regional level, and
- A link to an index for socio-economic welfare and environmental sustainability reporting of the various scenarios.

A synthesis of the chapter follows, restating the main problems identified in the literature study, the best management plans to address these problems and a method to integrate, model and evaluate the BMPs against each other. This leads to some guidelines for policy options to implement the selected BMPs to achieve the study objectives.

Problem: The problem is clearly identified as salinisation, possibly requiring drainage. However the installation of artificial drainage creates a point pollution source, exacerbating the problem downstream. Furthermore, drainage installation has tremendous cost implications, necessitating a benefit costs analysis. Other alternative salinity management strategies also need to be investigated.

BMP's: The best alternative salinity management practices identified are to switch to more salt tolerant crops, or to offset the high costs of artificial leaching by planting higher value crops in the better drained and easier to manage newly drained soils.

Method: A new integrated method to address salinisation in the study area has been formulated from a review of existing methods. This entails using the WRPM to generate stochastic hydrology and soil salinity data which is related to reduced crop yields through the use of the Maas and Hoffman equation. Reduced yields and hence economic effects are expanded to regional level to measure the secondary impacts of salinisation. From this an index for socio economic welfare can be compiled, to be able to evaluate scenarios from an economic, social and environmental perspective.

Data: The availability of data is a big deciding force as to which models to use. For the models selected most of the data required is secondary data, and the data sources should be able to supply the required data.

Policy: Janmaat (2005) warns to establish water markets before taxing environmental externalities, as only in the presence of properly functioning water markets can the incentives/disincentives created by taxing environmental externalities (i.e. irrigation drainage) produce the desired effect. Kijne *et al.* (1998) however state that because of the need for sustained and enhanced food production, the prevention, mitigation, and reversal of further degradation of soil and water resources in irrigated agriculture should be a first priority.

CHAPTER 4 THE INTEGRATED MODEL FRAMEWORK

It is my belief that the holistic point of view will prove important in the bearings on some of the main problems of science and philosophy, ethics, art and allied subjects.

Smuts (1926)

Research in a team context is still one of the best ways to ensure that you include a multiplicity of views, thereby enhancing the validity and relevance of your research attempts

Botes (2004)

4.1 INTRODUCTION

This chapter serves as a brief overview of how the various components that make up this study are integrated and flow from their individual disciplines towards an integrated whole. Subsequent chapters will outline the detail of each of these sub-components. As part of this introduction, the aims of the integrated model are listed.

A paragraph introducing the main components of the integrated model is followed by a separate paragraph on each of the main components individually, namely:

- The scenario setup process
- The input data and data processing
- The sub-disciplinary models
    - *Hydrology model (WRPM)*
    - *Bio-physical sub-components*
    - *Micro economic model*
    - *Regional economic model*
- The output data and results files

Under each individual model component paragraph, the setup data, spatial and temporal dimensions and linkages of the model components are discussed, with relevant reference made to other chapters in this document where the specific component is discussed in more detail.

Appendix 1 lists the step by step process and hyperlinks to each model file used in the construction of the complete integrated model.

The chapter concludes with a discussion of the main linkage limitations and assumptions, followed by a summary of the data sources and a chapter summary.

4.1.1 AIMS OF THE INTEGRATED MODEL

The aim of the SMsim (micro-economic salinity simulation model) suite of models is to integrate holistically the bio-physical components/processes (including the hydrology) involved in irrigation salinisation, into a long-term (dynamic) economic model. The objective of which is to improve the financial sustainability of irrigation agriculture while also ensuring social and environmental sustainability. A further objective is to achieve this aim using existing hydrology and bio-physical models as far as possible and to build on the salinity economics work already done in SALMOD by Armour and Viljoen (2002).

4.2 MAIN COMPONENTS OF THE INTEGRATED MODEL

SMsim consists of the following loosely coupled interlinking components without a continuous feedback loop:

- The scenario setup process
- The input data and data processing
- The sub-disciplinary models
  - *Hydrology model (WRPM)*
  - *Bio-physical sub-components*
  - *Micro economic model*
  - *Regional economic model*
- The output data and results files

Figure 4.1 is a schematic diagram of the components of SMsim and its linkages with the hydrology model and the regional economic model. The Hydrology data files generated in the WRPM as text files, are grouped together and rearranged within a model coded in GAMS (general algebraic modelling system) and the relevant data stored in spreadsheet format in MS Excel files, to feed the hydrology data into the micro-economic model section of SMsim. Crop enterprise budget (CEB) data and sub-WUA description data are also fed into SMsim to provide the financial drivers and resource composition differences between WUAs.

Certain per hectare and irrigation block level model outputs are calculated within SMsim, but the data required to link with the regional economic model is saved in a separate micro-economic output file, from where it is fed into the macro-economic model. Data output for both the SMsim and regional economic models provide valuable feedback information for setting up subsequent hydrology scenarios.

Once the integrated model is setup in its entirety in MSExcel, for each block in **Figure 4.1** any changes that are made will reflect all the way through the forward linkages in the model. To generate results from stochastic hydrology model output, there are macros that have to be run within the micro-economic model, which is set up only for one stochastic run at a time, to automatically run for all stochastic data input.

4.3 SCENARIO SETUP PROCESS

The scenarios setup process consists of the following (For a complete discussion see Chapter 7):

- the identification and compilation of the setup data
- the establishment of the spatial and temporal dimensions
- the establishment of the model linkages

4.3.1 SETUP DATA

The following setup data is needed:

- Crop coefficient data generated using the SAPWAT model by Van Heerden *et al.* (2001).
- The base-case year is set at 2005 levels and the cropping composition of the 20 (max) crops modelled is compiled from the sub-WUAs description data files.

- The cropping composition for the scenarios are then generated and set up for scenarios 1, 2, 3 and 3+. A salt tolerant crop mix is generated for scenario 1 and a salt sensitive (yet higher value) crop mix is generated for scenarios 2, 3 and 3+.
- The data changes required to simulate more crop drainage in the WRPM are required for scenario 3 and 3+, and for scenario 3+ the additional costs of the increased drainage are also factored into the crop costs, through increased water costs.

Other data from the sub-WUAs description data files used in the scenario setup are; the irrigated areas of each irrigation block, and the distribution losses.

4.3.2 SPATIAL AND TEMPORAL DIMENSIONS

The spatial unit at which the scenarios modelled are the irrigation blocks as set up in the WRPM and explained in Chapter 2. The cropping compositions and water use factors are set up at annual levels with a hydrologic year starting in May and ending in April the following year.

4.3.3 LINKAGES

To drive the scenarios required for economic modelling, the main input data linkages for scenario setup are the sub-WUAs description data files, providing cropping composition and area input data, and the SAPWAT model that provides the cropping factors for the maximum of 20 crops that can be modelled in the WRPM. The scenario setup data provide the variables for scenario analysis in the WRPM.

SMsim design (unless otherwise stated, links to all files in c:/SALMOD/SMsim/...)

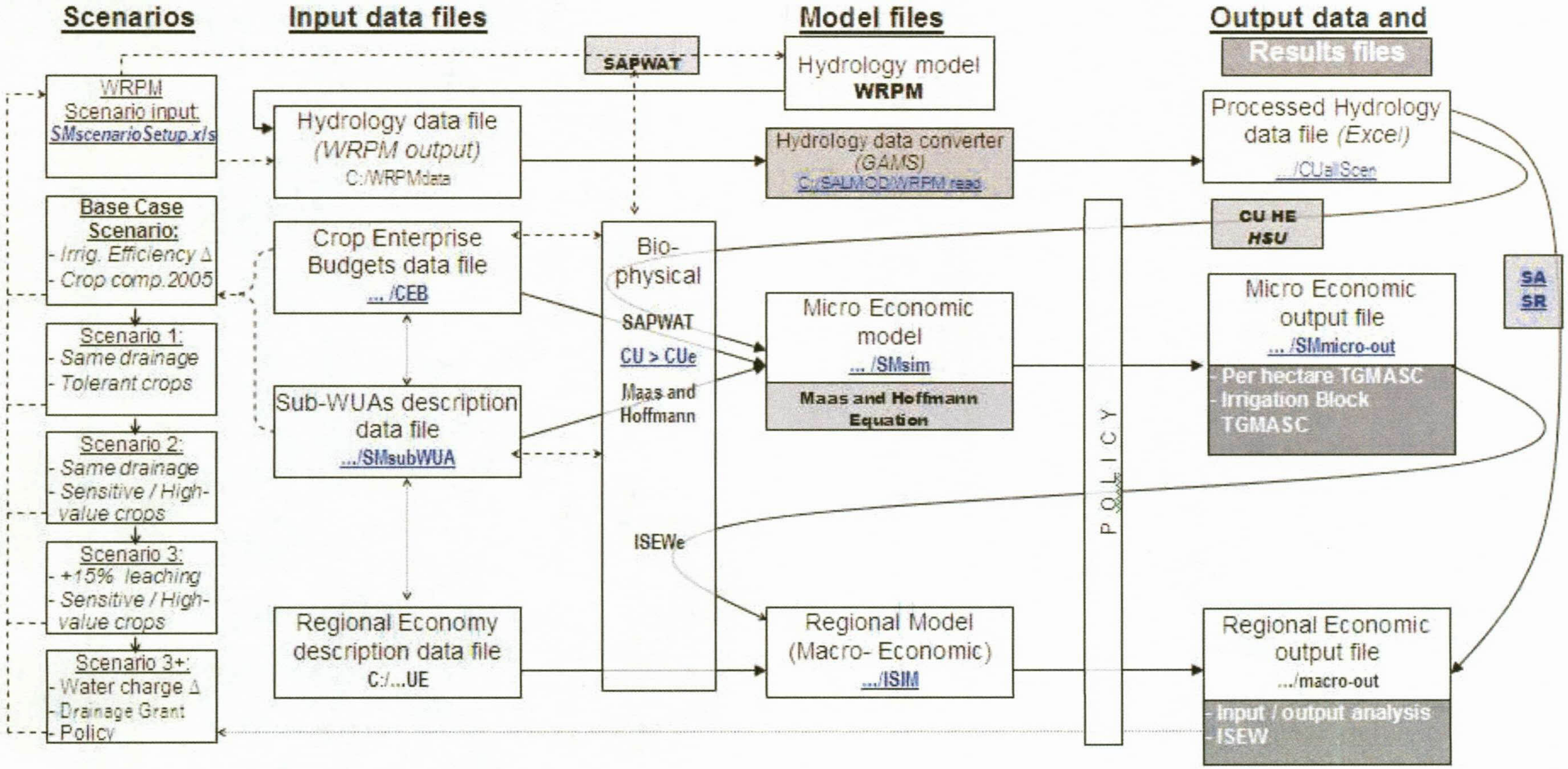


Figure 4.1. The integrated conceptual framework

4.4 INPUT DATA PROCESSING

The four sets of input data files that are generated / compiled are:

- Hydrology data files,
- Crop enterprise budget (CEB) data files,
- Sub-WUA description data file and the, and
- Macro economic description data files

4.4.1 SETUP DATA

The hydrology data files are the raw output from the WRPM, that have to be processed through a small sub-routine in GAMS to get them into MSExcel format. This is done to present the hydrology data effectively, and to prepare the data as input for the micro-economic model.

The CEB data files are compiled predominantly from GWK 2005 study group CEB results, and Sub-WUA data was obtained predominantly from the WUA management plans and adjusted for 2005 conditions using expert panel opinion.

The main source of data used in setting up the regional economic data files are secondary data from previous studies and national data required for setting up the input / output tables.

A summary of the data sources of each of the integrated model sub-components is presented in Table 6.1.

4.4.2 SPATIAL AND TEMPORAL DIMENSIONS

The hydrology and CEB data are all monthly data, while sub-WUA setup data is specifically for the year 2005, and the regional-economic data based on 2002 data and converted to 2005 data using appropriate indices. The hydrology and CEB data is irrigation block specific as defined in the sub-WUA setup data files. The macro-economic data is national and provincial level data, adjusted to the regional level.

4.4.3 LINKAGES

The setup and processing for the hydrology data is discussed in Paragraph 4.5.1, Hydrology model, the CEB and sub-WUA setup data in Chapter 6 and the regional economic model in Paragraph 8.8, Linkages to the regional economic model.

4.5 MODEL FILES

4.5.1 HYDROLOGY MODEL

The hydrology model is discussed briefly in Paragraph 4.5.1 of this thesis, but for a complete discussion see Chapter 4 of Viljoen *et al.* (2006).

4.5.1.1 Setup data

The hydrology model and data files are operated and generated, by WRP consultants Pty. Ltd.. The author compiled the setup data required for the scenarios to be run through the WRPM by WRP consultants. WRP consultants ran the model and generated the raw output data for the author to process, display and use as input in the micro and macro economic model.

4.5.1.2 Spatial and temporal dimensions

The hydrology model is specified for 4 irrigation blocks within the study area, namely:

- the Orange Vaal irrigation block (***Rscm***) comprising of the Orange-Riet irrigation farmers, the Riet River irrigation scheme and Ritchie in the OR-WUA.
- The Scholtzburg irrigation block (***Rszg***) in the OR-WUA.
- The Lower-Riet irrigation block (***RloR***), positioned downstream of both the ***Rscm*** and ***Rszg*** in the OR-WUA, and
- The whole of the Orange-Vaal WUA (***Vall***) all modelled together as one irrigation block.

The temporal scale of the hydrology model is monthly.

4.5.1.3 Linkages

The hydrology model receives its setup data from the scenario setup files, and its crop coefficients from a biophysical sub-component of the hydrology sub-component. Output from the hydrology model is raw hydrology data, outputted as a large set of separate text (._.txt) files. Using a small subroutine in GAMS recorded by the author, these individual text files get rearranged and further processed for easier use in MSExcel.

4.5.2 BIO-PHYSICAL SUB-COMPONENTS

The bio-physical section of the model is not a model on its own, but a collection of sub-components that facilitate the linkage from bio-physical to economic. For a full discussion on the biophysical sub-components see Chapter 5.

4.5.2.1 Setup data

The following setup data was used:

- crop functions
- salinity conversions
- salt index

The SAPWAT model generates the crop coefficients for use in the hydrology model. For the conversion from CU to CUe, HE generated in the WRPM and HSU, a constant used in setting up the WRPM, are required. Similarly, the abstraction (SA) and returns (SR) to and from the irrigation block in tonnes provide the salt mass balance used as the environmental component of the index for socio-economic welfare (ISEW).

4.5.2.2 Spatial and temporal dimensions

The crop coefficients and CUe values are both monthly data calculated for all irrigation blocks separately. The salt balance in the macro-economic model is calculated annually for each irrigation block, but summed up to the regional level for calculation of the ISEW.

4.5.2.3 Linkages

The biophysical sub-components, SAPWAT crop coefficients, CU-CUe and SA-SR, are critical biophysical–hydrology, hydrology–micro-economic and hydrology–macro-economic linkages respectively at different positions within the integrated model.

4.5.3 MICRO ECONOMIC MODEL

The micro-economic model, as the core model of the integrated model framework, is discussed in Chapter 6.

4.5.3.1 Setup data

The processed hydrology data, further refined in the biophysical sub-component (CY-CUe) together with CEB data and sub-WUA setup data, are fed into the micro-economic model to determine (using the Maas and Hoffmann (1977) equation), yield and subsequent per hectare CEB changes subject to saturated soil salinity.

4.5.3.2 Spatial and temporal dimensions

The per hectare CEB results are extrapolated to irrigation block level total gross margin above specified costs (TGMASC) to give the average annual irrigation block level impact of irrigation salinity for the scenarios modelled. The 15-year cumulative TGMASC is also calculated. This is *inter alia* to work out the costs and benefits of increasing returnflows through installation of artificial drainage and increased leaching for a long-term (15) year loan.

4.5.3.3 Linkages

Results generated in the micro-economic model are fed into the regional economic model as annual and cumulative crop TGMASCs for 100 stochastic runs for each of the scenarios.

4.5.4 REGIONAL ECONOMIC MODEL (MACRO-ECONOMIC LEVEL)

4.5.4.1 Setup data

The setup data used are:

- The individual CEB components that make up the CEB (e.g. total seed, fertilized, herbicide, etc. bought per year) for stochastic runs 001, 044 and 080, representing the 0.05, 0.95 and 0.50 percentiles,
- Individual CEB components averaged over the 100 stochastic runs
- Annual and cumulative crop TGMASCs for all 100 stochastic runs
- Relevant setup data from the micro-economic model setup data file is also inputted into the regional economic model.

The setup of the regional economic model (ISIM) is described in full in Chapter 7 of Viljoen *et al.* (2006) and the results interpreted and discussed in Chapter 10 of Viljoen *et al.* (2006).

4.5.4.2 Spatial and temporal dimensions

At the regional level all the irrigation-blocks are combined, together with secondary economic impacts to model regional impacts at the complete study-area level described in Chapter 2. The regional model described in Viljoen *et al.* (2006) models at an annual time scale, with the Index for Social Economic Welfare (ISEW) also in Viljoen *et al.* (2006) modelling the change from one year to the next with 2005 as the base year.

4.5.4.3 Linkages

The data inputted into the regional economic model are run through an input/output matrix to calculate the economic multipliers of the forward and backward economic linkages within the study area. The resulting annual change in gross geographgic product (GGP) and employment are expressed as the economic sustainability and social sustainability components of the ISEW respectively. The salt mass balance of each irrigation block summed together forms the environmental component of the ISEW.

4.6 OUTPUT DATA AND RESULTS FILES

The processed output data from the various levels of modelling are the results of this thesis, and are used to formulate policy decisions as discussed in Chapter 9.

4.6.1.1 Setup data

The output data files are populated with data from the preceding model files. Careful consideration has to be taken of the format in which the data is presented for results discussion and of the format in which the data is required for the following model.

4.6.1.2 Spatial and temporal dimensions

The processed hydrology data displays the spread of 100 stochastic runs, as an annual trend and as the monthly-expected distribution spread over 25 years. Although the economic model only examines a 15-year period, a 25-year period is used in the hydrology model to identify long-term hydrology trends; this facilitates the correct interpretation of the economic data.

Per hectare total gross margin above specified costs (TGMASC) and irrigation block level TGMASC for all crops analysed, are setup for annual and 15-year cumulative analysis and display of the micro-economic model. The regional economic output data is displayed as annual changes in regional GGP, employment and production in the different sectors of the regional economy resulting from the different scenarios modelled.

The ISEW, calculated in the regional economic model, is displayed as annual changes in production, employment and environmental indicators for the actual stochastic runs that best represent the 0.05, 0.50 and 0.95 percentiles of the cumulative TGMASC in the micro-economic model.

4.6.1.3 Linkages

Monthly soil salinity concentration (**CU**) and effective soil moisture (**HE**) in the upper zone data for each scenario and each irrigation block over 15 years is set up and transferred as input for the micro economic model. Annual average salt abstraction (**SA**) and return flow (**SR**) mass in tonnes for each scenario and each irrigation block over 15 years is set up and transferred as input for the regional economic model.

For input into the regional economic model, the full CEB composition (break-down) over 15 years, for each irrigation block, for each of the 3 stochastic runs selected to represent the 0.05, 0.50 and 0.95 percentiles of all 100 stochastic runs, for each scenario, are set up in, and transferred from the micro-economic model to the regional-economic model. The regional economic results generated in Viljoen *et al.* (2006) are interpreted and used to motivate the best policy options in Chapter 9.

4.7 SUMMARY

This chapter serves only as an introduction to the integration of various model components, which are discussed in more detail in the chapters to follow, and in the case of the hydrology and macro-economic models, these are discussed in Viljoen *et al.* (2006). The hydrology and biophysical models are discssed in Chapter 5, the micro economic model in Chapter 6, the scenarios modelled in Chapter 7, and the model results in Chapter 8.

CHAPTER 5 INTEGRATED BIOPHYSICAL SUB-MODELS AND THEIR RESULTS AND LINKAGES

We are members of a vast cosmic orchestra in which each living instrument is essential to the complementary and harmonious playing of the whole

J Allen Boone (b.1882, d.1965)

It is impossible to step twice into the same river. You step into a river; your step out; your step in again; but you do not step into the same river, for the water has flowed on and it is a different river. Everything is in a constantly changing state of flux.

Heraclitus, 560BC

5.1 INTRODUCTION

The aim of this chapter is to describe the various components and linkages that make up the biophysical sections of the integrated model, to present the model formulation and to present selected bio-physical model results.

The following sections are each discussed as main paragraphs of this chapter:

- The use of SAPWAT crop coefficients for hydrology model setup
- The derivation of the saturated soil salinity, ECe (mS/m)
- The setting up of salinity-yield functions using the Maas and Hoffmann equation
- The hydrology – macro-economic linkage and the Index for Socio-Economic Welfare (ISEW)

Under each section, the following sub-headings are used.

- the input data and source,
- mathematical formulation of the sub-model,
- relevant results and their interpretation
- model limitations and assumptions
- key linkages.

The chapter concludes with a summary of the main points made in this chapter.

5.2 THE USE OF SAPWAT CROP COEFFICIENTS FOR HYDROLOGY MODEL SETUP

5.2.1 THE INPUT DATA AND SOURCE

To set up the WRPM hydrology model, crop coefficients are required as input parameters of the monthly water requirements of each crop included in the surface characterization and water usage profiles of the WRPM. Using SAPWAT (van Heerden *et al.*, 2001) as a fully functional, standalone irrigation scheduling model, region/location and crop information is set up, and the crop coefficient, together with the reference evaporation (mm), is used to calculate the monthly crop water requirements of a specific crop. Figure 2.5 is the reference evaporation used for the calculation of the monthly crop coefficients in Figure 5.1. Note the similarity between the Douglas and Riet

River reference evaporations. These two sets of data cover the two WUAs that make up the study area of this research, giving a small level of spatial variability to the data used in the economic models.

5.2.2 COMPILATION OF THE SUB-MODEL.

For a full discussion on the derivation of crop coefficients see van Heerden (2001). Very simplistically put, crop water use factors determined by Green (1985) for each physiological growth stage of a crop for different regions in SA, are converted to monthly crop coefficients using the following data:

- Reference pan evaporation (mm) – see Figure 2.5 (a Screen from SAPWAT showing the reference Evaporation (mm) at the Douglas jail.)
- growing length of the specific crop, and

  planting date.

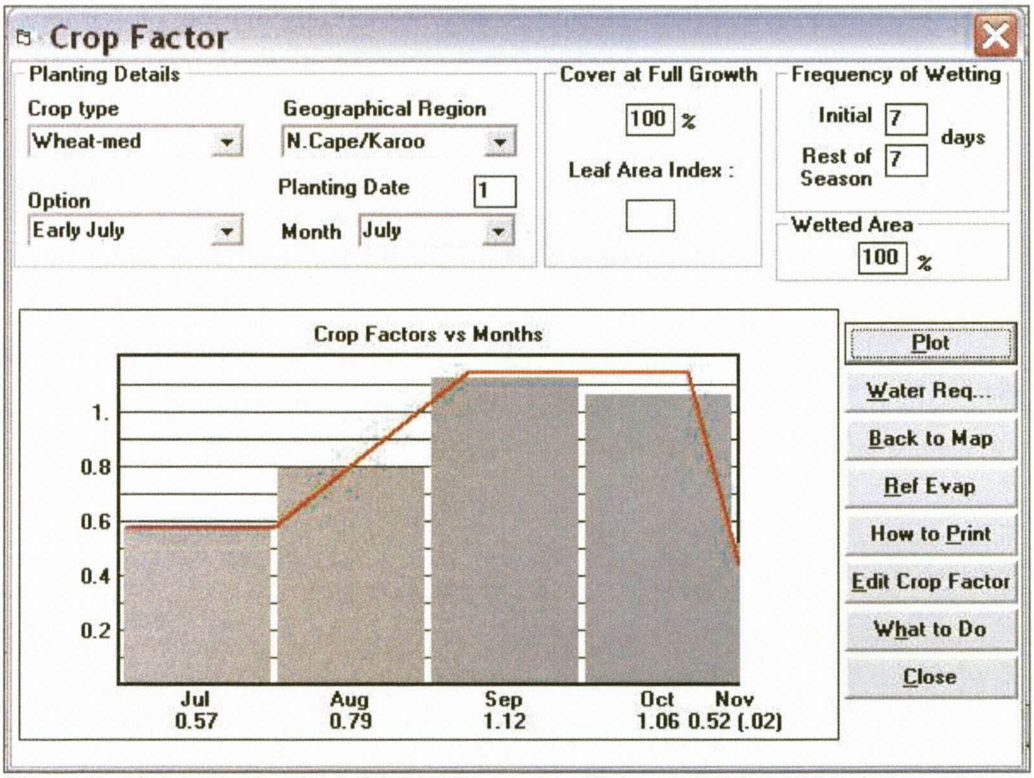


Figure 5.1 An example of the SAPWAT crop coefficients obtained for wheat

Table 5.1. Monthly mean pan evaporation (mm) as used in the WRPM setup

Month	*Douglas area*	*Riet River area*
May	119	112
Jun	93	85
Jul	110	94
Aug	139	138
Sep	196	204
Oct	262	272
Nov	300	322
Dec	344	365
Jan	349	354
Feb	259	272
Mar	208	224
Apr	134	158

The model interface as displayed in Figure 5.1 was set up for all 20 crops used in the WRPM, and the resulting monthly crop coefficients read off the screen and inputted into the WRPM setup tables. For all crops, the planting date was selected as the 1st day of the relevant planting month. The monthly mean pan evaporation values used in the WRPM model are listed in Table 5.1, and accepted from the initial setup and calibration of the WRPM model.

5.2.3 RELEVANT RESULTS AND THEIR INTERPRETATION

Table 5.2 lists the results of the monthly crop water factors for the Orange-Riet (Riet River) and Orange-Vaal (Douglas) WUAs. Certain crops can be planted over a long planting season, and other crops consist of a number of varieties with different characteristics, e.g. the generic name maize, includes early-, late, waxy-, popcorn-, yellow- and white- maize, and the generic name vegetables, include garlic and peas, etc.. But these crops have been grouped under a generic name because of the maximum limit of only 20 crops that can be modeled in WRPM. For these crops, a weighted average crop coefficient for that crop combination is calculated based on the actual crop combination area planted in the basis year of this model, i.e. 2005.

5.2.4 MODEL LIMITATIONS AND ASSUMPTIONS

Because *inter alia* of the weighted average crop coefficients used, it is assumed that the cropping combination remains constant for the full 15 years of analysis. Using an exact planting date as the beginning of the month is also unrealistic, one could have used a weighted average over the spread of the planting season, but this in reality is very variable and is weather dependent. Therefore the assumption that all crops planting date is the 1st of the relevant planting month.

5.2.5 KEY LINKAGES.

The key linkage of the crop coefficients is for the setup of the hydrology model (WRPM). Other related data used in the micro-economic model is the monthly crop water use of the total crop water requirement, which is related to these crop coefficients.

5.3 THE DERIVATION OF THE SATURATED SOIL SALINITY, ECe (mS/m)

5.3.1 THE INPUT DATA AND SOURCE

One of the main data outputs of the hydrology model (WRPM) is factor CU (mg/l), measuring the field level salt concentration in the upper soil zone, set up for each month (***t***) over 15 years (***y***) for each irrigation block (***s***) and run with 100 stochastic variations(***sr***). This data set needs to be converted to a saturated soil extract salinity concentration CUe (mg/l), and from there, an electrical conductivity of the saturated soil paste, ECe (mS/m) is determined. These monthly ECe values then need to be converted to crop specific annual averages by working out the weighted average ECe based on the monthly crop water requirement (see Table 5.3) and the ECe in each month.

Table 5.2. The monthly crop water coefficients used in the WRPM setup for calculating crop water use (Van Heerden *et al.*, 2001)

Orange-Riet WUA (Riet River) Crop coefficients used in the WRPM

Month	Barley	Beets	Carrots	Cotton	Cucurbits	Dry_Beans	Fruit	Lucerne	Maize	Olives	Onions	Pastures	Peanuts	Pecan_nuts	Potatoes	Soybeans	Sunflower	Vegetables	Vineyards	Wheat
May	-	-	-	0.15	-	-	0.20	-	-	0.16	0.46	0.32	-	0.22	-	-	-	-	0.17	-
Jun	0.16	-	-	-	-	-	0.20	-	-	0.12	0.26	0.19	-	0.16	-	-	-	-	0.17	0.16
Jul	0.35	-	-	-	-	-	0.20	-	-	-	0.24	0.04	-	0.15	-	-	-	-	0.17	0.35
Aug	0.81	-	-	-	0.43	-	0.20	0.40	-	0.15	0.39	0.07	-	0.21	-	-	-	-	0.17	0.81
Sep	1.00	0.30	-	-	0.35	-	0.23	0.50	-	0.27	0.59	0.36	-	0.28	-	-	-	0.30	0.17	1.00
Oct	0.86	0.39	-	-	0.50	-	0.27	0.70	0.26	0.38	0.01	0.59	-	0.46	-	-	-	0.39	0.18	0.86
Nov	0.16	0.67	-	0.18	0.72	-	0.31	0.80	0.46	0.65	0.02	0.98	-	1.13	-	0.01	-	0.67	0.28	0.16
Dec	-	0.70	-	0.29	0.47	-	0.41	0.80	0.66	1.14	0.03	0.65	0.46	1.20	-	0.35	-	0.70	0.31	-
Jan	-	0.70	0.86	0.69	-	0.64	0.50	0.80	0.88	1.13	0.00	0.65	1.07	1.20	0.29	0.75	0.38	0.70	0.34	-
Feb	-	0.18	0.73	0.80	-	1.07	0.59	0.80	0.70	1.04	-	0.60	0.84	1.11	0.69	1.03	0.91	0.18	0.33	-
Mar	-	-	0.37	0.60	-	0.69	0.42	0.70	0.46	0.72	-	1.24	0.62	0.76	0.98	0.88	1.11	-	0.25	-
Apr	-	-	-	0.50	-	-	0.20	0.50	0.11	0.44	0.74	1.08	0.44	0.55	1.00	0.41	0.05	-	0.20	-

Orange-Vaal WUA (Douglas) Crop coefficients used in the WRPM

Month	Barley	Beets	Carrots	Cotton	Cucurbits	Dry_Beans	Fruit	Lucerne	Maize	Olives	Onions	Pastures	Peanuts	Pecan_nuts	Potatoes	Soybeans	Sunflower	Vegetables	Vineyards	Wheat
May	0.50	-	-	-	-	-	0.20	0.30	-	0.15	0.32	0.24	-	0.20	-	-	-	-	0.20	0.30
Jun	0.30	-	-	-	-	-	0.20	0.30	-	-	0.38	0.06	-	0.24	-	-	-	-	0.20	0.50
Jul	0.50	-	-	-	0.43	-	0.20	0.40	-	0.21	0.57	0.10	-	0.31	-	-	-	-	0.20	0.09
Aug	0.09	-	-	-	0.35	-	0.23	0.50	-	0.40	0.87	0.53	-	0.42	-	-	-	0.30	0.20	1.00
Sep	1.00	0.30	-	-	0.50	-	0.27	0.70	-	0.57	0.02	0.87	-	0.69	-	-	-	0.39	0.23	0.70
Oct	0.70	0.39	-	0.28	0.72	-	0.31	0.80	0.20	0.74	0.03	1.12	-	1.29	-	0.01	-	0.67	0.38	-
Nov	-	0.67	-	0.53	0.47	-	0.41	0.80	0.30	1.30	0.03	0.75	0.52	1.37	0.17	0.40	-	0.70	0.38	-
Dec	-	0.70	1.00	0.84	-	0.75	0.50	0.80	0.65	1.32	0.01	0.76	1.25	1.40	0.40	0.88	0.47	0.70	0.38	-
Jan	-	0.70	0.82	0.88	-	1.20	0.59	0.80	0.97	1.18	-	0.68	0.95	1.25	0.65	1.17	0.91	0.18	0.38	-
Feb	-	0.18	0.39	0.47	-	0.73	0.42	0.70	1.00	0.75	-	1.30	0.65	0.80	0.90	0.92	1.07	-	0.30	-
Mar	-	-	-	0.43	-	-	0.20	0.50	0.67	0.44	0.75	1.08	0.44	0.55	1.00	0.41	-	-	0.20	-
Apr	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.09

Table 5.3. Total crop water reqirements per year (mm) in the OV- and OR- WUAs and the monthly percentages[1] of total requirement used (based on OV-WUA data)

Total crop water requirement (mm / year)	**Barley**	**Beets**	**Carrots**	**Cotton**	**Cucurbits**	**Dry_Beans**	**Fruit**	**Lucerne**	**Maize**	**Olives**	**Onions**	**Pastures**	**Peanuts**	**Pecan_nuts**	**Potatoes**	**Soybeans**	**Sunflower**	**Vegetables**	**Vineyards**	**Wheat**
OR-WUA	**613**	**400**	**385**	**768**	**520**	**335**	**1212**	**1179**	**764**	**558**	**246**	**843**	**604**	**639**	**556**	**645**	**419**	**616**	**637**	**613**
OV-WUA	**628**	**410**	**394**	**787**	**532**	**343**	**1241**	**1208**	**783**	**572**	**252**	**864**	**619**	**654**	**570**	**661**	**429**	**631**	**653**	**628**
May	0.04	-	-	-	-	-	0.01	-	-	-	0.11	0.01	-	0.03	-	-	-	0.04	0.02	0.04
Jun	0.09	-	-	-	-	-	0.03	-	-	0.03	0.16	0.01	-	0.04	0.00	-	-	0.06	0.03	0.09
Jul	0.23	-	-	-	0.02	-	0.05	0.07	-	0.05	0.25	0.07	-	0.05	0.00	-	-	0.10	0.05	0.23
Aug	0.36	0.20	-	-	0.04	-	0.08	0.13	-	0.08	0.01	0.11	-	0.08	0.00	-	-	0.21	0.08	0.36
Sep	0.28	0.37	-	0.22	0.06	-	0.12	0.17	0.00	0.10	0.01	0.14	-	0.15	0.00	0.00	-	0.28	0.14	0.28
Oct	-	0.43	-	0.38	0.06	-	0.17	0.18	0.11	0.18	0.01	0.09	0.14	0.16	0.00	0.11	-	0.30	0.16	-
Nov	-	-	0.45	0.40	0.34	0.28	0.17	0.18	0.23	0.18	0.00	0.10	0.33	0.16	0.19	0.23	0.19	-	0.16	-
Dec	-	-	0.37	-	0.26	0.45	0.15	0.16	0.31	0.16	-	0.09	0.25	0.14	0.28	0.31	0.37	-	0.14	-
Jan	-	-	0.18	-	0.21	0.27	0.10	0.12	0.24	0.10	-	0.17	0.17	0.09	0.31	0.24	0.44	-	0.09	-
Feb	-	-	-	-	-	-	0.06	-	0.11	0.06	0.21	0.14	0.12	0.06	0.21	0.11	-	-	0.06	-
Mar	-	-	-	-	-	-	0.03	-	-	0.03	0.16	0.05	-	0.03	-	-	-	-	0.03	-
Apr	-	-	-	-	-	-	0.02	-	-	0.02	0.09	0.03	-	0.02	-	-	-	-	0.02	-
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

[1] These values are very different from the crop coefficients shown in Table 5.2. They indicate the monthly water distribution of the total water requirement as calculated from the crop coefficients.

5.3.2 MATHEMATICAL FORMULATION OF THE SUB-MODEL.

Equation 5.1: $CUe_{t,s} = (CU_{t,s} . HE_t) / HSU$

where:

$CUe_{t,s}$	is the monthly saturated soil salinity concentration (mg/l) in the upper soil layer for each sub-WUA (***s***) for each time period (***t***)
$CU_{t,s}$	is the monthly natural field level (un-saturated) soil salinity concentration (mg/l) in the upper soil layer for each sub-WUA (***s***) for each time period (***t***)
HE_t	is the monthly (***t***) effective soil water volume (mm/ha)
HSU	soil moisture storage capacity in the upper zone (mm/ha) = constant 400 mm/ha

Equation 5.2: $ECe_{t,s} = CUe_{t,s} / SCF$

where:

$ECe_{t,s}$	is the monthly ECe in the upper soil layer for each sub-WUA (***s***) for each time period (***t***)
SCF	is the TDS to EC salinity conversion factor = constant 6.5 (Moolman and Quibell, 1995)

Equation 5.3: $ECc_{c,y,s} = \sum_{t,m} ECe_{t,s} * CWR_{c,m}$

where:

$ECc_{c,y,s}$	is the weighted average ECe for each crop (***c***) for each year (***y***) and in each irrigation block (***s***)
$CWR_{c,m}$	is the crop water requirement percentage, monthly (***m***) for all crops (***c***)

5.3.3 RELEVANT RESULTS AND THEIR INTERPRETATION

Graphs depicting CUe (mg/l) for the various scenarios in the different irrigation blocks are depicted in Figure 9.2.

5.3.4 MODEL LIMITATIONS AND ASSUMPTIONS

A limitation in the WRPM model is the number of soil zones, and the abstract division between the upper and lower zones. Because of the monthly time-step and great spatial diversity of soil types and depths at the irrigation block level, a spatial unit of the WRPM merely referring to the upper zone and lower zone without a quantitative divide is accepted in this study as one of the assumptions. The assumption therefore is that soil depth in the WRPM is roughly grouped into an upper and lower zone, with only soil salinity in the upper zone affecting crop yield.

From a farm level perspective, the unit for assessing soil salinity in the upper zone affecting crop yield, ECe (mS/m) is a very abstract measure, and also a value a farmer or WUA officer could not quickly and easily determine in the field. In response to this, the Australian CSIRO and American ARS of the USDA have produced a very basic conversion chart, named the "SWAGMAN Saltimeter" (Meyer *et al.* 1994) to convert irrigation water quality (TDS in mg/l) to soil water quality for extension purposes. Very basically, and adapted for South Africa:

- the "Saltimeter" calculates EC_e by multiplying irrigation water salinity (TDS_{iw} in mg/l) by a rule of thumb factor of 2 to get the soil salinity, TDS_e (mg/l) after concentration by evapotranspiration,

- TDS_e is then further divided by 6.5 to get an indication of saturated soil electrical conductivity (EC_e mS/m),
- From EC_e, by using the Maas and Hoffmann threshold and gradient functions, expected yield reductions are then calculated.

5.3.5 KEY LINKAGES.

The $ECc_{c,y,s}$ calculated up to Equation 5.3 is the critical hydrology-economy linkage to be fed into the Maas and Hoffmann equation and to be related into the impact that salinity has on crop yield.

5.4 THE SETTING UP OF SALINITY-YIELD FUNCTIONS USING THE MAAS AND HOFFMANN EQUATION

5.4.1 THE INPUT DATA AND SOURCE.

The electrical conductivity of the saturated zone, ECe (mS/m) is inputted into the Maas and Hoffmann equation to determine the impact on yield in the micro-economic model. The $ECc_{c,y,s}$ calculated in Equation 5.3 is the main input for the Maas and Hoffmann equation, together with crop salinity threshold (Thrsh) and crop salinity gradient (Grad) values.

5.4.2 MATHEMATICAL FORMULATION OF THE SUB-MODEL.

Equation 5.4: $$ThrshLF_c = Thrsh_c * (1 + LF_s)$$

where:

$ThrshLF_c$	is the crop (***c***) specific salinity threshold value adjusted for leaching
$Thrsh_c$	is the crop (***c***) specific salinity threshold value (assumed constant for all irrigation blocks)
LF_s	is the leaching fraction[1] (% additional water) applied in each irrigation block (***s***)

Equation 5.5: $$Yf_{c,y,s} = \{100 - Grad_c * (ECc_{c,y,s} - ThrshLF_c)\} / 100$$

where:

$Yf_{c,y,s}$	is the fraction of maximum yield obtainable when subject to salinity $ECc_{c,y,s}$
$ThrshLF_c$	is the crop (***c***) specific salinity yield reduction threshold value adjusted for leaching
$Grad_c$	is the crop (***c***) specific salinity yield reduction gradient (assumed constant for all irrigation blocks)
$ECc_{c,y,s}$	is the weighted average ECe for each crop (***c***) in each year (***y***) for each irrigation block (***s***)

Equation 5.6: $$Ys_{c,y,s} = Yf_{c,y,s} * Ym_c$$

[1] In this study the **Leaching Fraction (LF)** is defined as follows: If CWR is the crop water requirement, then the irrigation water requirement (IWR) is the CWR with the leaching requirement added. With a leaching fraction (LF) of x %, IWR=CWR+(CWR.x), or IWR=CWR(1+x).

where:

$Ys_{c,y,s}$ is the new yield (ton / ha) subject to salinity

$Yf_{c,y,s}$ is the fraction of maximum yield obtainable when subject to salinity $ECc_{c,y,s}$

Ym_c is the max potential / physiological yield (ton / ha)

5.4.3 RELEVANT RESULTS AND THEIR INTERPRETATION

A worked example of salinity-yield functions and the Maas and Hoffmann equation can be found in Figure 8.6

5.4.4 MODEL LIMITATIONS AND ASSUMPTIONS

The existence of better methodologies than the Maas and Hoffmann equation is acknowledged for quantifying the relationship between crop yield and soil salinity. In some models, functions of plant growth are compiled, which show a direct correlation to water uptake, and based on the premise that soil salinity creates a physiological drought in the soil, the function is proportionally adjusted, depending on the levels of salinisation and moisture in the soil. The SALTMED model (Ragab, 2000) uses this approach, based on incorporating the Penman-Monteith (evapo-transpiration) and Richards (transient-state soil water flow) equations with the Cardon and Letey plant water uptake model, in the presence of salts. The existing irrigation scheduling model, SWB (Annandale, *et al.* 2005) also uses a similar approach, and ACRUsalinity (Teweldebrhan, 2003) applies it to a catchment level, but all these models are too detailed and data intensive for the purposes of this study. Thus the combination of SAPWAT, WRPM and the Maas and Hoffmann equation was decided on.

The applicability of the thresholds and gradients to real life South African conditions with new crop varieties and management techniques may seem dated, but care was taken to get the most local and most up-to date threshold and gradient values (DWAF Water Quality Guidelines -1996, ILRI irrigation design manual, etc.).

The maximum physiological yield values were discussed at expert panel meetings and accepted as a good indication of very good yields. With new cultivars these yields could still improve. The assumption is that only salinity affects yield in the model – all other factors such as management, water, etc are assumed optimal.

5.4.5 KEY LINKAGES.

The key linkage is the conversion from soil salinity to yield reduction results, which forms the foundation on which the micro-economic model builds. $Ys_{c,y,s}$ is the key factor fed into the micro economic model that relates soil salinity into yield for further economic analysis.

5.5 THE HYDROLOGY MODEL LINKAGE

The choice of the applicable hydrology model is discussed in Paragraph 3.4.3.1 in the Literature Study Chapter. As the hydrology model setup refinement and operation for data generation was conducted by WRP consultants and fully explained in Viljoen *et al.* (2006), this discussion only serves to highlight the main components of the economic-hydrology coupling and results interpretation conducted by the author.

5.5.1 THE INPUT DATA AND SOURCE.

Study area irrigation block specific crop water factors were calculated as inputs into the WRPM hydrology model using SAPWAT by Van Heerden *et al.*,2002. The refinement of the OR-WUA irrigation block into 3 separate sub-WUA irrigation blocks in the WRPM and some small channel and node logical corrections / additions in the OV-WUA by WRP consultants were facilitated by the author. For all irrigation blocks, updated irrigation areas, returnflow factors and cropping compositions for all five scenarios (see Chapter 7) simulated were determined using *inter alia* Ninham Shand (2004) and CSIR (2004) and provided by the author.

5.5.2 RELEVANT RESULTS AND THEIR INTERPRETATION

The main output from the WRPM used in the economic model is the 100 stochastic sequences of monthly time series data of flow and TDS concentrations over 25 years in length (although only the first 15 years were used) undertaken for each of the scenarios. For a full description of the relevant results see the work by WRP consultants in Viljoen *et al.* (2006).

5.5.3 MODEL LIMITATIONS AND ASSUMPTIONS

The old DOS based coding, large size of the various data bases and the very un-user-friendliness of the model are the model limitation. The main assumptions made in using WRPM in the integrated framework proposed in this study are large irrigation blocks set up for the Lower Riet WUA, but especially the Orange Vaal WUA which is treated as one large irrigation block.

5.5.4 KEY LINKAGES.

The key linkages of the hydrology model are:

- the scenario input interface, an MS Excel spreadsheet that list all the variables that need to change for the different scenarios that are run, including the SAPWAT crop water factors that are inputted into the WRPM.
- The hydrology–micro-economic interface, which reads and structures the text based WRPM output for use in the MS Excel spreadsheet simulation model, and
- The hydrology–macro-economic linkage to provide the salinity flux as the environmental indicator for the Index for socio-economic welfare (ISEW) – see Viljoen *et al.* (2006).

5.5.5 MODEL SCHEME AND LINKAGES WITH THE ECONOMIC MODELS

Figure 5.2 is a schematic presentation of the workings of the WRPM model, depicting the water and salt flows, balances and interactions in the WRPM. The discussion that follows serves only to highlight the main WRPM variables used in the economic models SMsim (micro) and ISIM (regional).

The main linkages with the micro-economic level model are the HE, the effective soil moisture storage depth in the upper zone (UZ) and the SCU, the salt concentration in the UZ at effective soil moisture HE. With Equation 5.1 explained in this chapter, the saturated soil salt concentration is calculated from these two variables. The SCU and SCL, salt concentration in the lower zone, are used in the regional economic model for the calculation of the environmental sustainability index for the combined Index for Sustainable Economic Welfare (ISEW). The

ISEW is used in comparing different scenarios on the triple bottom line, i.e. financial, environmental and social sustainability (Viljoen *et al.* 2006).

The irrigation returnflow (-IR) variables (QIR and CIR) are also analysed in this thesis to calculate the impact of returnflows on downstream users. The gross irrigation demand (-ID) variables (QID and CID) and irrigation area are variables also synchronised between WRPM and SMsim.

5.5.6 HYDROLOGY DATA REQUIREMENTS

Data sets for each of the variables listed in Figure 5.2 were either calculated internally or provided by WRP consultants. All that the author supplied was the scenario input interface, which lists all the variables required for the set up of the base case and all those that need to change for the different scenarios that are run. Crops planted in each irrigation block were updated from the between 5 and 7 crops, to the maximum limit of 20 crops. Using SAPWAT, crop water factors were also inputted into the WRPM for all these 20 crops for each of the regions differentiated between.

5.6 HYDROLOGY – MACRO-ECONOMIC LINKAGE AND THE INDEX FOR SOCIO-ECONOMIC WELFARE (ISEW)

WRPM hydrology mass balance results are processed in this biophysical sub-routine for use in the Macro-economic model for the calculation of the Envirinmental indicator of the Index for Socio-Economic Welfare (ISEW).

5.6.1 THE INPUT DATA AND SOURCE.

The salt load associated with the irrigation abstractions (SA) and with the returnflows (SR), measured as the total tons per irrigation block (tons) are direct outputs of the hydrology model, calculated internally in the WRPM. The SA and SR values are used in the regional economic model to determine the environmental component of the ISEW.

5.6.2 MATHEMATICAL FORMULATION OF THE SUB-MODEL.

The environmental index of the ISEW, ISEWe, is an annual index of the soil salt mass balance derived from subtracting sum over all irrigation blocks annual average SR from SA, dividing by 10 000 and adding 1 to get a factor around 1 as shown in Equation 5.7.

Equation 5.7: $$ISEWe_y = 1 + ((\sum_m SA_{y,m} - \sum_m SR_{y,m}) / 10\,000)$$

where:

$ISEWe_y$	is the environmental component of the Index for Socio Economic Welfare (ISEW)
$SA_{y,m}$	is the monthly (***m***) salt load associated with the irrigation abstractions over 15 years (***y***)
$SR_{y,m}$	is the monthly (***m***) salt load associated with the irrigation returnflows over 15 years (***y***)

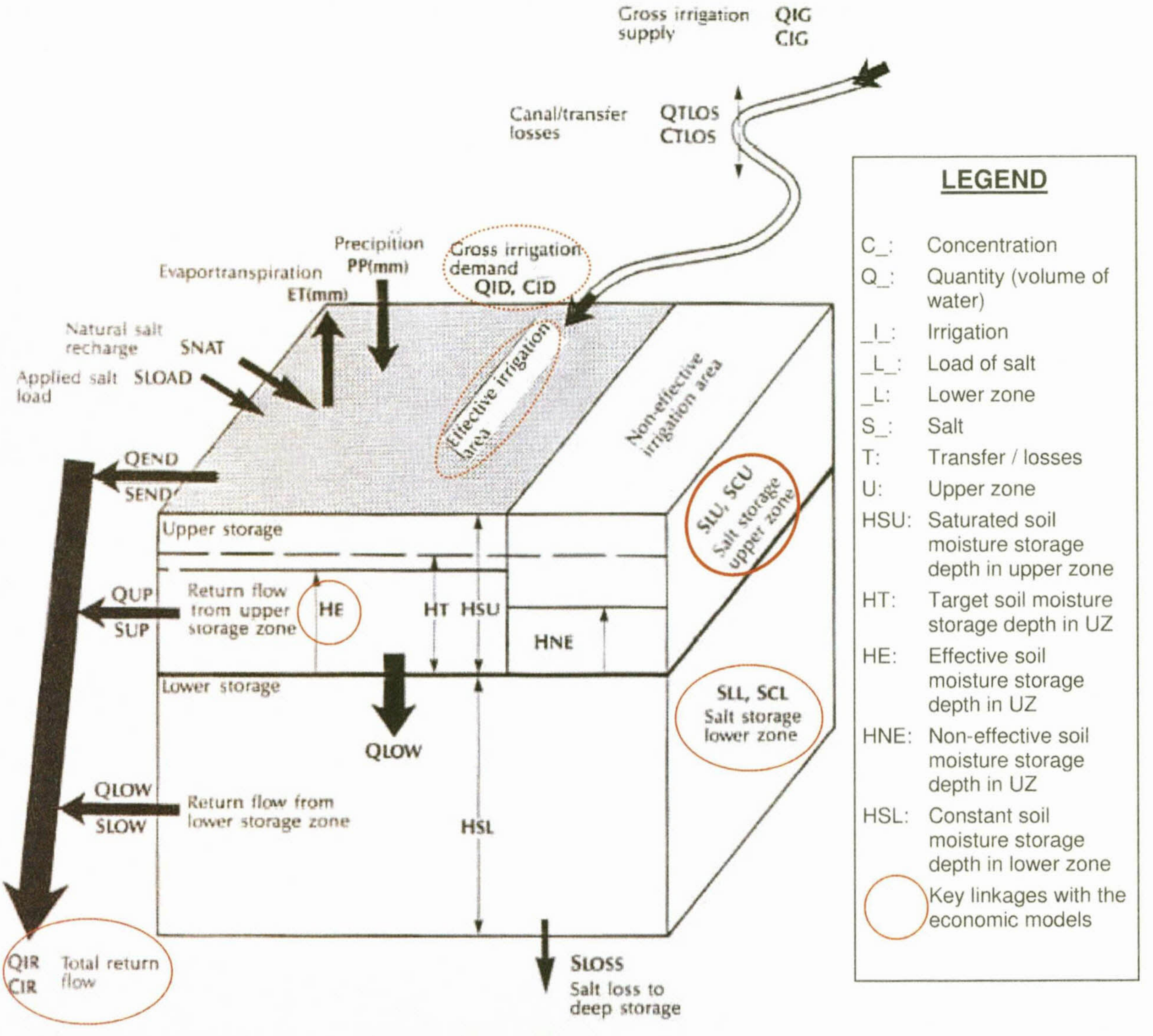


Figure 5.2. Model scheme depicting the salt and water balance paths in the WRPM (modified from Allen and Herold, 1988)

5.6.3 <u>RELEVANT RESULTS AND THEIR INTERPRETATION</u>

The results of the environmental leg of the ISEW are discussed in Chapter 8, Paragraph 8.8.2.

5.6.4 <u>MODEL LIMITATIONS AND ASSUMPTIONS</u>

As a starting point, soil salinity in the WRPM is manually set for the base-case scenario at an equilibrium level i.e. at a level so that no major trend exists for the timeframe of the model. The build-up and decline of salts in the soil at field scale from real levels are not observed in the base case. Deviations from the base-case in the subsequent scenarios however give an indication of the extent to which the scenario is an improvement / worsening from the basis.

5.6.5 KEY LINKAGES

The environmental component of the ISEW together with the economic and social components culminate in the ISEW which is the final value generated in the integrated model. This ISEW indicates whether a certain scenario is sustainable or unsustainable, and whether the scenario in question is tending towards becoming more of less sustainable.

5.7 SUMMARY

The biophysical sub-models discussed in this chapter refer to a group of biophysical-hydrology, hydrology-biophysical and biophysical-economic linkages, assumptions and procedures, using recognized existing models and algorithms to integrate the hydrology and economic models.

Paragraph 5.2 shows how SAPWAT is used to determine crop coefficients for setting up the hydrology model (WRPM). From the results of the WRPM, the saturated soil salinity, ECe (mS/m) is derived (see Paragraph 5.3) for the setting up of salinity-yield functions using the Maas and Hoffmann equation discussed in Paragraph 5.4.

The biophysical model generates the important linkage between the hydrology results and yield which form the basis of the economic models, as well as an important component of the final output in the regional economic model as the environmental component of the Index for Socio-Economic Welfare (ISEW). The biophysical model doesn't produce results of its own, but is an important linkage in transferring data from one scientific discipline to another, to culminate in the final answer.

CHAPTER 6 MICRO-ECONOMIC MODEL DESCRIPTION

To be effective in addressing water management problems, economists need to know the physical and biological relationships involved and integrate them into an economic model. Therefore the best way to promote effective water management is via collaboration among economists, and soil, water and plant scientists.

Freinerman. E. (2000)

6.1 INTRODUCTION

The aim of this chapter is to describe the process followed in setting up and running the micro-economic model.

The layout of this chapter is as follows:

- *Reasons for the use of a dynamic simulation model*
- *Model delineation*
- *Model aims*
- *Data requirements*
- *Mathematical specification of the model*
- *Model linkages*
- *Summary*

Under the paragraph on reasons for the use of a dynamic simulation model, the difficulties of optimizing, full model integration and data acquisition for optimization due to the nature of this work are discussed as motivation for the model framework selected.

The model delineation paragraph deals with the spatial and temporal dimensions, listing the model assumptions and limitations. These preceding paragraphs introduce the terms of reference for defining the aims of the micro-economic model, in context with the integrated whole. Paragraphs on the data requirements and the mathematical specification of the model follow. The chapter ends with the important linkages of the micro-economic model within the integrated whole, and a chapter summary.

6.2 REASONS FOR THE USE OF A DYNAMIC SIMULATION MODEL

The main reasons for adopting the dynamic simulation modelling approach lie in factors such as the number of decision variables required, the nature of the data required and the sub-model composition. As the hydrology isn't modelled implicitly within SMsim (i.e. not fully integrated), it produces a series of simulated data, on which the economic model builds. The micro-economic model is dynamic as it models over a 15 year time period and considers a stochastic range of 100 possible data series.

6.2.1 <u>NUMBER OF DECISION VARIABLES</u>

The exceedingly large number of decision variables required to set up an optimization model to solve the salinity problem described in this thesis makes it difficult to solve; and if results are generated they are not necessarily globally optimal soltions. A larger number of decision variables can be handled much easier with a simulation model, especially when making use of a series of stochastic data.

6.2.2 MODEL INTEGRATION

For optimization a fully integrated model would have to be built, incorporating sub-models from different disciplines into one model. The differing spatial and temporal scales of the different sub-models, make the integration for optimization very difficult.

6.2.3 DATA AVAILABILITY

The simulation option where only a selected cropping and management combination is selected is far less data intensive than an optimisation model where the data for all possible cropping and management combinations have to be compiled. In this regard Antle and Stoorvogel (2003) stated that "*It seems unlikely that a general, integrated model applicable to many different production systems will be available in the foreseeable future, nor will data adequate to support such a model be available.*" Furthermore, using the Maas and Hoffmann equation to calculate the crop response to soil salinity is also far less data intensive than using sophisticated crop growth and irrigation scheduling and management models such as SALTMED (Ragab 2000) and SWB (Annandale *et al.* 2005; Benade *et al.* 2002).

6.3 MODEL DELINEATION

6.3.1 SPATIAL DIMENSIONS

As described in Chapter 1, the spatial dimensions of the micro-economic model are set up and run for irrigation in two WUAs (the OV-WUA and the OR-WUA), one downstream of the other, comprising 4 irrigation blocks in accordance with the setup parameters of the hydrology model WRPM. The basic economic data needed for specifying the irrigation blocks are crop enterprise budgets (CEBs) set up on a per hectare level.

The objective of the SMsim model is to compare the effect of various cropping and drainage scenarios on the long-term sustainability of the study area as a whole, and for each irrigation block individually and in combination with one another. The model is set up to produce results that show the different financial and water use efficiencies of the different irrigation blocks on a per hectare level, and to identify the most sustainable management options for each irrigation block and the implication on a WUA as a whole. The irrigation blocks are differentiated physically according to the source of their irrigation water, general soil characteristics, and micro-economic variations reflected in CEBs mainly as a result of differences in distance from agricultural service providers.

The CEBs set up on a per hectare level are differentiated according to the various irrigation block characteristics. After determining the impact on yield on a gross margin per hectare level, the adjusted per hectare CEBs are multiplied by the irrigation block irrigable area (see scheduled areas in **Table 2.4**) to get irrigation block level CEBs. The assumption is that the irrigation block is one big farm, repeating exactly the same cropping combination for 15 years at the same 2005 base year crop prices.

At the regional economic level the study area is analysed to show the effect of scenario changes on the following components of the Index for Sustainable Socio-Economic Welfare (ISEW):

- Financial – change in agricultures contribution to regional GGP (including secondary effects)
- Social – chance in employment patterns
- Environmental – change in salt status of the various irrigation blocks

The micro-economic model output data used as inputs for the regional economic model and the ISEW is presented in Paragraph 8.8.1 and **8.8.2**, and regional model results in Paragraph 8.8.3.

6.3.2 TEMPORAL DIMENSIONS

The hydrology data produced by WRPM is monthly data, projected using 100 stochastic data sequences, over a period of 25 years. The economic models (micro and regional) are annual models, projected using 100 stochastic data sequences, over a period of the first 15 years obtained from the hydrology model, to produce annual economic model outputs.

6.3.3 MODEL ASSUMPTIONS AND LIMITATIONS

The core of the integrated model is the micro-economic model (SMsim). The following assumptions and limitation of SMsim are discussed:

- not an irrigation scheduling model
- limited to specific water quality management as set up in WRPM
- not a crop growth subject to salinity model
- besides converting soil salinity to saturated soil salinity and salt mass balance there is no further detailed soil chemistry incorporated into the model.

6.3.3.1 Irrigation scheduling

SMsim is not an irrigation scheduling model; it assumes sufficient irrigation water distribution and supply to fully meet crop needs as specified in the monthly crop water requirement percentages of the total annual crop water demand as set by the WUAs for the calculation of irrigation accounts (also determined in Van Heerden *et al.* 2001).

6.3.3.2 Water quantity management

As far a water quantity management is concerned, SMsim calculates the expected changes in water quantity demand for the various scenarios modelled. Care was taken in the setting up of scenarios modelled not to exceed the maximum monthly irrigation block water delivery volume constraints identified in the base case model setup (see **Table 8.6** in Chapter 8).

6.3.3.3 Crop growth

SMsim is also not a crop (subject to salinity) growth model (e.g. SALTMED by Ragab, 2000) based on evapo-transpiration. It solely uses the Maas and Hoffmann (1977) equation to relay the impact of saturated soil salinity (measured as electrical conductivity of the saturated soil paste, ECe in milli-Siemens per metre, mS/m) on crop yield, using laboratory determined, crop specific, salinity threshold and gradient values. The salinity threshold is the maximum ECe at which no reduction in yield will occur, and the gradient, the linear slope at which yield decreases with an increase in ECe above the threshold value.

6.3.3.4 Vadose zone chemistry

SMsim is not a soil chemical equilibrium model (e.g. UNSATCHEM, etc.); it purely uses a range of possible simulated soil salinity values calculated by the WRPM process-based hydrology model, based on the statistical analysis of 70 years of historical data in the study area in question. The impact of the SAR on the infiltration of water into the soil is also not taken into account.

6.3.3.5 Geo-hydrology

With reference to Ellington *et al.* (2004), and Ellington (2003), it was decided not to include a geo-hydrology component in the integrated model due to very long temporal dimensions of a geo-hydrology model, compared to the short time frame of the integrated model.

6.4 AIMS OF THE MODEL

The aim of the micro-economic model is to integrate holistically the key hydrology and bio-physical components influencing salinity into a long-term (dynamic) irrigation block level financial model to compare the financial response of irrigation blocks subject to various scenarios with each other. SMsim simulates the financial impact of water quality changes (inter-seasonal, annual and long-term), subject to various salinity management option setup scenarios.

6.5 DATA REQUIREMENTS

6.5.1 <u>DATA SOURCES</u>

Table 6.1 is a summary of the data sources used for the integrated model sub-components.

For the hydrology model, the initial setup data as compiled by Allen and Herold (1988) and later modified by Van Rooyen *et al.* (2004b) was used for the trial run. Once the critical factors are identified that need to change for scenario analysis, the base case scenario is compiled, updating the initial setup data with the most current data obtained from the DWAF and WUAs, mainly from the water management plans of the WUAs (Ninham Shand, 2004 and CSIR, 2004).

Crop coefficients required for the WRPM setup are generated using the SAPWAT model by Van Heerden *et al.* (2001). These crop coefficients differ somewhat from the monthly crop water requirements which are calculated from the crop coefficients as monthly percentages of the total annual crop water requirement. The total annual crop water requirements are fixed for the duration of the model at long-term average levels for each WUA as determined by the WUAs for calculation of water charges based on the hectares planted to a specific crop. The monthly crop water requirement percentages in Table 5.3 are used in SMsim to calculate the weighted average ECe that a crop will be exposed to.

Table 6.1 A summary of the input data sources

Category	Details	Sources
Hydrology	Crop coefficients WRPM setup Pumping capacities	SAPWAT (van Heerden *et al.* 2001), Green (1985) Alan and Herold (1988) and Van Rooyen *et al.* (2004b) WUAs, DWAF
Farm level data	Temporary labour requirements	Case study farmer survey, Expert panel opinion, GWK and WUAs
Micro-economic data	Regional average CEBs Farm level CEBs	GWK Case study farmer survey
Macro-economic data	National input/output matrix data	Statistics SA, National Survey Regional survey
Agronomy	Monthly crop water requirements Crop water demand	OV and OR WUA management plans, Van Heerden, *et al.* (2001) WUAs, DWAF
Salinity	Base salinity Threshold and Gradients Crop growth stage sensitivities	Case study farmer survey, WRPM manually set Maas and Hoffmann (1977) n/a
Soil data	Soil type division	Case study farmer survey, Expert panel opinion
Groundwater		n/a

The main farm level data collected is temporary labour requirements, comparisons of actual farm practice to GWK data and saturated soil salinity measures. The GWK CEBs, spatially differentiated for different irrigation blocks were verified as good representations of the reality, as were the temporary labour values used in the GWK CEBs. The saturated soil salinity measures were however not used due to unreliability of the data and the fact that in the WRPM setup, the starting soil salinity concentrations are manually set to irrigation block equilibrium levels to eliminate trends; that is to get the full effect of the stochastic nature of the hydrology in the system. The soil salinity data collected was however useful in delineating the sub-WUA areas. Other salinity related data used is the threshold and gradient data for each crop, derived from Du Preez *et al.* (2000), the ARC-ILI irrigation design manual (ARC-ILI, 1997) and Maas and Hoffmann (1977). Crop growth stage sensitivities and groundwater salinity data, initially proposed to be collected, were not deemed necessary after the conceptual model design was formulated.

6.5.2 PRIMARY DATA

6.5.2.1 Fixed cost component - financial constraints

A total gross margin above specified costs (TGMASC) approach is used to compare irrigation blocks based on their natural resource endowment position. Where a fixed / non-allocatable cost component is added in the model – i.e. where the subsurface artificial drainage area is increased as in scenario 3+, this fixed costs component, calculated from the total drainage costs in Table 6.2, is factored into the water use charge.

6.5.2.2 WUA level

Most of the WUA level operation data is obtained from the WUAs WMPs and verified through expert panel discussions and questionnaires.

The OV-WUA area as a whole was modelled as one irrigation block (***Vall***), where the OR-WUA area was modelled as 3 separate irrigation blocks, namely the Orange-Riet (***Rscm***) block (comprising the Canal, Scheme and Ritchie), the Scholtzburg (***Rszg***) block and the Lower Riet (***RloR***) block.

Table 6.2. The calculation of the costs of artificial drainage installation based on expert opinion from Reinders (2005) and Van der Merwe (2005)

	Unit	Minimum spacing	Average spacing	Maximum spacing
Inter row spacing distance (meters) of different soil types for effective drainage:				
Heavy soils (>35% clay)	m	20	25	30
Medium soils (15-35% clay)	m	40	45	50
Light soils (<15% clay)	m	70	75	80
The total meters of drainage required per hectare :				
Heavy soils (>35% clay)	m/ha	500.0	400.0	333.3
Medium soils (15-35% clay)	m/ha	250.0	222.2	200.0
Light soils (<15% clay)	m/ha	142.9	133.3	125.0
Cost of installing drainage	R/m	**100.00**	**100.00**	**100.00**
Total cost per ha of drainage on different soil types:				
Heavy soils (>35% clay)	R/ha	50 000.00	**40 000.00**	33 333.33
Medium soils (15-35% clay)	R/ha	25 000.00	**22 222.22**	20 000.00
Light soils (<15% clay)	R/ha	14 285.71	**13 333.33**	12 500.00

6.5.2.2.1 Water Transfer constraints

Care was taken in the selection of alternative cropping combinations not to exceed the maximum monthly water requirements of the study area as a whole. See **Table 7.8** for the resulting water requirements from the setup of the cropping combinations used in the various scenarios modelled.

6.5.2.2.2 Externality constraints

The WRPM models all the hydrology externalities within its specific setup data and capabilities, and these are captured in the hydrology results inputted into the micro-economic model. For the different scenarios, soil and water salt balances together with a surface salt wash-off module account for the upstream-downstream dynamics of salt deposition and transport throughout the catchments modelled in the WRPM. Externalities either take the form of point-source irrigation return-flows to affect farmers downstream, or a diffuse source where salts seep into the groundwater and either migrates back into the river or into shallow water tables on neighbouring farms.

6.5.3 SECONDARY DATA

The secondary data used in SMsim is presented in Table 6.3. Columns printed in bold are the data used in the final model runs.

For the 20 crops modelled, the first 2 data columns in Table 6.3 are the threshold and gradient values required in the Maas and Hoffmann equation, collected from Du Preez *et al.* (2000), ARC-ILI (1997) and Maas and Hoffmann (1977). The threshold and gradient for beets (which include beetroot and sugar beet) is set at 400 mS/m, the value for beetroot, as predominantly beetroot is grown, even though the threshold for sugar-beet is much higher at 700 mS/m.

Table 6.3. Main Crop Data used in the compilation of per hectare (ha) Crop Enterprise Budgets (CEBs)

	ECe Threshold[1,2]	ECe Gradient[1,2]	Max. Phys. Yield[2]	OR/OV - WUA Ave. Planned Yield	GWK Ave. Planned Yield	GWK / CEB Water require-ments	OV-WUA Water require-ments[2]	OR-WUA Water require-ments	Average Price[2] (1996-2005)	GWK CEB Prices
	mS/m	*%/mS/m*	*ton/ha*	*ton/ha*	*ton/ha*	*mm/ha*	*mm/ha*	*mm/ha*	*R/ton*	*R/ton*
Barley	**800**	**0.07**	**6.0**	*0.0*	6.00	660	**601**	590	**1 030**	1 410
Beets	**400**	**0.09**	**25.0**	*0.0*	25.00	*460*	**392**	450	**1 061**	1 061
Carrots	**100**	**0.14**	**25.0**	*0.0*	25.00	650	**377**	469	**1 142**	1 142
Cotton	**770**	**0.05**	**5.0**	*0.0*	5.00	850	**753**	753	**3 016**	1 800
Cucurbits	**250**	**0.13**	**50.0**	*0.0*	50.00	650	**509**	534	**560**	560
Dry Beans	**160**	**0.10**	**3.5**	*0.0*	3.00	450	**328**	351	**2 782**	3 000
Fruit	**170**	**0.21**	**6.0**	*0.0*	6.00	*971*	**1188**	1188	**3 000**	*3 000*
Lucerne	**200**	**0.07**	**20.4**	*0.0*	18.75	1300	**1156**	1275	**552**	318
Maize	**170**	**0.12**	**14.0**	*0.0*	12.00	700	**749**	728	**832**	475
Olives	**300**	**0.19**	**4.0**	*0.0*	4.00	*1029*	**547**	850	**5 400**	5 400
Onions	**120**	**0.16**	**55.0**	*0.0*	55.00	660	**241**	636	**1 378**	1 000
Pastures	**600**	**0.07**	**8.0**	8.00	8.00	1000	**827**	1284	**800**	800
Peanuts	**320**	**0.29**	**4.0**	*0.0*	4.00	580	**592**	592	**2 591**	2 867
Pecan nuts	**150**	**0.19**	**0.7**	*0.0*	0.69	*921*	**626**	1188	**16 500**	16 500
Potatoes	**170**	**0.12**	**45.0**	*0.0*	35.00	600	**545**	640	**1 412**	1 720
Soybeans	**500**	**0.20**	**6.0**	**6.0**	3.75	600	**633**	633	**1 693**	2 250
Sunflower	**500**	**0.09**	**4.0**	*0.0*	0.80	550	**411**	424	**1 451**	12 000[3]
Vegetables	**700**	**0.09**	**40.0**	40.00	40.00	1026	**604**	542	**750**	750
Vineyards	**150**	**0.10**	**5.2**	*0.0*	5.17	*1058*	**625**	819	**725**	725
Wheat	**600**	**0.07**	**7.0**	*0.0*	6.5	660	**601**	632	**1 208**	1 300

[1]Maas and Hoffmann (1977)
[2]Columns in bold are the final values used in the model. Other columns are included for comparison between various data sources
[3]Seed

The third column, maximum physiological yield (ton/ha), is the maximum of the fourth and fifth columns and verified with expert opinion as good maximum expected yield targets for the 20 crops modelled. The percentages of maximum yield calculated from the Maas and Hoffmann equation using the threshold and gradients in columns 1 and 2 are multiplied by this maximum physiological yield (ton/ha) to give the reduced crop yield (ton/ha) subject to soil salinity.

Columns 6, 7 and 8 compare the annual average crop water requirements as determined by GWK and the 2 WUAs in the setting up of CEBs. The GWK values are generally higher than the WUA values, and the OV-WUA and OR-WUA values differ due to differences in evapo-transpiration in the spatially different locations. GWK values are derived from actual water use measured by the study groups and include wastage, leaching and inefficiencies, whereas the WUA values reflect long term (last 5 production seasons) crop transpiration requirements calculated scientifically as measured from evaporation pans and do not include wastage and leaching. The WUA values are therefore more accurate for use in the integrated model as in the WRPM, as provision is also made for drainage, leaching, irrigation inefficiencies and distribution losses. Water and electricity prices[1] calculated in the CEBs are minimal costs and farmers using this information would have to factor in additional costs of water use above the OV-WUA values (column 7) selected.

The last 2 columns in Table 6.3 show the long-term (10 year) real average crop price, as also presented in Figure 6.1 and used in the model, and the 2005 GWK planned crop price.

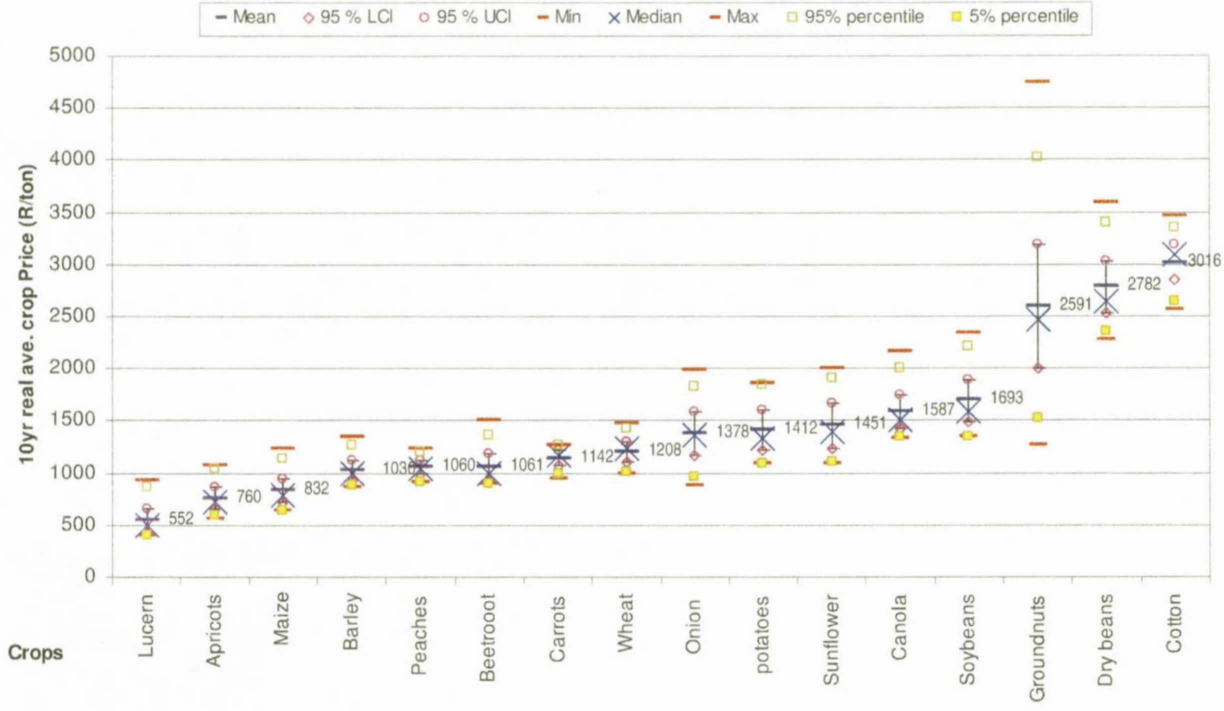


Figure 6.1. Ten year real crop price (R/ton) spread for the 20 crops modelled in SMsim (2005 base year)

6.5.3.1 The calculation of the crop prices used

Figure 6.1 lists the spread of real crop prices for a 10 year period using 2005 as the basis year. These values are based on the Abstract of Agricultural Statistics' Production Price Index, DoA (2005).The historical national average producer crop prices from 1995 to 2005 were converted to 2005 level real crop prices using the production price index from the Abstract of Agricultural Statistics (2005). By using these mean prices as the crop prices in SMsim, annual price fluctuations and intercrop price dynamics are eliminated.

6.5.3.2 Crop enterprise Budgets (CEBs)

6.5.3.2.1 <u>CEB Assumptions</u>

a. The crop enterprise budgets (CEBs) are set up on a per ha basis, reflecting only direct production costs, and ignoring the farm level specific fixed cost component. This is because these CEBs get extrapolated to irrigation block level, where the fixed / capital cost and tax component of specific farms are very different.

[1] Here actual 2005 water prices are used. It is however acknowledged that shadow prices could have been used to reflect the opportunity cost of the water used for drainage for other uses as well as the externality costs imposed on downstream users through increased salt concentration in the drainage water.

b. For this study, farm level modelling was not deemed necessary as per hectare data is extrapolated directly to irrigation block level data. Per hectare level data generated in SMsim can however be used by farmers wanting to conduct their own farm level analysis.

c. Long-term crops enterprise budget data are annualised: e.g. lucerne is a four year crop so one hectare out of four will be in the establishment phase and the other three in full production. Only one CEB will thus be set up for the full lifecycle of the crop to produce an annual average / weighted budget.

d. For this study it is assumed that no temporary labour is used for lucerne - only fulltime on-farm workers are used as lucerne harvesting is a regular action in the growing season.

   i. As lucerne harvesting costs are worked out on a per bale price, one square bale is assumed 40 kg therefore 25 bales are in a ton.

   ii. The contribution of fuel to harvesting costs is assumed constant for different lucerne yields.

e. Crop and inputs used over the 15 years are valued / modelled at constant 2005 prices.

f. Crop threshold and gradients are assumed constant for all irrigation blocks over the full crop growth cycle and for all 15 years modelled. Thresholds only vary per crop with the amount of drainage accounted for – a crop threshold is increased by the same percentage as the drainage / leaching percentage, to internalise the benefit of leaching on yield into the CEB. The additional water costs of leaching are also accounted for.

g. Maintenance and repair costs include maintenance and repair costs for centre pivot irrigation systems for all crops (i.e. for flood irrigated crops, maintenance and repair costs are added as centre pivot irrigation is the predominant form of irrigation at irrigation block level) .

h. Regional changes in CEB prices as identified in the GWK CEBs are used to differentiate between model CEBs. (i.e. instead of using case study / representative farm data). The main CEB costs components that differ between irrigation blocks are pesticides (distance from airfield for aerial spraying costs), insurance (hail, drought, water supply reliability), water (WUA differentiated price) and harvesting costs (distance from silos).

i. Packaging and contract transport costs are all included under harvesting costs.

j. Water use charges vary per irrigation block, but electricity costs are assumed the same for all irrigation blocks (it is assumed that everyone uses the same Flexi-Time / Peak-Time ratio and that all pump similar distances).

Table 6.4 to Table 6.7 are a demonstration of the conversion of standard per hectare CEBs to reduced yield per hectare CEBs, and the resulting per hectare to irrigation block level TGMASC results. The reduced crop yield due to salinity is converted through the CEB to per hectare TGMASC level, and to irrigation block level total expenditure on different crop inputs, total production value (gross income) and irrigation block level TGMASC.

All the examples are taken from stochastic run 80 for the Lower Riet irrigation block (***RloR***) base-case scenario, using 2005 values (for the other irrigation blocks see Appendix 3);

- Table 6.4 is a collection of 20 CEBs, setup for maximum yield over 1 year.

- Table 6.5 is the same collection of 20 CEBs, but setup for reduced yield as a result of the impact of the weighted average electrical conductivity of the saturated extract, $ECe_{y,c}$ on crop yield over 1 year.
- Table 6.6 is an example of the irrigation block level CEBs over 1 year, based on the per hectare CEBs in Table 6.4.
- Table 6.7 is the listing of the annual TGMASCs, culminating in the irrigation block level TGMASC for each year and the cumulative TGMASC for all 15 years.

Results show negative returns for carrots, peanuts, dry-beans and potatoes, and the largest TGMASC from onions, pumpkins, soybeans and beets, for stochastic run 80 of the base case models.

In Table 6.6 the total value of production or Gross Farm Income (GFI) is R69 million and TGMASC R6.6 million. The values of seed, fertilizer, etc. bought over the whole season in the irrigation block are also listed.

In Table 6.7 (the annual irrigation block level CEB breakdown) the pre-harvest input costs remain constant over the 15 years, with only the harvesting costs, gross income and TGMASC changing each year, as these are the only yield dependent variables. It is assumed that farmers plan for maximum yields even though they know that they have a salinity problem and therefore the pre-harvest input costs remain the same.

The 100 stochastic runs results of the TGMASC and cumulative TGMASC are discussed in paragraph 7.8 in the chapter that follows.

Table 6.4. CEBs for maximum yield, set up for the Lower Riet irrigation block base-case scenario, using 2005 values

LOWER RIET	Unit	Barley	Beets	Carrots	Cotton	Cucurbits	Dry Beans	Fruit	Lucerne	Maize	Olives	Onions	Pastures	Peanuts	Pecan nuts	Potatoes	Soybeans	Sunflower	Vegetables	Vineyards	Wheat
ECe Threshold (BC, S1 and S2)	mS/m	816	408	102	785	255	163	173	204	173	306	122	612	326	153	173	510	510	714	153	612
ECe Gradient	%/mS/m	0.071	0.090	0.140	0.052	0.130	0.096	0.210	0.073	0.120	0.190	0.160	0.071	0.290	0.190	0.120	0.200	0.087	0.090	0.096	0.071
Crop water requirement	mm/ha	613	400	385	768	520	335	1212	1179	764	558	246	843	604	639	556	645	419	616	637	613
Crop Enterprise Budgets:																					
PRICE	R/ton	1030	1061	1142	3016	560	2782	3000	552	832	5400	1378	800	2591	16500	1412	1693	1451	750	725	1208
Max Physiological yield	**ton/ha**	**6.00**	**35.00**	**50.00**	**5.00**	**50.00**	**3.50**	**21.00**	**20.40**	**14.00**	**6.40**	**55.00**	**8.00**	**4.00**	**1.60**	**45.00**	**6.00**	**4.00**	**40.00**	**20.38**	**7.00**
Total/Gross potential income	R/ha	6180	37133	57091	15079	28000	9739	63000	11255	11651	34560	75774	6400	10364	26400	63557	10160	5805	30000	14778	8454
SEED	R/ha	504	2680	3900	1114	224	1120	7683	375	1080	578	2742	1175	1040	373	16000	475	61	585	2349	756
FERTILIZER	R/ha	1424	2881	3162	2145	2389	1218	1535	1414	2402	1754	3372	1153	1120	1149	4718	1070	1167	1754	756	1858
HERBICIDES	R/ha	84	368	334	85	103	204	506	165	277	539	537		94	25	117	233	140	270	2204	84
PESTICIDES	R/ha	157	40	309	1792	257	1021	4	13	594	830	1156		754		9574	159	188	612		409
INSURANCE	R/ha	341		2376	2217	3780	1032	11201		373		5759		321		2224	0	192	2640	901	364
FUEL	R/ha	206	281	426	444	271	225	43	464	194	127	426	233	295	82	828	171	274	233	146	287
MAINTENANCE	R/ha	481			567		418	66	1078	336	1000	223	698	811	29	1154	145	418	406	207	913
Temp LABOUR	R/ha		4597	5307	988	1900	554	900			567	491		1070	643	268	160		300	1434	
ELEC. @ **R 0.489** / mm	R/mm/ha	*300*	*196*	*188*	*376*	*254*	*164*	*593*	*205*	*301*	*273*	*120*	*412*	*295*	*312*	*272*	*316*	*205*	*301*	*312*	*300*
WATER @ **R 0.677** / mm	R/mm/ha	*415*	*271*	*260*	*520*	*352*	*227*	*821*	*284*	*417*	*378*	*166*	*571*	*409*	*432*	*377*	*437*	*284*	*417*	*432*	*415*
HARVESTING COSTS	R/ton	122	539	600	280	20	249	82	44	50	3000	184		471	233	368	127	113	270	12	103
	R/ha	*734*	*18865*	*30000*	*1400*	*1000*	*873*	*1716*	*899*	*704*	*19200*	*10104*		*1886*	*373*	*16557*	*760*	*450*	*10812*	*240*	*723*
Total expenses pre harvest	R/ha	3913	11313	16263	10248	8530	6181	23351	3997	5974	6046	14992	4243	6210	3045	35532	3167	2928	7519	8741	5386
Total expenses with max harvest	R/ha	4647	30178	46263	11648	10530	7054	25067	4897	6678	25246	25095	4243	8096	3418	52089	3927	3378	18331	8981	6109
TGMASC	**R/ha**	**1533**	**6955**	**10829**	**3431**	**17470**	**2684**	**37933**	**6359**	**4973**	**9314**	**50679**	**2157**	**2268**	**22982**	**11467**	**6233**	**2426**	**11669**	**5797**	**2345**
Co-op interest charge	R/ha	88	298	725	257	409	159	603	96	145	593	404	359	151	63	959	66	67	187	880	128
Bank interest charge	R/ha	40	532	48	63	74	35	86	38	39	2184	286	108	71	31	473	42	26	317	108	40
Total Interest	R/ha	*128*	*830*	*773*	*320*	*483*	*194*	*689*	*135*	*184*	*2777*	*690*	*467*	*223*	*94*	*1432*	*108*	*93*	*504*	*988*	*168*
Crop TGMASC less Interest	**R/ha**	**1405**	**6125**	**10056**	**3110**	**16987**	**2490**	**37243**	**6224**	**4789**	**6537**	**49989**	**1691**	**2045**	**22888**	**10035**	**6125**	**2333**	**11165**	**4809**	**2177**

Table 6.5. CEBs for reduced crop yield, set up for the Lower Riet irrigation block base-case scenario, using 2005 values

LOWER RIET	Unit	Barley	Beets	Carrots	Cotton	Cucurbits	Dry Beans	Fruit	Lucerne	Maize	Olives	Onions	Pastures	Peanuts	Pecan nuts	Potatoes	Soybeans	Sunflower	Vegetables	Vineyards	Wheat
ECe Threshold (BC, S1 andS2)	mS/m	816	408	102	785	255	163	173	204	173	306	122	612	326	153	173	510	510	714	153	612
ECe Gradient	%/mS/m	0.071	0.090	0.140	0.052	0.130	0.096	0.210	0.073	0.120	0.190	0.160	0.071	0.290	0.190	0.120	0.200	0.087	0.090	0.096	0.071
Crop water requirement	mm/ha	613	400	385	768	520	335	1212	1179	764	558	246	843	604	639	556	645	419	616	637	613
Weighted ave. ECe	**mS/m**	**471**	**510**	**519**	**513**	**521**	**527**	**515**	**511**	**534**	**516**	**500**	**526**	**529**	**514**	**543**	**534**	**541**	**493**	**514**	**471**
Weighted ave. TDS	*mg/l*	3061	3317	3370	3333	3388	3427	3349	3319	3474	3357	3248	3417	3440	3341	3533	3474	3518	3205	3341	3061
Crop Enterprise Budgets:																					
PRICE	R/ton	1030	1061	1142	3016	560	2782	3000	552	832	5400	1378	800	2591	16500	1412	1693	1451	750	725	1208
Max Physiological yield	ton/ha	6.00	35.00	50.00	5.00	50.00	3.50	21.00	20.40	14.00	6.40	55.00	8.00	4.00	1.60	45.00	6.00	4.00	40.00	20.38	7.00
Modeled yield	***ton/ha***	***6.00***	***31.78***	***20.84***	***5.00***	***32.70***	***2.28***	***5.92***	***15.83***	***7.93***	***3.84***	***21.79***	***8.00***	***1.65***	***0.50***	***25.01***	***5.71***	***3.89***	***40.00***	***13.32***	***7.00***
Total/Gross potential income	R/ha	6180	33713	23799	15079	18310	6336	17770	8737	6603	20738	30025	6400	4270	8290	35330	9663	5647	30000	9658	8454
SEED	R/ha	504	2680	3900	1114	224	1120	7683	375	1080	578	2742	1175	1040	373	16000	475	61	585	2349	756
FERTILIZER	R/ha	1424	2881	3162	2145	2389	1218	1535	1414	2402	1754	3372	1153	1120	1149	4718	1070	1167	1754	756	1858
HERBICIDES	R/ha	84	368	334	85	103	204	506	165	277	539	537		94	25	117	233	140	270	2204	84
PESTICIDES	R/ha	157	40	309	1792	257	1021	4	13	594	830	1156		754	0	9574	159	188	612		409
INSURANCE	R/ha	341		2376	2217	2472	672	3160	0	211		2282		132	0	1237	0	186	2640	589	364
FUEL	R/ha	206	281	426	444	271	225	43	464	194	127	426	233	295	82	828	171	274	233	146	287
MAINTENANCE	R/ha	481			567		418	66	1078	336	1000	223	698	811	29	1154	145	418	406	207	913
Temp LABOUR	R/ha		4597	5307	988	1900	554	900	0	0	567	491		1070	643	268	160	0	300	1434	0
ELEC. **@ R 0.489** / mm	**0.49**	*300*	*196*	*188*	*376*	*254*	*164*	*593*	*205*	*301*	*273*	*120*	*412*	*295*	*312*	*272*	*316*	*205*	*301*	*312*	*300*
WATER **@ R 0.677** / mm	**0.68**	*415*	*271*	*260*	*520*	*352*	*227*	*821*	*284*	*417*	*378*	*166*	*571*	*409*	*432*	*377*	*437*	*284*	*417*	*432*	*415*
HARVESTING COSTS	R/ton	122	539	*600*	280	20	249	290	44	50	3000	184		471	233	368	127	116	270	18	103
	R/ha	*734*	*17127*	*12506*	*1400*	*654*	*568*	*1716*	*698*	*399*	*11521*	*4003*	*0*	*777*	*117*	*9204*	*723*	*450*	*10812*	*240*	*723*
Total expenses pre harvest	R/ha	3913	11313	16263	10248	7568	5821	15309	3997	5813	6046	11515	4243	6021	3045	34544	3167	2923	7519	8429	5386
Total expenses with max harvest	R/ha	4647	28441	28768	11648	8876	6389	17025	4695	6211	17567	15518	4243	6798	3162	43748	3890	3373	18331	8669	6109
TGMASC	**R/ha**	**1533**	**5272**	**-4969**	**3431**	**9434**	**-53**	**745**	**4041**	**392**	**3171**	**14507**	**2157**	**-2528**	**5128**	**-8418**	**5773**	**2274**	**11669**	**989**	**2345**
Co-op interest charge	R/ha	88	298	725	257	349	149	382	96	140	593	309	359	146	63	932	66	67	187	845	128
Bank interest charge	R/ha	40	484	48	63	58	26	86	33	31	1339	118	108	41	24	271	41	26	317	108	40
Total Interest	R/ha	*128*	*782*	*773*	*320*	*407*	*176*	*468*	*129*	*171*	*1932*	*427*	*467*	*187*	*87*	*1203*	*107*	*93*	*504*	*954*	*168*
Crop TGMASC less Interest	**R/ha**	**1405**	**4490**	**-5742**	**3110**	**9027**	**-229**	**277**	**3912**	**221**	**1239**	**14080**	**1691**	**-2715**	**5041**	**-9621**	**5666**	**2181**	**11165**	**35**	**2177**

Table 6.6. ***RIoR*** **irrigation block level crop specific CEB of stochastic run 80 of the base case scenario (2005 prices in Rand)**

	Barley	Beets	Carrots	Cotton	Cucurbits	Dry_ Beans	Fruit	Lucerne	Maize	Olives	Onions	Pastures	Peanuts	Pecan nuts	Potatoes	Soybeans	Sun-flower	Veg-etables	Vineyards	Wheat	TOTAL
GFI	**1 125 940**	**0**	**0**	**211 106**	**137 324**	**114 044**	**0**	**3 025 589**	**17 417 987**	**0**	**3 338 803**	**341 120**	**462 750**	**0**	**16 048 467**	**0**	**491 268**	**210 000**	**422 526**	**25 730 914**	**69 077 838**
SEED	91 829	0	0	15 596	1 679	20 160	0	129 710	2 848 835	0	304 931	62 628	112 715	0	7 267 840	0	5 312	4 094	102 790	2 301 030	13 269 147
FERT	259 491	0	0	30 034	17 918	21 915	0	489 693	6 335 255	0	374 939	61 428	121 363	0	2 143 082	0	101 551	12 277	33 068	5 656 120	15 658 133
HERB	15 350	0	0	1 196	770	3 676	0	57 090	731 438	0	59 727	0	10 216	0	53 288	0	12 197	1 890	96 440	256 431	1 299 709
PEST	28 682	0	0	25 084	1 930	18 381	0	4 463	1 566 648	0	128 509	0	81 676	0	4 348 921	0	16 356	4 281	0	1 245 420	7 470 352
INSUR	62 137	0	0	31 033	28 350	18 582	0	0	983 420	0	640 381	0	34 819	0	1 010 447	0	16 665	18 480	39 439	1 106 429	3 990 183
FUEL	37 514	0	0	6 217	2 034	4 048	0	160 838	512 247	0	47 384	12 432	32 013	0	376 169	0	23 807	1 633	6 390	872 390	2 095 115
MAINT	87 660	0	0	7 937	0	7 516	0	373 176	885 449	0	24 754	37 228	87 943	0	524 120	0	36 327	2 845	9 043	2 778 615	4 862 614
LABOR	0	0	0	13 835	14 250	9 963	0	0	0	0	54 574	0	115 977	0	121 555	0	0	2 100	62 731	0	394 985
WAT	54 624	0	0	5 262	1 906	2 945	0	71 001	794 764	0	13 364	21 979	32 006	0	123 515	0	17 837	2 109	13 639	912 499	2 067 449
ELEC	75 634	0	0	7 285	2 639	4 078	0	98 311	1 100 463	0	18 505	30 433	44 317	0	171 024	0	24 698	2 920	18 885	1 263 484	2 862 676
HARV	133 735	0	0	19 600	4 904	10 225	0	241 738	1 051 759	0	445 187	0	84 204	0	4 180 866	0	38 086	75 684	6 862	2 200 588	8 493 438
TGMASC	**279 284**	**0**	**0**	**48 028**	**60 944**	**-7 444**	**0**	**1 399 570**	**607 709**	**0**	**1 226 547**	**114 992**	**-294 499**	**0**	**-4 272 359**	**0**	**198 432**	**81 686**	**33 238**	**7 137 908**	**6 614 037**

Table 6.7. An example of the RIoR irrigation block level CEB breakdown for all crops combined, and the annual and cumulative TGMASC for stochastic run 80 (2005 prices in Rand)

	Total Income	*SEED*	*FERT*	*HERB*	*PEST*	*INSUR*	*FUEL*	*MAINT*	*LABOR*	*WAT*	*ELEC*	*HARV*	*TGMASC*	*Cumulative TGMASC*
2005	69 077 838	13 269 147	15 658 133	1 299 709	7 470 352	3 990 183	2 095 115	4 862 614	394 985	2 067 449	2 862 676	8 493 438	**6 614 037**	***6 614 037***
2006	69 635 849	13 269 147	15 658 133	1 299 709	7 470 352	3 990 183	2 095 115	4 862 614	394 985	2 067 449	2 862 676	8 525 272	**7 140 214**	***13 754 250***
2007	70 698 209	13 269 147	15 658 133	1 299 709	7 470 352	3 990 183	2 095 115	4 862 614	394 985	2 067 449	2 862 676	8 742 297	**7 985 549**	***21 739 799***
2008	67 924 175	13 269 147	15 658 133	1 299 709	7 470 352	3 990 183	2 095 115	4 862 614	394 985	2 067 449	2 862 676	8 321 023	**5 632 788**	***27 372 587***
2009	70 461 417	13 269 147	15 658 133	1 299 709	7 470 352	3 990 183	2 095 115	4 862 614	394 985	2 067 449	2 862 676	8 728 428	**7 762 626**	***35 135 213***
2010	68 083 358	13 269 147	15 658 133	1 299 709	7 470 352	3 990 183	2 095 115	4 862 614	394 985	2 067 449	2 862 676	8 395 812	**5 717 182**	***40 852 395***
2011	74 011 036	13 269 147	15 658 133	1 299 709	7 470 352	3 990 183	2 095 115	4 862 614	394 985	2 067 449	2 862 676	9 269 894	**10 770 778**	***51 623 174***
2012	72 537 933	13 269 147	15 658 133	1 299 709	7 470 352	3 990 183	2 095 115	4 862 614	394 985	2 067 449	2 862 676	9 061 124	**9 506 445**	***61 129 619***
2013	70 907 342	13 269 147	15 658 133	1 299 709	7 470 352	3 990 183	2 095 115	4 862 614	394 985	2 067 449	2 862 676	8 828 269	**8 108 709**	***69 238 328***
2014	70 102 901	13 269 147	15 658 133	1 299 709	7 470 352	3 990 183	2 095 115	4 862 614	394 985	2 067 449	2 862 676	8 683 600	**7 448 937**	***76 687 265***
2015	72 012 510	13 269 147	15 658 133	1 299 709	7 470 352	3 990 183	2 095 115	4 862 614	394 985	2 067 449	2 862 676	8 946 364	**9 095 782**	***85 783 047***
2016	70 279 621	13 269 147	15 658 133	1 299 709	7 470 352	3 990 183	2 095 115	4 862 614	394 985	2 067 449	2 862 676	8 646 272	**7 662 985**	***93 446 032***
2017	74 141 748	13 269 147	15 658 133	1 299 709	7 470 352	3 990 183	2 095 115	4 862 614	394 985	2 067 449	2 862 676	9 268 581	**10 902 803**	***104 348 836***
2018	69 527 060	13 269 147	15 658 133	1 299 709	7 470 352	3 990 183	2 095 115	4 862 614	394 985	2 067 449	2 862 676	8 586 301	**6 970 395**	***111 319 231***
2019	71 252 542	13 269 147	15 658 133	1 299 709	7 470 352	3 990 183	2 095 115	4 862 614	394 985	2 067 449	2 862 676	8 816 860	**8 465 319**	***119 784 550***

6.6 MATHEMATICAL SPECIFICATION OF THE MODEL

6.6.1 MODEL SETUP (DEFINITION OF THE SETS AND SUB-SETS)

6.6.1.1 Sets:

m	=	months in the model are as follows:	
		in the hydrology model, rainfall	***m*** = {Oct, Nov, ... Sep.}
		in WRPM output	***m*** = {May, Jun, ...Apr.}
		in SMsim an agricultural season	***m*** = {Jul, Aug, ... Jun.}
y	=	years in the model are as follows	
		in WRPM (25 Years)	***y*** = {yr1, yr2, ... yr25}
		in SMsim (15 years)	***y*** = {2005, 2003, ... 2019}
t	=	monthly (m) time step of the model over a number of years (y)	
t	=	f (***m, y***) = 1,2, ... ,180. (12 months x 15 years)	
s	=	irrigation blocks in the model	{***RloR, Rscm, Rszg, Vall***}
r	=	stochastic model runs	{1, 2, ... 100}
c	=	all crops modelled in SMsim	{wheat, maize, lucerne}
i	=	a set of all inputs / direct production costs	{seed, fertilizer, ... transport}

Sets ***m***, ***y*** and ***t*** describe the temporal dimensions of the model, set ***s*** the spatial dimensions, set ***r*** the 100 stochastic runs, set ***c*** the 20 crops modelled, and set ***i*** the direct crop input cost items.

6.6.1.2 Sub-Sets

sr of s	=	irrigation blocks of the OR-WUA	{***RloR, Rscm, Rszg*** }
sv of s	=	irrigation blocks of the OV-WUA	{ ***Vall***}
fi of I	=	all the fixed inputs (R/ha)	{seed, fertilizer, etc.}
yi of i	=	all the yield dependent production costs (R/ton)	{harvesting, packaging, transport, etc.}

The subsets of the model, ***sr*** and ***sv*** group the spatial dimensions of the model into the OR-WUA and OV-WUA. Subsets ***fi*** and ***yi*** differentiate the fixed input cost items from the yield dependent, post harvest input cost components.

6.6.1.3 Scalars / constants:

SCF TDS to EC salinity conversion factor = 6.5

The scalar or constant, SCF is the salinity conversion factor converting TDS (mg/l) to EC (mS/m).

6.6.2 INPUT DATA AND ITS USE

$TDScu_{t,s,r}$ is a data set of the salt concentration (mg/l) in the upper layer calculated in the WRPM as output data used as input for SMsim. The data set **$TDScu_{t,s,r}$** comprises monthly data for all years (***t***) in all irrigation blocks (***s***) for 100 stochastic runs (***r***).

$CWR_{c,m}$ is the crop water requirement percentage for each month (***m***) for all crops (***c***). The sum over ***m*** for each ***c*** gives a result of 1 = 100%.

$Thrsh_c$ is the crop (***c***) specific salinity yield reduction threshold value (mS/m) (assumed constant for all irrigation blocks)

$Grad_c$ is the crop (***c***) specific salinity yield reduction gradient value (ton/ mS/m) (assumed constant for all irrigation blocks)

$P_{c,y,s}$ is an array of different crop (***c***) prices (R/ton) in each year (***y***) and in each irrigation block (***s***). An assumption of the model is constant prices over the 15 years therefore ***y*** remains unchanged, however the price $P_{c,y,s}$ can change between irrigation blocks.

$I_{fi,c,y,s}$ are the fixed input costs (***fi***) i.e. seed, fertilizer, chemicals, etc. (R/ha), for the different crops (***c***) which remain unchanged in each year (***y***), but which can change between irrigation blocks (***s***).

$I_{yi,c,y,s}$ are the yield dependent production costs (***yi***) i.e. harvesting, packaging, transport, etc. (R/ton), for the different crops (***c***) in each year (***y***) and in each irrigation block (***s***).

6.6.3 MODEL CORE

The core of the model is Equation 6.1 where reduced crop yield due to salinity ($Ys_{c,y,s,r}$) is related to a per hectare financial value, namely $TGMASCh_{c,y,s,r}$ (Total Gross Margin Above Specified Costs).

Equation 6.1:

$$TGMASCh_{c,y,s,r} = Ys_{c,y,s,r} * P_{c,y} - \sum I_{fi,c,y,s} - \sum I_{yi,c,y,s} * Ys_{c,y,s,r}$$

where:

$TGMASCh_{c,y,s,r}$ is the TGMASC per hectare (R/ha) for each crop (***c***) in each year (***y***) in each irrigtion block (***s***) for each stochastic run (***r***)

$Ys_{c.y.s.r}$ is the new yield (ton / ha) as impacted on by salinity for each stochastic run (***r***)

$P_{c,y,s}$ are the different crop (***c***) prices (R/ton) in each year (***y***) and in each irrigation block (***s***)

$I_{fi,c,y,s}$ are the fixed input costs (***fi***) i.e. seed, fertilizer, chemicals, etc. (R/ha), for the different crops (***c***) which remain unchanged in each year (***y***), but which can change between irrigation blocks (***s***).

$I_{yi,c,y,s}$ are the yield dependent production costs (***yi***) i.e. harvesting, packaging, transport, etc. (R/ton), for the different crops (***c***) in each year (***y***) and in each irrigation block (***s***).

$I_{fi,c,y,s}$ and **$I_{yi,c,y,s}$** are accounted for right through to the macro level model as their individual sub-components where the regional and secondary impact of each of the sectors supplying the inputs is determined.

Equation 6.2 converts per hectare TGMASCh to irrigation block level TGMASCs by adding the products of the per hectare TGMASCs, irrigation block irrigable areas (SA) and cropping percentage (CP) for each irrigation block.

Equation 6.2: $TGMASCs_{y,s,r} = \sum_c TGMASCh_{c,y,s,r} * SA_s * CP_{c,s}$

where:

$TGMASCs_{c,y,s,r}$	is the irrigation block TGMASC (R) of crop (***c***) planted in irrigation block (***s***) for each year (***y***) and stochastic run (***r***)
SA_s	is the Irrigation block irrigated area
$CP_{c,s}$	Percentage of crop (***c***) planted per irrigation block (***s***) (= % planted per representative farm)

Equation 6.3 and Equation 6.4 distinguishes the irrigation blocks into OR-WUA and OV-WUA blocks, adding the WUA level blocks to provide the two WUA level (***sr*** and ***sv***) annual (***y***) TGMASC results for each stochastic run (***r***).

Equation 6.3: $TGMASCwr_{y,sr.r} = \sum_{sr} TGMASCs_{y,sr.r}$

where:

$TGMASCwr_{y,sr,r}$ is the OR-WUA level (***sr***) annual TGMASC for each stochastic run (***r***)

Equation 6.4: $TGMASCwv_{y,sv,r} = \sum_{sv} TGMASCs_{y,sv,r}$

where:

$TGMASCwv_{y,sv,r}$ is the OV-WUA level (***sv***) annual TGMASC for each stochastic run (***r***)

Equation 6.5 calculates regional annual TGMASC for each of the 100 stochastic model runs (***r***)

Equation 6.5: $TGMASCr_{y,r} = \sum_s TGMASCs_{y,s,r}$

where:

$TGMASCr_{y,r}$ is the regional level TGMASC for each year (***y***)

Equation 6.6 calculates the 15 year cumulative TGMASC for each of the 100 stochastic model runs (***r***)

Equation 6.6: $TGMASCrc_r = \sum_y TGMASCr_{y,r}$

where:

$TGMASCrc_r$ is the regional level TGMASC for the full number of years examined (15 years in this model) for each stochastic run (***r***)

The agragation of the 100 stochastic run results of the various TGMASC are discussed as model results in Chapter 8 of this thesis.

6.7 MICRO ECONOMIC MODEL INPUT / OUTPUT LINKAGES

Inputs into the micro-economic model include:

- per hectare basis CEB data (SMCEBs.xls),
- sub-WUA (/irrigation block) level setup data (SMsub-WUA.xls), and
- hydrology model output data generated from the WRPM; specifically CU, measuring the salt concentration in the upper zone of the irrigation block (...CUallScen.xls).

As an output, CEB component specific irrigation block level data for the average scenario and stochastic runs 001, 044 and 080, are arranged in a collection of files (...ISMmicro-out.xls) for each scenario for use as input in the regional economic model (...ISIM.Macro.xls) as described in Appendix 1.

6.8 MACRO ECONOMIC LINKAGE

The micro-economic model, SMsim, provides an annual total value of production and inputs used data-set for use in the regional economic model, ISIM. This includes the annual gross farm income and all the production and harvest variable inputs cost for each crop in the two WUAs. The macro-economic model determines the secondary impacts on the economy and on job creation of the micro-economic economic modelled effects of changes in yield due to salinity. The changes in the total value of production and in GGP (Gross Geographical Product) are incorporated in the ISEW as the production effect (economic indicator), and the jobs created, as the social indicator. The change in salt flux in the soil is a direct link between the bio-physical models (WRMP) and the regional economic model, to provide the environmental leg for the ISEW (see Viljoen *et al.* 2006).

6.9 SUMMARY

This chapter starts by indicating the reasons for using a dynamic simulation model instead of a dynamic optimisation model. The nature and extent of data availability, the complexity of sub-models, as well as research budget, research time and human resource constraints, are some of the main reasons.

The spatial dimensions of the model are delineated to build from per hectare level CEBs to irrigation block level and higher up. The CEBs set up on a per hectare level are differentiated according to the various irrigation block characteristics. After determining the impact on yield on a gross margin per hectare level, the adjusted per hectare CEBs are multiplied by the irrigation block irrigable area (see scheduled areas in **Table 2.4**) to get irrigation block level CEBs. The assumption is that an irrigation block is one big farm, repeating exactly the same cropping combination for 15 years at the same 2005 base year crop prices. Irrigation blocks are combined to make up their respective WUAs, and the two WUAs combined to form the irrigation industry input for the regional economic model.

The temporal dimensions of the model are delineated to monthly, annual and 15 year cumulative results. The model aims to simulate over a range of 100 stochastic runs the per hectare financial impacts and possible range of financial results due to salinisation for different irrigation blocks annually and over 15 years. Data requirements are discussed in this chapter with particular reference to the primary data collected through mainly expert panel opinion and the secondary data obtained predominantly from GWK and the WUA WMPs.

The mathematical specification of the model is an expansion of per hectare level CEBs to per hectare TGMASCs, expanded to irrigation block and WUA level TGMASC results for use in micro-level analysis and as input into the regional economic model. Farm level analysis incorporating the fixed cost component is not conducted in this thesis as for the scope of the project a broader analysis was applicable.

The data input requirements, and data outputs of the micro-economic model are discussed in the final paragraph of this chapter, explaining the interdisciplinary linkage from bio-physical to micro-economic to regional models.

CHAPTER 7 DESCRIPTION OF SCENARIOS MODELLED

A greater volume of information or greater attention to accuracy increases the cost and complexity of monitoring without necessarily impacting the final management decisions.

Stirzaker* et al *(2004)

7.1 INTRODUCTION

The aim of this chapter is to present information on the scenarios modelled during this research:

- first the rationale in selecting scenarios is presented,
- then the different scenarios are specified with regard to crop composition,
- criteria used in testing the executeability of the scenarios is discussed (scenario setup checks), and
- interpretation of scenario results for a number of stochastic runs is presented

The chapter concludes with a summary of the scenario setup process and key features of each scenario.

7.1.1 RATIONALE

Confronted with different hydrology cycles and associated irrigation water salinity regimes, farmers would like to know what the impact of different farm management options can be on the profitability of farming for the different situations. Two obvious farm management options would be to change the crop composition and to change the leaching and drainage practices. Scenarios were thus developed to investigate the impact of these options on a per hectare crop enterprise budget (CEB) level, irrigation block level, Water Users Association (WUA) level and regional level.

The number of scenarios that could be evaluated are many, consisting of endless cropping, resource base and management combinations, but the challenge is to identify only the key scenarios for critical evaluation within the time and resource constraints of the project.

The retirement of saline land is not included as a scenario as most farmers have more irrigable land than they have water rights, and there is sufficient new land to develop for irrigation. Irrigable land is therefore not a constraint, but water rights to irrigate with.

7.1.2 SCENARIO SETUP PROCESS

The following five scenarios are setup and discussed in this chapter:

1. The **base-case scenario** is set up to reflect status quo conditions for the base year of 2005
2. **Scenario 1** is set up with status quo drainage, but with a more salt tolerant cropping composition
3. **Scenario 2** is set up with status quo drainage, but with a more salt sensitive, (yet higher value) cropping composition
4. **Scenario 3** is set up with the same salt sensitive (yet higher value) cropping composition as in scenario 2, but with additional drainage and leaching

5. **Scenario 3+** is exactly the same as scenario 3 except that the infrastructure cost of the additional leaching and drainage is factored into the irrigation water usage charge.

Paragraphs 7.2 to 7.6 discuss the base-case, scenarios 1 to 3+ respectively as set out in Table 7.1 below.

Table 7.1. The 5 scenarios set up for analysis based on crop choice and drainage

		CROP CHOICE		
		status quo	more salt tolerant	more salt sensitive yet higher value
DRAINAGE	status quo	**Base-case**	**Scen1**	**Scen2**
DRAINAGE COSTS	increased *Not factored in*	-	-	**Scen3**
	increased *factored in*	-	-	**Scen3+**

Table 7.2 and Table 7.3 compare the setup data of the scenarios in Table 7.1 according to the crop choice combinations, checking the reality of the combinations against the change in water use patterns brought about. Improved drainage is only applicable in scenarios 3 and 3+.

Table 7.2. Percentage cropping composition and changes of the different scenarios

	% Crop composition for different scenarios			% change from the base-case	
Crops	*Base-case*	*High Value*	*Salt Tolerant*	*High Value*	*Salt Tolerant*
Barley	5.08	4.5	6.2	-11	22
Beets	0.09	0.09	0.89	0	881
Carrots	1.70	2.3	1.3	32	-22
Cotton	0.86	1.4	11.5	57	1235
Cucurbits	1.87	4.5	1.3	141	-29
Dry Beans	0.90	4.5	0.4	400	-51
Fruit	*0.01*	0.5	*0.01*	4405	-11
Lucerne	16.18	15.3	6.2	-5	-62
Maize	64.62	54.1	44.3	-16	-32
Olives	0.20	0.3	0.3	38	35
Onions	1.23	1.3	0.1	2	-94
Pastures	6.09	4.5	15.0	-26	147
Peanuts	2.01	3.6	0.9	79	-56
Pecan nuts	0.79	1.4	*0.7*	71	-11
Potatoes	3.99	5.4	3.5	36	-11
Soybeans	0.25	2.7	0.2	991	-29
Sunflower	3.83	3.6	11.5	-6	201
Vegetables	0.24	0.9	0.3	280	12
Vineyards	1.75	*2.1*	*2.1*	20	18
Wheat	51.10	49.56	53.11	-3	4
TOTAL	**162.78**	**162.32**	**159.82**	***64.85***	***21.48***

The percentage cropping composition of the 20 main crops (column 1) grown in the study area is shown in column 2 in Table 7.2. The total of 162.78% for the base-case indicates that farmers in the whole study area are planting an average of 1.62 crops per irrigated area per year. This factor is used as an indicator in setting up new cropping scenarios. The total for the more salt sensitive yet higher value crop selection is 162.32% and for the salt resistant crop selection 159.82%. The adjusted areas for salt sensitive yet high value crops (column 3) and salt tolerant crops (column 4) were finalised in consultation with agriculturalists in the study area.

7.2 BASE CASE SCENARIO

The first step in setting up the scenarios is to update the irrigation block module data files of the WRPM to reflect a certain base level of actual irrigation conditions. This set of data, setup for the base level year of 2005 serves as the base-case scenario. Extreme care is taken in setting up the base case, as it is the common basis from which all the scenarios are adapted, where, for the different scenarios, various factors relating to cropping choice and drainage are changed to analyse the impacts of different cropping patterns and drainage installation scenarios. All other WRPM setup factors not mentioned above are assumed the same as the initial setup values as determined by Allen and Herold (1988). The calculations of these factors are done in the scenario setup file, which is part of a group of files making up the Biophysical sub-model as described in Chapter 5.

Table 7.3. The area (ha) cropping composition of different scenarios in the study area

	Crop area (ha) of different scenarios			Change from base-case (ha)	
	Base-case	**Tolerant**	**Sensitive**	**Tolerant**	**Sensitive**
Barley	1 229	1 091	1 501	-138	271
Beets	22	22	214	-0	193
Carrots	412	546	322	133	-91
Cotton	209	327	2 787	119	2 578
Cucurbits	452	1 091	322	639	-130
Dry Beans	218	1 091	107	873	-111
Fruit	-	109	2	109	2
Lucerne	3 919	3 710	1 501	-209	-2 418
Maize	15 650	13 093	10 720	-2 556	-4 930
Olives	48	66	64	18	17
Onions	299	306	19	7	-279
Pastures	1 475	1 091	3 645	-384	2 169
Peanuts	487	873	214	386	-272
Pecan nuts	191	327	169	136	-22
Potatoes	966	1 309	858	343	-109
Soybeans	60	655	43	595	-17
Sunflower	927	873	2 787	-54	1 860
Vegetables	57	218	64	161	7
Vineyards	425	512	503	87	78
Wheat	12 375	12 002	12 863	-373	489
TOTAL	**39 422**	**39 312**	**38 705**	**-110**	**-716**

Table 7.4 forms the basis for the calculation of the cropping composition percentage index for the different scenarios for the whole scheme shown in Table 7.2. Table 7.4 together with index Table 7.2 therefore form the basis from which Table 7.5, Table 7.6 and Table 7.7 are calculated.

Table 7.4. The cropping composition of the 4 irrigation blocks on which the Base-case scenario is based

	Vall	RloR	Rscm	Rszb	
Irrigaton Block Code:	*5*	*482*	*239*	*479*	***TOTAL***
Area (ha)	*7 389.6*	*3 852.8*	*12 335.1*	*641.2*	***24 218.7***
Barley	7.1%	4.7%	4.2%	0.0%	**1 229.4**
Beets	0.0%	0.0%	0.2%	0.0%	**21.9**
Carrots	0.1%	0.0%	3.3%	0.0%	**412.9**
Cotton	0.0%	0.4%	1.6%	0.0%	**208.8**
Cucurbits	1.1%	0.2%	2.9%	0.0%	**451.9**
Dry Beans	0.0%	0.5%	1.5%	3.1%	**218.4**
Fruit	0.0%	0.0%	0.0%	0.0%	**0.0**
Lucerne	22.5%	9.0%	15.5%	0.0%	**3 919.0**
Maize	53.5%	68.5%	69.2%	81.6%	**15 649.7**
Olives	0.1%	0.0%	0.3%	0.0%	**47.5**
Onions	1.7%	2.9%	0.5%	0.0%	**298.7**
Pastures	3.8%	1.4%	9.2%	0.0%	**1 475.4**
Peanuts	0.0%	2.8%	3.1%	0.0%	**486.6**
Pecan nuts	1.1%	0.0%	0.9%	0.0%	**191.3**
Potatoes	2.6%	11.8%	2.0%	12.0%	**966.1**
Soybeans	0.0%	0.0%	0.5%	0.0%	**60.0**
Sunflower	4.5%	2.3%	3.2%	17.0%	**926.7**
Vegetables	0.1%	0.2%	0.4%	0.0%	**57.4**
Vineyards	2.3%	1.1%	1.7%	0.0%	**424.9**
Wheat	50.1%	79.0%	45.7%	0.0%	**12 375.0**
TOTAL	**150.7%**	**184.7%**	**165.7%**	**113.7%**	**39 421.5**
		Study area level base-case cropping percentage:			**162.77%**

Table 7.5. Base Case areas (ha) planted to various crops in the irrigation blocks

Base scenario	*Vall*	*RloR*	*Rscm*	*Rszb*	TOTAL
Area (ha)	7 390	3 853	12 335	641	**24 219**
Barley	526	182	522	0	**1 229**
Beets	3	0	19	0	**22**
Carrots	10	0	403	0	**413**
Cotton	0	14	195	0	**209**
Cucurbits	83	8	361	0	**452**
Dry Beans	0	18	180	20	**218**
Fruit	0	0	0	0	**0**
Lucerne	1 660	346	1 913	0	**3 919**
Maize	3 955	2 638	8 534	523	**15 650**
Olives	10	0	38	0	**48**
Onions	129	111	59	0	**299**
Pastures	282	53	1 140	0	**1 475**
Peanuts	0	108	378	0	**487**
Pecan nuts	80	0	111	0	**191**
Potatoes	192	454	243	77	**966**
Soybeans	0	0	60	0	**60**
Sunflower	335	87	396	109	**927**
Vegetables	7	7	43	0	**57**
Vineyards	167	44	214	0	**425**
Wheat	3 699	3 044	5 632	0	**12 375**
TOTAL ha	**11 137**	**7 114**	**20 441**	**729**	**39 422**
		Study area level base-case cropping percentage:			**162.77%**

7.3 SCENARIO 1: STATUS QUO DRAINAGE AND LEACHING WITH SALT TOLERANT CROPS

For scenario 1, a salt tolerant cropping combination is selected, taking precaution not to exceed expert opinion and physical infrastructure constraints that the new cropping compositions would place. Artificial drainage and leaching is kept constant at the base case scenario level. The reason for choosing a scenario with more salt tolerant crops planted is to be able to compare the benefits of management option of drainage versus changing cropping composition to more tolerant crops. If for instance strict regulation and heavy fines were to be implemented on irrigation returnflows then this would be one of the few salinity mitigation management options available. Furthermore, for financially poor farmers the exorbitant capital outlay required by the installation of artificial drainage, if not subsidised, would also limit this option leaving virtually only the option of planting salt tolerant crops.

A scenario of increased drainage together with salt tolerant crops would be superfluous in the study area in question as the irrigation water and soils' salinity is far from being so bad that even salt tolerant crops would need drainage and leaching. The salt tolerant crops are also generally lower value crops, or crops with limited room for expansion due to a very limited or closed market, or as with sugar beet, the large area required to create the economies of scale to justify the creation of new facilities to process it.

Table 7.6 lists the hectares calculated for planting the salt tolerant cropping combination for scenario 1. For the study area as a whole, very close to 160% of the area is planted, indicating 1.6 crops per area per year. The main crops planted in scenario 1 are wheat (12 963 ha), followed by maize (10 720 ha – less than in base case), pastures (3 645 ha – less than in base case), sunflowers and cotton (both 2 787ha), barley and lucerne (both 1 501 ha each) and beets (214 ha – up from 22 ha in the base case). See Table 7.3 for the change in hectares from the base-case.

Table 7.6. Scenario 1: Area (ha) planted to a more salt resistant cropping combination

Salt Resistant scenario (ha)	*Vall*	*RloR*	*Rscm*	*Rszb*	**TOTAL**
Area (ha)	7 390	3 853	12 335	641	24 219
Barley	641.7	222.4	636.6	-	**1 501**
Beets	25.6	-	188.8	-	**214**
Carrots	7.8	-	313.8	-	**322**
Cotton	-	186.9	2 600.2	-	**2 787**
Cucurbits	59.3	5.3	257.0	-	**322**
Dry Beans	-	8.8	88.5	9.8	**107**
Fruit	0.7	0.3	1.1	0.1	**2**
Lucerne	635.7	132.6	732.4	-	**1 501**
Maize	2 708.7	1 806.8	5 845.8	358.2	**10 720**
Olives	12.9	-	51.5	-	**64**
Onions	8.3	7.2	3.8	-	**19**
Pastures	697.3	131.7	2 815.6	-	**3 645**
Peanuts	-	47.8	166.6	-	**214**
Pecan nuts	70.9	-	98.5	-	**169**
Potatoes	170.7	403.2	215.3	68.3	**858**
Soybeans	-	-	42.9	-	**43**
Sunflower	1 006.7	261.7	1 191.0	327.8	**2 787**
Vegetables	7.8	7.8	48.6	-	**64**
Vineyards	197.6	51.8	253.6	-	**503**
Wheat	3 845.5	3 163.8	5 854.1	-	**12 863**
TOTAL ha	**10 097**	**6 438**	**21 406**	**764**	**38 705**
		Study area level scenario 1 cropping percentages:			**159.82%**

7.4 SCENARIO 2: STATUS QUO DRAINAGE AND LEACHING WITH SALT SENSITIVE (AND HIGHER VALUE) CROPS

For scenario 2, a salt sensitive yet high value cropping combination is selected, taking careful precaution not to exceed expert opinion and physical infrastructure constraints the new cropping compositions would place. Artificial drainage and leaching is kept constant at the base case scenario level.

Table 7.7 lists the hectares calculated for planting to salt sensitive yet higher value cropping combinations for scenarios 2 and 3. For the study area as a whole, just over 162% of the area is planted, indicating 1.62 crops per area unit per year. The main crops planted in scenarios 2 and 3 are maize (13 093 ha – still less than in the base case scenario) followed by, wheat (12 002 ha), lucerne (both 3 710 ha), potatoes (1 309 ha) and barley, cucurbits, dry-beans and pastures (all 1 091 ha). See Table 7.3 for the change in hectares from the base-case.

Scenario 2 lists only the cropping area changes to more sensitive, yet higher value crops, to test whether the increased returns from higher value crops would compensate for the reduced yields due to salinity. Furthermore, a scenario is also run (just through the micro-economic model) for optimal yield, where the reduced yield due to salinity is replaced with maximum yield, to give an indication of the maximum productivity of the irrigation blocks under optimal conditions without the impact of salinity.

Table 7.7. Scenario 2 and 3: Area (ha) planted to a Salt Sensitive / Higher Value cropping combination

High Value scenario (ha)					
	Vall	*RloR*	*Rscm*	*Rszb*	TOTAL
Area (ha)	7 390	3 853	12 335	641	24 219
Barley	467	162	463	-	**1 091**
Beets	3	-	19	-	**22**
Carrots	13	-	532	-	**546**
Cotton	-	22	305	-	**327**
Cucurbits	201	18	872	-	**1 091**
Dry Beans	-	90	901	100	**1 091**
Fruit	33	17	56	3	**109**
Lucerne	1 572	328	1 810	-	**3 710**
Maize	3 309	2 207	7 140	438	**13 093**
Olives	13	-	52	-	**65**
Onions	132	114	60	-	**306**
Pastures	209	39	843	-	**1 091**
Peanuts	-	194	678	-	**873**
Pecan nuts	137	-	190	-	**327**
Potatoes	261	616	329	104	**1 309**
Soybeans	-	-	655	-	**655**
Sunflower	315	82	373	103	**873**
Vegetables	27	27	165	-	**218**
Vineyards	201	53	258	-	**512**
Wheat	3 588	2 952	5 462	-	**12 002**
TOTAL ha	**10 479**	**6 920**	**21 165**	**747**	**39 312**
	Study area level scenario 2 and 3 cropping percentages:				**162.32%**

7.5 SCENARIO 3: IMPROVED DRAINAGE AND LEACHING WITH SALT SENSITIVE (AND HIGHER VALUE) CROPS

In scenario 3 the same cropping combination is used as in scenario 2, but artificial drainage and leaching is accounted for by increasing the return-flow factor by 15% to calculate the financial benefits of increased leaching and drainage.

By reducing salinisation with additional artificial drainage and leaching, production risks for salt sensitive crops are reduced, automatically resulting in farmers planting an increased area to these generally higher value salt sensitive crops. On the other hand, the increased returns from planting higher value crops can justify the increased drainage to improve the sustainability of the farm.

7.6 SCENARIO 3+: IMPROVED DRAINAGE AND LEACHING WITH SALT SENSITIVE (AND HIGHER VALUE) CROPS – ADDITIONAL DRAINAGE COSTS FACTORED IN

A scenario 3+ is run, set up exactly like scenario 3, except that the additional costs of increased leaching and drainage are factored into the water costs, to test if the additional outlay could be justified by higher returns.

The factors used in calculating the annual repayments in scenario 3+ are as follows:

- Installation of artificial drainage **R 30 000**[1] per ha (in-between the cost of drainage for medium and heavy soils – see Table 6.2, and slightly inflated for the average soil types irrigated in the study area, to include in the costs of drainage other secondary / hidden costs),
- A sustainability grant portion of **10%, 50%** and **100%** of the total drainage costs;
- repaid over a period of **15, 20, 25** and **30** years, and
- at a **9%** interest rate (subsidised at prime = 11% in 2005, minus 2%), and for policy analysis discount rates of **0%, 5%, 8%** and **10%**.

These factors are all variables and can be changed to determine the impacts of different combinations of the assistance grant, term and interest rate on the repayment-ability (liquidity) of the farmers. The results are discussed further in Chapter 9 that deals with the various policy options.

7.7 SCENARIO SETUP CHECKS

Two checks are done, namely a water check and an area check. Table 7.8 indicates the change in monthly water use brought about by the change in cropping composition from the base-case (*status quo*) to salt tolerant and salt sensitive (yet high value) cropping composition scenarios. The two columns on the right indicate the unit change in water consumption for the salt sensitive (yet high value) and salt tolerant scenarios. Results for the salt sensitive (high value) scenario show that less water will also be used in each month, except for May and June, a considerable environmental benefit for a water scarce country. May and June are the months in which

[1] Note: drainage costs can range from R12000-R15000 on sandy soils (<15% clay), R20000-R25000 on Medium soils (15-35% clay), and R30000-R50000 on heavy soils (>35% clay) – see Table 6.2.

the least water is historically used, so there is therefore little chance of exceeding the delivery capacity of the study area in these two months.

As a benchmark of the maximum capacity of the study area, the highest monthly value in the base-case scenario is used, namely 1 345 690 000 m^3. In both the salt sensitive (high value) and salt tolerant scenarios, water demand in this critical month (February) is reduced by 10% and 26% respectively. The maximum water demand of all the months in the salt sensitive (high value) scenario occurs in February and is 10% less than the critical February maximum of the base-case. The maximum water demand in the salt tolerant scenario occurs in October, where the demand is 5% less than in the base year. In the salt tolerant scenario the base-case water requirements are also exceeded in July and August, the second least critical months after May and June.

The large reduction in water demand for the salt resistant scenario for the months from December to April, results in a net reduction of water demanded for the salt resistant scenario of 16.82% versus the 6.74% reduction for the salt sensitive scenario (% change in Table 7.8). This option could therefore results in a more even distribution of monthly water demand, reducing the management load and probability of distribution losses.

Table 7.8. Water use (m^3 '000 / month) for the OV-WUA for different scenarios[1]

			(m^3 '000 / month)		*% change from base*	
		Base	***Salt Sensitive***	***Salt Tolerant***	***Salt Sensitive***	***Salt Tolerant***
Pre – year	Jul	119 186	116 940	125 766	*-0.02*	*0.06*
	Aug	246 213	240 278	260 775	*-0.02*	*0.06*
	Sep	733 479	706 793	707 597	*-0.04*	*-0.04*
	Oct	**1 193 960**	**1 149 702**	**1 136 866**	***-0.04***	***-0.05***
	Nov	1 109 372	1 073 072	1 006 182	*-0.03*	*-0.09*
Aft – year	Dec	701 133	649 570	430 462	*-0.07*	*-0.39*
	Jan	**1 137 043**	**1 045 197**	**789 427**	*-0.08*	*-0.31*
	Feb	**1 345 690**	**1 215 916**	**996 910**	***-0.10***	***-0.26***
	Mar	**1 117 949**	**1 006 114**	**921 737**	*-0.10*	*-0.18*
	Apr	400 732	352 639	338 405	*-0.12*	*-0.16*
	May	21 283	21 260	34 157	*-0.00*	*0.60*
	Jun	13 699	14 010	22 126	*0.02*	*0.62*
Scenario TOTAL		**8 139 740**	**7 591 491**	**6 770 409**		
% change:		***100.00%***	***-6.74%***	***-16.82%***		
Total change from Base:			**-548 249**	**-1 369 331**		
Monthly extremes compared to check delivery exceedance						
Min		**13 699**	14 010	22 126	***0.02***	***0.62***
Max		**1 345 690**	1 215 916	1 136 866	***-0.10***	***-0.26***
Pre- and Aft- years compared						
Pre-	Total	3 402 211	3 286 785	3 237 186	*-0.03*	*-0.05*
Aft-	Total	4 737 529	4 304 706	3 533 224	*-0.09*	*-0.25*
TOTAL SEASON CHANGE		8 139 740	7 591 491	6 770 410	***-0.07***	***-0.17***

[1] The OV-WUA irrigation block is used for testing that new water demand does not exceed delivery capacity because it has two water seasons, a pre-year and an after-year, with water being relatively more scares in the pre-year than in the other irrigation blocks. The OV-WUA is also more limited in its options for acquiring additional water than the OR-WUA irrigation blocks.

From the comparison it follows that the two alternative cropping choice scenarios selected will not exceed the monthly water supply capacity of the study area. Both will actually contribute to a more even distribution of water demand over the year, especially the salt tolerant scenario, effectively reducing water delivery risk and capacity strain on the delivery network.

7.8 STOCHASTIC HYDROLOGY RUNS

For each scenario discussed in this chapter, 100 stochastic model runs are completed as described in Chapter 4. These runs depict 100 possible monthly sequences based on statistical analysis of approximately 70 years of actual recorded data from 1920-1994 (van Rooyen, *et al.* 2004b).

These stochastic runs implicitly model the following:

- seasonal hydrology
- long-term wet and dry cycles
- unexpected exceptional flood / drought events

These extremes and trends are not run as separate scenarios, but the 0.05 (lower sequence in graph) and 0.95 (higher sequence in graph) percentile results of the 100 runs are calculated and analysed to point out the effect and impact of these extremes and trends as a separate analysis within a scenario. As the 0.05 and 0.95 percentiles are only averages, actual stochastic sequences are selected which best fit the cumulative total gross margin above specified costs (TGMASC) described in Chapter 6, and as depicted in Figure 7.1. Stochastic run (SR) 001, 044 and 080 are selected from the 100 stochastic runs of each year to represent the 0.05 and 0.95 percentile extremes and 0.50 percentile "average" respectively in the discussion of scenario results that follows in Chapter 8.

When viewing the TGMASC as cumulative results in Figure 7.1 as compared with the annual TGMASC results in Figure 7.2, the close fit of stochastic runs 001, 044 and 080 to the 0.05, 0.95 and 0.50 percentiles can no longer be observed. The selected stochastic runs however represent the realistic fluctuation of events and capture the dynamic nature of the data far better than the percentile sequences.

Furthermore, the stochastic runs are useful in comparing a realistic "best case", "worst case" and "average case" probability of events for each irrigation block, such as depicted in Figure 7.3. In Figure 7.3 the stochastic spread of the saturated soil salinity concentration, CUe (mg/l) in the four irrigation blocks is compared, using only the selected stochastic runs to show the extent of variation.

Each specific stochastic run in the WRPM, models a sequence of catchment level hydrology of which the area analysed in this study forms only a very small part, encompassing the four irrigation blocks. Stochastic run 080 for example in the Lower Riet irrigation block is set up with the same hydrology reference as stochastic run 080 for all the other scenarios as well as in all the other irrigation blocks, as all the irrigation blocks are linked in a hydrologic sequence.

For the analysis of the stochastic runs, the more realistic selected "best case", "worst case" and "average case" stochastic runs are used for each of the 5 main scenarios as set up and described in sections 7.2 to 7.6.

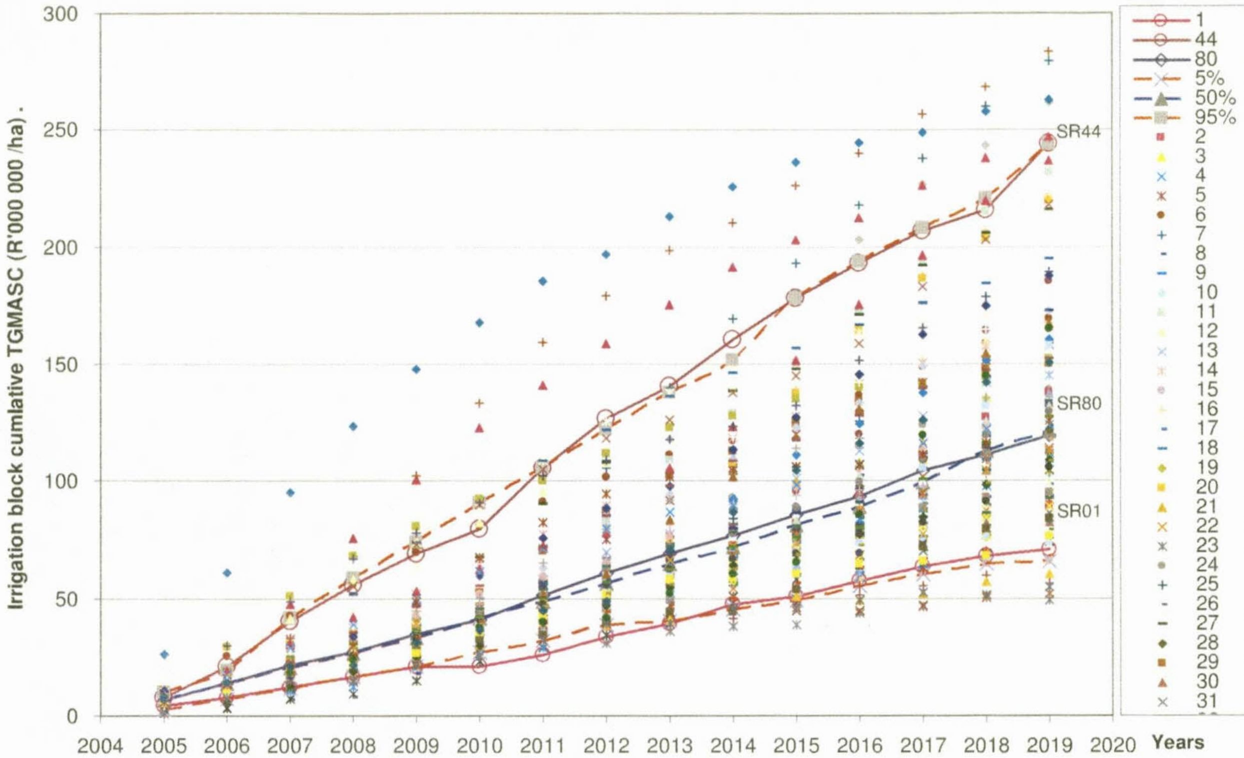


Figure 7.1. Cumulative TGMASC of the Lower Riet irrigation block (*RloR*) base-case scenario run for the selection of specific stochastic runs to analyse as "best-" "average-" and "worst-case" hydrology sequences when comparing scenarios

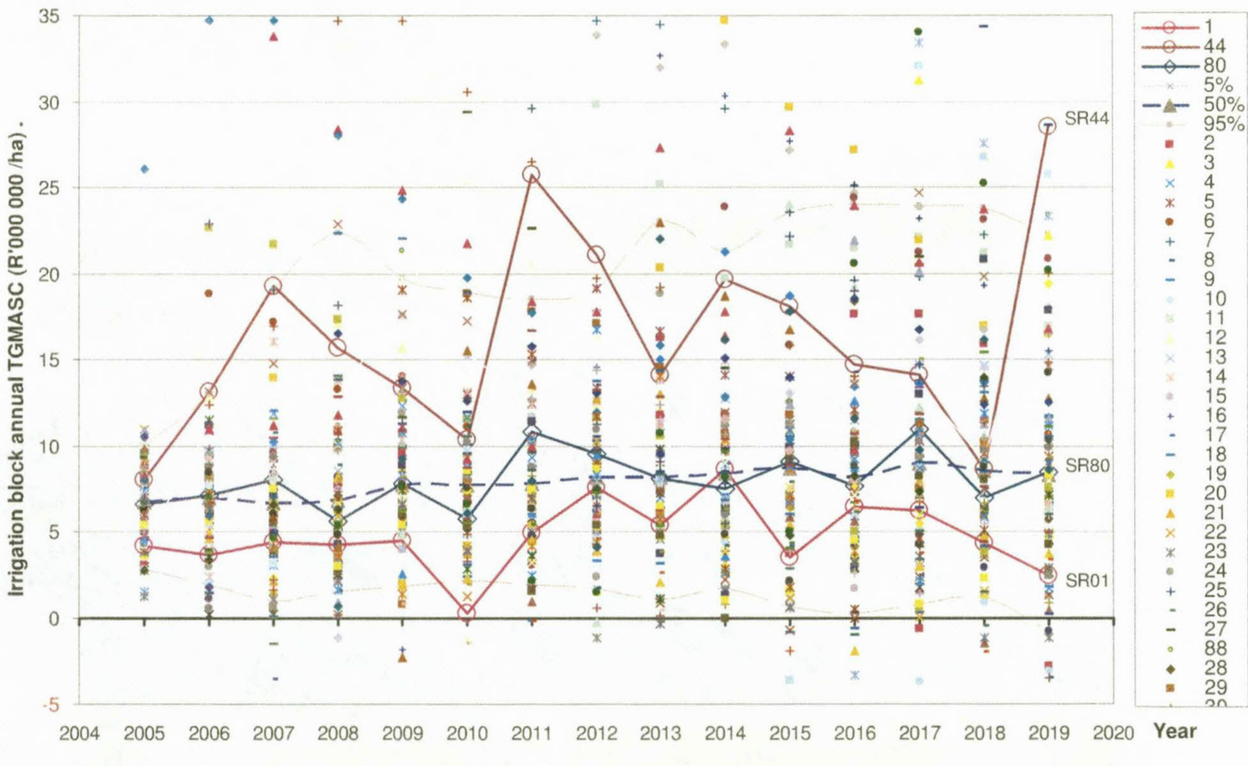


Figure 7.2. Annual TGMASC for the *RloR* base-case scenario over 15 years for 100 stochastic runs showing selected stochastic runs 1, 80 and 44 in relation to the 0.05, 0.50 and 0.95 percentiles

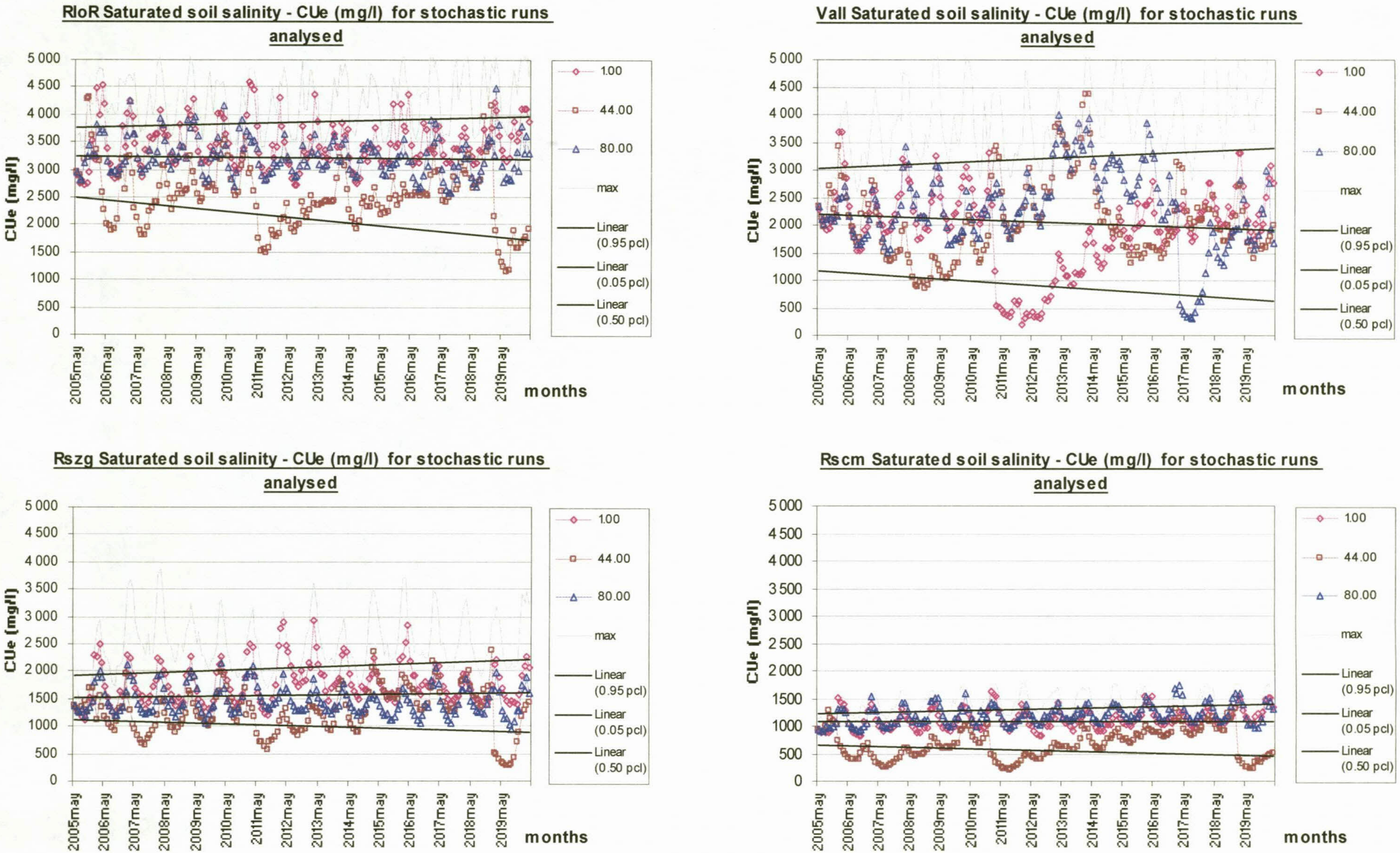


Figure 7.3. A comparison of saturated soil salinity concentrations - CUe (mg/l) - in different irrigation blocks for the Base Case stochastic runs analysed, with linear trends indicated

7.9 IRRIGATION BLOCKS COMPARED

Figure 7.3 consists of a comparison of the saturated salt concentration values in the upper zone (CUe) over 15 years in the Lower-Riet (***RloR***), Scholtzburg (***Rszg***), Riet Scheme (***Rscm***) and Orange Vaal WUA (***Vall***) irrigation blocks. The CUe values of stochastic runs 001, 044 and 080, as well as the linear trends of the 0.05, 0.50 and 0.95 percentile values are depicted in each of the four graphs to enable easy comparison and trend evaluation. Maximum CUe values for each irrigation block are also drawn in light grey to show the frequency over 15 years that certain thresholds are reached.

In Figure 7.3 ***RloR*** consistently has the highest CUe values of all irrigation blocks for all three stochastic runs, with maximum values exceeding 5000 mg/l almost yearly. The 0.05 percentile trend line decreases at a sharper gradient than the other irrigation blocks, the 0.50 percentile trend line is very level and the 0.95 percentile trend line increases only slightly.

Although in comparison, ***Vall*** in Figure 7.3 shows an average magnitude decrease in CUe of approximately 1000 mg/l, the ***Vall*** irrigation block displays a more dramatic fluctuation of CUe values for all three stochastic runs, with maximum values also reaching 5000 mg/l every few years. In comparison with ***RloR,*** the 0.05 percentile trend line also decreases at a steep gradient, but the 0.50 percentile trend line also decreases as opposed to all the other irrigation blocks, possibly indicating a sustainable improvement in the soil salinity status. This however counters the increase in the 0.95 percentile trend line, which is greater than the other irrigation blocks. The wide gap between the 0.05 and 0.95 percentiles reflects the dramatic fluctuations, and therefore production risks, in the ***Vall*** irrigation block.

At a magnitude decrease in CUe of approximately a further 1000 mg/l, is the ***Rszg*** irrigation block, and at approximately a further 500 mg/l decrease, the ***Rscm*** which gets its water predominantly from the Orange River. In the ***Rszg*** maximum values only exceed 3500 mg/l every few years and in the ***Rscm,*** maximum values never exceed 2000 mg/l. Visible in especially the ***Rszg*** and ***Rscm*** irrigation blocks are the strong seasonal cycles of the CUe.

7.10 SUMMARY

The stochastic nature of the WRPM hydrology data generated for scenario analysis necessitates selecting 3 actual stochastic model runs from the 100 that reflect the 0.05, 0.50 and 0.95 percentiles instead of only using an average, so as to capture the stochastic/dynamic nature of the data for presentation. The micro-economic model is however run for all 100 runs and the resulting data also subsequently presented as described above.

The percentiles selected of the 100 stochastic runs are in themselves worst-, average- and best-case "scenarios" of each of the main scenarios discussed.

Extreme care was taken in the setting up of the scenarios in selecting the alternative cropping compositions so as not to exceed water delivery infrastructure, processing capacity and market demand constraints. Maize area was also reduced in both the salt tolerant and salt sensitive (yet high value) scenarios in the light of the apparent short-term maize over supply of 2005 (much publicised in the media) and long-term consumer trends.

The base-case scenario is essentially the first scenario, whereby the WRPM is updated, as described in the first section of this chapter, to reflect a chosen base year; 2005 for this study. The starting point salt concentration values used in the setup of the WRPM model are manually adjusted by the WRPM operators to tale out any trend in the data. These starting points remain fixed for the other scenarios that follow.

Scenario 1 is set up using a more salt tolerant cropping combination of crops (i.e. greater area planted to wheat, barley, cotton, pastures and sunflowers) without increasing drainage and leaching from the base-case values. The objective of scenario 1 is to test the long term sustainability of this option.

For scenario 2 and 3 a more salt sensitive, yet higher yielding cropping combination (i.e. greater area planted to fruit, vegetables, legumes and potatoes) is used without increasing drainage and leaching from the base-case values for scenario 2. The objective of scenario 2 is to test if the increased profits of higher value crops would not compensate for the yield losses due to salinity. Scenario 2 is run with 100% yield to calculate an indication of the maximum productivity of the irrigation blocks.

In scenario 3 the same cropping combination is used as in scenario 2, but artificial drainage and leaching is accounted for by increasing the return-flow factor by 15% to calculate the financial benefits of increased leaching and drainage. Scenario 3+ is also run whereby the additional costs of increased leaching and drainage are factored into the water costs, to test if the additional outlay could be justified by higher returns.

A scenario showing the impact of improved drainage and leaching in status quo crops would have provided interesting results, but due to the limitation in scenarios to run, the four selected and discussed in this chapter were the priority. The option of growing more higher value crops was chosen above the status quo to examine the impact of reduced maize production (all be it only 5% less) in the light of the much speculated overproduction of maize in 2005.

The chapter concludes with a comparison of the stochastic CUe values between the four irrigation blocks. ***RloR*** clearly displays the highest CUe values, followed respectively by ***Vall***, ***Rszg*** and ***Rscm*** with the lowest values. Although ***Vall*** displays lower values than ***RloR***, the fluctuation is more dramatic and very high CUe levels are also reached, though not as frequently as in the ***RloR***.

CHAPTER 8 MICRO-ECONOMIC MODEL COMPONENT RESULTS

Salinisation usually develops insidiously over many years, and can present a serious threat to the long-term viability of an irrigation scheme.

Johnson (1994)

8.1 INTRODUCTION

The purpose of this chapter is to present the final results of the integrated suite of models up to the Micro-economic level, i.e. the economic impacts on irrigation block level as set up in the Water Resources Planning Model (WRPM).

The fifty-percentile value of 100 WRPM stochastic runs is used in presenting most of the results instead of the average, as the fifty percentile value gives a more realistic indication of the most predominant occurrence of a data series analysed than the average. Both the average and the fifty percentile however fail to account for the large variability in some cases that can be experienced and thus the five and ninety fifth percentiles were also calculated to present the data meaningfully.

The chapter starts with an explanation of the irrigation block level hydrology results for the various scenarios applicable to the economic modelling. With hydrology results showing that the Lower Riet irrigation block (***RloR***) (downstream in the Orange-Riet WUA) is the irrigation block worst affected by salinity, it is used in the results that follow as a case study example, where only one irrigation block is referred to. Results comparing all irrigation blocks are also presented.

Following the hydrology results, a worked example is used to present some of the results of the bio-physical model to show the linkage between the hydrology results and their impact on yield, which changes crop income in the economic model. An example using the per hectare crop enterprise budgets (CEBs) of the three main crops grown in the study area follows, which forms the basis for the micro-economic model. The results of the micro-economic model, the irrigation block level economic results, are then presented for 100 stochastic hydrology model runs for each scenario. Based mainly on these results, three actual stochastic runs are selected that most closely fit the 0.05, 0.50 and 0.95 percentile probability of occurrence of the fifteen year cumulative total gross margin above specified costs (TGMASC). Further analysis of the economic results proceeds using these stochastic run data sequences for each scenario.

The irrigation block level micro-economic model result linkages to the regional economic model are then discussed together with the social (change in employment patterns) and environmental (change in soil salt balance) linkages. The chapter concludes with a summary of the main results emphasising the significance of the results.

8.2 HYDROLOGY MODEL RESULTS ANALYSIS

The hydrology results consist of the processed WRPM data output. The main factor used as input in the bio-physical model is the monthly salt concentration (mg/l) in the irrigation block soil upper zone (CU). CU is converted to the monthly saturated soil concentration, CUe (mg/l) using monthly effective water volume data, HE (mm) and the maximum upper soil zone water volume capacity factor values used in the WRPM setup.

Irrigation water salinity, TDS (mg/l) changes are discussed in Paragraph 8.2.2 but as the impact of the irrigation water on the soil salinity is calculated internally in the WRPM, the irrigation water salinity is not explicitly used in the micro-economic model. As the only regular and tangible measure of the salinity status on the farm or WUA, that farmers and WUA managers respectively have, irrigation water salinity results are presented here for better clarity and understanding of the linkage to soil salinity and resulting reduced yields as shown in the sections to follow.

8.2.1 SOIL SALINITY CHANGES

Soil type is differentiated in the study in the setup of the WRPM model by varying the return-flow factors and proportion returnflows from the upper zone and lower zone factors, and by setting the water holding capacity of upper (HU) and lower zones (HL) and the target soil moisture.

Figure 8.1 is a comparison of the base-case scenario 0.50 percentile of the CUe of the various irrigation blocks, clearly showing similar definite seasonal trends for all irrigation blocks and a slight long-term trend of decreasing CUe. On the right-hand-side Y-axis, the corresponding ECe (mS/m) is listed as an indication of the TDS to EC conversion, a factor of 6.5 is used. The decreasing trend over the 15 years in Figure 8.1 is however deceiving as when one looks at the data over a longer period (25 years) there is a slightly increasing trend again. The period of analysis for this study is fifteen years and the first fifteen years as depicted in Figure 8.1 are used.

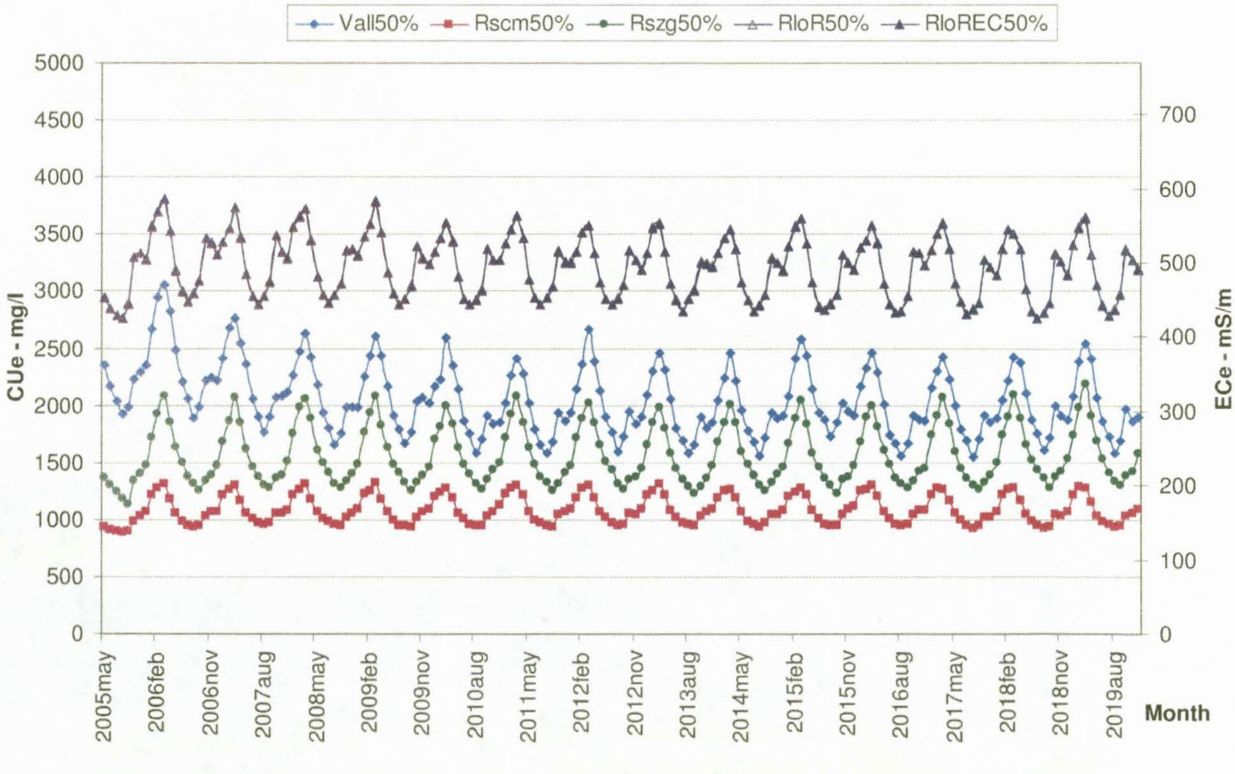


Figure 8.1. The 0.50 percentiles of 100 stochastic runs of the base-case scenario upper zone saturated soil salinity - CUe (mg/l) for all irrigation blocks

Of the scenarios tested, the largest impact on saturated extract salt concentration is clearly scenario 3 (see Figure 8.2 and Figure 8.3 for the Lower Riet and Vaal irrigation blocks respectively), where the WRPM return flow factor is increased by 15%, representing an effective increase of irrigation drainage and leaching of 15%. Changing crop composition from status quo to salt tolerant to sensitive sensitive crops, has a very small impact on the hydrology as a whole as shown by the very close correlation of lines base-case, Scen1 and Scen2 in Figure 8.2 and Figure 8.3, but increasing leaching (Scen3) clearly greatly improves soil salinity – i.e. reduced CUe.

It must be mentioned that all salts that accumulate in the study area are not only as a results of irrigation practices. Municipal, mining, stock watering, industry etc. are all users of water that contribute to the use and concentration of salts in the study area. There is also a salt wash-off module in the WRPM explained in Viljoen *et al.* (2006).

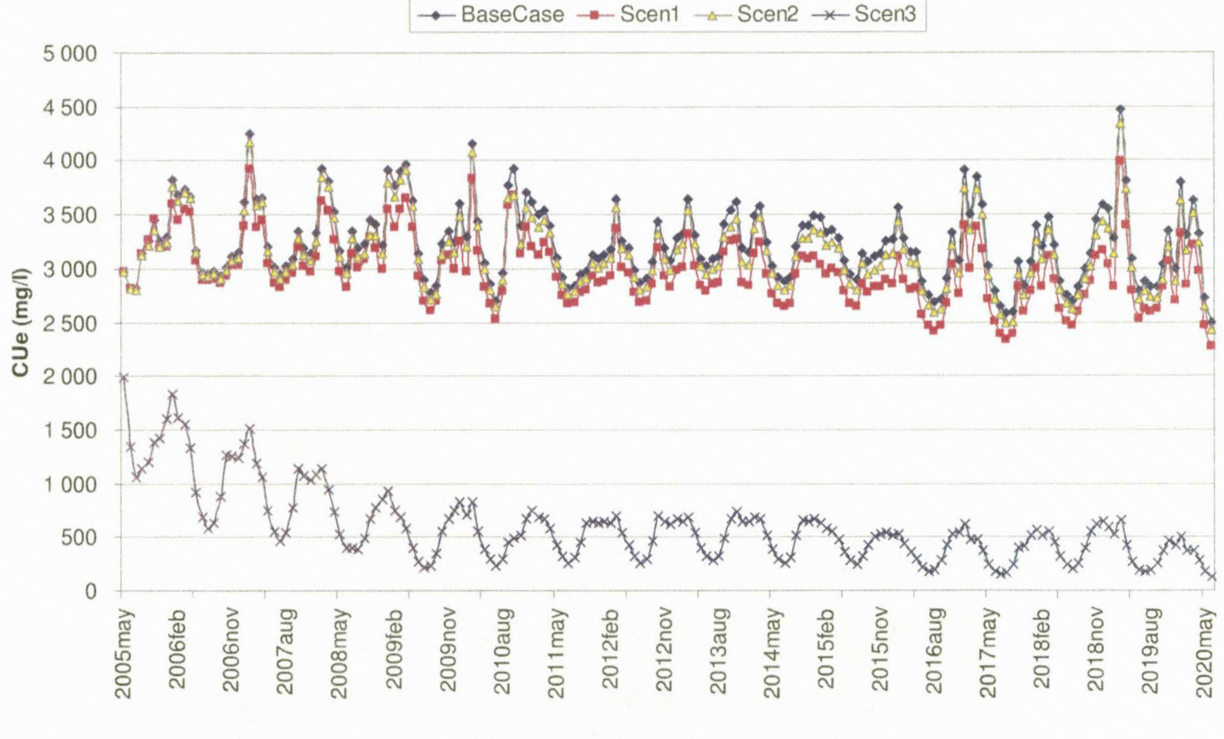


Figure 8.2. The impact of different scenarios on the saturated extract salt concentration - CUe (mg/l) for Stochastic run 080 in the Lower Riet irrigation block (*RloR*) for 15 years.

8.2.2 <u>IRRIGATION WATER SALINITY DATA</u>

Figure 8.4 shows the expected monthly irrigation water salinity concentration, TDS (mg/l) spread in WRPM channel number 490 which feeds into the Lower Riet irrigation block (***RloR***). The months of April to August have the largest variation and are also the months with the highest TDS values. Winter crops and crops germinating in these months therefore face the largest risk of salinity damage if sensitive to salinity.

Figure 8.5 shows the annual spread of irrigation water quality in the Lower-Riet irrigation block. The annual average irrigation water quality is stable at around 800 mg/l while the fifty percentile is around 500 mg/l, indicating that the maximum values (represented by the 0.95 percentile) fluctuate more widely. Looking only at the average irrigation water quality (mg/l) in Figure 8.5, one would conclude that the salinity is worse than it really is, if you do not also look at the 0.50 percentile. The 0.50 percentile indicates the level at which the irrigation water quality would be at 50% of the time, or put otherwise, there is a 50 / 50 (even) chance that irrigation water salinity could be more or less than the value indicated. The flux of irrigation water salinity around the average and 0.50 percentiles are however very important as displayed by the spread of micro-economic TGMASC results in Figure 8.10.

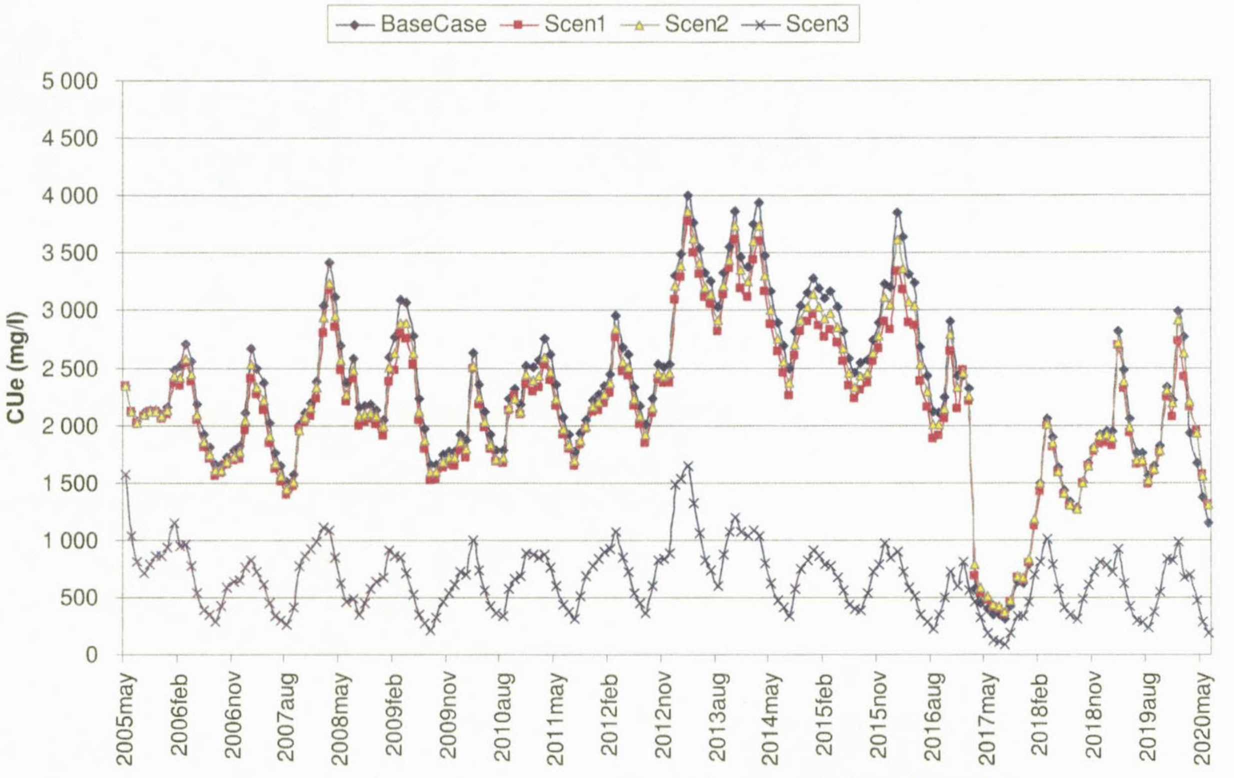


Figure 8.3. The impact of increased drainage in scenario 3 on the saturated extract salt concentration - CUe (mg/l) for Stochastic run 080 in the Orange Vaal WUA block (*Vall*) for 15 years

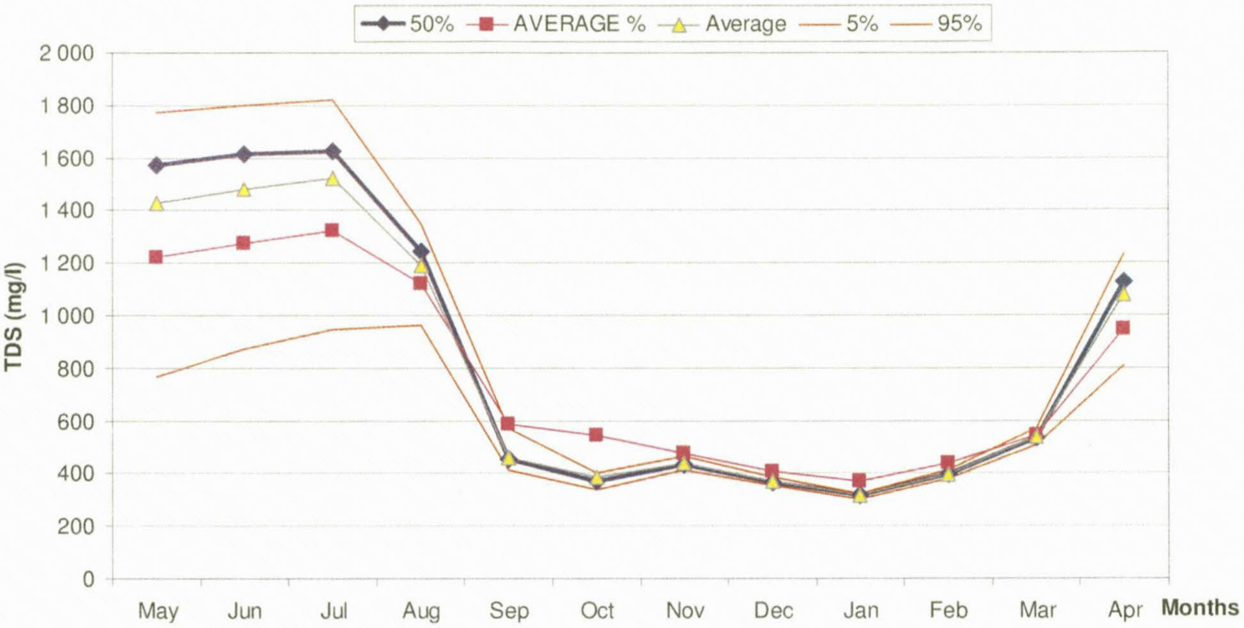


Figure 8.4. Monthly irrigation water salinity concentration, TDS (mg/l) spread in WRPM channel number 490 which feeds into the Lower Riet irrigation block (*RloR*)

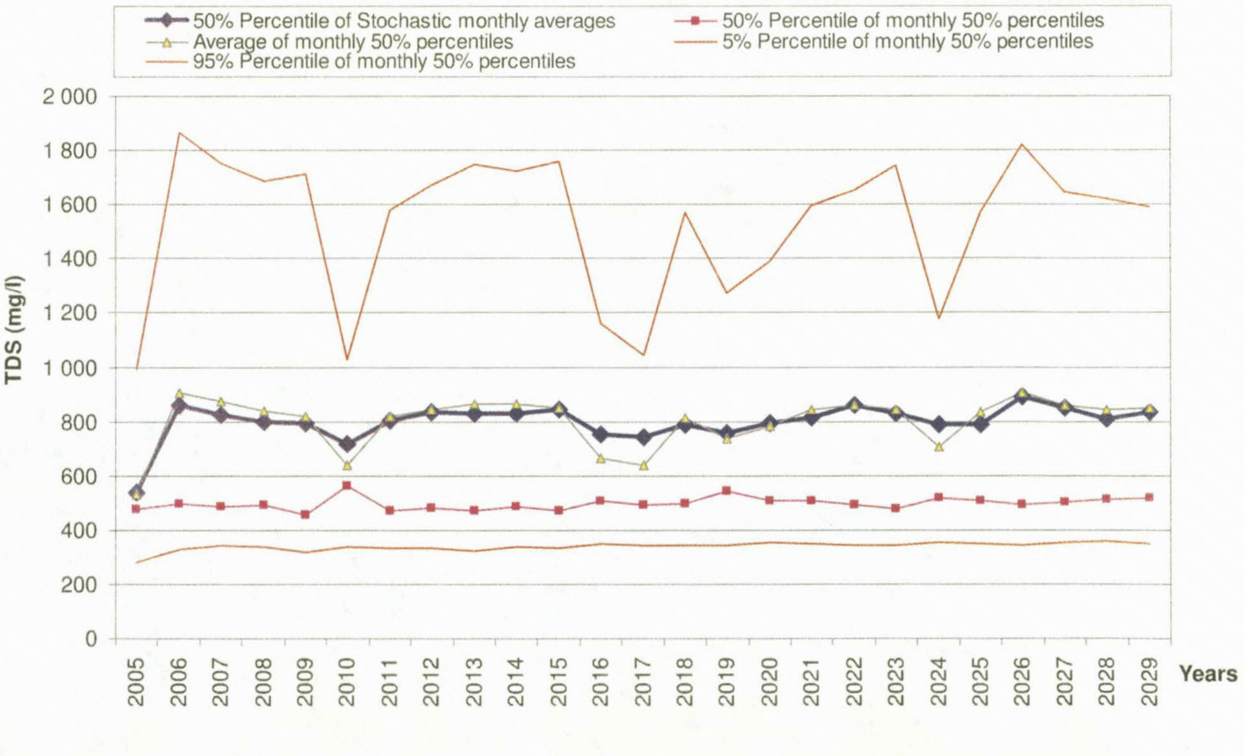


Figure 8.5. Annual irrigation water expected salinity, TDS (mg/l) spread in Channel 490, which feeds into the Lower Riet irrigation block (*RloR*)

8.3 BIO-PHYSICAL EXAMPLE OF THE HYDROLOGY–ECONOMIC LINKAGE RESULTS

The key results of the bio-physical model are the conversion of the WRPM model soil salt concentration, CU (mg/l) results into saturated soil salt concentration, CUe (mg/l) and the subsequent conversion from salt concentration (mg/l) into electrical conductivity ECe (mS/m). The ECe is applied to the Maas and Hoffmann (1977) equation using crop threshold and gradients to determine the linear crop yield functions shown in Figure 8.6. The reduction in crop yield due to salinity is then used in the micro economic model as demonstrated in Table 8.2.

Figure 8.6 is a worked example of the Maas and Hoffmann equation (explained in full in Chapter 5). For this example the ECe of the saturated soil paste is set to 480 mS/m (3 120 mg/l) at which level maize gives an 8.85 ton yield (63% of the maximum yield of 14 ton/ha). Lucerne produces a yield of 16.29 ton/ha, only 80% of the maximum yield, and salt tolerant wheat yields 100% at this soil salinity level. The subsequent CEBs for these three crops are shown in Table 8.1. Winter, summer and annual crops however will not be subject to the same annual average ECe because, depending on the months of production, monthly crop water requirements and the monthly ECe, a crop-specific weighted average ECe is calculated each year.

Expected crop yields (represented by the 0.50 percentile based on the 100 WRPM stochastic runs) for the base-case scenario (i.e. status quo) in the Lower Riet irrigation block are shown in Figure 8.7. The five crops that maintain 100% yield over the 15 years of analysis in this worst affected irrigation block are, wheat, barley, pastures, cotton and vegetables (more specifically, garlic and peas).

		Crop		
		LUCERNE	MAIZE	WHEAT
ECe Threshold (2% leaching)	mS/m	204	173.4	612
ECe Gradient	%/mS/m	0.073	0.120	0.071
Weighted ave. ECe (mS/m)	480	= *3120*	*mg/l*	
Max Physiological yield	ton/ha	20.40	14.00	7.00
% of max Physiological yield	%	80	63	100
Modeled yield	ton/ha	16.29	8.85	7.00
		% max Yield		
	ECe	LUCERNE	MAIZE	WHEAT
	0	100.0	100.0	100.0
	50	100.0	100.0	100.0
	100	100.0	100.0	100.0
	150	100.0	100.0	100.0
	200	100.0	96.8	100.0
	250	96.6	90.8	100.0
	300	93.0	84.8	100.0
	350	89.3	78.8	100.0
	400	85.7	72.8	100.0
	450	82.0	66.8	100.0
	500	78.4	60.8	100.0
	550	74.7	54.8	100.0
	600	71.1	48.8	100.0
	650	67.4	42.8	97.3

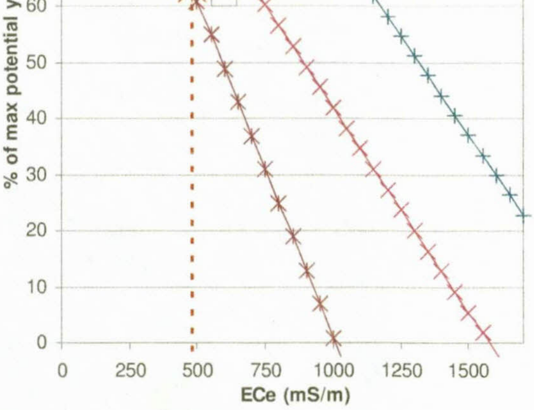


Figure 8.6 The working of the Maas and Hoffmann (1977) threshold and gradient graph for determining yield response to saturated soil salinity - ECe (mS/m) for the Lower Riet irrigation block, stochastic run 080 (closest fit to the 0.50 percentile)

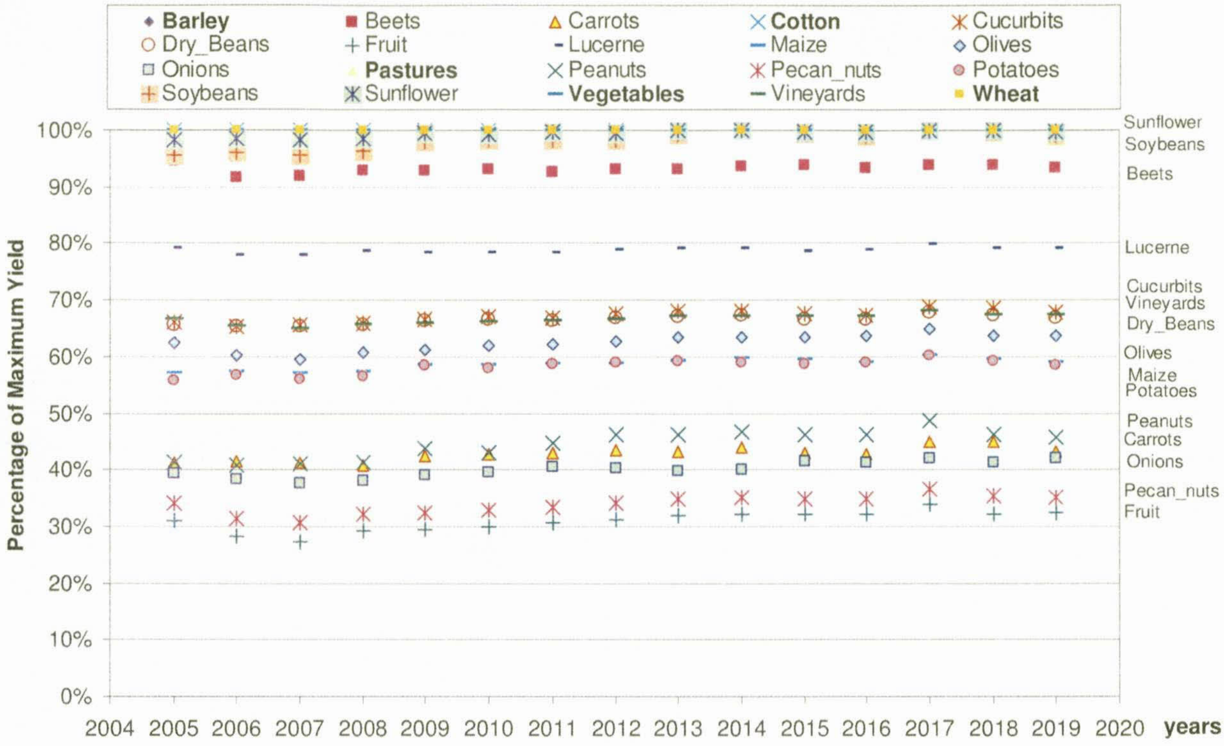


Figure 8.7. The fifty percentile (0.50) crop yield of the 20 main crops over 15 years in the Lower-Riet irrigation block (Crop names written in bold type achieve a 100% yield)

The average expected yield over the 15 years, indicated in Figure 8.7 of the other major crops grown in the Lower Riet irrigation block are as follows:

Maize	59%	Soybeans	99%
Lucerne	78%	Sunflowers	99%
Potatoes	60%	Peanuts	45%

Beets in the base-case scenario refer to beet root while in scenario 3 it refers to a combination of beetroots and sugar-beet that has a higher salt tolerance. The 95% yield for beets shown in Figure 8.7 would therefore be 100% when modelled in scenario 3.

The average maize yield in Figure 8.7 is 59%, but if one looks at Figure 8.8 the 0.50 percentile also varies around 59% yield, while stochastic run 080 shows a higher level of fluctuation around 59% (between 56% and 64%). In a "good case" hydrology sequence, i.e. stochastic run 044, yield fluctuates between 59% and 90% of potential maximum yield, while in a "bad case" hydrology sequence, i.e. stochastic run 001, yield only fluctuates between 50% and 60%. The extreme yield fluctuations shown by the 0.05 and 0.95 percentiles show that there is a 95% probability that maize yield in the Lower Riet irrigation block will not exceed 80% and a 5% probability that yield will be lower than 48% of maximum potential yield.

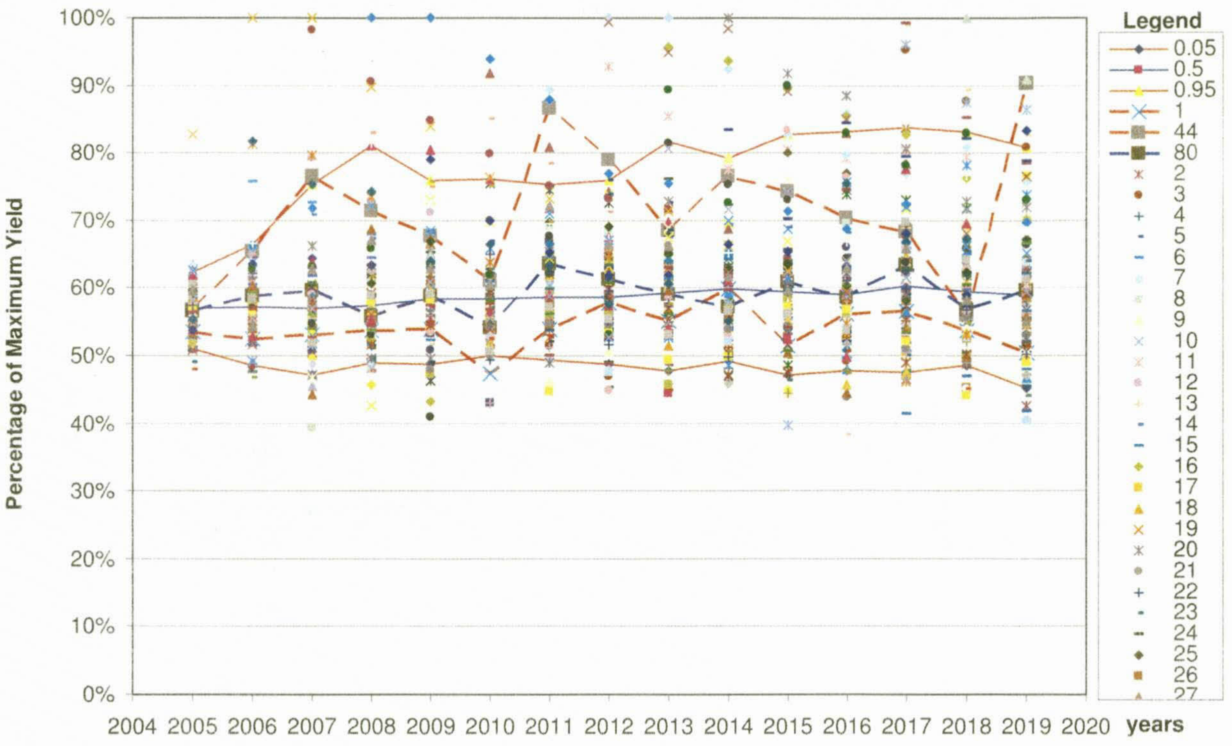


Figure 8.8. Stochastic spread of maize yield over 15 years in the Lower-Riet irrigation block

8.4 PER HECTARE LEVEL CROP ENTERPRISE BUDGET RESULTS

Crop enterprise budgets are set up for the 20 main irrigation crops in the study area on a per hectare basis with variation between irrigation blocks depending on:

- The average distance of the irrigation block from silos reflected in post harvest transport costs and influenced by crop yield
- The average distance of the irrigation block from an air field, factored into the aerial spraying costs of chemicals (GWK, 2005) influencing pre-harvest CEB costs
- The riskiness of crops grown in the different irrigation blocks as is reflected in the insurance costs supplied by GWK (2005)
- Water costs per irrigation block depend on the rates charged by the WUA and these are used in this study as supplied by GWK (2005)
- Electricity costs per irrigation block depend on the irrigation water volume pumped and are used in this study as supplied by GWK (2005)
- Yield variation between irrigation blocks are based on historical yields obtained from the OV- and OR- WUAs and GWK (2005) as well as expert opinion.

There are 80 (20 crops x 4 irrigation blocks) CEBs set up. For each of the 80 CEBs compiled there are a further two variations for scenario 3 where 15% additional drainage is applied (reflected in increased irrigation water requirements), and scenario 3+ where the cost of the additional drainage is also factored into the cost of the irrigation water. The Lower Riet irrigation block CEBs are shown in Table 6.4 and Table 6.5, with the CEBs of the other irrigation blocks shown in Appendix 2. A simplified example, consisting of only 3 crops planted in the Lower Riet irrigation block follows.

8.4.1 PER HECTARE CROP GROSS MARGINS

In Table 8.1, the threshold values are adjusted according to the leaching percentages used in the WRPM setup. The corresponding increase in crop water requirements is updated accordingly. Where the cost of additional drainage is factored into the price of water as in scenario 3+ the cost of water (R/mm/ha) is adjusted.

The yield reduction due to soil salinity as demonstrated in Figure 8.6 is factored into the CEB in Table 8.2 and the CEB re-calculated accordingly. At the average expected saturated soil salinity for the Lower Riet irrigation block, a TDS of 3120 mg/l (480 mS/m), direct returns to lucerne and maize are reduced from R5314 and R4312 to R3956 and R503 and wheat remains unchanged at R2177. The largest change in the CEB due to reduced yields is a reduction in gross income and also a reduction in harvesting costs. All other input costs remain unchanged as reflected in Figure 8.9.

Table 8.3 is a summary of the CEBs for different stochastic runs, leaching fractions and water costs in the RloR, also showing the percentage change on a per hectare basis of the TGMASC of the base-case versus scenario 3 and scenario 3+. Stochastic runs 001, 080 and 044 selected to represent the 0.05, 0.50 and 0.95 percentiles are compared to the 100% yield target. Lucerne shows a 25-, 36- and 41% and maize a 64-, 90- and 100% TGMASC reduction from the maximum TGMASC for stochastic runs 044, 080 and 001 respectively for the base-case where a return flow factor of 2% is applied.

Table 8.1. CEBs of 3 main crops, wheat, maize and lucerne in the Lower Riet irrigation block (*RloR*) calculated at maximum (target) yield using 2005 data.

LOWER RIET	*Unit*	*Lucerne*	*Maize*	*Wheat*
ECe Threshold (BC, S1 and S2)	mS/m	204	173	612
ECe Gradient	%/mS/m	0.073	0.120	0.071
Crop water requirement	mm/ha	1 179	764	613
Crop Enterprise Budgets:		**Lucerne**	**Maize**	**Wheat**
PRICE	R/ton	552	832	1 208
Max Physiological yield	ton/ha	20.40	14.00	7.00
Modeled yield (max)	***ton/ha***	***20.40***	***14.00***	***7.00***
Gross income	**R/ha**	**11 255**	**11 651**	**8 454**
SEED	R/ha	375	1 080	756
FERT	R/ha	1 414	2 402	1 858
HERB	R/ha	165	277	84
PEST	R/ha	13	594	409
INSUR	R/ha	0	373	364
FUEL	R/ha	464	194	287
MAINT	R/ha	1 078	336	913
Temp LABOR	R/ha	0	0	0
WATER @ R 0.489 /mm	R/mm/ha	*577*	*374*	*300*
ELECT. @ R 0.677 /mm	R/mm/ha	*798*	*517*	*415*
HARVESTING COSTS	*R/ton*	*44*	*71*	*103*
HARVESTING COSTS	R/ha	899	996	723
Total expences pre harvest	R/ha	4 883	6 147	5 386
Total expenses with max harvest	R/ha	5 783	7 143	6 109
Gross margin	**R/ha**	**5 473**	**4 508**	**2 345**
Co-op financed interest costs	R/ha	96	145	128
Bank financed interest costs	R/ha	63	52	40
Total interest costs	*R/ha*	*159*	*196*	*168*
TGMASC	**R/ha**	**5 314**	**4 312**	**2 177**

Table 8.2 CEBs of 3 main crops, wheat, maize and lucerne in the Lower Riet irrigation block (*RloR*) calculated at soil salinity EC_e = 480 mS/m (TDS = 3120 mg/l), using 2005 data.

LOWER RIET			*Unit*	*Lucerne*	*Maize*	*Wheat*
ECe Threshold (BC, S1 andS2)			mS/m	204	173	612
ECe Gradient			%/mS/m	0.073	0.120	0.071
Crop water requirement			mm/ha	1 179	764	613
Crop Enterprise Budgets:				**Lucerne**	**Maize**	**Wheat**
PRICE			R/ton	552	832	1 208
Max Physiological yield			ton/ha	20.40	14.00	7.00
Modeled yield			***ton/ha***	***16.29***	***8.85***	***7.00***
Gross income			**R/ha**	**8 988**	**7 364**	**8 454**
SEED			R/ha	375	1 080	756
FERT			R/ha	1 414	2 402	1 858
HERB			R/ha	165	277	84
PEST			R/ha	13	594	409
INSUR			R/ha	0	373	364
FUEL			R/ha	464	194	287
MAINT			R/ha	1 078	336	913
Temp LABOR			R/ha	0	0	0
WATER @	R 0.489	/mm	R/mm/ha	*577*	*374*	*300*
ELECT. @	R 0.677	/mm	R/mm/ha	*284*	*417*	*415*
TGMASC			***R/ha***	***3 761***	***504***	***2 177***
HARVESTING COSTS			*R/ton*	*44*	*71*	*103*
HARVESTING COSTS			R/ha	718	630	723
Total expences pre harvest			R/ha	4 369	6 046	5 386
Total expenses with max harvest			R/ha	5 087	6 676	6 109
Gross margin			**R/ha**	**3 901**	**688**	**2 345**
Co-op financed interest costs			R/ha	96	145	128
Bank financed interest costs			R/ha	43	39	40
Total interest costs			*R/ha*	*140*	*184*	*168*

Table 8.3. Base-case (2% return-flow) vs. Scen3 (17% return-flow) vs. Scen3 + (water charge added) crop TGMASC for stochastic runs (SR) 001, 080 and 044 in the Lower Riet irrigation block (*RloR*) using 2005 data

Scen.	*Stochastic run*	*Lucerne TGMASC*	*Maize TGMASC*	*Wheat TGMASC*	*ECe (mS/m)*	*TDS (mg/l)*	*Leaching Return flow*
S3 100%		6 224	4 789	2 177	170	1105	2%
BC,	SR 044	4 688	1 747	2 177	391	*2542*	2%
S1,	SR 080	3 956	503	2 177	480	*3120*	2%
S2	SR 001	3 669	14	2 177	515	*3348*	2%
	SR 044	4 465	1 973	2 132	391	*2542*	17%
S3	SR 080	3 734	728	2 132	480	*3120*	17%
	SR 001	3 446	239	2 132	515	*3348*	17%
	SR 044	3 407	1 287	1 582	391	*2542*	17%+WC
S3+	SR 080	2 676	43	1 582	480	*3120*	17%+WC
	SR 001	2 388	-447	1 582	515	*3348*	17%+WC
		Percentage change from scenario 3 (S3 100%)					
BC,	SR 044	-25%	-64%	0%	/ All 100%		2%
S1,	SR 080	-36%	-90%	0%	/ All 100%		2%
S2	SR 001	-41%	-100%	0%	/ All 100%		2%
	SR 044	-5%	13%	-2%	/ 2% leaching		17%
S3	SR 080	-6%	45%	-2%	/ 2% leaching		17%
	SR 001	-6%	1668%	-2%	/ 2% leaching		17%
	SR 044	-27%	-26%	-27%	/ 2% leaching		17%+WC
S3+	SR 080	-32%	-92%	-27%	/ 2% leaching		17%+WC
	SR 001	-35%	-3405%	-27%	/ 2% leaching		17%+WC

For scenario 3, the return flow factor is increased by 0.15 to 17%. Compared to the base-case scenario of 2% return flow, this results in a decrease in lucerne's TGMASC of 5% for stochastic run 044 and 6% for both stochastic runs 080 and 001. The cost of increased leaching for lucerne is not made up for by the resulting improved yield. For maize, the increased leaching however shows a 13-, 45- and 1668% increase from the base-case TGMASC for stochastic runs 044, 080 and 001 respectively. The increased water use for leaching results in the wheat TGMASC decreasing by 2%.

When factoring in the costs of additional drainage into the water charge, TGMASC for lucerne is decreased by 27-, 32- and 35%, for maize decreased 26-, 92- and 3405% and for wheat by 27% for stochastic runs 044, 080 and 001 respectively, indicating the difficulty farmers have to afford the additional drainage costs, even though it may not be required by tolerant crops such as wheat. For a single crop at per hectare level, the additional cost of drainage don't seem financially feasible, it is therefore to be calculated for a mix of crops over a series of years as appears in the following section.

8.5 IRRIGATION BLOCK LEVEL MICRO-ECONOMIC RESULTS

Figure 8.9 shows the sub-components of the base-case total annual CEB composition for the sum of all crops in the ***RloR*** irrigation block. These values are the sum of the CEB components over the areas planted to the specific crops. The breakdown of the CEBs at irrigation block level provides sectoral information for the macro model. As all crop input related factors that may impact yield are assumed optimum they remain constant, and only soil salinity impacts on yield. In Figure 8.9 it can clearly be seen that it is only harvesting costs and gross income that change as a result of yield changes, and subsequently impact on the total gross margin above specified costs (TGMASC).

Figure 8.10 shows the change in stochastic spread of annual TGMASC over 15 years, for all stochastic runs for the base case scenario for ***RloR***. As time goes by, the possibility of a zero annual TGMASC increases, but also the probability of improved annual TGMASC. The trend in the 0.50 percentile TGMASC is slightly improving.

In Figure 8.11 the annual values of Figure 8.10 are added to produce the cumulative TGMASC over 15 years. To use realistic data to fully capture the stochastic nature of the hydrology in the analyses that follow, stochastic runs 001, 080 and 044 were selected that most closely fitted the 0.05, 0.50 and 0.95 percentiles. Positive results stemming from Figure 8.11 are that even at the worst case sequence of hydrology events predicted for the Lower Riet irrigation block, the cumulative TGMASC still improves over time, although the annual TGMASC may only improve slightly. This shows that the system is in equilibrium and stabilised around the current farming and WUA management actions practiced. The close fit of stochastic runs 001, 080 and 044 respectively to the 0.05, 0.50 and 0.95 percentiles in the cumulative TGMASC of Figure 8.11 is no longer as tight in Figure 8.12 (annual TGMASC), but provides more realistic dynamics in the results to be presented, than if the 0.05, 0.50 and 0.95 percentiles were used.

Stochastic run 044 in Figure 8.12 shows the massive changes that can be expected in TGMASC that a farmer will have to account for in his forward and cash flow planning. TGMASC can halve / double from one year to the next. Stochastic run 001 reflects a bad hydrology sequence that can result in zero TGMASC for some years (i.e. 1 in 15).

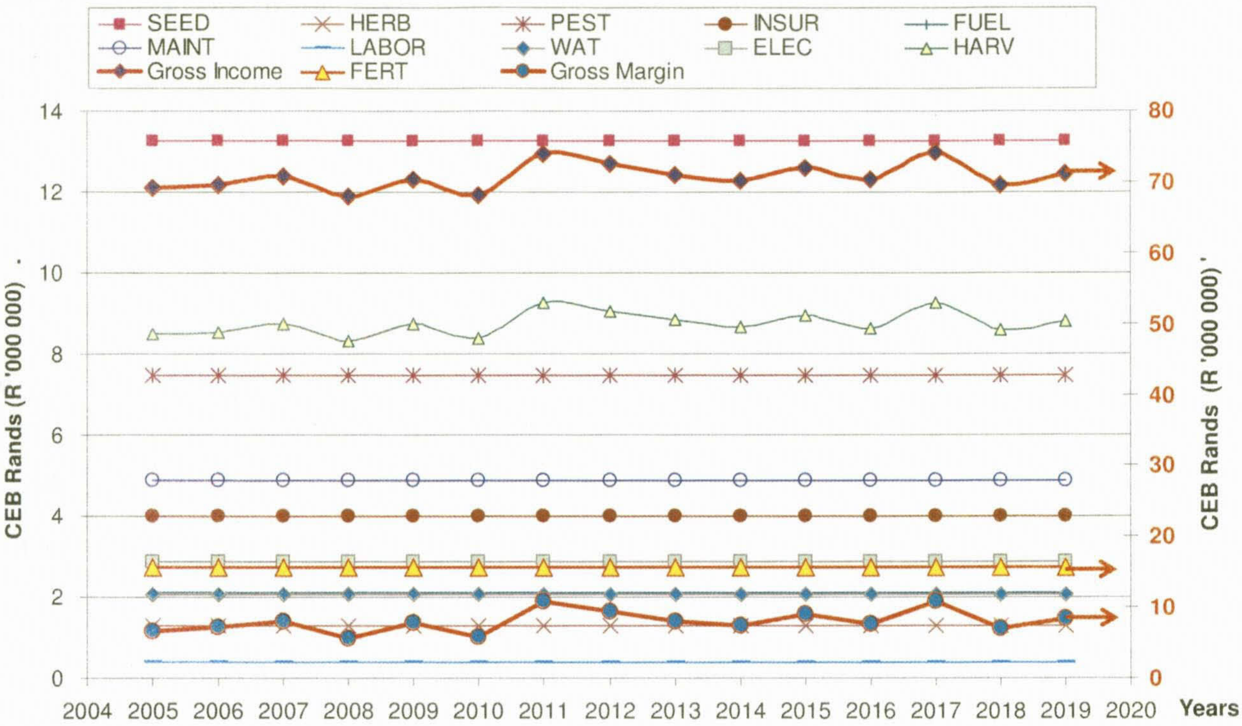


Figure 8.9. Base-case total annual CEB composition values for all crops in the RIoR irrigation block for stochastic run 80 over 15 years

Figure 8.10. Base-case scenario annual TGMASCs (R' million) for the Lower Riet irrigation block showing the 0.05, 0.50 and 0.95 percentiles for 100 stochastic runs

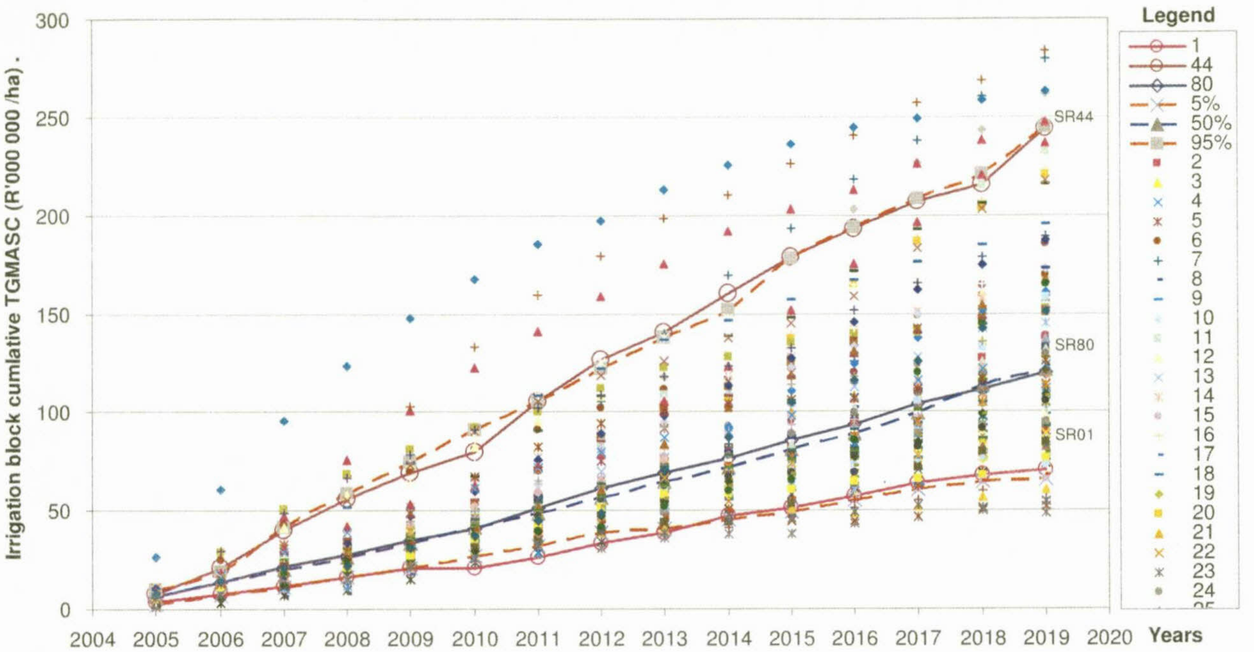


Figure 8.11. Base-case scenario cumulative annual TGMASCs (R'million) for the Lower Riet irrigation block showing the 0.05, 0.50 and 0.95 percentiles and most closely fitting stochastic runs 001, 080 and 044 respectively for 100 stochastic runs

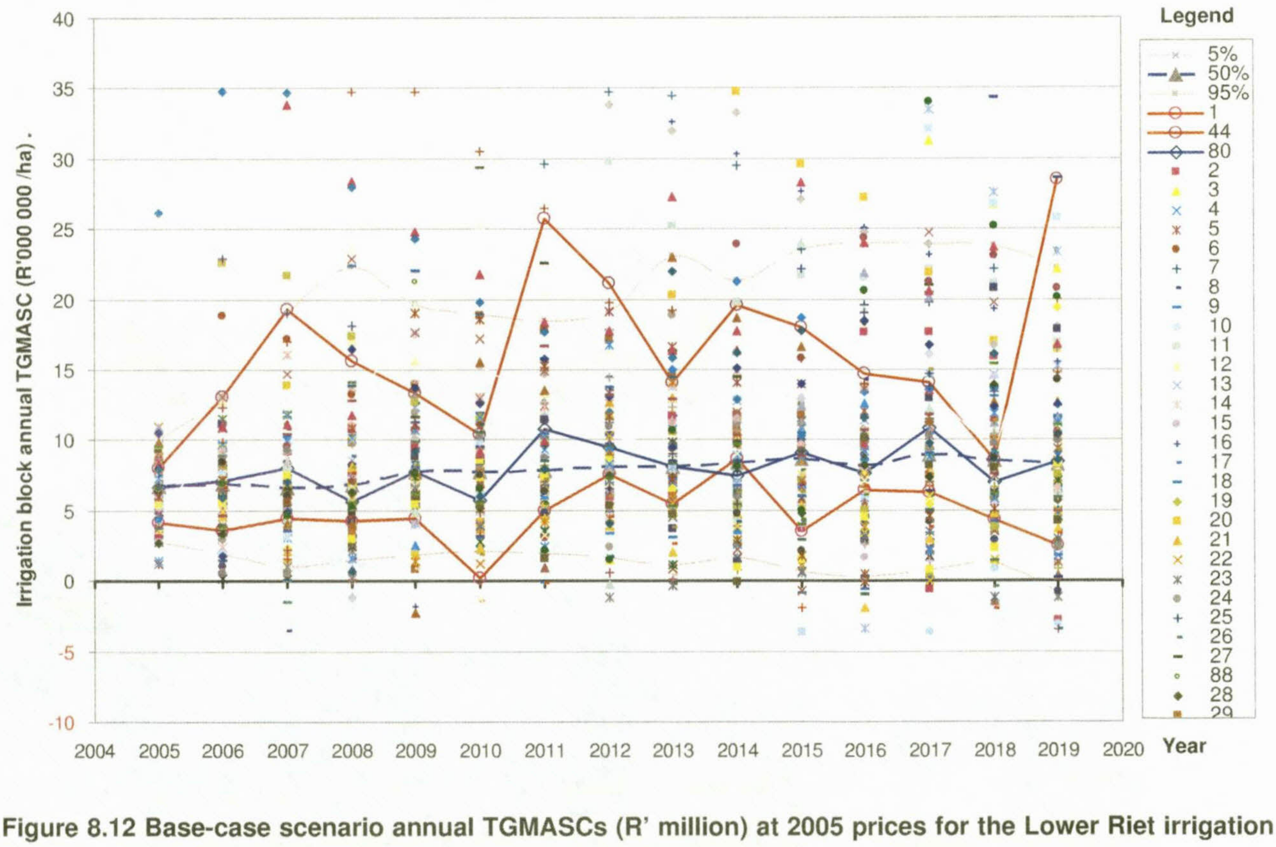


Figure 8.12 Base-case scenario annual TGMASCs (R' million) at 2005 prices for the Lower Riet irrigation block showing the 0.05, 0.50 and 0.95 percentiles and corresponding selected stochastic runs 001, 080 and 044 respectively, for 100 stochastic runs.

8.6 COMPARING THE SCENARIOS

8.6.1 IRRIGATION BLOCKS COMPARED

From the fifteen year cumulative TGMASCs presented In Table 8.4 for the base-case and scenarios 1 to 3, the total cost of salinity is calculated for each irrigation block. In Table 8.5 these costs are reduced to per hectare costs, by first dividing by 15 (the number of years) and then the number of hectares irrigated in the irrigation block, to make comparisons between irrigation blocks on an equal basis.

8.6.1.1 Cost of salinisation

Table 8.4 lists the fifteen-year cumulative TGMASC of each irrigation block for each scenario in millions of Rands (R'000 000). The base-case, representing the status quo, is subtracted from scenario 3 with yield forced to 100% (Scen3 100%Yield), representing a theoretical top level of productivity achievable without the constraint of salinity, to give an indication of the total cost of salinisation (net benefit forgone due to salinity). On a per hectare basis in Table 8.5 the greatest loss due to salinity is experienced in the Lower Riet irrigation block (***RloR***) to the value of R6962 per hectare per year, followed by Scholtzburg (***Rszg***) with R2596 and the Orange-Vaal irrigation block (***Vall***) with R2218. This can provide a farmer in the specific irrigation block with a good indication of the costs of poor drainage on his farm. At an average costs of drainage per ha on medium to heavy soils of R30 000 (Reinders, 2005 *personal communication*), a 15 year loan at 9% interest would cost R3722 per year to service – it would definitely be economical to spend in RloR, though not as convincing without assistance grant in ***Rszg*** and ***Vall***. Implemented for the whole study area (all irrigation blocks combined), the total real cost (2005 basis) of salinisation over a period of 15 years is R995 million, a good benchmark to use to leverage funds for remediation action.

Table 8.4. Cumulative 15 year annual average TGMASC (R'000 000) for all scenarios of all the irrigation blocks compared (real 2005 prices), based on 100 stochastic runs

	RloR	Rscm	Rszg	Vall	TOTAL	
Ha	*3 853*	*12 335*	*641*	*7 390*		
BaseCase	**132.9**	**1 294.9**	**59.8**	**608.3**	**2 096**	
Scen1	149.0	1 182.7	60.6	470.6	**1 863**	
Scen2	124.2	1 576.4	75.0	633.6	**2 409**	
Scen3	531.1	1 616.8	84.7	853.6	**3 086**	
Scen3+ drainage repay	476.4	1 576.5	82.5	815.8	**2 951**	
Scen3 100%Yield[1]	535.3	1 616.8	84.8	854.2	**3 091**	
Cost of salinity ('mil)	**402.4**	**321.9**	**25.0**	**245.9**	**995**	
	% CHANGE from base					**Change (R'mil)**
Scen1	0.12	-0.09	0.01	-0.23	-0.11	**-233**
Scen2	-0.07	0.22	0.25	0.04	0.15	**313**
Scen3	3.00	0.25	0.42	0.40	0.47	**990**
Scen3+ drainage repay	*2.58*	*0.22*	*0.38*	*0.34*	*0.41*	**855**
Scen3 100%Yield[1]	*3.03*	*0.25*	*0.42*	*0.40*	*0.47*	**995**
Drainage repay impact	***0.10***	***0.02***	***0.03***	***0.04***	***0.04***	***135***

[1] The 100% yield scenario is a theoretical top benchmark used in calculating net benefit forgone

Table 8.5. Per hectare average annual TGMASC (R) for all scenarios of all the irrigation blocks compared (real 2005 prices), based on 100 stochastic runs

	RloR	Rscm	Rszg	Vall	TOTAL	
Ha	*3853*	*12335*	*641*	*7390*	***24219***	
BaseCase	**2 299.9**	**6 998.3**	**6 215.6**	**5 488.2**	**5 769**	
Scen1	2 577.4	6 391.9	6 295.7	4 246.0	**5 128**	
Scen2	2 148.8	8 520.1	7 793.7	5 716.3	**6 632**	
Scen3	9 190.4	8 738.1	8 811.0	7 701.2	**8 496**	
Scen3+ drainage repay	8 243.5	8 520.5	8 573.9	7 359.5	**8 124**	
Scen3 100%Yield[1]	9 262.3	8 738.1	8 812.0	7 706.7	**8 509**	
Cost of salinity (R / ha / yr)	**6 962.4**	**1 739.8**	**2 596.3**	**2 218.4**	**2 739.3**	
R/ha gain from leaching 15%	5 943.57	1 522.23	2 358.26	1 871.30	2 354.23	
Per ha annual cost of drainage (R/ha)	-946.97	-217.56	-237.13	-341.64	-371.97	
Soil Productivity gain (R/ha)	**4 996.60**	**1 304.67**	**2 121.13**	**1 529.66**	**1 982.26**	
	% CHANGE from base case					**Change (R/ha)**
Scen1	0.12	-0.09	0.01	-0.23	-0.11	-642
Scen2	-0.07	0.22	0.25	0.04	0.15	862
Scen3	3.00	0.25	0.42	0.40	0.47	2 726
Scen3+ drainage repay	*2.58*	*0.22*	*0.38*	*0.34*	*0.41*	2 354
Scen3 100%Yield[1]	*3.03*	*0.25*	*0.42*	*0.40*	*0.47*	2 739
Drainage repay impact	***0.10***	***0.02***	***0.03***	***0.04***	***0.04***	***371.97***

[1] The 100% yield scenario is a theoretical top benchmark used in calculating net benefit forgone

8.6.1.2 Scenarios compared

In comparing the scenarios, the base-case is accepted as the status quo and percentage changes from the status quo are presented in the bottom half of Table 8.5 (these values are the same as in the bottom half of Table 8.4).

When planting the more salt tolerant cropping combination, as simulated in scenario 1, it is only the ***RloR*** that shows a reasonable improvement from the base-case scenario (12%). ***Rszg*** shows a minor improvement of 1%. The ***Rscm*** and ***Vall*** irrigation blocks show a 9% and 23% reduction in TGMASC (be it either the 15 year cumulative Table 8.4 or the per ha Table 8.5). Implemented for the whole study area (all irrigation blocks) the salt tolerant scenario 1 results in a R233 million cumulative loss over the 15 years, and per hectare an average of R642 per year loss in Table 8.4 and Table 8.5 respectively, compared with the base-case scenario.

In scenario 2, the implementation of a more salt sensitive yet higher value cropping combination, there is a 7% reduction for ***RloR*** from the base-case TGMASC to the Scen2 TGMASC, while for ***Rscm*** and ***Rszg*** there is a remarkable TGMASC improvement of 22% and 25% respectively, and a slight improvement of 4% for ***Vall***. When implemented on the whole study area (all irrigation blocks) the salt sensitive yet higher value scenario 2 results in a R313 million cumulative improvement over the 15 years, and per hectare an average of R862 per year improvement in Table 8.4 and Table 8.5 respectively, compared with the base-case scenario.

The implementation of the same more salt sensitive yet higher value cropping combination, but with 15% additional leaching and drainage in scenario 3, results in a 300% improvement in the ***RloR*** TGMASC and a not as dramatic yet still marked improvement of 25%, 42% and 40% for the ***Rscm***, ***Rszg*** and ***Vall*** respectively. This translates to a R990 million TGMASC cumulative improvement over the 15 years, and per hectare an average of R2726 per year improvement in Table 8.4 and Table 8.5 respectively, compared with the base-case scenario. Internalising the cost of irrigation drainage in scenario 3+ results in an 10% decrease in returns for the ***RloR***, 2% for ***Rscm***, 3% for ***Rszg*** and 4% for ***Vall*** when compared to scenario 3 where the costs of additional drainage is not included.

A final scenario is run in the economic model (Scen3 100%Yield) where all yield is set at maximum (100%) yield levels (i.e. cancelling out the impact of salinity) to give maximum TGMASC values. These values are used to calculate the total cost of salinity (net benefit forgone), all other factors of production being optimal.

The deduction from this analysis is that each irrigation block is very sensitive to a specific salinity threshold level (dependent of cropping combination) and therefore not all irrigation blocks should be treated the same. Only ***RloR*** benefited slightly from planting crops that are more tolerant as its soil salinity threshold had been exceeded by the base-case cropping composition. Increased drainage and leaching however proved to be far more financially effective than planting tolerant crops. Furthermore, the return-flow externality effects of ***RloR*** on ***Vall*** downstream do not have a major impact when ***Vall*** is also drained, as indicated by far better results in ***Vall*** as well.

8.6.1.3 Water use changes

The cropping combinations selected for scenarios 1 and 2 all result in a decrease in water use when compared to the base-case scenario shown in Table 8.6, but with the additional leaching required in scenario 3, which has the same cropping choice as scenario 2, the total annual water requirements (m^3) exceed the base-case water requirements. The additional water required for drainage however is a non-consumptive use and most of it ends up back in the river again, less wastage and loss. The impact of the increased salt load from additional leaching is factored into the whole hydrology system in the WRPM.

Table 8.6. Average annual irrigation water use and percentage changes (m^3) across irrigation blocks for the different scenarios modelled, based on 100 stochastic runs

	RloR	*Rscm*	*Rszg*	*Vall*	**Total**
Base-case	**4 881 786**	**14 836 968**	**762 149**	**8 506 028**	***28 986 931***
Scen1	4 276 398	15 001 319	767 091	7 075 078	***27 119 885***
Scen2	4 664 869	14 734 871	758 668	7 933 108	***28 091 516***
Scen3	5 350 879	16 912 438	869 692	9 071 832	***32 204 842***[1]
% CHANGE from Base-case in water use					
Scen1	-0.12	0.01	0.01	-0.17	-0.06
Scen2	-0.04	-0.01	-0.00	-0.07	-0.03
Scen3	0.10	0.14	0.14	0.07	0.11[1]

[1]Although there is an 11% increase in water use for scenario 3, this is due to additional water required for leaching, and is a non consumptive use of the water – a large portion of this additional water returns to the river as a point source irrigation drainage return flow

8.6.1.4 Land and Water use productivity and risk between irrigation blocks

Land use and irrigation water use productivity is shown in Figure 8.13 and Figure 8.14 for all irrigation blocks and all scenarios. In both Figure 8.13 and Figure 8.14, the four graphs on the left are the land use productivity expressed as the TGMASC per hectare per year (R/ha/yr) and the four graphs on the right the water use productivity expressed as the TGMASC per millimetre water requirement per hectare per year (R/mm/ha/yr). To achieve these results, the irrigation water use productivity is calculated from the 15 year cumulative TGMASC per block (R), divided by the block area (ha), divided by 15 years (yr), divided by the weighted average crop water use (mm/ha). Land productivity is calculated the same except that the weighted average crop water use is not included.

In Figure 8.13 the slope of the cumulative probability function indicates the spread of possible results; the more horizontal the spread the more risky an option. Planting more salt tolerant crops in scenario 1 did reduce the risk slightly for all blocks, but only improved the results in ***RloR***. Scenario 3, where additional drainage and leaching is implemented, clearly shows nearly vertical curves. In Figure 8.14, the greater the spread between the tops of the 0.05, 0.50 and 0.95 percentile bars, the greater the spread of risk. Once again, scenario 3, where additional drainage and leaching is implemented, clearly shows almost level bar tops, indicating a very stable return per hectare and per millimetre water used. Figure 8.13 and Figure 8.14 clearly show that to reduce the risk of income loss due to irrigation salinity one has to install drainage and leach more.

For the base-case and scenarios 1 and 2 in Figure 8.13 and Figure 8.14, the same pattern generally occurs and the irrigation blocks have the same order of riskiness. With the salt tolerant cropping choice, namely scenario 2, ***Rscm*** and ***Rszg*** present very similar curves. ***RloR*** remains the block with the most risk and lowest results followed by ***Vall***, then ***Rszg*** and least risky and highest yielding is ***Rscm***. In scenario 3 however, where additional drainage and leaching is implemented, ***RloR***, moves from having the lowest land and water factor productivity (and greatest risk), to producing the best results. Even the 0.05 percentile yields better than the other irrigation blocks. The small spread in the ***RloR*** land factor productivity of scenario 3 indicates a further small increase in drainage could still be implemented to further reduce risk and possibly improve results.

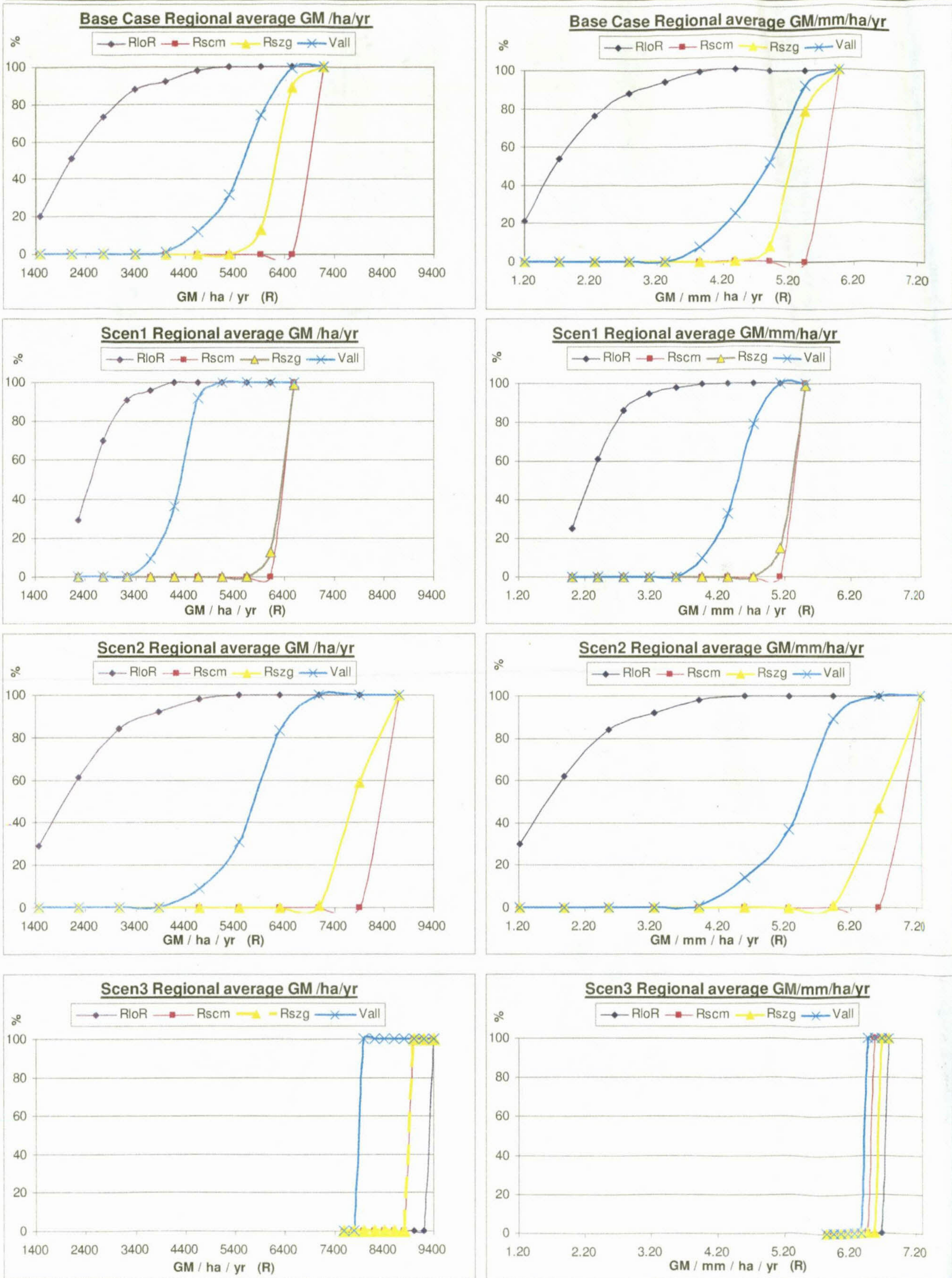


Figure 8.13. Land (R/ha/yr) and water (R/mm/ha/yr) productivity and cumulative probability functions based on 2005 prices (GM=TGMASC in this graph) for different scenarios based on 100 stochastic runs

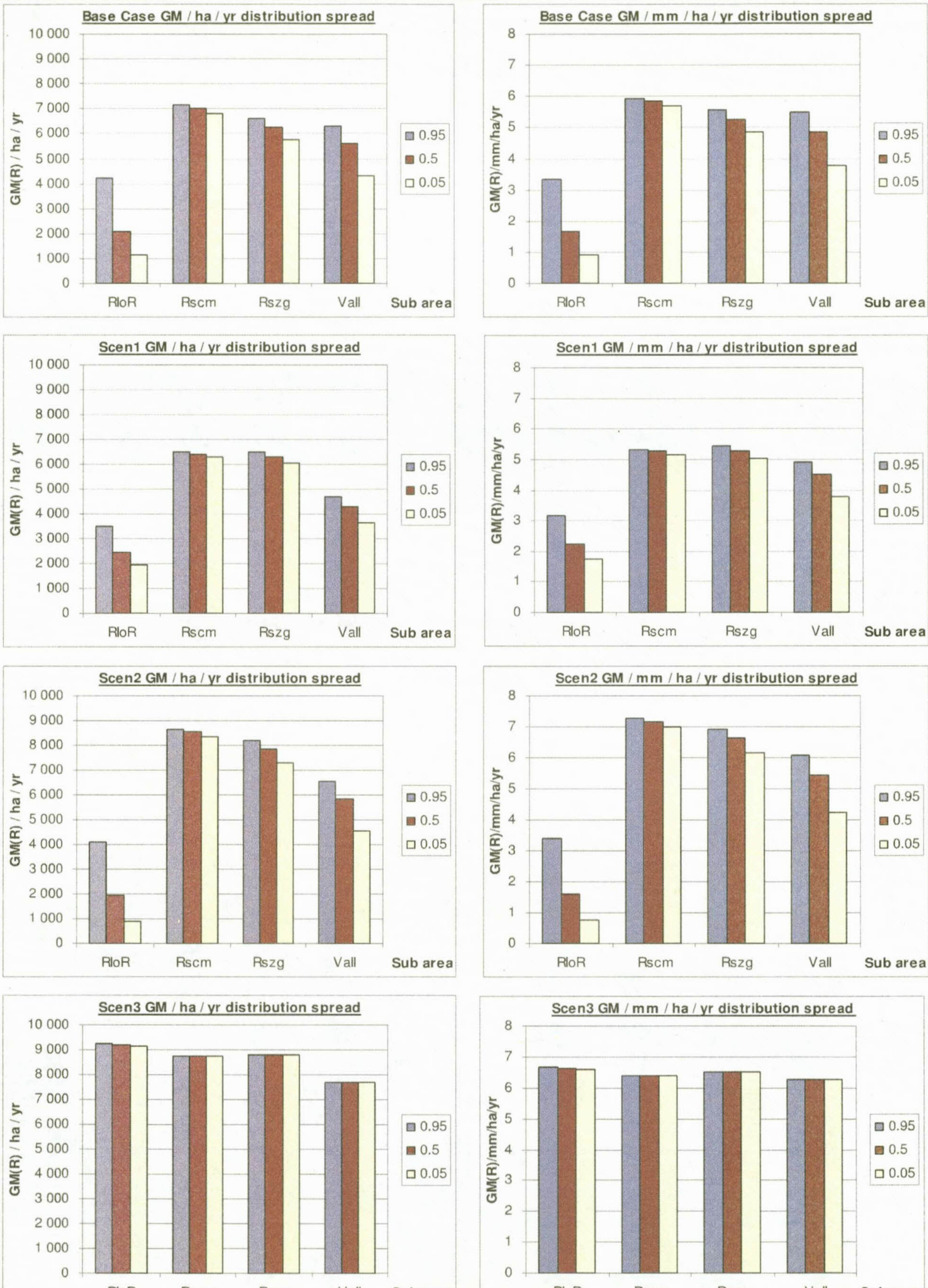


Figure 8.14. Land (R/ha/yr) and water (R/mm/ha/yr) productivity percentile spreads per irrigation block based on 2005 prices (GM=TGMASC in this graph) for different scenarios based on 100 stochastic runs

Table 8.7 is a summary of the results discussed in this chapter using the 0.50 percentile, with an elaboration using stochastic runs 001, 080 and 044 to represent realistic hydrology sequences most closely fitting the 0.05, 0.50 and 0.95 percentiles to try capture the whole spectrum of stochastic results using only 3 instead of 100 stochastic runs. Only the main results from Figure 8.7 are discussed further.

Important results from the scenario 1 change from the base-case (Scen1 % change from base) is that for stochastic run 001 (5% probability), the planting of a more salt tolerant cropping combination leads to a 66% increase in TGMASC for ***RloR***. Stochastic run 080 (50% probability) improves only 23% and run 044 (95% probability that it could be worse) results in a 24% decrease from the base-case results. In the other irrigation blocks it is only ***Rszg*** that shows a minor 1% improvement at 0.05 percentile level simulated by stochastic run 001. In the scenario 2 percenatge change from base (Scen2 % change from base), where more salt sensitive crops, yet higher values crops are planted (without additional leaching) ***RloR*** shows a TGMASC decrease, indicating that the crop combination salinity threshold has been exceeded and the increased returns do not compensate for the reduced yields.

Table 8.7. A summary of various SMsim model results comparing stochastic runs 001, 080 and 044 and the 0.50 percentile value of the 100 stochastic runs (2005 prices)

Base Case 15yr cumulative TGMASC (R'000 000)	*RloR*	*Rscm*	*Rszg*	*Vall*	*Ave.*
0.50%	*133*	*1 295*	*60*	*608*	***2 096***
001	71	1 290	56	625	**2 043**
080	120	1 264	62	548	**1 994**
044	244	1 329	64	615	**2 252**

Scen1 % CHANGE from base	*RloR*	*Rscm*	*Rszg*	*Vall*	*Ave.*	Change *(R'mil)*
0.50%	*0.12*	*-0.09*	*0.01*	*-0.23*	***-0.11***	***-233***
001	0.68	-0.08	0.06	-0.24	**-0.10**	**-207**
080	0.24	-0.08	-0.01	-0.20	**-0.09**	**-183**
044	-0.24	-0.09	-0.03	-0.23	**-0.15**	**-327**

Total Cost of salinity (R 'mil)	*RloR*	*Rscm*	*Rszg*	*Vall*	*Ave.*
0.50%	*402*	*322*	*25*	*246*	***995***
001	465	326	29	229	**1 048**
080	416	353	23	307	**1 097**
044	291	288	21	239	**839**

Scen2 % CHANGE from base	*RloR*	*Rscm*	*Rszg*	*Vall*	*Ave.*	Change *(R'mil)*
0.50%	*-0.07*	*0.22*	*0.25*	*0.04*	***0.15***	***313***
001	-0.16	0.22	0.28	0.04	**0.15**	**312**
080	-0.05	0.22	0.24	0.05	**0.16**	**313**
044	-0.03	0.21	0.25	0.04	**0.14**	**313**

Cost of salinity (R / ha / yr)	*RloR*	*Rscm*	*Rszg*	*Vall*	*Ave.*
0.50%	*6 962*	*1 740*	*2 596*	*2 218*	***2 739***
001	8 040	1 764	2 968	2 065	**2 886**
080	7 190	1 905	2 364	2 766	**3 021**
044	5 036	1 557	2 132	2 158	**2 309**

Scen3 % CHANGE from base	*RloR*	*Rscm*	*Rszg*	*Vall*	*Ave.*	Change *(R'mil)*
0.50%	*3.01*	*0.25*	*0.42*	*0.41*	***0.48***	***999***
001	6.53	0.26	0.51	0.37	**0.51**	**1 052**
080	3.44	0.28	0.37	0.56	**0.55**	**1 101**
044	1.18	0.22	0.32	0.39	**0.37**	**844**

R/ha gain from leaching 15%	*RloR*	*Rscm*	*Rszg*	*Vall*	*Ave.*
0.50%	*5 944*	*1 522*	*2 358*	*1 871*	***2 354***
001	7 009	1 546	2 729	1 719	**2 499**
080	6 165	1 688	2 126	2 422	**2 636**
044	4 030	1 339	1 894	1 809	**1 925**

Scen3+ % CHANGE from base	*RloR*	*Rscm*	*Rszg*	*Vall*	*Ave.*	Change *(R'mil)*
0.50%	*2.58*	*0.22*	*0.38*	*0.34*	***0.41***	***855***
001	5.73	0.22	0.47	0.30	**0.44**	**908**
080	2.97	0.25	0.33	0.49	**0.48**	**958**
044	0.95	0.19	0.28	0.33	**0.31**	**699**

Soil Productivity gain (R/ha)	*RloR*	*Rscm*	*Rszg*	*Vall*	*Ave.*
0.50%	*4 997*	*1 305*	*2 121*	*1 530*	***1 982***
001	6 060	1 328	2 492	1 378	**2 127**
080	5 222	1 470	1 888	2 080	**2 264**
044	3 081	1 122	1 657	1 467	**1 553**

Scen3 100% CHANGE from base	*RloR*	*Rscm*	*Rszg*	*Vall*	*Ave.*	Change *(R'mil)*
0.50%	*3.03*	*0.25*	*0.42*	*0.40*	***0.47***	***995***
001	6.58	0.25	0.51	0.37	**0.51**	**1 048**
080	3.47	0.28	0.37	0.56	**0.55**	**1 097**
044	1.19	0.22	0.32	0.39	**0.37**	**839**

8.7 WUA LEVEL RESULTS

The Lower-Riet (***RloR***), Riet Scheme (***Rscm***) and Scholtzburg (***Rszg***) irrigation blocks together form the Orange-Riet WUA level results to compare directly with the Vaal irrigation block (***Vall***) that represents most of the Orange-Vaal WUA. Excluded in the Vaal irrigation block (***Vall***) from the Orange-Vaal WUA, due to the setup in the Hydrology model WRPM, is the area irrigated directly from out of the Orange River, as from the Hydrology model perspective, this forms part of another irrigation block. ***Vall*** therefore only represents about 85% of the whole Orange-Vaal WUA.

Figure 8.15 shows the annual (right-hand side of figure) and cumulative (left-hand side of figure) TGMASC for the irrigation bocks ***RloR, Rscm*** and ***Rszg*** combined to make up the OR-WUA (***Rall***). This is compared to the ***Vall*** irrigation block, representing the OV-WUA. Results show that all the Orange-Riet WUA irrigation blocks together (***Rall***) and its main sub-block ***Rscm*** outperform ***Vall*** in total magnitude for all scenarios. Also evident from the graphs on the right is that for the ***RloR*** (and its impact in ***Rall***) the base-case scenario fluctuates the most, followed by scenario 2, then scenario 1, with scenario 3 being the most stable (i.e. least risk). The other irrigation blocks are more stable, with the exception of ***Rscm*** that shows a decline for scenarios 1 and 2. Important to note is that although the cumulative graph may be showing an increasing trend, the annual graph may be remaining constant or decreasing, as is the case with scenario 2, showing possible diminishing marginal TGMASC.

8.8 LINKAGES TO THE REGIONAL ECONOMIC MODEL

8.8.1 MICRO-MACRO LINKAGES

This data linking the micro and macro (regional) models consists of the irrigation block level individual crop CEB breakdown data, such as the results data used to set up Figure 8.9. For the macro-economic model only the 0.50 percentile and stochastic runs 001, 080 and 044 are generated and saved as an output file Scen...SR...SMmicro-out.xls for use in the regional model.

8.8.2 INDEX FOR SOCIO ECONOMIC WELFARE (ISEW)

A brief description of the data required to calculate the the Index for Socio Economic Welfare (ISEW) follows. The economic leg of the three pillars on which the sustainability of the scheme rests and as calculated in the ISEW is calculated from the year to year change in gross production value from the micro-economic model SMsim. The social leg is calculated from the year to year change in the value of temporary employment calculated in the micro-economic model SMsim, and the environmental leg is calculated from the year on year salt balance for each scenario as explained in Paragraph 5.6.

8.8.2.1 Economic leg – change in gross production

The total value of production component (e.g. see Figure 8.9 – Gross Income) of the per-hectare CEB combinations for the different scenarios is carried through from per hectare to irrigation block level changes and saved as inputs for the regional economic model.

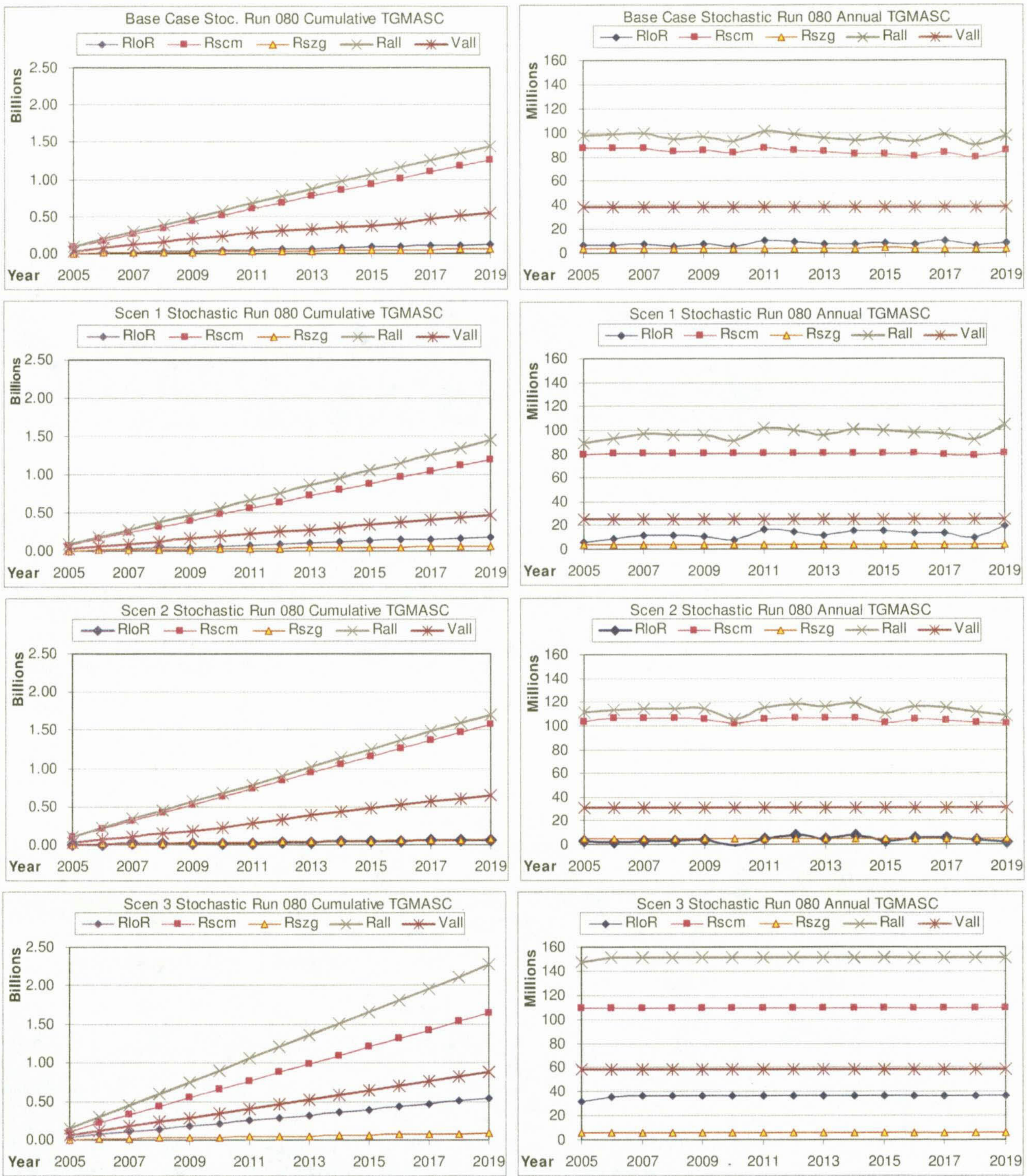


Figure 8.15. OV-WUA (*Vall*) versus OR-WUA (*Rall*) annual and 15 year cumulative average TGMASCs (2005 prices) for stochastic run 80

8.8.2.2 Social leg – change in temporary employment

Changes in the temporary employment component (e.g. see Figure 8.9 - Labour) of the-per hectare CEB combinations for the different scenarios are carried through from per hectare to irrigation block level changes and saved as inputs for the regional economic model.

8.8.2.3 Environmental leg – change in salt accumulation

Figure 8.16 is an example of the processed WRPM Salt abstraction (SA) and return-flow (SR) mass data (tonnes) that is saved as input for the regional economic model for use in the calculation of the Index for Social Economic Welfare, ISEW. Figure 8.16 shows that for the base-case scenario in ***Vall*** SA and SR slightly decline over 15 years resulting in a salt balance that increases over time, indicating increased salinisation for the status quo and therefore and un-sustainable situation.

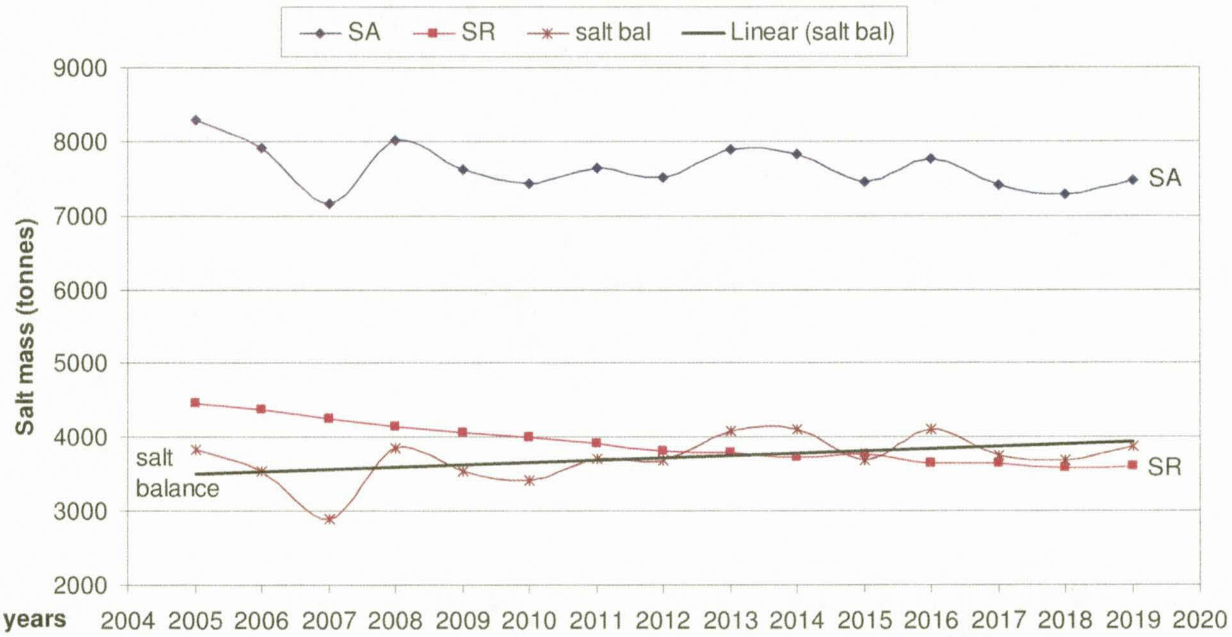


Figure 8.16. The salt mass balance (tonnes) calculated from the Vall base-case irrigation abstraction mass, SA(tonnes) minus the return-flow mass, SR (tonnes).

Figure 8.17 shows the resulting salt balance (tonnes) of the salt mass in the abstractions (**SA**) minus the salt mass in the returnflows (**SR**) of scenario 3 in the ***RloR*** irrigation block. With a greater mass of salts entering the ***RloR*** irrigation block than that leaving, there is an increase in the salt mass remaining in the soil in the irrigation block, even after 15 years when an equilibrium is reached, and is therefore not sustainable. The whole ***Rscm*** and ***Rszg*** is upstream from ***RloR*** and 15% increased drainage has also been implemented there, therefore possibly the reason for the prolonged salt accumulation. The declining salt balance values (Sbal) in the first 3 years indicate more salt are being washed out in the first three years after increasing returnflows by increasing drainage and leaching, but the salt balance returns to the initial levels after 15 years (2020 minus 2005) as equilibrium is reached again.

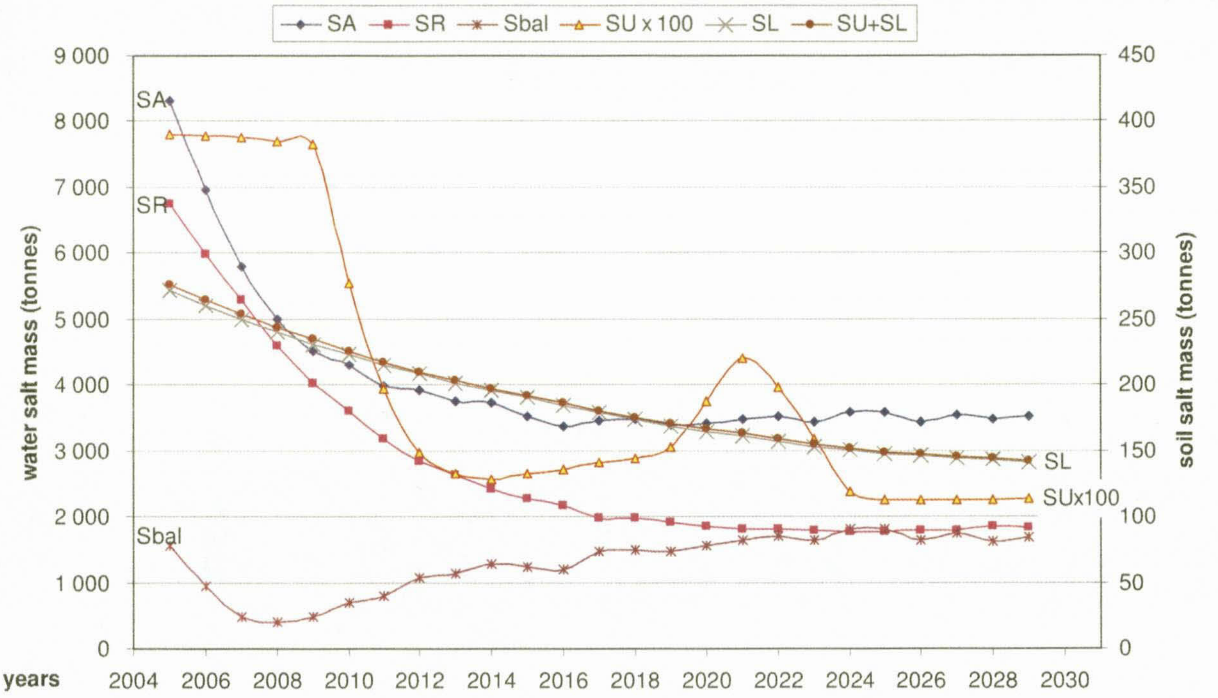


Figure 8.17. The salt mass balance (Sbal in tonnes) from irrigation abstraction (SA) minus returnflows (SR) for scenario 3 in RloR

With the change in the hydrology dynamics brought about by the 15% increased leaching and drainage as simulated in scenario 3, a large mass of salts is initially drained from the soils and a new equilibrium reached at approximately 2000 tonnes of return-flow mass after 10 years (2015). The full 25 years of stochastic data generated by the WRPM model is used here to show the longer-term trends than the 15 years of analysis in this study to confirm that a new equilibrium is in fact reached after 15 years and that the decreasing trend doesn't continue.

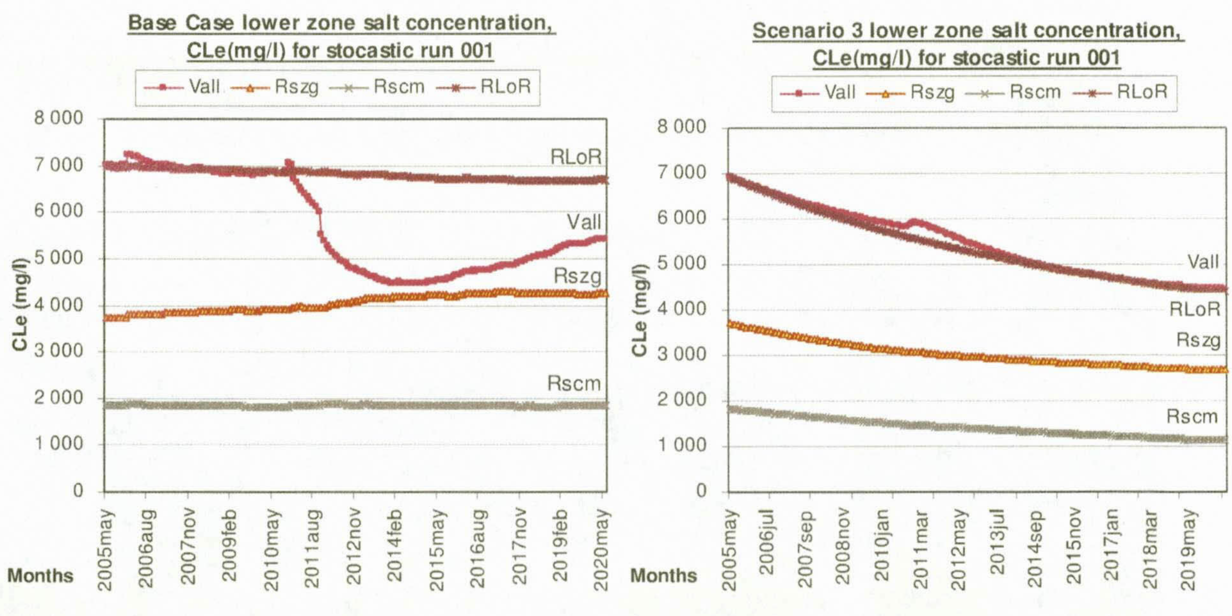


Figure 8.18. The impact of increased drainage on the lower zone salinity concentration, CLe(mg/l) – base-case vs. scenario 3.

To be analysed together with Figure 8.16 and Figure 8.17 is Figure 8.18 that shows the salinity concentration in the lower zone for the different irrigation blocks, and compares the base-case situation with 15% increased return-flow modelled in scenario 3. Figure 8.18 shows that for the base-case, salt concentration in the lower zone remains fairly constant, except for drastic changes as with ***Vall*** triggered in year 2010 resulting in a sharp drop, but thereafter heading back towards the initial level at a relatively long lag-time. Scenario 3 on the right however shows a constant gradual washing out of salts over 15 year after which there seems to be a flattening out towards a new equilibrium level. These large masses of salts initially washing out with scenario 3 explain the high returnflows in Figure 8.17.

8.8.3 REGIONAL MODEL RESULTS

Citing the results of the work by Urban-Econ in Viljoen *et al.* (2006), it is evident that the overall level of impact on the regional economy of the study area increases as alternative scenarios are considered. Scenario 2 produces higher values in total output, GGP and jobs than scenario 1. Similarly, scenario 3 and 3(+) results in higher values than scenarios 1 and 2. Scenarios 1 and 2 are also very cyclical in nature due to varying gross income levels, which in turn is linked to varying salinity levels and yield. Scenarios 3 and 3(+) have a more stable regional impact. These impacts did not consider price fluctuations or market volatility. Scenario 1 is the only scenario in which the overall regional economic impacts are lower than those assessed for the Base Case scenario. It is also evident that scenarios 3 and 3+ results in a substantial improvement in terms of production output, GGP generation and job creation.

When considering the indices for sustainable economic welfare (ISEW), it is also evident that all three scenarios will contribute towards increased economic welfare, based on the indicators measured, but that scenarios 3 and 3(+) will have a steeper improvement in the overall sustainability levels (Viljoen *et al.*, 2006).

8.9 SUMMARY

The hydrology results show that the irrigation block with the highest soil salt concentration in the upper zone (CU) is the Lower Riet irrigation block (***RloR***), followed by the Orange-Vaal irrigation block (***Vall***), the Scholtzburg irrigation block (***Rszg***), and with the lowest soil salt concentration, the Orange-Riet Scheme irrigation block (***Rscm***).

In comparing the hydrology results from the different scenarios run, changing the cropping choice from the status quo (base-case scenario) to more tolerant crops (scenario 1) to more salt sensitive yet higher value crops (scenario 2) has very little impact on the hydrology results. Though changing the return flow factor by increasing leaching and drainage, has a major impact on the hydrology by bringing the CU (mg/l) down substantially in the irrigation blocks. Hydrology results also show that the greatest variation, and highest values, in monthly irrigation water salt concentration and TDS (mg/l) occur in the months from April to August with the worst being from May to July. This indicates that salt sensitive crops grown or germinating during these months will be worst off than crops grown and germinating in the other months, i.e. spring and summer month crops.

Running the hydrology results through the bio-physical model converts the soil salt concentration, CU (mg/l) to CUe (mg/l), the saturated soil salt concentration. CUe is multiplied by the electrical conductivity factor to produce ECe (mS/m) and this is run through the Maas and Hoffmann equation to give the impact of soil salinity on crop yield. Results showed that in the irrigation blocks where the CU is highest, there crop yields are affected the most.

These changes in crop yield are then run through the micro-economic model to first produce per hectare crop enterprise budgets (CEBs) which are then extrapolated to irrigation block level.

On a per hectare basis (as shown in Table 8.5) the greatest financial loss (2005 values) due to salinity is experienced in the Lower Riet irrigation block (***RloR***), with the loss of R6962 per hectare per year, followed by Scholtzburg (***Rszg***) with R2596 and the Orange-Vaal irrigation block (***Vall***) with R2218. This provides the farmer in the specific irrigation block with a good indication of the per hectare costs (net benefit forgone) of poor drainage on his farm. At an average costs of drainage per ha on medium to heavy soils of R30 000[1] (Reinders, 2005), a 15 year loan at 9% interest would cost R3722 per year to service – worth spending in ***RloR***, though not as convincing without a funding grant in ***Rszg*** and ***Vall***.

Implemented for the whole study area (all irrigation blocks combined), the total real cumulative cost (2005 basis) of salinisation over a period of 15 years is R995 million, a good benchmark to use to leverage funds for remediation action.

Figure 8.13 and Figure 8.14 clearly show that to reduce the risk of income loss due to irrigation salinity one has to install drainage and leach more.

The conclusion is that an irrigation block is very sensitive to a specific salinity threshold level and therefore all irrigation blocks should not be treated the same. Only ***RloR*** benefited slightly from planting more tolerant crops as its soil salinity threshold is exceeded by the base-case cropping composition. Increased drainage and leaching however proved to be far more financially effective than planting tolerant crops, and the return-flow externality effects are more than compensated for as ***Vall*** downstream also achieved far better results when it is also drained. A scenario was not run where the OR-WUA drains and the OV-WUA (Vall) does not. It is expeted that the returnflows from the OR-WUA will have an impact on yields in the OV-WUA if the OV-WUA doesn't drain.

Comparing the Orange-Vaal WUA (***Vall***) and Orange Riet-WUA (***Rall***), the ***Rall*** naturally did better in absolute terms as it is nearly twice the size of the ***Vall***, although the worst irrigation block (***RloR***) is part of ***Rall***, its TGMASC improved at a better rate than ***Vall*** over the 15 years of analysis.

In the final paragraph the scenarios are compared from a regional perspective using the macro-economic results based on the micro economic model, SMsim. Scenarios 3 and 3+ performed best at regional economic level providing the most sustainable ISEW values.

[1] Note: drainage costs can range from R12000-R15000 on sandy soils (<15% clay), R20000-R25000 on medium soils (15-35% clay), and R30000-R50000 on heavy soils (>35% clay) – see Table 6.2.

CHAPTER 9 POLICY IMPLICATIONS AND RECOMMENDATIONS

Taking account of the fact that sustainable development planning is multidisciplinary by nature, the contributors concede that a single exemplary model does not exist. The aims of the stakeholders, along with preferences and priorities surrounding the planned objectives determine the ways and means of sustainable development planning

Quaddus & Siddique (2004)

9.1 INTRODUCTION

In this chapter some policy options for the management of salinity are discussed, together with the applicability of the various options on per hectare, irrigation block, WUA and regional levels. Although this chapter is largely based on paragraph 3.7 of the literature study, applicable additional literature is also cited in this chapter.

The first section of this chapter deals with the various policy options available for implementation at the various levels. Specifically, a sensitivity analysis of scenario 3+, whereby farmers' ability to pay for increased drainage and various cross subsidisation options is analysed. The next section of this chapter reviews the conclusions from the results of policy options and discusses their policy implications for various spatial levels of modelling.

The regional impacts of salinisation and various possible policy implications at regional level are discussed next, stressing the regional importance of irrigation agriculture and the impact that improved agricultural production due to better salinity management and control can have on the region as a whole. The final section of this chapter is a discussion on the optimal timing of the installation of irrigation drainage in the life cycle of a scheme.

9.2 POLICY OPTIONS

The following policy options to manage salinity are discussed in this section:

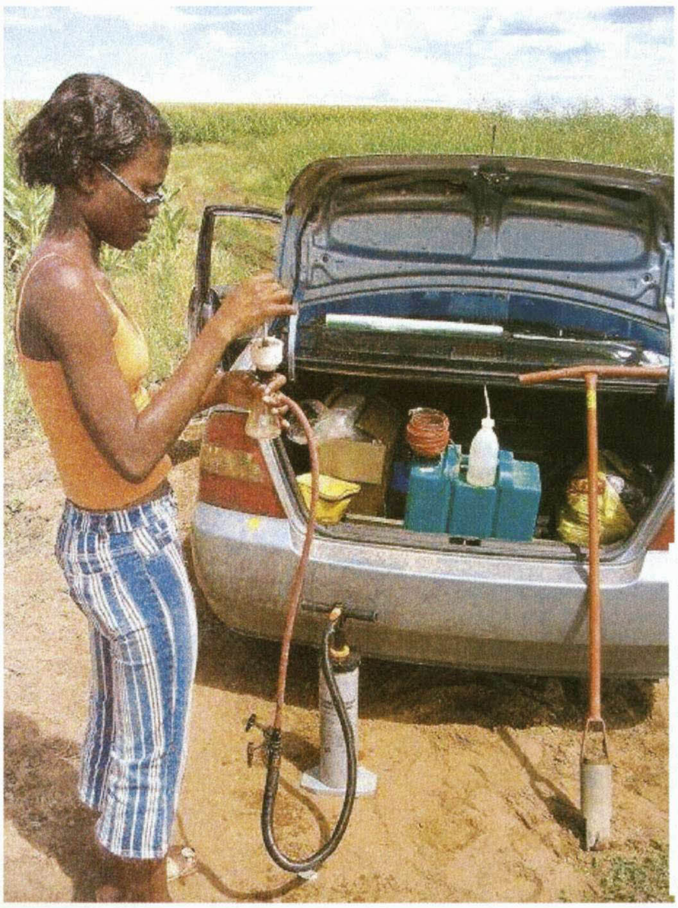
- Leaching incentives
- Drainage grant assistance
- Return-flow management options
- Efficient and effective water usage charges
- Farmers' willingness to pay for drainage: a sensitivity analysis and cross subsidisation options
- Changes in crops grown
- Institutional frameworks for salinity management
- Salinity awareness program
- Saline land retirement

A holistic approach incorporating most / all of the above options needs to be implemented to optimally manage salinity. Leaching cannot be practiced if there is not sufficient drainage. Once drainage has been installed, irrigation returnflows become a point source of pollution and needs to be managed, through either on-farm or irrigation block / sub-WUA level drainage collection canals and storage dams. These drainage and return-flow infrastructure costs have to be recouped through efficient and effective water charges, where the farmers' willingness to pay has been properly considered. Where drainage and return-flow management are not an option and soil has become salinised, all that remains is to change to more salt tolerant crops. Where a whole WUA, or irrigation block is salinised then the WUA and / or the local agricultural co-operative / company (e.g. GWK) may need to facilitate the change to more tolerant crops by providing enough water at the right price or the processing capacity for the new crops. For all of the above to happen the correct institutional framework has to be in place, and irrigators need to be made aware of the risks and management options for effective sustainable salinity management.

9.2.1 SALINITY LEACHING INCENTIVES

Increasing the cost of irrigation water results in irrigators being more careful with their water, leading to less unintentional leaching and an increase in salinisation, hence the leaching paradox (Armour and Viljoen, 2002). This paradox is prevented if the increased water costs are used at WUA level to improve the irrigation water quality through dilution with more Orange River water pumped into the system. Dilution however, does not facilitate the leaching of the salts already accumulated in the soils. Free or reduced cost irrigation water could be made available during periods of high river flow (see Figure 8.4) or in periods of low distribution canal usage (Table 7.8) to provide an incentive for farmers to flush the salts out of their soils.

The farmers also need to know that they do have a salinity problem, or potential salinity problem before they will be convinced to leach. Encouraging regular soil salinity measurement, through either subsidising it or further developing easy infield measurement techniques (see Figure 9.1) will help promote leaching. Fertilizer companies should also include soil salinity testing in their soil test at the beginning of each season before cropping choice and cultivar is decided on by the farmer.



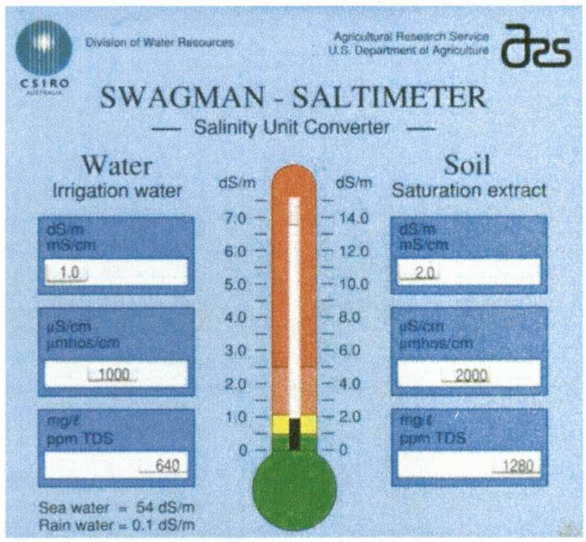


Figure 9.1. A possible infield ECe testing kit comprising of a soil bore, vacuum pump and filter (far left), salt meter (left) and a conversion chart (top)

The current water tariff charge system in the study area is based on the hectares of a crop planted, and therefore a derived water use, and not on an exact measured water use. Therefore, if farmers pump themselves and are not dependent on the canal infrastructure to deliver water to their farms, and they are irrigating on fallow land, or in-between crops, they do not necessarily pay the WUA for the water used. These irrigators do however pay for the electricity to pump the water, and face possible constraints in time before they can get their tractors back onto the land for preparation and planting of the following crop.

9.2.2 DRAINAGE GRANT ASSISTANCE

The rapid improvement in soil salinity (CUe) of the average of scenario 3 (Ave Scen3) as a result of drainage in Figure 9.2 clearly shows the significant impact of increasing the return-flow factor by 15% on the saturated soil salinity in the upper zone (CUe). In the first month already, there is a salt concentration reduction of 1000 mg/l, with a declining trend over the following 5 years to stabilize at a safe new equilibrium of just under 500 mg/l. Below a saturated soil salinity of 600 mg/l there is very little impact on crop yield.

Table 9.1. The determination of the increased water charge to pay for 15% additional underground leaching for scenario 3

Scenario 3+ additional leaching costs					
Sub Irrigation Block	**Vall**	**RloR**	**Rscm**	**Rszg**	**ALL**
Base Case return-flow factor	4.5%	2.0%	1.5%	2.5%	2.5%
Scenario 3 return-flow factor	19.5%	17.0%	16.5%	17.5%	17.5%
Area (ha) per sub- block	7389.6	3852.8	12335.1	641.2	**24218.7**
WRPM modeled drainage increase					
	15.0%	*15.0%*	*15.0%*	*15.0%*	*15.0%*
Drainage increase (ha)	1108.4	577.9	1850.3	96.2	**3632.8**
Total additional drainage Costs (R)	33 253 200	17 337 600	55 508 040	2 885 400	108 984 240
Minus 10% subsidised deposit (R)	29 927 880	15 603 840	49 957 236	2 596 860	98 085 816
Amortised annual payments (R)	**3 712 819**	**1 935 795**	**6 197 639**	**322 164**	**12 168 417**
Value of assistance (R)	3 325 320	1 733 760	5 550 804	288 540	10 898 424
Water use cost	**Vall**	**RloR**	**Rscm**	**Rszg**	**ALL**
Water cost (R/m^3/ha)	0.35	0.49	0.82	0.45	*0.61*
Water quota (m^3/ha)	1 100	1 100	1 100	1 100	*1 100*
Water quota use (m^3)	8 128 560	4 238 080	13 568 632	705 320	26 640 592
Water Charge (R/block)	2 844 996	2 072 652	11 144 288	319 645	*16 381 580*
TOTAL WUA/block obligations (R)	6 557 815	5 298 977	17 341 926	641 808	*31 335 966*
Water Cost with drainage (R/m^3/ha)	**0.81**	**1.25**	**1.28**	**0.91**	***1.18***
Percentage increase in water costs	*57%*	*61%*	*36%*	*50%*	*48%*
Actual water use (m^3)					
Base-case	**8 506 028**	**4 881 786**	**14 836 968**	**762 149**	*28 986 931*
Scen1	7 075 078	4 276 398	15 001 319	767 091	*27 119 885*
Scen2	7 933 108	4 664 869	14 734 871	758 668	*28 091 516*
Scen3 and Scen3+	9 071 832	5 350 879	16 912 438	869 692	*32 204 842*
Change in Water revenue (%)					
Base-case	**0.04**	**0.13**	**0.09**	**0.07**	***0.08***
Scen1	-0.15	0.01	0.10	0.08	*0.02*
Scen2	-0.02	0.09	0.08	0.07	*0.05*
Scen3 and Scen3+	0.10	0.21	0.20	0.19	*0.17*

At the bad case stochastic run 001, a saturated soil salinity level of around 3 350 mg/l results in significant yield losses from sensitive and medium tolerant crops. The increased installation of artificial drainage should therefore clearly have a dramatic effect on the saturated soil salinity levels in the soil and hence on crop yields, farm profit and regional socio-economic welfare.

The factors used in calculating the annual repayments in scenario 3+ in Table 9.1 are as follows:

- Installation of artificial drainage at **R 30 000**[1] per ha (in-between the cost of drainage for medium and heavy soils – see Table 6.2, and slightly inflated for the average soil types irrigated in the study area, to include in the costs of drainage other secondary / hidden costs),
- A fully subsidised deposit of **10%** of the total drainage costs,
- repaid over a period of **15** years,
- and at a **9%** interest rate (subsidised)

Table 9.1 demonstrated the calculations required to internalise the costs of irrigation drainage into the water charge. Modelled in the WRPM scenario is a 15% increase to the existing irrigation and drainage return flow factors for each irrigation block. With the additional costs of drainage factored into the water charge, using the factors listed above, an increase in water charge of between 36% for the ***Rscm*** and 61% for ***RloR*** result. From existing water costs, water quotas and irrigated area the change in the current actual water use and revenue is determined.

9.2.3 RETURN-FLOW MANAGEMENT OPTIONS

9.2.3.1 Implementing the Polluter Pays Principle for salinity

A definition of the Polluter Pays Principle (PPP) from the MSN Encarta web dictionary is "**principle that causer of pollution pays:** the principle that a company that causes pollution should pay for the cost of removing it, or provide compensation to those who have been affected by it"

(http://encarta.msn.com/dictionary_561547833/polluter-pays_principle.html.)

The installation of artificial drainage creates a point source for irrigation water pollution. A point source facilitates collection, management and disposal of returnflows, for which a management fee, as opposed to a fine should be paid in accordance with the polluter pays principle. Introducing the additional cost as a management fee, instead of as a fine, has a positive connotation and therefore better willingness to pay by irrigators.

9.2.3.2 Waste Discharge Charge System

Research conducted by DWAF (2003) to determine the rates to charge for waste discharge into rivers in accordance with the PPP provides guidelines for a Waste Discharge Charge System (WDCS). Charges for salinisation however still need to be formulated in the WDCS. Irrigation salinisation is an interesting problem as

[1] Note: drainage costs can range from R12000-R15000 on sandy soils (<15% clay), R20000-R25000 on medium soils (15-35% clay), and R30000-R50000 on heavy soils (>35% clay) – see Table 6.2.

once the soil salinity balance is in equilibrium it receives salt from the river source and concentrates it before returning it back to the river. Until equilibrium conditions are reached however, irrigation dissolves and mobilises salts already in the soils and adds these to the water source, making it less usable for downstream users. Before equilibrium conditions are reached, a Waste Discharge Charge (WDC) could be charged on the contribution of additional salts to a river, while at equilibrium the WDC could be levied against the concentration of salts (e.g. a stepwise charge above a certain threshold concentration, progressively more expensive as the concentration increases). A rebate on water volume returned to the river may have to be factored in as a non-consumptive use and to balance the water balance of the WUA, however for this meters will have to be placed on returnflow drains, the cost of which could be prohibitive. To counter this and provide and incentive to leach, a suggestion from the OR-WUA is to give a farmer who has drainage installed a proportional discount on the cost of water.

Where drainage collection dams are built, a stepwise scaled discharge charge could be levied, based on the dilution capacity of the river. During periods of high river flow, lower rates should be charged for saline wastage discharged. The capacity sharing concept has been applied to wastage discharge (Dudley 1992), whereby shareholders hold a proportionate share of the dilution capacity of a body of water. Shareholders can either use their dilution capacity share or trade it if not required at a particular time.

Where the damage or impact due to salinity is high and high rates charged, the high opportunity cost of water will lead to other uses for the salinised drain water. An example of the reuse of such drainage water is applied in the concept of Sequential Biological Concentration (SBC) in Blackwell, 2002.

9.2.3.3 Regional return-flow capture by WUAs

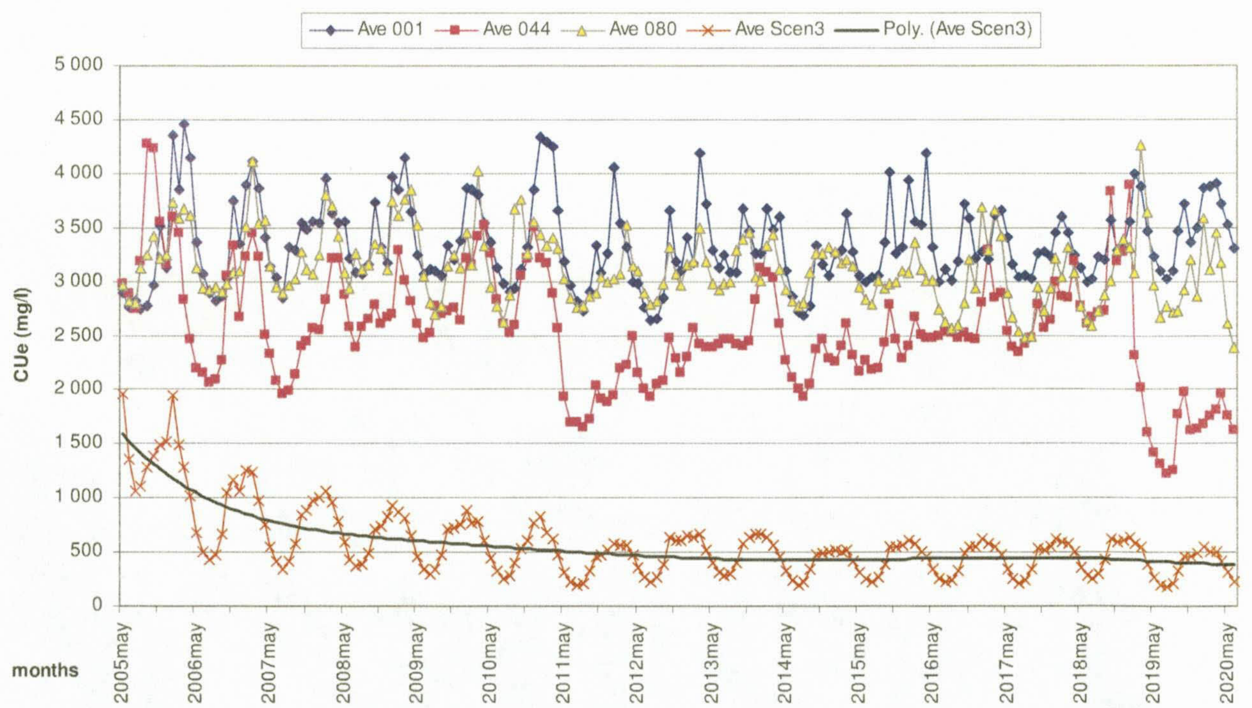


Figure 9.2. CUe for the 3 stochastic runs under analysis averaged for the base-case, scenario 1 and scenario 2 and the average of the 3 stochastic runs for scenario 3 for all irrigation blocks

Due to limited on-farm space, limited financial resources and a lower water use productivity of farm level storage dams, sub-WUA level collection, storage and management of irrigation returnflows would be financially a more sustainable option. The externality prevented in this way should be internalized into the irrigation water tariff for the sub-WUA. Downstream irrigators benefiting from the return-flow management intervention could also be charged more for better water quality to subsidize the drainage management costs upstream.

Financial results show that after the first 2 years of increasing drainage by 15% stable maximum returns are obtained, indicating that the CUe has gone below levels that impact crop yield in the ***RloR*** irrigation block (+-700 mg/l). Figure 9.2 shows how the CUe for scenario 3 stabilises (with steady seasonal cycles) after 5 years from drainage installation, way below levels affecting crop yields.

9.2.4 EFFICIENT AND EFFECTIVE WATER CHARGING

9.2.4.1 Willingness to pay for water of different qualities

The marginal willingness to pay for water quality (i.e price to pay for one additional unit improvement in water quality) determines the demand curve for water of a specific water quality. Within a season, a farmer may only need a certain water quality for germination when a plant is particularly vulnerable to salinity, but thereafter crop growth may no longer be sensitive to salinity. The marginal willingness to pay for water of a specific quality is therefore crop and time specific. With many farmers all using the same water delivery canal or river, it is very difficult for a WUA to meet all their individual requirements.

9.2.5 FARMERS' WILLINGNESS TO PAY FOR DRAINAGE: A SENSITIVITY ANALYSIS AND CROSS SUBSIDISATION OPTIONS

The hydrology basis at which this analysis is conducted, is for scenarios 3 and 3+ whereby a 15% increase in irrigation returnflows is simulated in the WRP model. The financial analysis of scenarios 3 and 3+ revealed that the ***Rscm*** and ***Rszg*** irrigation blocks didn't require as much drainage as 15%, and that the ***RloR*** was in need of more, proportional to the respective irrigated areas. By parametrically changing the return flow factor (leaching and drainage percentage) by factors of 5%, the best irrigation block TGMASC results were obtained where return flow percentage was increased from 15% to 20% in ***RloR***, reduced to 10% in ***Vall*** and reduced to 5% for both the ***Rscm*** and ***Rszg***, by evaluating the resulting economic impact. The results of this analysis are shown in Table 9.2 to Table 9.5 and discussed in Paragraph 9.2.9 and 9.4.

9.2.5.1 Regional cost benefit analysis

Two cost benefit analyses are conducted, one with 15% drainage throughout all irrigation blocks (the setup on which the WRPM hydrology results are based) and one with the drainage percentages changed, so that ***RloR*** is drained 20%, ***Vall*** 10% and both ***Rscm*** and ***Rszg*** only drained 5%. Discount rates of 0%, 5%, 8% and 10% are used to determine the net present value (NPV) of the sequence of increased TGMASC as a result of increased drainage over 15, 20, 25 and 30 years, depending on the effective lifespan of the drainage system. Although occasional maintenance is acknowledged for optimal functioning of the drains (ARC-ILI ,1997, for care and maintenance of irrigation drains) these costs have been left out of the calculation of the NPV in the costs benefit analysis as these costs are highly variable and are generally borne by the farmer and not government who is assumed to initially subsidising the drains. The results of this analysis are shown in Table 9.6 and Table 9.7 and discussed in Paragraph 9.4.

9.2.5.2 Cross-subsidisation options

Irrigation blocks receiving Orange River water directly (***Rscm*** and parts of ***Vall***) do not display yield loses due to salinisation for most crops, yet the returnflows from these irrigation blocks do affect irrigation blocks downstream. A higher water charge for the upstream farmers to compensate / remediate water quality for affected downstream farmers may be a viable policy option.

The percentage change in TGMASC between scenario 3, where the standard water charge is levied, and scenario 3+, where a proportional 43% increase in water charges across the study area are levied, results in a minimal change in TGMASC of only between 5.7 and 7.6% as shown in the last column of Table 9.4 (% change between 3 and 3+). TGMASC is therefore relatively inelastic to changes in water charges.

9.2.6 CHANGES IN CROPS GROWN

The farmers' choice of crops to grow is not based purely on the most profitable crop as depicted in Table 9.3, but on the alignment of the most profitable crops with the physical, resource, capital, financial and managerial capacity of the farming operation.

At the WUA level, cropping choice influences water use consumption patterns and volumes. Internal WUA policy to alleviate possible water delivery constraints can be made whereby incentives are given to plant more of certain crops that will help alleviate constraints. The OV-WUA has an internal policy in place whereby pre-year and after-year water is charged at different rates to discourage farmers from using more expensive, scarce pre-year water in the low rainfall winter months.

9.2.7 INSTITUTIONAL FRAMEWORK FOR SALINITY MANAGEMENT

9.2.7.1 Water trading / water markets

The WUAs have implemented a system of water trading, but only on a very small scale and only for a season in advance at a time. Institutional frameworks for effective and efficient water trading between farmers within and in-between WUAs could automatically divert water from less efficient to more efficient water users.

9.2.7.2 Fractional water allocation (capacity sharing)

The concept of a fractional water allocation (Pott & Creemers 2000), or a capacity sharing (Dudley, 1992) of a water resource (or body) only accounts for a specific quantity of the water, and doesn't specifically guarantee a certain quality. The whole concept would have to be revised to account for a quality dimension. One option is to have an effective water market in place whereby the irrigators with highly elastic demand curves for water quality (bulk commodity, salt tolerant, low value products) can sell their water capacity share to irrigators with more inelastic water quality demand curves (long term and high value crops). Generally, the higher value the crop (e.g. fruit trees), the smaller the percentage of total production costs are attributed to water costs. Permanent crops are also generally more inelastic in their demand for water than annual crops.

9.2.8 SALINITY AWARENESS PROGRAM

The following awareness programmes could be initiated by the Department of Agriculture, WUAs, GWK, etc. in the irrigation areas:

- The regular measurement of soil salinity on a cost recovery basis by agricultural extension officers
- The promotion of soil salinity status readings by fertilizer companies when conducting soil analyses and making fertilization recommendation
- The inquiry / measurement of the salinity status of soils when purchasing irrigation land
- The raising of the awareness of insurance companies of the potential increased risk of salinised soils if not managed properly.

These salinity awareness programmes must be coupled with a centralised soil salinity database to facilitate the accumulation of soil salinity data for better policy analysis and research in the future, as one of the limitations identified in this study is a shortage of historical soil salinity data.

9.2.9 SALINE LAND RETIREMENT

The retirement of saline land is a policy option that could be considered where irrigation land is a constraint, however most farmers have more irrigable land than they have water rights, and there is sufficient new land to develop for irrigation. Irrigable land is therefore not a constraint, but water rights with which to irrigate with.

Retiring irrigable land in excess of water rights that has become salinised does however reduce the fallow land component of a crop rotation and therefore does have an economic cost. Furthermore it is the mandate of the Protection of Agricultural Resources Act to maintain the productivity of the agricultural resource base.

In the absence of a constraint on potential irrigable land for development, if the cost of developing the new irrigation land is less than the cost of drainage installation it is then financially feasible to retire salinise land and develop new land.

9.3 FARM LEVEL POLICY IMPLICATIONS

Farm level policy impact is derived from analysis of the resulting total gross margin above specified costs (TGMASC) of per hectare crop enterprise budgets (CEBs) as displayed in Table 9.3. The TGMASCs of the CEBs in Table 9.3 are derived from the crop specific weighted average saturated soil salinity values shown in Table 9.2. Among others, the change in the TGMASC for the increased water charge initiated in scenario 3+ is shown for a 15% increase in drainage and leaching, and also for different leaching fraction changes for different irrigation blocks. To prevent the installation of unnecessary drainage and to install additional drains where most needed, the uniform installation increase of 15% from scenario 3 is adjusted to the following:

- RIoR increased from the base case level of 2% to 17% (+15) and increased by a further 5% to 22%
- Rscm increased from the base case level of 1.5% to 16.5% (+15), but decreased by 10% to 6.5%
- Rszg increased from the base case level of 2.5% to 17.5% (+15), but decreased by 10% to 7.5%
- Vall increased from the base case level of 4.5% to 19.5% (+15) but decreased by 5% to 14.5%

The decrease in soil salinity as a result of increased drainage and leaching is clearly evident from Table 9.2. When comparing the base-case crop specific weighted average ECe (mS/m) with the scenario 3 ECe, ECe is reduced by between 68% and 86%. The very low ECe values for ***Rscm*** and ***Rszg*** are unnecessarily low at 15% leaching and drainage and it was therefore decided to only increase drainage in ***Rscm*** and ***Rszg*** by 5%.

Where a percentage more area of drainage is installed, a corresponding equal percentage leaching fraction is applied, resulting in additional water and electricity costs over and above the physical drainage costs. It is this increase in the costs of additional leaching and drainage that are being weighed up against the financial benefits to determine the farmers ability to pay for drainage.

Irrigation farmers know what cropping combination they are able to plant on their particular farm. Table 9.3 gives an indication of the potential per hectare TGMASC attainable from different crops in the various irrigation blocks. For policy analysis at farm level, these crop specific values can be multiplied by the hectares planted / planned to plant overall to determine the potential / expected annual marginal income above fixed / operational costs.

Table 9.2. Corresponding weighted average ECe (mS/m) with 15% increased drainage area and a 15% leaching fraction

	Irrigation Block	Barley	Beets	Carrots	Cotton	Cucurbits	Dry-Beans	Fruit	Lucerne	Maize	Olives	Onions	Pastures	Peanuts	Pecan-nuts	Potatoes	Soybeans	Sunflower	Vege-tables	Vineyards	Wheat	**Average**	**WQ improve-ment %**
Base Case	*RloR*	*471*	*510*	*519*	*496*	*505*	*512*	*498*	*491*	*515*	*499*	*497*	*503*	*513*	*497*	*521*	*515*	*519*	*472*	*497*	*456*	***500***	
Scenario 3 and 3+	RloR	184	194	240	103	111	118	100	97	117	101	84	99	116	98	118	117	120	79	98	63	**118**	**0.76**
Base Case	*Rscm*	*148*	*152*	*166*	*173*	*186*	*192*	*182*	*177*	*193*	*183*	*192*	*188*	*190*	*182*	*200*	*193*	*197*	*167*	*182*	*165*	***180***	
Scenario 3 and 3+	Rscm	53	47	46	18	22	25	20	19	24	21	21	21	24	20	26	24	26	15	20	14	**25**	**0.86**
Base Case	*Rszg*	*195*	*194*	*227*	*196*	*216*	*224*	*214*	*204*	*226*	*214*	*240*	*223*	*222*	*214*	*237*	*226*	*231*	*193*	*214*	*194*	***215***	
Scenario 3 and 3+	Rszg	61	49	125	30	54	65	47	40	63	47	59	52	58	46	71	63	70	24	46	24	**55**	**0.75**
Base Case	*Vall*	*324*	*327*	*337*	*335*	*354*	*364*	*347*	*335*	*367*	*347*	*369*	*354*	*364*	*346*	*377*	*367*	*369*	*315*	*346*	*305*	***347***	
Scenario 3 and 3+	Vall	127	124	144	102	116	126	105	99	125	106	100	106	122	104	130	125	130	78	104	65	**112**	**0.68**

Table 9.3. Average annual TGMASC (R/ha) with different leaching fractions (2005 input costs and average 10yr real average crop prices)

	Irrigation Block	*Barley*	*Beets*	*Carrots*	*Cotton*	*Cucurbits*	*Dry_Beans*	*Fruit*	*Lucerne*	*Maize*	*Olives*	*Onions*	*Pastures*	*Peanuts*	*Pecan_nuts*	*Potatoes*	*Soybeans*	*Sunflower*	*Vegetables*	*Vineyards*	*Wheat*	**Average**	***change from BC %***
Base Case	RloR	1533	5272	-4969	3431	9678	-284	-3823	4190	481	3687	11286	2157	-2324	5976	-8163	6019	2353	11669	998	2345	**2576**	
Scenario 3 LF17%	RloR	1428	6886	6088	3299	18381	2587	37540	6287	4825	9218	50008	2013	2164	22724	11147	6122	2354	11564	5646	2240	**10626**	***4.13***
Scenario 3+LF17%	RloR	1107	6677	5886	2896	18109	2411	36905	6067	4502	8926	49880	1571	1848	22389	10855	5784	2135	11241	5312	1919	**10321**	***4.01***
Scenario 3+LF22%	RloR	946	6572	5975	2695	17973	2333	36661	5958	4350	8780	49899	1350	1690	22247	10767	5615	2025	11080	5152	1758	**10191**	***3.96***
Base Case	Rscm	1334	6825	8268	4317	22081	3000	36038	6223	3918	9133	44074	1883	2049	21941	10789	6023	2174	13725	6075	2146	**10601**	
Scenario 3 LF16.5%	Rscm	1199	6737	10619	4148	21967	3174	37272	6130	4050	9010	51354	1698	1916	23276	12189	5881	2082	13589	6351	2011	**11233**	***1.06***
Scenario 3+LF06.5%	Rscm	1191	6732	10614	4139	21960	3170	37257	6125	4042	9003	51351	1687	1908	23268	12182	5873	2077	13582	6343	2003	**11226**	***1.06***
Scenario 3+LF16.5%	Rscm	879	6528	10418	3747	21696	3000	36640	5912	3728	8719	51225	1258	1601	22943	11899	5544	1863	13268	6018	1691	**10929**	***1.03***
Base Case	Rszg	1551	6967	6133	4590	22261	2856	32896	5478	3550	9331	39192	2183	2263	20683	8962	6252	2323	13944	5883	2364	**9983**	
Scenario 3 LF17.5%	Rszg	1450	6901	10483	4463	22179	3311	37768	5312	4109	9238	51454	2043	2163	23537	12416	6145	2254	13842	6612	2262	**11397**	***1.14***
Scenario 3+LF07.5%	Rszg	1419	6881	10084	4425	22154	3295	37708	5254	4071	9211	51442	2001	2133	23506	12389	6113	2233	13811	6580	2231	**11347**	***1.14***
Scenario 3+LF17.5%	Rszg	1127	6690	10280	4058	21906	3135	37130	4692	3707	8945	51325	1599	1845	23201	12124	5805	2033	13517	6276	1939	**11067**	***1.11***
Base Case	Vall	1603	7001	2065	3572	14944	1029	15785	5399	2528	7818	25156	2253	1045	14187	179	6271	2469	11758	3187	2421	**6533**	
Scenario 3 LF19.5%	Vall	1510	6940	9882	3456	18451	2672	37888	6343	4956	9293	50559	2126	2245	23601	11447	6209	2411	11664	5773	2328	**10988**	***1.68***
Scenario 3+LF14.5%	Vall	1331	6824	9581	3232	18299	2574	37535	6221	4776	9131	50378	1880	2069	23414	11285	6020	2289	11485	5588	2150	**10803**	***1.65***
Scenario 3+LF19.5%	Vall	1182	6726	9677	3045	18173	2493	37239	6119	4626	8995	50427	1675	1922	23259	11149	5863	2186	11335	5432	2000	**10676**	***1.63***

* all based on stochastic run number 80 for all scenarios and all irrigation blocks, with a 10% grant on the increased drainage in scenario 3 and 3+

9.4 IRRIGATION BLOCK (/SUB-WUA) LEVEL POLICY IMPLICATIONS

Table 9.4 and Table 9.5 are an extension of Table 9.3, taking the average cropping composition for the base-case (upper half of tables) and the salt sensitive, yet higher value (lower half of tables) scenario values and working out the total annual per hectare productivity (TGMASC / ha / year). As irrigation blocks utilize land for more than one crop per year (>100%) at different rates, crop composition is standardised to 150% for all irrigation blocks (i.e. all plant 1.5 crops per year per hectare), to enable equal comparison between irrigation blocks (the bottom halves of the two scenario crop composition sub-tables in Table 9.4).

Table 9.4 is an annual TGMASC (R/ha/year) analysis of the scenarios run through the WRPM (hydrology model) where 15% additional leaching and drainage is applied to all irrigation blocks, and Table 9.5 an annual TGMASC (R/ha/year) analysis of irrigation blocks with the following additional leaching and drainage implemented: ***Vall*** 10%, ***RloR*** 20%, ***Rscm*** 5% and ***Rszg*** 5%.

Table 9.4. Annual TGMASC (R/ha/year) for different scenarios with a 15% increase in leaching and drainage implemented in all irrigation blocks (for actual and standardized crop composition percentages)

Irrigation block cropping composition		SCENARIO			% change between		
Base-case average cropping composition (% area)		Base-Case	Scenario 3	Scenario 3+	BC & 3	BC & 3+	3 & 3+
Vall	151%	4953	7351	6884	148%	139%	-6.36%
RloR	185%	2075	**8750**	**8175**	422%	394%	-6.57%
Rscm	166%	**6889**	7025	6510	102%	94%	-7.34%
Rszg	114%	4456	5329	4923	120%	110%	-7.62%
Vall	*150%*	4929	**7317**	**6851**	*148%*	*139%*	*-6.36%*
RloR	*150%*	1685	7108	6641	*422%*	*394%*	*-6.57%*
Rscm	*150%*	**6236**	6359	5892	*102%*	*94%*	*-7.34%*
Rszg	*150%*	5879	7031	6495	*120%*	*110%*	*-7.62%*
Scenario 3 average cropping composition		Base-Case	Scenario 3	Scenario 3+	BC & 3	BC & 3+	3 & 3+
Vall	142%	5070	7606	7168	150%	141%	-5.77%
RloR	180%	1612	**9004**	**8448**	558%	524%	-6.17%
Rscm	172%	**8416**	8588	8064	102%	96%	-6.09%
Rszg	117%	4846	5872	5484	121%	113%	-6.60%
Vall	*150%*	5363	**8046**	**7582**	*150%*	*141%*	*-5.77%*
RloR	*150%*	1347	7519	7055	*558%*	*524%*	*-6.17%*
Rscm	*150%*	**7357**	7507	7050	*102%*	*96%*	*-6.09%*
Rszg	*150%*	6236	7556	7057	*121%*	*113%*	*-6.60%*

The bold scenario values in Table 9.4 and Table 9.5 show the irrigation blocks with the greatest comparative advantage. When looking at the current cropping composition in both tables, ***RloR*** (180%) has the greatest TGMASC per hectare per year for scenarios 3 and 3+ because it plants 185% of the cropping area each year (1.85 crops per hectare per year), but with readjustment of the leaching and drainage percentage that all irrigation blocks only plant 1.5 crops per year, the ***Vall*** (150%) has the greatest comparative advantage for both scenario 3 and 3+, and for both the base case cropping composition and higher value crops scenarios. ***Rscm*** has the greatest comparative advantage for the base-case scenario levels (i.e. no additional leaching and drainage) at both the irrigation block specific cropping percentage and at the equated percentage of 150%, also for both the base case cropping composition and higher value cropping compositions, with very poor TGMASC per hectare per year results from the ***RloR***.

Table 9.5. Change in annual TGMASC (R/ha/year) for different scenarios with adjusted additional leaching and drainage implemented for the different irrigation blocks (for actual and standardized crop composition percentages)

Irrigation block cropping composition		SCENARIO			*% change between*			*Change due to leaching area*	
Base-case average cropping composition (% area)		**Base Case**	**Scenario 3**	**Scenario 3+**	***BC & 3***	***BC & 3+***	***3 & 3+***	***Scen-ario 3***	***Scen-ario 3+***
Vall	151%	4953	7393	7095	149%	143%	4.04%	0.01	0.03
RloR	185%	2075	**8703**	**7904**	**419%**	**381%**	**9.18%**	-0.01	-0.03
Rscm	166%	**6889**	7171	7013	104%	102%	2.19%	0.02	0.07
Rszg	114%	4456	5414	5291	122%	119%	2.29%	0.02	0.07
Vall	*150%*	4929	**7358**	**7061**	149%	143%	4.04%	0.01	0.03
RloR	*150%*	1685	7070	6420	419%	381%	9.18%	-0.01	-0.03
Rscm	*150%*	6236	6491	6348	104%	102%	2.19%	0.02	0.07
Rszg	*150%*	5879	7144	6980	122%	119%	2.29%	0.02	0.07
Scenario 3 average cropping composition		**Base Case**	**Scenario 3**	**Scenario 3+**	***BC & 3***	***BC & 3+***	***3 & 3+***	***Scen-ario 3***	***Scen-ario 3+***
Vall	142%	5070	7645	7365	151%	145%	3.67%	0.01	0.03
RloR	180%	1612	**8961**	8188	**556%**	**508%**	**8.63%**	-0.00	-0.03
Rscm	172%	**8416**	8735	**8576**	104%	102%	1.83%	0.02	0.06
Rszg	117%	4846	5954	5835	123%	120%	1.99%	0.01	0.06
Vall	*150%*	5363	**8087**	**7791**	151%	145%	3.67%	0.01	0.03
RloR	*150%*	1347	7483	6838	**556%**	**508%**	**8.63%**	-0.00	-0.03
Rscm	*150%*	**7357**	7636	7497	104%	102%	1.83%	0.02	0.06
Rszg	*150%*	6236	7661	7509	123%	120%	1.99%	0.01	0.06

Table 9.5 includes an additional two columns for the comparison of results where 15% drainage is implemented throughout (Table 9.4) versus the adjusted levels of additional leaching and drainage (Table 9.5). Results show that at the per hectare level, annual TGMASCs (R/ha/year) are affected -3% to +6% by the changes in the leaching and drainage percentage between Table 9.4 and Table 9.5. Extrapolating these seemingly small changes from per hectare to irrigation block level, the 6% change on an annual TGMASC of R5000 per hectare is R300, this multiplied by the 12 335 hectares making up ***Rscm***, gives an irrigation block level financial improvement of R3.7 million per year.

Increasing drainage in the ***RloR*** from 15% to 20% results in a less than 1% reduction in annual TGMASC per hectare if fully subsidised, and a 3% reduction in annual TGMASC per hectare if only subsidised 10% and the farmers, through increased water tariffs have to repay the rest. This indicates that 20% leaching in the ***RloR*** is too much and that 15% yielded better financial results. It is expected that when optimising the leaching and drainage percentages for maximum TGMASC, that a leaching and drainage percentage value of closer to 20% than 15% will result. Increasing the irrigation and drainage percentage has a smaller impact on scenario 3 where the cost of the drainage isn't factored into the water charge than in scenario 3+, indicating a sensitivity to the cost of water.

In Table 9.6 and Table 9.7 the irrigation block level cost of grant assistance of additional artificial drainage installation at levels of 10%, 50% and 100% are compared for ***Vall*** and ***RloR*** respectively. As ***RloR*** has positive net returns for all discount rates, a full discussion for ***Vall*** follows as it is a "border-line" block (i.e. positive to negative net returns for different discounts rates). Net returns are less (more negative) for the ***Rszg*** and ***Rscm*** as their levels of salinisation are not as bad as ***Vall*** and ***RloR***.

As the choice of discount rate depends on *inter alia* the following economic and social factors: the opportunity cost of capital, the cost of borrowing money and the social rate of time preference, the results are presented at four different discount rates, 0%, 5%, 8% and 10%. Zero percent is included to give an idea of the direct net returns when not factoring in the time value of money. The greater the discount rate used, the less favourable the results. Drainage maintenance costs are assumed zero in all analyses, and the positive secondary impacts on job creation and the environment have also not been factored in to the annual costs and benefits calculations, as these amounts are very subjective.

9.5 WUA LEVEL POLICY IMPLICATIONS

9.5.1 CROP CHOICE IMPACT ON THE SHORT-TERM VERSUS LONG-TERM DEMAND FOR WATER

The short-term versus the long-term demand for water is determined by:

- the factors that influence the decision to plant a long-term crop,
- what the stability of water supply (quantity) is, and
- the probability that the quality over the long term will be acceptable.

At farm level these factors will influence the decision to make a large capital investment in a long term crop. From a WUA perspective, if only a few farmers demand a certain quantity and quality it will be far more difficult than if many demand it, however if the WUA can guarantee a certain water quality and quantity then more farmers may change their cropping choice. This may however subject the WUA to litigation and great expense if the guaranteed standards can not be met once farmers have implemented large capital investments in long-term, high value crops.

A financial analysis was conducted by Backeberg (1981) to evaluate capital expenditure on irrigation drainage based on the internal rate of return (IRR), the net present value (NPV) and the benefit cost ratio (BCR). Costs of drainage were calculated for 1981 at between R1039 and R2711 per hectare based on information supplied by the same Reinders (2005) as referenced in this thesis.

For the calculations in this thesis, the time period is 15 years and discount rates of 0%, 5%, 8% and 10% are used. 0% is used to indicate the potential returns to the sub-WUA (/irrigation block) if the full cost of drainage was covered by the state as a sustainability grant.

Table 9.6 Vall net returns of subsidised drainage costs (2005 constant prices - R'000 000)

Year	real	Cost 1	Marginal Income * 1-15	NPV	Net Return (Cost+NPV)
Assistance costs	***10%***	***-3.33***			
Maintenance costs		0.00			
discount rate	0%	-3.33	**0.36**	5.40	**2.08**
discount rate	5%	-3.33	0.36	3.74	**0.41**
discount rate	8%	-3.33	0.36	3.08	**-0.24**
discount rate	10%	-3.33	0.36	2.74	**-0.59**
Year		*1*	***1-20***		
discount rate	0%	-3.33	0.36	7.20	**3.88**
discount rate	5%	-3.33	0.36	4.49	**1.16**
discount rate	8%	-3.33	0.36	3.54	**0.21**
discount rate	10%	-3.33	0.36	3.07	**-0.26**

Year	real	Cost 1	Marginal Income 1-15	NPV	Net Return (Cost+NPV)
Assistance costs	***50%***	***-16.63***			
Maintenance costs		0.00			
discount rate	0%	-16.63	**1.80**	27.02	**10.39**
discount rate	5%	-16.63	1.80	18.70	**2.07**
discount rate	8%	-16.63	1.80	15.42	**-1.21**
discount rate	10%	-16.63	1.80	13.70	**-2.93**
Year		*1*	***1-20***		
discount rate	0%	-16.63	1.80	36.02	**19.40**
discount rate	5%	-16.63	1.80	22.45	**5.82**
discount rate	8%	-16.63	1.80	17.68	**1.06**
discount rate	10%	-16.63	1.80	15.33	**-1.29**

Year	real	Cost 1	Marginal Income 1-15	NPV	Net Return (Cost+NPV)
Assistance costs	***100%***	***-33.25***			
Maintenance costs		0.00			
discount rate	0%	-33.25	**3.60**	54.03	**20.78**
discount rate	5%	-33.25	3.60	37.39	**4.14**
discount rate	8%	-33.25	3.60	30.83	**-2.42**
discount rate	10%	-33.25	3.60	27.40	**-5.85**
Year		*1*	***1-20***		
discount rate	0%	-33.25	3.60	72.05	**38.79**
discount rate	5%	-33.25	3.60	44.89	**11.64**
discount rate	8%	-33.25	3.60	35.37	**2.11**
discount rate	10%	-33.25	3.60	30.67	**-2.58**
Year		*1*	***1-25***		
discount rate	0%	-33.25	3.60	90.06	**56.80**
discount rate	5%	-33.25	3.60	50.77	**17.52**
discount rate	8%	-33.25	3.60	38.45	**5.20**
discount rate	10%	-33.25	3.60	32.70	**-0.56**
Year		*1*	***1-30***		
discount rate	0%	-33.25	3.60	108.07	**74.82**
discount rate	5%	-33.25	3.60	55.38	**22.12**
discount rate	8%	-33.25	3.60	40.55	**7.30**
discount rate	10%	-33.25	3.60	33.96	**0.71**

* Marginal income = change in gross margin between drainage and no drainage

Table 9.6 shows the Net Returns (NR) of the different assistance levels at different discount rates for ***Vall***. At a 10% assistance grant, the total costs to government for only one year will be R3.33 mil (million). At a discount rate of 0%, i.e. the time value of money not factored in, the increased (marginal) value to the farmers of the assistance grant over 15 years is R0.36 mil x 15 = R5.40 mil (= the net present value (NPV)). The net return (NR), which is the assistance grant costs minus the NPV = R2.08mil.

At a 5% discount rate the NPV = R3.74mil and the NR = R0.41mil.

At a 8% discount rate the NPV = R3.08mil and the NR = R-0.24mil., a relative loss.

If the NPV is calculated over 20 years, then at an 8% discount rate the NPV = R3.54 mil and the NR = R0.21 mil. Over 20 years at a discount rate of 10% the NR = R-0.26 mil.

At a government assistance grant rate of both 50% and 100% a similar pattern in positive and negative NR's is presented for the same respective discount rates.

For the 100% assistance grant rate the life span of marginal returns is extended to 25 and 30 years. At a lifespan of only over 30 years can a positive NR be attained at a 10% discount rate.

Table 9.7 *RloR* net returns of subsidised drainage costs (2005 constant prices - R'000 000)

Year	real	Cost 1	Marginal Income * 1-15	NPV	Net Return (Cost+NPV)
Assistance costs	***10%***	***-1.73***			
Maintenance costs		0.00			
discount rate	0%	-1.73	**0.24**	3.57	**1.84**
discount rate	5%	-1.73	0.24	2.47	**0.74**
discount rate	8%	-1.73	0.24	2.04	**0.30**
discount rate	10%	-1.73	0.24	1.81	**0.08**
Year		***1***	***1-20***		
discount rate	0%	-1.73	0.24	4.76	**3.03**
discount rate	5%	-1.73	0.24	2.97	**1.23**
discount rate	8%	-1.73	0.24	2.34	**0.60**
discount rate	10%	-1.73	0.24	2.03	**0.29**
Year	***real***	**Cost** ***1***	**Marginal Income** ***1-15***	**NPV**	**Net Return** ***(Cost+NPV)***
Assistance costs	***50%***	***-8.67***			
Maintenance costs		0.00			
discount rate	0%	-8.67	**1.19**	17.85	**9.18**
discount rate	5%	-8.67	1.19	12.35	**3.68**
discount rate	8%	-8.67	1.19	10.19	**1.52**
discount rate	10%	-8.67	1.19	9.05	**0.38**
Year		***1***	***1-20***		
discount rate	0%	-8.67	1.19	23.80	**15.13**
discount rate	5%	-8.67	1.19	14.83	**6.16**
discount rate	8%	-8.67	1.19	11.68	**3.02**
discount rate	10%	-8.67	1.19	10.13	**1.46**
Year	***real***	**Cost** ***1***	**Marginal Income** ***1-15***	**NPV**	**Net Return** ***(Cost+NPV)***
Assistance costs	***100%***	***-17.34***			
Maintenance costs		0.00			
discount rate	0%	-17.34	**2.38**	35.70	**18.36**
discount rate	5%	-17.34	2.38	24.70	**7.37**
discount rate	8%	-17.34	2.38	20.37	**3.03**
discount rate	10%	-17.34	2.38	18.10	**0.77**
Year		***1***	***1-20***		
discount rate	0%	-17.34	2.38	47.60	**30.26**
discount rate	5%	-17.34	2.38	29.66	**12.32**
discount rate	8%	-17.34	2.38	23.37	**6.03**
discount rate	10%	-17.34	2.38	20.26	**2.93**

* Marginal income = change in gross margin between drainage and no drainage

Table 9.7 shows the Net Returns (NR) of the different assistance grant levels at different discount rates for ***RloR***.

As opposed to drainage grant assistance investment in the ***Vall*** where a positive net return is only realised at low discount rates and over longer periods of time, for all discount rates, all assistance grant levels and for 15 and 20 year repayment terms, the net return of assistance grant investment for the ***RloR*** is positive, indicating a very favourable return to subsidised drainage investment over a range of possible circumstances and conditions.

9.6 REGIONAL LEVEL POLICY IMPLICATIONS

The regional level results include *inter alia* the combined economic output from all the irrigation blocks within both WUAs. Scenarios 3 and 3+ results show a positive affect on the economy over the period of analysis, yet far less than the positive impacts of scenarios 1 and 2, but still considered far more stable. Furthermore, scenarios 3 and scenario 3+ have a steeper improvement in the overall sustainability levels than the other scenarios, proving that increased leaching and drainage does improve the long-term sustainability of an irrigation scheme.

Scenario 3 and 3+ as compared to scenarios 1 and 2 results show the regional economic impact that increased leaching and drainage has on a regional economy.

Results in Viljoen *et al.* (2006) indicate that the regional economy for scenario 1 could generate a gross geographical product (GGP) around R757 to R770 million and sustain 5370 to 5450 jobs from year 1 to 15 respectively. Scenario 2 could generate a GGP of around R872 to R891 million and sustain 6180 to 6300 jobs from year 1 to 15 respectively. Scenario 3 and 3+ could generate a GGP of around R977 to R985 million and sustain 6920 to 6990 jobs from year 1 to 15 respectively. These results clearly showed that at the end of 15 years scenario 2 yields a R121 million GGP improvement from scenario 1 and scenarios 3 and 3+ a further R94 million improvement from scenario 2. The total jobs sustained by the regional economy at the end of 15 years rises by 850 from scenario 1 to scenario 2 and a further 690 from scenario 2 to scenario 3 and 3+.

These dramatic improvements in the regional economy further motivated the case for the full grant assistance of additional leaching and drainage where required. From an environmental perspective, leaching and drainage was also a more sustainable option (ISEW results converge closer to 1) than planting more salt resistant crops (scenario 1) or planting higher value crops without sufficient drainage (scenario 2), and with results from scenario 2 also proving the least stable economic results.

9.7 OPTIMAL TIMING OF THE INSTALLATION OF IRRIGATION DRAINAGE IN THE LIFE CYCLE OF A SCHEME: DISCUSSION

There are various examples from the literature that arid area irrigation schemes or more temperate irrigation schemes receiving poor water quality are unsustainable over the long term unless suitable leaching and drainage practices are implemented to wash out the salts that build up insidiously over time.

Bristow *et al.* (2005) for instance referred to an irrigation scheme in Northern Australia that was badly salinised within 5 years of inception due to a decision to only install drainage at a later stage, once it became a problem. This decision resulted in large financial losses and a legal battle between the farmers, who had invested in the land, and the state, for compensation and for losses in expected / projected revenues.

Based on the magnitude of the improvement in TGMASC demonstrated by scenario 3 in Chapter 10, and demonstrated in Figure 9.2, the installation of drainage at the implementation phase of a new scheme can be justified.

Remedial action only taken when the salinity reaches harmful proportions can be unsustainable as:

- by the time drainage is needed the irrigators' financial position may already be weakened,
- the installation of the drainage can further result in the loss of at least one seasons production, further affecting cash-flow
- the total value of grant assistance would have to be greater as the farmers' are in a poorer off position to pay
- if done through the WUAs, increasing of water tariffs at this stage to cover the drainage costs, may be difficult for already struggling irrigators to accept
- if irrigators need to pay for the drainage themselves, finance may be difficult to acquire due to recent declining profit margins from salinity build-up

If drains are installed at inception of a scheme:

- unnecessary financial losses as salinity builds up over time in the scheme will be eliminated,
- irrigators will start off paying a higher water tariff, but major adjustments will not need to be made later on when drainage becomes necessary,
- there are the financial advantages of economies of scale in constructing all the drains and planning the return-flow drains and return-flow management options at inception, instead of haphazardly during the lifecycle of the scheme as emergency operations.

Although not applicable to the existing irrigation blocks analysed in the study area, it is highly recommended that irrigation drainage be installed right from initialisation of any new irrigation scheme.

Within the study area there are plans to develop the Oppermansgronde area as a new sub-WUA of the OR-WUA. Although the area does have deep red sandy soil to facilitate natural drainage, it is suggested that artificial drainage, if required following an in-depth investigation, be installed right from the beginning in the new scheme.

9.8 SUMMARY

The conclusions from the analysis of the results can be briefly summed up with resulting policy implications as follows:

- ***Farm level*** – drainage is a better management option than changing to more tolerant crops, but only where needed and depending on assistance grant and cash flow.
- ***Irrigation block level*** – grant assistance is necessary to drain before salinity levels become too high in areas not too badly affected yet.
- ***WUA level*** – cross subsidisation / grant assistance of downstream return-flow users from upstream Orange River water users is possibly a viable option.
- ***Regional level*** – the improvement of agricultural productivity from increased investment in irrigation drainage far outweighs the costs and has a positive ripple effect through the economy. In calculating the secondary effects to the economy the returns to investment are great. Agricultural water use productivity is also far better with the secondary impacts accounted for.

Drainage installation for facilitation of leaching is a more financially and environmentally sustainable option than the planting of tolerant crops. Factoring in the costs of drainage into irrigators' water tariffs is less than the additional financial benefits derived from the drainage and should therefore be acceptable to farmers. Although ***Rscm*** and ***Rszg*** irrigation blocks do not require immediate remediation action they should possibly be charged more for water by internalizing the downstream externality they produce on the ***RloR*** and some ***Vall*** farmers. Cross-subsidising a portion of the ***RloR*** and the ***Vall*** farmers drainage with increased ***Rscm*** and ***Rszg*** water tariffs may be a plausible policy option.

At base-case scenario levels (i.e. no additional leaching and drainage) the ***Rscm*** consistently has the greatest comparative advantage, with very poor TGMASC per hectare per year results from the ***RloR***.

When equalising irrigation blocks to 150% (1.5 crops per hectare per year) ***Vall*** proves to be the irrigation block with the greatest comparative advantage for all scenarios and leaching and drainage combinations.

Having identified the ***RloR*** as the most critical irrigation block requiring additional artificial leaching and drainage, over a range of discount rates, assistance grant levels and repayment terms, the net return of assistance grant investment for the ***RloR*** is positive, indicating a very favourable return to subsidised drainage investment over a range of possible circumstances and conditions.

9.9 RECOMMENDATIONS

Drainage installation for facilitation of leaching needs to be promoted in the Orange-Vaal WUA (***Vall***) and especially in the Lower Riet (***RloR***) irrigation blocks in the study area. Results from the research indicate that 10% and 20% of the ***Vall*** and ***RloR*** irrigation blocks' irrigable area respectively need to be considered for addition drainage for efficiency and sustainability benefits to the area and region.

If the ***Rscm*** and ***Rszg*** irrigation blocks are to be drained, before salinity builds up to levels which result in financial losses, at least a 50% assistance grant of the total drainage costs may be needed to make the offer financially viable and acceptable by the irrigators. Just as in an environmental management plan, remedial actions of possible environmental and unsustainable practices have to be planned and budgeted for at initialization. There is definite need for the planning and budgeting for installation of drainage before the settlement of a new irrigation area.

CHAPTER 10 SYNTHESIS, SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A wrong attitude towards nature implies, somewhere, a wrong attitude toward God

T.S. Elliot (1939)

If you start doing wrong, the Lord will turn rivers into deserts,

flowing streams into scorched land, and fruitful fields into beds of salt.

But the Lord can also turn deserts into lakes and scorched land into flowing streams.

King David - Psa 107:33-35 (CEV)

10.1 INTRODUCTION

The aims of this chapter are:

- to provide a synthesis of the process followed during the course of this research,
- to give a brief summary of each of the chapters of this thesis ,
- to list the conclusions deducted from this study, and
- to provide recommendations stemming from this work, and for new research to be conducted.

10.2 SYNTHESIS

In the course of this study the following tasks were undertaken:

- Background research and a literature study was conducted
- An integrated model framework was developed
- Following a research method a model was designed within the integrated model framework
- Data was accumulated and analysed with the model
- Results were generated and interpreted, and
- Findings were reported at various levels.

The purpose of this synthesis is to briefly highlight the most important aspects of each of these various tasks.

10.2.1 BACKGROUND RESEARCH

A broad literature study, including an interdisciplinary evaluation of the multi-dimensional components underlying the integrated modelling was undertaken. A better understanding of the interdisciplinary nature of the problem was achieved and the following relevant applicable models / methodologies identified, together with their setup data and manpower requirements:

- WRPM to simulate stochastic hydrology sequences and importantly, linked soil salinity values,

- The Maas and Hoffmann equation to translate saturated soil salinity values into reduced crop yield,
- CEB simulation analysis to interpret the reduced yield in per hectare-, sub-WUA-, WUA- and Regional-TGMASC terms,
- A link to macro-economic models for input / output analysis, to interpret the socio-economic changes in agriculture at regional level.
- A link to an index for social, economic and environmental sustainability (ISEW) for reporting of the various scenarios.
- During this phase, profiles, trends and the main problem areas were identified and formulated.

A combination of study area specific information gleaned from existing reports and documents was used in compiling Chapter 2 (A Description of the Study Area) and discipline specific information was used for the formulation of Chapter 4 (The Integrated Model Framework), Chapter 5 (Integrated Bio-physical sub-models) and Chapter 6 (Micro-economic model description).

10.2.2 INTEGRATED CONCEPTUAL FRAMEWORK

The development of the integrated conceptual framework provided a vital reference framework to combine the applicable models / methodologies identified into an integrated salinity modelling process, guiding the design, organisation, runs and output of the model. A series of workshops was held with key role-players and technical experts to finalise the conceptual and generic modelling approach of the study. The resulting final integrated model framework is displayed in **Figure 4.1**.

10.2.3 METHOD AND MODEL DESIGN

The aim of the model is to integrate holistically the bio-physical and hydrology components involved in irrigation salinisation, into a long-term economic model to improve the financial sustainability of irrigation agriculture.

The method followed for the model development process to achieve this consisted of the following:

- The setup of the base-case and subsequent scenario for analysis
- The collection of input data and data processing
- The setting up, integrating and running the sub-disciplinary models:
  - *Hydrology model (WRPM)*
  - *Bio-physical sub-components (Maas and Hoffmann equation)*
  - *Micro economic model (CEB simulation)*
  - *Regional economic model (input/output analysis) – with Urban Econ.*
- The interpretation of output data and results files for report writing.

10.2.4 DATA ACCUMULATION AND ANALYSIS

Study area surveys were conducted for the collection of primary data used, to:

- identify the problem areas and the magnitude and scope of the salinity problem, to sensibly divide the study area into logically grouped sub-WUAs

- identify key role players for expert panel opinion and data verification
- locate sources of secondary data for model inputs and analysis

Secondary data was mainly used as model inputs, mainly provided by WUA water management plans (Ninham Shand , 2004 and CSIR, 2004), GWK Pty. Ltd. (CEBs) and expert panel opinion gleaned for meetings and technical workshops.

10.2.5 RESULTS INTERPRETATION

Recommendations are formulated based on the integrated economic, biophysical and hydrologic modelling results. Strategic guidelines for micro and regional level management are also suggested and policy formulated. A most valuable model output not initially planned for, is an economic interpretation of DWAF's hydrology model (WRPM), with particular reference to the salinity component.

10.2.6 REPORTING

With the eventual client in mind, the different levels of reporting are as follows:

- For the WRC and policy planners, policy guidelines, an indication of the nature and extent of the problem at regional level and a better integration of various disciplines
- For the WUA managers, an indication of the source of the cause of the salinity problem, the financial extent of the problem, the potential gains of remedying the problem and cost effective options to manage irrigation salinity
- For farmers, practical per hectare benchmarks of the impact and extent of salinity, and a simple method of calculating the per hectare reduction in yield and subsequent impact of crop profitability.

10.3 SUMMARY

The purpose of this paragraph is to summarise the chapters of this thesis, namely the chapters on:

- The study area
- A literature review of integrated salinisation modelling
- The integrated conceptual framework
- The integrated biophysical model linkages
- The micro-economic model description
- The scenarios modelled
- Economic model results
- Policy implications and recommendations

10.3.1 THE STUDY AREA

A detailed discussion on the study area is presented in Chapter 2. In short, the area is not suited to dryland agriculture except extensive grazing, and is reliant on the stability that irrigated agriculture brings. However, increasing pressure on the use of water for irrigation, together with degrading irrigated soils due to salinity, is placing increasing financial pressure on farmers, and hence on the regional economy.

Hydrologically , the study area falls within these boundaries;

- Vaal River, downstream of the Bloemhof Dam to the confluence with the Orange River
- Orange River, the Orange-Riet and Orange-Vaal Canal extraction points downstream of the Vanderkloof Dam to the Orange-Vaal Confluence where the returnflows of the study area re-enter the Orange River
- Riet River, downstream of the Kalkfontein Dam to the confluence with the Vaal River

This encompasses the Orange-Vaal (OV) and Orange-Riet (OR) Water Users Associations (WUAs).

At micro hydrology level, four irrigation blocks in the two WUAs, represent the main receiving water quality areas within the Orange-Vaal-Riet-Modder confluence area, namely:

- the Riet River Scheme, Orange Riet Canal and Ritchie sub-WUA of the OR-WUA combined, ***Rscm***, all receiving Orange river water directly from the Orange Riet Canal,
- the Schotzburg sub-WUA of the OR-WUA, ***Rszg***, lying mainly at the confluence of the Modder and Riet Rivers, but receiving a large portion of Orange River water diluting the tail ends of the Riet and Modder Rivers upstream,
- the Lower Riet River sub-WUA of the OR-WUA, ***RloR,*** from Ritchie to Soutpansdrift, mainly receiving Riet Scheme and Scholtzburg returnflows, and
- the whole Orange Vaal WUA, ***Vall***, receiving Vaal River system excess spillage and a large portion of Orange River water pumped via the Orange-Vaal and Orange-Riet Canals, with the latter carrying the returnflows of the whole OR-WUA.

The main characteristics of the study identified of particular importance for integrated salinity modelling are:

- The spatial dimensions and boundaries spanning two provinces, various municipal management areas (see Figure 2.10), the confluence of the two major rivers in South Africa, various quaternary catchments and different water management areas (Figure 2.4) that influence the anthropogenic (social, political, economic) and natural (bio-physical, hydrology, environment) dynamics over time in the study area.
- According to Van Veele (2004), "the Riet-Modder catchment is a "feast or famine" catchment with only 8 years in 50 being 'average' years".

Realising these dynamics in the study area led to using actual stochastic sequence data as basis for the modelling (and not aggregated data), selected to represent the full spectrum of possible sequences, to try capture the true dynamics of salinity in the study area.

10.3.2 LITERATURE STUDY

In the literature study an interdisciplinary evaluation of the multi-dimensional components underlying the integrated modelling is undertaken. A better understanding of the interdisciplinary nature of the problem is strived for and the following models / methodologies are identified (taking into consideration their setup data and manpower requirements):

- WRPM to simulate stochastic hydrology sequences and importantly, linked soil salinity values,

- The Maas and Hoffmann equation to translate saturated soil salinity values into reduced crop yield,
- CEB simulation analysis to interpret the reduced yield in per hectare-, sub-WUA-, WUA- and Regional-TGMASC terms,
- A link to macro-economic models for input / output analysis, to interpret the socio-economic changes in agriculture at regional level, and
- A link to the index for socio-economic welfare (ISEW) for environmental and sustainability reporting of the various scenarios.

In the literature study, profiles, trends and the main problem areas are identified and formulated, and a combination of study area specific information has been gleaned from existing reports and documents.

10.3.3 INTEGRATED MODEL STRUCTURE

See **Figure 4.1** for a diagrammatic representation of the integrated conceptual framework. In short, a hydrology model, WRPM, simulates stochastic hydrology sequences and corresponding soil salinity values (CU in mg/l), CU is converted to saturated soil salinity values (ECe in mS/m), the Maas and Hoffmann equation translates ECe into reduced crop yield (ton/ha), and CEB simulation is used to interpret the reduced yield in economic terms (TGMASC in R/ha), that are used in an input / output analysis to interpret the economic changes in agriculture at regional level (GGP in Rands and employment).

10.3.3.1 Critical Linkages – assumptions and limitations

Hydrology to Economic - and back (temporal) –The hydrology sequence of events that drive SMsim, yield certain economic results which in turn may have an impact on the hydrology again. With the hydrology in reality being influenced every second in real time, but the economy being reasonally well captured on a monthly time scale, the use of the necessary common monthly time scale results in a loss of hydrology detail. The main limitation of the integrated model presented, due to poor tempotal compatibility therefore, is the uncoupled, virtually mono-directional linkage between the hydrology and economic models. A feedback loop is possible as was used to set up the base-case scenario, but due to the nature of WRPM (limited operator-ship and complexity) many more scenarios could not be run.

Per hectare to irrigation block level (spatial) – The assumption made when converting per hectare CEB data to irrigation block level data is that the irrigation block is representative of the farmers within that irrigation block. The WRPM model setup however has constrained the number of representative irrigation sub-WUAs to the irrigation blocks in the WRPM. Ideally the Orange-Vaal WUA irrigation block should have been split into the 5 representative sub-WUA blocks as discussed in Chapter 2.

The Orange-Riet WUA sub-WUAs fit the WRPM irrigation block split relatively well. Further differentiation could however have been made for the irrigation block (***Rscm***) combining the Orange-Riet canal, Scheme and Ritchie, to have them each as a separate irrigation block, and the Scheme further divided to reflect the sandy soil sub-WUA and heavy clay soil sub-WUAs. Their water source however is very similar and representative of the farmers in the subsequent WRPM irrigation blocks.

10.3.4 BIOPHYSICAL MODEL

The biophysical sub-models discussed in Chapter 5 refer to a group of biophysical-hydrology, hydrology-biophysical and biophysical-economic linkages, assumptions and procedures, using recognized existing models and algorithms to integrate the hydrology and economic models. Paragraph 5.2 shows how SAPWAT is used to determine crop coefficients for setting up the hydrology model (WRPM). From the results of the WRPM, the saturated soil salinity, ECe (mS/m) it derived (see Paragraph 5.3) for the setting up of salinity-yield functions using the Maas and Hoffmann equation discussed in Paragraph 5.4.

A full discussion of the WRPM hydrology model used to generate the soil water and salt concentration input data for this study can be found in Viljoen *et al.* (2006). The hydrology data generated is the salinity contents of the water supply as well as the modelling of the salinity balance in the soil profiles of the irrigated areas using the WRPM. Since monthly water supply time series data (both volumes and TDS concentrations) were required for the modelling of the irrigation activities within the study area, the WRPM as configured for the Integrated Vaal River System (IVRS) was identified as a good source of information. An attraction of the WRPM model was its capability to generate and analyse alternative stochastic stream-flow sequences, providing 100 possible water quantity and quality outcomes for risk analysis.

The biophysical model generates the important linkage between the hydrology results and yield which form the basis of the economic models, as well as an important component of the final output in the regional economic model as the environmental component of the Index for Socio-Economic Welfare (ISEW). The biophysical model doesn't produce results of its own, but is an important linkage in transferring data from one disciplinary model to another.

10.3.5 MICRO ECONOMIC MODEL

The spatial dimensions of the model are delineated to build from per hectare level CEBs to irrigation block level and higher up. Irrigation blocks are combined into WUAs, and WUAs are combined to form the regional economic model. The temporal dimensions of the model are delineated to monthly, annual and 15 year cumulative results. The model further simulates for a range of 100 stochastic runs, the per hectare financial impacts and possible range of financial results subject to salinisation, for different irrigation blocks per year, and over 15 years.

Data requirements are discussed with particular reference to the primary data collected through mainly expert panel opinion and the secondary data obtained predominantly from GWK, the WUA WMPs and expert opinion panels and workshops. The mathematical specification of the model is an expansion of per hectare level CEBs that produce TGMASC to irrigation block and WUA level TGMASC results for use in micro-level analysis and as input into the regional economic model.

10.3.6 REGIONAL MODEL

In defining the regional model, the macro economic project team first sketched the regional economy and used the description of the base case scenario to illustrate the processes and development of the ISIM model, consisting basically of input / output tables and multipliers.
The following was concluded in Viljoen *et al.*(2006) from the regional model results of the base case scenario:

- The total population in the study area (municipal boundaries) is estimated at 317 610 people in 2005. Approximately 60.5% of the population is considered to be *Potentially Economically Active.* Approximately 33.7% of the 2005 population can be considered economically active, leaving approximately 45 402 people unemployed.
- The mining sector and the tertiary economic sectors are the largest contributors to the local economy of the study area. The mining sector contributed 19.0% to the total GGP, followed by financial services (17.1%), government (16.3%) and transport (15.0%). The agriculture sector contributed 4.5% to total GGP in the area, 4.8% to production output, 16.6% to employment and only 2.8% to total labour compensation.
- The agriculture sector registered a negative growth rate of -0.9 percentage points during the period 2000 to 2004. Municipal areas where a positive annual growth rate was experienced include Tembelihle (6.5%), Siyancuma (0.9%) and Diamondfields (0.4%). Sol Plaatje Municipal Area and Letsemeng Municipal Area both registered high negative growth rates of -5.1% and -5.9% respectively. This growth is measured in terms of constant prices with 2000 as base year. Given the above rates, it can be expected that the study area's GGP contribution in the agriculture sector in 2019 will amount to R10.1 billion (at constant price values).
- Total output in the agriculture sector grew by 0.6% during the period 2000 to 2004, while total output in the regional economy grew with 3.2 percentage points. Agriculture output in the Siyancuma Local Municipal Area was the highest at 29.1% contribution to the total agricultural output in the study area by the start of 2005.

Three categories of data were analysed during the base case scenario analysis of the regional model, namely data for stochastic runs number 01, 44 and 80. To provide an indication of the probability of the results taking place, data obtained from the 50th percentile was also included.

The ISEW was calculated by taking into consideration the production level (or value added to the irrigation sector), the employment structure of the area and the sector (as a social pillar) and the environmental changes brought on by changing salinity levels. This was done over the period from 2005 to 2019. The ISEW clearly indicates that, for the base case scenario, there are positive trends in the sustainable economic welfare of the study area. However, stochastic run number 80, which closely resembles the 50% average, indicates an overall decline in the sustainability of the economic welfare in the region (Viljoen *et al.*, 2006).

10.3.7 SCENARIOS MODELLED

The stochastic nature of the WRPM hydrology data generated for scenario analysis necessitates selecting 3 actual stochastic model runs from the 100 that reflect the 0.05, 0.50 and 0.95 percentiles instead of only using and average, so as to capture the stochastic/dynamic nature of the data for presentation. The micro-economic model is however run for all 100 runs and the resulting data also subsequently presented as described above. The percentiles selected of the 100 stochastic runs are in themselves worst-, average- and best-case "scenarios" of each of the main scenarios discussed.

Extreme care was taken in the setting up of the scenarios in selecting the alternative cropping compositions so as not to exceed water delivery infrastructure, processing capacity and market demand constraints. Maize area was also reduced in both the salt tolerant and salt sensitive, yet high value crop scenarios in light of the aparant maize oversupply of 2005 much publicised in the media.

The base-case scenario is essentially the first scenario, whereby the WRPM is updated, as described in the first section of this chapter, to reflect a chosen base year; 2005 for this study. The starting point salt concentration values used in the setup of the WRPM model are manually adjusted by the WRPM operators to tale out any trend in the data. These starting points remain fixed for the other scenarios that follow.

Scenario 1 is set up using a more salt tolerant combination of crops (i.e. greater area planted to wheat, barley, cotton, pastures and sunflowers) without increasing drainage and leaching from the base-case values. The objective of scenario 1 is to test the long term sustainability of this option.

For scenario 2 and 3 a more salt sensitive, yet higher yielding combination of crops (i.e. greater area planted to fruit, vegetables, legumes and potatoes) without increasing drainage and leaching from the base-case values for scenario 2. The objective of scenario 2 is to test if the increased profits of higher value crops would not compensate for the yield losses due to salinity. Scenario 2 is run with 100% yield to calculate an indication of the maximum productivity of the irrigation blocks.

In scenario 3 the same cropping combination is used as in scenario 2, but artificial drainage and leaching is accounted for by increasing the return-flow factor by 15% to calculate the financial benefits of increased leaching and drainage. A scenario 3+ is also run whereby the additional costs of increased leaching and drainage are factored into the water costs, to test if the additional outlay could be justified by higher returns.

A scenario showing the impact of improved drainage and leaching in status quo crops would have provided interesting results, but due to the limitation in scenarios to run, the four selected and discussed in this chapter were the priority. The option of growing more higher value crops was chosen above the status quo to examine the impact of reduced maize production (all be it only 5% less) in the light of the much speculated overproduction of maize in 2005.

10.3.8 MICRO-ECONOMIC RESULTS

The hydrology results show that the irrigation block with the highest soil salt concentration in the upper zone (CU) is the Lower Riet irrigation block (**RloR**), followed by the Orange-Vaal irrigation block (**Vall**), the Scholtzburg irrigation block (**Rszg**), and with the lowest soil salt concentration, the Orange-Riet Scheme irrigation block (**Rscm**).

In comparing the hydrology results from the different scenarios run, changing the cropping choice from the status quo (base-case scenario) to more tolerant crops (scenario 1) to more salt sensitive yet higher value crops (scenario 2) has very little impact on the hydrology results. Though changing the return flow factor by increasing leaching and drainage, has a major impact on the hydrology by bringing the CU (mg/l) down substantially in the irrigation blocks. Hydrology results also show that the greatest variation, and highest values, in monthly irrigation water salt concentration and TDS (mg/l) occur in the months from April to August with the worst being from May to July. This indicates that salt sensitive crops grown or germinating during these months will be worst off than crops grown and germinating in the other months, i.e. spring and summer month crops.

Running the hydrology results through the bio-physical model converts the soil salt concentration, CU (mg/l) to CUe (mg/l), the saturated soil salt concentration. CUe is multiplied by the electrical conductivity factor to produce ECe (mS/m) and this is run through the Maas and Hoffmann equation to give the impact of soil salinity on crop yield. Results showed that in the irrigation blocks where the CU is highest, there crop yields are affected the most.

These changes in crop yield are then run through the micro-economic model to first produce per hectare crop enterprise budgets (CEBs) which are then extrapolated to irrigation block level.

On a per hectare basis (as shown in Table 8.5) the greatest financial loss (2005 values) due to salinity is experienced in the Lower Riet irrigation block (**RloR**), with the loss of R6962 per hectare per year, followed by Scholtzburg (**Rszg**) with R2596 and the Orange-Vaal irrigation block (**Vall**) with R2218. This provides the farmer in the specific irrigation block with a good indication of the per hectare costs (net benefit forgone) of poor drainage on his farm. At an average costs of drainage per ha on medium to heavy soils of R30 000[1] (Reinders, 2005), a 15 year loan at 9% interest would cost R3722 per year to service – worth spending in **RloR**, though not as convincing without a funding grant in **Rszg** and **Vall.** Implemented for the whole study area (all irrigation blocks combined), the total real cumulative cost (2005 basis) of salinisation over a period of 15 years is R995 million, a good benchmark to use to leverage funds for remediation action.

Figure 8.13 and Figure 8.14 clearly show that to reduce the risk of income loss due to irrigation salinity one has to install drainage and leach more.

The conclusion is that an irrigation block is very sensitive to a specific salinity threshold level and therefore all irrigation blocks should not be treated the same. Only **RloR** benefited slightly from planting more tolerant crops as its soil salinity threshold is exceeded by the base-case cropping composition. Increased drainage and leaching however proved to be far more financially effective than planting tolerant crops, and the return-flow externality effects are more than compensated for as **Vall** downstream also achieved far better results when it is also drained. A scenario was not run where the OR-WUA drains and the OV-WUA (Vall) does not. It is expeted that the returnflows from the OR-WUA will have an impact on yields in the OV-WUA if the OV-WUA doesn't drain.

Comparing the Orange-Vaal WUA (**Vall**) and Orange Riet-WUA (**Rall**), the **Rall** naturally did better in absolute terms as it is nearly twice the size of the **Vall**, although the worst irrigation block (**RloR**) is part of **Rall**, its TGMASC improved at a better rate than **Vall** over the 15 years of analysis.

Resulting data further processed by the microeconomic model SMsim, to be used in the macro model is also discussed briefly.

10.3.9 <u>REGIONAL MODEL RESULTS</u>

It is evident in Viljoen *et al.*(2006) that the overall level of impact on the regional economy of the study area increases as alternative scenarios are considered. Scenario 2 produces higher values in total output, GGP and

[1] Note: drainage costs can range from R12000-R15000 on sandy soils (<15% clay), R20000-R25000 on medium soils (15-35% clay), and R30000-R50000 on heavy soils (>35% clay) – see Table 6.2.

jobs than scenario 1. Similarly, scenario 3 and 3+ results in higher values than scenarios 1 and 2. Scenarios 1 and 2 are also very cyclical in nature due to varying gross income levels, which in turn is linked to varying salinity levels and yield. Scenarios 3 and 3+ are considered to have a more stable regional impact. These impacts did not consider price fluctuations or market volatility.

The overall GGP value lost to the regional economy for farmers having to pay 90% of the additional drainage costs themselves (10% is subsidised in the calculations) at a loan repayment rate of 9% over 15 years is in excess of R10 million per year (Viljoen *et al.*, 2006).

When considering the indices for sustainable economic welfare (ISEW), it is also evident in Viljoen *et al.*(2006) that all three scenarios will contribute towards increased economic welfare, based on the indicators measured, but that scenarios 3 and 3+ will have a steepest improvement in the overall sustainability levels.

10.3.10 POLICY IMPLICATIONS

The conclusions from the analysis of the results can briefly be summed up with resulting policy implications as follows:

- Farm level – drainage is a better management option that changing to more tolerant crops, but only where needed and depending on assistance grant and cash flow.
- Irrigation block level – grant assistance is necessary to drain before salinity levels become too high in areas not too badly affected yet.
- WUA level – cross subsidisation of downstream return-flow users from upstream Orange river water users is a viable option as the price elasticity of water quantity is relatively small. However due to the large price elasticity of water quality, affected farmer can almost afford to pay for the drainage themselves.
- Regional level – according to Viljoen *et al.*(2006) the improvement of agricultural productivity from increased investment in irrigation drainage far outweighs the costs and has a positive ripple effect through the economy. In calculating the secondary effects to the economy the returns to investment are great. Agricultural water use productivity is also far better with the secondary impacts accounted for.

Drainage installation for facilitation of leaching is a more financially and environmentally sustainable option than the planting salt tolerant crops. Factoring in the costs of drainage into irrigators' tariffs is acceptable payable by farmers. Although ***Rscm*** and ***Rszg*** irrigation blocks do not require immediate remediation action they should pay more for water as they produce a downstream externality on the ***RloR*** and some ***Vall*** farmers. Cross-subsidising a portion of the ***RloR*** and the ***Vall*** farmers drainage with increased ***Rscm*** and ***Rszg*** water tariffs is a feasible option.

At base-case scenario levels (i.e. no additional leaching and drainage) the ***Rscm*** consistently has the greatest comparative advantage, with very poor TGMASC per hectare per year results from the ***RloR***. When equalising irrigation blocks to 150% (1.5 crops per hectare per year) ***Vall*** proves to be the irrigation block with the greatest comparative advantage for all scenarios and leaching and drainage combinations.

Having identified the ***RloR*** as the most critical irrigation block requiring additional artificial leaching and drainage, over a range for discount rates, assistance grant levels and repayment terms, the net return of assistance grant investment for the ***RIoR*** is positive, indicating a very favourable return to subsidised drainage investment over a range of possible circumstances and conditions.

10.4 CONCLUSIONS

By unmasking the risks faced by irrigation-based societies - including water scarcity, soil salinisation, and conflicts over rivers - Postel (1999) connects the lessons of the past with the challenge of making irrigation thrive into the twenty-first century and beyond. It is hoped that this study will similarly connect the various disciplinary lessons of the past and unmask the risk of salinisation in the Lower Vaal and Riet Rivers through an integrated approach.

This research has succeeded in refining and identifying critical obstacles towards fully integrated salinity economics modelling, and to a certain degree in coming up with plausible results suitable for meaningful per hectare-, sub-WUA-, WUA-, regional- and national- management, policy intervention and strategic decision making.

The most compelling results from this research are:

- A total GGP value lost to the regional economy of R10 million per year as a result of farmers having to pay for the additional drainage costs themselves (difference between scenario 3 and scenario 3+ results) (Viljoen *et al.*, 2006)
- The total once off costs of additionally leaching 20% more in RIoR, 10% more in Vall and 5% more in both Rscm and Rszg only amounts to R 64.75 million.
- The full grant assistance of these costs can be justified in just 7 years if not taking the time value of money into account. This is not even taking into account the improvement from the base case situation to scenario 3 level.
- Over 15 years R 995 million in agricultural TGMASC is cumulatively lost in the study area due to salinity alone (with all other factors of production optimal)
- The total region output generated under base-case conditions in 2005 amounts to R 804.37 million. With increased drainage this total regional economic output can be increased to R977 million, an improvement of R173.63 million in one year alone (Viljoen *et al.*, 2006).
- When considering the indices for sustainable economic welfare (ISEW), it is evident that scenarios 3 and 3+ have a steeper improvement in the overall sustainability levels than the other scenarios.

The above facts present a good case for grant assistance of additional irrigation drainage in the interest of increased regional socio-economic welfare.

10.4.1 CRITICAL MODEL EVALUATION AND USEFULNESS

Sometimes advancement in a science is made by an in-depth enquiry into a very small aspect thereof, but sometimes advancement in the sciences is made by a superficial inquiry into a lot of sciences and through the identification of critical linking factors, the binding of them into a better understood whole (inspired from Smuts, 1926 – Holism and Evolution).

The main limitation of the integrated model presented is the uncoupled, static, virtually mono-directional linkage between the hydrology and economic models, although a full loop is modelled in this study. Further refinement through the addition of additional irrigation blocks in the hydrology model would have also been more representative of the sub-WUA level irrigation water quality and soil salinity status of the Orange Vaal WUA study area in particular.

Table 10.1 is a summary of the original aims, indicating the the Improvements that can be made and achievements together with the limitations / shortcomings.

Table 10.1. A table summarising the level to which original objectives have been met

Initial WRC project aims	New model	Improvements / achievements	Limitations / shortcomings
Development and integration of multi-dimensional models	√	Hydrology, Agronomy, micro- and regional economic models linked	Groundwater, unsaturated root zone chemistry and climate models lacking. Feedback loops lacking.
Sustainable management of water quantity and quality	√	Drainage & leaching proved more sustainable than planting salt resistant crops. water use efficiency modelled	Water distribution infrastructure and blending options not analysed
a. Better understand the polluting chemical processes and interactions	√	A better understanding of the spatial variability and fluctuation of salts	Only salinity impacts modelled and not those of other salts (e.g. Cl, Br) and trace elements
b. Develop new models - i. Micro	√	SMsim + linkages	Not Farm Level – excluded fixed and capital expenses, Tax etc. – Purely a TGMASC model
- Dynamic	√	Used stochastic model data over time to capture dynamics	Decision variable interaction from linear programming
- Optimisation	×	identified that biophysical problems contain too many decision variables to easily optimize	No shadow prices and optimal crop combinations can be calculated
ii. Macro	√	Full regional dynamic Input/Output model + Index for Social Economic Welfare (ISEW)	National input/output matrix data is used for regional interpretation
c. Economic integration		Hydrology -> bio -> micro-econ. -> macro-econ.	Only direct costs are taken into consideration
i. Hydrology / hydraulic	√	WRPM model	The WRPM is not "open source" and not user friendly for own adaptation / use
ii. Chemical balance	√ / ×	Only salt balance in WRPM model	Other chemical balances not incorporated
iii. Groundwater	√ / ×	Lower layer in WRPM model linked to ISEW	Impact on deep groundwater not investigated
iv. Crop growth	√ / ×	The Maas and Hoffmann (1977) equation & SAPWAT crop growth coefficients used as plant growth factors	More sophisticated plant growth in salts models could be used (e.g. SATLMED by Ragab, 2000)
d. Best management practices		Drainage and leaching identified	Optimal distribution infrastructure not identified
i. Micro (Field and Farm)	√ / ×	Risk distribution (stochastic analysis)	Manual scenario selection (objective not optimisation)
ii. Macro (policy, catchment, WUA)	√	Mainly provincial (and municipal) + ISEW	Agricultural secondary impact on the economy not indicated
e. Enhance water use efficiency	√	Temporal redistribution and better crop selection by scenario	Spatial redistribution of water not modelled
f. Policy guidelines	√	A spatial relative comparison is made and scenarios are used	4 Sub-WUA in the OV-WUA rather than 1 Irrigation Block (***VaII***) would have improved results
g. Robust method used	√ / ×	The method used is robust if other more user friendly and adaptable hydrology models are used	WRPM is not robust (though can be applied almost anywhere in SA – but must make use of WRP consultants)

Further hydrology model irrigation block refinement and feedback loops between the hydrology and economic models are possible, but because of the separate and professional human resources required to do the modelling at the different levels, time and cost is prohibitive. Very careful planning, data checks and co-ordination are therefore essential to guarantee the desired results.

10.4.2 PROOF / DISPROOF OF THE HYPOTHESES & ANSWERING THE RESEARCH QUESTIONS

The hypotheses that follow tie up with the sub-problems identified in the Introductory Chapter, and each one is followed by a relevant research question, that is answered in the conclusion of this thesis:

- Soil / plant / atmosphere interactions and salt balance models can be successfully incorporated into economic models to effectively interpret soil salinity at micro and regional levels. The research question is which models and how?

  Yes, bio-physical models can be successfully linked and / or incorporated into economic models to effectively interpret soil salinity at micro and regional levels. WRPM was set up and run independently to give the soil and water data, converted to changes in yield due to salinity and drainage using the Maas and Hoffman equation. This change in yield was fed into a per hectare level crop enterprise budget model that was extrapolated to sub-WUA, irrigation block and WUA level, from where it was fed into a regional economic Input /Output analysis model to determine the regional economic impacts of salinisation. At the outset dynamic optimisation was attempted, but due to the great number of variables as a result off spatial and temporal heterogeneity a stochastic simulation approach was used.

- In low rainfall areas, the inevitable salinisation of soils irrigated with poor quality water can be managed sustainably through either increased leaching, or shifting to more salt tolerant crops. The research question is which management option is more sustainable?

  Increased leaching and drainage proved to be the most sustainable option.

- Through the application of correct policy and management interventions, the downstream externalities associated with additional leaching and drainage can be internalized with a positive net regional benefit. The research question is which policy and management interventions are required and what institutional framework needs to be in put in place?

  Volumetric water pricing for farm water use for better measurement and control of water by the WUA, and Green box grants for drainage installation provided by the government to improve the sustainability, efficient water use and productivity of existing irrigation land.

- Irrigation agriculture is essential for sustainable regional social economic welfare in the study area. The research question is how would one go about determining regional social economic welfare, and to what extent does salinisation influence regional social economic welfare?

  Yes, irrigation was shown to have a large impact on the socio-economic welfare in the study area. The impact of reducing salinisation by installing drainage could lead to an increase in GGP and a 20% increase in regional employment (Viljoen et al., 2006).

10.4.2.1 Industry specific usefulness of this research

For GWK, the impact of cropping choice changes on regional crop input component value, processing capacity and storage can be determined that will help GWK plan strategically and aid better management of the transition phases from one crop to another.

For the insurance industry, the question of "what percentage of loss is due to a natural disaster, and what would have taken place anyway due to salinisation?" could be attempted using this work.

10.4.2.2 Applicability for expansion to other irrigation areas

A main constraint to the expansion and adaptation of the integrated models to other irrigation areas is the WRPM. If however recent WRPM hydrology setup data can be transferred to a more user friendly model (e.g DHI's Mike Basin, or ACRUSalinity) or any other hydrology model that calculates the EC in the soil, the micro-economic model could be applied after certain adaptation is made. The ease of application of the regional economic model will depend on the availability of suitable input / output tables and multipliers for the area under consideration.

10.4.3 LESSONS LEARNED IN WORKING IN A MULTI-DISCIPLINARY TEAM

Lessons learned from working on the project on which this thesis is based, from observing the course of other projects and from the literature, are as follows:

- In-house specialist dedicated teams (as in an institute) are logistically better and easier to work in and with than spatially diverse and segmented teams to conduct integrated / multidisciplinary research.
- Choose the sub-disciplinary teams well and obtain definite buy-in (almost contractual) at the project proposal phase already.
- Choose sub-disciplinary teams whom you know well and have previously worked with as far as possible.

A challenge of a project requiring long-term inter-disciplinary co-operation is the possibility of team members resigning where contractual obligation is not required (as in the academic setting), and of them dying, of which one cannot do much about. Good backup specialist staff, depth in research knowledge and ability of the sub-discipline team appointed and a good grasp by the sub-discipline team leader of the team members direction and thinking throughout the study is important and necessary.

10.5 RECOMMENDATIONS

Drainage installation for facilitation of leaching needs to be promoted in the Orange-Vaal WUA (***Vall***) and especially in the Lower Riet (***RloR***) irrigation blocks in the study area. 10% and 20% of ***RloR*** and ***Vall*** irrigation blocks irrigable area respectively are indicated to be drained. This should however be evaluated with a detailed feasibility study.

If the Rscm and Rszg irrigation blocks are to be drained, before salinity builds up to levels which result in financial losses, at least a 50% assistance grant of the total drainage costs is recommended to make the offer financially viable and acceptable by the irrigators.

Just as in an environmental management plan, remedial actions for possible environmental and unsustainable practices have to be planned and budgeted for at initialization. There is therefore a strong recommendation for the planning and budgeting for installation of drainage before the implementation of any new scheme.

10.5.1 PROPOSED FARM LEVEL MANAGEMENT STRATEGY

In Chapter 8 the greatest loss due to salinity is calculated for the Lower Riet irrigation block (***RloR***) to the value of R6962 per hectare per year, followed by Scholtzburg (***Rszg***) with R2596, the Orange-Vaal irrigation block (***Vall***) with R2218 and the Riet Scheme (***Rscm***) R1740. This can provide a farmer in the specific irrigation block with a good indication of the costs of poor drainage on his farm. At an average costs of drainage per ha on medium to heavy soils of R30 000 (Reinders, 2005), a 15 year loan at 9% interest would cost R3722 per year to service, it would definitely be economical to drain in the ***RloR***, though not as convincing without an assistance grant in ***Rszg***, ***Vall*** and ***Rscm***.

10.5.2 IRRIGATION BLOCK (/SUB-WUA) LEVEL OPTIONS

Positive results stemming from Chapter 8 are that even at the worst case sequence of hydrology events predicted for the Lower Riet irrigation block, the cumulative TGMASC still improves over time, although the annual TGMASC may only improve slightly. This shows that the system is in equilibrium and stabilised around the current farming and WUA management actions practiced.

Stochastic run 044 in Figure 8.12 in Chapter 8 shows the massive changes that can be expected in TGMASC that a farmer in the ***RloR*** will have to account for in his forward and cash flow planning. TGMASC can halve / double from one year to the next. Stochastic run 001 reflects a "bad case" hydrology sequence and can result in zero TGMASC for some years (1 in 15).

In Table 9.6 and Table 9.7 in Chapter 9 the irrigation block level cost of grant assistance of additional artificial drainage installation at levels of 10%, 50% and 100% are compared for ***Vall*** and ***RloR*** respectively. As ***RloR*** has positive net returns for all discount rates the net return of assistance grant investment for the ***RloR*** is positive, indicating a very favourable return to subsidised drainage investment over a range of possible circumstances and conditions. This is opposed to drainage grant assistance investment in the ***Vall*** where a positive net return is only realised at low discount rates, over longer periods of time, for all discount rates, all assistance grant levels and for 15 and 20 year repayment terms. At base-case scenario levels (i.e. no additional leaching and drainage) the ***Rscm*** consistently has the greatest comparative advantage, with very poor TGMASC per hectare per year results from the ***RloR***

10.5.3 PROPOSED WUA LEVEL MANAGEMENT STRATEGY

Chapter 8 shows the annual TGMASC for the irrigation bocks ***RloR, Rscm*** and ***Rszg*** combined to make up the OR-WUA (***Rall***). This is compared to the ***Vall*** irrigation block, representing the OV-WUA. Results show that all the Orange-Riet WUA irrigation blocks together (***Rall***) and its main sub-block ***Rscm*** outperform ***Vall*** in total magnitude for all scenarios indicating that OR-WUA has a comparative advantage over the OV-WUA economically because of the source of its irrigation water being mainly from the Orange River.

From a WUA perspective, if only a few farmers demand a certain quantity and quality it will be far more difficult than if many demand it. However, if the WUA can guarantee a certain water quality and quantity then more farmers may change their cropping choice. This may subject the WUA to litigation and great expense if the guaranteed standards can not be met once farmers have implemented large capital investments in long-term, high value crops

10.5.4 PROPOSED REGIONAL MANAGEMENT STRATEGY

Johnson (1994) warns "most of the irrigation schemes in South Africa are affected to some degree by soil salinity. This accumulation of salts in the soil is normally associated with water-logging that occurs primarily in the poorly- drained regions of the landscape. Salinisation usually develops insidiously over many years, and can present a serious threat to the long-term viability of an irrigation scheme. There is a need therefore to monitor trends in soil salinity levels on irrigation schemes." Not heading to this warning by Johnson (1994) made over 10 years ago, there is still currently no reliable data on soil salinity trends. This study therefore reinforces this recommendation made by Johnson (1994), to set in place a soil salinity monitoring programme at national level on all irrigation schemes.

Implemented for the whole study area (all irrigation blocks combined), the total real cumulative cost (2005 basis) of salinisation over a period of 15 years is R995 million (Viljoen *et al.*, 2006), a good benchmark to use to leverage funds for remediation action.

10.5.5 PROPOSED POLICY RECOMMENDATIONS

The following policy implications and suggestions were identified in Chapter 9:

- ***Farm level*** – drainage is a better management option that changing to more tolerant crops, but only where needed and depending on assistance grant and cash flow.
- ***Irrigation block level*** – grant assistance is necessary to drain before salinity levels become too high in areas not too badly affected yet.
- ***WUA level*** – cross subsidisation of downstream return-flow users from upstream Orange river water users is possibly a viable option.
- ***Regional level*** – the improvement of agricultural productivity from increased investment in irrigation drainage far outweighs the costs and has a positive ripple effect through the economy. In calculating the secondary effects to the economy the returns to investment are great. Agricultural water use productivity is also far better with the secondary impacts accounted for.

Drainage installation for facilitation of leaching is a more financially and environmentally sustainable option than the planting of tolerant crops. Factoring in the costs of drainage into irrigators' water tariffs is less than the additional financial benefits derived from the drainage and should therefore be acceptable to farmers. Although ***Rscm*** and ***Rszg*** irrigation blocks do not require immediate remediation action they should possibly be charged more for water to internalize the downstream externality they produce on the ***RloR*** and some ***Vall*** farmers. Cross-subsidising a portion of the ***RloR*** and the ***Vall*** farmers drainage with increased ***Rscm*** and ***Rszg*** water tariffs may be a plausible policy option.

At base-case scenario levels (i.e. no additional leaching and drainage) the ***Rscm*** consistently has the greatest comparative advantage, with very poor TGMASC per hectare per year results from the ***RloR***. When equalising irrigation blocks to 150% (1.5 crops per hectare per year) ***Vall*** proves to be the irrigation block with the greatest comparative advantage for all scenarios and leaching and drainage combinations.

Having identified the ***RloR*** as the most critical irrigation block requiring additional artificial leaching and drainage, over a range for discount rates, assistance grant levels and repayment terms, the net return of assistance grant investment for the ***RloR*** is positive, indicating a very favourable return to subsidised drainage investment over a range of possible circumstances and conditions.

Drainage installation for facilitation of leaching needs to be promoted in the Orange-Vaal WUA (***Vall***) and especially in the Lower Riet (***RloR***) irrigation blocks in the study area. 10% and 20% of the ***Vall*** and ***RloR*** irrigation blocks' irrigable area respectively are recommended to be drained. If the ***Rscm*** and ***Rszg*** irrigation blocks are to be drained, before salinity builds up to levels which result in financial losses, at least a 50% assistance grant of the total drainage costs may be needed to make the offer financially.viable and acceptable for the irrigators.

The following programmes (author's opinion) could be implemented or initiated by the Department of Agriculture, WUAs, GWK, etc. in the irrigation areas:

- Subsidise agricultural extension to regularly measure soil salinity
- Promote soil salinity status readings by fertilizer companies when conducting soil analyses and making fertilization recommendation
- Promote inquiring about the salinity status of soils when purchasing irrigation land
- Increase awareness to insurance companies of the potential increased risk of salinised soils if not managed properly.

These salinity awareness programmes must be coupled with a centralised soil salinity database to facilitate the accumulation of soil salinity data for better policy analysis and research in the future, as one of the limitation identified in this study is a shortage of historical soil salinity data.

10.6 FUTURE RESEARCH NEEDS

10.6.1 WHOLE FARM LEVEL ECONOMIC MODEL REFINEMENT (OPTIMISATION)

The externalities need to be internalised to determine the best way and the acceptability to internalise the costs of salinisation created by farmers at different locations along the river. Separate optimisation models at farm level and all along a river reach should be attempted if the limitations of optimising bio-physical interactions with too many decision variables can be overcome.

10.6.2 HYDROLOGY REFINEMENT

The refinement of the WRPM to include the sub-WUAs identified in Chapter 3 as irrigation blocks will provide better results especially for the Orange-Vaal WUA (***Vall***) irrigation block. A more user friendly version of the WRPM model needs to be developed that other operators can use. A suggestion would be to transfer the existing data bases and setup information from the out dated model coding into a GIS based model already developed, for instance MIKE Basin from the Danish Hydraulic Institute (DHI).

10.6.3 LOCAL SALINITY YIELD RESPONSE

Research conducted at the UFS Department of Soil Science, not completed at the time of this thesis on crop response to infield salinity should be incorporated into similar studies as this research. More up to date and locally applicable measures of crop salinity threshold and gradient values, provided by this research may be more applicable and relevant as those used in this study, which are mostly calculated in laboratory situations in California.

10.6.4 SOIL SALINITY DATA BASE

One of the limitations identified in this study was a shortage of historical soil salinity data. Salinity awareness programmes must be coupled with a centralised soil salinity database to facilitate the accumulation of soil salinity data for better policy analysis and research in future.

10.6.5 GIS LINKAGES

McKinney *et al.*(1999, ix) state that "*the future direction of modelling will lie in GIS-based decision support systems that integrate economic, agronomic, institutional and hydraulic components*". The authors fully agree with this statement and recognise the need for multidisciplinary teams to conduct this type of research.

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APPENDIX 1. SMSIM MODELLING SEQUENCE AND FILES

i.) *Setup scenario inputs for WRPM*

To edit the scenarios to be run through WRPM open file C:\SALMOD\SMsim\SMscenarioSetup.xls. Once the scenarios setup for the WRPM are correct, run the macro "*SaveScenarios"* saved in "*SMscenarioSetup*" to get the WRPM setup data required into the correct form for easy input into the WRPM. The macro saves the text (*.txt – space delimited*) files under the following: "*C:\SALMOD\WRPM scenarios*" "*-Base Case*", "*-Scen1*", "*-Scen2*" and "*-Scen3*"

To edit the input data used in setting up the "SMscenarioSetup" file open C:\SALMOD\SMsim\SMsubWUA.xls, edit the input data and rerun the macro.

ii.) *Receive and save WRPM results data*

WRP consultants returns the files zipped per irritation block and channel flows.

Save the zipped files to "*C:\WRPMdata\WRPM output data raw"* taking care to place the respective files in the "*BaseCase*", "*Scen1*", "*Scen2*" and "*Scen3*" sub-folders.

Systematically unzip each folder copying only the *CL…, CU… and HE…* files to the same folder.

iii.) *Process WRPM data*

Run the macro, "*TSRR_Fix*" saved in *C:\WRPMdata\WRPM read coding\ GAMS CU CL HE.xls* to resize the collumn widths. The output from this Macro is saved in "*C:\WRPMdata\Resize*" "*-Base Case*", "*-Scen1*", "*-Scen2*" and "*-Scen3*" sub-folders

Run the GAMS sub-routines *"C:\WRPMdata\WRPM read coding\060130 WRPM read CuClHe" "-BaseCase"*, "*-Scen1*", "*-Scen2*" and "*-Scen3" ".gms"* to open, edit, rearrange and save the data to the files: "*C:\SALMOD\SMsim\Scenario input data*" "*-Base Case*", "*-Scen1*", "*-Scen2*" and "*-Scen3*" for use in SMsim.xls.

In each folder "*-Base Case*", "*-Scen1*", "*-Scen2*" and "*-Scen3*" update the CU-, CE- and HE-AllScen.xls files checking links.

The *CeAll.xls* file is subsequently linked to these and feeds *CeAllScens.xls*, which is the final hydrology link, to SMsim.

iv.) *Use processed WRPM data as inputs to SMsim*

The WRPM data is processed through the biophysical models for use in the economic models.

v.) *Bio-physical data as inputs in SMsim*

Open and run the model SAPWAT (van Heerden *et al.* 2001) and fill in the required data fields to calculate crop coefficients to be used as input in the WRPM setup.

Convert the WRPM output factor CU from each irrigation block to CUe for each irrigation block using HE and the constant HSU saving a separate CUe file for each scenario.

Other WRPM output for the macro model biophysical calculation are the SA and SR data that are used to calculate the ISEWe.

vi.) *Study area setup data as inputs to SMsim*

Open C:\SALMOD\SMsim\SMsubWUA.xls to edit the irrigation block level data used as input into SMsim

vii.) *Crop Enterprise Budget (CEB) data as input to SMsim*

Open C:\SALMOD\SMsim\SMCEBs.xls to set up / update / edit the CEBs

APPENDIX 2. IRRIGATION BLOCK CEBS

Table A2.1. The CEBs (2005 prices) of the Riet Scheme irrigation block of the OR-WUA

RIET SCHEME	*Unit*	Barley	Beets	Carrots	Cotton	Cucurbits	Dry_Beans	Fruit	Lucerne	Maize	Olives	Onions	Pastures	Peanuts	Pecan_nuts	Potatoes	Soybeans	Sunflower	Vegetables	Vineyards	Wheat
ECe Threshold without leaching	mS/mt	800	400	100	770	250	160	170	200	170	300	120	600	320	150	170	500	170	170	150	600
ECe Threshold (BC, S1 and S2)	mS/m	812	406	102	782	254	162	173	203	173	305	122	609	325	152	173	508	508	711	152	609
ECe Gradient	%/mS/m	0.071	0.090	0.140	0.052	0.130	0.096	0.210	0.073	0.120	0.190	0.160	0.071	0.290	0.190	0.120	0.200	0.087	0.090	0.096	0.071
Crop water requirement	mm/ha	610	398	383	765	517	333	1206	1173	761	555	245	839	601	635	553	642	417	613	634	610
Crop Enterprise Budgets:																					
PRICE	R/ton	1030	1061	1142	3016	560	2782	3000	552	832	5400	1378	800	2591	16500	1412	1693	1451	750	725	1208
Max Physiological yield	*ton/ha*	*6.00*	*35.00*	*50.00*	*5.00*	*50.00*	*3.50*	*21.00*	*20.40*	*14.00*	*6.40*	*55.00*	*8.00*	*4.00*	*1.60*	*45.00*	*6.00*	*4.00*	*40.00*	*20.38*	*7.00*
Gross income	**R/ha**	**6 180**	**37 133**	**57 091**	**15 079**	**28 000**	**9 739**	**63 000**	**11 255**	**11 651**	**34 560**	**75 774**	**6 400**	**10 364**	**26 400**	**63 557**	**10 160**	**5 805**	**30 000**	**14 778**	**8 454**
SEED	R/ha	504	2 680	3 900	1 114	224	1 120	7 683	375	1 080	578	2 742	1 175	1 040	373	16 000	475	61	585	2 349	756
FERTILIZER	R/ha	1 424	2 881	3 162	2 145	2 389	1 218	1 535	1 414	2 402	1 754	3 372	1 153	1 120	1 149	4 718	1 070	1 167	1 754	756	1 858
HERBICIDES	R/ha	84	368	334	85	103	204	506	165	277	539	537	0	94	25	117	233	140	270	2 204	84
PESTICIDES	R/ha	157	40	309	1 792	257	1 021	4	13	594	830	1 156	0	754	0	9 574	159	188	612	0	409
INSURANCE	R/ha	341	0	2 376	1 080	0	360	11 201	0	960	0	4 950	0	344	0	1 200	0	307	384	0	364
FUEL	R/ha	206	281	426	444	271	225	43	464	194	127	426	233	295	82	828	171	274	233	146	287
MAINTENANCE	R/ha	481	0	0	567	0	418	66	1 078	336	1 000	223	698	811	29	1 154	145	418	406	207	913
Temp LABOUR	R/ha	0	4 597	5 307	988	1 900	554	900	0	0	567	491	0	1 070	0	268	160	0	300	1 434	0
ELEC. @ R 0.82 /mm	R/mm/ha	*501*	*327*	*314*	*628*	*425*	*273*	*990*	*343*	*504*	*456*	*201*	*689*	*494*	*522*	*454*	*527*	*343*	*504*	*521*	*501*
WATER@ R 0.68 /mm	R/mm/ha	*413*	*269*	*259*	*518*	*350*	*225*	*817*	*282*	*415*	*376*	*166*	*568*	*407*	*430*	*375*	*435*	*282*	*415*	*430*	*413*
HARVESTING COSTS	R/ton	122	539	600	280	20	249	82	44	50	3 000	184	0	471	233	368	127	113	270	12	103
	R/ha	734	18 865	30 000	1 400	1 000	873	1 716	899	704	19 200	10 104	0	1 886	373	16 557	760	450	10 812	240	723
Total expenses pre harvest	R/ha	4 112	11 443	16 388	9 362	4 919	5 618	23 745	4 133	6 761	6 227	14 263	4 517	6 429	2 610	34 688	3 377	3 180	5 463	8 047	5 585
Total expenses with max harvest	R/ha	4 846	30 308	46 388	10 762	6 919	6 491	25 461	5 033	7 465	25 427	24 366	4 517	8 315	2 983	51 245	4 137	3 630	16 275	8 287	6 308
Gross Margin	**R/ha**	**1 334**	**6 825**	**10 704**	**4 317**	**21 081**	**3 248**	**37 539**	**6 223**	**4 186**	**9 133**	**51 408**	**1 883**	**2 049**	**23 417**	**12 311**	**6 023**	**2 174**	**13 725**	**6 491**	**2 146**
Co-op financed	R/ha	88	0	725	226	236	0	0	96	161	593	382	359	152	0	931	66	70	125	781	128
Bank financed	R/ha	45	0	1 401	70	81	0	0	42	45	2 204	288	138	77	0	478	47	30	323	131	45
Total Interest	R/ha	*133*	*0*	*2 126*	*296*	*317*	*0*	*0*	*138*	*205*	*2 797*	*670*	*497*	*229*	*0*	*1 409*	*114*	*100*	*448*	*912*	*173*
TGMASC	**R/ha**	**1 200**	**6 825**	**8 578**	**4 022**	**20 764**	**3 248**	**37 539**	**6 084**	**3 980**	**6 336**	**50 738**	**1 387**	**1 820**	**23 417**	**10 902**	**5 909**	**2 075**	**13 278**	**5 580**	**1 972**

Table A2.2. The CEBs (2005 prices) of the Scholtzburg irrigation block of the OR-WUA

SCHOLTZBURG	Unit	Barley	Beets	Carrots	Cotton	Cucurbits	Dry_Beans	Fruit	Lucerne	Maize	Olives	Onions	Pastures	Peanuts	Pecan_nuts	Potatoes	Soybeans	Sunflower	Vegetables	Vineyards	Wheat
ECe Threshold without leaching	mS/m	800	400	100	770	250	160	170	200	170	300	120	600	320	150	170	500	170	170	150	600
ECe Threshold (BC, S1 and S2)	mS/m	820	410	103	789	256	164	174	205	174	308	123	615	328	154	174	513	513	718	154	615
ECe Gradient	%/mS/m	0.071	0.090	0.140	0.052	0.130	0.096	0.210	0.073	0.120	0.190	0.160	0.071	0.290	0.190	0.120	0.200	0.087	0.090	0.096	0.071
Crop water requirement	mm/ha	616	402	386	772	522	336	1218	1185	768	561	247	847	607	642	559	648	421	619	641	616
Crop Enterprise Budgets:																					
PRICE	R/ton	1030	1061	1142	3016	560	2782	3000	552	832	5400	1378	800	2591	16500	1412	1693	1451	750	725	1208
Max Physiological yield	*ton/ha*	*6.00*	*35.00*	*50.00*	*5.00*	*50.00*	*3.50*	*21.00*	*20.40*	*14.00*	*6.40*	*55.00*	*8.00*	*4.00*	*1.60*	*45.00*	*6.00*	*4.00*	*40.00*	*20.38*	*7.00*
Gross income	**R/ha**	**6 180**	**37 133**	**57 091**	**15 079**	**28 000**	**9 739**	**63 000**	**11 255**	**11 651**	**34 560**	**75 774**	**6 400**	**10 364**	**26 400**	**63 557**	**10 160**	**5 805**	**30 000**	**14 778**	**8 454**
SEED	R/ha	504	2 680	3 900	1 114	224	1 120	7 683	375	1 080	578	2 742	1 175	1 040	373	16 000	475	61	585	2 349	756
FERTILIZER	R/ha	1 424	2 881	3 162	2 145	2 389	1 218	1 535	1 414	2 402	1 754	3 372	1 153	1 120	1 149	4 718	1 070	1 167	1 754	756	1 858
HERBICIDES	R/ha	84	368	334	85	103	204	506	165	277	539	537	0	94	25	117	233	140	270	2 204	84
PESTICIDES	R/ha	157	40	309	1 792	257	1 021	4	13	594	830	1 156	0	754	0	9 574	159	188	612	0	409
INSURANCE	R/ha	341	0	2 376	1 080	0	360	11 201	0	960	0	4 950	0	344	0	1 200	0	307	384	0	364
FUEL	R/ha	206	281	426	444	271	225	43	464	194	127	426	233	295	82	828	171	274	233	146	287
MAINTENANCE	R/ha	481	0	0	567	0	418	66	1 078	336	1 000	223	698	811	29	1 154	145	418	406	207	913
Temp LABOUR	R/ha	0	4 597	5 307	988	1 900	554	900	0	0	567	491	0	1 070	0	268	160	0	300	1 434	0
ELEC. @ R 0.45 /mm	R/mm/ha	*279*	*182*	*175*	*350*	*237*	*152*	*552*	*191*	*281*	*254*	*112*	*384*	*275*	*291*	*253*	*294*	*191*	*281*	*290*	*279*
WATER@ R 0.68 /mm	R/mm/ha	*417*	*272*	*262*	*523*	*354*	*228*	*825*	*285*	*419*	*380*	*167*	*574*	*411*	*435*	*378*	*439*	*285*	*419*	*434*	*417*
HARVESTING COSTS	R/ton	122	539	600	280	20	249	82	44	50	3 000	184	0	471	233	368	127	113	270	12	103
	R/ha	734	18 865	30 000	1 400	1 000	873	1 716	899	704	19 200	10 104	0	1 886	373	16 557	760	450	10 812	240	723
Total expenses pre harvest	R/ha	3 894	11 301	16 251	9 089	4 734	5 499	23 314	3 985	6 543	6 029	14 175	4 217	6 215	2 383	34 490	3 148	3 031	5 244	7 820	5 367
Total expenses with max harvest	R/ha	4 628	30 166	46 251	10 489	6 734	6 372	25 030	4 884	7 246	25 229	24 279	4 217	8 100	2 756	51 048	3 908	3 481	16 056	8 060	6 090
Gross margin	**R/ha**	**1 551**	**6 967**	**10 840**	**4 590**	**21 266**	**3 367**	**37 970**	**6 372**	**4 404**	**9 331**	**51 495**	**2 183**	**2 263**	**23 644**	**12 509**	**6 252**	**2 323**	**13 944**	**6 718**	**2 364**
Co-op financed	R/ha	88	0	725	226	236	0	0	96	161	593	382	359	152	0	931	66	70	125	781	128
Bank financed	R/ha	39	0	1 395	63	73	0	0	62	43	2 182	286	105	71	0	473	41	25	317	106	39
Total Interest	R/ha	*127*	*0*	*2 120*	*288*	*309*	*0*	*0*	*158*	*204*	*2 775*	*668*	*464*	*223*	*0*	*1 404*	*107*	*96*	*442*	*887*	*167*
TGMASC	**R/ha**	**1 424**	**6 967**	**8 720**	**4 302**	**20 957**	**3 367**	**37 970**	**6 214**	**4 201**	**6 556**	**50 827**	**1 719**	**2 041**	**23 644**	**11 105**	**6 145**	**2 228**	**13 503**	**5 831**	**2 196**

Table A2.3. The CEBs (2005 prices) of the Vaal All irrigation block of the OV-WUA

VAAL ALL	Unit	Barley	Beets	Carrots	Cotton	Cucurbits	Dry_Beans	Fruit	Lucerne	Maize	Olives	Onions	Pastures	Peanuts	Pecan_nuts	Potatoes	Soybeans	Sunflower	Vegetables	Vineyards	Wheat
ECe Threshold without leaching	mS/m	800	400	100	770	250	160	170	200	170	300	120	600	320	150	170	500	170	170	150	600
ECe Threshold (BC, S1 and S2)	mS/m	836	418	105	805	261	167	178	209	178	314	125	627	334	157	178	523	523	732	157	627
ECe Gradient	%/mS/m	0.071	0.090	0.140	0.052	0.130	0.096	0.210	0.073	0.120	0.190	0.160	0.071	0.290	0.190	0.120	0.200	0.087	0.090	0.096	0.071
Crop water requirement	mm/ha	628	410	394	787	532	343	1241	1208	783	572	252	864	619	654	570	661	429	631	653	628
Crop Enterprise Budgets:																					
PRICE	R/ton	1030	1061	1142	3016	560	2782	3000	552	832	5400	1378	800	2591	16500	1412	1693	1451	750	725	1208
Max Physiological yield	*ton/ha*	*6.00*	*35.00*	*50.00*	*5.00*	*50.00*	*3.50*	*21.00*	*20.40*	*14.00*	*6.40*	*55.00*	*8.00*	*4.00*	*1.60*	*45.00*	*6.00*	*4.00*	*40.00*	*20.38*	*7.00*
Gross income	**R/ha**	**6 180**	**37 133**	**57 091**	**15 079**	**28 000**	**9 739**	**63 000**	**11 255**	**11 651**	**34 560**	**75 774**	**6 400**	**10 364**	**26 400**	**63 557**	**10 160**	**5 805**	**30 000**	**14 778**	**8 454**
SEED	R/ha	504	2 680	3 900	1 114	224	1 120	7 683	375	1 080	578	2 742	1 175	1 040	373	16 000	475	61	585	2 349	756
FERTILIZER	R/ha	1 424	2 881	3 162	2 145	2 389	1 218	1 535	1 414	2 402	1 754	3 372	1 153	1 120	1 149	4 718	1 070	1 167	1 754	756	1 858
HERBICIDES	R/ha	84	368	334	85	103	204	506	165	277	539	537	0	94	25	117	233	140	270	2 204	84
PESTICIDES	R/ha	157	40	309	1 738	257	1 021	4	13	588	830	1 156	0	754	0	9 574	159	188	594	0	403
INSURANCE	R/ha	341	0	2 376	2 217	3 780	1 032	11 201	0	373	0	5 759	0	321	0	2 224	0	192	2 640	901	364
FUEL	R/ha	206	281	426	444	271	225	43	464	194	127	426	233	295	82	828	171	274	233	146	287
MAINTENANCE	R/ha	481	0	0	567	0	418	66	1 078	336	1 000	223	698	811	29	1 154	145	418	406	207	913
Temp LABOUR	R/ha	0	4 597	5 307	988	1 900	554	900	0	0	567	491	0	1 070	0	268	160	0	300	1 434	0
ELEC. @ R 0.35 /mm	R/mm/ha	*220*	*143*	*138*	*276*	*186*	*120*	*435*	*150*	*221*	*200*	*88*	*302*	*217*	*229*	*199*	*231*	*150*	*221*	*229*	*220*
WATER@ R 0.68 /mm	R/mm/ha	*425*	*277*	*267*	*533*	*360*	*232*	*841*	*291*	*427*	*387*	*170*	*585*	*419*	*443*	*386*	*448*	*291*	*427*	*442*	*425*
HARVESTING COSTS	R/ton	122	539	600	280	20	249	82	44	50	3 000	184	0	471	233	368	127	113	270	12	103
	R/ha	734	18 865	30 000	1 400	1 000	873	1 716	899	704	19 200	10 104	0	1 886	373	16 557	760	450	10 812	240	723
Total expenses pre harvest	R/ha	3 843	11 268	16 219	10 107	8 471	6 143	23 213	3 949	5 898	5 982	14 964	4 147	6 141	2 330	35 468	3 094	2 880	7 430	8 669	5 310
Total expenses with max harvest	R/ha	4 577	30 133	46 219	11 507	10 471	7 016	24 929	4 849	6 601	25 182	25 067	4 147	8 027	2 703	52 026	3 854	3 330	18 242	8 909	6 033
Gross margin	**R/ha**	**1 603**	**7 001**	**10 872**	**3 572**	**17 529**	**2 722**	**38 071**	**6 407**	**5 049**	**9 378**	**50 707**	**2 253**	**2 337**	**23 697**	**11 531**	**6 306**	**2 474**	**11 758**	**5 870**	**2 421**
Co-op financed	R/ha	88	0	725	256	409	0	0	96	144	593	404	359	151	0	959	66	67	187	880	128
Bank financed	R/ha	38	0	1 394	61	71	0	0	37	37	2 177	285	98	69	0	471	40	25	315	100	38
Total Interest	R/ha	*126*	*0*	*2 118*	*316*	*480*	*0*	*0*	*133*	*182*	*2 770*	*689*	*456*	*221*	*0*	*1 431*	*106*	*92*	*502*	*980*	*166*
TGMASC	**R/ha**	**1 477**	**7 001**	**8 754**	**3 256**	**17 049**	**2 722**	**38 071**	**6 273**	**4 868**	**6 608**	**50 017**	**1 797**	**2 116**	**23 697**	**10 100**	**6 200**	**2 383**	**11 256**	**4 890**	**2 255**

Table A2.4. Irrigation block comparison of the Crop TGMASC less interest values (2005 prices)

TGMASC Irrigation blocks compared			Barley	Beets	Carrots	Cotton	Cucurbits	Dry_Beans	Fruit	Lucerne	Maize	Olives	Onions	Pastures	Peanuts	Pecan_nuts	Potatoes	Soybeans	Sunflower	Vegetables	Vineyards	Wheat
LOWER RIET		R/ha	1 405	6 125	10 056	3 110	16 987	2 490	37 243	6 224	4 789	6 537	49 989	1 691	2 045	22 887	10 035	6 125	2 333	11 165	4 809	2 177
RIET SCHEME		R/ha	1 200	6 825	8 578	4 022	20 764	3 248	37 539	6 084	3 980	6 336	50 738	1 387	1 820	23 417	10 902	5 909	2 075	13 278	5 580	1 972
SCHOLTZBURG		R/ha	1 424	6 967	8 720	4 302	20 957	3 367	37 970	6 214	4 201	6 556	50 827	1 719	2 041	23 644	11 105	6 145	2 228	13 503	5 831	2 196
VAAL ALL		R/ha	1 477	7 001	8 754	3 256	17 049	2 722	38 071	6 273	4 868	6 608	50 017	1 797	2 116	23 697	10 100	6 200	2 383	11 256	4 890	2 255
Average			1 377	6 729	9 027	3 672	18 939	2 957	37 706	6 199	4 459	6 509	50 393	1 648	2 005	23 411	10 535	6 095	2 255	12 300	5 277	2 150
Min			1 200	6 125	8 578	3 110	16 987	2 490	37 243	6 084	3 980	6 336	49 989	1 387	1 820	22 887	10 035	5 909	2 075	11 165	4 809	1 972
Max			1 477	7 001	10 056	4 302	20 957	3 367	38 071	6 273	4 868	6 608	50 827	1 797	2 116	23 697	11 105	6 200	2 383	13 503	5 831	2 255
Change from average. R/ha	rank	sum																				
LOWER RIET	4	-5 421	28	-604	1 029	-562	-1 952	-467	-462	25	330	28	-404	42	40	-524	-501	30	79	-1 135	-468	27
RIET SCHEME	2	2 008	-176	96	-449	349	1 825	291	-167	-115	-479	-173	345	-262	-185	6	367	-185	-180	977	302	-178
SCHOLTZBURG	1	6 270	48	238	-307	630	2 018	410	264	15	-259	47	435	71	35	233	569	50	-27	1 202	554	46
VAAL ALL	3	-2 856	100	271	-273	-417	-1 890	-234	365	74	408	99	-375	149	110	286	-435	105	128	-1 044	-388	105

APPENDIX 3. MATHEMATICAL FORMULATION OF SMSIM

The sets, sub-sets, scalars and input data codes are listed here, together with a complete list of all the Equations used in this study with reference to the page numbers where the formulae are defined.

SETS:

t	=	monthly (m) time step of the model over a number of years (y)	
t	=	f (***m, y***)	
m	=	months in the model as follows:	
		in the hydrology model, rainfall	***m*** = {Oct, Nov, ... Sep.}
		in WRPM output	***m*** = {May, Jun, ...Apr.}
		in financial model Tax year	***m*** = {Mar, Apr, ... Feb.}
		in SMsim an agricultural season	***m*** = {Jul, Aug, ... Jun.}
y	=	years in the model as follows	
		in WRPM (25 Years)	***y*** = {yr1, yr2, ... yr25}
		in SMsim (15 years)	***y*** = {2005, 2003, ... 2019}
t	=	1,2, ... 180. (12 months x 15 years)	
s	=	irrigation blocks in the model	{***RloR, Rscm, Rszg, Vall***}
r	=	stochastic model runs	{1, 2, ..., 100}
c	=	all crops modelled in SMsim	{wheat, maize, lucerne}
i	=	a set of all inputs / direct production costs	{seed, fertilizer, ..., transport}

SUB-SETS

sr of s	=	irrigation blocks of the OR-WUA	{***RloR, Rscm, Rszg***}
sv of s	=	irrigation blocks of the OV-WUA	{***Vall***}
fi of I	=	are all the fixed inputs (R/ha)	{seed,fertilizer,chemicals,etc.}
yi of I	=	are all the yield dependent production costs (R/ton)	{harvesting, packaging, transport, etc.}

SCALARS / CONSTANTS:

SCF TDS to EC salinity conversion factor = 6.5

INPUT DATA:

$TDScu_{t,s,r}$ is a data set of the salt concentration (mg/l) in the upper layer calculated in the WRPM as output data used as input for SMsim. The data set **$TDScu_{t,s,r}$** comprises monthly data for all years (***t***) in all irrigation blocks (***s***) for 100 stochastic runs (***r***).

$CWR_{c,m}$ is the crop water requirement percentage for each month (***m***) for all crops (***c***). The sum over ***m*** for each ***c*** gives a result 1 = 100%.

$Thrsh_c$ is the crop (***c***) specific salinity yield reduction threshold value (mS/m) (assumed constant for all irrigation blocks)

$Grad_c$ is the crop (***c***) specific salinity yield reduction gradient value (ton/ mS/m) (assumed constant for all irrigation blocks)

GradLF is the crop (***c***) specific salinity yield reduction gradient value adjusted for leaching

$P_{c,y,s}$ is an array of different crop (***c***) prices (R/ton) in each year (***y***) and in each irrigation block (***s***). An assumption of the model is constant prices over the 15 years therefore ***y*** remains unchanged, however the price $P_{c,y,s}$ can change between irrigation blocks.

$I_{fi,c,y,s}$ are the fixed input costs (***fi***) i.e. seed, fertilizer, chemicals, etc. (R/ha), for the different crops (***c***) which remain unchanged in each year (***y***), but which can change between irrigation blocks (***s***).

$I_{yi,c,y,s}$ are the yield dependent production costs (***yi***) i.e. harvesting, packaging, transport, etc. (R/ton), for the different crops (***c***) in each year (***y***) and in each irrigation block (***s***).

SUMMARY OF EQUATIONS: Page Number: