Modelling the financial vulnerability of farming systems to climate change in selected case study areas in South Africa

by

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Declaration

By submitting this dissertation electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

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ABSTRACT

Numerous studies indicate that the agricultural sector is physically and economically vulnerable to climate change. In order to determine possible impacts of projected future climates on the financial vulnerability of selective farming systems in South Africa, a case study methodology was applied. The integrated modelling framework consists of four modules, viz.: climate change impact modelling, dynamic linear programming (DLP) modelling, modelling interphases and financial vulnerability assessment modelling. Empirically downscaled climate data from five global climate models (GCMs) served as base for the integrated modelling. The APSIM crop model was applied to determine the impact of projected climates on crop yield for certain crops in the study. In order to determine the impact of projected climates on crops for which there are no crop models available, a unique modelling technique, Critical Crop Climate Threshold (CCCT) modelling, was developed and applied to model the impact of projected climate change on yield and quality of agricultural produce. Climate change impact modelling also takes into account the projected changes in irrigation water availability (ACRU hydrological model) and crop irrigation requirements (SAPWAT3 model) as a result of projected climate change. The model produces a set of valuable results, viz. projected changes in crop yield and quality, projected changes in availability of irrigation water, projected changes in crop irrigation needs, optimal combination of farming activities to maximize net cash flow, and a set of financial criteria to determine economic viability and financial feasibility of the farming system. A set of financial criteria; i.e. internal rate of return (IRR), net present value (NPV), cash flow ratio, highest debt ratio, and highest debt have been employed to measure the impact of climate change on the financial vulnerability of farming systems. Adaptation strategies to lessen the impact of climate change were identified for each case study through expert group discussions, and included in the integrated modelling as alternative options in the DLP model. This aims at addressing the gap in climate change research, i.e. integrated economic modelling at farm level; thereby making a contribution to integrated climate change modelling.

OPSOMMING

Die fisiese sowel as ekonomiese kwesbaarheid van die landbousektor as gevolg van klimaatverandering word deur verskeie studies beklemtoon. ‘n Gevallestudie-benadering is gebruik ten einde die potensiële impak van klimaatsverandering op die finansiële kwesbaarheid van verskillende boerderystelsels te bepaal. Die geïntegreerde klimaatsveranderingmodel bestaan uit vier modelleringsmodules, naamlik: klimaatsverandering, dinamiese liniêre programmering (DLP), interfases en finansiële-kwesbaarheidsontleding. Empiries afgeskaalde klimatologiese data van vyf verskillende klimaatmodelle dien as basis vir die geïntegreerde klimaatsveranderingmodel. Die APSIM gewas-model word aangewend om die impak van klimaatsverandering op gewasse-opbrengs te bepaal. Vir sekere gewasse is daar egter nie modelle beskikbaaar nie en het gevolglik die ontwikkeling van ‘n nuwe model genoodsaak. Die Kritiese Gewasse Klimaatsdrempelwaarde (KGKD) modelleringstegniek is ontwikkel ten einde die impak van klimaatsverandering op die opbrengs en kwaliteit van gewasse te kwantifiseer. Die geïntegreerde klimaatsveranderingmodel neem ook die verwagte verandering in besproeiingswaterbeskikbaarheid (ACRU-hidrologiemodel) en gewas-besproeiingsbehoeftes (SAPWAT3-model) as gevolg van klimaatsverandering in ag. Die model lewer waardevolle resultate op, naamlik: geprojekteerde veranderinge in gewasse-opbrengs en -kwaliteit, geprojekteerde verandering in beskikbaarheid van besproeiingswater en gewasse-besproeiingsbehoeftes, die optimale kombinering van boerdery-aktiwiteite om netto kontantvloei te maksimeer, asook ‘n stel finansiële resultate wat die impak van klimaatsverandering kwantifiseer. Die finansiële kriteria sluit in: interne opbrengskoers, netto huidige waarde, kontanvloeiverhouding, hoogste skuldverhouding en hoogste skuldvlak. Deur middel van deskundige-groepbesprekings is aanpassingstrategieë vir elk van die gevallestudies geïdentifiseer en by die geïntegreerde model ingesluit as alternatiewe opsies in die DLP-model. Die studie poog om die gaping in die huidige klimaatsveranderingnavorsing met betekking tot ‘n geïntegreerde ekonomiese model op plaasvlak aan te spreek en sodoende ‘n bydrae tot geïntegreerde klimaatveranderingmodellering te maak.

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During the course of the study the following research outputs were presented at conferences:

- JOHNSTON, P., OOSTHUIZEN, H.J. and LOUW, D.B. 2014. Using downscaled climate scenarios to model the financial vulnerability of farming systems to climate change – a case study for rainfed wheat in the SW Cape of South Africa. Presented at the International Conference on African Agriculture, Rural Development and Sino-African Cooperation (CAARDSAC) 23 – 23 September 2014, Nanjing, China.
- OOSTHUIZEN, H.J., LOUW, D.B., SCHULZE, R.E., JOHNSTON, P., LOMBARD, J.P. and BACKEBERG, G.R. 2014. Modelling the impact of climate on the financial vulnerability of farms – a Hoedspruit irrigation farm study. Paper delivered at International Water Association (IWA), Water, Energy and Climate Conference 21 May 2014, Mexico City, Mexico. Abstract ID 2535940.
- JOHNSTON, P., OOSTHUIZEN, H.J. and LOUW, D.B. 2013. Using downscaled climate change scenarios to model the impact on farming systems for

a financial vulnerability point of view. Paper delivered at the International Conference on regional climate – CORDEX 2013, 4-7 November 2013, Brussels, Belgium.

- OOSTHUIZEN, H.J., LOUW, D.B., SCHULZE, R.E., JOHNSTON, P., LOMBARD, J.P. and BACKEBERG, G.R. 2012. Modelling the financial vulnerability of farming systems due to climate change. Paper delivered at South African National Committee on Irrigation and Drainage (SANCID) symposium, 20-23 November 2012, Drakensberg, KwaZulu-Natal, South Africa.

DEDICATION

Dedicated to my mother Marie Oosthuizen - for your unconditional love, trust and unwavering belief in me. Every human endeavour is inspired by a certain desire. A need to do better, to make a meaningful difference to the world that surrounds us. With your constant prayers and many blessings, I hope that I have not squandered your wishes and exceeded all your expectations.

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Acronym	Description
ACM	APSIM crop model
ACRU	Agricultural Catchments Research Unit
AEZs	Agro-Ecological Zones of Africa
Apr	April
APSIM	Agricultural Production Systems Simulator
APSRU	Agricultural Production Systems Research Unit
Aug	August
Blyde WUA	Blyde Water Users Association
CAADP	Comprehensive Africa Agriculture Development Programme
CCC	General Circulation Model: CGCM3.1(T47), Canadian Center for Climate Modelling and Analysis (CCCma), Canada
CCCma	Canadian Center for Climate Modelling and Analysis, Canada
CCCT	Crop Critical Climate Threshold
CFR	Cash Flow Ratio
CH_4	Methane
CNRM	Centre National de Recherches Meteorologiques, France
CO_2	Carbon dioxide
CRM	General Circulation Model: CNRM-CM3, Meteo-France / Centre National de Recherches Meteorologiques (CNRM), France
CSAG	Climate Systems Analysis Group
CSIR	Council for Scientific and Industrial Research
CSIRO	Commonwealth Scientific and Industrial Research Organization
D:A ratio	Debt:asset ratio
Dec	December
DLP	Dynamic Linear Programming
DSSAT	Decision Support System for Agrotechnology Transfer
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
ECH	General Circulation Model: ECHAM5/MPI-OM, Max Planck Institute for Meteorology, Germany
Ep	Evapotranspiration
Er	Reference potential evaporation
ET0	Reference evapotranspiration
FAO	Food and Agricultural Organization
Feb	February
FFBC	Farming for a better climate
GAMS	General Algebraic Modeling System
GCM	General Circulation Model
GDP	Gross Domestic Product
GIS	Geographic Information System

Acronym	Description
GISS	General Circulation Model: GISS-ER, NASA / Goddard Intstitute for Space Studies, USA
Ha	Hectare
HU	Heat units
IAASTD	International Assessment of Agricultural Science and Technology for Development
ICID	International Commission on Irrigation and Drainage
IDRC	International Development Research Centre
IFPRI	International Food Policy Research Institute
IGBP	International Geosphere-Biosphere Program
IISD	International Institute for Sustainable Development
IPCC	Intergovernmental Panel on Climate Change
IPCC SRES	Intergovernmental Panel on Climate Change - Special Report on Emissions Scenarios
IPCC TAR	Intergovernmental Panel on Climate Change, Third Assessment Report
IPS	General Circulation Model: IPSL-CM4, Institut Pierre Simon Laplace, France
IPSL	Institut Pierre Simon Laplace, France
IRR	Internal Rate of Return
ISCW	Institute for Soil, Climate and Water
Jan	January
Jul	July
Jun	June
Km	Kilometer
LDCs	Least Developed Countries
LORWUA	Lower Olifants River Water Users Association
LP	Linear programming
LSU	Large stock unit
LT	Long term
M^3	Cubic metre
MAP	Mean Annual Precipitation
Mar	March
MDGs	Millenium Development Goals
MKB	Moorreesburgse Koringboere (Edms) Beperk
mm	Millimeter
MPI-M	Max Planck Institute for Meteorology, Germany
N_2O	Nitrous oxide
NCAR	National Center for Atmospheric Research
Nov	November
NPV	Net Present Value
NRE	Natural Resources and Environment
Oct	October

Acronym	**Description**
ODWMA	Olifants/Doring Water Management Area
PCM	PCM General Circulation Model developed in the USA
Ppm	Parts per million
QCB	Quaternary Catchments Database
QnCDB	Quinary Catchments Database
R	Rand
RCMs	Regional Climate Models
RH	Relative Humidity
RSA	Republic of South Africa
SAD	Safari Dried Fruits
SAPWAT3	South African Plant WATer
Sept	September
SIRI	Soil and Irrigation Research Institute
SSU	Small stock unit
ST	Short term
Tmnd	Daily minimum temperature
Tmxd	Daily maximum temperature
UCT	University of Cape Town
UKCIP	United Kingdom Climate Impact Programme
UKZN	University of KwaZulu-Natal
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention for Climate Change
WMA	Water Management Area
WMO	World Meteorological Organisation
WRC	Water Research Commission
WRI	World Resources Institute
WUA	Water Users Association

CHAPTER 1 : INTRODUCTION

"Climate change is a defining challenge of our times. Its impact and implications will be global, far-reaching and largely irreversible. Climate change is already increasing the risk of exposure to hunger, malnutrition and food insecurity among the poorest and most vulnerable people. Natural disasters are becoming more frequent and intense, land and water are becoming more scarce and difficult to access, and increases in agricultural productivity are becoming more difficult to achieve."

(*Parry et al*. 2009)

1.1 Background

By 2050, the number of people at risk of hunger as a result of climate change is expected to increase by 10% to 20% more than would be expected without climate change and the number of malnourished children is expected to increase by approximately 24 million – 21% more than without climate change. Sub-Saharan Africa is likely to be the worst affected region. There is growing consensus amongst the international humanitarian community that adaptation measures are urgently needed to help vulnerable people cope with the changing environments in which they are living. This requires adapting global and local food production methods through investments, technical capacity transfers and technological innovations, while also making existing agricultural production systems more resilient, sustainable and equitable (Parry *et al.*, 2009).

Evidence from global climate models developed so far suggests that the agricultural sector in the Southern Africa region is highly sensitive to future climate shifts and increased climate variability (Gbetibouo and Hassan, 2004). The availability of water is a major limiting factor for agricultural production in South Africa. The country experiences a high risk climatic environment, with a highly variable and spatially uneven rainfall distribution, as well as climate-related extremes. Any change in rainfall and temperature attributes could have far-reaching implications for agricultural production, and hence the vulnerability of farming systems.

In some African countries there is limited research on climate change and related impacts on livelihood and the natural resources. Responding to climate change impacts requires practical and resilient technological, social and economic adaptation strategies and mitigation mechanisms. These can be developed through systematic research on climate change and associated impacts (Environmental Alert, 2010; Louw *et al*., 2012).

There is much that is unknown about the socioeconomic implications of climate change and how best to design policy to promote adaptation and reduce household vulnerability. Social scientists need to step up to this agenda. Heltberg *et al*. (2008) propose four distinct pillars for the social science research agenda on adaptation: (1) monitoring change; (2) predicting the consequences; (3) assessing policy alternatives; and (4) institutional arrangements and sharing the costs internationally.

It is critical to determine the possible impacts and consequences of projected future climates on the financial vulnerability of different farming systems and to evaluate suggested adaptation strategies. The proposed methodology integrates a number of models viz. empirically downscaled General Circulation Models (GCMs), hydrological, crop yield and quality models, Dynamic Linear Programming (DLP) and Financial Vulnerability Assessment models to accurately assess the impact of projected future climates on the financial vulnerability of different farming systems.

1.2 Problem statement

Farmers have developed various strategies to cope with the current climate variability experienced in South Africa. These strategies, however, may not be sufficient to cope with projected future climatic changes which could potentially increase the financial vulnerability of farming systems significantly. The identification of new adaptation strategies and in some instances the re-thinking of existing strategies to reduce financial vulnerability is of paramount importance for future sustainability of the agricultural sector in South Africa.

There are currently very few "proofs of concept" i.e. examples of agricultural decision makers that have successfully drawn on climate change projection data to take decisions that have improved agricultural productivity or human well-being. This is a function of the temporal and spatial models at which climate data are provided as well as the way in which they are reported, perceived in terms of the reliability of the data, questions of their relevance to agriculture, and difficulty in accessing and understanding the data (Ziervogel *et al*., 2008).

Because of the complexity of South Africa's physiography, climate and socio-economic milieu, detailed local scale analyses are needed to assess potential impacts (Schulze, 2011). In order to address this "disconnectedness" between climate science and African agriculture, the capacity capable to link existing climate data and agricultural decision making needs to be created. This is as much an institutional challenge as it is a technical and human resource challenge. The nature of climate change adaptation demands that efforts to support African agriculture in the face of climate change incorporate a multi-disciplinary set of stakeholders including climate science experts, agricultural practitioners and technicians, local communities/civil society, donors and policy makers (Ziervogel *et al.*, 2008).

1.3 Objectives of the study

The primary objective of this research is to develop an integrated analytical model to investigate the financial vulnerability of farming systems to projected climate change scenarios.

In order to achieve the primary objective the following secondary objectives will be addressed:

- Develop appropriate whole-farm DLP models, based on selected case study farming systems.
- Develop a modelling tool to quantify the impact of climate change on crop yield and quality for crops for which APSIM[1] crop models do not exist.
- Develop interphases to link the DLP model with modelling results from the hydrological model and crop yield and quality models based on empirically downscaled GCMs.
- Evaluate the financial vulnerability of the selected case studies to projected future climates.
- Determine and evaluate adaptation strategies to offset projected climate change impact.

In order to determine the financial vulnerability of farming systems to climate change, research is needed to link projected climates on farm level to crop yield and quality, irrigation water availability and crop irrigation requirements.

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[1] Agricultural Production Systems sIMulator

1.4 Hypotheses

The following research hypothesis will guide this study:

- Farmers may be financially vulnerable to future climatic change conditions.
- Adaptation strategies may decrease financial vulnerability towards potential climate change.

1.5 The study area

The research covers four selected case study areas. These case study areas are based on typical farming systems in the following districts:

- Vredendal, Western Cape Province (LORWUA[2]): Irrigation - winter rainfall region.
- Moorreesburg, Western Cape Province: Dryland - winter rainfall region.
- Hoedspruit, Limpopo Province (Blyde River WUA[3]): Irrigation - summer rainfall region.
- Carolina, Mpumalanga Province: Dryland - summer rainfall region.

The selection of the case study areas can be motivated as follows:

Vredendal, Western Cape Province (LORWUA)

- It is a water stressed region (semiarid) with relatively low assurance of water supply.
- The contribution of long-term crops to total area irrigated is relatively high (89%) - main crops are wine grapes, raisins and table grapes.
- It is located in a winter rainfall region.

Moorreesburg, Western Cape Province

- It is a dryland rainfed production area.
- Dominant farming activities include small grain, canola, pastures and small livestock production (mainly mutton and wool).
- It is located in a winter rainfall region.

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[2] Lower Olifantsriver Water Users Association

[3] Blyde River Water Users Association

Hoedspruit, Limpopo Province (Blyde River WUA)

- The main irrigation source (the Blydepoort Dam) has a high current assurance of supply.
- The contribution of long-term crops to total area irrigated is relatively high (88%) - main crops are citrus and mangoes.
- It is located in a summer rainfall region.

Carolina, Mpumalanga Province

- It is a dryland rainfed production area.
- Maize, soybeans, sugar beans, mutton and beef production are the main enterprises.
- It is located in a summer rainfall region.

These four selected case study areas are largely representative of dryland and irrigation farming for both summer and winter rainfall regions in South Africa. Even so, the case studies are very case-specific and by no means imply that the results will be the same for other areas and/or farms. However, the methodology which was developed can be applied to any other agricultural production region in South Africa (and in African countries where climate and hydrological models are available).

1.6 Research method

A case study methodology was applied instead of considering representative farms for the selected study areas. The benefit of considering specific farms on a case study level is that a much more detailed analysis can be performed. The participating case study farmers were selected in conjunction with local role-players.

The case study was modelled in two phases:

- An Excel spread sheet was used to construct the base case (farming system with present climate conditions).
- In the second phase, a DLP model was constructed for each case study and a base analysis was done (farming system with present climate conditions). The results were then compared with the Excel model in order to validate the DLP models.

The technical, production and financial input data were validated during expert group discussions with the producers and various experts from different institutions and agribusinesses. The discussions were held to ensure accuracy of the data and also that the data is representative of the area. At the same discussions the critical climate thresholds for crops and possible climate change impact on production and yields were debated and validated (see Appendix A for attendance registers).

In recognising the context of the farmers' multi-stressor environment it is important to uncover strategies for dealing with a variety of stressors by using different angles and questions. During the expert group discussions the following questions were aimed at the role-players' perspectives on climate change and their response to stressors:

- How does the weather affect your farming decisions?
- Does the general weather vary from year to year? If "yes", how?
- Do these variations in weather from year to year impact your farming activities? If "yes", how?
- Has the weather pattern somehow changed over the years you have been farming? If "yes", how has it changed?
- Which climatic thresholds do you face in your farming system?
    - How has this affected your farming practices?
    - Have you found any ways to deal with the extreme events above?
- Have you changed practices/strategies on the farm since you started farming? If "yes", how, and to what were these changes a response?

The most valuable of the above questions is the one in respect of climatic thresholds. These critical climate thresholds for crops would be applied in the newly developed Crop Critical Climate Thresholds (CCCT) modelling technique in order to quantify the impact of projected future climates on crop yield and quality.

In order to analyse the financial vulnerability of the selected case studies to climate change, an integrated climate change model was developed. The modelling framework consists of four modules. These are:

- Climate change impact modelling:
    - Modelling of physical climate data (daily minimum and maximum temperatures and daily rainfall from different downscaled GCMs) that impact on crop yield and quality through APSIM and CCCT modelling.

    - Hydrological modelling (ACRU[4] model) - impact of climate change on the availability of irrigation water (for the Blyde River WUA).
    - Changing crop irrigation requirements (as a result of climate change) through SAPWAT3[5] model.
- DLP model.
- Modelling interphases.
- Financial Vulnerability Assessment model.

Adaptation strategies along with their cost/benefit implications were incorporated in the model to evaluate their suitability and ability to overcome the potential negative financial impacts as a result of changing climates.

1.7 Contribution of the research

This research will contribute towards the development of an integrated analytical framework to investigate the financial vulnerability of agricultural producers on farm level in the face of predicted climate changes. The study contributes towards improved decision making in the planning and management of climate risk for agriculture and water resources management with reference to the case study areas in South Africa, and for a wider application in other regions with similar climate characteristics.

Different rainfall areas (summer and winter), as well as rainfed versus irrigated agricultural production regions, were considered in order to analyse the expected financial vulnerability of farming systems due to climate change along with the different adaptation strategies applicable to the different areas.

This research differs from previous research (see Section 2.9) in a number of ways. These are:

- The research integrates several specialist fields into one optimisation model, viz. empirically downscaled climate models, ACRU hydrology model, APSIM crop model, the newly developed CCCT modelling technique, DLP model and financial assessment model.
- The CCCT modelling technique, which was developed in this study, creates the link to quantify and integrate expert group discussion results into the integrated climate change model.

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[4] Agricultural Catchments Research Unit model

[5] South African Plant WATer model

- The CCCT model quantifies the impact of climate change on crops for both yield and quality. It differs from other crop modelling techniques, e.g. APSIM, that only determines the impact of climate change on yield.
- The research focuses on the financial vulnerability of farming systems, thereby implicating not only the effect of climate change on agricultural production, but also the long term sustainability of different farming systems in different regions.
- The impact of climate change on the availability of irrigation water under different climate change scenarios is discounted in the modelling through the ACRU hydrological model and the link to farm level. Although Louw *et al* (2012) applied the same methodology it was on a regional level and not at micro/farm level.
- The impact of climate change on crop irrigation needs is discounted in the modelling, using the SAPWAT3 program and point-scale current and future climate data.

1.8 Data used

In order to construct a mathematical programming model which accurately represents the impact of climate change on the financial vulnerability of the selected case studies, both primary and secondary data are required. These data requirements are:

- Primary data of selected case study farms.
- Crop enterprise budgets data.
- Point-scale daily climate data (temperature and rainfall) for current and future projected climates.
- Hydrological data to determine availability of irrigation water (current and future) and crop irrigation requirements (current and future).
- APSIM crop modelling data (current and future).
- CCCT model data for crops where no crop models exist.
- Possible adaptation strategies and alternative crops.

Farm surveys were conducted in order to gather primary information. Various role-players contributed to identify representative farming systems and make available crop enterprise budgets and other data required for the study.

The Climate Systems Analysis Group (CSAG) from the University of Cape Town (UCT) provided the point-scale daily climate data, which formed the basis of climate change projections in this study. The University of KwaZulu-Natal (UKZN) provided the hydrological data from which available irrigation water and crop irrigation needs were derived through application of the ACRU and SAPWAT3 models. The APSIM crop modelling was conducted by CSAG.

Various experts from different fields contributed to several workshops that were held in order to validate the data used in the research. They also contributed to the methodologies, identification of alternatives and adaptation strategies and the determination of crop critical climate thresholds.

1.9 Chapter outline

Chapter 1 describes the background, problem statement and objective of the study. It demarcates the study area, defines the hypothesis that will guide the study, discusses the research method as well as the contribution of the research and the data used.

Chapter 2 focuses on Literature review, including the definitions of climate change, a brief history of climate change research, impacts of climate change and climate change projections for the study areas. Vulnerability assessment and adaptation to climate change are discussed, followed by an overview of relevant local and international research.

The description of case study farms and norms in **Chapter 3** includes discussions on climate, soil characteristics, water availability, adapted crops and livestock, cultivation practices, crop irrigation requirements, crop enterprise budgets and adaptation strategies.

Chapter 4 is a layman's description of the integrated climate change model which consists of four modules, viz. climate change impact modelling, whole-farm dynamic linear programming, modelling interphases and financial vulnerability assessment.

The mathematical specification of the DLP and Financial Vulnerability Assessment model follow in **Chapter 5**.

The integrated modelling results for each case study are discussed in **Chapter 6**. Discussions include projected climate change impacts on: quality and yield of crops, crop irrigation requirements and availability of irrigation water. Financial vulnerability assessment results and the evaluation of adaptation strategies are also described.

Chapter 7 comprises the summary and conclusions for this study and recommends topics for further research.

CHAPTER 2 : LITERATURE REVIEW

"Climate change represents one of the greatest environmental, social, and economic threats facing the planet today. In developing countries, climate change will have a significant impact on the livelihoods and living conditions of the poor. It is a particular threat to the attainment of the Millennium Development Goals (MDGs) and progress in sustainable development in Sub-Saharan Africa. Increasing temperatures and shifting rain patterns across Africa reduce access to food and create effects that impact regions, farming systems, households, and individuals in varying ways. Additional global changes, including changed trade patterns and energy policies, have the potential to exacerbate the negative effects of climate change on some of these systems and groups. Thus, analyses of the biophysical and socioeconomic factors that determine exposure, adaptation, and the capacity to adapt to climate change are urgently needed so that policymakers can make more informed decisions."

(Nzuma et al., 2010)

2.1 Introduction

Human activities such as the burning of fossil fuels, changes in land use and deforestation release greenhouse gases into the atmosphere. The main anthropogenic greenhouse gases are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The increasing concentration of greenhouse gases in the atmosphere disturbs the earth's natural temperature control mechanisms resulting in the warming of the earth's atmosphere – a phenomenon commonly referred to as "global warming". This warming in turn disrupts the Earth's climate system resulting in climate change. The effects of climate change include changes in wind and precipitation patterns, as well as increases in the frequency of climatic extremes including heat waves and heavy precipitation. The changes set in motion by past human activities are so significant that climate change is already a reality and it will continue to cause impacts in the future (CSIR-NRE, 2009).

The accelerating pace of climate change, combined with global population and income growth, threaten food security in many places of the Earth. Agriculture is extremely vulnerable to climate change. Higher temperatures can reduce yields of desirable crops while encouraging weed and pest proliferation. Changes in precipitation patterns increase the likelihood of short-term crop failures and long-term production declines. Although there will be yield gains in some crops in some regions of the world, the overall impacts of climate change on agriculture are expected to be negative, threatening global food security. Populations in the developing world, which are already vulnerable and food insecure, are likely to be the most seriously affected (Nelson *et al*., 2009).

2.2 Defining climate change

The Intergovernmental Panel for Climate Change (IPCC), a scientific intergovernmental body set up by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) to provide decision-makers and others interested in climate change with an objective source of information about climate change, defines climate change as:

'…any change in climate over time, whether due to natural variability or as a result of human activity' (IPCC, 2007).

The United Nations Framework Convention for Climate Change (UNFCCC), an international environmental treaty, defines climate change as:

'…change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable periods' (UNFCCC, 1994).

Climate change is also defined as any long-term and significant change in the expected patterns of a specific region's average weather for an appropriately significant period of time. It is the result of several factors, including the earth's dynamic processes, external forces and more recently, human activity. External factors that shape climate include such processes as variations in solar radiation, deviations in the earth's orbit and variations in the level of greenhouse gas concentrations. Evidence of climatic change taken from a variety of sources can, in turn, be used to reconstruct past climates. Most climate evidence is inferred from changes in key climate indicators, including vegetation, ice cores, dendrochronology, sea-level change, and glacial geology (Nzuma *et al*., 2010).

2.3 Brief history of climate change research

"To a patient scientist, the unfolding greenhouse mystery is far more exciting than the plot of the best mystery novel. But it is slow reading, with new clues sometimes not appearing for several years. Impatience increases when one realizes that it is not the

fate of some fictional character, but of our planet and species, which hangs in the balance as the great carbon mystery unfolds at a seemingly glacial pace."

(Schindler, 1999)

The history of the centuries-long effort to document and understand climate change is often complex, marked by successes and failures, and has followed a very uneven pace. Testing scientific findings and openly discussing the test results have been the key to the remarkable progress that is now accelerating in all domains, in spite of inherent limitations to predictive capacity (Le Treut *et al*., 2007).

Arrhenius (1896) was the first scientist to quantify the contribution of carbon dioxide to the greenhouse effect and to hypothesise that increases in the atmospheric concentration of carbon dioxide would contribute to long-term variations in climate. Callender (1937) published an article “The artificial production of carbon dioxide and its influence on temperature”. In his article it is stated that through fuel combustion, man had added about 150 000 million tons of carbon dioxide to the air during the half century preceding his paper. He estimated, from the best available data at the time, that approximately three quarters of this had remained in the atmosphere. The temperature observations at zoo meteorological stations were used to show that world temperatures had actually increased at an average rate of 0.005 °C per year during the preceding half century.

In the early 1970s, the rise of environmentalism started to raise public doubts about the benefits of human activity for the planet. Curiosity about climate turned into anxious concern (Weart, 2008). Alongside the greenhouse effect, some scientists pointed out that human activity was emitting dust and smog particles into the atmosphere, where they could block sunlight and cool the earth. Broecker (1975) popularized the term “global warming” and explained how ocean currents affect abrupt climate change.

Greatly improved computer models began to suggest how abrupt temperature jumps could happen, for example through a change in the circulation of ocean currents. Experts predicted droughts, storms, rising sea levels, and other disasters (Weart, 2008). An unexpected finding was that the level of certain other gases was rising, which would exacerbate global warming. Some of these gases also degraded the atmosphere’s protective ozone layer, and the news inflamed public worries about the fragility of the atmosphere (Weart, 2008). Moreover, by the late 1970s global temperatures had evidently begun to rise again. International panels of scientists began to warn that the world should take active steps to cut greenhouse gas emissions. The scientists' claims about climate change first caught wide public attention in the summer of 1988, the hottest on record until then (most years since then have been hotter). But the many scientific uncertainties, and the sheer complexity of climate, elicited vehement debate over what actions, if any, governments should take (Weart, 2008). The first Southern African Climate Change conference was also held in 1988.

Scientists intensified their research, organizing programs on an international scale. The world's governments created the IPCC to give them the most reliable possible advice, as negotiated among thousands of climate experts and officials. By 2001, the IPCC had managed to reach a consensus, phrased so cautiously that scarcely any expert dissented. They announced that, although the climate system was so complex that scientists would never reach complete certainty, it was much more likely than not that our civilization faced severe global warming.

The scientists who had predicted back in the 1980s that by the end of the 20th century the world would be warmer were now demonstrably correct, and the press and other influential people began to trust them. Many of the public did continue to doubt, supported by a small minority of scientists who clung to earlier views from ideological conviction or sheer stubbornness or vested interests in the oil industry. But an ever increasing number of individuals, government agencies, and corporate entities realized that something had to be done to mitigate the possible effects of climate change (Weart, 2008).

2.4 Impacts of climate change and global warming

Climate change is a complex biophysical process. It is not possible to predict precise future climate conditions, but the scientific consensus is that global land and sea temperatures are warming under the influence of greenhouse gases, and will continue to warm regardless of human intervention for at least the next two decades (IPCC, 2007).

The world's climate experts almost all agree that the impacts listed below are more likely than not to happen (Weart, 2008). For some items, the probabilities range up to almost certain. Consequences will vary by region; in some places the effect will be minimal at first, except perhaps indirectly, while other places will be affected more severely.

The following are the likely consequences of warming by two or three degrees Celsius:

- Most places will continue to become warmer, especially at night and during winter. The temperature change will benefit some regions while harming others - for example, patterns of tourism will shift. The warmer winters will improve health and agriculture in some areas, but globally, mortality is likely to rise and food supplies will be under pressure as a result of more frequent and extreme summer heat waves and other effects. Regions not directly harmed will suffer indirectly from higher food prices and an influx of refugees from afflicted regions.
- Sea levels will continue to rise for many centuries.
- Weather patterns will continue to change, resulting in an intensified water cycle with stronger floods and droughts. Most regions now subject to droughts will probably get drier (because of increased temperatures as well as less precipitation), and most wet regions will get wetter. Extreme weather events will become more frequent and worse. In particular, storms with more intense rainfall are likely to trigger extreme floods. Some places will get more snowstorms, but most mountain glaciers and winter snow packs will shrink, jeopardizing important water supply systems and winter tourism. Each of these has already begun to happen in some regions of the world.
- Ecosystems will be stressed, although some agricultural and forestry systems will benefit, at least in the early decades of warming. Large numbers of valuable species, especially in the Arctic, mountain areas, and tropical seas, will need to shift their ranges. Many that cannot will face extinction. A variety of pests and tropical diseases are expected to spread to warmed regions. These problems have already been observed in numerous places.
- Increased carbon dioxide levels will affect biological systems independent of climate change. Some crops will benefit from CO_2 fertilization, as will some invasive weeds (the balance of benefit vs. harm is uncertain). The oceans will continue to become markedly more acidic, gravely endangering coral reefs, and probably harming fisheries and other marine life.
- There will be significant unforeseen impacts. Most of these will probably be harmful, since human and natural systems are well adapted to the present climate.

Approximately one billion people worldwide are currently already suffering from food insecurity, i.e. they do not at all times have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life (FAO, 2009a). The underlying reasons for food insecurity are embedded across all spatial scales, from global, regional and national levels, to community, household and individual levels. In dealing with the problem of hunger, underlying structural causes of poverty and food insecurity must be addressed through development of the agricultural sector and the socio-economic improvement of poor rural communities (World Bank, 2007; IAASTD, 2009; NEPAD, 2007). Climate change is already playing, and will increasingly play, a pivotal role in food security, through impacts on production, distribution and food prices (Easterling *et al.*, 2007; FAO, 2007b). How and where this will play itself out is still uncertain, but it can be expected that as an additional stressor, the greatest impact will be on those who are already food-insecure, subjected to existing high levels of climate variability and stress, and unable to cope with or adapt to the added pressure.

2.4.1 Climate change impacts on agriculture

Consensus has been reached that agriculture, as a sector within the world economy, would be extremely vulnerable to climatic changes (Kaiser and Drennen, 1993; Darwin *et al*., 1995; IISD, 1997; IPCC, 2001; Mukheibir and Sparks, 2003; IFPRI, 2009).

The croplands, pastures and forests that occupy 60% of the Earth's surface are progressively being exposed to threats from increased climatic variability and, in the longer run, to climate change. Abnormal changes in air temperature and rainfall and increases in frequency and intensity of drought and flood events have long-term implications for the viability of these agricultural ecosystems. As climatic patterns change, so also do the spatial distribution of agro-ecological zones, habitats, distribution patterns of plant diseases and pests as well as fish populations and ocean circulation patterns which can have significant impacts on agriculture and food production (FAO inter-departmental working group on climate change, 2007; Schulze, 2011).

Increased intensity and frequency of storms, drought and flooding, altered hydrological cycles and precipitation variance have implications for future food availability. The potential impacts on rainfed agriculture vis-à-vis irrigated systems are still not well understood. The developing world already contends with chronic food problems. Climate change presents yet another significant challenge to be met. While overall food production may not be threatened, those least able to cope will likely bear additional adverse impacts (WRI, 2005). The estimate for Africa is that 25% to 42% of species habitats could be lost, affecting both food and non-food crops. Habitat change is already underway in some areas, leading to species range shifts, changes in plant diversity which includes indigenous foods and plant-based medicines (McClean *et al.*, 2005). In developing countries, 11% of arable land could be affected by climate change, including a reduction of cereal production in up to 65 countries, about 16% of agricultural GDP (FAO Committee on Food Security, Report of 31st Session, 2005). Changes in ocean circulation patterns, such as the Atlantic conveyor belt, may affect fish populations and the aquatic food web as species seek conditions suitable for their lifecycle. Higher ocean acidity (resulting from carbon dioxide absorption from the atmosphere) could affect the marine environment through deficiency in calcium carbonate, affecting shelled organisms and coral reefs.

Climate change impacts can broadly be divided into two groups (FAO inter-departmental working group on climate change, 2007):

Biophysical impacts

- Physiological effects on crops, pastures, forests and livestock (quantity and quality).
- Changes in land, soil and water resources (quantity and quality).
- Increased weed and pest challenges.
- Shifts in spatial and temporal distribution of impacts.
- Rise in sea level.
- Changes in ocean salinity.
- Rise in sea temperature causing fish to inhabit different ranges.

Socio-economic impacts

- Decline in yields and production.
- Reduced marginal GDP from agriculture.
- Fluctuations in world market prices.
- Changes in geographical distribution of trade regimes.
- Increased number of people at risk of hunger and food insecurity.
- Migration and civil unrest.

The most vulnerable countries are in the less developed regions such as South Asia, South-East Asia, North Africa and Sub-Saharan Africa. In these regions one of the most exposed sectors is agriculture, and the impact on crop productivity is by far the most important source of damages (Bosello *et al*., 2012).

2.4.2 Climate change and African agriculture

The IPCC's Fourth Assessment Report Summary for Africa (2007) describes a trend of warming in Africa at a rate faster than the global average, and increasing aridity. Climate change exerts multiple stresses on the biophysical as well as the social and institutional environments that underpin agricultural production. Some of the induced changes are expected to be abrupt, while others involve gradual shifts in temperature, vegetation cover and species distributions. Climate change is expected to, and in parts of Africa has already begun to, alter the dynamics of drought, rainfall and heat waves, and trigger secondary stresses such as the spread of pests, increased competition for resources, the collapse of financial institutions, and attendant biodiversity losses.

In regions of East and Southern Africa, this vulnerability is further heightened by the large number of households that depend on the already marginalized natural resource base for their livelihoods. Agricultural production and the biophysical, political and social systems that determine food security in Africa are expected to be placed under considerable additional stress by climate change (Basher and Brecino, 2005; Meadows, 2006; FAO, 2007).

Predicting the impact of climate change on the complex biophysical and socio-economic systems that constitute agricultural sectors is difficult. In many parts of Africa it seems that warmer climates and changes in precipitation will destabilise agricultural production. This is expected to undermine the systems that provide food security (Gregory *et al*., 2005). Whilst farmers in some regions may benefit from longer growing seasons and higher yields, the general consequences for Africa are expected to be adverse and particularly adverse for the poor and the marginalized who do not have the means to withstand shocks and changes.

Christensen *et al*. (2007) summarises the key attributes of the IPCC's Fourth Assessment Report for Africa as follows:

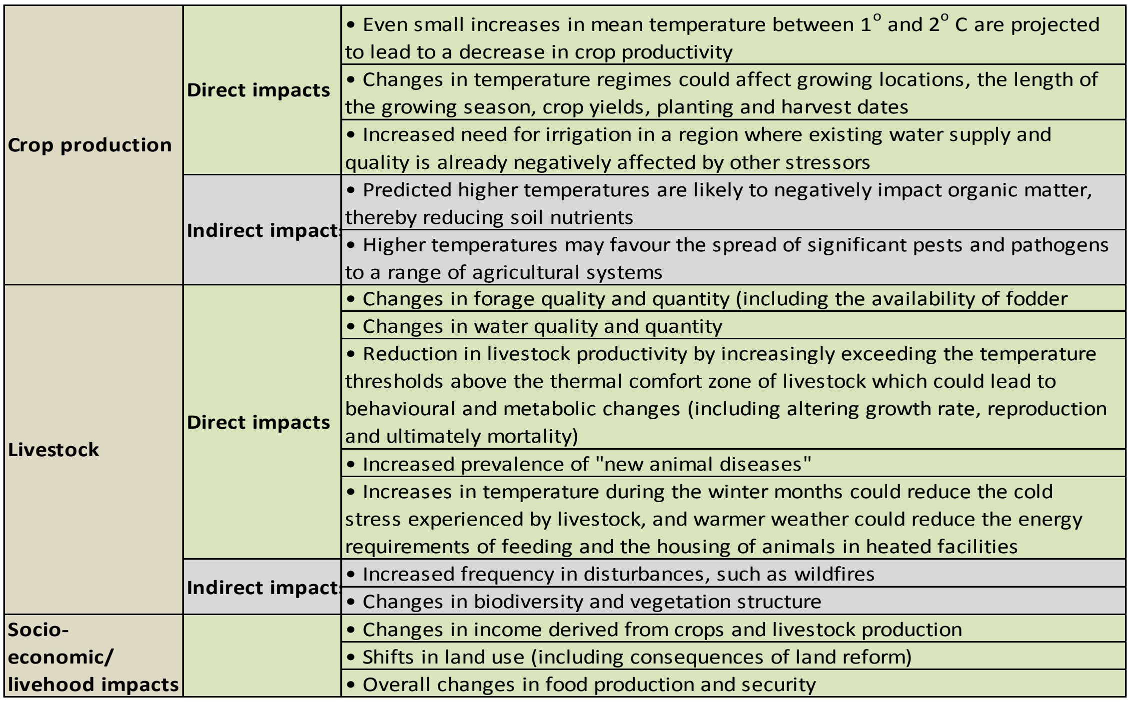
- Warming is very likely to be larger than the global annual mean warming throughout the continent and during all seasons, with drier subtropical regions warming more than the moister tropics.
- Annual rainfall is likely to decrease in much of Mediterranean Africa and the northern Sahara, with a greater likelihood of decreasing rainfall as the Mediterranean coast is approached.
- Rainfall in southern Africa is likely to decrease in much of the winter rainfall region and western margins.
- Mean annual rainfall is likely to increase in East Africa.
- It is unclear how rainfall in the Sahel, the Guinean Coast and the southern Sahara will evolve.

2.4.3 Climate change in Southern Africa

Climate change is expected to exacerbate existing climate-related problems in Southern Africa where 38% of the population is rural (UN, 2014) and dependent on agriculture for basic livelihood. Climate change is already having an adverse impact on food security in Southern Africa, notably in the Least Developed Countries (LDCs) such as Lesotho that have a large rural population dependent on rainfed agriculture. Projected changes in future temperature and rainfall patterns for 2030 in Southern Africa indicate a significant decline in the production of major staple crops such as maize, wheat and sorghum (Dejene *et al*., 2011).

A comprehensive analysis on impacts of climate change (Lobell *et al.,* 2008) indicates that Southern Africa is likely to suffer negative impacts on several crops (e.g. maize and sorghum) that are very important to large food-insecure populations. Davis (2011) summarizes the likely impact on crop and livestock production for Southern Africa in Table 2.1.

Table 2.1: Impacts of projected climate change on crop and livestock production for Southern Africa



Crop production	**Direct impacts**	• Even small increases in mean temperature between 1° and 2° C are projected to lead to a decrease in crop productivity
		• Changes in temperature regimes could affect growing locations, the length of the growing season, crop yields, planting and harvest dates
		• Increased need for irrigation in a region where existing water supply and quality is already negatively affected by other stressors
	Indirect impact	• Predicted higher temperatures are likely to negatively impact organic matter, thereby reducing soil nutrients
		• Higher temperatures may favour the spread of significant pests and pathogens to a range of agricultural systems
Livestock	**Direct impacts**	• Changes in forage quality and quantity (including the availability of fodder
		• Changes in water quality and quantity
		• Reduction in livestock productivity by increasingly exceeding the temperature thresholds above the thermal comfort zone of livestock which could lead to behavioural and metabolic changes (including altering growth rate, reproduction and ultimately mortality)
		• Increased prevalence of "new animal diseases"
		• Increases in temperature during the winter months could reduce the cold stress experienced by livestock, and warmer weather could reduce the energy requirements of feeding and the housing of animals in heated facilities
	Indirect impact	• Increased frequency in disturbances, such as wildfires
		• Changes in biodiversity and vegetation structure
Socio-economic/ livehood impacts		• Changes in income derived from crops and livestock production
		• Shifts in land use (including consequences of land reform)
		• Overall changes in food production and security

Source: Davis (2011)

Climate change is expected to not only impact on crop and livestock production, but also alter the agriculturally related socio-economic environment and general livelihood of the region.

2.5 Climate change forecasting - South Africa

GCMs have been developed to project future climates based on different greenhouse gas scenarios and complex earth-atmosphere interactions. As such GCMs provide the means of making climate change projections. The development of climate projections for Africa is evolving rapidly (Ziervogel *et al.*, 2008). GCMs at the present point in time project climate parameters at a resolution of 250 km^2, while downscaled models provide projections at 50 km^2. Whilst GCMs can more accurately project changes in average global temperature, these projections are often of little use to decision makers working on regional or local scales (Ziervogel *et al.*, 2008).

Two approaches dominate the downscaling efforts, each based on a specific set of assumptions and methodologies: empirical and dynamical downscaling (also known as Regional Climate Models or RCMs). Figure 2.1 shows how these different types of climate modelling approaches fit together. These downscaled climate change models take values from GCMs and interpret them in relation to local climate dynamics (Tadross *et al*., 2005).

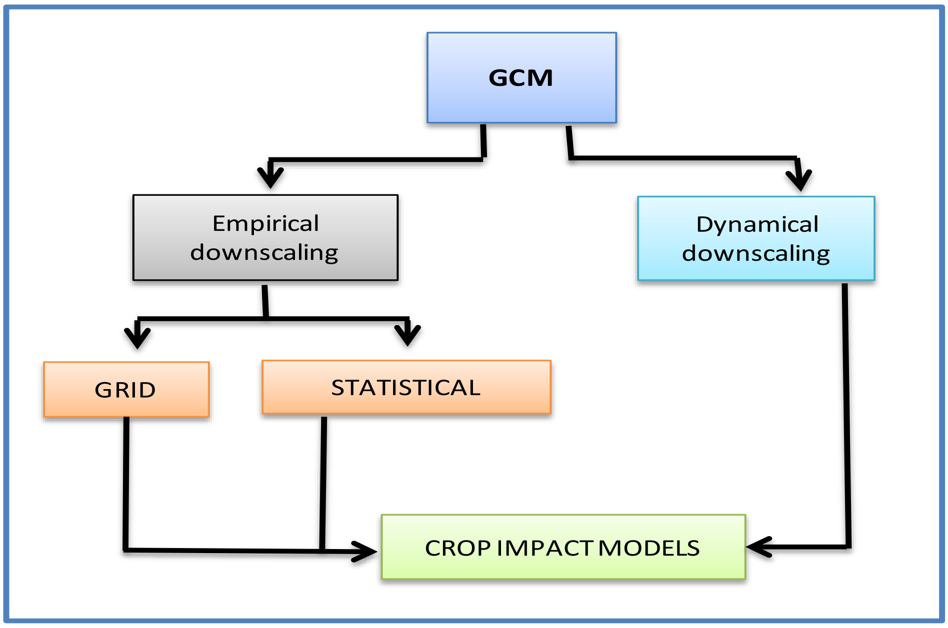


Figure 2.1: Overview of different types of climate models
Source: Ziervogel et al. (2008)

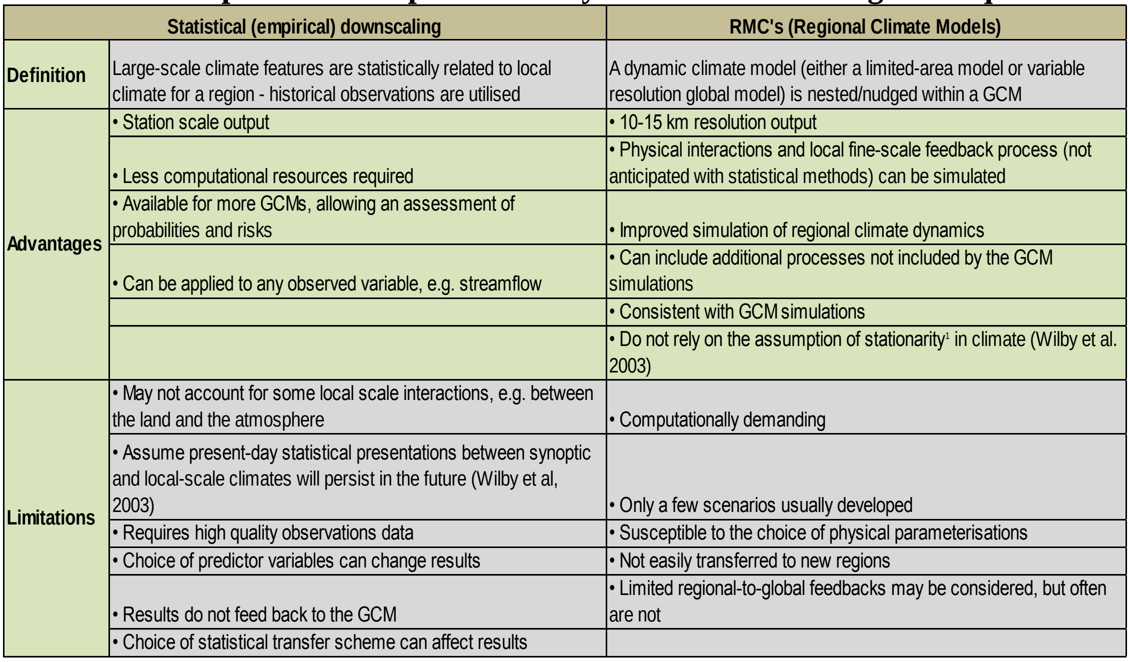
Empirical downscaling makes use of the quantitative relationships between the state of the larger scale climatic environment and local variations sourced from historical data. Coupling specific local baseline climate data with GCM output provides a valuable solution to overcoming the mismatch in scale between climate model projections and the unit under investigation. Empirical downscaling can be applied to a grid or to a particular meteorological station. The later application of empirical downscaling is more common and is referred to as statistical empirical downscaling.

CSAG operates the pre-eminent empirically downscaled model for Africa and provides meteorological station level responses to global climate forcings for a growing number of stations across the African continent. The data and technical skills intensity required for empirical downscaling have resulted in no other institutions in Africa currently producing such data. Existing adaptation studies and programs outside of South Africa have had limited awareness of the availability of such data (Ziervogel, *et al*. 2008).

Dynamical downscaling and RCMs make use of the boundary conditions (e.g. atmospheric parameters from a GCM such as surface pressure, wind, temperature and water) and principles of physics within an atmospheric circulation system to generate small scale (high resolution) datasets. Owing to its reliance on high resolution physical datasets, the approach is useful in the representation of extreme events. However, dynamical downscaling is a computationally and technically expensive method, a characteristic that has limited the number of institutions employing the approach (Ziervogel *et al.*, 2008). Since 2009, the Council for Scientific and Industrial Research (CSIR) [Climate Studies, Modelling and Environmental Health Research Group] uses the dynamical downscaling technique to produce regional climate models (Engelbrecht, 2013).

Table 2.2 displays the advantages and limitations of two downscaling techniques, namely empirical and dynamical downscaling.

Table 2.2: Comparison of empirical and dynamical downscaling techniques



	Statistical (empirical) downscaling	**RMC's (Regional Climate Models)**
Definition	Large-scale climate features are statistically related to local climate for a region - historical observations are utilised	A dynamic climate model (either a limited-area model or variable resolution global model) is nested/nudged within a GCM
Advantages	• Station scale output	• 10-15 km resolution output
	• Less computational resources required	• Physical interactions and local fine-scale feedback process (not anticipated with statistical methods) can be simulated
	• Available for more GCMs, allowing an assessment of probabilities and risks	• Improved simulation of regional climate dynamics
	• Can be applied to any observed variable, e.g. streamflow	• Can include additional processes not included by the GCM simulations
		• Consistent with GCM simulations
		• Do not rely on the assumption of stationarity[1] in climate (Wilby et al. 2003)
Limitations	• May not account for some local scale interactions, e.g. between the land and the atmosphere	• Computationally demanding
	• Assume present-day statistical presentations between synoptic and local-scale climates will persist in the future (Wilby et al, 2003)	• Only a few scenarios usually developed
	• Requires high quality observations data	• Susceptible to the choice of physical parameterisations
	• Choice of predictor variables can change results	• Not easily transferred to new regions
	• Results do not feed back to the GCM	• Limited regional-to-global feedbacks may be considered, but often are not
	• Choice of statistical transfer scheme can affect results	

Source: Davis (2011)

An important component of climate change science involves the description, understanding and representation of the inherent uncertainties in the modelling efforts. Uncertainty in climate change science is a function of the difficulties of modelling a complex and not entirely understood pair of inter-related systems (i.e. oceans and atmospheres), lack of complete knowledge on natural variability, an imperfect understanding of future greenhouse gas concentrations, and the likely impacts that surprises will bring to the climate system (Stainforth *et al.*, 2007). Whilst it is known that specific models are more "skilled" at predicting specific parameters in certain regions, without a comprehensive exploration of multiple model outputs, choosing a single model for a specific region is not advisable (IPCC, 2007). An analysis of results from an "ensemble" of models, rather than a single model, is a sound way of addressing the uncertainty inherent in making a decision which is influenced by the future evolution of the climate system.

For the purpose of this study, values derived from empirical downscaling (done by CSAG) were used as input data to the integrated model. It would be useful to undertake the same exercise using values derived from the dynamical downscaling technique and to compare the results. The focus of this study, however, was to develop the methodology and integrated model rather than to compare results from climate model outputs.

2.5.1 Climate change projections for South Africa based on the empirically downscaled technique

2.5.1.1 The climate change context

There is overwhelming evidence, contained in thousands of scientific papers and summarised in a series of seminal reports emanating from the IPCC, that anthropogenically induced greenhouse gas emissions, often expressed through increases in atmospheric CO_2 concentrations (Figure 2.2 bottom left), are increasing and accordingly global temperatures and sea level (Figure 2.2 bottom middle and right) are rising. These and other pieces of climate change evidence have been used by the International Geosphere-Biosphere Program (IGBP, 2009) in order to produce a composite climate change index, akin to composite stock exchange indices, and Figure 2.2 (top) shows the clear rise in this index since 1980 (Schulze, 2011).

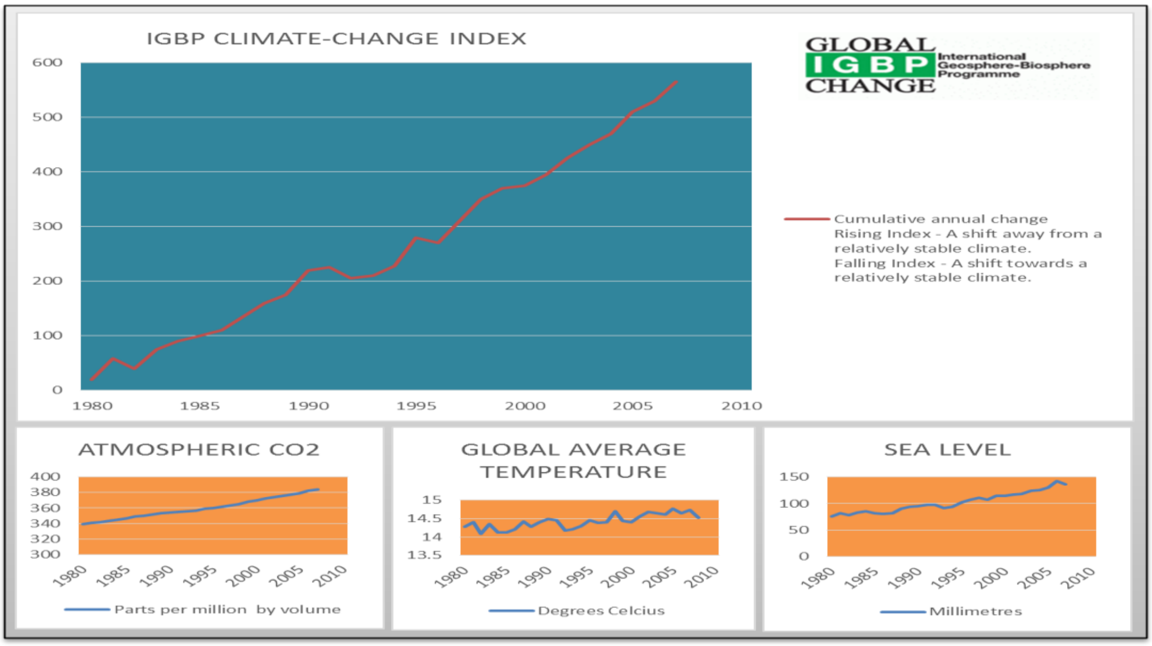


Figure 2.2: The IGBP's composite climate change index (top) and some of the indicators used in its derivation (bottom)
Source: After IGBP (2009)

With further projected changes in global climates into the future, changes in the South African agriculture sector will be inevitable, especially since the regional climate in South Africa is dependent on global climate, both presently and in the future (Schulze, 2012). No one knows exactly how the future global climate will develop and what the resultant consequences in South Africa will be in, for example, the agriculture sector. However, South Africa lies in one of the regions of the world that is most vulnerable to climate variability and change (IPCC, 2007).

Impacts from a changing climate can be considerable. Different regions of the country will likely be affected in many different ways. For this reason alone local scale analyses are needed to assess potential impacts (Andersson *et al.*, 2009). Changes in optimum growing areas and yields are anticipated, and with that many knock-on effects ranging from application of new crop varieties to increased pest infestations to issues of food security and international trade (Davis, 2011; Schulze, 2011).

2.5.1.2 Dispelling misconceptions on climate change impacts over South Africa

There are many misconceptions in the popular and even the official as well as scientific literature in South Africa with regard to projected changes in magnitude and direction of key climate change variables and the associated impacts of these. They have arisen either out of ignorance, and/or by citing from dated research results, and/or having pre-conceived ideas that climate change implies only “gloom and doom” on the one hand, or is a non-issue on the other, and/or taking isolated statements/cases/criticisms out of context and disregarding the overwhelming body of evidence on climate change, and/or having been “conditioned” by what turns out to be very broad generalizations contained in IPCC reports (Schulze, 2011).

2.5.1.3 GCMs – downscaling and databases

Output from GCMs is the most widely applied method of assessing impacts of climate change since GCMs, despite many uncertainties associated with them, are able to simulate the most important features of the global climate (Schulze, 2011).

However, because agricultural impacts occur at more local scales, outputs from the global scale GCMs have to be downscaled to an appropriate finer scale spatial resolution. The empirical downscaling of values to climate station level, used in this study, was undertaken by the UCT (CSAG).

Daily rainfall as well as maximum and minimum temperature values were the output from five accredited GCMs from the IPCC (2007), viz. CGCM3.1(T47), CNRM-CM3, ECHAM5/MPI-OM, GISS-ER and IPSL-CM4, in each case for two 20 year scenarios, viz. for-

- present climate, from 1971 - 1990, and
- intermediate future climate, from 2046 – 2065.

2.5.1.4 Projected changes to temperature and rainfall

The following paragraphs summarize projected temperature and rainfall changes into the intermediate future for South Africa, as per Schulze (2011), based on the empirical downscaling results of five GCMs by CSAG, UCT. The explanatory content of this section is cited for the purpose of providing the reader with essential background information.

2.5.1.4.1 Temperature

Temperature affects a wide range of processes in agriculture and is used as an index of the energy status of the environment. It is the one climatic variable for which there is a high degree of certainty that it will increase with global warming.

Annual temperatures

- Into the intermediate future (2046 – 2065) annual temperatures are projected to increase by 1.5 °C to 2.5 °C along the coast (illustrating the moderating influence of the oceans) to 3.0 °C to 3.5 °C in the far interior.
- By the end of the century an accelerating increase in temperatures becomes evident with projected increases between 3.0 °C to 5.0 °C along the coast and up to > 6.0 °C in the interior.
- Year-to-year variability of annual temperatures tends to increase in the northern half of the country and decrease in the south.

From assessments based on outputs from multiple GCMs, a number of points requires emphasizing in regard to projected temperature changes over South Africa, inter alia, that changes in patterns of critical seasonal temperatures differ from one another and from distributions of changes in annual temperatures (see Figure 2.3 to Figure 2.5) in which summer maxima are represented by January’s temperatures and winter minima by those of July.

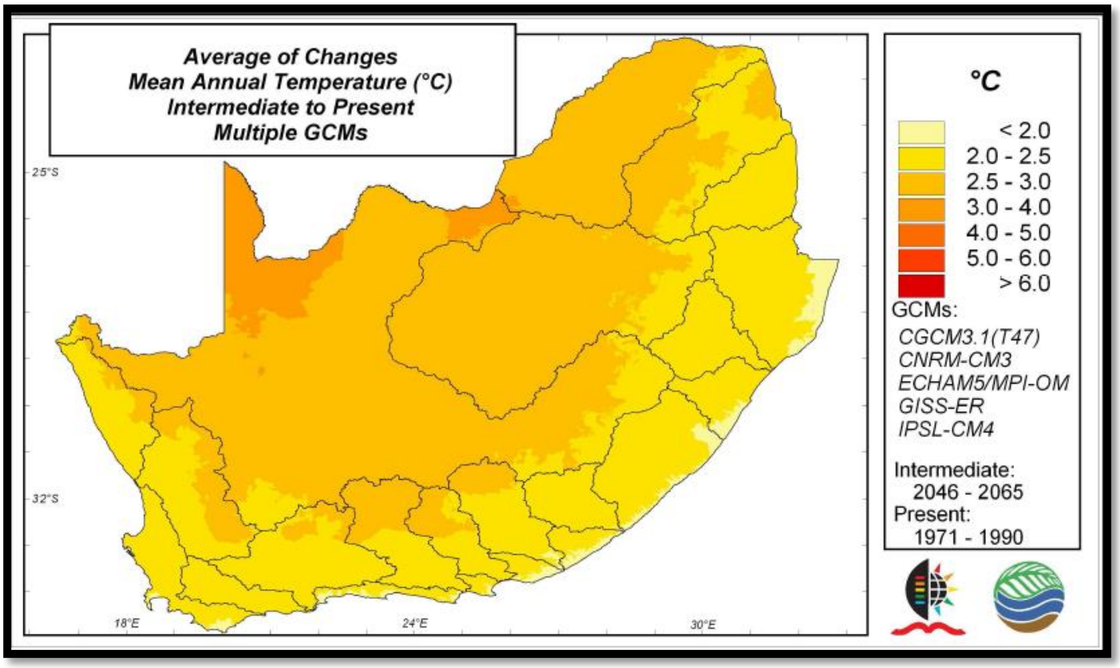


Figure 2.3: Averages of changes (°C) between the intermediate future and present climates in mean annual, derived from multiple GCMs
Source: Schulze (2011)

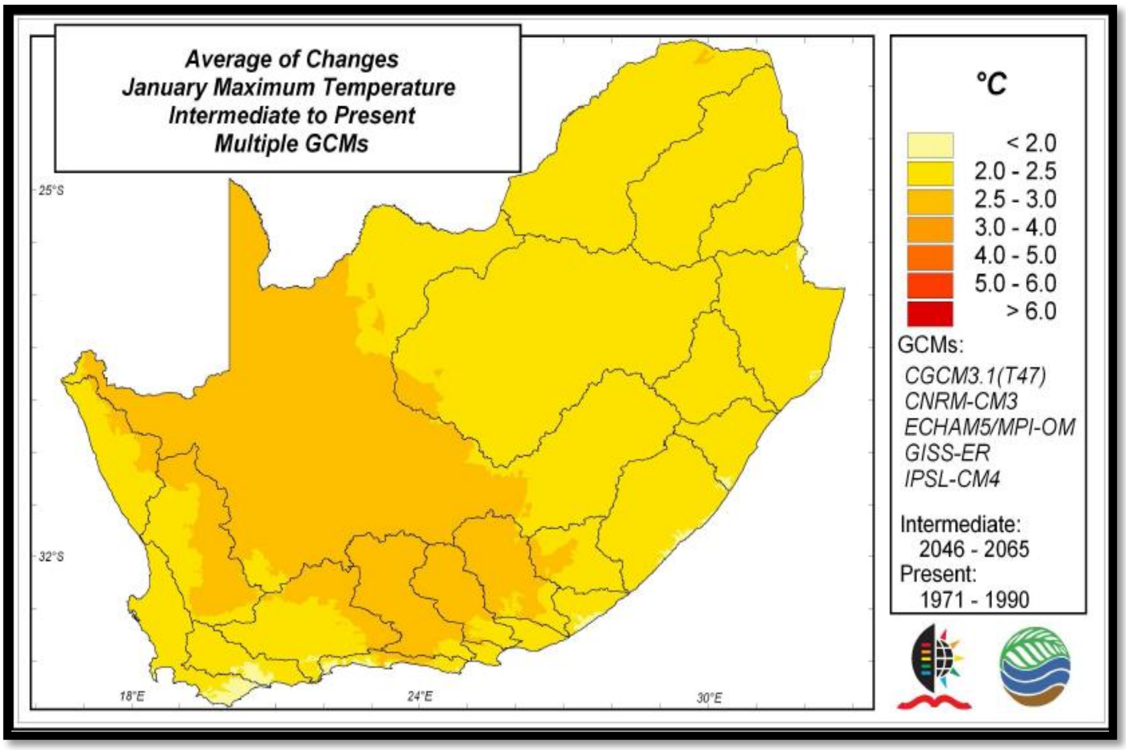


Figure 2.4: Averages of changes (°C) between the intermediate future and present climates in January maximum, derived from multiple GCMs
Source: Schulze (2011)

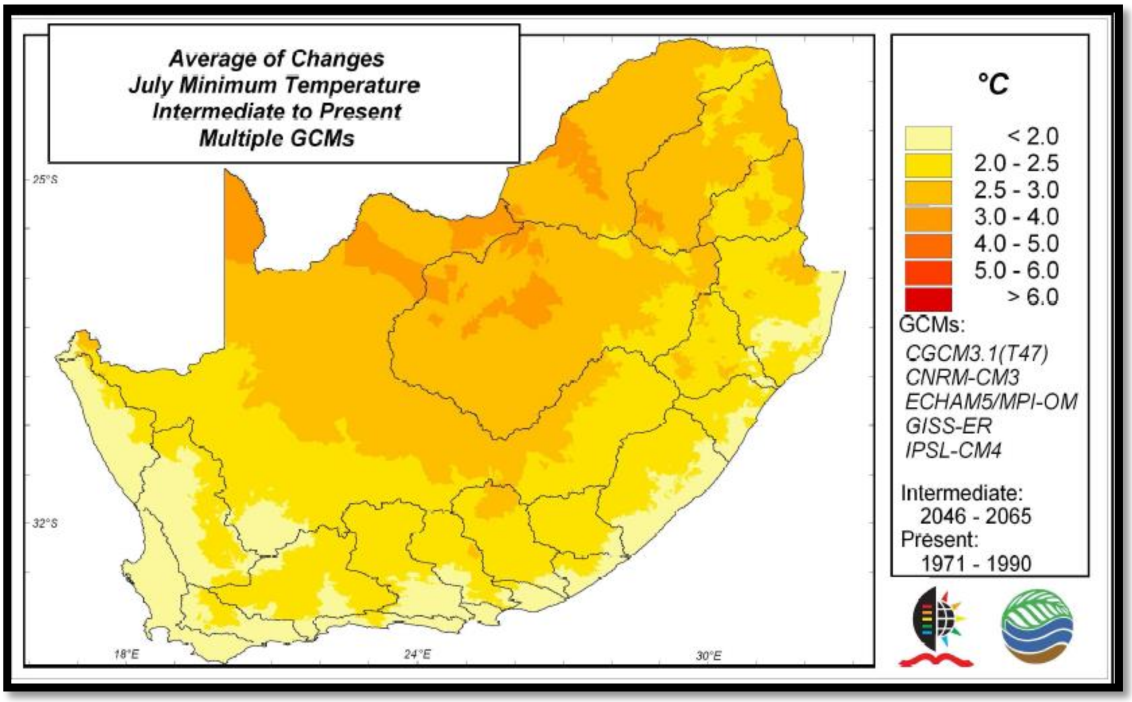


Figure 2.5: Averages of changes (°C) between the intermediate future and present climates in July minimum temperatures, derived from multiple GCMs
Source: Schulze (2011)

For the A2 emission scenarios, the rate of temperature increases by annual temperature changes in the range of 0.25 °C to 0.50 °C per decade into the intermediate future (Figure 2.6 below).

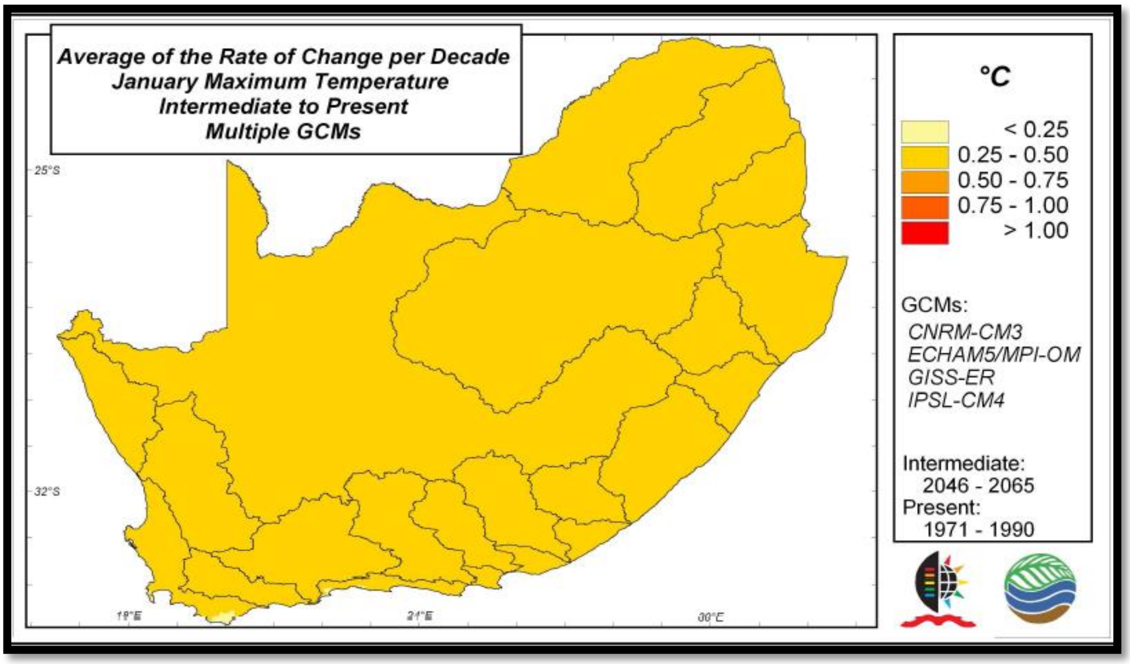


Figure 2.6: Averages of rates of change per decade of mean annual temperatures between the intermediate future and present, derived from multiple GCMs
Source: Schulze (2011)

Summer and winter temperatures

- Geographic patterns of changes in maximum temperatures in January (summer) and minimum temperatures in July (winter) vary in both the intermediate future and the more distant future.
- Again, projected temperature differences between the more distant future and the present are considerably higher than between the intermediate future and present.

Heat waves

- In regard to heat waves (i.e. occurrences with $T_{mxd} > 30$ °C on 3 or more consecutive days) and extreme heat waves (occurrences with $T_{mxd} \geq 35$ °C on 3 or more consecutive days), the median number of heat waves per annum from the five GCMs used in this study is projected to increase by anything from 30% to more than doubling from the present to both the intermediate and more distant futures.
- In the case of extreme heat waves, the median number from the five GCMs used is projected to more than double into the intermediate future, with the most affected areas being those that are already hot even today, viz. the eastern and northern borders of South Africa and the Northern Cape.
- All the GCMs used display increases in the numbers of heat waves in future. However, differences between the GCMs remain as to how many more heat waves there will be.

Cold spells

- While the numbers of cold spells (defined as ≥ three or more consecutive days with minimum temperatures < 2.5 °C) and severe cold spells (≥ three or more consecutive days with minima < 0 °C) are shown not to change along the coast of South Africa under future climatic conditions, in the more continental interior a reduction to < 70% of present cold spells is projected by the GCMs used.
- The overall patterns between the intermediate and more distant future ratios to the present are very similar.
- Much of the interior of South Africa displays a high consistency between GCMs of cold spell and severe cold spell reductions in future climates.

2.5.1.4.2 Rainfall

In agriculture, limitations in water availability are a restricting factor in plant development, with water being essential for the maintenance of physiological and chemical processes within the plant, acting as an energy exchanger and carrier of nutrient food supply in solution (Schulze, 2011). In any regional study of agricultural production, rainfall, as a basic driving force and pulsar input in many agricultural processes, is therefore of fundamental importance. Focus is invariably on the patterns of rainfall in time and over an area, by enquiring how much it rains, where it rains, when it rains, how frequently it rains, and what the duration and intensity of rainfall events are (Schulze, 2011).

Annual rainfall

It has already been alluded to that overall changes in future scenarios of climate depend strongly on which GCMs were used, and how many GCMs were in the ensemble used. Output from GCMs applied in this study indicated that:

- Even under current climatic conditions, South Africa is regarded as a semiarid country with 20% receiving < 200 mm per annum, 47% < 400 mm and only 9% with a Mean Annual Precipitation (MAP) in excess of 800 mm. Inter-annual variability is high (Lynch, 2004).
- Projected medians of changes in MAP from the ensemble of GCMs used show an overall wetting into the intermediate future, very slight in the west and more pronounced in the east, particularly in the more mountainous areas. In the more distant future intensifications of changes in MAP become evident, with areas of decreases in the west and the increases in the east from 200 mm and up to 500 mm in the escarpment and mountainous runoff producing areas. The period of significant change in the west appears to be in the latter half of the century.
- The averaged ratio changes from multiple GCMs in the inter-annual variability of rainfalls show standard deviations (a measure of absolute variability) to be intensifying from the intermediate to the more distant future, with significant increases in the year-to-year variability of annual precipitation in the east (from 30% up to a doubling), but with decreases in the west.
- The overall increase in rainfall variability has severe repercussions for the management of water resources and operations of major reservoirs as well as on the year-on-year consistency of agricultural production.

Monthly rainfall

- Changes in distribution patterns over South Africa of medians of precipitation in cardinal months are not uniform, but can vary markedly:
  - in direction
  - in intensity
  - spatially within South Africa in a given month
  - between different months of the year for the same statistic
  - between the intermediate future and the more distant future for the same statistic
  - in intensification and acceleration of impacts of climate change over time.
- A recurring feature is a general wetting trend of varying intensity and distribution in all three periods of change considered, particularly in the east. This wetting trend is, in general, projected to be beneficial to South Africa's agricultural production and to water availability for agriculture, but the flood damage or erosion associated with this trend could cause it to be detrimental.
- There is a drying trend evident in the west, mainly towards the end of its rainy season. Combined with increases in temperature, the repercussions for agricultural production, irrigation demand and water resources could thus be severe in the west.
- The GCMs used in this study also display a drying trend in the northern areas of South Africa in the latter half of this century, mainly in the middle and towards the end of the wet season (i.e. January and April), with projected negative impacts on crop yields and water availability.
- The area which is transitional between the summer and winter rainfall areas in South Africa frequently displays marked relative increases in rainfall.
- For the period up to the intermediate future marked differences in averaged ratio changes of standard deviations are seen in the four cardinal months, as are differences in direction and intensity within a given month. January and April display a narrow coastal strip of decreased rainfall variability into the future, but with a general increase over the interior which intensifies into autumn.
- By mid-winter virtually the entire South Africa displays significant increases in the inter-annual variability of rainfall. Over much of the country this has little impact on agriculture and water resources as mid-winter coincides with the dry

season, but it does impact on the winter rainfall region of the southwest. By October, when the rainy season starts for much of the country, the eastern half of South Africa and the southwest show reductions in variability, with only the semiarid central interior displaying averaged increases in variability.

Rainfall concentration

- The rainfall concentration statistics indicate whether the rainfall season is concentrated over a short period of the year only or extended over a longer period.
- Median changes in ratios of intermediate future to present rainfall concentration computed from the five GCMs used, display a general reduction over much of South Africa, indicative of a slightly more even spread of the rainy seasons by the mid-century.
- However, in the all year rainfall belt, as well as the transitional area between the winter and summer rainfall regions, the rainy season is projected to become more concentrated into shorter periods than at present.
- Confidence in these projections is generally in the 'High' category in the northern areas of South Africa, but reduces to the 'Low' category in the south and east.

Rainfall Seasonality

- Large tracts of the current winter and summer rainfall regions are projected with high certainty by the various GCMs used in this study to remain as they are now.
- However, the major uncertainties between the models in changes of future rainfall seasonality are in the transitional areas between the winter and summer regions in the west, and in the future location of the all year rainfall region, with confidence in the composite projections only in the 'Medium High' to 'Medium Low' categories.
- Within the summer rainfall region individual GCMs display a contraction in the mid-summer rainfall region into the intermediate and the more distant future, and a corresponding expansion of late and very late rains.

In regard to annual precipitation, the averages of the ratio changes in MAP from five GCMs which were available for detailed analysis in this study show relatively high increases from the present into the intermediate future, i.e. 40 years from now, especially in the western transitional belt between the winter and summer rainfall regions (see Figure 2.7). The year-to-year variability of annual precipitation, expressed through the standard deviation and derived using output from multiple GCMs, is shown in Figure 2.8 below to increase throughout South Africa between the present and intermediate future.

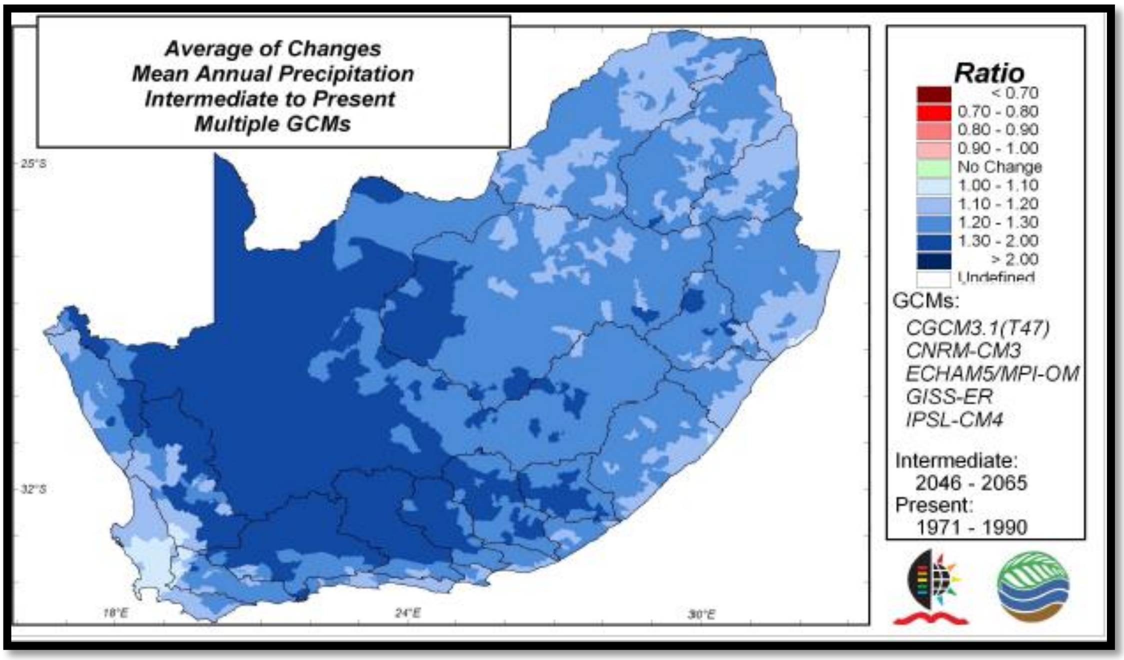


Figure 2.7: Averages of ratio changes in mean annual precipitation between the intermediate future and present, derived from multiple GCMs
Source: Schulze (2011)

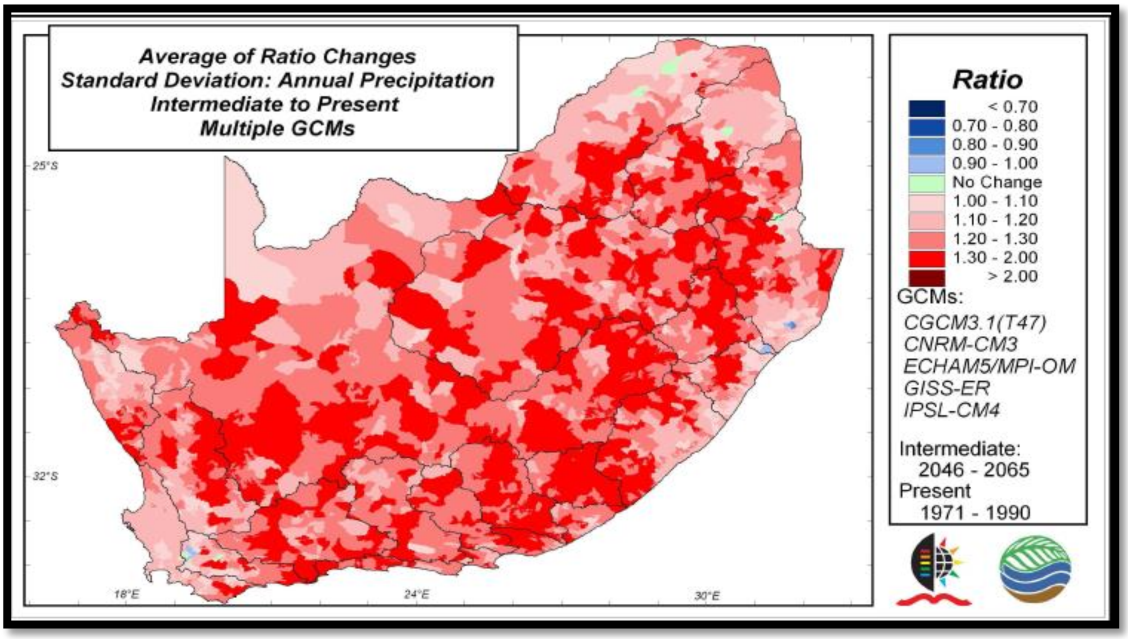


Figure 2.8: Averages of ratio changes in the standard deviation of annual precipitation between the intermediate future and present, derived from multiple GCMs
Source: Schulze (2011)

Changes in annual characteristics of rainfall, however, obscure the many important attributes of rainfall that may change at sub-annual level, in which the distinct spatial differences in both magnitude and direction are shown for amounts and variabilities of rainfall in both a summer (January) and spring (October) month (see Figure 2.9 to Figure 2.12 below).

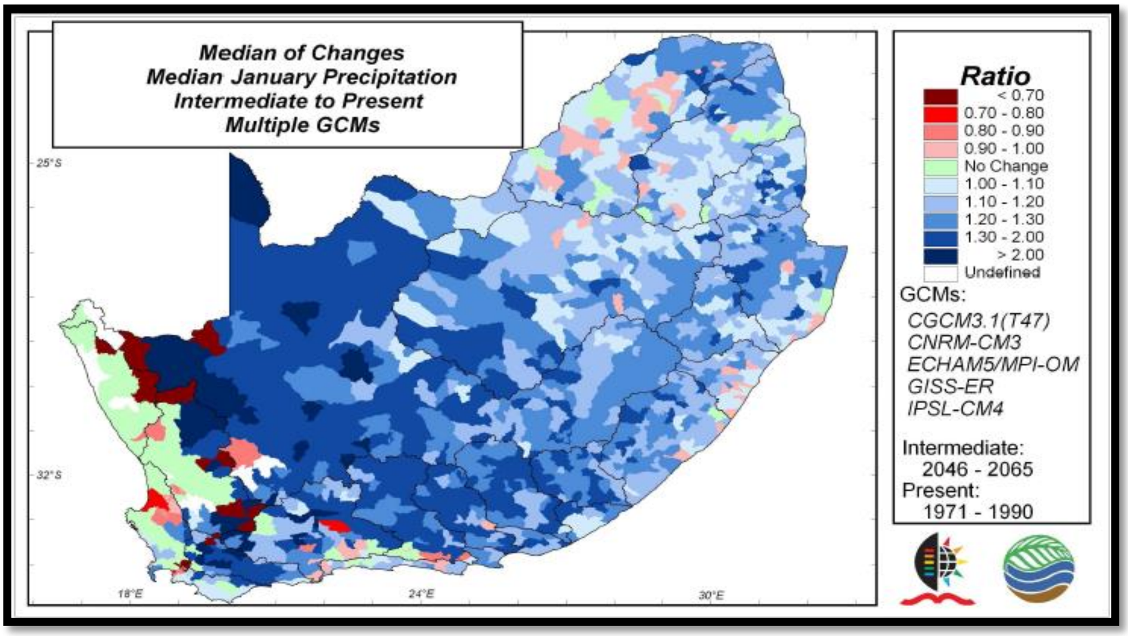


Figure 2.9: Medians of ratio changes in January rainfalls between the intermediate future and present, derived from multiple GCMs
Source: Schulze (2011)

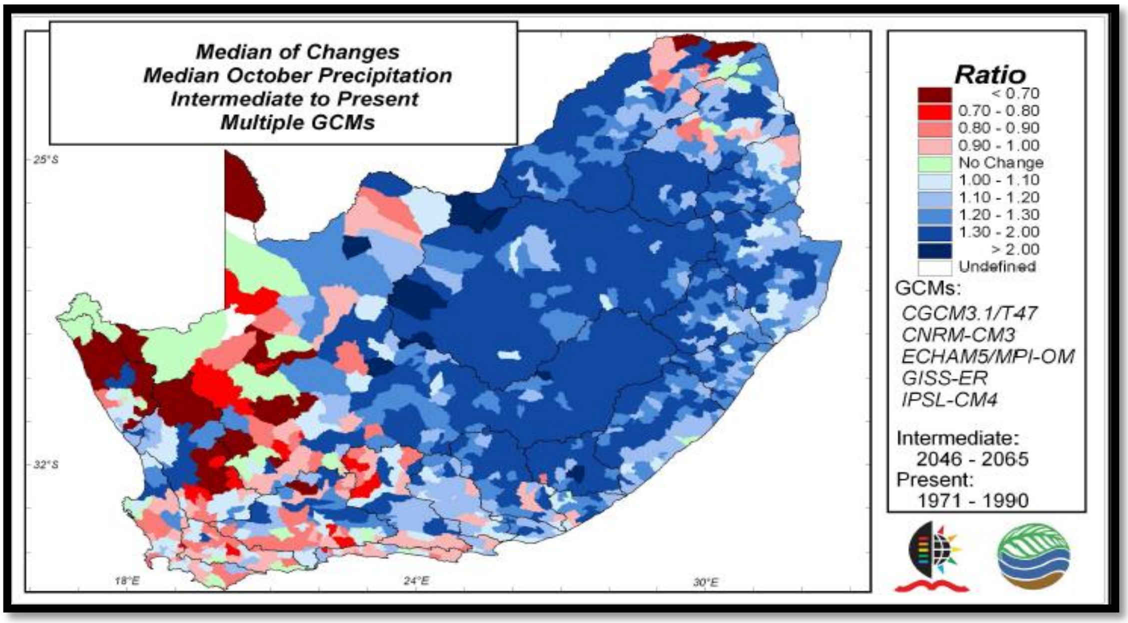


Figure 2.10: Medians of ratio changes in October rainfalls between the intermediate future and present, derived from multiple GCMs
Source: Schulze (2011)

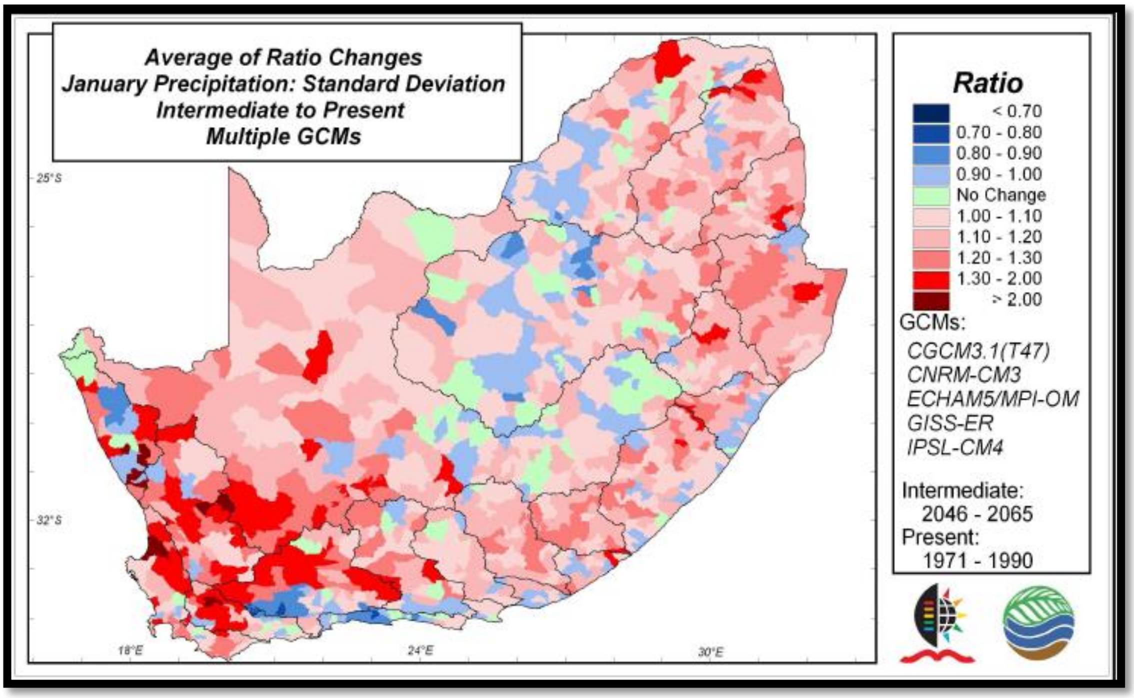


Figure 2.11: Averages of ratio changes in January rainfalls between the intermediate future and present, derived from multiple GCMs
Source: Schulze (2011)

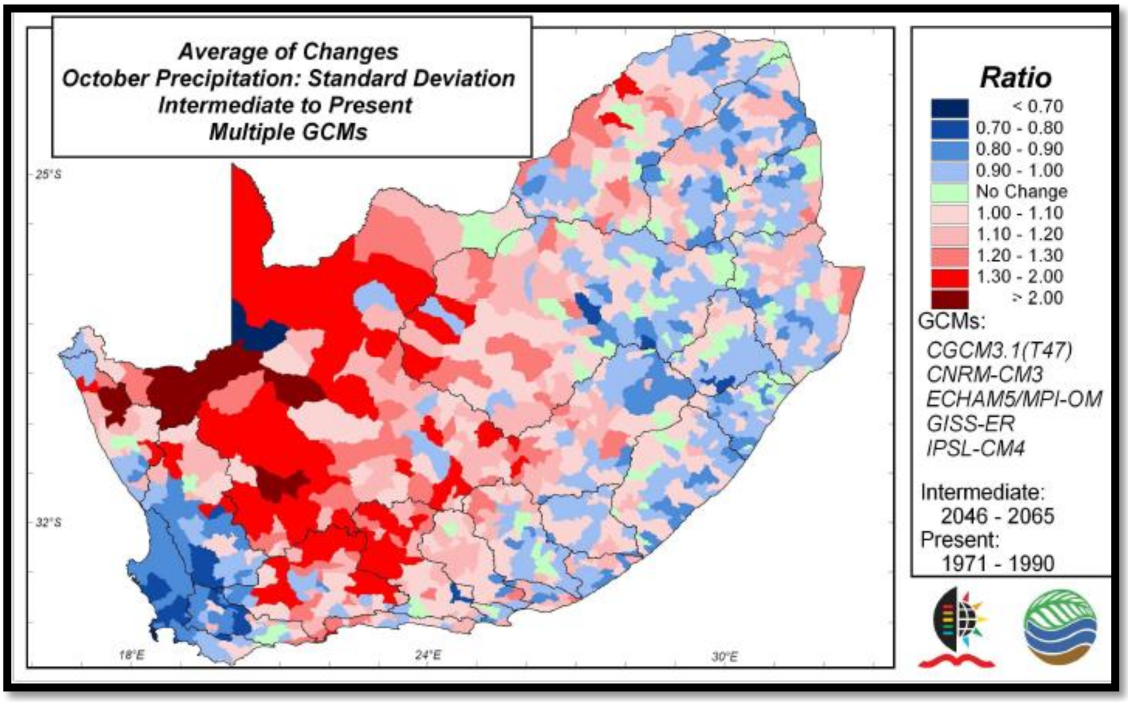


Figure 2.12: Averages of ratio changes in October standard deviations of rainfall between the intermediate future and present, derived from multiple GCMs
Source: Schulze (2011)

2.6 Climate change projections for study areas

The climate change projections for the different study areas were undertaken by UCT (CSAG) and are described in the following paragraphs. The reader is referred to Section 4.2.1.1 for more detail on the methodology of empirical downscaling.

The plots below show the range of projected future changes across various empirically downscaled GCMs. The solid bars represent the range between the middle 80% of projected change, and so exclude the upper and lower 10% as these are often considered to be outliers. However, the grey lines show the projected change for each model, so it is possible to see how individual models (intentionally not named) project the future changes.

2.6.1 Vredendal

Summary: Rainfall: Most projections point to a drying in early winter, with the most likely decrease in May (up to 10 mm) and June (up to 12 mm), with an increase of up to 5 mm in September. Temperature: Warming is illustrated in maximum temperature (approximately 1°C to 1.5 °C), and minimum temperature (1 °C to 1.5 °C) by 2050.

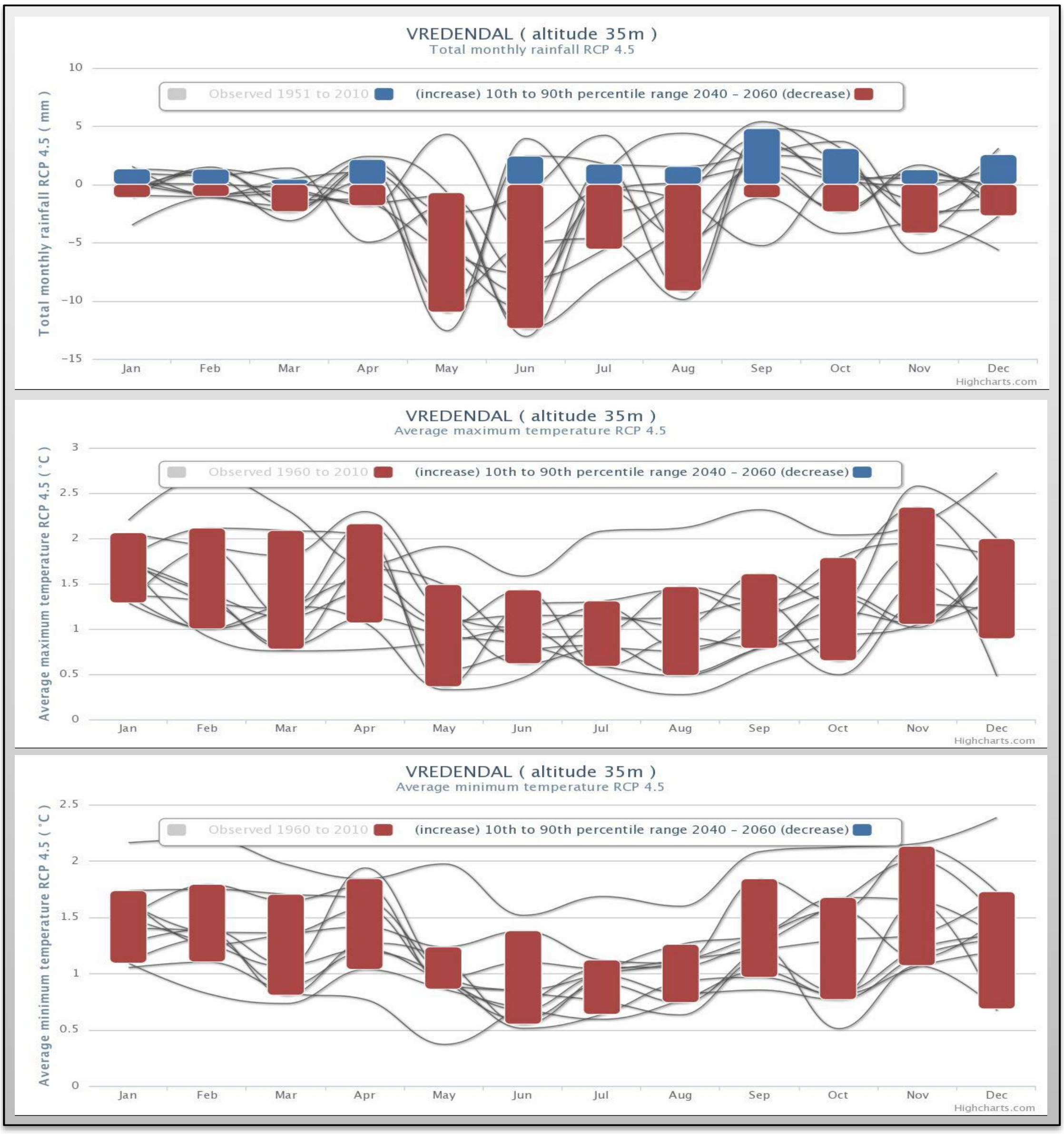


Figure 2.13: Climate projections for Vredendal from empirically downscaled GCMs

Source: Calculations by CSAG (2013)

2.6.2 Hoedspruit

Summary: Rainfall: Most projections indicate an increase in summer, with the most likely increases in January to March (of up to 20 mm per month), with a decrease of up to 12 mm in May and possible decrease in December of up to 10 mm. Temperature: Warming both in maximum temperature (approximately 1.5 °C to 2.0 °C) and minimum temperature (1.5 °C to 2.0 °C) is projected by 2050.

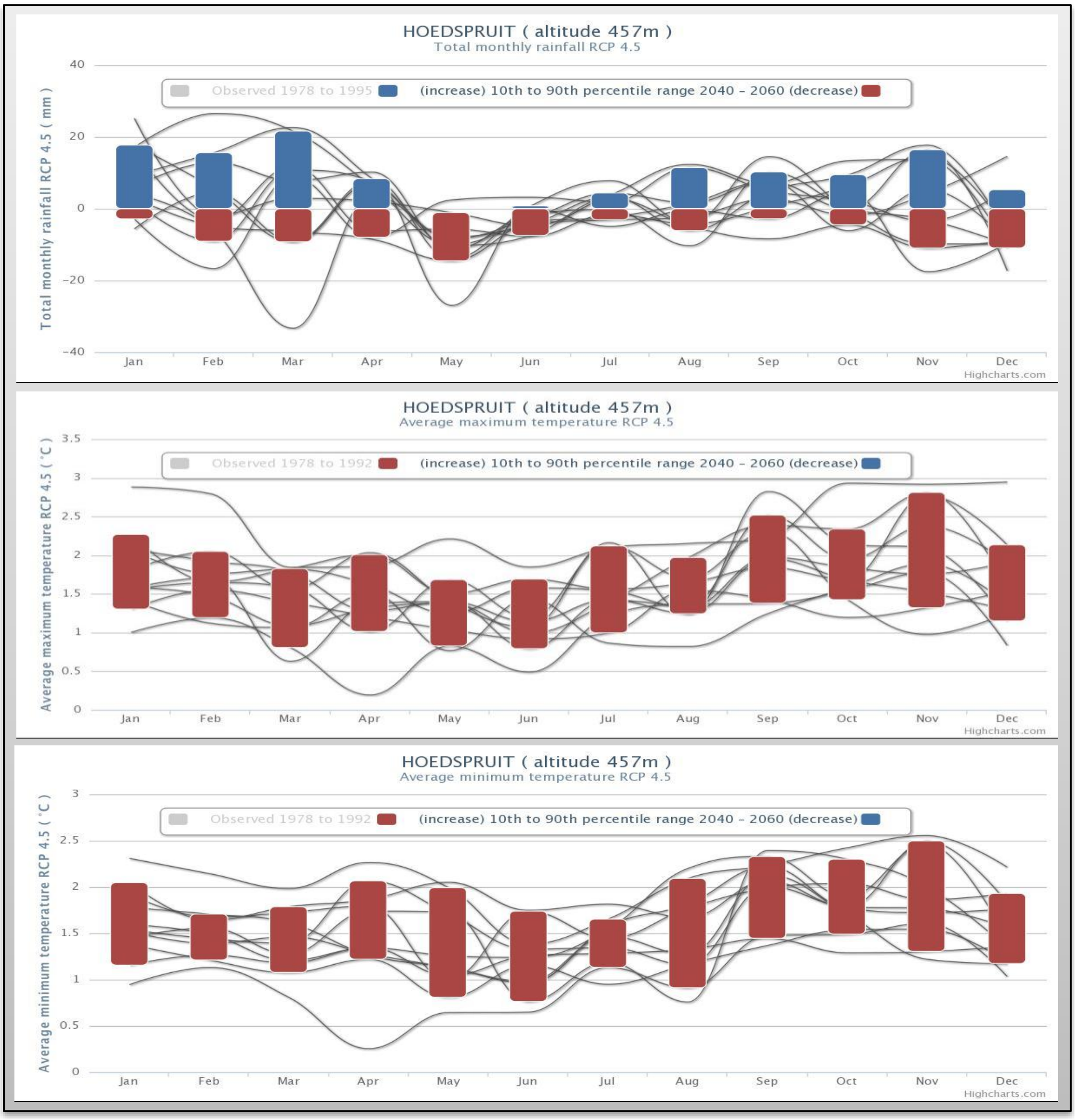


Figure 2.14: Climate projections for Hoedspruit from empirically downscaled GCMs

Source: Calculations by CSAG (2013)

2.6.3 Moorreesburg

Summary: Rainfall: Most projections point to a drying in summer and early winter, with the most likely decrease in June (of up to 10 mm), with an increase of up to 15 mm in September. Temperature: Warming is shown in maximum temperature (approximately 1 °C to 1.5 °C) and minimum temperature (1 °C to 1.5 °C) by 2050.

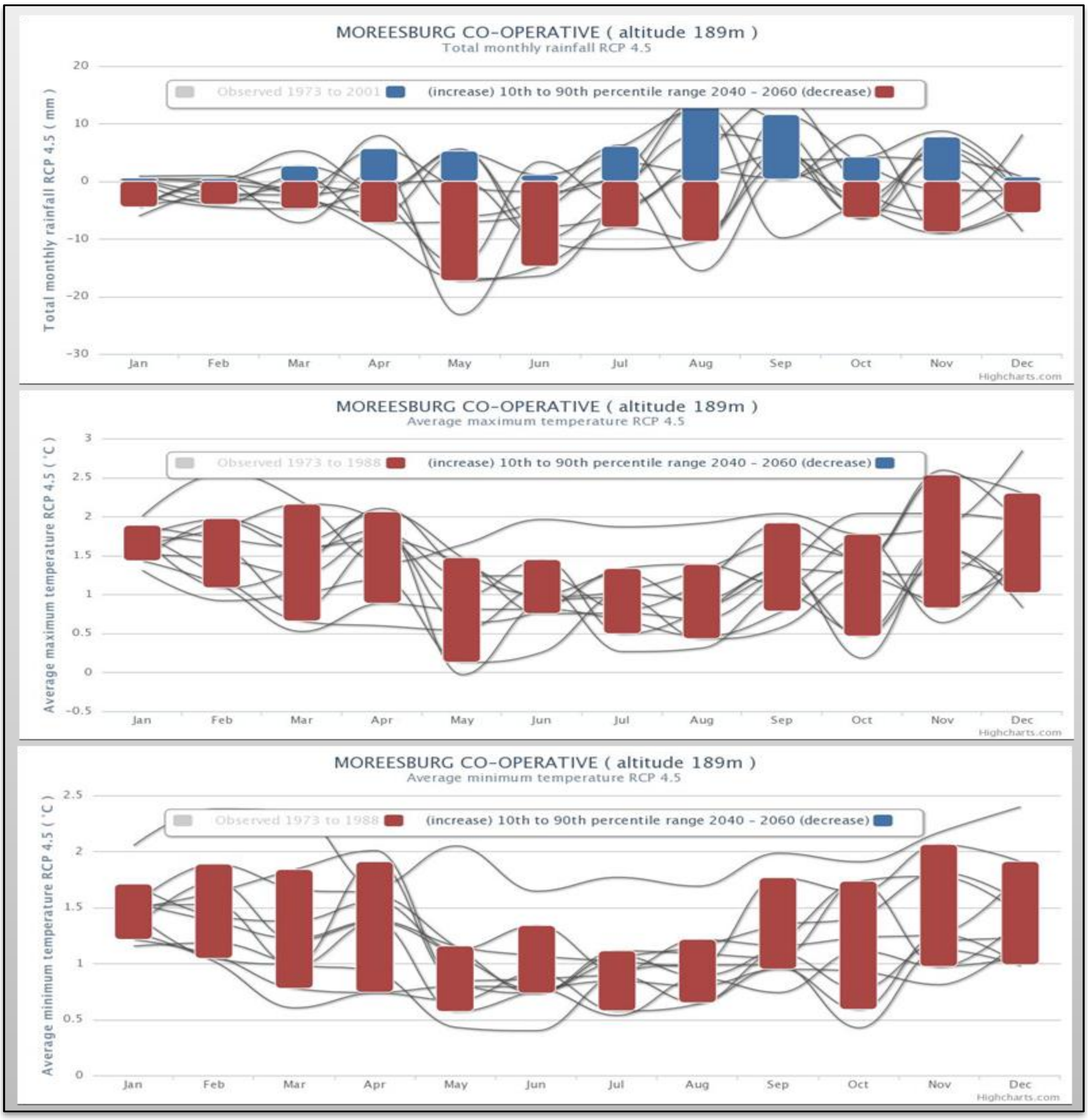


Figure 2.15: Climate projections for Moorreesburg from empirically downscaled GCMs
Source: Calculations by CSAG (2013)

2.6.4 Carolina

Summary: Rainfall: Most projections display an increase in summer, with the most likely increases in January (of up to 30 mm per month), with a decrease of up to 20 mm in May and possible decreases in March, April, May (up to 20 mm per month) and August, October and December of up to 15 mm per month. Temperature: Warming both in maximum temperature (approximately 1.5 °C to 2.5 °C) and minimum temperature (1.5 °C to 2.6 °C) by 2050.

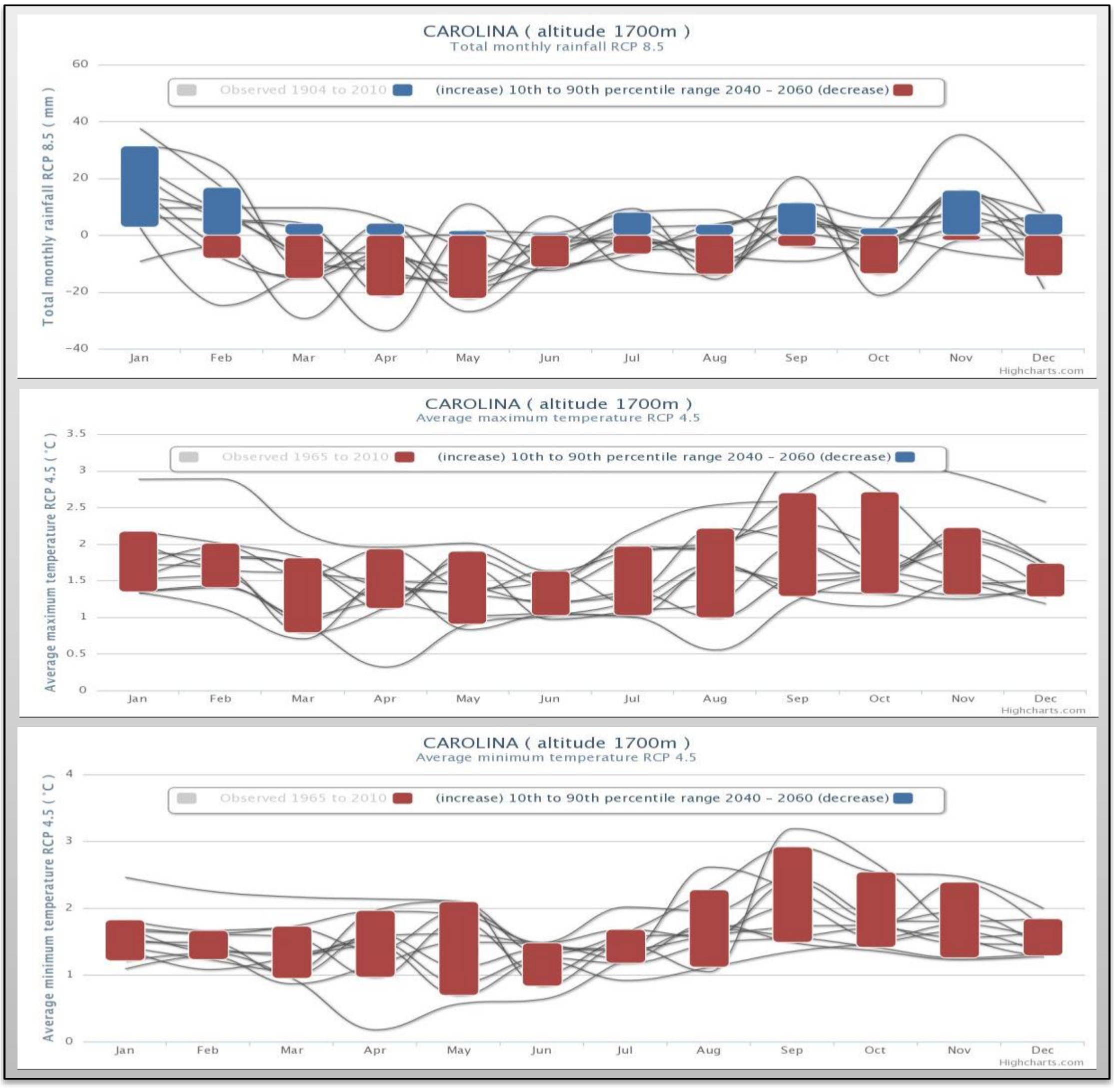


Figure 2.16: Climate projections for Carolina from empirically downscaled GCMs
Source: Calculations by CSAG (2013)

2.7 Vulnerability assessment

2.7.1 Defining vulnerability

The IPCC, in its Second Assessment Report, defines vulnerability as "the extent to which climate change may damage or harm a system". It adds that vulnerability "depends not only on a system's sensitivity, but also on its ability to adapt to new climatic conditions" (Watson *et al*., 1996). In a presentation made at the Sixth Conference of the Parties of the UNFCCC (COP-6), Watson, the then Chairperson of the IPCC, defined vulnerability as "the extent to which a natural or social system is susceptible to sustaining damage from climate change, and is a function of the magnitude of climate change, the sensitivity of the system to changes in climate and the ability to adapt the system to changes in climate. Hence, a highly vulnerable system is one that is highly sensitive to modest changes in climate and one for which the ability to adapt is severely constrained" (IPCC, 2000a).

Looking at vulnerability from the food security point of view, the FAO (1999) publication - *The State of Food Insecurity in the World*, defines vulnerability as "the presence of factors that place people at risk of becoming food insecure or malnourished". Clearly, this definition encompasses causes of food insecurity other than climate change (e.g. armed conflict, landlessness, etc.). Nevertheless, the concept of vulnerability includes hunger vulnerability, which refers to the vulnerability of individuals or households rather than that of regions or economic sectors (Olmos, 2001).

Following Blaikie *et al*. (1994), Kelly and Adger (2000) defines vulnerability as "the ability or inability of individuals or social groupings to respond to, in the sense of cope with, recover from or adapt to, any external stress placed on their livelihoods and well-being".

In the context of this study vulnerability will focus on the inability of individual commercial farmers to respond to, or cope with, climate change effects on crop yields from a financial vulnerability point of view. Financial vulnerability criteria that were applied in this study will be discussed in the following section.

2.7.2 Financial vulnerability criteria

Traditionally, lenders apply the five C‟s of credit when determining the creditworthiness of agricultural borrowers (Wilson *et al*., 2006):

- The borrowers **Capacity** to repay the loan obligation and bear the associated financial risks, calculated by analysing both past and projected profitability and cash flow of the farm business. If a farmer has previously installed drainage, increased return as a result of drainage records will be useful; otherwise data from a close neighbour with similar conditions who has installed drainage, or verified simulation models can also be used.
- The borrowers **Capital** available for farm operations, assessed from balance sheets with liquidity and solvency calculations to gauge equity investment in the farm and how effectively it generates cash flows. Without sufficient capital (and managerial expertise) to optimise the returns from the investment in drainage (e.g. planting more capital intensive higher value long term crops), the investment may be underutilised.
- The borrowers‟ security **Collateral** as a final source of repayment if the borrower defaults on the terms of the loan agreement or dies. The higher the risk of the operation for which the loan is requested, the higher level of Collateral required. As drainage has no salvage value, the full costs of the drains often needs to be covered by some form of collateral. The higher the percentage of a farmers' total land that needs to be drained, the less likely that the land itself can cover the collateral obligations.
- The **Conditions** for use of the funds, or the intended purpose of the funds required by the borrower are considered in terms of general economic conditions, interest rates, inflation and the demand for money in order to come up with a discount rate with which to calculate the net present value (NPV), benefit cost ratio (B/C) and internal rate of return (IRR), all useful in comparing funding alternatives.
- The **Character** of the borrower, i.e. the attitude of the borrower towards risk and financial track record available from credit bureaus, is also a very important factor for commercial lenders considering a loan application. In the case of subsidised state funding and grants the potential recipients character in terms of "money grabbing" and not applying the funds productively also needs to be evaluated to ensure efficient use of public funds.

“Collateral”, “Conditions” and “Character” cannot be calculated using quantitative inputs only and will differ for each analysis and also for different financiers. However, the financial model addresses “Capacity” and “Capital” using the following ratios:

- Cash flow ratio (an indicator of repayment ability and the enterprise’s ability to survive financial setbacks)
- Debt ratio (an indicator of solvency)

To determine the financial vulnerability of a farming system, the financial model provides a set of criteria. These are:

- IRR (Internal rate of return)
- NPV (Net present value)
- Cash flow ratio
- Highest debt ratio
- Highest debt.

The definitions for these criteria are expounded below.

Internal rate of return (IRR)

The internal rate of return (IRR) is probably the most widely used sophisticated capital budgeting technique. The IRR is the compound annual rate of return that the firm will earn if it invests in the project and receives the given cash inflows (Gitman, 2009).

Net present value (NPV)

Because net present value (NPV) gives explicit consideration to the time value of money, it is considered a sophisticated capital budgeting technique (Gitman, 2009). NPV can be described as the “difference amount” between the sums of discounted cash inflows and cash outflows. It compares the present value of money today to the present value of money in the future, taking inflation, risk and opportunity cost of capital into account.

Cash flow ratio

A measure of how well cash flow out is covered by the cash flow in. The cash flow ratio can gauge a company's liquidity in the short term. Using cash flow as opposed to income is sometimes a better indication of liquidity simply because cash is how bills are normally paid (Pienaar and Louw, 2002).

Debt ratio

The debt position of a firm indicates the amount of other people’s money (debt) being used to generate profits (Gitman, 2009). It is the total liabilities divided by total assets. If the ratio is less than 0.5, most of the company's assets are financed through equity. If the ratio is greater than 0.5, most of the company's assets are financed through debt.

Highest debt

Within the context of this study it is simply the highest debt in any specific year over the 20-year planning horizon.

2.8 Adapation to climate change

> ***Many natural systems, as well as the human drivers and respondents of such systems, are able to adapt naturally to change and, if they can do so, it is likely that they will be less vulnerable to potential impacts of climate change. However, many systems and components of such systems are likely to be vulnerable to certain climate impacts and not be able to adapt adequately or rapidly enough themselves. It is therefore important to identify who and what is most vulnerable to impacts of climate change, in order that support for adaptation can be targeted appropriately to reach the most vulnerable groups.***
>
> ***(Ziervogel, 2008)***

2.8.1 Defining adaptation to climate change

In climate change literature numerous definitions of adaptation have been proposed, as summarised below.

Adaptation involves adjustments to enhance the viability of social and economic activities and to reduce their vulnerability to climate change, including its current variability and extreme events as well as longer term climate change (Smit, 1993).

The term adaptation means any adjustment, whether passive, reactive or anticipatory, that is proposed as a means for ameliorating the anticipated adverse consequences associated with climate change (Stakhiv, 1993).

Adaptation to climate change includes all adjustments in behaviour or economic structure that reduce the vulnerability of society to changes in the climate system (Smith *et al.*, 1996).

Adaptability refers to the degree to which adjustments are possible in practices, processes, or structures of systems to projected or actual changes of climate. Adaptation can be spontaneous or planned, and can be carried out in response to or in anticipation of change in conditions (Watson *et al.*, 1996).

Adaptation is the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploit beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation (IPCC TAR, 2001a).

Adaptation consists of the practical steps to protect countries and communities from the likely disruption and damage that will result from effects of climate change. For example, flood walls should be built and in numerous cases it is probably advisable to move human settlements out of flood plains and other low-lying areas…" (UNFCCC, cited by Levina and Tirpak, 2006).

Adaptation is a process by which individuals, communities and countries seek to cope with the consequences of climate change, including variability. The process of adaptation is not new; throughout history, people have been adapting to changing conditions, including natural long term changes in climate. What is innovative is the idea of incorporating future climate risk into policy-making (UNDP, 2010).

Adaptation is the process or outcome of a process that leads to a reduction in harm or risk of harm, or realisation of benefits associated with climate variability and climate change. (UK Climate Impact Programme [UKCIP], 2003).

The aforementioned definitions have much in common. They all refer to adjustments in a system in response to (or in light of) climatic stimuli, but they also indicate differences in scope, application and interpretation of the term adaptation. For example, the question *"adaptation to what"* is answered in different ways. It can refer to climate change, to change and variability, or to just climate. It can be in response to adverse effects or vulnerabilities, but it can also be in response to opportunities. It can be in response to past, actual or anticipated conditions, changes or opportunities (Smit *et al.*, 2000).

There are also differences in how the definitions relate to the question *"who or what adapts?"* It can be people, social and economic sectors and activities, managed or unmanaged natural or ecological systems, or practices, processes or structures of systems. The nature of adaptation and its effects will vary not only according to whether the object is natural or socio-economic, small or large scale, single sector/species or complex system, but also according to properties that relate to adaptation propensity such as adaptability, vulnerability, viability, sensitivity, susceptibility, resilience and flexibility.

The definitions also hint at the ways in which forms or types of adaptation can be distinguished; in other words, *"how does adaptation occur?"* Adaptation refers to both the process of adapting and the resulting outcome or condition. Most definitions imply a change "to better suit" the new conditions. Adaptations can be passive, reactive or anticipatory; they can be spontaneous or planned.

As summarized in Figure 2.17, these three elements together circumscribe the overall question "what is adaptation?" A thorough description of adaptation would specify the system of interest (who or what adapts), the climate-related stimuli (adaptation to what), and the processes and forms involved (how adaptation occurs). The exercise of identifying recommended adaptation options or measures as part of a response strategy involves the additional step of evaluation, in order to judge the merit of potential adaptations *(how good is the adaptation?)*. Evaluations of adaptations can be based on criteria such as costs, benefits, equity, efficiency, urgency and ease/difficulty of implementation (Smit *et al*., 2000).

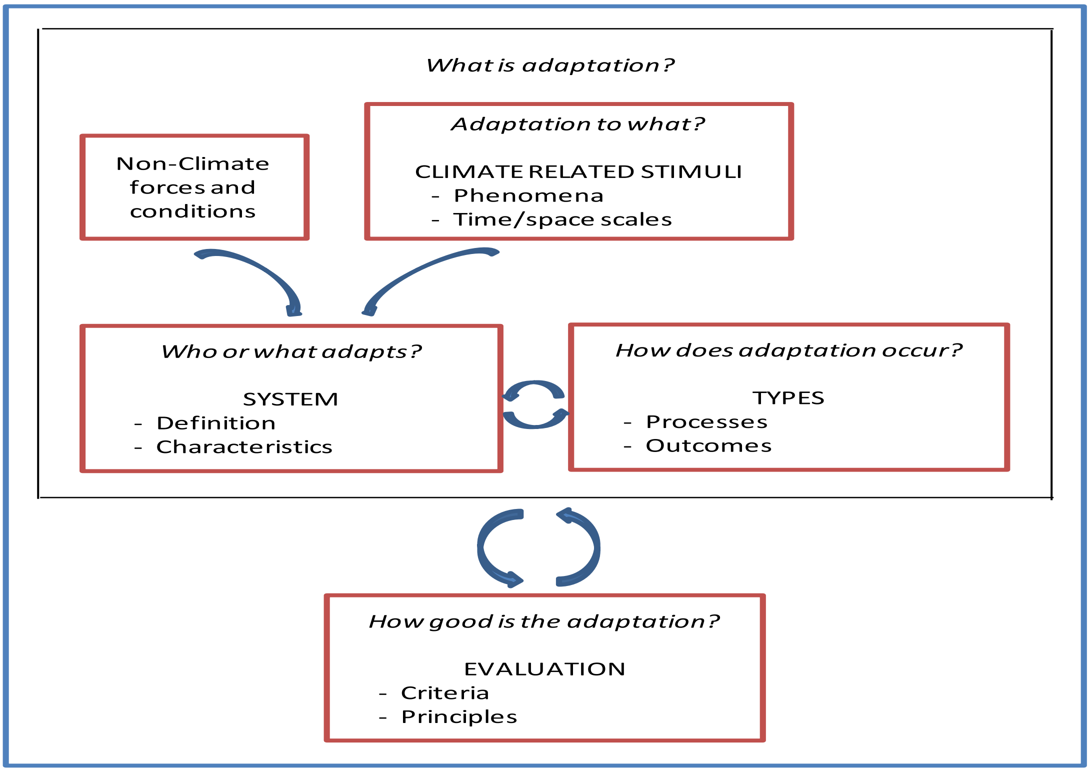


Figure 2.17: Gross anatomy of adaptation to climate change and variability
Source: Smit et al. (2000)

The success of adaptation strategies in this study will be evaluated by comparing financial vulnerability criteria of different climate and management scenarios.

2.8.2 Types of adaptation

Two main types of adaptation are autonomous and planned adaptation. **Autonomous adaptation** is the reaction of, for example, a farmer to changing precipitation patterns, in that the farmer changes crops or uses different harvest and planting/sowing dates. **Planned adaptation** measures are conscious policy options or response strategies, often multi-sectoral in nature, aimed at altering the adaptive capacity of the agricultural system or facilitating specific adaptations. Examples would include deliberate crops selection and distribution strategies across different agriclimatic zones, substitution of new crops for old ones and resource substitution induced by scarcity (Easterling, 1996).

Farm level analyses have shown that large reductions in adverse impacts from climate change are possible when adaptation is fully implemented (Mendelsohn and Dinar, 1999). Short-term adjustments are seen as autonomous in the sense that no other sectors (e.g. policy, research, etc.) are needed in their development and implementation.

Long-term adaptations are major structural changes to overcome adversity such as changes in land-use to optimize yield under new conditions, application of new technologies, new land management techniques, and water-use efficiency related techniques. Reilly and Schimmelpfennig (1999) define the following “major classes of adaptation”:

- Seasonal changes and sowing dates
- Different variety or species
- Water supply and irrigation system
- Other inputs (fertilizer, tillage methods, grain drying, other field operations)
- New crop varieties
- Forest fire management, promotion of agroforestry, adaptive management with suitable species and silvicultural practices.

Accordingly, the types of responses include:

- Reduction of food security risk
- Identifying present vulnerabilities
- Adjusting agricultural research priorities
- Protecting genetic resources and intellectual property rights
- Strengthening agricultural extension and communication systems
- Adjustment in commodity and trade policy
- Increased training and education
- Identification and promotion of (micro-) climatic benefits and environmental services of trees and forests.

With changes in precipitation and thus water availability, temperature, length of growing season and frequency of extreme weather events, considerable efforts would be required to prepare developing countries to deal with climate-related impacts in agriculture. Among the key challenges will be to assist countries that are constrained by limited economic resources and infrastructure, low levels of technology, poor access to information and knowledge, inefficient institutions, and limited empowerment and access to resources. Managed carefully, climate adaptation strategies could have environmental benefits for some countries (FAO, 2007b).

Within the context of this study the focus will be on autonomous adaptation, in other words, adaptation strategies which can be applied at farm level without support from other levels e.g. policies, etc.

2.9 Integrated Climate Change Modelling

2.9.1 International research

Recent international research on integrated climate change modelling includes two IFPRI (The International Food Policy Research Institute) studies which are summarized in the sections below.

2.9.1.1 Climate change impact on agriculture and cost of adaptation (Nelson *et al*., 2009)

The study brings together detailed modelling of crop growth under climate change with insights from a detailed global agriculture model, using two climate scenarios to simulate future climate. The results of the analysis suggest that agriculture and human well-being will be negatively affected by climate change:

- In developing countries, climate change may result in yield declines for the most important crops. South Asia will be particularly hard hit.
- Climate change may have varying effects on irrigated yields across regions, but irrigated yields for all crops in South Asia are projected to experience large declines.
- Climate change may result in additional price increases for the most important agricultural crops such as rice, wheat, maize, and soybeans. Higher feed prices may result in higher meat prices. As a result, climate change may reduce the growth in meat consumption slightly and cause a more substantial fall in cereals consumption.
- Calorie availability in 2050 may not only be lower than in the no–climate-change scenario. It may actually decline relative to 2000 levels throughout the developing world.
- By 2050, the decline in calorie availability may increase child malnutrition by 20% relative to a world with no climate change. Climate change may eliminate much of the improvement in child malnourishment levels that would occur with no climate change.
- Thus, aggressive agricultural productivity investments are needed to raise calorie consumption enough to offset the negative impacts of climate change on the health and well-being of children.

The research uses a global agricultural supply-and-demand projection model (IMPACT 2009) linked to a biophysical crop model (DSSAT) of the impact of climate change on five important crops: rice, wheat, maize, soybeans, and groundnuts.

Because climate change simulations are inherently uncertain, two climate models have been used to simulate future climate, using the A2 scenario of the IPCC's Fourth Assessment Report: the National Center for Atmospheric Research, US (NCAR) model and the Commonwealth Scientific and Industrial Research Organization, Australia (CSIRO) model. The study refers to the combination of model runs with A2 inputs as the NCAR and CSIRO scenarios. Both scenarios project higher temperatures in 2050, resulting in higher evaporation and increased precipitation as this water vapour returns to earth.

The report assesses climate-change effects on food security and human well-being using two indicators: per capita calorie consumption and child malnutrition numbers. It estimates the cost of investments - in three primary sources of increased agricultural productivity (agricultural research, rural roads, and irrigation) - needed to return the values of these two indicators from their 2050 values with climate change to their 2050 values without climate change. In other words, this report isolates the effects of climate change on future well-being and identifies only the costs of compensating for climate change.

This analysis brings together detailed modelling of crop growth under climate change with insights from a detailed global agriculture model. The results show that agriculture and human well-being will be negatively affected by climate change. Crop yields may decline, production may be affected, crop and meat prices may increase, and consumption of cereals may fall, leading to reduced calorie intake and increased child malnutrition (Nelson *et al*., 2009).

2.9.1.2 Simulating the impact of Climate Change and Adaptation Strategies on Farm Productivity and Income – A Bio-economic Analysis (Fofana, 2011)

This study aims at understanding the impact of climate change on agriculture in Africa. A bio-economic model that combines biophysical or cropping systems and farm optimization modelling is used to replicate the system of production of El Khir, a large commercial farm in Tunisia.

The study argues that climate is crucial in defining the production area for plant species and varieties. Even for crops that are well adapted to their environment, the effect of climate on yield remains important. It highlights the general action of climate variables, in particular temperature and precipitation, on plant growth and crop yield.

Climate change possibilities are presented through climate scenarios. Because of the uncertainties surrounding the forecasts on climate change, the study runs various climate sensitivity tests based on increases in daily temperature of about 1 °C, 2 °C, and 3 °C; decreases in daily precipitation of 10% and 20%; and a doubling of the CO_2 level from 350 ppm to 700 ppm.

The study reveals that the El Khir farm may experience a significant decline in productivity and income with climate change. The severity of productivity and income losses depends on the magnitude of changes in temperature and precipitation. Higher temperatures (plus 2 °C and above) or a significant decline in precipitation (minus 10% and below) or both may seriously affect most of the crop activities. In the perspective of the IPCC scenarios, farm productivity is most likely to fall by 15% to 20% in the near-term, depending on the magnitude of changes in precipitation. In the long run, the declines are expected to be much higher: 35% to 55% for productivity and 45% to 70% for income.

For this study the effects of climate change on irrigated crops are driven by temperature only, whereas rainfed crops face the effects of both temperature and precipitation. Consequently, irrigated crops are less affected than rainfed crops with about 10 percentage points of the productivity gap. Crops are affected differently by climate change. Among irrigated crops in this study, oat hay is less affected than hard wheat. Among rainfed crops, hard wheat, fava bean, and chickpeas experience a higher loss of yields. The reduction in yields is less important, but still high for soft wheat, whereas barley fodder is the least affected.

Simple adaptation strategies (more irrigation and nitrogen fertilization and delay in sowing dates) contribute to coping with the adverse impact of climate change on farm productivity and income. But as the climate gets warmer, their mitigation effects are lessened. For the case of hard wheat, new management techniques implemented to cope with the adverse impact of climate change do not appear to be significantly more efficient than baseline management techniques. Compensations for the negative effects of climate change are found to be worthwhile for the 1 °C increase in temperature scenario. However, the success of adaptation strategies depends very much on the availability of more water and the lower additional cost to mobilize it at farm level.

2.9.2 South African research

Climate change studies conducted in South Africa (including Africa wide studies) focus on:

- Physical impacts - implications of climate change on crop yield and production (Schulze *et al*., 1993; Du Toit *et al*., 2002; Midgley *et al*., 2007; Walker and Schulze, 2008; Haverkort *et al*., 2013).
- Economic impacts derived from yield losses (Erasmus *et al*., 2000; Blignaut *et al*., 2009; Gbetibouo and Hassan, 2005; Kurukulasuriya *et al*., 2006).
- More comprehensive economic studies including vulnerability (Daressa *et al*., 2007; Seo *et al*., 2009; Gbetibouo *et al*., 2010; Hassan *et al*., 2010) and adaptation options (Deressa *et al*., 2005; Gbetibouo and Hassan, 2005; Benhin, 2008).
- Advanced integrated climate change modelling linking empirically downscaled climate models, a hydrological module and dynamic linear modelling to contribute to water resources policy, planning and management (Louw *et al*., 2012).

Schulze *et al*. (1993) developed an analysis tool to simulate primary productivity and crop yields for both present and possible future climate conditions. Southern Africa was delineated into 712 relatively homogeneous climate zones, each with specific climate, soil and vegetation response information. The primary productivity and crop yield models were linked with the climate zones via a cell-based agro-hydrological model, with the final output coordinated using a Geographic Information System (GIS). The results of this preliminary study show a large dependence of production and crop yield on the intra-seasonal and inter-annual variation of rainfall. The most important conclusion from the study is the readiness of the developed tool and associated infrastructure for future analysis into social, technological and political responses to food security in Southern Africa.

Erasmus *et al*. (2000) link two different methodologies to determine the effects of climate change on the Western Cape farm sector. First, it uses a general circulation model (GCM) to model future climate change in the Western Cape, particularly with respect to precipitation. Second, a sector mathematical programming model of the Western Cape farm sector is used to incorporate the predicted climate change, specifically rainfall, from the GCM to determine the effects on key variables of the regional farm economy. In summary, results indicate that future climate change will lead to lower precipitation, which implies that less water will be available to agriculture in the Western Cape. This will have a negative overall effect on the Western Cape farm economy. Both producer welfare and consumer welfare will decrease. Total employment in the farm sector will also decrease as producers switch to a more extensive production pattern. The total decline in welfare, therefore, will fall disproportionately on the poor.

Deressa *et al*. (2005) employed a Ricardian model that captures farmers' adaptation to analyse the impact of climate change on South African sugarcane production under irrigation and dryland conditions. The study utilized time series data for the period 1977 to 1998 pooled over 11 districts. Results showed that climate change has significant non-linear impacts on net revenue per hectare of sugarcane in South Africa with higher sensitivity to future increases in temperature than precipitation. Irrigation did not prove to provide an effective option for mitigating climate change damages on sugarcane production in South Africa. The study suggests that adaptation strategies should focus special attention on technologies and management regimes that will enhance sugarcane tolerance to warmer temperatures during winter and especially the harvesting phases.

Gbetibouo and Hassan (2005) employed a Ricardian model to measure the impact of climate change on South Africa's field crops and analysed potential future impacts of further changes in the climate. A regression of farm net revenue on climate, soil and other socio-economic variables was conducted to capture farmer-adapted responses to climate variations. The analysis was based on agricultural data for seven field crops (maize, wheat, sorghum, sugarcane, groundnut, sunflower and soybean), climate and edaphic data across 300 districts in South Africa. Results indicate that production of field crops was sensitive to marginal changes in temperature as compared to changes in precipitation. Temperature rise positively affects net revenue whereas the effect of reduction in rainfall is negative. The study also highlights the importance of season and location in dealing with climate change; showing that the spatial distribution of climate change impact and consequently needed adaptations will not be uniform across the different agro-ecological regions of South Africa. Results of simulations of climate change scenarios indicate many impacts that would induce (or require) very distinct shifts in farming practices and patterns in different regions. Those include major shifts in crop calendars and growing seasons, switching between crops to the possibility of complete disappearance of some field crops from some regions.

Kurukulasuriya *et al*. (2006) used data from a survey of more than 9 000 farmers across 11 African countries and a cross-sectional approach to estimate how farm net revenues are affected by climate change compared with current mean temperature. With warming, revenues fall for dryland crops (temperature elasticity of –1.9) and livestock (–5.4), whereas revenues rise for irrigated crops (elasticity of 0.5) that are located in relatively cool parts of Africa and are buffered by irrigation from the effects of warming. At first, warming has little net aggregate effect as the gains for irrigated crops offset the losses for dryland crops and livestock. Warming, however, will most likely reduce dryland farm income immediately. The final effects will also depend on changes in precipitation, because revenues from all farm types increase with precipitation. Because irrigated farms are less sensitive to climate, irrigation is a practical adaptation to climate change in Africa, if water is available.

Benhin (2008) assesses the economic impact of the expected adverse changes in the climate on crop farming in South Africa using a revised Ricardian model and data from farm household surveys, long term climate data, major soils and runoffs. Using selected climate scenarios, the study predicts that crop net revenues are expected to fall by as much as 90% by 2100, mostly affecting small-scale farmers. Policies therefore need to be fine-tuned and more focused to take advantage of the relative benefits across seasons, farming systems and spatially, and by so doing climate change may be beneficial rather than harmful.

Walker and Schulze (2008) modelled nine plausible future climate scenarios over a 44-year period, using the CERES-maize model. The results showed that climatic changes could have major negative effects on the already drier western, and therefore more vulnerable, areas of the South African Highveld. An increase in temperature increases the variability of yields in the relatively moist Piet Retief area (MAP 903 mm), while at the more sub-humid Bothaville, with a MAP of only 552 mm, the inter-annual variability remains the same, but mean yield over 44 seasons is reduced by 30%.

Seo *et al*. (2009) examines the distribution of climate change impacts across the 16 Agro-Ecological Zones (AEZs) of Africa. They combine net revenue from livestock and crops and regress total net revenue on a set of climate, soil, and socio-economic variables with and without country fixed effects. Although African crop net revenue is very sensitive to climate change, combined livestock and crop net revenue proves to be more resilient to climate change. With the hot and dry CCC climate scenario, average damage estimates reach 27% by 2100, but with the mild and wet PCM climate scenario, African farmers will benefit. The analysis of AEZs implies that the effects of climate change will be quite different across Africa. For example, currently productive areas such as dry/moist savannah are more vulnerable to climate change while currently less productive agricultural zones such as humid forest or sub-humid AEZs become more productive in the future.

Blignaut *et al*. (2009) employed a panel data econometric model to estimate how sensitive the nation's agriculture may be to changes in rainfall. Net agricultural income in the provinces, contributing 10% or more to the total production of both field crops and horticulture, is likely to be negatively affected by a decline in rainfall, especially rainfed agriculture. For the country as a whole, each 1% decline in rainfall is likely to lead to a 1.1% decline in the production of maize (a summer grain) and a 0.5% decline in winter wheat. These results are discussed with respect to both established and emerging farmers, and the type of agriculture that should be favoured or phased out in different parts of the country, in view of current and projected trends in climate, increasing water use, and declining water availability.

Hassan (2010) measured the economic impacts of climate change on crop and livestock farming in Africa based on a cross-sectional survey of over 8,000 farming households from 11 countries in East, West, North and Southern Africa. The response of net revenue from crop and livestock agriculture across various farm types and systems in Africa to changes in climate normals (i.e. mean rainfall and temperature) is analysed. The analyses controlled for effects of key socio-economic, technology, soil and hydrological factors influencing agricultural production. Results show that net farm revenues are in general negatively affected by warmer and drier climates. The small-scale mixed crop and livestock system predominantly typical in Africa is the most tolerant whereas specialized crop production is the most vulnerable to warming and lower rainfall. These results have important policy implications, especially for the suitability of the increasing tendency toward large-scale mono-cropping strategies for agricultural development in Africa and other parts of the developing world in light of expected climate changes. Mixed crop and livestock farming and irrigation offer better adaptation options for farmers against further warming and drying predicted under various future climate scenarios.

Gbetibouo *et al*. (2010) examined climate adaptation strategies of farmers in the Limpopo Basin of South Africa. Survey results show that while many farmers noticed long-term changes in temperature and precipitation, most could not take remedial action. Lack of access to credit and water were cited as the main factors inhibiting adaptation. Common adaptation responses reported include diversifying crops, changing varieties and planting dates, using irrigation, and supplementing livestock feed. A multinomial logit analysis of climate adaptation responses suggests that access to water, credit, extension services and off-farm income and employment opportunities, tenure security, farmers' asset base and farming experience are key to enhancing farmers' adaptive capacity. This implies that appropriate government interventions to improve farmers' access to and the status of these factors are needed for reducing vulnerability of farmers to climate adversities in such arid areas.

Gbetibouo *et al*. (2010a) analysed the vulnerability of South African agriculture to climate change and variability by developing a vulnerability index and comparing vulnerability indicators across the nine provinces of the country. Nineteen environmental and socio-economic indicators were identified to reflect the three components of vulnerability: exposure, sensitivity, and adaptive capacity. The results of the study show that regions most exposed to climate change and variability do not always overlap with those experiencing high sensitivity or low adaptive capacity. Furthermore, vulnerability to climate change and variability is intrinsically linked with social and economic development.

An International Development Research Centre (IDRC) study "Managing climate risk for agriculture and water resources development in South Africa: Quantifying the costs, benefits and risks associated with planning and management alternatives" (Louw *et al*, 2012) was concluded in 2012. The objective of the project was to develop the capacity of South African and regional institutions in the private and public sectors, in order to better integrate information about climate change and climate variability into water resources policy, planning and management, as well as demonstrate how this information can be used to evaluate alternative strategies and projects for adjusting/adapting to climate change and climate variability for application in other regions.

The objective was accomplished through the development of three key modules to integrate information about climate change and climate variability in a systematic way to be used to influence water resources policy, planning and management. They are:

- The regional climate change module by downscaling GCMs.
- A hydrological module by using the ACRU model to estimate incremental runoff at specific locations within the study region.
- A dynamic programming module with three components, viz.
    - Regional typical farm models (21 farms) to simulate the demand for agricultural water under different climate regimes (scenarios).
    - An inter-temporal spatial equilibrium model to simulate the bulk water infrastructure (main storage dams, canals, pipelines and tunnels) and farm dams.
    - An urban demand module to simulate the demand for urban water use sectors.

In addition the integrated framework also made provision for external inputs such as:

- Policies, plans and technology options for increasing water supplies (input by various stakeholders, amongst others the Department of Water Affairs, Western Cape Systems Analysis, Water Users Associations and the Berg River Catchment Management Agency).
- Reducing water demand through water demand management options (input by all stakeholders in the region).

The output of the model consists of:

- Benefits and costs of structural and non-structural water management options.
- Water values and water tariffs (prices).
- Reservoir inflows, storage, transfers, releases and evaporation.
- Water use by the urban and agricultural water use sectors.

The integrated modelling framework which was developed by Louw *et al*. (2012) is unique in that it had not yet been done anywhere else in Africa and in very few other places in the world. The project contributed towards the improvement of the methodologies to study the impact of climate change, climate vulnerability and evaluation methodology of adaptation strategies. The project focused on a macro level and did not include detailed farm-level integrated modeling.

From the international, African and South African research it is clear that there is a gap in the research in regard to integrated economic modelling at micro level. This includes the linkages between changing projected climates, changing yield and quality of produce, hydrology (availability of irrigation water), changing crop irrigation needs (with new projected climates), financial vulnerability and financial sustainability of farming systems. This study sets out to fill that gap to some extent by making a contribution to integrated climate change modelling.

2.10 Chapter summary

Chapter 2 summarises the literature review that was undertaken for this study. The chapter starts off defining climate change followed by a brief history of climate change research. The impacts of climate change and global warming, and more specifically the likely consequences for agriculture, including bio-physical and socio-economic impacts are discussed.

GCMs and the two downscaling approaches, viz. empirical and dynamical downscaling are elaborated on. The CSAG, based at the University of Cape Town, South Africa, operates the pre-eminent empirically downscaled model for Africa and provides meteorological station level responses to global climate forcings for a growing number of stations across the African continent.

The empirical downscaling of values to climate station level, used in this study, was undertaken by the CSAG. Daily rainfall, as well as maximum and minimum temperature values, was the output from five accredited GCMs from the IPCC (2007), in each case for two 20 year scenarios for present climate (1971 – 1990) and an intermediate future climate (2046 – 2065).

Chapter 2 also includes climate change projections for South Africa and more specifically for the case study areas. Warming for minimum and maximum temperatures is projected over all four case study areas. Most projections favour an increase in rainfall for the summer rainfall areas. For the winter rainfall areas most projections point to a decrease in rainfall for early winter and a slight increase during springtime.

In the context of this study vulnerability will focus on the inability of individual commercial farmers to respond to, or cope with, climate change effects on crop yields from a financial vulnerability point of view. In order to determine the impact of climate change, the case study farming systems will be measured against a set of financial vulnerability assessment criteria, viz. IRR, NPV, cash flow ratio, highest debt ratio and highest debt.

Two main types of adaptation are autonomous and planned adaptation. In this study the focus will be on autonomous adaptation, in other words, adaptation strategies which can be applied at farm level without support from other levels e.g. policies, etc. The success of adaptation strategies will be evaluated by comparing financial vulnerability criteria of different climate and management scenarios.

From the literature research it became clear that a gap exists in the integrated economic modelling at farm level, which this study is attempting to address.

CHAPTER 3 : DESCRIPTION OF STUDY REGIONS AND CASE STUDY FARMS

3.1 Introduction

The purpose of this chapter is to give the reader an overview of the four study areas.

Different rainfall areas (summer and winter) as well as rainfed versus irrigated agricultural production regions are considered to analyse the projected financial vulnerability of different farming systems to climate change.

Case studies from the following areas were earmarked to be included in the study:

- Irrigation farm – Vredendal/LORWUA
- Irrigation farm – Hoedspruit/Blyde River WUA
- Dryland farm in Moorreesburg, Western Cape
- Dryland farm in Carolina, Mpumalanga.

The sections below give a condensed description of the LORWUA, Blyde River WUA, Carolina and the Moorreesburg regions and their respective case studies. The four areas broadly represent the summer- and winter rainfall areas as well as irrigation and dryland crop production areas of South Africa. Two case studies per irrigation area and one case study per dryland area were selected to be included in the study. The greater degree of homogeneity in the dryland areas is the reason for including only one case study per dryland area.

3.2 Description of Lower Olifants River Water Users Association (LORWUA)

3.2.1 Background

The Olifants-Doorn Water Management Area is situated along the west coast of South Africa, close to the cold Benguela sea current of the Atlantic Ocean. The catchment is characterised by a Mediterranean climate with a strong deterministic water supply (winter rainfall) from mid-May to the end of August. The summer months, November to February, are very warm and dry, and are characterised by extremely high evaporation losses. Climate variation is extreme, with summer temperatures reaching 45 ºC in the Vredendal/Koekenaap area, and the occurrence of snowfalls until mid-September in the Cederberg wilderness area. Precipitation varies from over 1 000 mm/annum in the

Cederberg Mountains to less than 100 mm/annum in the northern coastal areas (DWAF, 2009).

The Olifants-Doorn Water Management Area has been proclaimed in Government Notice No. 20491, dated 1 October 1999, as Water Management Area (WMA) No.17 and is described as follows: "The WMA is bounded by the Berg and the Breede WMAs to the south, the Gouritz WMA to the south-east, the Lower Orange WMA to the east and north and the Atlantic Ocean to the west. It lies on the West Coast of South-Africa, spread across two provincial jurisdictions, namely the Western Cape and the Northern Cape Provinces" (DWAF, 2009).

The Clanwilliam Dam was originally built in 1935, and was later raised by pre-stressed cables and by adding gates. The current height of the dam wall is 43 m and the storage capacity of the dam is 122 million m^3. The Bulshoek Dam which merely serves as a balancing dam is 15 km downstream and has a storage capacity of 5.3 million m^3. The total irrigated area dependent on the Clanwilliam Dam is 11 316 ha. Various small towns receive water from the dam, but the bulk of the water goes to the three irrigation areas below the dam, comprising the area served by the canal immediately below the dam, the area along the river between the Clanwilliam Dam and Bulshoek Dam and the area served by the canal below Bulshoek Dam. The main channel system is 261 km long with an additional 60 km of smaller channels (DWAF, 2009).

3.2.2 Water infrastructure

In the 1800s, irrigation practices along the Olifants and Doring Rivers were based on the use of higher summer flows. Predictably, these were not very reliable and, together with the erosion-related problems, it became necessary to seek alternative methods of irrigation (DWAF, 2009).

The construction of the Bulshoek Weir, located 24 km downstream of the Clanwilliam Dam on the Olifants River, commenced in 1913 and was completed in 1924. The full supply capacity of the dam was determined as 5 754 million m^3. The construction of the Clanwilliam Dam was completed in 1935 with a capacity of 69.86 million m^3. In 1962, it was decided to raise the Clanwilliam Dam by 6.10 m to increase the capacity to 128 million m^3 (DWAF, 2009).

Irrigation infrastructure in the ODWMA (Olifants/Doring Water Management Area) consists of irrigation directly out of the river, water pumped out of the river and stored in off-channel dams, and diversions of the river into irrigation canals. Below the Clanwilliam Dam, the Olifants River is used as the main conveyance system. Below the Bulshoek Dam, the Lower Olifants River Water Users Association (LORWUA) canal is the main conveyance system. Current canal losses are estimated as very high, and the canals and associated infrastructure are generally in a poor state (DWAF, 2009).

The water distribution infrastructure in the Clanwilliam Water Users' Association area consists of abstraction directly from the Clanwilliam Dam basin, a lined canal from the Clanwilliam Dam, and natural streams and rivers (DWAF, 2009).

The study will focus on the Lower Olifants River Water Users Association (LORWUA) which comprises the listed area of 9 510 ha below the Bulshoek Dam. Withdrawal rights as per listed hectares is 12 200 m^3/ha/year with a maximum extraction rate of 325 m^3/week. Although the official listing per hectare equals 12 200 m^3/ha/year, the maximum quota water received per year by irrigators will not exceed 8 400 m^3/ha/year, due to the maintenance programme and canal limitations.

3.2.3 Operating rules and principles

The operating rules for Clanwilliam Dam and Bulshoek Dam entail the following:

- The starting date of the new water year is 1 October every year.
- The water quota for irrigators is revised on a bi-weekly basis after taking into account the following:
    - 5% of Clanwilliam Dam’s capacity as reserve for household usage
    - Estimated evaporation losses
    - Transit and canal losses between Clanwilliam Dam and Bulshoek Dam.
- Industrial water allocation (industrial operations, municipalities, households, etc.) to users downstream of Bulshoek Dam.

A maximum quota of 8 400 m^3/ha per annum will be allocated to irrigators if the Clanwilliam Dam still overflows by end of November.

3.2.4 Restrictions on water source

During years of drought, the Clanwilliam Dam does not fill up and then restrictions are placed on the irrigation water users. The uncertainty of the quota for the next year causes the farmers to be more conservative in their irrigation development.

Table 3.1 lists the actual volume of water received per ha over the last eighteen years of restrictions that were implemented in the ODWMA, including the year and the restrictions for the LORWUA. The average over the 18 year period amounts to 6 485 m^3/ha/annum.

Table 3.1: List of actual volume of water received in the LORWUA (m^3/ha)

Year	Irrigation restrictions (m$^{3)}$	Year	Irrigation restrictions (m$^{3)}$
1994	6 100	2003	5 700
1995	5 929	2004	4 745
1996	4 400	2005	6 278
1997	4 400	2006	6 700
1998	5 400	2007	7 650
1999	7 150	2008	7 400
2000	5 530	2009	8 150
2001	7 600	2010	8 400
2002	8 200	2011	7 000

Source: LORWUA (2012)

3.2.5 Climate, natural resources and production potential

3.2.5.1 Climate

Refer to Section 2.6.1 for the climate change forecast for the Vredendal area.

3.2.5.2 Soil characteristics

Table 3.2 illustrates the soil characteristics in the LORWUA area.

Table 3.2: Soil characteristics - LORWUA

Location (Quinary nr.)	Thickness of Topsoil (m)	Thickness of Subsoil (m)	Wilting Point of Topsoil (m/m)	Wilting Point of Subsoil (m/m)	Field Capacity of Topsoil (m/m)	Field Capacity of Subsoil (m/m)	Porosity of Topsoil (m/m)	Porosity of Subsoil (m/m)	Saturated Drainage (fraction/ day)
2511	0.26	0.31	0.101	0.108	0.19	0.204	0.45	0.445	0.51

Source: School of agricultural, earth and environmental sciences, UKZN (2012)

The soils characteristics in Table 3.2 are area weighted from the land type information in the Institute for Soil, Climate and Water (ISCW) Land Type Survey Staff: 1972 - 2002 soils database for the Quinary Catchment in which the location of interest is sited. The 4-digit number (location) is the Quinary number in the SA Quinary Catchments Database (Schulze *et al*., 2010). The methods by which these characteristics for a 2-horizon soil have been derived are described in Schulze and Horan (2008) using the AUTOSOILS decision support system developed by Schulze and Pike (1995 and updates). Values of wilting points, field capacities and porosities (i.e. at saturation) imply the soil water content (in meter of water per meter thickness of soil) at those thresholds. Saturated drainage implies the fraction of soil water above field capacity that drains into the next horizon (i.e. from the topsoil to the subsoil or from the subsoil out of the active rooting zone) per day. The soils at LORWUA tend to be well drained and relatively sandy.

3.2.5.3 Adapted crops for the region

Main perennial crops produced in the area include wine grapes (7 175 ha), table grapes (900 ha) and raisins (694 ha). Table 3.3 illustrates the crop composition for the area (LORWUA survey, 2007).

Table 3.3: Types of crops planted in the LORWUA

Cash crops	Hectare (ha)	%
Tomatoes processing	215	2%
Tomatoes table	166	2%
Tomatoes tunnels	14	0%
Seed production	95	1%
Pastures		0%
Vegetables (open)	615	6%
Vegetables (protected)	60	1%
Total	**1 165**	**11%**
Perennial crops		
Table grapes	900	9%
Wine grapes	7 175	70%
Raisins	694	7%
Lucerne	130	1%
Other	164	2%
Total	**9 063**	89%
Total crops planted	**10 228**	**100%**

Source: Survey by LORWUA (2007)

Wine grapes are by far the most dominant crop in the LORWUA area and occupy more than 70% of hectares planted.

3.2.5.4 Crop irrigation requirements

Table 3.4 illustrates the annual crop irrigation requirements for wine grapes, raisins and table grapes. These crops were included in the model.

Table 3.4: Crop water requirements (m^3/ha)

Item	Wine grapes (m^3/ha)	Raisins (m^3/ha)	Table grapes (m^3/ha)
Jan	1 400	1 400	1 700
Feb	1 100	1 100	1 300
Mar	1 000	1 000	1 300
Apr	600	600	700
May	400	400	400
Jun	200	200	200
Jul	200	200	200
Aug	300	300	300
Sep	400	400	400
Oct	600	600	1 200
Nov	800	800	1 000
Dec	1 000	1 000	1 200
Total	8 000	8 000	9 900

Source: Joubert (2012)

3.2.5.5 Current cultivation practices

Table 3.5 summarises current cultivation practices of dominant crops for the LORWUA study area.

Table 3.5: Current cultivation practices

Cultivation practice	Wine grapes	Raisins	Table grapes
Optimum planting dates	Jul - Aug (If not enough water: Sept - Oct)	Jul - Aug (If not enough water: Sept - Oct)	Jul - Aug (If not enough water: Sept - Oct)
Lifespan of vineyard	20 years	20 years	20 years
Harvesting dates	Jan - Mar	Jan - Mar	Dec - Feb
Nitrogen application	Sept - Jan - 80 kg/ha Mar - Apr - 30 kg/ha	Sept - Jan - 80 kg/ha Mar - Apr - 30 kg/ha	Sept - Jan - 90 kg/ha Mar - Apr - 40 kg/ha

Source: LORWUA workshop and expert group discussions (2012)

3.2.5.6 Critical crop climate thresholds

The critical crop climate thresholds for different crops were collected during a workshop that was attended by various role-players, including amongst others, industry experts and farmers.

Table 3.6 summarises the critical crop climate thresholds for wine grapes, raisins and table grapes. These threshold values were used in the CCCT modelling to determine the impact of climate change on yield and quality.

Table 3.6: Critical climate thresholds for wine grapes, raisins and table grapes

Critical climate thresholds	Impact
Wine grapes	
Tmxd > 38 °C for 5 days	Negative
Tmxd> 45 °C in Nov	Negative
Tmxd> 42 °C Nov - Dec	Negative
Difference Tmax and Tmnd > 20 °C in Dec	Negative
Tmnd <9 °C and Tmxd < 20 °C May - Jun	Positive
Average temperature < 22 °C in summer	Positive
5 days above 40 °C	Negative
> 33 °C for > 5 days with high Tmnd	Negative
5-10 mm rain Dec - Jan	Negative
> 5 mm rain for 3 days Dec - Jan	Negative
Any Rain from Dec to Apr = bursting/rotting	Negative
Raisins	
Tmxd > 38 °C for 5 days	Negative
Tmxd > 45 °C in Nov	Negative
Tmxd > 42 °C Nov - Dec	Negative
Difference Tmax and Tmnd > 20 °C in Dec	Negative
Tmnd < 9 °C and Tmxd < 20 °C May - Jun	Positive
Average temperature < 22 °C in summer	Positive
5 days above 40 °C	Negative
> 33 °C for > 5 days with high Tmnd	Negative
5 - 10 mm rain Dec - Jan	Negative
> 5 mm for 3 days Dec - Jan	Negative
Any Rain from Dec to Apr = bursting/rotting	Negative
Table grapes	
Tmxd > 38 °C for 5 days	Negative
Tmxd > 45 °C in Nov	Negative
Tmxd > 42 °C Nov - Dec	Negative
Difference Tmax and Tmnd > 20 °C in Dec	Negative
Tmnd < 9 °C and Tmxd < 20 °C May - Jun	Positive
Average temperature < 22 °C in summer	Positive
Difference Tmxd and Tmnd < 10 °C Oct - Nov	Negative
> 33 °C for > 5 days with high Tmnd	Negative
5 - 10 mm rain Dec - Jan	Negative
> 5 mm for 3 days Dec - Jan	Negative

Source: LORWUA workshop and expert group discussions (2012)

Refer to Table 3.6 and Appendix B for threshold penalty weights for yield and quality. The critical thresholds for wine grapes can be interpreted as follows:

- Tmxd > 38 °C for 5 days during flowering – maximum daily temperature in excess of 38 °C for more than 5 consecutive days have a negative impact of -5% on yield.
- Tmxd > 45 °C in Nov – maximum daily temperature in excess of 45 °C in November have a negative impact of -5% on yield.
- Tmxd > 42 °C in Nov - Dec – maximum daily temperature in excess of 42 °C in November to December have a negative impact of -5% on yield.

- Difference Tmax and Tmnd > 20 °C in Dec – a difference between daily minimum and daily maximum temperature in excess of 20 °C during the month of December has a -5% impact on yield.
- Tmnd < 9 °C and Tmxd < 20 °C May-Jun – low temperatures during May and June positively impacts on yield (+10%).
- Average temperature < 22 °C in summer – average temperature below 22 °C during summer months positively impacts on yield (+10%).
- 5 days above 40 °C – daily maximum temperature in excess of 40°C for 5 days or more impact negatively on yield (-5%).
- > 33 °C for > 5 days with high Tmnd – daily maximum temperature in excess of 33 °C with high daily minimum temperatures impact negatively on quality (-5%).
- 5-10 mm rain Dec-Jan – 5-10 mm rain (or more) per day during the months of December and January impacts negatively on quality (-5%).
- > 5 mm rain for 3 days Dec-Jan – more than 5 mm rain per day for three consecutive days during the months of December and January impacts negatively on quality (-5%).
- Any rain from Dec-Apr = bursting/rotting – any rain from December to April cause bursting/rotting, which impacts negatively on quality (-5%).

Refer to Table 3.6 and Appendix B for threshold penalty weights for yield and quality. The critical thresholds for table grapes can be interpreted as follows:

- Tmxd > 38 °C for 5 days during flowering – maximum daily temperature in excess of 38 °C for more than 5 consecutive days have a negative impact of -5% on quality.
- Tmxd > 45 °C in Nov – maximum daily temperature in excess of 45 °C in November have a negative impact of -10% on yield and -5% on quality.
- Tmxd > 42 °C in Nov-Dec – maximum daily temperature in excess of 42 °C in November to December have a negative impact of -10% on yield and -5% on quality.
- Difference Tmax and Tmnd > 20 °C in Dec – a difference between daily minimum and daily maximum temperature in excess of 20 °C during the month of December have a -10% impact on yield and -5% impact on quality.

- Tmnd < 9 °C and Tmxd < 20 °C May-Jun – low temperatures during May and June positively impacts on yield (+10%) and quality (+10%).
- Average temperature < 22 °C in summer – average temperature below 22 °C during summer months positively impacts on yield (+10%) and quality (+10%).
- Difference Tmxd and Tmnd < 10 °C Oct-Nov – average of less than 10 °C in difference between maximum and minimum daily temperatures has negative impact (-5%) on quality.
- > 33 °C for > 5 days with high Tmnd – daily maximum temperature in excess of 33 °C with high daily min temperatures impact negatively on quality (-5%).
- 5-10 mm rain Dec-Jan – 5-10 mm rain (or more) per day during the months of December and January impacts negatively on quality (-5%).
- > 5 mm rain for 3 days Dec-Jan – more than 5 mm rain per day for three consecutive days during the months of December and January impacts negatively on quality (-5%).

Refer to Table 3.6 and Appendix B for threshold penalty weights for yield and quality. The critical thresholds for raisins can be interpreted as follows:

- Tmxd > 38 °C for 5 days during flowering – maximum daily temperature in excess of 38 °C for more than 5 consecutive days have a negative impact of -5% on yield.
- Tmxd > 45 °C in Nov – maximum daily temperature in excess of 45 °C in November has a negative impact of -10% on yield.
- Tmxd > 42 °C in Nov-Dec – maximum daily temperature in excess of 42 °C in November to December have a negative impact of -5% on yield.
- Difference Tmax and Tmnd > 20 °C in Dec – a difference between daily minimum and daily maximum temperature in excess of 20 °C during the month of December has a -5% impact on yield.
- Tmnd < 9 °C and Tmxd < 20 °C May-Jun – low temperatures during May and June positively impacts on yield (+10%).
- Average temperature < 22 °C in summer – average temperature below 22 °C during summer months positively impacts on yield (+10%).
- 5 days above 40 °C – daily maximum temperature in excess of 40 °C for 5 days or more impact negatively on yield (-10%).
- > 33 °C for > 5 days with high Tmnd – daily maximum temperatures in excess of 33 °C with high daily minimum temperatures impact negatively on quality (-5%).

- 5-10 mm rain Dec-Jan – 5-10 mm rain (or more) per day during the months of December and January impacts negatively on quality (-5%).
- > 5 mm rain for 3 days Dec-Jan – more than 5 mm rain per day for three consecutive days during the months of December and January impacts negatively on quality (-5%).
- Any rain from Dec-Apr = bursting/rotting – any rain from December to April cause bursting/rotting, which impacts negatively on quality (-5%).

3.2.5.7 Crop enterprise budgets

Table 3.7 and Table 3.8 summarise the crops enterprise budgets that were used in the modelling.

Table 3.7: Crop enterprise budget summary: Perennial crops

Red wine grapes Year	**0**	**1**	**2**	**3**	**4**	**5 - 20**
Yield (tonne/ha)		0	0	6	13	19
Gross income (R)		0	0	17 600	41 600	59 200
Yearly cash expenditure (R)	120 000	12 000	11 820	18 910	21 274	23 687
Margin above specified costs (R)	-120 000	-12 000	-11 820	-1 310	20 326	35 513
White wine grapes Year	**0**	**1**	**2**	**3**	**4**	**5 - 20**
Yield (tonne/ha)		0	0	11	26	30
Gross income (R)		0	0	21 450	50 700	58 500
Yearly cash expenditure (R)	108 000	12 000	10 745	17 191	19 340	21 534
Margin above specified costs (R)	-108 000	-12 000	-10 745	4 259	31 360	36 966
Table grapes Year	**0**	**1**	**2**	**3**	**4**	**5 - 20**
Yield (tonne/ha)		0	0	12	28	40
Gross income (R)		0	0	20 700	48 300	69 000
Yearly cash expenditure (R)	136 800	12 000	19 230	25 640	28 845	32 050
Margin above specified costs (R)	-136 800	-12 000	-19 230	-4 940	19 455	36 950
Raisins Year	**0**	**1**	**2**	**3**	**4**	**5 - 20**
Yield (tonne/ha)		0	0	11	25	36
Gross income (R)		0	0	26 169	59 475	85 644
Yearly cash expenditure (R)	136 800	12 000	20 287	27 050	30 431	33 812
Margin above specified costs (R)	-136 800	-12 000	-20 287	- 881	29 044	51 832

Source: Own calculations based on info from Vinpro, SAD and individual farmers (2012)

Table 3.8: Crop enterprise budget summary: Cash crops

Item	**Tomato**	**Butternut**	**Gem squash**
Yield (tonne/ha)	60	20	30
Gross income (R)	180 000	25 400	39 900
Yearly cash expenditure (R)	139 938	21 271	37 383
Margin above specified costs (R)	40 062	4 129	2 517

Source: Own calculations based on info from individual farmers (2012)

3.2.6 Description of selected case study farms

Two case studies that are representative of the study area were selected. The case studies were selected in association with Vinpro who runs several study groups in the area. Case Study 1 represents a typical small farm of 22 ha of wine grapes, raisins and table grapes. Case Study 2 represents an 86 ha farm which produces wine grapes, raisins and vegetables (see Table 3.9).

Table 3.9: Description of case study farms: LORWUA

Description	**Case study 1**	**Case study 2**
Farm size	92 ha	26 ha
Irrigable	86 ha	22 ha
Actual irrigated	86 ha	22 ha
Wasteland	6 ha	4 ha
Total farm size	**92 ha**	**26 ha**
Land use		
Perennial crops		
Wine grapes	71 ha	16.6 ha
Raisins	6 ha	1.8 ha
Table grapes		3.3 ha
Total area perennial crops	**77 ha**	**22 ha**
Cash crops		
Vegetables	9 ha	
Total area cash crops	**9 ha**	**0 ha**
Total area perennial and cash crops	**86 ha**	**22 ha**
Irrigation system (total area)		
Drip	86 ha	22 ha
Total	**86 ha**	**22 ha**
Water sources		
Canal	86 ha	22 ha
Entitlement per ha per annum	12,200 m^3	12,200 m^3
Valuation of farm	**(R)**	**(R)**
Fixed improvements	3 775 200	1 652 000
Vehicles, machinery, implements, livestock & other	3 813 000	962 000
Land	10 967 455	2 594 805
Total assets	**18 555 655**	**5 208 805**
Liabilities	**(R)**	**(R)**
Short term	0	0
Medium term	800 000	87 000
Long term	3 000 000	800 000
Total liabilities	**3 800 000**	**887 000**
Net asset value	**14 755 655**	**4 321 805**
Debt ratio	**20%**	**17%**

Source: Case study farmers' records (2012)

3.3 Description of Blyde River Water Users Association (Blyde River WUA)

3.3.1 Background

The Blyde River Catchment is approximately 2 000 km^2 in size covering an area inclusive of Graskop and Pilgrim's Rest in the south-east, Ohrigstad in the centre, and Hoedspruit in the east/north-east. The main river is the Blyde River (a tributary of the Olifants River) which is an international water course, shared by South Africa and Mozambique. The Blyde River has its origins in Mauchsberg in the Drakensberg range south of Pilgrim's Rest. For the first 60 km the Blyde River flows through the mountainous area surrounding Graskop and Pilgrim's Rest and through the scenic Blyde River Canyon. The main tributary of the Blyde River is the Ohrigstad River, which flows in a parallel northerly direction to the west of the Blyde River. The Ohrigstad River joins the Blyde River just upstream from Blydepoort Dam near the escarpment of the Drakensberg. The Blyde River flows 30 km into the Lowveld and into the Olifants River immediately north of the Blyde River irrigation area. The Blyde River Canyon is the third largest canyon in the world. Blydepoort Dam, situated upstream of the confluence of the Blyde and Olifants Rivers, was completed in 1974 in order to stabilise the flow of the Blyde River for irrigation and for urban and industrial use in the Phalaborwa region (DWAF, 2010).

3.3.2 Water abstractions

The main abstractions from the Blyde River are from irrigators that either obtain their water from the pipeline at the dam or pump from the river. There are no other major abstractors along the Blyde River except for the back-up station for Hoedspruit town which now gets its water from the pipeline. This pump station is no longer used. The other large abstraction takes place at the Phalaborwa Barrage which is operated by Lepelle Northern Water (DWAF, 2010).

There is 8 978 ha agricultural land for irrigation listed under the Blyde River Water Users Association (Blyde WUA). The pipeline supply water to 7 010 ha while irrigation water for 1 968 ha is pumped from the river. Irrigators are entitled to 9 900 m^3/listed ha.

3.3.3 Operating rules and principles

The new operating rule that was developed for the Blyde System is based on the knowledge gained from the yield analyses, existing operating rules and understanding of the total system and its requirements. From the long-term yield analyses it was found that the Blyderivierpoort Sub-system has a portion of excess yield (approximately 27 million m^3/a at a 1 in 10 year reliability of supply) that could possibly be allocated in the future if the full allocation of the Lepelle demand is shared between available flows in the Olifants River and Blyderivierpoort Dam. Short-term yield characteristics were built into the operating rule. The proposed new operating rule is fairly simple and entails the following:

- Apply the short-term yield characteristics for the Blyderivierpoort Sub-system every year on 1 February, 1 May, 1 August and 1 November to determine the surplus or deficit in the system by using the relevant storage level in the dam as reference.
- When there is a deficit in the Sub-system, impose curtailments according to the agreed priority classification. First curtail the low assurance use, then the medium low, followed by the medium high and high assurance use.

3.3.4 Restrictions on water source

The water supply from the Blyde catchment is fairly consistent. In the past ten years the only restrictions imposed on irrigators were during November and December 2003.

3.3.5 Climate, natural resources and production potential

3.3.5.1 Climate

See Section 2.6.2 for the climate change forecast for the Hoedspruit area.

3.3.5.2 Soil characteristics

Table 3.10 illustrates the soil characteristics in the Blyde River WUA area.

Table 3.10: Soil characteristics – Blyde River WUA

Location (Quinary nr.)	Thickness of Topsoil (m)	Thickness of Subsoil (m)	Wilting Point of Topsoil (m/m)	Wilting Point of Subsoil (m/m)	Field Capacity of Topsoil (m/m)	Field Capacity of Subsoil (m/m)	Porosity of Topsoil (m/m)	Porosity of Subsoil (m/m)	Saturated Drainage (fraction/ day)
0675	0.3	0.31	0.117	0.146	0.205	0. 230	0.454	0.442	0.43

Source: School of agricultural, earth and environmental sciences, UKZN (2012)

The soils characteristics given in the table are area weighted from the land type information in the ISCW soils database (ISCW, 2005) for the Quinary Catchment in which the location of interest is cited. The 4-digit number (location) is the Quinary number in the SA Quinary Catchments Database (Schulze *et al.*, 2010). The methods by which these characteristics for a 2-horizon soil have been derived are described in Schulze and Horan (2008) using the AUTOSOILS decision support system developed by Schulze and Pike (1995 and updates). Values of wilting points, field capacities and porosities (i.e. at saturation) imply the soil water content (in meter of water per meter thickness of soil) at those thresholds. Saturated drainage implies the fraction of soil water above field capacity that drains into the next horizon (i.e. from the topsoil to the subsoil or from the subsoil out of the active rooting zone) per day. The soils tend to gradually become sandier and less clayey in the Blyde River WUA area.

3.3.5.3 Adapted crops for the region

Main crops produced in the area include citrus (3 700 ha) and mangoes (3 500 ha) (see Table 3.11). Other crops produced on a smaller scale include, amongst others, vegetables (open and protected), sweet corn and maize seed. The production of peppers under net irrigation constitutes approximately fifty hectares but cannot be regarded as typical for the region. During the past couple of years there seems to be a shift in production patterns. Citrus production increased and vegetable production decreased substantially when Tiger Brands decided to close down their tomato processing plant in Hoedspruit.

Table 3.11: Types of crops planted in Blyde River WUA area

Cash crops	Hectare	%
Sweetcorn	200	2%
Seed production (maize)	200	2%
Vegetables (open)	550	7%
Vegetables (protected)	50	1%
Total	**1 000**	**12%**
Perennial crops		
Citrus	3 700	45%
Mangoes	3 500	43%
Total	**7 200**	**88%**
Total crops planted	**8 200**	**100%**

Source: Own estimates based on interviews with industry leaders (2012)

For the purpose of a representative case study the production of citrus and mangoes are included as main crops.

3.3.5.4 Crop irrigation requirements

Table 3.12 illustrates annual crop water requirements for mangoes and citrus.

Table 3.12: Crop water requirements (m^3/ha)

Item	Mangoes	Citrus
Jan	840	1 020
Feb	840	1 020
Mar	525	935
Apr	525	510
May	233	425
Jun	233	255
Jul	233	255
Aug	525	425
Sep	525	765
Oct	840	850
Nov	840	1 020
Dec	840	1 020
Total	7 000	8 500

Source: Du Preez (2012)

3.3.5.5 Current cultivation practices

Table 3.13 summarises the current cultivation practises for citrus and mangoes in the Blyde River WUA area.

Table 3.13: Current cultivation practices

Cultivation practice	Citrus	Mangoes
Optimum planting dates	Feb - Apr	Sept - Feb
Lifespan of orchards	25 years	35 years
Harvesting dates	Apr - Aug	Jan - Mar
Nitrogen application	Oct - Dec - 30 kg/ha Jul - Sept - 90 kg/ha	Jan - Mar - 35 kg/ha Jul - Sept - 15 kg/ha

Source: Blyde River WUA expert group discussions (2012)

3.3.5.6 Crop critical climate thresholds

When breaching a critical climate threshold, the impact on yield and/or quality can be either positive or negative. The critical crop climate thresholds for different crops were collected during a workshop which was attended by various role-players, including amongst others, industry experts and farmers.

Table 3.14 shows the critical climate thresholds for different citrus types namely oranges (Valencia), lemons and grapefruit.

Table 3.14: Critical climate thresholds for citrus

Critical climate thresholds	Impact
Citrus - Valencia	
Tmxd > 40 °C and RH < 30% for 2 days Sept	Negative
Tmxd >35 °C and RH < 30% for 2 days Sept	Negative
Tmxd > 35 °C and RH < 20% for 2 days Sept	Negative
Fruit drop (Nov/Dec) >7 days of Tmxd > 36 °C and RH < 40%	Negative
During picking temp > 36 °C - increase rind problems	Negative
> 14 days continuous rain during picking (autumn) causes leaf wetness and overripe fruit	Negative
Citrus - Lemons	
Tmxd > 40 °C and RH < 30% for 2 days Sept	Negative
Tmxd >35 °C and RH < 30% for 2 days Sept	Negative
Tmxd > 35 °C and RH < 20% for 2 days Sept	Negative
Fruit drop (Nov/Dec) >7 days of Tmxd > 36 °C and RH < 40%	Negative
During picking temp > 36 °C - increase rind problems	Negative
>14 days continuous rain during picking (autumn) causes leaf wetness and overripe fruit	Negative
Citrus - Grapefruit	
Tmxd > 40 °C and RH < 30% for 2 days Sept	Negative
Tmxd >35 °C and RH < 30% for 2 days Sept	Negative
Tmxd > 35 °C and RH < 20% for 2 days Sept	Negative
Fruit drop (Nov/Dec) >7 days of Tmxd > 36 °C and RH < 40%	Negative
2 °C warmer in May - colour deteriorates	Negative
During picking temp > 36 °C - increase rind problems	Negative
>14 days continuous rain during picking (autumn) causes leaf wetness and overripe fruit	Negative

Source: Blyde River WUA workshop and expert group discussions (2012)

Refer to Table 3.14 and Appendix B for threshold penalty weights for yield and quality. The critical thresholds for citrus can be interpreted as follows:

Valencia

- Tmxd > 40 °C and RH < 30% for 2 days Sept – daily maximum temperature in excess of 40 °C and relative humidity less than 30% for 2 days or more during the month of September have a negative impact of -25% on yield.
- Tmxd >35 °C and RH < 30% for 2 days Sept - daily maximum temperature in excess of 35 °C and relative humidity less than 30% for 2 days or more during the month of September have a negative impact of -15% on yield.
- Tmxd >35 °C and RH < 20% for 2 days Sept - daily maximum temperature in excess of 35 °C and relative humidity less than 30% for 2 days or more during the month of September have a negative impact of -15% on yield.

- Fruit drop (Nov/Dec) > 7 days of Tmxd > 36 °C and RH < 40% - daily maximum temperatures in excess of 36 °C and relative humidity less than 40% for 7 days and more during November and December cause fruit drop and have a negative impact on yield (-40%).
- During picking temp > 36 °C - increase rind problems – maximum daily temperatures in excess of 36 °C increase rind problems and have a negative effect on quality (-1%).
- >14 days continuous rain during picking (autumn) causes leaf wetness and overripe fruit – negative impact of -8% on quality.

Lemons

- Tmxd > 40 °C and RH < 30% for 2 days Sept – daily maximum temperature in excess of 40 °C and relative humidity less than 30% for 2 days or more during the month of September have a negative impact of -25% on yield.
- Tmxd >35 °C and RH < 30% for 2 days Sept - daily maximum temperature in excess of 35 °C and relative humidity less than 30% for 2 days or more during the month of September have a negative impact of -15% on yield.
- Tmxd >35 °C and RH < 20% for 2 days Sept - daily maximum temperature in excess of 35 °C and relative humidity less than 30% for 2 days or more during the month of September have a negative impact of -15% on yield.
- Fruit drop (Nov/Dec) > 7 days of Tmxd > 36 °C and RH < 40% - daily maximum temperatures in excess of 36 °C and relative humidity less than 40% for 7 days and more during November and December cause fruit drop and have a negative impact on yield (-40%).
- During picking temp > 36 °C - increase rind problems – maximum daily temperatures in excess of 36 °C increase rind problems and have a negative effect on quality (-1%).
- >14 days continuous rain during picking (autumn) causes leaf wetness and overripe fruit – negative impact of -15% on quality.

Grapefruit

- Tmxd > 40 °C and RH < 30% for 2 days Sept – daily maximum temperature in excess of 40 °C and relative humidity less than 30% for 2 days or more during the month of September have a negative impact of -40% on yield.

- Tmxd >35 °C and RH < 30% for 2 days Sept - daily maximum temperature in excess of 35 °C and relative humidity less than 30% for 2 days or more during the month of September have a negative impact of -40% on yield.
- Tmxd >35 °C and RH < 20% for 2 days Sept - daily maximum temperature in excess of 35 °C and relative humidity less than 30% for 2 days or more during the month of September have a negative impact of -40% on yield.
- Fruit drop (Nov-Dec) > 7 days of Tmxd > 36 °C and RH < 40% - daily maximum temperatures in excess of 36 °C and relative humidity less than 40% for 7 days and more during November and December cause fruit drop and have a negative impact on yield (-30%) and quality (-10%).
- 2 °C warmer temperatures in May cause colour to deteriorate - impact negatively on quality (-4%).
- During picking temp > 36 °C - increase rind problems – maximum daily temperatures in excess of 36 °C increase rind problems and have a negative effect on quality (-1%).
- >14 days continuous rain during picking (autumn) causes leaf wetness and overripe fruit and has a negative impact of -10% on quality.

Table 3.15 shows the critical climate thresholds for different mango cultivars namely Keitt, Kent and Tommy Atkins.

Table 3.15: Critical climate thresholds for mangoes

Critical Climate Thresholds	**Impact**
Mango - Keitt	
Average May Tmnd 3 °C warmer	Negative
Tmnd < 2 °C Jul - Aug	Negative
Sept - Dec (HU requirement 350 hours > 17.9 °C) cool temps averaging < 17.9 °C cause late maturation and market delivery delay	Negative
Tmxd > 38 °C Dec - Jan	Negative
Mango - Kent	
Average May Tmnd 3 °C warmer	Negative
Tmnd < 2 °C Jul - Aug	Negative
Tmxd > 38 °C Sept	Negative
Sept - Dec (HU requirement 350 hours > 17.9 °C) cool temps averaging < 17.9 °C cause late maturation and market delivery delay	Negative
Tmxd > 38 °C Dec - Jan	Negative
Mango - Tommy Atkins	
Average May Tmnd 3 °C warmer	Negative
Tmnd < 2 °C Jul - Aug	Negative
Sept - Dec (HU requirement 350 hours > 17.9 °C) cool temps averaging < 17.9 °C cause late maturation and market delivery delay	Negative
Tmxd > 38 °C Dec - Jan	Negative

Source: Blyde River WUA workshop and expert group discussions (2012)

Refer to Table 3.15 and Appendix B for threshold penalty weights for yield and quality. The critical thresholds for mangoes can be interpreted as follows:

Keitt

- Average May Tmnd 3 °C warmer – an increase of 3% in average minimum temperatures for the month of May will impact negatively on yield (-4%).
- Tmnd < 2 °C Jul – Aug – minimum daily temperatures less than 2 °C have a negative impact on yield (-4%).
- Sept-Dec (HU requirement 350 hours > 17.9 °C) cool temps averaging < 17.9 °C cause late maturation and market delivery delay – less than the required 350 hours heat units > 17.9 °C during September to December has a negative impact on quality (-10%).
- Tmxd > 38 °C Dec-Jan – maximum daily temperature in excess of 38 °C during the months of December to January have a negative impact on yield (-1%) and quality (-1%).

Kent

- Average May Tmnd 3 °C warmer – an increase of 3% in average minimum temperatures for the month of May will impact negatively on yield (-8%).
- Tmnd < 2 °C Jul – Aug – minimum daily temperatures less than 2 °C have a negative impact on yield (-8%).
- Tmxd > 38 °C Sept – maximum daily temperatures in excess of 38 °C during the month of September impact negative on yield (-1%) and quality (-1%).
- Sept-Dec (HU requirement 350 hours > 17.9 °C) cool temps averaging < 17.9 °C cause late maturation and market delivery delay – less than the required 350 hours heat units > 17.9 °C during September to December have a negative impact on quality (-10%).
- Tmxd > 38 °C Dec – Jan – Maximum daily temperature in excess of 38 °C during the months of December to January has negative impact on yield (-1%) and quality (-1%).

Tommy Atkins

- Average May Tmnd 3 °C warmer – an increase of 3% in average minimum temperatures for the month of May will impact negatively on yield (-6%).
- Tmnd < 2 °C Jul-Aug – Minimum daily temperatures less than 2 °C have a negative impact on yield (-6%).

- Sept-Dec (HU requirement 350 hours > 17.9 °C) cool temps averaging < 17.9 °C cause late maturation and market delivery delay – less than the required 350 hours heat units > 17.9 °C during September to December has a negative impact on quality (-20%).
- Tmxd > 38 °C Dec-Jan – Maximum daily temperature in excess of 38 °C during the months of December to January have a negative impact on yield (-1%) and quality (-1%).

3.3.5.7 Crop enterprise budgets

Table 3.16 to Table 3.17 summarise the crop enterprise budgets for mangoes and citrus for the Blyde River WUA case studies.

Table 3.16: Crop enterprise budget summary: mangoes

Item Year	0	1	2	3	4	5	6	7	8	9 - 30
Yield (tonne/ha)		0	0	3	5	7	12	18	22	27
Gross income (R)		0	0	10 914	18 190	25 466	43 656	65 484	80 036	98 226
Yearly cash expenditure (R)	41 433	10 500	30 705	36 048	41 948	43 843	49 489	55 174	58 964	63 702
Margin above specified costs (R)		- 10 500	- 30 705	- 25 134	- 23 758	- 18 377	- 5 833	10 310	21 072	34 524

Source: Own calculations with inputs from Mango Growers Association (2012)

Table 3.17: Crop enterprise budget summary: citrus

Item Year	0	1	2	3	4	5	6	7 - 30
Yield (tonne/ha)		0	0	5	10	20	40	60
Gross income (R)		0	0	11 795	23 590	47 180	94 360	141 540
Yearly cash expenditure (R)	55 134	10 200	13 116	25 515	36 769	50 720	77 709	104 737
Margin above specified costs (R)	- 55 134	- 10 200	- 13 116	- 13 720	- 13 179	- 3 540	16 651	36 803

Source: Own calculations with inputs from Citrus Growers Association (2012)

3.3.6 Description of selected case study farms

Two case studies that are representative of the study area were selected (see Table 3.18). The selected case studies were selected from the survey which was undertaken during

2011. Case Study 1 represents a typical farm of sixty five hectares of mangoes and citrus. Case Study 2 represents a bigger farm (130 ha) farm which produces citrus and mangoes.

Table 3.18: Description of case study farms: Blyde River WUA

Description	**Case study 1**	**Case study 2**
Farm size	70 ha	140 ha
Irrigable	65 ha	130 ha
Actual irrigated	65 ha	130 ha
Waste land	5 ha	10 ha
Total farm size	**70 ha**	**150 ha**
Land use		
Perennial crops		
Mangos	55 ha	10 ha
Citrus	10 ha	120 ha
Total area perennial crops	**65 ha**	**130 ha**
Cash crops		
	0 ha	0 ha
Total area cash crops	**0 ha**	**0 ha**
Total area perennial and cash crops	**65 ha**	**130 ha**
Irrigation system (total area)		
Drip	65 ha	130 ha
Total (ha)	**65 ha**	**130 ha**
Water sources		
Pipeline	65 ha	130 ha
Total (ha)	65 ha	130 ha
Entitlement per ha per annum	9 900 m^3	9 900 m^3
Valuation of farm	**(R)**	**(R)**
Fixed improvements	1 140 000	2 940 000
Vehicles, machinery, implements, livestock, etc	560 000	1 500 000
Land	5 950 000	13 150 000
Total assets	**7 650 000**	**17 590 000**
Liabilities	**(R)**	**(R)**
Short term	1 050 000	2 000 000
Medium term	200 000	500 000
Long term	2 000 000	2 000 000
Total liabilities	**3 250 000**	**4 500 000**
Net asset value (R)	**4 400 000**	**13 090 000**
Debt ratio	**42%**	**26%**

Source: Case study farmers' records (2012)

3.4 Description of the Moorreesburg dryland mixed farming area

3.4.1 Background

A case study farm was selected in Moorreesburg, Western Cape, to model the impact of climate change on a typical winter rainfall dryland mixed farming system. The selection of the case study was done in conjunction with the Moorreesburgse Koringboere (Edms) Beperk (MKB), who also assisted with the provision of data, information and study group results. The participating case study farm has a high level of record keeping and provided, with assistance of the MKB, most of the information needed to do the modelling.

3.4.2 Climate, natural resources and production potential

3.4.2.1 Climate

See Section 2.6.3 for the climate change forecast for the Moorreesburg area.

3.4.2.2 Soil characteristics

Table 3.19 illustrates the soil characteristics in the Moorreesburg area.

Table 3.19: Soil characteristics - Moorreesburg

Location (Quinary nr.)	Thickness of Topsoil (m)	Thickness of Subsoil (m)	Wilting Point of Topsoil (m/m)	Wilting Point of Subsoil (m/m)	Field Capacity of Topsoil (m/m)	Field Capacity of Subsoil (m/m)	Porosity of Topsoil (m/m)	Porosity of Subsoil (m/m)	Saturated Drainage (fraction/ day)
2625	0.29	0.77	0.069	0.076	0.163	0.18	0.455	0.466	0.63

Source: School of agricultural, earth and environmental sciences, UKZN (2012)

The soils characteristics supplied in Table 3.19 are area weighted from the land type information in the ISCW soils database (ISCW, 2005) for the Quinary Catchment in which the location of interest is sited. The 4-digit number (location) is the Quinary number in the SA Quinary Catchments Database (Schulze *et al.*, 2010). The methods by which these characteristics for a 2-horizon soil have been derived are described in Schulze and Horan (2008) using the AUTOSOILS decision support system developed by Schulze and Pike (1995 and updates). Values of wilting points, field capacities and porosities (i.e. at saturation) imply the soil water content (in meter of water per meter thickness of soil) at those thresholds. Saturated drainage implies the fraction of soil water above field capacity that drains into the next horizon (i.e. from the topsoil to the subsoil or from the subsoil out of the active rooting zone) per day. The soils in the Moorreesburg area tend to be well drained and relatively sandy.

3.4.2.3 Adapted crops for the region

Wheat is by far the dominant crop produced in the area and accounted for 96% of crop production in 1996 (MKB, 2012). Other smaller crops include canola, lupines, oats and triticale. Livestock production consists mainly of sheep (mutton and wool production).

Table 3.20 reflects the physiological lifecycle of wheat.

Table 3.20: Physiological lifecycle of wheat

Wheat	
Planting	May
Germination	May
Tillering stage	Jun - Jul
Jointing and booting stage	Jul
Heading and flowering stage	Aug
Harvesting	Oct - Nov

Source: Moorreesburg workshop and expert group discussions (2012)

3.4.2.4 Current cultivation practices

Table 3.21 summarises the current cultivation practises for wheat in the Moorreesburg area.

Table 3.21: Current cultivation practices

Cultivation practice	Wheat
Optimum planting dates	May
Lifespan	1 year
Harvesting dates	Oct - Nov
Nitrogen application	May - 15 kg/ha Jun - 20 kg/ha Jul - 20 kg/ha

Source: Moorreesburg workshop and expert group discussions (2012)

3.4.2.5 Livestock

The case study farm shows typical Swartland mixed farming activities consisting of wheat and livestock (mutton and wool production).

Table 3.22 reflects the carrying capacity for the farm.

Table 3.22: Carrying capacity for the Moorreesburg case study

Carrying capacity	
Medics	1.25 SSU/ha/year
Wheat stubble	5 SSU/ha for 90 days

Source: Moorreesburg workshop and expert group discussions (2012)

3.4.2.6 Crop climate thresholds

When breaching a critical climate threshold, the impact on yield and/or quality can be either positive or negative. The critical crop climate thresholds for different crops were collected during a workshop that was attended by various role-players, including amongst others, industry experts and the case study farmer.

Table 3.23 shows the critical climate thresholds for wheat.

Table 3.23: Critical climate thresholds for wheat

Critical climate thresholds	Impact
Mid May - Aug Tmxd > 20 °C	Negative
Tmxd > 25 °C in Sept	Negative
Rainfal May - less than 50 mm	Negative
Rainfal May - Sept < 200 mm	Negative
Rainfal May - Sept > 400 mm	Positive
Rainfal May - Sept > 10 mm/week	Positive
Rainfal Sept weeks 1 and 2 > 10 mm	Positive
Rainfal Sept weeks 3 and 4 > 10 mm	Positive
May-Jun no rain	Negative
Jun - Jul < 70 mm	Negative
Jul - Aug < 70 mm	Negative
Sept < 15 mm	Negative
Sept < 5 mm	Negative

Source: Moorreesburg workshop and expert group discussions (2012)

Refer to Table 3.23 and Appendix B for threshold penalty weights for yield and quality. The critical thresholds for wheat can be interpreted as follows:

- Mid May-Aug Tmxd > 20 °C – maximum daily temperatures in excess of 20 °C from mid-May to August have a negative impact of -10% on yield.
- Tmxd > 25 °C in Sept – maximum daily temperatures in excess of 25 °C in September have a negative impact of -10% on yield.
- Rainfall May - less than 50 mm – less than 50 mm of rain in the month of May impacts negatively on yield (-10%).
- Rainfall May - Sept < 200 mm – less than 200 mm of rainfall for the period from May to September has a -30% negative impact on yield.
- Rainfall May - Sept > 400 mm – more than 400 mm of rainfall from May to September has a positive impact on yield (+20%).
- Rainfall May-Sept > 10 mm/week – weekly rainfall of 10 mm or more from May to September positively impact on yield (33%).
- Rainfall Sept weeks 1 and 2 > 10 mm – rainfall of 10 mm or more during week 1 and week 2 of September impacts positively on yield (+10%).
- Rainfall Sept weeks 3 and 4 > 10 mm – rainfall of 10 mm or more during week 3 and week 4 of September has a positive impact on yield (+10%).
- May-Jun no rain – no rain during May and June results in -10% impact on yield.

- Jun - Jul < 70 mm – less than 70 mm of rain from June to July has a negative impact on yield (-10%).
- Jul - Aug < 70 mm – less than 70 mm of rain from July to August has a negative impact on yield (-10%).
- Sept < 15 mm – less than 15 mm of rainfall in September impacts negatively on yield (-10%).
- Sept < 5 mm – less than 5 mm of rain during the month of September has a negative impact on yield (-10%).

3.4.2.7 Crop enterprise budgets

Table 3.24 and Table 3.25 summarise the crop enterprise budgets for wheat, medics, mutton and wool production for the Moorreesburg case study.

Table 3.24: Crop enterprise budget summary: wheat and medics

Item	Wheat after medics	Medics yearly cost
Yield (tonne/ha)	3	0
Price per tonne (R)	2 500	0
Income/ha (R)	7 500	0
Total cash expenditure/ha (R)	3 940	459
Margin above specified costs (R)	3 560	- 459

Source: Hough and Coetzee (2012)

Table 3.25: Crop enterprise budget summary: mutton and wool production

Assumptions	
Weaning %	90%
Weaning weight (kg)	20 kg
Price/kg (R)	R42
Kg wool/ewe	2 kg
Price/kg (R)	R75
Income and cost (gross margin)	
Income per ewe (R)	R906
Total cost per ewe (R)	R284
Gross margin per ewe (R)	R622

Source: Hough and Coetzee (2012)

3.4.3 Description of selected case study farm

Table 3.26 reflects the composition of the selected winter rainfall case study farm.

Table 3.26: Description of case study farm: Moorreesburg

Description	
Farm size	1 010 ha
Dryland	445 ha
Pastures	445 ha
Veldt	107 ha
Waste land	13 ha
Total farm size	**1 010 ha**
Land use	
Perennial crops	
Medics	445 ha
Total area perennial crops	**445 ha**
Cash crops	
Wheat after medics	445 ha
Total area cash crops	**445 ha**
Total area perennial and cash crops	**890 ha**
Livestock	
Sheep (producing ewes)	1 300
Valuation of farm	**(R)**
Fixed improvements	2 600 000
Vehicles, machinery, implements, livestock, etc	7 235 800
Land	9 520 000
Total assets	**19 355 800**
Liabilities	**(R)**
Short-term	1 570 000
Medium term	750 000
Long-term	630 000
Total liabilities	**2 950 000**
Net asset value (R)	**16 405 800**
Debt ratio	**15%**

Source: Case study farmer's records (2012)

3.5 Description of the Carolina dryland mixed farming area

3.5.1 Background

A case study farm was selected in Carolina, Mpumalanga to model the impact of climate change on a typical summer rainfall dryland farming system. The participating case study farm has a high level of record keeping and provided most of the information needed to do the modelling.

Agriculture in the Carolina region is generally dominated by extensive grain production and the grazing of beef cattle and sheep. Mainline grain production includes maize, sugar beans, soybeans and sunflowers.

3.5.2 Climate, natural resources and production potential

3.5.2.1 Climate

See Section 2.6.4 for the climate change forecast for the Carolina area.

3.5.2.2 Soil characteristics

Table 3.27 illustrates the soil characteristics in the Carolina area.

Table 3.27: Soil characteristics – Carolina

Location (Quinary nr.)	Thickness of Topsoil (m)	Thickness of Subsoil (m)	Wilting Point of Topsoil (m/m)	Wilting Point of Subsoil (m/m)	Field Capacity of Topsoil (m/m)	Field Capacity of Subsoil (m/m)	Porosity of Topsoil (m/m)	Porosity of Subsoil (m/m)	Saturated Drainage (fraction/ day)
0429	0.3	0.58	0.116	0.158	0.205	0.243	0.456	0.433	0.44

Source: School of agricultural, earth and environmental sciences, UKZN (2012)

The soils characteristics are area weighted from the land type information in the ISCW soils database (ISCW, 2005) for the Quinary Catchment in which the location of interest is sited. The 4-digit number (location) is the Quinary number in the SA Quinary Catchments Database (Schulze *et al*., 2010). The methods by which these characteristics for a 2-horizon soil have been derived are described in Schulze and Horan (2008) using the AUTOSOILS decision support system developed by Schulze and Pike (1995 and updates). Values of wilting points, field capacities and porosities (i.e. at saturation) imply the soil water content (in meter of water per meter thickness of soil) at those thresholds. Saturated drainage implies the fraction of soil water above field capacity that drains into the next horizon (i.e. from the topsoil to the subsoil or from the subsoil out of the active rooting zone) per day. From the characteristics in the table the soils tend to have a sandy loam texture at Carolina.

3.5.2.3 Adapted crops for the region

Main crops produced in the area include maize, sugar beans and soybeans. Livestock production consists mainly of cattle (weaner production), sheep (mutton and wool production) and dairy production.

Table 3.28 reflects the physiological lifecycle of maize, sugar beans and soybeans.

Table 3.28: Physiological lifecycle of maize, sugar beans and soybeans

Maize	
Planting	Oct and first half of Nov
Germination	Nov
Leaf development stage	Nov, Dec to mid Jan
Plume & cob development	Mid Jan to end Feb
Harvesting	May, Jun and Jul
Sugar beans	
Planting	Mid Nov
Germination	Nov
Leaf development stage	Dec to mid Jan
Flowering stage	Mid to end Jan
Pods development	Feb
Harvesting	Mar
Soybeans	
Planting	Mid Nov
Germination	Nov
Leaf development stage	Dec to mid Jan
Flowering stage	Mid to end Jan
Pods development	Feb
Harvesting	Apr - May

Source: Carolina workshop and expert group discussions (2012)

3.5.2.4 Current cultivation practices

Table 3.29 summarises the current cultivation practices for maize, soybeans and sugar beans in the Carolina area.

Table 3.29: Current cultivation practices

Cultivation practice	**Maize - dryland**
Optimum planting dates	Oct
Lifespan	1 year
Harvesting dates	May - Jul
Nitrogen application	Oct - 20 kg/ha Dec - 90 kg/ha
Cultivation practice	**Soybeans - dryland**
Optimum planting dates	Nov
Lifespan	1 year
Harvesting dates	Apr - May
Nitrogen application	Nov - 10 kg/ha
Cultivation practice	**Sugar beans - dryland**
Optimum planting dates	Nov
Lifespan	1 year
Harvesting dates	Mar
Nitrogen application	Nov - 20 kg/ha

Source: Carolina workshop and expert group discussions (2012)

Crop rotation includes maize and soybeans/sugar beans.

3.5.2.5 Livestock

The case study farm has typical Highveld mixed farming activities consisting of grain and livestock production. Activities include weaner calf, lamb and wool production.

Table 3.30 reflects the carrying capacity for the farm.

Table 3.30: Carrying capacity – Carolina case study

Carrying capacity	
Natural veld	3 ha/LSU/year
Natural veld	1 SSU/ha/year
Field (post harvest)	1 LSU/ha for 75 days
Field (post harvest)	6 SSU/ha for 75 days

Source: Case study farmer (2012)

3.5.2.6 Crop climate thresholds

When breaching a critical climate threshold, the impact on yield and/or quality can be either positive or negative. The critical crop climate thresholds for different crops were collected during a workshop which was attended by various role-players, including amongst others, industry experts and the case study farmer.

Table 3.31 shows the critical climate thresholds for maize, soybeans and sugar beans.

Table 3.31: Critical climate thresholds for maize, soybeans and sugar beans

Critical Climate Thresholds	**Impact**
Maize	
Tmnx < -5 °C in Dec	Negative
Tmxd > 35 °C for 3+ days Jan - Feb	Negative
Tmnd < 12 °C in Nov	Negative
Rainfall < 40 mm in Oct	Negative
Rainfall < 60 mm in Nov	Negative
Rainfall < 80 mm in Dec	Negative
Rainfall < 100 mm in Jan	Negative
Rainfall < 60 mm in Feb	Negative
Rainfall > 80 mm in Feb	Positive
Rainfall > 80 mm in Mar	Positive
Rainfall > 160 mm in Feb - Mar	Positive
Soybeans	
Tmnd < -5 °C Oct - Jan	Negative
Tmxd > 28 °C for 3+ days in mid Jan - Feb	Negative
Average temperature > 25 °C in Nov	Negative
Tmxd > 35 °C Jan	Negative
Tmxd > 30 °C with low RH in Jan	Negative
Rainfall < 50 mm in Nov	Negative
Rainfall < 80 mm in Dec	Negative
Rainfall < 100 mm in Jan	Negative
Rainfall < 60 mm in Feb	Negative
Rainfall < 40 mm Jan	Negative
Rainfall > 60 mm and < 150 mm in Feb	Positive
Rainfall > 60 mm and < 150 mm in Mar	Positive
Rainfall > 120 mm and < 300 mm in Feb - Mar	Positive
Sugar beans	
Tmnd < -5 °C Oct - Jan	Negative
Tmxd > 26 °C for 3+ days in mid Jan - Feb	Negative
Tmxd > 30 °C with high RH in Jan	Negative
Tmxd > 30 °C during Jan	Negative
Rainfall < 50 mm in Nov	Negative
Rainfall < 80 mm in Dec	Negative
Rainfall < 100 mm in Jan	Negative
Rainfall < 60 mm in Feb	Negative
Rainfall > 140 mm in Jan	Positive
Rainfall > 60 mm en < 100 mm in Feb	Positive
Rainfall > 60 mm en < 100 mm in Mar	Positive
Rainfall > 120 mm en < 200 mm in Feb - Mar	Positive

Source: Carolina workshop and expert group discussions (2012)

Refer to Table 3.31 and Appendix B for threshold penalty weights for yield and quality.

The critical thresholds for wheat can be interpreted as follows:

Maize

- Tmnx < -5 °C in Dec – daily minimum temperature of less than -5 °C results in a -5% reduction in yield.
- Tmxd > 35 °C for 3+ days Jan-Feb – maximum daily temperatures of 35 °C for 3 days or more during January and February have a negative impact on yield (-5%).
- Tmnd < 12 °C in Nov – minimum daily temperatures of less than 12 °C negatively impact on yield (-1%).
- Rainfall < 40 mm in Oct – less than 40 mm of rain during the month of October has a negative impact on yield (-5%).
- Rainfall < 60 mm in Nov - less than 60 mm of rain during the month of November has a negative impact on yield (-5%).
- Rainfall < 80 mm in Dec - less than 80 mm of rain during the month of December has a negative impact on yield (-5%).
- Rainfall < 100 mm in Jan - less than 100 mm of rain during the month of January has a negative impact on yield (-15%).
- Rainfall < 60 mm in Feb - less than 60 mm of rain during the month of February has a negative impact on yield (-5%).
- Rainfall > 80 mm in Feb – more than 80 mm of rain during the month of February has a positive impact on yield (+10%).
- Rainfall > 80 mm in Mar – more than 80 mm of rain during the month of March has a positive impact on yield (+10%).
- Rainfall > 160 mm in Feb-Mar – more than 160 mm of rain during February and March has a positive impact on yield (+10%).

Soybeans

- Tmnd < -5 °C Oct – Jan – daily minimum temperatures less than -5 °C during October to January impact negatively on yield (-50%).
- Tmxd > 28 °C for 3+ days in mid Jan-Feb – maximum daily temperatures in excess of 28 °C for 3 days or more from mid-January to end of February have a negative impact on yield (-5%).
- Average temperature > 25 °C in Nov – average temperature in excess of 25 °C impacts negatively on yield (-10%).
- Tmxd > 35 °C Jan – maximum daily temperatures in excess of 35 °C during the month of January have a negative impact on yield (-10%).

- Tmxd > 30 °C with low RH in Jan - maximum daily temperatures in excess of 30 °C with low relative humidity during the month of January have a negative impact on yield (-10%).
- Rainfall < 50 mm in Nov - less than 50 mm of rain during the month of November has a negative impact on yield (-10%).
- Rainfall < 80 mm in Nov - less than 80 mm of rain during the month of December has a negative impact on yield (-10%).
- Rainfall < 100 mm in Jan - less than 100 mm of rain during the month of January has a negative impact on yield (-10%).
- Rainfall < 60 mm in Feb - less than 60 mm of rain during the month of February has a negative impact on yield (-10%).
- Rainfall < 40 mm in Jan - less than 40 mm of rain during the month of January has a negative impact on yield (-10%).
- Rainfall > 60 mm and < 150 mm in Feb – total rainfall of more than 60 mm but less than 150 mm during the month of February has a positive impact on yield (+5%).
- Rainfall > 60 mm and < 150 mm in Mar - total rainfall of more than 60 mm but less than 150 mm during the month of March has a positive impact on yield (+5%).
- Rainfall > 120 mm and < 300 mm in Feb-Mar - total rainfall of more than 120 mm but less than 300 mm during February and March has a positive impact on yield (+5%).

Sugar beans

- Tmnd < -5 °C Oct-Jan – daily minimum temperatures less than -5 °C during October to January impact negatively on yield (-50%).
- Tmxd > 26 °C for 3+ days in mid Jan-Feb – maximum daily temperatures in excess of 26 °C for 3 days or more from mid-January to end of February have a negative impact on yield (-10%).
- Tmxd > 30 °C with low RH in Jan - maximum daily temperatures in excess of 30 °C with low relative humidity during the month of January have a negative impact on yield (-10%).
- Tmxd > 30 °C Jan – maximum daily temperatures in excess of 30 °C during the month of January have a negative impact on yield (-10%).

- Rainfall < 50 mm in Nov - less than 50 mm of rain during the month of November has a negative impact on yield (-10%).
- Rainfall < 80 mm in Nov - less than 80 mm of rain during the month of December has a negative impact on yield (-10%).
- Rainfall < 100 mm in Jan - less than 100 mm of rain during the month of January has a negative impact on yield (-10%).
- Rainfall < 60 mm in Feb - less than 60 mm of rain during the month of February has a negative impact on yield (-5%).
- Rainfall > 140 mm Jan - total rainfall of more than 140 mm during the month of January has a positive impact on yield (+5%).
- Rainfall > 60 mm and < 100 mm in Feb - total rainfall of more than 60 mm but less than 100 mm during the month of February has a positive impact on yield (+5%).
- Rainfall > 60 mm and < 100 mm in Mar - total rainfall of more than 60 mm but less than 150 mm during the month of March has a positive impact on yield (+5%).

3.5.2.7 Crop enterprise budgets

Table 3.32 to Table 3.33 summarise the crop enterprise budgets for the Carolina case study.

Table 3.32: Crop enterprise budget summary: maize, sugar beans and soybeans

	Maize - dryland	Sugar bean - dryland	Soybean - dryland
Yield (tonne/ha)	6	2	2
Price per tonne (R)	1 800	8 000	4 500
Income/ha (R)	10 800	12 000	8 100
Total cash expenditure/ha (R)	6 062	7 352	4 890
Margin above specified costs (R)	4 738	4 648	3 210

Source: Own calculations, with inputs from case study farmer

Table 3.33: Crop enterprise budget summary: beef and mutton production

Assumptions - beef production	
Weaning %	80%
Weaning weight (kg)	220 kg
Price/kg [R]	R16
Income and cost	
Income per cow	R2 816
Total cost per cow	R1 000
Net income per cow	R1 816
Assumptions - mutton production	
Weaning %	90%
Weaning weight (kg)	22 kg
Price/kg [R]	R45
Kg wool/ewe	2 kg
Price/kg [R]	R75
Income and cost	
Income per ewe	R1 041
Total cost per ewe	R 340
Net income per ewe	R 701

Source: Own calculations, with inputs from case study farmer

3.5.3 Description of selected case study farm

The table below reflects the composition of the summer rainfall dryland case study farm.

Table 3.34: Description of case study farm: Carolina

Description	
Farm size	3 305 ha
Dryland	1 050 ha
Pastures	70 ha
Veldt	2 170 ha
Odd	15 ha
Total farm size	**3 305 ha**
Land use	
Cash crops	
Maize dryland	700 ha
Sugar beans dryland	50 ha
Soybeans dryland	300 ha
Total area cash crops	**1 050 ha**
Livestock	
Cattle (producing cows)	600
Sheep (producing ewes)	2 500
Valuation of farm	**(R)**
Fixed improvements	5 000 000
Vehicles, machinery, implements, livestock, etc	26 363 500
Land	57 325 000
Total assets	**88 688 500**
Liabilities	**(R)**
Short-term	11 000 000
Medium term	1 200 000
Long-term	16 500 000
Total liabilities	**28 700 000**
Net asset value	**59 988 500**
Debt ratio	**32%**

Source: Case study farmer's records (2012)

3.6 Chapter summary

Chapter 3 gives an overview of the four study areas, i.e. LORWUA, Blyde River WUA, Moorreesburg and Carolina, which broadly represent the summer- and winter rainfall, as well as irrigation and dryland crop production, areas of South Africa.

The description of case study areas include discussions on climate, natural resources, adapted crops, crop irrigation requirements, crop cultivation practices and crop enterprise budgets. The critical climate thresholds for crops in the different regions, which form an integral part of the integrated climate modelling in this study, are also specified.

The different case studies are defined in terms of farm size, land use, irrigation water availability and valuation of assets and liabilities.

CHAPTER 4 : DESCRIPTION OF THE INTEGRATED CLIMATE CHANGE MODEL

"A mathematical model can be defined as a representation of the essential aspects of an existing system (or a system to be constructed) which presents knowledge of that system in usable form. Mathematical models can take many forms, including but not limited to dynamical systems, statistical models, differential equations, or game theoretic models."

Eykhoff (1974)

4.1 Introduction

Chapter 3 described the LORWUA, Blyde River WUA, Carolina and Moorreesburg regions and their respective case studies. In this chapter the model is developed to predict the impact of climate change on the financial vulnerability of different farming systems. The modelling framework includes 4 modules that will be discussed in more detail below.

4.2 Layman's description of the model

Figure 4.1 is a diagrammatical illustration of the modelling framework which consists of 4 modules:

- Climate change impact modelling:
    - Modelling of physical climate data (daily minimum and maximum temperatures and daily rainfall from different downscaled GCMs) that impact on crop yield and quality.
    - Changing crop irrigation requirements (as a result of climate change).
    - Hydrological modelling - impact of climate change on the availability of irrigation water (for the Blyde WUA).
- DLP model.
- Modelling interphases.
- Financial Vulnerability Assessment model.

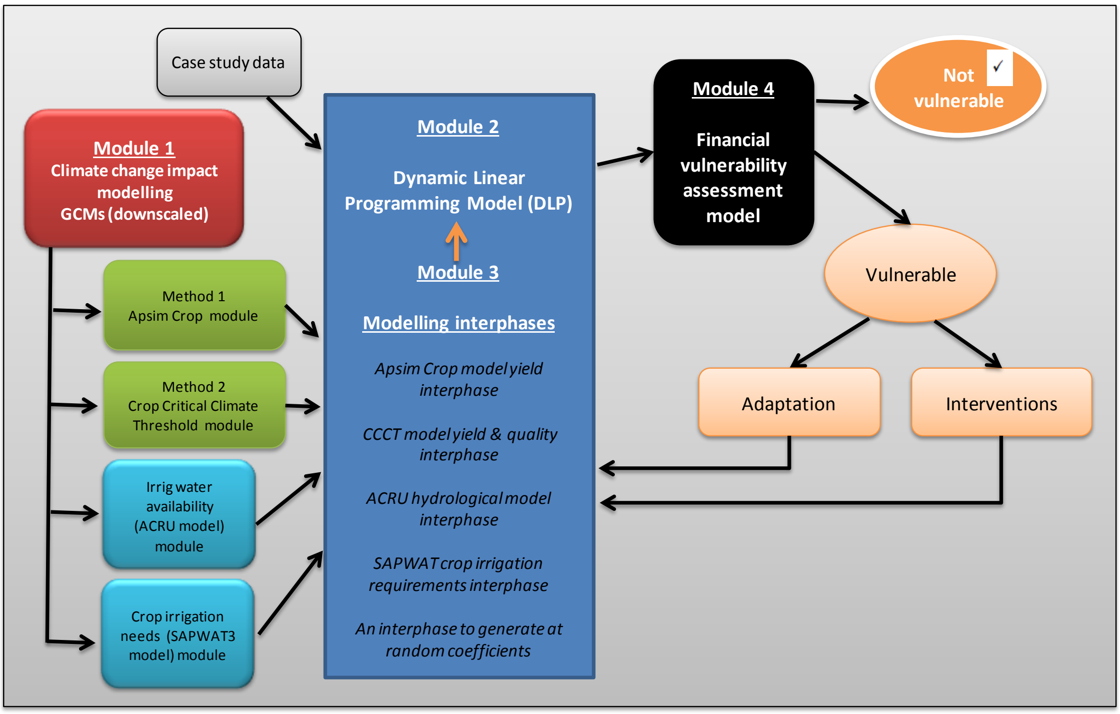


Figure 4.1: Diagrammatic illustration of the modelling framework

In the next four sections these modules are discussed in more detail.

4.2.1 Climate change impact modelling

The impact of climate change on the financial vulnerability of the case study farms is modelled by using downscaled climate information from different GCMs to determine the impact of climate change on:

- Yield and quality of agricultural produce in the case study areas
- Crop irrigation requirements (for irrigation case studies LORWUA and the Blyde River WUA)
- Availability of irrigation water (for the Blyde River WUA case study).

The subsections of climate change impact modelling are discussed in more detail below.

4.2.1.1 Downscaled GCMs

4.2.1.1.1 GCMs

The interactions between the many processes that govern the Earth's climate are so complex and extensive that quantitative predictions of the impacts of increasing concentrations of greenhouse gases on climate cannot be made through simple intuitive reasoning (Shaka, 2008). For this reason computer models, i.e. GCMs, have been developed, which are mathematical representations of the Earth's system, and in which physical and biogeochemical processes are described numerically to simulate the climate system as realistically as possible (Jacob and van den Hurk, 2009).

GCMs are founded on assumptions about the evolution of drivers of climate change, for example the distributions of aerosols and greenhouse gases, and their respective concentrations, in the atmosphere (Jacob and van den Hurk, 2009). These depend directly on natural and anthropogenic emissions, which are estimated through emission scenarios developed by using so-called "storylines" (Nakićenović *et al*., 2000) that describe possible developments in global population growth and other aspects of the socio-economic system (Cox and Stephenson, 2007; Jacob and van den Hurk, 2009). These emission scenarios are used to drive atmospheric chemistry and carbon cycle models that simulate changes in the concentration of greenhouse gases and aerosols (Cox and Stephenson, 2007). The resulting concentration scenarios are then input into GCMs, which generate climate change scenarios that in turn drive models of the impacts on human and natural systems (Cox and Stephenson, 2007).

4.2.1.1.2 Uncertainties inherent to GCMs

Uncertainties inherent in GCMs have been well documented (UKCIP, 2003; Cox and Stephenson, 2007; Giorgi *et al*., 2008; Jacob van den Hurk, 2009; Schulze, 2009). In addition to the limitations resulting from uncertainties, GCMs are less capable of simulating second order atmospheric processes such as precipitation, compared to those related to first order atmospheric processes such as surface heat and vapour fluxes (Hardy, 2003). These limitations include (Schulze *et al*., 2011):

- Failure to simulate individual convective rainfall events, owing to the coarse spatial resolutions of GCMs, and the smaller spatial and temporal nature of convective rainfall, which poses problems in many parts of the world, including most of southern Africa, where convective rainfall is a dominant form of precipitation.
- Difficulty in simulating the intensity, frequency and distribution of extreme rainfall (IPCC, 2007).
- Tending to simulate too many light rainfall events and generally too few heavy rainfall events, whilst maintaining a fairly realistic mean precipitation (IPCC, 2007).

- Poorly representing major drivers of climate variability, such as the El Niño - Southern Oscillation phenomenon (Hulme *et al*., 2001), which is associated with a broad band of variability throughout southern Africa (Tyson, 1996).
- Poorly accounting for climatological variables that represent other atmospheric conditions that lead to high magnitude precipitation and flood-producing events.

These factors tend to reduce the accuracy of precipitation output from GCMs. Additionally, global mean temperatures can be quite unrepresentative at the local scale (Jacob and van den Hurk, 2009) and so can any subsequent estimations of potential evaporation. Therefore, questions remain in regard to the usability of direct GCM output in detailed hydrological studies, where precipitation, temperature and potential evaporation at the local scale are primary inputs into hydrological models (Schulze *et al*., 2011).

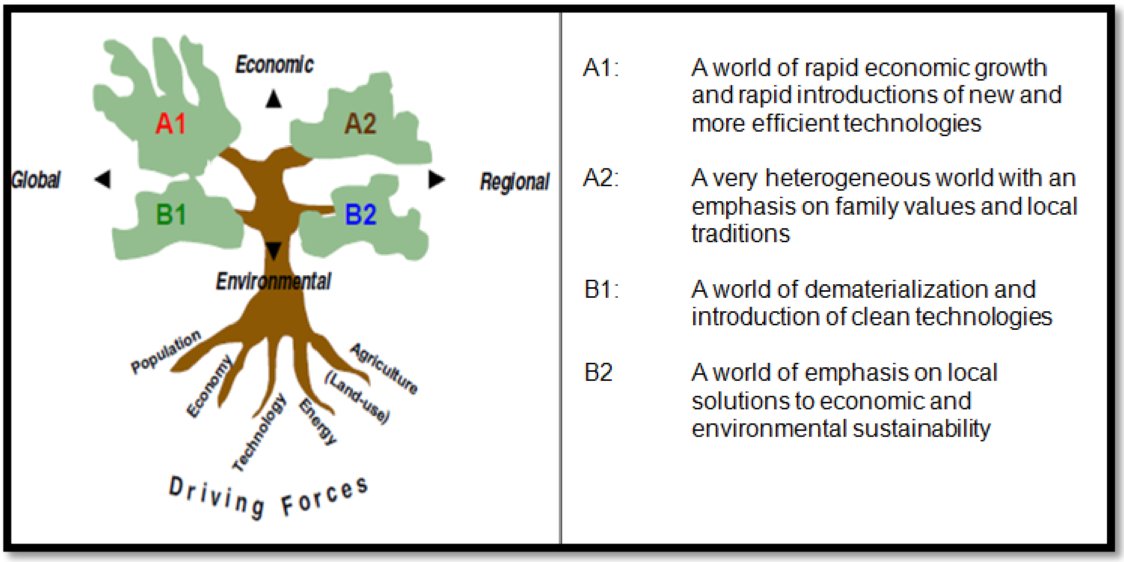
Nevertheless, output from GCMs forms the basis for climate change impact assessments. A significant discontinuity, however, exists between the output from GCMs (spatial scales of 10^4 - 10^5 km^2) and the catchment scale (10^1 - 10^2 km^2) at which local decisions are sought and local adaptation options need to be considered (Schulze, 2009). It is due to this discontinuity that GCM output needs to be translated from the coarse to more local scales by the process of regional climate downscaling (Giorgi *et al*., 2008, cited by Schulze, 2011).

4.2.1.1.3 Empirically/Statistically downscaled GCMs

Empirical downscaling involves developing a quantitative relationship between local-scale variables and large-scale atmospheric variables, which is subsequently applied to the GCM output to obtain local and regional climate change signals (Jacob and van den Hurk, 2009). An advantage of this technique is that GCM output can be downscaled to a point, which is useful for obtaining projections for, say, rainfall at a particular site, which can then be input into a hydrological or crop yield model. A major disadvantage of this approach is the implicit assumption that these statistical relationships will remain stationary under a future climate (UKCIP, 2003; Jacob and van den Hurk, 2009).

The resolving scale of GCMs has improved significantly in the past ten years with many state of the art GCMs able to resolve at a scale of around 100 km. Downscaled climate data (daily rainfall and temperature) were obtained from CSAG.

The climate change scenarios developed by CSAG for application in this project were derived from global scenarios produced by five GCMs, all of which were applied in the IPCC's (2007) Fourth Assessment Report [AR4] (Schulze *et al*., 2011). Details of the five GCMs used in this study are provided in Table 4.1. All of the future global climate scenarios that were downscaled by CSAG to point scale for use in this study were based on the A2 emissions scenario (Figure 4.2) defined by the IPCC SRES (Nakićenović *et al*., 2000).



A1:	A world of rapid economic growth and rapid introductions of new and more efficient technologies
A2:	A very heterogeneous world with an emphasis on family values and local traditions
B1:	A world of dematerialization and introduction of clean technologies
B2	A world of emphasis on local solutions to economic and environmental sustainability

Figure 4.2: SRES scenario storylines considered by the IPCC
Source: After Nakićenović et al., 2000; graphic illustration from IPCC-TGICA (2007)

Table 4.1 gives a condensed description of the information on GCMs, the global climate change scenarios of which were empirically downscaled by CSAG to point scale for application in this project. Five GCMs were used from various respected international organisations.

Table 4.1: GCMs description

Institute	GCM
Canadian Center for Climate Modelling and Analysis (CCCma), Canada ***Abbreviation: CCC***	**Name:** CGCM3.1(T47) **First published:** 2005 Website: http://www.cccma.bc.ec.gc.ca/models/cgcm3.shtml
Meteo-France / Centre National de Meteorologiques (CNRM), France ***Abbreviation: CRM***	**Name:** CNRM-CM3 **First published:** 2004 Website: http://www.cnrm.meteo.fr/scenario2004/indexenglish.html
Max Planck Institute for Meteorology Germany ***Abbreviation: ECH***	**Name:** ECHAM5/MPI-OM **First published:** 2005 Website: http://www.mpimet.mpg.de/en/wissenschaft/modelle.html
NASA / Goddard Institute for Space (GISS), USA ***Abbreviation: GISS***	**Name:** GISS-ER **First published:** 2004 Website: http://www.giss.nasa.gov/tools/modelE
Institut Pierre Simon Laplace (IPSL), France ***Abbreviation: IPS***	**Name:** IPSL-CM4 **First published:** 2005 Website: http://mc2.ipsl.jussieu.fr/simules.html

The empirically downscaled climate data from the various GCMs include daily minimum and maximum temperatures and rainfall. The climate change scenarios were developed for the "present" (1971 – 1990) and "intermediate future" (2046 – 2065).

These empirically downscaled GCMs values were used in various modelling phases including determining:

- Climate change impacts on yield and quality of crops
- Climate change impacts on crop irrigation requirements
- Climate change impacts on irrigation water availability.

4.2.1.1.4 A note of caution on the GCMs used in this study

Overall changes in future scenarios of climate depend strongly on (Schulze *et al*., 2011):

- which GCMs were used, and
- how many GCMs were in the ensemble used.

The five GCMs which were available for use in this study, viz. CGCM3.1(T47), CNRM-CM3, ECHAM5/MPI-OM, GISS-ER and IPSL-CM4 are considered by climatologists to produce rainfall output possibly on the wetter side of the spectrum (Hewitson, 2010. Personal communication with Prof Schulze), and this has to be borne in mind in interpreting any impacts in which rainfall is an input variable. Furthermore, an error in GISS GCM's rainfall values for parts of South Africa was reported during the course of the project and all statistics from multiple GCMs involving rainfall had to be re-calculated in order to eliminate the known error from that GCM (Schulze *et al*., 2011).

However, the reader should note that the main contribution of this study is to develop the methodology to analyse the financial vulnerability of farmers on a micro level. The accuracy of the selected GCMs and the error which was discovered in one of the GCMs is therefore irrelevant for the purpose of this study. The methodology developed in this study can use the data/information generated by any existing/future GCM. However, at this point in time the GCMs remain the only credible tools we have for climate change impact studies (Schulze, 2014).

The following sections will focus on the methodologies applied to quantify the impact of climate change on the financial vulnerability of farming systems.

4.2.1.2 Climate change impact on yield and quality of crops

Two different methodologies were used to determine the impact of projected future climates on yield and quality (only for CCCT scenarios) of crops in the different case study areas. In both these methodologies the empirically downscaled climate values were used as input to determine present and projected future yield and quality. The methodologies used to determine the impact of climate change are:

- APSIM for impact on yield.
- CCCT for impact on yield and quality.

The methodologies will be discussed in the following sections.

4.2.1.2.1 APSIM

The APSIM software is a modular modelling framework that has been developed by the APSIM Initiative and its predecessor, the Agricultural Production Systems Research Unit (APSRU) in Australia (McCown, 1995).

APSIM was developed to simulate biophysical processes in agricultural systems, particularly as it relates to the economic and ecological outcomes of management practices in the face of climate risk. It is structured around plant, soil and management modules. These modules include a diverse range of crops, pastures and trees, soil processes including water balance, N and P transformations, soil pH, erosion and a full range of management controls. APSIM resulted from a need for tools that provided accurate predictions of crop production in relation to climate, genotype, soil and management factors while addressing the long-term resource management issues (Keating *et al*., 2003).

The APSIM modelling framework is made up of the following components (Keating *et al*., 2003):

- A set of biophysical modules that simulate biological and physical processes in farming systems.
- A set of management modules that allow the user to specify the intended management rules that characterise the scenario being simulated and that control the simulation.
- Various modules to facilitate data input and output to and from the simulation.

- A simulation engine that drives the simulation process and facilitates communication between the independent modules.

APSIM has been used in a broad range of applications, including support for on-farm decision making, farming systems design for production or resource management objectives, assessment of the value of seasonal climate forecasting, analysis of supply chain issues in agribusiness activities, development of waste management guidelines, risk assessment for government policy making and as a guide to research and education activity (Keating *et al*., 2003).

APSIM was used to determine probable yield changes that could materialise with different downscaled GCMs data from present to intermediate future climate scenarios. APSIM calibration and simulation for this study were performed by CSAG relying on project data made available and summarised in the WRC (2012) report.

Crop yields were simulated under climate change scenarios for the following:

- Wheat (Moorreesburg)
- Maize (Carolina)
- Grape vineyards (LORWUA) – *[prototype model]*

The APSIM crop model for vineyard is a prototype model and does not distinguish between wine grapes, table grapes and raisins. Hence, results for future wine grape simulations should be interpreted carefully.

Fruit tree models are uncommon, and no mango model was found to respond to the process-based, future climate driven, including management options, requirements of the study. APSIM does not currently have a model for citrus or mangoes and could therefore not contribute to the modelling of the impact of climate change on yield and/or quality of mango or citrus crops. Like most numerical models, the APSIM model strength relies on quantitative information, while qualitative information is difficult to extract.

The results of the APSIM crop modelling (crop yield for different crops) will be discussed with the different case study analyses. The projected yields are integrated into the DLP model via an interphase namely APSIM crop model interphase (see Section 4.2.3.2.).

In the absence of crop models to model the impact of climate change on yield and/or quality of certain crops, a new methodology was developed namely the CCCT modelling technique, which will be discussed in Section 4.2.1.2.2 below.

4.2.1.2.2 CCCT modelling

The CCCT modelling technique is based on the following pillars:

- Empirically downscaled daily climate values (rainfall, minimum and maximum temperatures).
- Physical/biological critical climate thresholds for different crops.
- Expert group discussions (for guidance on crop critical climate thresholds and also the impact on yield and/or quality should a threshold be exceeded).

The use of expert group discussions, as a research method is suitable, firstly, for gathering information in a meaningful manner and, secondly, to stimulate individual creativity by presenting alternative perspectives provided by various participating experts (Hoffmann, 2010). However, due to the various uncertainties in the models, when analysing CCCT modelling results the emphasis should be on trends in projected yield and quality, rather than absolute values.

The CCCT modelling consists of the following steps:

- The crop critical climate thresholds for different crops were determined during workshops with farmers and experts. This includes the impact on yield and/or quality of the crop if the threshold is breached.
- These thresholds are then applied to different climate scenarios (present and intermediate) of the downscaled GCMs to determine the number of breaches per threshold for the different climate scenarios.
- The effects of critical climate threshold breaches (which can be positive or negative) are then calculated to determine the impact on yield and/or quality of crops.

The results of the crop critical threshold modelling are integrated into the DLP model through an interphase (critical crop climate threshold interphase), to be discussed in Section 4.2.3.3.

4.2.1.3 Climate change impacts on crop irrigation requirements

The term crop water requirement is defined as the "amount of water required to compensate the evapotranspiration loss from the cropped field" (Allen *et al.*, 1998). The ICID (2000) describes it as the "total water needed for evapotranspiration, from planting to harvest for a given crop in a specific climate regime, when adequate soil water is maintained by rainfall and/or irrigation so that it does not limit plant growth and crop yield". "Although the values for crop evapotranspiration and crop water requirement are identical, crop water requirement refers to the amount of water that needs to be supplied, while crop evapotranspiration refers to the amount of water that is lost through evapotranspiration" (Allen *et al.*, 1998).

Crop irrigation requirements are a function of various climate variables and therefore will vary under different climate scenarios. In order to provide for changing crop irrigation requirements in the integrated model, the SAPWAT3 program was used to calculate crop irrigation requirements under different climate scenarios. The following section will briefly described the SAPWAT3 program.

4.2.1.3.1 SAPWAT3

SAPWAT3 is essentially an enhanced and improved version of SAPWAT (South African Plant WATer), a program that is extensively applied in South Africa and was developed to establish a decision-making procedure for the estimation of crop irrigation requirements by irrigation engineers, planners and agriculturalists. Subsequent to the development of the initial SAPWAT programme, the FAO published the Irrigation and Drainage Report No. 56, Crop Evapotranspiration - Guidelines for computing crop water requirements (Allen *et al*., 1998) – hereafter referred to as FAO 56. This comprehensive document is highly acclaimed and has become accepted internationally. As the calculation of crop evapotranspiration is the first and essential element of any routine for estimating crop irrigation requirement, the decision was taken to reprogram the initial model and SAPWAT3 has at its core the computer procedures contained in FAO 56 and all recommendations have been applied to the letter (Van Heerden *et al*., 2009).

The irrigation requirement of crops is dominated by weather, particularly in the yearly and seasonal variation in the evaporative demand of the atmosphere as well as precipitation. SAPWAT3 has included in its installed database comprehensive weather data that is immediately available to the user (Van Heerden *et al*., 2009):

- Firstly it includes the complete FAO Climwat climate data base encompassing not only South Africa, but many other countries in the world where there is irrigation development. Climwat comprises 3 262 weather stations from 144 countries, including South Africa, and contains long-term monthly average data for calculating Penman-Monteith ET_0 values as well as rainfall. While Climwat climate data output is monthly averages, SAPWAT3 calculations are based on daily values, thus requiring interpolation. This has been facilitated in SAPWAT3 by statistically fitting a curve to the monthly ET_0 values.
- The second installed set of weather data in SAPWAT3 consists of data derived from weather stations and is only applicable to South Africa. This database was developed from the "South African Atlas of Climatology and Agro hydrology" by the team from the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal (Schulze, 2008). The data were generated from actual weather stations and then interpolated to locations at the centroids of the polygons that represent each of the 1 946 Quaternary Catchments (drainage regions) covering the country, thereby provide not only comprehensive spatial coverage, but also 50 years of historical (1950 to 1999) daily climate data for each Quarternary Catchment on a calendar basis (Schulze, 2008). This capability has major implications when it comes to planning and strategy development. It is possible to select any day during this period and access the maximum and minimum temperatures, humidity, rainfall, solar radiation and ET_0.

SAPWAT3 provides facilities for importing data from additional weather stations. If the weather station database consists of average monthly values, similar to Climwat, then manual importation is recommended, but if the data are more detailed there are facilities for formatting and importing the data files as a package (Van Heerden *et al*., 2009).

SAPWAT3 can be applied for estimating the irrigation requirements for a single crop, for a field with multiple cropping, for a single farm, for a group of farms (e.g. WUA), for a group of WUAs or even a river basin. Output is provided, where appropriate, in millimetres and cubic metres. Provision is made for printing comprehensive output tables and/or saving to file and/or exporting for further processing by spread sheet applications (Van Heerden *et al*., 2009).

SAPWAT3 utilises the four stage crop development curve procedure based on relating crop evapotranspiration in each stage to the short grass (Penman-Monteith) reference evapotranspiration by applying a crop coefficient. Typical values of expected average crop coefficients under a mild, standard climatic condition are published in FAO 56 and are applied in SAPWAT3 (Van Heerden *et al.*, 2009).

SAPWAT3 incorporates the internationally recognised Köppen-Geiger climatic system. The system is based on temperature-rainfall combinations so that the climate of the weather station can be classified by using the temperature and rainfall data of a weather station record (Van Heerden *et al.*, 2009).

SAPWAT3 makes use of the FAO 56 procedure that separates soil water evaporation from plant transpiration and, therefore, conforms to the FAO 56 defaults that determine soil water characteristics and evaporation parameters. Fortunately, FAO 56 specifies soils according to the familiar sand, silt and clay criteria into nine texture classes. The profile water balance during irrigation is also calculated and tabulated strictly in accordance with FAO 56 methodology (Van Heerden *et al.*, 2009).

The methodology for estimating crop evapotranspiration under so-called "standard" conditions has been well researched and due allowance can be made for non-standard conditions arising from unusual circumstances and the realities of practical management (Van Heerden *et al.*, 2009).

The SAPWAT3 program was applied to determine changing crop irrigation requirements under present and future climate scenarios using downscaled climate data of the various GCMs used in this study. The changing crop irrigation requirements will be discussed with the different case study analyses.

The crop irrigation requirements data is introduced to the DLP model via the crop irrigation requirements interphase which will be elaborated upon in later sections.

4.2.1.4 Climate change impacts on the availability of irrigation water

The availability of irrigation water is dependent on dam levels that are a function of, amongst others, rainfall patterns and catchment responses to rainfall. To determine the impact of climate change on the financial vulnerability of irrigation farming systems, the availability of irrigation water should be investigated (subject to data availability).

The projected future dam levels for the Blydepoort Dam were computed by the Centre of Water Resources Research in the School of Agricultural, Earth and Environmental

Science, University of KwaZulu-Natal (UKZN). The daily present and intermediate climate values from downscaled GCMs were used in the ACRU model to project future changes in dam levels. The following sections give a brief description of the background and methodology followed to arrive at the projected dam levels.

For this study the projected dam level information for LORWUA was not available and the availability of irrigation water could thus not be factored into the integrated model. The proposed enlargement of the Clanwilliam Dam is another uncertainty which contributed to the decision to rather treat the availability of irrigation water in the Olifants-Doorn system as a constant and focus on the projected impact of climate change on yield and quality of crops in that catchment.

4.2.1.4.1 The concept of quinary catchments

The erstwhile South African Department of Water Affairs and Forestry (DWAF; later DWA - the Department of Water Affairs and as of June 2014 DWS – the Department of Water and Sanitation) delineated the RSA, together with Swaziland and Lesotho, into 22 primary catchments, which in turn were disaggregated into secondary, then tertiary and finally, into 1 946 interlinked and hydrologically cascading quaternary catchments (QCs), as shown in Figure 4.3. This "fourth level" of discretisation has, to date, constituted the most detailed spatial level of operational catchment in the DWA (now DWS) for general planning purposes (Schulze *et al*., 2011).

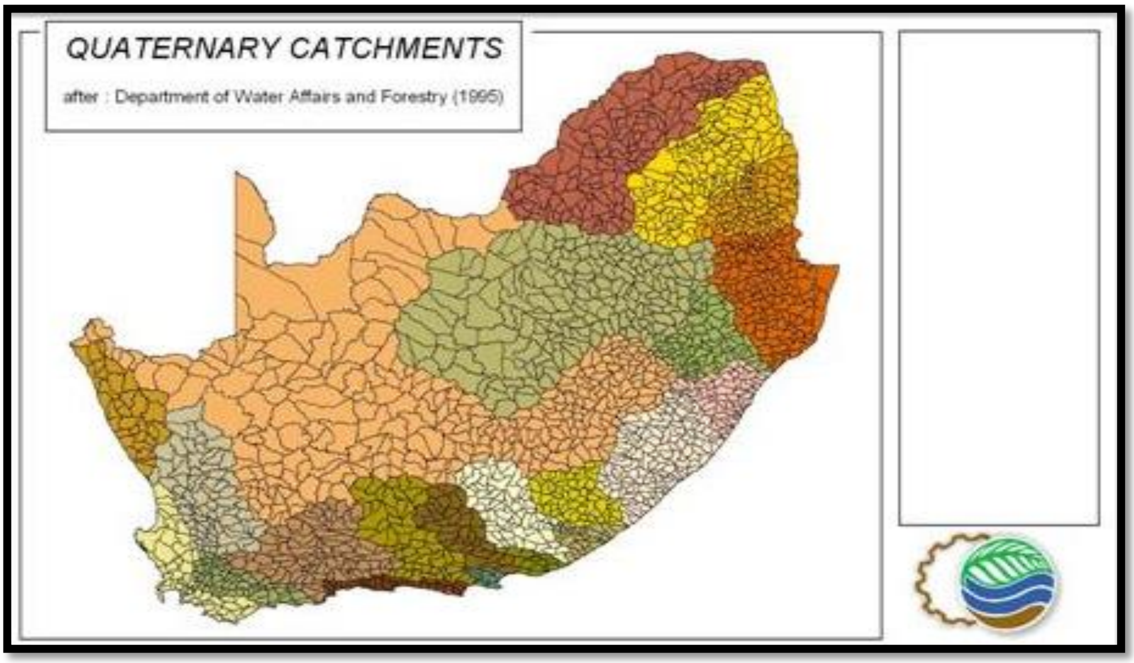


Figure 4.3: Primary and quaternary catchments covering the RSA, Lesotho and Swaziland
Source: After Midgley et al. (1994)

Schulze and Horan (2007; 2010) have shown that many fourth level quaternary catchments in southern Africa are physiographically too diverse for hydrological responses from them to be considered relatively homogeneous. By applying Jenks' optimisation procedures available within the ArcGIS software suite, a three-fold altitude break based sub-delineation of QCs into fifth level quinary catchments (the Upper, middle and lower quinaries of a QC) has been carried out (Figure 4.4). These quinary catchments were then configured within the QC configuration, such that the outflow of the upper quinary enters the middle, which in turn flows into the lower quinary. However, the lower quinary outflow of a QC does not enter the upper quinary of the next downstream quaternary catchment, because that QC's upper quinary may be at a higher altitude than the lower quinary of the immediate upstream quaternary. Therefore, the outflow of the lower quinary has been configured to rather enter the downstream Quaternary at its exit (Schulze and Horan, 2010). A schematic of the flowpath configuration between quinaries and quaternaries, taken from the Upper Thukela Catchment, is given in Figure 4.5.

The sub-delineation of quaternary into quinary catchments has resulted in 5 838 hydrologically interlinked and cascading quinaries (Figure 4.6) covering the RSA, Lesotho and Swaziland. These have been demonstrated to be physiographically considerably more homogeneous than the quaternaries (Schulze and Horan, 2007; 2010) and on a national and smaller scale are considered to be relatively homogeneous hydrological (as well as agricultural) response zones.

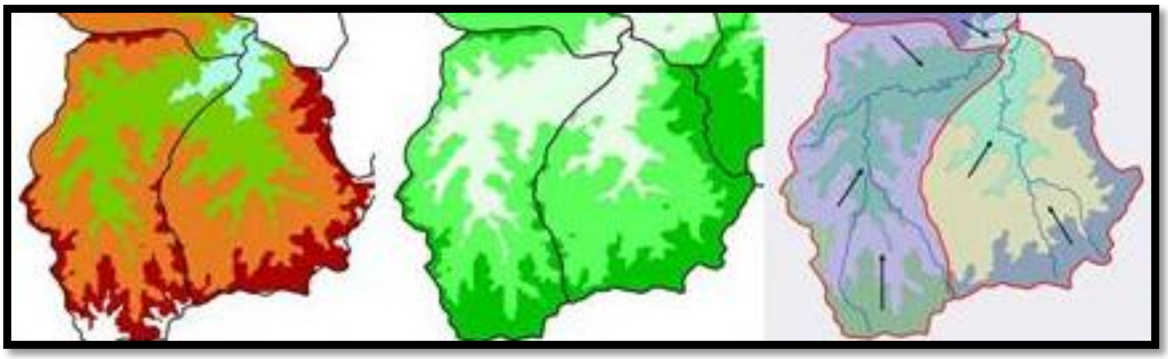


Figure 4.4: Sub-delineation of quaternary catchments from altitude (left) into three quinaries by natural breaks (middle) with flow paths (right) of water
Source: Schulze and Horan (2010)

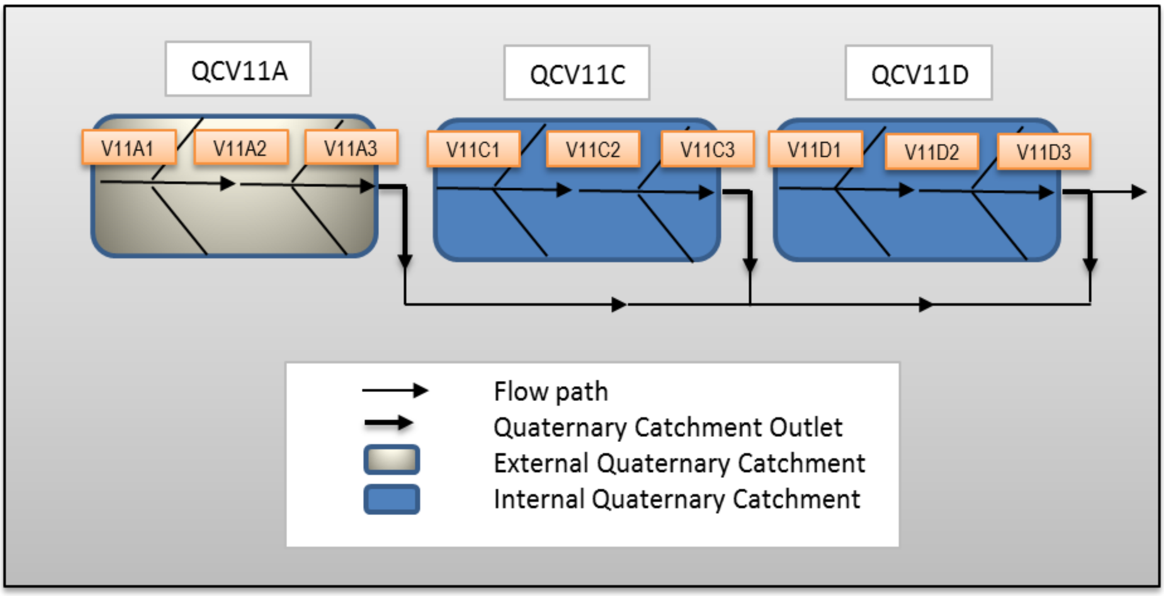


Figure 4.5: Flowpaths between quinary and quaternary catchments, with the example taken from the Upper Thukela catchment
Source: Schulze and Horan (2010)

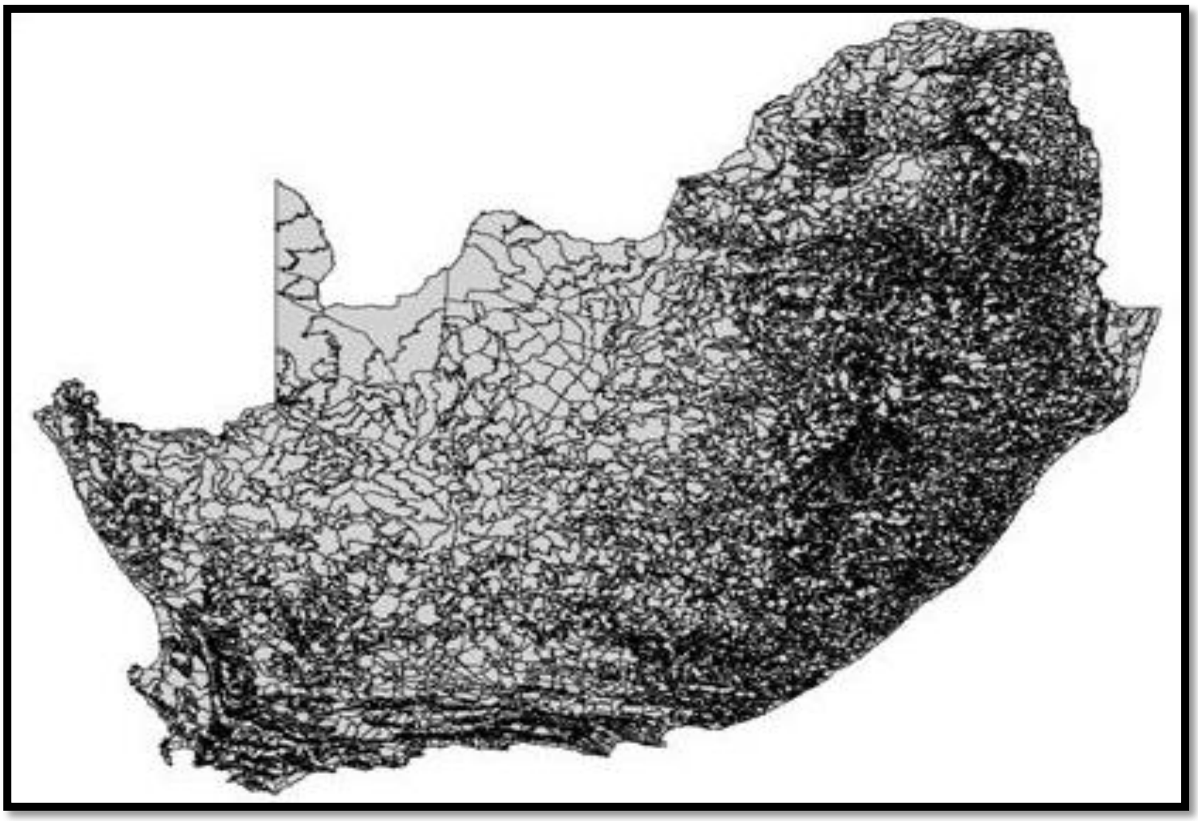


Figure 4.6: Delineation of the RSA, Lesotho and Swaziland into 5 838 hydrologically interlinked and cascading quinary catchments
Source: Schulze and Horan (2010)

4.2.1.4.2 From a quaternary to quinary catchments database

Following the delineation of the southern African countries of the RSA, Lesotho and Swaziland into hydrologically interlinked quinary catchments, the formerly used Quaternary Catchments Database (QCB) (Schulze *et al*., 2005) needed to be expanded to form a new database, viz. the Southern African Quinary Catchments Database, QnCDB (Schulze *et al*., 2011). The expansion of the QCD to the newly created QnCDB was achieved in collaboration with researchers from another climate change impact study (Schulze *et al*., 2010a).

The key climatic and catchment input into the QnCDB include (Schulze *et al*., 2011):

- Daily rainfall input per quinary catchment:
    - Estimations of daily rainfall values for simulations under baseline historical climatic conditions.
    - Estimations of daily rainfall values for simulations with GCM derived present and future climate scenarios.

  Rainfall is generally considered to be the most important input into any hydrological model.
- Daily temperature input per quinary catchment:
    - Estimations of daily values of maximum and minimum temperatures for simulations under baseline historical climatic conditions.
    - Estimations of daily values of maximum and minimum temperatures for simulations with GCM derived present and future climate scenarios.

  Daily maximum and minimum temperature values, derived from procedures described in detail by Schulze and Maharaj (2004), facilitate estimations to be made, either implicitly or explicitly, of solar radiation, vapour pressure deficit and potential evaporation (Schulze, 2008). Using these variables in addition to rainfall, as input into hydrological models such as ACRU, the generation of soil moisture content, runoff and/or irrigation demand becomes possible (Schulze *et al*., 2010b).
- Estimations of daily values of reference crop evapotranspiration per quinary catchment:
    - Estimations of daily values of reference crop evapotranspiration for simulations under baseline historical climatic conditions.

  - Estimations of daily values of reference crop evapotranspiration for simulations with GCM derived present and future climate scenarios.

  Methods of estimating potential evapotranspiration (Ep) range from complex physically based equations to relatively simple surrogates based on single variables such as temperature. The various methods all yield different estimates under different climatic conditions, and a reference potential evaporation (Er) therefore has to be selected as that evaporation against which other methods must be adjusted appropriately. In simulating the hydrological landscape with a vegetative cover and/or under irrigation, the physically based FAO (1992) version of the Penman-Monteith equation (Penman, 1948; Monteith, 1981) has now become the *de facto* international standard of what is termed reference crop evapotranspiration, replacing the A-Pan and other techniques (Schulze *et al*., 2010b).

- Soils information

  The ACRU model (Schulze, 1995 and updates) revolves around multi-layer soil water budgeting and therefore requires soils information as input. Being a threshold based model, ACRU needs input values on the following soils variables (Schulze *et al*., 2010b):

  - thickness (m) of the topsoil and the subsoil
  - soil water contents (m/m) at:
    - saturation (porosity)
    - drained upper limit (also commonly referred to as field capacity)
    - permanent wilting point (i.e. the lower limit of soil water availability to plants)
  - rates of saturated drainage from topsoil horizon into the subsoil, and from the subsoil horizon into the intermediate groundwater zone
  - erodibility of the soil (Schulze *et al*., 2010b).

  Values of these variables have been derived by Schulze and Horan (2008) using the AUTOSOILS decision support tool (Pike and Schulze, 1995 and updates) applied to the soils database from the Institute for Soil, Climate and Water (SIRI, 1987 and updates) for each of the soil mapping units, called Land Types, which cover South Africa, on the basis that the hydrological properties of all the soil series making up an individual land type were area-weighted. For each quinary catchment the values of the hydrological soils variables required by the ACRU model were derived from the land types identified in that quinary, again on an area-proportioned basis (Schulze *et al*., 2010b).

- Baseline land cover information

  It is reported in Schulze *et al*. (2010b) that in order to assess impacts of land use or of climate change on hydrological responses, a baseline land cover is required as a reference against which to evaluate the impacts. For the RSA, Lesotho and Swaziland the 70 veld types delineated by Acocks (1988) have become the recognised baseline (i.e. reference) land cover for application in hydrological impact studies (Schulze, 2004).

  Based on a set of working rules, month-by-month hydrological attributes, developed by and given in Schulze (2004), were assigned to each of the 70 Acocks veld types and were incorporated into the QCD. These attributes are (Schulze *et al*., 2010b):

    - the water use coefficient (Kcm)
    - interception loss per rain day (Il)
    - fraction of roots in the topsoil (RA)
    - a coefficient of infiltrability (c) dependent on rainfall intensity estimates
    - soil surface cover by litter (Cs%), an index of suppression of soil water evaporation by a litter / mulch layer.

  For each of the 5 838 quinaries in the database the spatially most dominant veld type was then selected as the representative baseline land cover (Schulze *et al*., 2010b).

From all of the above daily runoff could be computed using the climate input from the GCMs used and dam levels generated. The projected dam levels of the Blydepoort Dam for the GCMs used in this study (present and future climate scenarios) are introduced to the DLP model as constraints through the irrigation water availability interphase.

4.2.2 Whole-farm dynamic linear programming approach

The main objective of the mathematical modelling exercise is to simulate the selected farming systems (case studies) with the best available information. Climate change scenario data are then imported into the models to study the impact on economic and financial vulnerability with no adaptation. In the second round of analysis adaptation strategies are tested to analyse their efficiency in reducing vulnerability. Linear programming (LP) is one of the most practical agricultural economic tools to simulate farming systems and has been used by various South African researchers, e.g. Hancke and Groenewald, 1972; Van Rooyen, 1979; Brotherton and Groenewald, 1982. Later researchers used dynamic linear programming (DLP) (Backeberg, 1984; Oosthuizen, 1994; Maré, 1995; Louw, 1996; Louw and Van Schalkwyk, 1997; Haile *et al.*, 2003). DLP is a mathematical technique that can be employed by management to determine the optimal utilisation of limited resources. It comprises the formulation of a model, which is solved mathematically to provide an optimal answer (Redelinghuis *et al.*, 1985). In order to analyse a problem using DLP, it must be moulded into a particular structure that must at least contain the following components:

- Objective – to obtain the best or optimal solution, i.e. maximizing profit.
- Activities or decision variables which define what to do.
- Constraints or restrictions that limit the availability of a resource.

Therefore it is important that any attempt to simulate the farm system should include the objectives of the farm unit, the resources available to reach these objectives as well as the alternative activities to reach them. These elements are presented in the following conceptual framework below (see Figure 4.7).

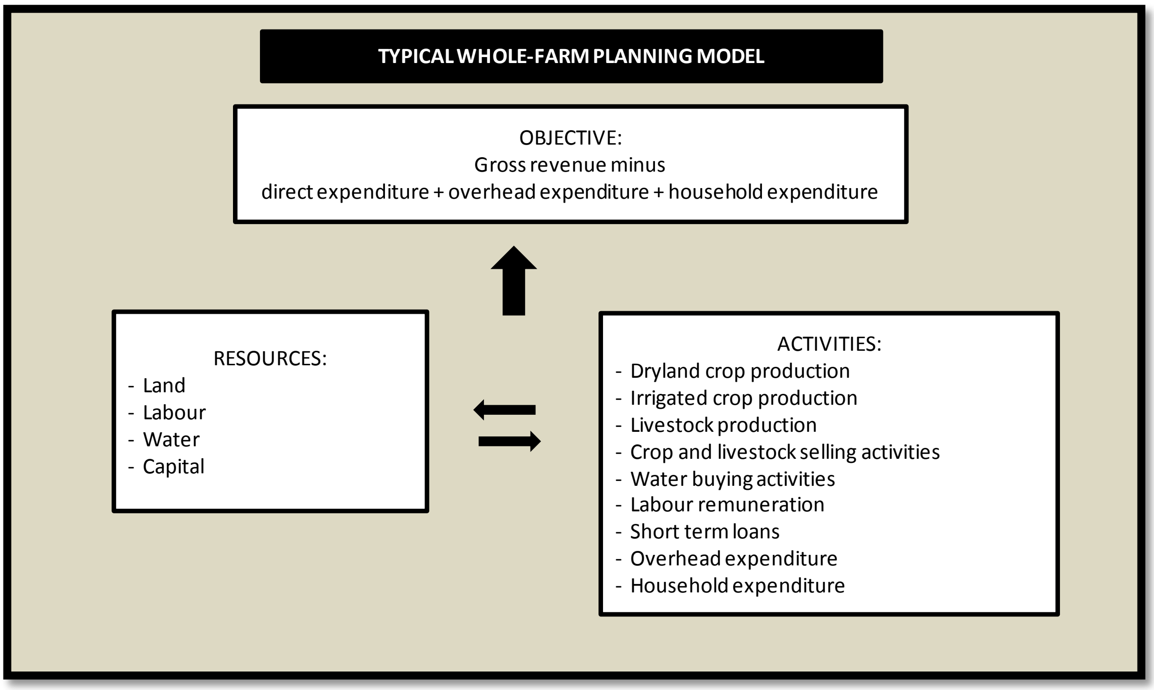


Figure 4.7: Conceptual dynamic linear programming modelling framework
Source: Louw and Jooste (2006)

The structure of a whole-farm planning model with the capability to simulate the impact of climate change should contain at least the following elements:

- A description of producers' economic behaviour (the objective function).
- A description of production functions, and technology sets.
- The relationship between climate (temperature and rainfall) and crop yield/quality.
- The relationship between climate and the availability of irrigation water.
- A specification of the market environment in which the producer operates.
- A specification of the policy environment of the sector.

The primary objective with economic planning is to establish the best choice between alternative uses of limited resources in order to maximise return on capital. Independent of the scale of farming, five objectives must be reached:

- Establish which plan reflects the best use of land, water, capital and human resources.
- Establish the financial implications of the plan based on the expected future cash flow.
- Establish the capital required and the time when needed from own and borrowed sources.
- Analyse the complexity of marketing, financial and production management and the demands it will put on management capability.
- Analyse the financial incentive to put the plan into operation.

With this information it is possible to put forward the implications of alternative choices. The aim is to maximise return on capital. The plan put forward is not a guarantee for success but it is undoubtedly of help for better decision making. In farm planning the human element is the starting point: What are the objectives of the farmer, can the farm comply with these objectives and what are the financial consequences? Technology determines what is possible, economic analysis shows what is feasible and financial analysis shows how much money is needed and when. Analysis and planning, therefore evaluate current performance as well as potential changes to this performance (Louw, 1996).

Evaluating the profitability and financial feasibility of farms within the context of climate change requires a high level of specialisation. The task is challenging and requires the analyst to integrate information regarding climate change, hydrology, crop irrigation requirements, crop yield and quality response to changing water and temperature, infrastructural constraints, credit availability and input and output prices into the modelling framework in order to conduct a thorough feasibility analysis. The analyses are furthermore complicated by the stochastic (risky) and dynamic environment in which decisions are made. Mathematical programming techniques are pre-eminently suited for conducting this study of the financial vulnerability of farming systems without and with climate change adaptations. Modern programming languages such as GAMS (General Algebraic Modelling System) allow the modeller to realistically represent the link between crop production (yield and quality) and projected climate change.

For the purpose of this study two generic types of DLP models were programmed in GAMS and then adapted for each of the regions. These are:

- Irrigation model (applicable to LORWUA and Blyde River WUA case studies).
- Dryland model with livestock (applicable to Moorreesburg and Carolina case studies).

The sections below are brief descriptions of the models (not in mathematical terms).

4.2.2.1 Irrigation DLP

4.2.2.1.1 Description of the objective of households in mathematical terms

The objective of households is to make a living out of farming. In quantitative terms this means that the farmer must at least be able to pay for:

- operational expenditure
- overhead expenditure
- household expenditure.

If there is any surplus left this can be invested to make provision for expansions and/or provision for risk.

The objective functions of the LORWUA and Blyde River WUA case studies are calculated in two steps (b = region, tu = case study, ph = year):

- **Equation NDICALC(b,tu,ph)** calculates the net disposable income per farm (b,tu) and per year (ph)

  Plus gross income from product sales
  Plus non farm income (if applicable)
  Minus direct allocated production costs
  Minus overhead cost
  Minus household cost
  Minus water tariffs

Minus pumping costs
Plus loans (cash inflow)
Minus payback of loans (cash outflow)
Plus surplus (if any from the previous year) + interest on surplus
Plus terminal values
= EndB(b,tu,ph)

- **Objective function Z** (quantified in mathematical terms)

  Z = **Maximize sum (EndB(b,tu,ph))**

Although two case studies (per region) are included in one model, all the calculations are done per case study. By including the two case studies in one model enables the user to use one climate data set to impose on both the farms and thereby save time to run scenarios.

4.2.2.1.2 Activities/variables

The variables include both short and long-term crop activities but no livestock activities. The variables included in the models are:

- Z (total cumulative net cash balance per case study)
- Area of crop production per year
- Total crop area per LT crop per growth stage per farm per year
- Total LT irrigation crop area for all regions
- Total ST irrigation crop area for all region
- Sum of total production volume per crop per farm
- Irrigation crops total monthly water use in any specific year
- Overhead expenditure per case study farm
- Household expenditure per case study farm
- Own capital in the first year per case study farm
- Short term production loans per case study farm per year
- Investment of surplus funds in per year
- End balance at end of planning horizon
- Terminal value of LT crops at the end of the planning horizon.

4.2.2.1.3 Resource constraints

Resource constraints included in the models are:

- Irrigation land (area).

- Water delivery capacity (canal delivery constraint by month) – linked to monthly water availability depending on climate change. Also linked to the crop irrigation requirements (a function of climate scenarios).
- Total water allocation (by year) – linked to climate scenarios.
- Operational capital requirements (linked to the annual surplus available plus the maximum loans available if there is inadequate funds available from own sources).
- Maximum loans.
- Overhead costs – forced into the model and currently based on the existing overhead costs.
- Household costs – forced into the model.
- Non-farm income.
- Minimum and maximum temperature thresholds.
- Rainfall and temperature thresholds linked to yield.
- Rainfall and temperature thresholds linked to both yield and quality.
- Calibration constraints to trim the model in order to simulate the current farm structure – these are released when calculating the farming system's adaptive capacity.

4.2.2.2 Dryland with livestock DLP model

The dryland model is similar to the irrigation model in many aspects. Unique features are highlighted in the sections below.

4.2.2.2.1 Description of the objective of households in mathematical terms

The objectives in mathematical terms are exactly the same as for the irrigation model; however, the objective also includes maximizing livestock production within the limitation of natural veld carrying capacity, crop residue and own feed production.

4.2.2.2.2 Activities/Variables

The following variables are unique to the dryland and livestock model:

Livestock variables

- Present livestock numbers
- Sell livestock products per annum

- Reproduction of livestock
- Total number in specific year
- Calculates maximum weight of livestock sales in kg
- Calculates wool production in kg
- Sums terminal values for livestock

Feed transfer variables

- Initial stock of feed
- Feed bank transfer to period j+1
- Purchase feed
- Use of natural veld
- Transfer of feed production to feed use
- Total animal feed mix
- Total stock plus production

4.2.2.2.3 Resource constraints

The resource constraints unique to the dryland livestock model are:

- Minimum feed requirements in terms of dry matter, crude protein and energy per livestock unit
- Dry matter production of feed and fodder crop per ha
- Nutrient production (protein and energy) per tonne of dry matter
- Transfer of dry matter (where possible) from one year to the next year

The mathematical specification of the DLP model will be discussed in Chapter 5.

4.2.3 Modelling interphases

4.2.3.1 Introduction

The development of interphases between the downscaled climate data sets which were applied in the CCCT, ACRU and SAPWAT3 models and the DLP model is of paramount importance. Not only do they enable a better understanding of the relative changes in the observed and projected climate, but they also make a substantial contribution towards the interpretation and the dissemination of the results. For the purpose of this project, four interphases were developed. They are:

- The APSIM crop yield model – DLP model interphase

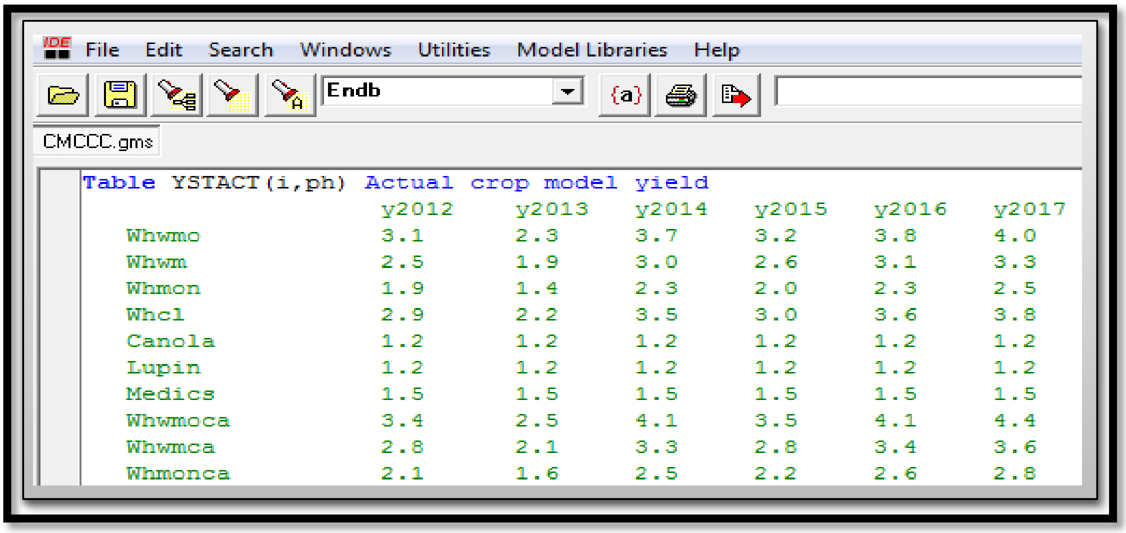
- The CCCT yield and quality model – DLP model interphase
- The ACRU hydrological model - DLP model interphase
- The SAPWAT3 crop irrigation requirement – DLP model interphase
- An interphase to generate at random variation coefficients to be imposed on all the crops in the model where APSIM/CCCT models are not available.

In the sections below each of the interphases is briefly discussed.

4.2.3.2 APSIM crop yield model interphase

APSIM crop models were used to simulate crop yields for different climate scenarios where available. These crops include: grapes (LORWUA) [only a generalised prototype model available], wheat (Moorreesburg) and maize (Carolina). Where APSIM crop models were not available, the research team had to rely on expert knowledge to attempt to simulate the impact of climate change on these crops by applying crop critical climate thresholds to different climate scenarios (Section 4.2.1.2.2).

Figure 4.8 illustrates the APSIM crop model interphase in GAMS file format.



```
Table YSTACT(i,ph) Actual crop model yield
                         y2012     y2013    y2014    y2015    y2016    y2017
   Whwmo                 3.1       2.3      3.7      3.2      3.8      4.0
   Whwm                  2.5       1.9      3.0      2.6      3.1      3.3
   Whmon                 1.9       1.4      2.3      2.0      2.3      2.5
   Whcl                  2.9       2.2      3.5      3.0      3.6      3.8
   Canola                1.2       1.2      1.2      1.2      1.2      1.2
   Lupin                 1.2       1.2      1.2      1.2      1.2      1.2
   Medics                1.5       1.5      1.5      1.5      1.5      1.5
   Whwmoca               3.4       2.5      4.1      3.5      4.1      4.4
   Whwmca                2.8       2.1      3.3      2.8      3.4      3.6
   Whmonca               2.1       1.6      2.5      2.2      2.6      2.8
```

Figure 4.8: APSIM crop model interphase – GAMS file format

After normalization of the APSIM crop model results, the annual projected crop yields are imported into the DLP model through a link to the GAMS file which contains the crop yield information. Table YSTACT (i,ph) in the figure above is the projected crop yield per annum derived from APSIM crop model results.

4.2.3.3 The CCCT yield and quality model interphase

Crop models for annual crops are fairly straight forward (Crespo (2012); Midgley (2012)). However, there is a considerable gap in the knowledge and the technology to simulate the response of perennial crops to climate change. The need for an alternative simulation method ultimately resulted in the development of the CCCT modelling technique, which proved to be a reliable tool for the purpose of this study. The output of the technique depends heavily on the quality of the input. For this reason the input that went into the modelling was obtained from expert group discussions in the various case study areas.

The downscaled climate data sets for the various GCMs feed into the CCCT model. The basic output of the CCCT model is projected yield and quality (annually and per crop cycle) over the planning horizon for each GCM data set in this project specifically in respect of-

- the present (observed) - 1971 to 1990, and
- the intermediate future - 2046 to 2065.

The output of the CCCT model (projected annual yield and quality) feeds into the DLP model.

The following section gives an overview of the different elements in the modelling process.

Similar to Hoffmann's (2010) approach, the minimum and maximum climate thresholds (temperature and rainfall) for all the important crops were identified during a validation workshop and through expert group discussions.

These climate thresholds are used as input to the CCCT model, which is then run with different climate data sets. The model calculates the number of times that each critical threshold is breached. A factor (positive or negative) is assigned to each critical threshold, which implies that the crop yield/quality will be adjusted each time a threshold is breached.

Table 4.2 reflects the crop critical climate thresholds for citrus (grapefruit) in the Blyde River WUA area as well as the expected impact on yield and/or quality.

Table 4.2: Example of Blyde River WUA citrus (grapefruit) critical climate thresholds

Critical climate thresholds	Yield penalty factor	Quality penalty factor
Tmxd > 40 °C and RH < 30% for 2 days Sept	-0.40	0.00
Tmxd >35 °C and RH < 30% for 2 days Sept	-0.40	0.00
Tmxd > 35 °C and RH < 20% for 2 days Sept	-0.40	0.00
Fruit drop (Nov/Dec) >7 days of Tmxd > 36 °C and RH < 40%	-0.30	-0.10
2 °C warmer in May - colour deteriorates	0.00	-0.04
During picking temp > 36 °C - increase rind problems	0.00	-0.01
>14 days continuous rain during picking (autumn) causes leaf wetness and overripe fruit	0.00	-0.10

The following procedures are then executed:

Step 1

The daily temperature and rainfall for each climate change scenario per planning horizon (present [1971 – 1990] and intermediate future [2046 – 2065]) as received from the climatologists are converted to a pivot table in Excel. This includes daily data for five downscaled climate models (GCMs). The data are then processed through a procedure where the threshold breaches for temperature and rainfall are identified.

The threshold breach results for a specific crop are summarised into one table (see Table 4.2 above and Table 4.3 below). The yield/quality is then penalised with a certain percentage according to the breaches of each threshold. In this specific model all the threshold breaches have a negative effect on the yield/quality. Owing to a lack of positive factors, a dummy scaling factor is used to normalise the data, without disturbing the trends. The combined effect of all the threshold breaches that occurred in that specific year is then calculated.

For yield calculation, the DLP model provides for 19 levels of impact ranging from -50% to plus 50% at intervals of 5% to 10% (which can easily be changed). During the procedure any number from 1 to 19 is allocated in the event that the climate condition exceeds the threshold. These are converted into tables for each crop (it can be any number) that is compatible with the GAMS program.

Similar to the yield calculation, the impact of climate change on quality is calculated. The DLP model provides for 10 levels of impact ranging from -40% to plus 50% of the base quality (price). The results are summarised in a table to be fed into the DLP model.

For illustration purposes, quality scaling as a result of climate change will be illustrated in the rest of this section. Table 4.3 presents the process to arrive at a quality scaling code due to temperature and rainfall threshold breaches. For each year under consideration the quality deviation from the base quality (realistic price) is incorporated in the respective row e.g. for 2047 there is a 25% negative impact and a 5% positive impact (scaling dummy). The net effect is therefore -20% which results in a quality scaling Code 3 which GAMS will read as 80% x base quality. See Step 2.

Table 4.3: Allocation of quality deviation per code derived from Step 1

Climate impact quality scaling	Tmxd > 40 °C and RH < 30% for 2 days Sept	Tmxd >35 °C and RH < 30% for 2 days Sept	Tmxd > 35 °C and RH < 20% for 2 days Sept	Fruit drop (Nov/Dec) >7 days of Tmxd > 36 °C and RH < 40%	2 °C warmer in May - colour deteriorates	During picking temp > 36 °C - increase rind problems	>14 days continuous rain during picking (autumn)	Scaling dummy	Temp Quality Scaling factor	Rainfal Quality Scaling factor	Temp & Rain Quality Scaling factor	Climate model Quality scaling code
2046					-0.04	-0.1875		0.05	**-0.1775**		**-0.1775**	**3**
2047					-0.04	-0.21		0.05	**-0.2**		**-0.2**	**3**
2048					-0.04	-0.1425		0.05	**-0.1325**		**-0.1325**	**4**
2049					-0.04	-0.1875		0.05	**-0.1775**		**-0.1775**	**3**
2050						-0.15		0.05	**-0.1**		**-0.1**	**4**
2051					-0.04	-0.1725		0.05	**-0.1625**		**-0.1625**	**3**
2052						-0.12		0.05	**-0.07**		**-0.07**	**4**
2053					-0.04	-0.21		0.05	**-0.2**		**-0.2**	**3**
2054					-0.04	-0.1725		0.05	**-0.1625**		**-0.1625**	**3**
2055					-0.04	-0.1875		0.05	**-0.1775**		**-0.1775**	**3**
2056					-0.04	-0.15		0.05	**-0.14**		**-0.14**	**4**
2057						-0.18		0.05	**-0.13**		**-0.13**	**4**
2058					-0.04	-0.165		0.05	**-0.155**		**-0.155**	**3**
2059					-0.04	-0.18		0.05	**-0.17**		**-0.17**	**3**
2060					-0.04	-0.1875		0.05	**-0.1775**		**-0.1775**	**3**
2061					-0.04	-0.21		0.05	**-0.2**		**-0.2**	**3**
2062					-0.04	-0.15		0.05	**-0.14**		**-0.14**	**4**
2063						-0.1425		0.05	**-0.0925**		**-0.0925**	**4**
2064					-0.04	-0.18		0.05	**-0.17**		**-0.17**	**3**
2065					-0.04	-0.165		0.05	**-0.155**		**-0.155**	**3**

The GAMS program now uses the scaling code number in Table 4.3 and applies the adjustment factor in Table 4.4 to determine with how much the model must increase/decrease the base quality (price). It should be clear that by following this procedure it is possible to trace back the specific reason why the experts were of the opinion that the quality will decrease in a specific year.

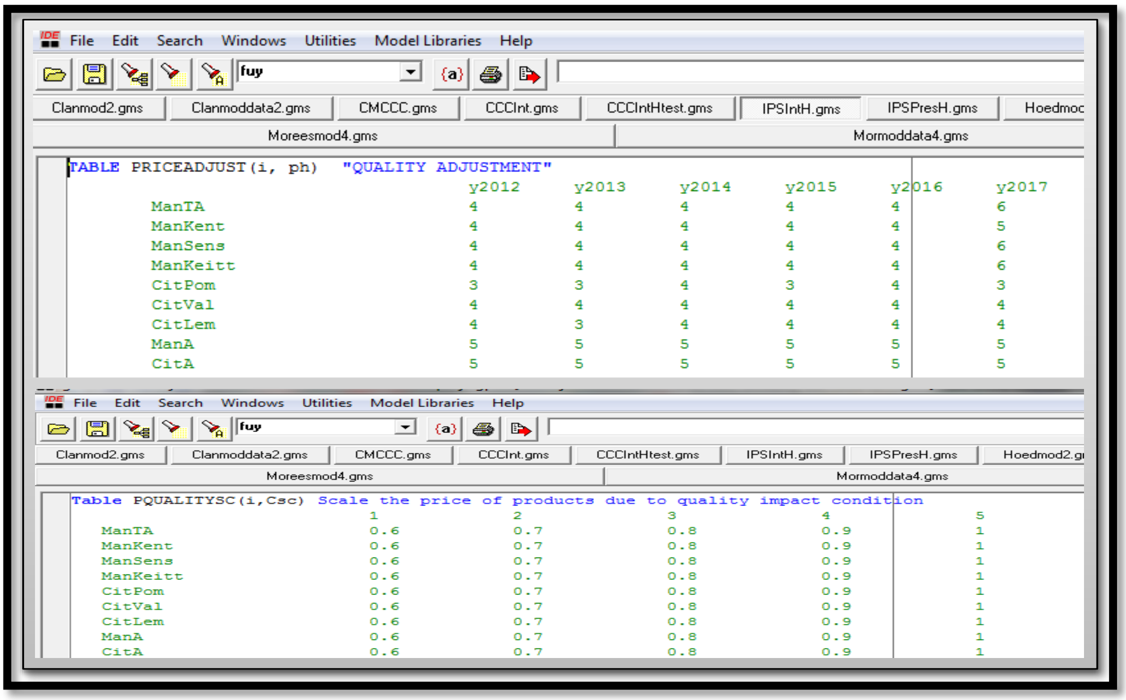
Step 2

In this step a scaling percentage is attached to the quality scaling codes which were calculated in Step 1. The quality code is adjusted by allocating a model code of 1 to 9 to the event (where 5 means no change and the others are four factors negative and four factors positive).

Table 4.4: Allocating a code to scale quality (price) of crops

Scaling code	1	2	3	4	5	6	7	8	9	10
ManTA	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
ManKent	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
ManSens	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
ManKeitt	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
CitPom	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
CitVal	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
CitLem	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
ManA	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
CitA	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5

For example, if a Code 5 is allocated the GAMS model will establish that there is zero change in quality/price. Figure 4.9 illustrates the CCCT quality model interphase with the DLP model in GAMS file format. A Code 4 will result in the model changing the quality of, for example, crop CitPom (Citrus Grapefruit) to 80% of base quality (price).

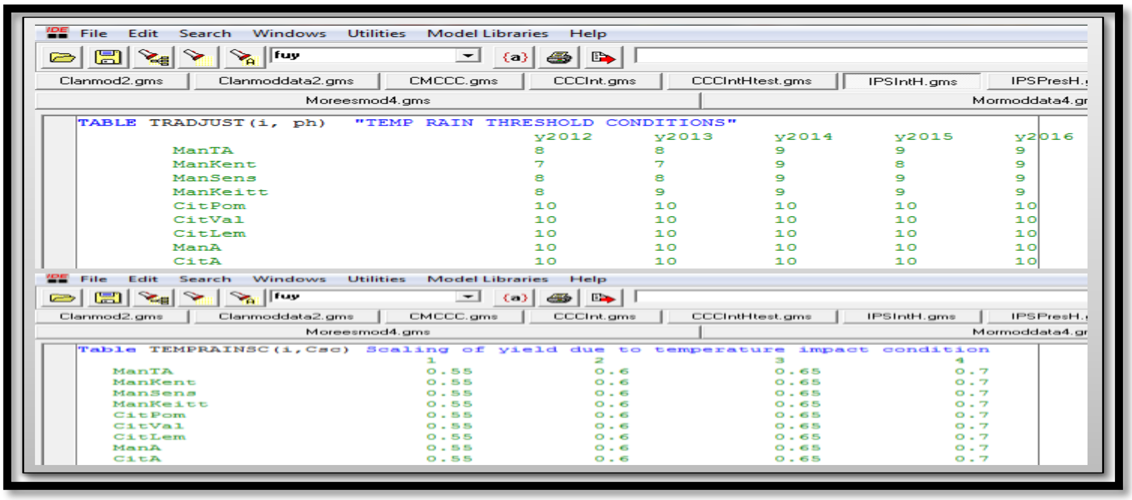


```
TABLE PRICEADJUST(i, ph)  "QUALITY ADJUSTMENT"
                              y2012     y2013     y2014     y2015     y2016     y2017
       ManTA                  4         4         4         4         4         6
       ManKent                4         4         4         4         4         5
       ManSens                4         4         4         4         4         6
       ManKeitt               4         4         4         4         4         6
       CitPom                 3         3         4         3         4         3
       CitVal                 4         4         4         4         4         4
       CitLem                 4         3         4         4         4         4
       ManA                   5         5         5         5         5         5
       CitA                   5         5         5         5         5         5
```

```
Table PQUALITYSC(i,Csc) Scale the price of products due to quality impact condition
                         1          2           3           4           5
   ManTA                 0.6        0.7         0.8         0.9         1
   ManKent               0.6        0.7         0.8         0.9         1
   ManSens               0.6        0.7         0.8         0.9         1
   ManKeitt              0.6        0.7         0.8         0.9         1
   CitPom                0.6        0.7         0.8         0.9         1
   CitVal                0.6        0.7         0.8         0.9         1
   CitLem                0.6        0.7         0.8         0.9         1
   ManA                  0.6        0.7         0.8         0.9         1
   CitA                  0.6        0.7         0.8         0.9         1
```

Figure 4.9: CCCT quality model interphase – GAMS file format

Figure 4.10 illustrates the CCCT yield model interphase with the DLP model in GAMS file format. A Code 4 will result in the model changing the quality of, for example, crop CitPom (Citrus Grapefruit) to 70% of base yield.



```
TABLE TRADJUST(i, ph)   "TEMP RAIN THRESHOLD CONDITIONS"
                                  y2012      y2013      y2014      y2015      y2016
        ManTA                     8          8          9          9          9
        ManKent                   7          7          9          8          9
        ManSens                   8          8          9          9          9
        ManKeitt                  8          9          9          9          9
        CitPom                    10         10         10         10         10
        CitVal                    10         10         10         10         10
        CitLem                    10         10         10         10         10
        ManA                      10         10         10         10         10
        CitA                      10         10         10         10         10
```

```
Table TEMPRAINSC(i,Csc) Scaling of yield due to temperature impact condition
                            1              2              3              4
   ManTA                    0.55           0.6            0.65           0.7
   ManKent                  0.55           0.6            0.65           0.7
   ManSens                  0.55           0.6            0.65           0.7
   ManKeitt                 0.55           0.6            0.65           0.7
   CitPom                   0.55           0.6            0.65           0.7
   CitVal                   0.55           0.6            0.65           0.7
   CitLem                   0.55           0.6            0.65           0.7
   ManA                     0.55           0.6            0.65           0.7
   CitA                     0.55           0.6            0.65           0.7
```

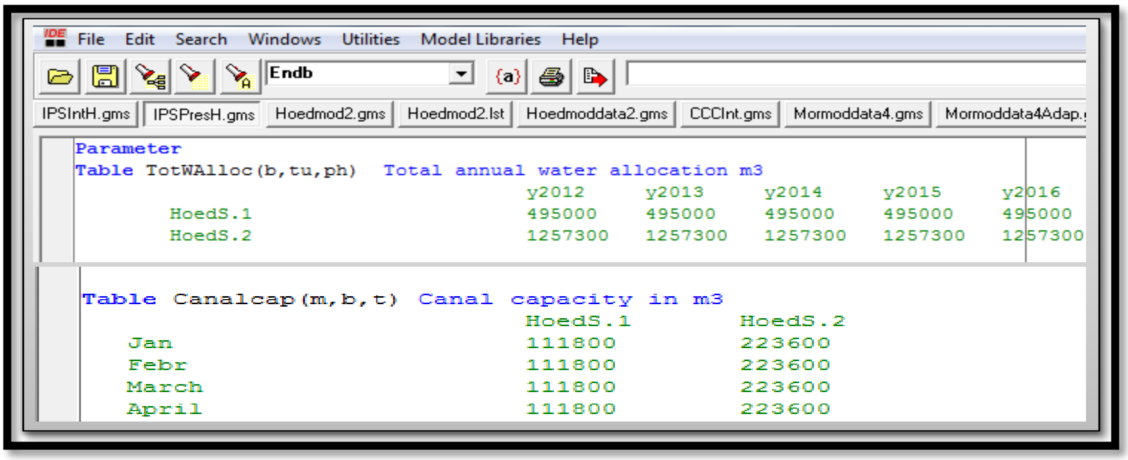
Figure 4.10: CCCT yield model interphase – GAMS file format

The procedure described here is a practical solution to estimate yield and quality variation based on critical climate thresholds for crops. It can be very useful where crop models either do not exist, or where there is doubt about the reliability of the crop models or where crop models do not account for the quality of produce.

4.2.3.4 The ACRU hydrological model interphase

The present and intermediate daily climate values from downscaled GCMs were used in the ACRU model to project future dam levels, which form the base to calculate the annual allocation of irrigation water quotas to farmers. The projected total annual irrigation water quota (m^3) allocated to a farming system and monthly canal capacity is included in the DLP model as a resource constraint.

The ACRU hydrological model interphase and canal capacity restraint in GAMS code file format are illustrated in Figure 4.11.



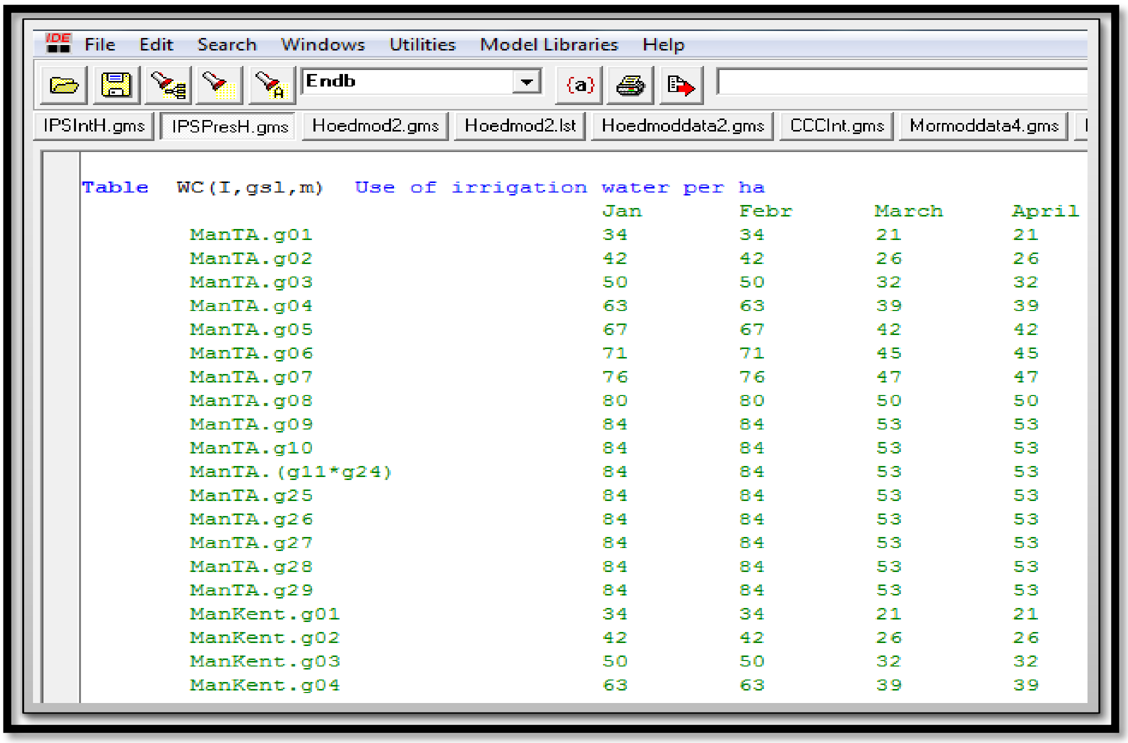
```
Parameter
Table TotWAlloc(b,tu,ph)  Total annual water allocation m3
                                y2012      y2013      y2014      y2015      y2016
            HoedS.1             495000     495000     495000     495000     495000
            HoedS.2             1257300    1257300    1257300    1257300    1257300
```

```
Table Canalcap(m,b,t)  Canal capacity in m3
                          HoedS.1        HoedS.2
      Jan                 111800         223600
      Febr                111800         223600
      March               111800         223600
      April               111800         223600
```

Figure 4.11: Annual irrigation quota allocation and monthly canal constraint – Blyde River WUA example (GAMS code)

4.2.3.5 The SAPWAT3 crop irrigation requirements interphase

The SAPWAT 3 program was used to determine changing crop irrigation requirements under present and future climate scenarios using downscaled climate data of the various GCMs used in this study. The monthly irrigation water requirements per crop per growth stage are included in the DLP model (see Figure 4.12 - crop irrigation requirements interphase in GAMS code file format).



```
Table  WC(I,gsl,m)  Use of irrigation water per ha
                                          Jan      Febr     March    April
          ManTA.g01                       34       34       21       21
          ManTA.g02                       42       42       26       26
          ManTA.g03                       50       50       32       32
          ManTA.g04                       63       63       39       39
          ManTA.g05                       67       67       42       42
          ManTA.g06                       71       71       45       45
          ManTA.g07                       76       76       47       47
          ManTA.g08                       80       80       50       50
          ManTA.g09                       84       84       53       53
          ManTA.g10                       84       84       53       53
          ManTA.(g11*g24)                 84       84       53       53
          ManTA.g25                       84       84       53       53
          ManTA.g26                       84       84       53       53
          ManTA.g27                       84       84       53       53
          ManTA.g28                       84       84       53       53
          ManTA.g29                       84       84       53       53
          ManKent.g01                     34       34       21       21
          ManKent.g02                     42       42       26       26
          ManKent.g03                     50       50       32       32
          ManKent.g04                     63       63       39       39
```

Figure 4.12: Monthly crop irrigation requirements – Blyde River WUA example (GAMS code)

4.2.3.6 An interphase to generate at random variation coefficients

There are several smaller crops where very little information on the thresholds is available. However, it is possible to impose decreases or increases in variation in GAMS through a very simple but useful function in the program. This function can be incorporated to generate at random variation in yield from a base yield. The upper and lower variation can be changed to increase or decrease variation based on estimates from the climate data. For example, if a climate change scenario indicates that the standard deviation from the base is increasing (for both temperature and rainfall or for a combination thereof), it can be interpreted as an increase in climate variability and also possibly an increase in yield variability.

Figure 4.13 illustrates a random variation in yield over a twenty-year projected period with -10% and 10% as the lower and upper boundaries.

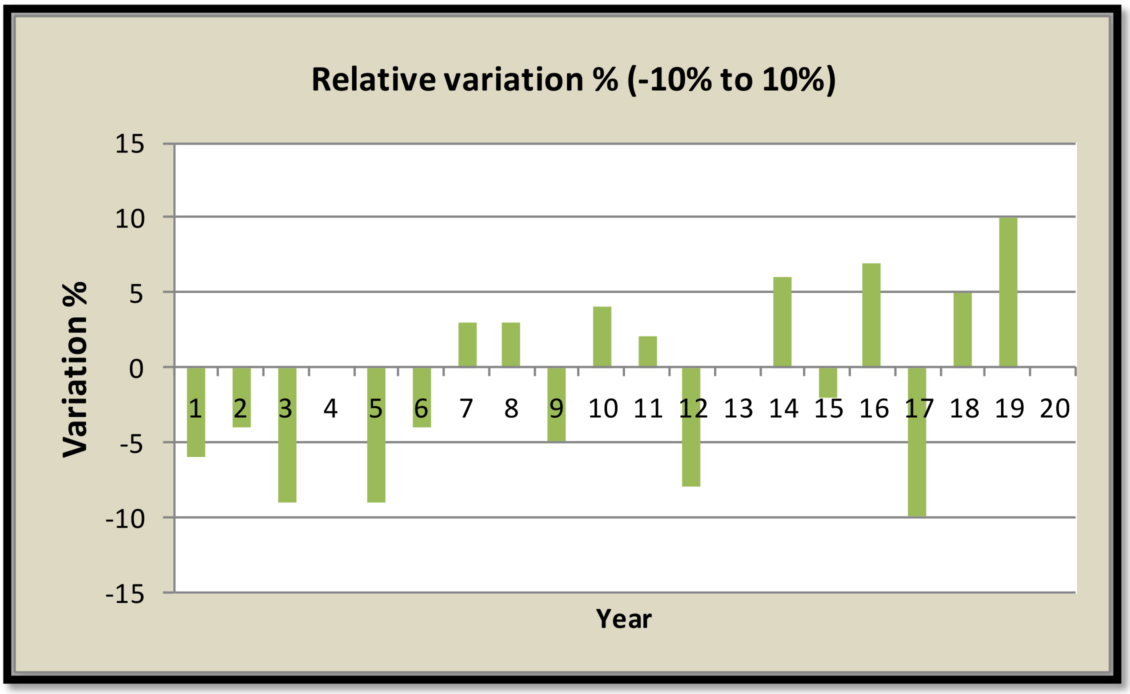


Figure 4.13: Relative variation in yield (-10% to 10%)

Variation can simply be increased by increasing the upper and lower boundary. Also, if the resilience of a farming system needs to be tested it is possible to increase the pessimistic boundary to establish whether or not the farm will still be economically viable.

This tool is extremely useful in studying the impact of climate variability on farming systems in a realistic way considering the many uncertainties surrounding climate change predictions.

4.2.4 Financial Vulnerability Assessment model

The output of the DLP whole-farm model feeds into an excel-based financial assessment model. In order to determine the financial vulnerability of the farming system, a set of criteria provided for in the financial model are applied.

These criteria are:

- IRR
- NPV
- Cash flow ratio

- Highest debt ratio
- Highest debt

Refer to Section 2.7.2 for definitions for each of the financial criteria.

The financial vulnerability assessment in respect of each case study includes individual assessment runs for present and intermediate climate scenarios for each of the five GCMs included in the study. The results for each case study will be discussed in Chapter 6.

4.3 Chapter summary

In Chapter 4 the development of the integrated climate change model was discussed. It comprises a layman's description of the integrated model and the four modules that form the pillars of the integrated climate model. These four modules are: (a) climate change impact modelling, (b) DLP model, (c) modelling interphases, and (d) the Financial Vulnerability Assessment model.

Climate change impact modelling comprises the modelling of empirically downscaled data climate data which impacts on crop yield and quality, changing crop irrigation requirements as a result of climate change and hydrological modelling to determine the availability of irrigation water due to changing weather patterns.

Chapter 4 outline the role of GCMs, empirical downscaling, the APSIM crop modelling and the newly developed CCCT modelling technique. The contribution of the ACRU hydrological model and the SAPWAT3 model, as well as where the respective modelling outputs fit into the integrated climate model are also described.

The objective, purpose and reasons for using the DLP modelling technique in the study are discussed in detail. The primary objective with the economic planning for a farming system is to establish the best choice between the alternative uses of limited resources to maximise return on capital invested. Independent of the scale of farming, five objectives must be reached:

- Establish which plan reflects the best use of land, water, capital and human resources.
- Establish the financial implications of the plan based on the expected future cash flow.

- Establish the capital required and the time when needed from own and borrowed sources.
- Analyse the complexity of marketing, financial and production management and the demands it will put on management capability.
- Analyse the financial incentive to put the plan into operation.

Mathematical programming techniques are pre-eminently suited to conducting the study of the financial vulnerability of farming systems without and with climate change adaptations.

The modelling interphases that link the output from the climate change modelling, hydrological modelling, crop irrigation requirements modelling and an interphase that generate at random variation coefficients, are discussed and graphically illustrated.

The Financial Vulnerability Assessment model comprises a set of criteria namely: IRR, NPV, cash flow ratio, debt ratio and highest debt.

The mathematical specification of the whole-farm DLP and Financial assessment model follows in Chapter 5.

CHAPTER 5 : MATHEMATICAL SPECIFICATION OF THE DLP AND FINANCIAL VULNERABILITY ASSESSMENT MODELS

5.1 Introduction

Chapter 4 discussed the integrated climate change model of which the Dynamic Linear Programming (DLP) model forms an integral part. The reader is referred to Section 4.2.2 for more detail regarding the DLP model and Section 4.2.4 for the Financial Vulnerability Assessment model. This Chapter specifically deals with the mathematical specification of the DLP.

The following section expounds the structural outlay of the DLP model with the various components. A section on the basic algebraic terminology follows. The third section presents the models mathematically and the chapter is concluded with a summary of the special characteristics of the models.

For the sake of brevity the two DLP models (irrigation model and dryland model) will be discussed under the same headings. The main discussion will be in respect of the irrigation model followed by the additional info regarding the dryland model. For example, after the sets structure for the irrigation model the additional sets, which are included in the dryland model, will be stated in a subsection. The LORWUA and Moorreesburg case study models will be used to illustrate the specifications of the respective irrigation and dryland models.

5.2 Mathematical specification of the DLP model

5.2.1 Basic algebraic terminology

The DLP model was developed in the GAMS. Brooke *et al*. (1998) define the basic components of a GAMS model as:

- sets
- data
- variables
- equations.

The following sections will provide the reader with a short description of the meaning of each of these components (Brooke *et al*. 1998 and Louw, 2001).

5.2.1.1 Sets

Sets are the basic building blocks of a GAMS model, corresponding exactly to the indices in the mathematical representations of models. The members of sets are defined as elements. For example, if:

I = crops then wine grapes, table grapes, citrus, etc., are defined as the elements of set **I** and they are denoted as *i*. It should be clear that the elements in set **I** could be infinite. It can sometimes be useful to have subsets for a set. For instance, if it proves to be necessary **C** can be declared as a subset of **I** with element citrus as the only element in the subset.

Sets can also be used to relate elements to each other. For example, **H** is the set for irrigation intensity with elements (*h*) dryland, optimal, supplemental and deficit irrigation and **L** the set for land type with elements (*l*) dryland and irrigation. It may be useful to create a set *h* to *l*, meaning that optimal, supplemental and deficit irrigation relates to the irrigation land type and dryland production relate to the dryland land type.

5.2.1.2 Data

Data can be captured into a model through tables, lists and direct assignments, all referred to as parameters in this study. Each parameter is given a name. The data in a table can either refer to all the elements of a set or to specific data items not declared as sets or elements of sets. In the latter case the data in a table is indicated by using asterisks (*) where the asterisks denote any of the data items in the table (e.g. labour, water, yield).

To clarify the meaning of * in a parameter the following are provided as examples:
Table Overhead(***b*,*t*,***) Overhead and household costs of farm ***t*** in region ***b***

	Household	**Overheads**
HoedS.1	300 000	231 099
HoedS.2	600 000	639 951

When the parameter Overhead(***b*,*t*,***) is stated in an equation to refer to household or overhead expenses, it will be used as Overhead(***b,t,"Household"***) and Overhead(***b,t,"Overheads"***) respectively.

5.2.1.3 Variables

The decision variables (or endogenous variables) are also given names and must be declared as variables through a variable statement. A ***z*** variable must be declared to serve as the quantity to be minimised or maximised.

5.2.1.4 Equations

The power of algebraic modelling languages like GAMS is most apparent in the creation of the equations and the inequalities that comprise the model under construction. This is because whenever a group of equations or inequalities have the same algebraic structure, all the members of the group are created simultaneously, not individually (Louw, 2001).

The DLP model operates by maximising an objective function subject to a set of mathematical constraints. The set structure, parameters and variables are presented below, followed by the objective function and the equations (constraints) of the model. Parameters and scalars are presented in upper case and variables in lower case.

5.2.2 Set structure – irrigation model

Stating the set first and then the elements within each of the sets provides the set structure. If not in table format, the abbreviation for elements is provided in brackets. C = set of all farm enterprises, elements of which are donated as c. The enterprises are presented in Table 5.1.

Table 5.1: Elements of the set C – irrigation model

Description	Element
Raisons	Irrigation raisins
Tgrape	Irrigation table grapes
Rwine	Irrigation red wine cultivars
Wwine	Irrigation white wine cultivars
RaisinsA	Irrigation raisins with adaptation stategies
TgrapeA	Irrigation table grapes with adaptation strategies
RwineA	Irrigation red wine cultivars with adaptation strategies
WwineA	Irrigation white wine cultivars with adaptation strategies
GBeans	Irrigation green beans
Buttern	Irrigation butternuts
Peas	Irrigation peas
Potat	Irrigation potatoes
Cabbag	Irrigation cabbage
Gpep	Irrigation greenpepper
Gsque	Irrigation gem squash
Tomat	Irrigation tomatoes
Onions	Irrigation onions

I = set of all crop enterprises, elements are donated as ***i***. **I** is a subset of **C**. Elements and subsets of I are listed in Table 5.2. Enterprises are grouped into subsets:

- $\mathbf{I}_{oji}$ is the set for cash term crop enterprises
- $\mathbf{I}_{mji}$ is the set of all long-term crop enterprises
- $\mathbf{I}_{v}$ is the set of vegetable enterprises

Table 5.2: Elements and subsets of I – Irrigation model

Item		Subsets of I		
Description	**Element**	I_{oji}	I_{mji}	I_{v}
Raisons	Irrigation raisins		*	
Tgrape	Irrigation table grapes		*	
Rwine	Irrigation red wine cultivars		*	
Wwine	Irrigation white wine cultivars		*	
RaisinsA	Irrigation raisins with adaptation stategies		*	
TgrapeA	Irrigation table grapes with adaptation strategies		*	
RwineA	Irrigation red wine cultivars with adaptation strategies		*	
WwineA	Irrigation white wine cultivars with adaptation strategies		*	
GBeans	Irrigation green beans	*		*
Buttern	Irrigation butternuts	*		*
Peas	Irrigation peas	*		*
Potat	Irrigation potatoes	*		*
Cabbag	Irrigation cabbage	*		*
Gpep	Irrigation greenpepper	*		*
Gsque	Irrigation gem squash	*		*
Tomat	Irrigation tomatoes	*		*
Onions	Irrigation onions	*		*

L = set of land types with elements denoted by ***l***. There are only two land types:

Irrigation land (Irr)
Dryland (Dryland)

J = set of all water use types with elements donated by ***j***. There is only one irrigation region included in the model (Clanw). The model however makes provision for other uses e.g. urban region, the ecology, reserve, etc.

T = set of possible users, elements of which are denoted as ***t***. The LORWUA model includes 2 case study farms.

M = set of months, elements of which are denoted by ***m*** (January to December).

Sm = a sub-set of *m* of summer months, elements are denoted as ***sm*** (October to March).

Wm = a sub-set of *m* of winter months, elements are denoted as ***wm*** (April to September).

GSL = growth stage, elements of which are denoted by ***g*** (1 to 20).

Th = total time serie, elements of which are denoted by (1992 to 2031).

Ph = planning horizon, elements of which are denoted by ***ph*** (2012 to 2031).

Py = previous years, elements of which are denoted by ***py*** (1992 to 2011).

Fy = first year of the planning horizon, (2012).

Sa = savings of surplus cash flow (Invest).

Lo = debt required to finance operations (Stloan).

Oh = set of overheads, elements are denoted as ***Oh***.
Household cost (Housh)
Overhead costs (Overh)

Res = set of resources for crops, elements are denoted as ***Res***.
Input cost (Cost)
Produce price (Price)
Produce yield (Yield)

Csc = scaling of yield due to climate impact, elements are denoted as ***Csc*** (1 - 19).

Qsc = scaling of quality due to climate impact, elements are denoted as ***Qsc*** (1 - 10).

H = set of irrigation intensity possibilities, elements which are denoted as ***h***. There are four levels:

Optimal irrigation	(Opt)
Supplemental irrigation	(Supp)
Deficit irrigation	(Defc)

Supplemental irrigation is defined as three to four irrigations per season. Deficit irrigation is defined as lower intensity irrigation over the whole season with the exception of irrigation during specific critical phases of the production season (for instance during blooming, fruit set and post-harvest irrigations). However, strict quality demands by the fresh produce markets preclude the possibility to do supplemental or deficit irrigation on some crops. It is for instance not possible to produce high quality table grapes, prunes and vegetables under lower intensity irrigation (Louw, 2001).

h_to_l(h,l) = a set of relating irrigation intensity to land type

Optimal, deficit and supplemental irrigation intensities relate to irrigation land ((Opt,Supp,Defc).Irrigat) and dryland relates to dryland (Dry.Dry).

5.2.2.1 Set structure – dryland model

Similar to the irrigation model, **C = set of all farm enterprises**, elements of which are donated as ***c***. The enterprises are presented in Table 5.3.

Table 5.3: Elements of the set C – dryland model (Moorreesburg)

Description	Element
Whwmo	Wheat-wheat-medics-saltbush (old man) crop rotation with conventional cropping system
Whwm	Wheat-wheat-medics crop rotation with conventional cropping system
Whmon	Wheat monoculture production with conventional cropping system
Whcl	Wheat-canola-lupin crop rotation with conventional cropping system
Canola	Canola with conventional cropping system
Lupin	Lupin with conventional cropping system
Medics	Medics with conventional cropping system
Whwmoca	Wheat-wheat-medics-saltbush (old man) crop rotation with conservation agricultural practices
Whwmca	Wheat-wheat-medics crop rotation with conservation agricultural practices
Whmonca	Wheat monoculture production with conservation agricultural practices
Whclca	Wheat-canola-lupin crop rotation with conservation agricultural practices
Canolaca	Canola with conservation agricultural practices
Lupinca	Lupin with conservation agricultural practices
Medicsca	Medics with conservation agricultural practices
HpVeld	Natural veld
Sheep	Mutton and wool production
Lick	Sheep lick
LHay	Wheat hay

I = set of all crop enterprises, elements are donated as ***i***. **I** is a subset of **C**. Elements and subsets of **I** are listed in Table 5.4. Enterprises are grouped into subsets:

- $\mathbf{I}_g$ is the set of grain crops
- $\mathbf{I}_f$ the set of feed crops
- $\mathbf{I}_c$ is the set of no-feed crops
- $\mathbf{I}_w$ is the set of wheat crops

Table 5.4: Elements and subsets of I – Dryland model (Moorreesburg)

Item		Subsets of *i*			
Description	**Element**	g_i	f_i	c_i	w_i
Whwmo	Wheat-wheat-medics-saltbush (old man) crop rotation with conventional cropping system	*	*		*
Whwm	Wheat-wheat-medics crop rotation with conventional cropping system	*	*		*
Whmon	Wheat monoculture production with conventional cropping system	*		*	
Whcl	Wheat-canola-lupin crop rotation with conventional cropping system	*		*	
Canola	Canola with conventional cropping system	*		*	
Lupin	Lupin with conventional cropping system	*		*	
Medics	Medics with conventional cropping system		*		
Whwmoca	Wheat-wheat-medics-saltbush (old man) crop rotation with conservation agricultural practices	*	*		*
Whwmca	Wheat-wheat-medics crop rotation with conservation agricultural practices	*	*		*
Whmonca	Wheat monoculture production with conservation agricultural practices	*		*	
Whclca	Wheat-canola-lupin crop rotation with conservation agricultural practices	*		*	
Canolaca	Canola with conservation agricultural practices	*		*	
Lupinca	Lupin with conservation agricultural practices	*		*	
Medicsca	Medics with conservation agricultural practices		*		

Note that for the remainder of the section, only sets that appear in the dryland model and not in the irrigation model, are discussed.

P = set of by-products, elements include:
Grain1 = Grain 1^{st} grade
Grain2 = Grain 2^{nd} grade
Grain3 = Grain 3^{rd} grade

Cp = a sub-set of p of cash products, elements are denoted as ***cp***. Elements include: Grain1, Grain2, Grain3 and Hay

Qp = a sub-set of p of product quality, elements are denoted as ***qp***. Elements include: Grain1, Grain2 and Grain3

Hp = a sub-set of p of small grain hay product, elements are denoted as ***Hp***.

V = a sub-set of i of veld camps, elements are denoted as ***v***.

A = a sub-set of c of livestock production, elements are denoted as ***a***. Mutton and wool production are included.

Ap = a set of livestock products, elements are denoted as ***ap***. Elements include: Live sheep and wool.

At = a sub-set of *ap* of terminating livestock products, elements are donated as ***at***.

N = a set of nutrients, elements are denoted as ***n***. Elements include: Bulk, TDN and TRP.

Fb = a sub-set of *p* of feedbank possibilities, elements are donated as ***fb***. Elements include: Grain1, Grain2, Grain3 and hay.

F = a sub-set of i of purchase feed, elements are donated as ***f***. Elements include: Lick and Lhay.

5.2.3 Parameters

Parameters are the exogenous data supplied to the model and consist largely of the input coefficients, restriction values (right-hand side values) and scalars for the model. In the description of the parameters, the sets are not always described in the sequence that they appear in the parameter. This is done to make the description logical. It will, for example, not make much sense to describe ALAND$_{btl}$ as region ***b*** farm ***t*** availability of landtype ***l***. Instead, availability of land type ***l*** to farm ***t*** in region ***b*** makes more sense. The irrigation model (LORWUA) has the following parameters:

TYPD$_{jt}$	Defines water users ***t*** in region ***j***
ALAND$_{btl}$	Availability of land type ***l*** to farm ***t*** in region ***b***
AREAU$_{im}$	Monthly land requirement for land type of crop ***i*** in month ***m***
YEARSOC$_{i}$	Lifespan of crop ***i***
RESCRRES$_{igsll*}$	Operating cost and yield per hectare of crop ***i*** for land type ***l*** and growth stage ***gsl***
RESCRGSL$_{igsllph}$	Area crop production of crop ***i*** per growth stage ***gsl*** for land type ***l*** over planning horizon ***ph***
RESCROTH$_{i*}$	Produce price per unit of crop ***i***
PRICESCALE$_{ilt}$	Scale produce price per unit of crop ***i*** for land types ***l***
WC$_{igslm}$	Water requirement of crop ***i*** in period ***m*** per growth stage ***gsl***
TRADJUST$_{iph}$	Scaling of yield due to temperature threshold conditions for crop ***i*** over planning horizon ***ph*** (for CCCT modelling)
TEMPRAINSC$_{iCsc}$	Scaling of yield for crop ***i*** due to climate impact (for CCCT modelling)
PQUALITYSC$_{iCsc}$	Scaling of quality for crop ***i*** due to climate impact (for CCCT modelling)

PRICEADJUST$_{iph}$	Attach climate threshold breaches to price adjustment of crop ***i*** over planning horizon ***ph*** (for CCCT modelling)
YSTACT$_{igsllph}$	Yield projection for crop ***i*** per growth stage ***gsl*** for land types ***l*** over planning horizon ***ph*** (for APSIM crop modelling)
WT$_{bt}$	Scaling factors for water requirements in region ***b*** on farm ***t***
IRINT$_{ih}$	Irrigation intensity possibilities ***h*** for crop ***i***
IRINTSC$_{mh}$	Scaling of irrigation intensity possibilities ***h*** per month ***m***
IRINCSC$_{ih}$	Scaling of the gross margin of crop ***i*** when using irrigation intensity ***h***
TOTWDEF$_{\mathbf{ihbth}}$	Calculation of total deficit and supplemental water for irrigation intencity ***h*** for crop ***i*** in region ***b*** over time serie ***th***
OVERHEAD$_{bt*}$	Overhead and household expenses of farm ***t*** in region ***b***
TYP$_{ibt}$	Defines enterprise combinations ***i*** for farm ***t*** in region ***b***
MAXAREA$_{ilbt}$	Maximum base amount of enterprise ***i*** for land type ***l*** on farm ***t*** in region ***b***
MAXGRCT$_{bt*}$	Maximum base amount for a combination of vegetables of farm ***t*** in region ***b*** where * denotes the vegetable area
BUDSC$_{ibt}$	Scaling of budget information for enterprise ***i*** on farm ***t*** in region ***b***
CRBD$_{i*}$	Budget data coefficients * for crop ***i.*** The * denotes yield (Yield) and present value of gross margins (PV)
INTST$_{lo}$	Real interest rate on loans
INTINV$_{sa}$	Real investment rate on investments
MAXLOAN$_{btlo}$	Maximum short term loan ***lo*** per user ***t***
MAXOC$_{btph}$	Maximum own capital per user ***t*** over planning horizon ***ph***
TERMVAL$_{ilgsl}$	Terminal values for perennial crops ***i*** per growth stage ***gsl*** per land type ***l***
AREASPLIT$_{btipy}$	Production of perennial crops ***i*** farm ***t*** in region ***b*** for previous years ***py***
VERDISKT$_{ph}$	Calculates NPV of cash flow
CANALCAP$_{mbt}$	Canal capacity per month ***m*** in region ***b*** on farm ***t***
LOBND	Relative lower bound for flexibility constraints
UPBND	Relative upper bound for flexibility constraints
WENTITLE$_{bt}$	Area allocation in region ***b*** for farm ***t***

WC$_{igslm}$	Irrigation requirements of crop ***i*** per hectare per growth stage ***gsl*** per month ***m***
TOTWALLOC$_{btph}$	Total annual water allocation in region ***b*** on farm ***t*** over planning horizon ***ph***
TRYIELDCALC$_{igsllPh}$	Calculates yield of crop ***i*** per growth stage ***gsl*** per land type ***l*** over planning horizon ***ph*** due to threshold breaches – Step 1 (for CCCT modelling)
YIELDCALC2$_{igsllPh}$	Calculate yield of crop ***i*** per growth stage ***gsl*** per land type ***l*** over planning horizon ***ph*** due to threshold breaches – Step 2 (for CCCT modelling)
PRICESET$_{iphCsc}$	Calculate price set due to climate threshold condition ***csc*** for crop ***i*** over planning horizon ***ph*** (for CCCT modelling)
PRICEQUAL$_{ilph}$	Calculate annual price of crop ***i*** per land type l over planning horizon ph due to quality considerations

5.2.3.1 Parameters – dryland model (Moorreesburg)

The following unique parameters are exclusive to the dryland model and not already specified in the irrigation model:

Veldarea$_{v}$	Calculate maximum dry matter yield of veld ***v***
OS$_{ipPh}$	Specify begin stocks of feed ***p*** in tonne
ESV$_{ip}$	Calculate value of end stocks of feed ***p***
PRB$_{ip}$	Declare production possibilities by-products ***p***
Pfeedpr$_{fp}$	Specify prices of purchased feed ***fp*** per tonne
Anin$_{aPhRes}$	Specify inputs for animal enterprises ***a***
TermvLS$_{a}$	Calculate terminal value for livestock ***a***
Aprice$_{a}$	Specify price per kg for livestock ***a*** products
YA$_{aap}$	Calculate yield for livestock products ***ap*** in kg
Maxlive$_{aPh}$	Specify maximum present livestock ***a*** numbers
LiveG$_{a}$	Limit annual growth in livestock ***a*** numbers
LiveS$_{a}$	Limit maximum livestock ***a*** selling percentage
NRC$_{na}$	Specify livestock ***a*** groups nutrient ***n*** requirement per unit (%)
INC$_{ipa}$	Specify maximum inclusion levels of nutrients ***n*** and by-products ***p***

$\mathbf{NC}_{ipn}$	Specify nutrient ***n*** and by-products ***p*** contents in percentage
$\mathbf{QD}_{Pha}$	Specify feed quantity demanded per stock unit ***a*** in tonne per day
$\mathbf{FBPOS}_{ip}$	Declare feed bank possibilities of by-products ***p***
$\mathbf{YST}_{ip}$	Crop ***i*** by-products ***p*** yield in tonne
$\mathbf{TRCscCalc}_{iphcsc}$	Calculate set for yield impact of climate
$\mathbf{TRYIELDCAL}_{Cilph}$	Calculate yield based on climate thresholds Step 1
$\mathbf{YIELDCALC2}_{ilpph}$	Calculate yield based on climate thresholds Step 2
$\mathbf{TOTYIELD}_{ilph}$	Calculate yield for Grade 1 to Grade 3 products

5.2.4 Variables

The LORWUA irrigation model contains two types of variables. They are described in terms of the variables contained in the objective function and the agricultural production variables.

5.2.4.1 Variables included in the objective function

The variable included in the objective function is:

z Total welfare (objective function value)

5.2.4.2 Agricultural production variables

The agricultural production variables are the building blocks for the construction of the case study farms in the model. For the irrigation model (LORWUA), they are the following:

$\mathbf{cr}_{ihbtth}$	Area of crop ***i*** grown with irrigation intensity ***h*** on farm ***t*** in region ***b*** for the total time serie ***th***
$\mathbf{crILTtot}_{btMjith}$	Total long-term crop ***Mji*** on farm ***t*** in region ***b*** for the total time serie ***th***
$\mathbf{TotGSL}_{Mjibtgslph}$	Total long-term crop ***Mji*** per growth stage gsl on farm ***t*** in region ***b*** for the planning horizon ***ph***
$\mathbf{crISTtot}_{btOjith}$	Total cash crop ***Oji*** on farm ***t*** in region ***b*** for the total time serie ***th***
$\mathbf{crILTt}_{Mjiph}$	Total long-term irrigation crop ***Mji*** for all regions over planning horizon ***ph***
$\mathbf{crISTt}_{Ojiph}$	Total irrigation cash crop ***Oji*** for all regions over planning horizon ***ph***

$\mathbf{RCP}_{cbtph}$	Sum of regional production volume for crop ***c*** for region ***b*** for the planning horizon ***ph***
$\mathbf{TCP}_{cph}$	Sum of total production volume for crop ***i*** for all regions over planning horizon ***ph***
$\mathbf{TFMW}_{btmph}$	Monthly ***m*** water demand for farm ***t*** in region ***b*** for the planning horizon ***ph***
$\mathbf{TFAW}_{btph}$	Total annual irrigation water demand for farm ***t*** in region ***b*** for the planning horizon ***ph***
$\mathbf{OC}_{btph}$	Overhead costs for farm ***t*** in region ***b*** for the planning horizon ***ph***
$\mathbf{HC}_{btph}$	Household costs for farm ***t*** in region ***b*** for the planning horizon ***ph***
$\mathbf{Owncap}_{btph}$	Own capital in the first year for farm ***t*** in region ***b***
$\mathbf{Loanst}_{btloph}$	Short term production loan ***lo*** for farm ***t*** in region ***b*** for the planning horizon ***ph***
$\mathbf{Investmnt}_{btph}$	Investment of surplus funds for farm ***t*** in region ***b*** for the planning horizon ***ph***
$\mathbf{End}_{bt}$	End balance at end of planning horizon for farm ***t*** in region ***b***
$\mathbf{EndInv}_{bt}$	End investment for farm ***t*** in region ***b***
$\mathbf{EndInc}_{bt}$	End income for farm ***t*** in region ***b***
$\mathbf{Tvalues}_{bt}$	Terminal values at the end of the planning horizon for farm ***t*** in region ***b***

5.2.4.3 Agricultural production variables – dryland model (Moorreesburg)

The following unique production variables are exclusive to the dryland model and not specified in the irrigation model:

$\mathbf{CS}_{ipph}$	Sell by-products ***p*** of cash crops ***i*** over planning horizon ***ph***
$\mathbf{Livebeg}_{aph}$	Present livestock ***a*** numbers over planning horizon ***ph***
$\mathbf{LSTpurch}_{aph}$	Livestock ***a*** purchases over planning horizon ***ph***
$\mathbf{Livesell}_{aph}$	Sell livestock ***a*** over planning horizon ***ph***
$\mathbf{Liverepro}_{aph}$	Reproduction of livestock ***a*** over planning horizon ***ph***
$\mathbf{LSTTOT}_{aph}$	Total number of livestock ***a*** in specific year over planning horizon ***ph***
$\mathbf{LTAP}_{aapph}$	Calculates weight of livestock products ***ap*** sales (kg) per year over planning horizon ***ph***

$\mathbf{WoolS}_{aapph}$	Calculates wool production (kg) of livestock ***a*** in specific year over planning horizon ***ph***
$\mathbf{TermLSval}_{a}$	Sums terminal values for livestock ***a***
$\mathbf{FBstock}_{ipph}$	Initial stock of feed ***ip***
$\mathbf{Fbtr}_{ipph}$	Feed bank transfer to period $j+1$
$\mathbf{PF}_{ipaph}$	Purchase feed ***ip*** for livestock ***a*** in specific year over planning horizon ***ph***
$\mathbf{Veld}_{ipaph}$	Use of natural veld ***ip*** for livestock ***a*** in specific year over planning horizon ***ph***
$\mathbf{AFR}_{ipaph}$	Transfer of feed production ***ip*** to feed use in specific year over planning horizon ***ph***
$\mathbf{TAFR}_{aph}$	Total livestock ***a*** feed mix in specific year over planning horizon ***ph***
$\mathbf{TOTTP}_{fcpph}$	Total stock ***fc*** plus feed production ***p*** in specific year over planning horizon ***ph***

5.2.5 Objective function

The objective is to maximise the aggregated net disposable income (NDI) of case study farms ***t*** in region ***b***.

$$\max Z \; = ndicalc$$

Where *ndicalc* is the aggregated net disposable income of farm ***t*** in region ***b***.

$$ndicalc \; = \sum_{bt}^{ph} ndi$$

5.2.6 Equations

The agricultural production equations are typical of those normally used in whole-farm planning models. This section discusses these equations in more detail.

5.2.6.1 Land use and production equations – irrigation model (LORWUA)

Constraint 1 aggregates the crop area for all crop types and irrigation levels in each region and soil type and should be less than or equal to the area of each soil type (dryland or irrigation) in each region.

$$\sum_{it}^{btl} cr \quad \leq \quad ALAND_{\,btl}$$

Constraint 2 aggregates the total regional area under long-term crops in region ***b***.

$$TotLTcrop_{Mji} = \sum_{btTh}^{Mji} cr$$

Constraint 3 aggregates the total crop per growth stage per annum.

$$TotGSLcalc_{Mji} = \sum_{btgslhTh}^{Mji} cr$$

Constraint 4 aggregates the total regional area under cash crops in region ***b*** for all technologies.

$$TotSTcrop_{Oji} = \sum_{hbtph}^{Oji} cr$$

Constraint 5 represents the regional production of all crops and this should be equal to the sum of the crop production on all typologies, land types and irrigation levels in each region.

$$RCprod_i = \sum_{hbtTh}^{i} cr \quad x \quad YIELDCALC2_{tgsllph} \quad x \quad IRINCSC_{ch} \quad x \quad IRINT_{th}$$

Constraint 6 represents the total production of all crops in all regions.

$$TCprod_i = \sum_{ph}^{i} tcp$$

5.2.6.2 Other resource equations – irrigation model (LORWUA)

Constraint 7 represents farm irrigation water demand and must be less or equal to the irrigation system delivery capacity.

$$TFMWatu_i = \sum_{hbtTh}^{i} cr \quad x \; WC_{\mathrm{cgslm}} \; x \; WT_{\mathrm{bt}} \; x \; IRINTSC_{\mathrm{mh}} \; x \; IRINT_{\mathrm{ch}}$$

Constraint 8 represents the monthly water demand per case study farm and must be less equal to canal capacity.

$$\sum_{btmph}^{i} TFMW \quad \leq \; Canalcap_{mbt}$$

Constraint 9 represents the annual water per farm per year constraint and must be less or equal to the annual irrigation water availability/quota.

.

$$\sum_{btmph}^{TFMW} m \quad \leq \; TFAW_{btPh}$$

Constraint 10 represents the total annual water demand per farm per year constraint by annual water allocation.

$$\sum_{btph}^{i} TFAW \quad \leq \; TotWAlloc_{btPh}$$

5.2.6.3 NDI calculations

The first two equations force overhead and household cost activities into the solution. This is followed by an equation that calculates the NDI for case study farms.

Constraint 11 represents total overhead cost and it is equal to the overhead cost per case study farm.

$$Ocost_{btPh} \; = \; OC_{btPh} *$$

The asterisk denotes overhead costs.

Constraint 12 represents total household cost and it is equal to the household cost per case study farm.

$$Hcost_{btPh} \; = \; HC_{btPh} *$$

The asterisk denotes household costs.

Constraint 13 calculates the net disposable income per case study farm in each of the irrigation regions.

$$NDICALC_i = \sum_{hbtPh}^{i} cr \ \ x \ PriceQual_{ilPh} \ \ x \ \ PriceScale_{ilt} \ \ x \ \ VerdiskT_{Ph} \ \ x \ \ Budsc_{ibt}$$

The terms above calculates the total gross margin per farm in each region.

The following terms are the direct allocated production costs.

$$- \sum_{hbtTh}^{i} i \ \ x \ \ Rescrres_{igsll*} \ \ x \ \ VerdiskT_{Ph} \ \ x \ \ IRINT_{ih}$$

The asterisk denotes cost.

The following terms are the aggregated overhead and household costs.

$$- \ OC_{btPh} \ - \ \ HC_{btPh}$$

The left-hand term is the aggregated overhead cost and the right-hand term is the aggregated household cost.

The following terms represent the financing part of the farm model.

$$+ \ Loanst_{btloPh} \ - \ \ Loanst_{btloPh-1} \ \ x \ \ INTST_{lo+1}$$

The left-hand term is the loan for the current year the middle term is the loan for the previous year and the right-hand term is the real interest rate on loan.

The following term represents the investment of surplus funds.

$$+ \ Investmnt_{btlPh-1} \ \ x \ \ INTINV_{sa+1}$$

The left-hand term is the investment amount of the previous year and the right-hand term is the real investment rate. The following term represents the maximum own capital investment in the first year.

$$+ \ MaxOC_{btPh}$$

The calculation of the NDI can be summarised as follows: The net disposable income for each farm in every region is equal to the sum of the gross margins for the production activities over all land types and irrigation intensities minus overhead and household cost minus interest paid on loan plus interest received on investment.

5.2.6.4 Resource equations – dryland model

Resource equations unique to the Dryland model are as follows:

Constraint 1 represents the maximum number of livestock per year.

$$\sum_{ph}^{a} Livebeg \;+\; \sum_{ph}^{a} Liverepro \;+\; \sum_{ph}^{a} LSTpurch \;-\; \sum_{ph}^{a} Livesell \;=\; LSTTOT_{aPh}$$

Constraint 2 calculates reproduction of livestock per year.

$$LSTTOT_{aph} \;\; x \;\; LiveG_{a} \;=\; Liverepro_{aph}$$

Constraint 3 calculates maximum selling of living livestock per year.

$$Livesell_{afuy} \;\leq\; LSTTOT_{afuy} \;\; x \;\; LiveS_{a}$$

Constraint 4 sums livestock sales numbers per year.

$$\left(Livesell_{aph} \;\; x \;\; (YA_{alive} \;\; x \;\; Manl \;)\right) \;-\; LTAP_{aliveph} \;=\; 0$$

Constraint 5 sums wool production per year.

$$\left(LSTTOT_{aph} \;\; x \;\; (YA_{awool} \;\; x \;\; Manl \;)\right) \;-\; WoolS_{awoolph} \;=\; 0$$

Constraint 6 calculates total feed stock per year.

$$TCP_{fcpph} + Fbstock_{fcpph} \;=\; TOTTP_{fcpph}$$

Constraint 7 calculates bulk transfer of by-products ***p*** to livestock or sell.

$$AFR_{fcpaph} + \left(CS_{fcpph} \;\; x \;\; PRB_{fcp}\right) + \left(Fbtr_{fcpph} \;\; x \;\; FBPOS_{fcp}\right) - \left(Fbtr_{fcpph-1} \;\; x \;\; FBPOS_{fcp}\right) \;=\; 0$$

Constraint 8 calculates nutrient transfer of bulk feed.

$$(AFR_{fcpaph}\ x\ NC_{fcpbulk}) + (PF_{fpaph}\ x\ NC_{fpbulk}) + (Veld_{vpaph}\ x\ NC_{vpbulk}) = (TAFR_{aph}\ x\ NRC_{Bulka})$$

Constraint 9 calculates minimum percentage total digestible nutrients (TDN).

$$(AFR_{fcpaph}\, x\ NC_{fcpTDN}) + (PF_{fpaph}\ x\ NC_{fpTDN}) + (Veld_{vpaph}\ x\ NC_{vpTDN}) \geq \geq (TAFR_{aph}\ x\ NRC_{TDNa})\ x\ 0.9$$

Constraint 10 calculates maximum percentage total digestible nutrients (TDN).

$$(AFR_{fcpaph}\, x\ NC_{fcpTDN}) + (PF_{fpaph}\ x\ NC_{fpTDN}) + (Veld_{vpaph}\ x\ NC_{vpTDN}) \leq (TAFR_{aph}\ x\ NRC_{TDNa})\ x\ 1.1$$

Constraint 11 calculates minimum total crude protein percentage (TCP).

$$(AFR_{fcpaph}\, x\ NC_{fcpTCP}) + (PF_{fpaph}\ x\ NC_{fpTCP}) + (Veld_{vpaph}\ x\ NC_{vpTCP}) \geq (TAFR_{aph}\ x\ NRC_{TCPa})\ \mathrm{x}\ 0.9$$

Constraint 12 calculates maximum total crude protein percentage (TCP).

$$(AFR_{fcpaph}\, x\ NC_{fcpTCP}) + (PF_{fpaph}\ x\ NC_{fpTCP}) + (Veld_{vpaph}\ x\ NC_{vpTCP}) \leq (TAFR_{aph}\ x\ NRC_{TCPa})\ x\ 1.1$$

Constraint 13 calculates maximum bulk feed.

$$AFR_{fcpaph} + PF_{fpaph} + Veld_{vpaph} \leq TAFR_{aph}$$

Constraint 14 calculates maximum inclusion levels of own proceeds.

$$AFR_{fcpaph}\ x\ PRB_{fcp} \leq INC_{fcpa}\ x\ TAFR_{aph}$$

Constraint 15 calculates maximum inclusion levels of purchased feeds.

$$PF_{aph} \leq INC_{fpmixa}\ x\ TAFR_{aph}$$

Constraint 16 calculates maximum inclusion levels of veld in total mix.

$$Veld_{vpaph} \leq INC_{vpasturea} \; x \; TAFR_{aph}$$

Constraint 17 calculates maximum inclusion levels of veld in total mix.

$$Veld_{vpaph} \leq INC_{vpasturea} \; x \; TAFR_{aph}$$

Constraint 18 sums total animal feed demand.

$$TAFR_{aph} - \left((QD_{aph} \text{ x } DPP) \; x \; LSTTOT_{aph} \right) \leq 0$$

Section 5.2 deals with the structural outlay and mathematical specification of the DLP model. The results of the DLP model feeds into the Financial Vulnerability Assessment model. Section 5.3 deals with the mathematical specification of the Financial Vulnerability Assessment model.

5.3 Mathematical specification of the Financial Vulnerability Assessment model

The Financial Vulnerability Assessment model is an excel-based model which feeds from the DLP model results. The Financial Vulnerability Assessment model calculates a set of financial criteria to determine the financial vulnerability of farming systems. The financial criteria are:

- IRR
- NPV
- Cash flow ratio
- Highest debt ratio
- Highest debt

The following sections will deal with the mathematical specification of each criterion. The reader is referred to Section 2.7.2 for definitions and Section 4.2.4 for graphical illustration of financial vulnerability assessment criteria.

The following terms represent the mathematical formula for the internal rate of return (IRR). Denoting the IRR by ***r***, we have

$$\sum_{i=0}^{T} \frac{C_i}{(1+r)^i} = 0$$

where ***T*** is the time at which the cash flow ***Ci*** occurs.

The following terms represent the mathematical formula for net present value (NPV).

$$NPV = -C_0 + \sum_{i=1}^{T} \frac{C_i}{(1+r)^i}$$

Where: $- C_0$ = *Initial investment*
C = *Cash flow*
R = *Discount rate*
T = *Time*

The following terms represent mathematical formula for cash flow ratio.

$$\text{Cash flow ratio} = \sum CI \quad / \quad \sum CO \quad x \quad 100$$

Where ***CI*** is annual cash inflow and ***CO*** is annual cash outflow.

The following represents the mathematical formula of debt ratio

$$Debt\,ratio = \sum TD \quad / \quad \sum TA \quad x \quad 100$$

Where ***TD*** is total debt and ***TA*** is total assets.

5.4 Chapter summary

Chapter 5 presents the design and the mathematical specification of the DLP and Financial Vulnerability Assessment models. The agricultural part of the model is to a large extent based on work done in Australia and applied in South Africa by Louw (2001), who added several newly developed formulas and techniques to the model.

The interphases between the DLP model and other models that were developed in this study are unique and contribute to the existing DLP model. These interphases include:

- The APSIM crop model data whole-farm model interphase
- The CCCT yield model data whole-farm model interphase
- The CCCT quality model data whole-farm model interphase
- The ACRU hydrological model data whole-farm model interphase
- The SAPWAT3 crop irrigation requirements data whole-farm model interphase

The link between the output of the DLP model and the Financial Vulnerability Assessment model also constitutes a new contribution to the DLP model.

The integrated modelling results will be discussed in Chapter 6.

CHAPTER 6 : INTEGRATED MODELLING RESULTS FOR THE SELECTED CASE STUDIES

6.1 Introduction

In Chapter 5 the DLP and the Financial Vulnerability Assessment model were mathematically specified. In Chapter 6 the integrated modelling results, impact of future projected climates on financial vulnerability and possible adaptation strategies will be discussed.

The modelling results for each of the case study areas will be discussed under the following headings (where applicable):

- Climate change impact on quality and yield of crops
    - APSIM (for selected crops - depending on availability)
    - CCCT modelling.
- Climate change impact on crop irrigation requirements (for irrigation crops only – SAPWAT3 modelling).
- Climate change impact on the availability of irrigation water requirements (only in respect of Blyde River WUA – ACRU modelling).
- Available adaptation strategies.
- Financial vulnerability assessment results.
- Summary.

6.2 LORWUA

6.2.1 Climate change impact on quality and yield of crops modelling results

6.2.1.1 APSIM crop modelling results

It needs to be reiterated that the APSIM model for grapes is currently still a prototype and therefore the outcome needs to be interpreted with caution.

Figure 6.1 shows the projected yield for grapes for the intermediate future (2046 – 2065) in the LORWUA area, derived from APSIM calculations. The figures are expressed as percentage of the yield used in the base analysis.

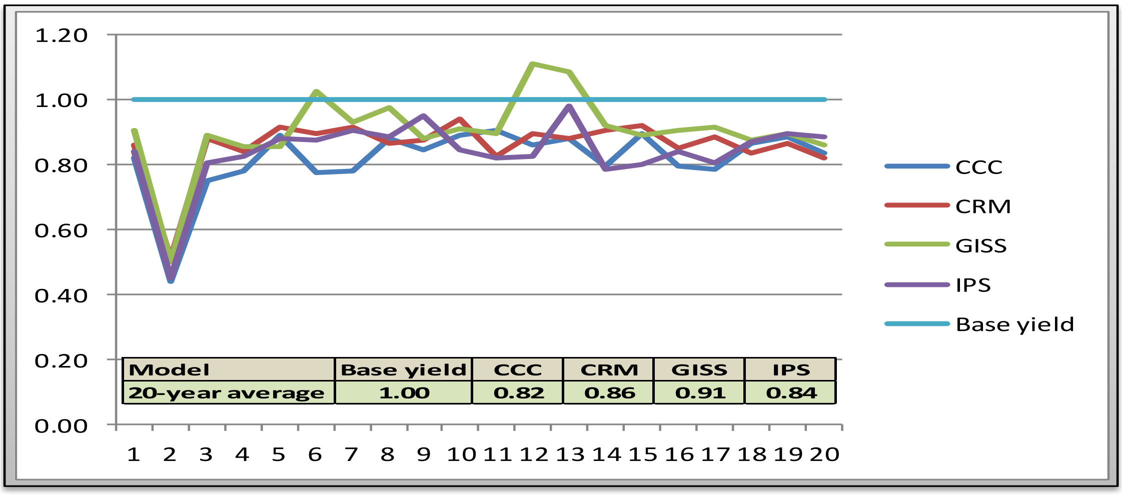


Figure 6.1: Projected yield (%) [2046 – 2065] for grapes in the LORWUA area based on APSIM calculations

Climate data from four GCMs were applied in the APSIM modelling. All the GCMs project a 20-year average decrease in yield, varying from 9% to 18%.

6.2.1.2 CCCT modelling results

Table 6.1 shows the CCCT modelling results for the different GCMs for the present and intermediate future (2046 – 2065). The values are 20-year average values for the different models. All the GCMs project a decrease in yield for wine grapes, table grapes and raisins and a decrease in quality for table grapes. E.g. average yield for raisins decreases from code 11 tot code 10, implying a 5% decrease in projected yield. Average projected quality for table grapes decreases from code 5 to code 4, equalling 10% decrease in projected quality.

Table 6.1: CCCT modelling yield and quality projections for wine grapes, table grapes and raisins in the LORWUA area

	Wine grapes		Table grapes		Raisins	
Model	**Yield**	**Quality**	**Yield**	**Quality**	**Yield**	**Quality**
CCC Pres	12	4	12	5	12	4
CCC Int	10	4	9	4	10	4
CRM Pres	12	4	12	5	12	4
CRM Int	10	4	9	4	10	4
ECH Pres	12	4	12	5	12	4
ECH Int	10	4	10	5	10	4
GISS Pres	11	4	11	5	11	4
GISS Int	10	4	10	5	10	4
IPS Pres	11	4	11	5	11	4
IPS Int	10	4	10	4	10	4
AVE Pres	**11**	**4**	**11**	**5**	**11**	**4**
AVE Int	**10**	**4**	**10**	**4**	**10**	**4**

Legend: Yield (% of base yield)

8 = 90%
9 = 95%
10 = 100%
11 = 105%
12 = 110%

Legend: Quality (% of base quality)

3 = 80%
4 = 90%
5 = 100%
6 = 110%
7 = 120%

6.2.2 Climate change impact on crop irrigation requirements results

Tables 6.2 to Table 6.4 display the simulated irrigation requirements for table grapes, wine grapes and raisins for the current and intermediate future projected climates.

A 10% average annual increase in irrigation requirements is projected for table grapes for intermediate future climates in order to obtain the same yield as with present climates (Table 6.2).

Table 6.2: SAPWAT3 simulated irrigation requirements for table grapes for the present and intermediate future projected climates

Table grapes - present														
Case study region	**Irri01**	**Irri02**	**Irri03**	**Irri04**	**Irri05**	**Irri06**	**Irri07**	**Irri08**	**Irri09**	**Irri10**	**Irri11**	**Irri12**	**Total**	
Vredendal_CCC_PR3	146	137	115	61	9	0	0	0	0	12	113	153	**746**	
Vredendal_ECH_PR3	159	126	98	55	7	0	0	0	0	9	124	155	**733**	
Vredendal_GISS_PR3	175	151	126	74	28	0	0	0	0	25	142	186	**907**	
Vredendal_IPS_PR3	159	135	128	61	14	0	0	0	0	21	132	162	**812**	
Average	**160**	**137**	**117**	**63**	**15**	**0**	**0**	**0**	**0**	**17**	**128**	**164**	**800**	
Table grapes - intermediate future														
Case study region	**Irri01**	**Irri02**	**Irri03**	**Irri04**	**Irri05**	**Irri06**	**Irri07**	**Irri08**	**Irri09**	**Irri10**	**Irri11**	**Irri12**	**Total**	**% change**
Vredendal_CCC_INT	180	139	126	60	16	0	0	0	0	21	132	172	**846**	13%
Vredendal_ECH_INT	160	142	110	57	12	0	0	0	0	12	128	180	**801**	9%
Vredendal_GISS_INT	185	164	144	77	29	0	0	0	0	36	150	199	**984**	8%
Vredendal_IPS_INT	170	145	130	71	17	0	0	0	0	22	143	180	**878**	8%
Average	**174**	**148**	**128**	**66**	**19**	**0**	**0**	**0**	**0**	**23**	**138**	**183**	**877**	**10%**

For wine grapes, an average annual increase of 11% in irrigation requirements is projected for intermediate future climates in order to obtain the same yield as with present climates (Table 6.3).

Table 6.3: SAPWAT3 simulated irrigation requirements for wine grapes for the present and intermediate future projected climates

Wine grapes - present														
Case study region	**Irri01**	**Irri02**	**Irri03**	**Irri04**	**Irri05**	**Irri06**	**Irri07**	**Irri08**	**Irri09**	**Irri10**	**Irri11**	**Irri12**	**Total**	
Vredendal_CCC_PR3	119	109	86	50	11	0	0	0	0	5	90	124	**594**	
Vredendal_ECH_PR3	132	100	81	38	7	0	0	0	0	4	94	131	**587**	
Vredendal_GISS_PR3	147	129	96	66	28	0	0	0	0	12	125	150	**753**	
Vredendal_IPS_PR3	133	112	92	54	9	0	0	0	0	13	104	138	**655**	
Average	**133**	**113**	**89**	**52**	**14**	**0**	**0**	**0**	**0**	**9**	**103**	**136**	**647**	
Wine grapes - intermediate future														
Case study region	**Irri01**	**Irri02**	**Irri03**	**Irri04**	**Irri05**	**Irri06**	**Irri07**	**Irri08**	**Irri09**	**Irri10**	**Irri11**	**Irri12**	**Total**	**% change**
Vredendal_CCC_INT	147	116	94	54	14	0	0	0	0	10	106	149	**690**	16%
Vredendal_ECH_INT	139	109	84	47	8	0	0	0	0	7	101	143	**638**	9%
Vredendal_GISS_INT	154	140	119	68	24	0	0	0	0	20	130	158	**813**	8%
Vredendal_IPS_INT	142	120	102	61	20	0	0	0	0	8	126	150	**729**	11%
Average	**146**	**121**	**100**	**58**	**17**	**0**	**0**	**0**	**0**	**11**	**116**	**150**	**718**	**11%**

An 11% average annual increase in irrigation requirements is projected for raisins for intermediate future climates in order to obtain the same yield as with present climates (Table 6.4).

Table 6.4: SAPWAT3 simulated irrigation requirements for raisins for the present and intermediate future projected climates

Raisins - present														
Case study region	**Irri01**	**Irri02**	**Irri03**	**Irri04**	**Irri05**	**Irri06**	**Irri07**	**Irri08**	**Irri09**	**Irri10**	**Irri11**	**Irri12**	**Total**	
Vredendal_CCC_PR3	119	109	86	50	11	0	0	0	0	5	90	124	**594**	
Vredendal_ECH_PR3	132	100	81	38	7	0	0	0	0	4	94	131	**587**	
Vredendal_GISS_PR3	147	129	96	66	28	0	0	0	0	12	125	150	**753**	
Vredendal_IPS_PR3	133	112	92	54	9	0	0	0	0	13	104	138	**655**	
Average	**133**	**113**	**89**	**52**	**14**	**0**	**0**	**0**	**0**	**9**	**103**	**136**	**647**	
Raisins - intermediate future														
Case study region	**Irri01**	**Irri02**	**Irri03**	**Irri04**	**Irri05**	**Irri06**	**Irri07**	**Irri08**	**Irri09**	**Irri10**	**Irri11**	**Irri12**	**Total**	**% change**
Vredendal_CCC_INT	147	116	94	54	14	0	0	0	0	10	106	149	**690**	16%
Vredendal_ECH_INT	139	109	84	47	8	0	0	0	0	7	101	143	**638**	9%
Vredendal_GISS_INT	154	140	119	68	24	0	0	0	0	20	130	158	**813**	8%
Vredendal_IPS_INT	142	120	102	61	20	0	0	0	0	8	126	150	**729**	11%
Average	**146**	**121**	**100**	**58**	**17**	**0**	**0**	**0**	**0**	**11**	**116**	**150**	**718**	**11%**

6.2.3 Climate change impact on the availability of irrigation water requirements

The projected dam level data for Clanwilliam Dam (ACRU calculation), which determine the availability of irrigation water, was not available at the time and is not included as a constraint in the calculations for the LORWUA case studies. Another reason for not including projected dam levels and availability of irrigation water for the Clanwilliam Dam is the uncertainty associated with the expansion of the dam, of which construction is due to start by the end of 2014. The final distribution of additional water between different sectors of the economy also still needs to be finalised.

6.2.4 Adaptation strategies available

For the grape producing area of LORWUA the adaptation strategies that were identified to be included in the integrated model are:

- Shift wine grape cultivars towards cultivars that are more tolerant towards projected climate change.
- Increase raisin and table grape production.
- Install shade nets over table grapes production areas.

6.2.4.1 Shift in wine grape cultivars

The world is experiencing a warming trend. Warming may bring benefits to cool viticultural regions, but is likely to create problems in areas that are already close to the upper temperature limits for the cultivars and wine styles concerned. In these cases, relocation, or replacement with varieties that are better adapted to the higher temperatures will be necessary if it is not possible to ameliorate the effects of climate change through management practices (Wooldridge, 2007). Problems that could occur due to climate change include: (a) delayed or uneven bud break, (b) change in phonological stages, (c) yield reduction, (d) change in harvest date, and (e) change in wine type and style (Vink *et al.,* 2012).

Bonnardot *et al.* (2011) emphasises the importance of understanding regional and wine cultivar differences as cultivars have fairly narrow optimal ranges within which they can produce wines of a certain style. As the climate changes, certain regions may move out of these optimal temperature ranges resulting in altered wine style or even altered optimal cultivars that should be planted.

It is important to state that one must take mesoclimatic differences into account. Within a larger area, local climates that are determined by slope aspect, altitude and distance from the sea, can result in average growing season temperatures that are very different (Carey, 2001, cited by Bonnardot *et al*., 2011).

Certain wine cultivars may, however, be more tolerant to increased temperatures than others and a shift to more heat tolerant cultivars in wine production can also be an adaptation strategy. Vink *et al*. (2012) highlighted the fact that South Africa's wine grape growing regions are characterised by diversity (in climate, topography, soil type, etc.) and for most farmers diversity is the key to managing the effects of climate change, mainly in terms of increasing wine complexity brought by blending wines from different terroir units/regions.

The expert panel indicated that within the case study region, white wine grape cultivars that will be more tolerant towards climate change include Chenin Blanc and Colombard. White wine grape cultivars that will be most vulnerable towards climate change include Sauvignon Blanc and Chardonnay.

Red wine grape cultivars that will be more tolerant towards climate change include Cabernet Sauvignon, Pinotage and Ruby. Red wine grape cultivars that will be most vulnerable towards climate change are Shiraz and Merlot.

6.2.4.2 Increase raisin and table grape production

Raisin and table grapes cultivars in general are more resilient to climate change projections (Bonnardot *et al.*, 2011). The expert panel agreed that a shift from wine grape production to raisin and table grape production can be an adaptation strategy which will reduce the negative impact of climate change on wine grape production.

6.2.4.3 Shade nets

Netting is used in agriculture to protect crops from either excessive solar radiation, i.e. shading, or environmental hazards, e.g. hail, strong winds, sand storms, or flying pests such as birds, fruit-bats, insects (Shahak *et al.*, 2004).

The production of table grapes under shade nets has already started to take place in the LORWUA area, but to a limited extent. In other areas e.g. Marble Hall and Groblersdal it is common practice to produce table grapes under shade nets, although the initial main driver was the risk of hail damage.

The expert panel agreed that shade nets over table grapes can eliminate most problems associated with projected climate change and will have the following advantages:

- More efficient water use
- More consistent yield and quality
- Increase in quality (less wind damage, less quality loss due to birds)
- Lower input cost (lower labour cost due to increased quality)

6.2.4.4 Other adaptation strategies (not included in the model)

The following are a list of adaptation strategies debated but not included in the integrated climate change model:

- Irrigate at night to save water
- Plastic or mulch cover to conserve moist
- Soil preparation and site selection are important for future plantings to ensure optimum production – rather scale down and eliminate marginal blocks.

6.2.5 Financial vulnerability assessment results

6.2.5.1 Financial vulnerability assessment methodology

To determine the financial vulnerability of a farming system, the financial model provides a set of criteria, viz. IRR, NPV, cash flow ratio, highest debt ratio and highest debt.

The financial vulnerability assessment for each case study includes individual assessment runs for present and intermediate climate scenarios for each of the five GCMs included in the study.

The modelling scenarios can be divided into four broad categories namely:

- Base run use current average yields and prices to project over a 20 year period – 15% variability in yield and price.
- Present climate scenario – static production system
    - Crop Critical Climate Threshold (CCCT modelling technique) - use crop critical climate thresholds and present climate scenarios data to determine potential yield and grading of crop produce as input to the model.
- Intermediate climate scenario – static production system
    - CCCT modelling technique - use crop critical climate thresholds and intermediate future climate scenarios data to determine potential yield and grading of crop produce as input to the model – model is restrained to simulate current production structures.
    - Use APSIM crop model results for the intermediate future climate scenarios as input (yield) to the model – model is restrained to simulate current production structures.
- Intermediate climate scenario - including adaptation strategy options
    - CCCT modelling technique - use crop critical climate thresholds and intermediate future climate scenarios data to determine potential yield and grading of crop produce as input to the model – adaptation strategy options are included.
    - Use APSIM crop model results for the intermediate future climate scenarios as input to the model – adaptation strategy options are included.

The first runs can be described as static runs, where the production structure is not altered and only climate change is imposed on the farming system. During the second round, the adaptation strategy options are included in the modelling in order to quantify the potential reduction in vulnerability by including adaptation strategy options.

6.2.5.2 Financial vulnerability assessment results – LORWUA case studies

6.2.5.2.1 Case Study 1

Table 6.5 summarises the financial ratios of the different climate scenarios that were modelled. The model assumes a 20% start-up debt ratio.

Table 6.5: Financial assessment results for LORWUA Case Study 1

Model	IRR	NPV	Cash flow ratio	Highest debt ratio	Highest debt
Base run	8%	13,661,925	126%	34%	(6,133,936)
CCC Present (1971 - 1990)	8%	12,761,558	124%	38%	(7,110,334)
CRM Present (1971 - 1990)	8%	11,501,920	123%	36%	(6,648,816)
ECH Present (1971 - 1990)	8%	11,009,134	123%	36%	(6,410,320)
GISS Present (1971 - 1990)	7%	9,369,220	121%	33%	(5,892,668)
IPS Present (1971 - 1990)	7%	7,285,521	120%	37%	(6,578,781)
CCC Intermediate (2046 - 2065)	-1%	(10,978,058)	77%	182%	(30,392,710)
CRM Intermediate (2046 - 2065)	2%	(3,588,125)	107%	38%	(6,862,694)
ECH Intermediate (2046 - 2065)	4%	(363,189)	110%	37%	(6,651,443)
GISS Intermediate (2046 - 2065)	4%	176,284	112%	40%	(7,066,932)
IPS Intermediate (2046 - 2065)	3%	(2,448,110)	108%	38%	(6,721,745)
CM CCC Intermediate (2046 - 2065)	-1%	(11,719,450)	73%	223%	(35,560,588)
CM CRM Intermediate (2046 - 2065)	0%	(9,068,582)	86%	123%	(22,928,438)
CM GISS Intermediate (2046 - 2065)	3%	(2,982,295)	108%	47%	(8,290,861)
CM IPS Intermediate (2046 - 2065)	0%	(8,879,978)	85%	125%	(23,705,675)
CCC Intermediate (2046 - 2065) Adaptations	4%	230,363	95%	119%	(31,512,108)
CRM Intermediate (2046 - 2065) Adaptations	5%	2,538,502	101%	87%	(23,509,123)
ECH Intermediate (2046 - 2065) Adaptations	6%	6,689,431	105%	69%	(18,791,899)
GISS Intermediate (2046 - 2065) Adaptations	6%	6,074,350	104%	75%	(20,546,507)
IPS Intermediate (2046 - 2065) Adaptations	5%	4,467,748	103%	82%	(22,200,220)
CM CCC Intermediate (2046 - 2065) Adaptations	-2%	(12,011,770)	67%	398%	(51,850,648)
CM CRM Intermediate (2046 - 2065) Adaptations	2%	(4,189,793)	105%	56%	(10,389,262)
CM GISS Intermediate (2046 - 2065) Adaptations	5%	2,788,969	117%	52%	(9,954,975)
CM IPS Intermediate (2046 - 2065) Adaptations	2%	(5,743,530)	98%	70%	(12,998,011)
Colour code legend:					
Base run					
CCCT technique for different GCM's - Present climate - static runs					
CCCT technique for different GCM's - Intermediate climate - static runs					
Apsim technique for different GCM's - Intermediate climate - static runs					
CCCT technique for different GCM's - Intermediate climate - adaptation options included					
Apsim technique for different GCM's - Intermediate climate - adaptation options included					

The modelling results for Case Study 1 (20% start-up debt ratio) can be interpreted as follows:

- An average internal rate of return (IRR) of 8% is projected under the present climate scenario. When intermediate climate scenarios are imposed on the model, the IRR decreases to respectively 2% for the CCCT model and 0% for the APSIM crop model (ACM). The inclusion of adaptation strategies tends to have a positive effect on profitability with the IRR increasing to 5% (CCCT) and 2%

(ACM). Intermediate climate projections will ultimately impact negatively on profitability and return on investment.

- An average net present value (NPV) of R10.3 million is projected under present climate conditions. For intermediate climate conditions a negative NPV is projected for both the CCCT (-R3.4 million) and ACM models (-R8.2 million). Both these projections are positively influenced by the inclusion of adaptation strategies in the model. A NPV of R4 million is projected for the CCCT model and a NPV of (-R4.8 million) for the ACM model. Intermediate climate projections will ultimately impact negatively on profitability and return on investment.
- A cash flow ratio of 122% is projected under present climate conditions. This ratio, however, declines to 103% (CCCT model) and 88% (ACM) when intermediate climate scenarios are imposed on the model. Both models show an improvement in cash flow ratio when adaptation strategies are included in the model (CCCT model = 102%, ACM model = 97%). The intermediate climate projections will strain cash flow and repayment ability and may put the farming business in a financial position that falls outside the generally accepted financing norms. A cash flow ratio of less than 110% for a farming business is not attractive to any financier.
- A highest debt ratio of 36% is projected under present climate scenarios. When intermediate climate scenarios are imposed on the model, the highest debt ratio increases to 67% (CCCT model) and 130% (ACM model). The inclusion of adaptation strategies negatively influences the highest debt ratio to 86% and 144% for the CCCT model and the ACM model respectively. This is however due to expensive capital outlay forced into the model over a very short period of time. In order to be attractive to outside financiers, the highest debt ratio should not exceed 50%. It seems that without adaptation, intermediate climate projections will push the farming business outside this norm.
- A highest debt level of R6.5 million is projected under present climate conditions. This level increased to R11.5 million (CCCT model) and R22.6 million (ACM model) when intermediate climate scenarios are imposed on the model. With the inclusion of adaptation strategies in the model, the highest debt levels of R23.3

million (CCCT model) and R21.3 million (ACM model) are projected. It is clear that intermediate climate projections will ultimately increase debt levels.

6.2.5.2.2 Case Study 2

Table 6.6 summarises the financial ratios of the different climate scenarios that were modelled. The model assumes a 20% start-up debt ratio.

Table 6.6: Financial assessment results for LORWUA Case Study 2

	IRR	NPV	Cash flow ratio	Highest debt ratio	Highest debt
Base run	7%	2,799,405	125%	33%	(1,640,398)
CCC Present (1971 - 1990)	8%	3,291,840	126%	29%	(1,445,470)
CRM Present (1971 - 1990)	7%	2,916,788	125%	35%	(1,771,662)
ECH Present (1971 - 1990)	7%	2,374,958	123%	38%	(1,881,231)
GISS Present (1971 - 1990)	6%	1,909,257	122%	33%	(1,664,205)
IPS Present (1971 - 1990)	5%	1,020,348	119%	43%	(2,143,920)
CCC Intermediate (2046 - 2065)	1%	(2,228,002)	87%	120%	(4,757,187)
CRM Intermediate (2046 - 2065)	1%	(1,792,781)	94%	75%	(3,377,952)
ECH Intermediate (2046 - 2065)	2%	(1,389,240)	100%	55%	(2,621,659)
GISS Intermediate (2046 - 2065)	2%	(1,279,782)	100%	55%	(2,770,071)
IPS Intermediate (2046 - 2065)	1%	(1,628,370)	100%	55%	(2,590,152)
CM CCC Intermediate (2046 - 2065)	1%	(2,378,007)	79%	169%	(6,687,537)
CM CRM Intermediate (2046 - 2065)	1%	(2,245,535)	84%	138%	(5,582,665)
CM GISS Intermediate (2046 - 2065)	2%	(1,485,437)	93%	81%	(4,116,514)
CM IPS Intermediate (2046 - 2065)	1%	(2,284,209)	84%	142%	(5,650,910)
CCC Intermediate (2046 - 2065) Adaptations	9%	6,095,140	106%	96%	(5,810,083)
CRM Intermediate (2046 - 2065) Adaptations	10%	8,487,143	110%	93%	(5,813,761)
ECH Intermediate (2046 - 2065) Adaptations	11%	9,146,352	112%	83%	(5,403,461)
GISS Intermediate (2046 - 2065) Adaptations	11%	9,399,558	112%	88%	(5,518,351)
IPS Intermediate (2046 - 2065) Adaptations	11%	9,675,078	112%	88%	(5,689,920)
CM CCC Intermediate (2046 - 2065) Adaptations	1%	(2,266,151)	67%	331%	(13,480,037)
CM CRM Intermediate (2046 - 2065) Adaptations	2%	(1,448,736)	91%	99%	(4,951,281)
CM GISS Intermediate (2046 - 2065) Adaptations	4%	(329,267)	110%	80%	(4,170,584)
CM IPS Intermediate (2046 - 2065) Adaptations	1%	(2,058,579)	82%	154%	(6,562,455)
Colour code legend:					
Base run					
CCCT technique for different GCM's - Present climate - static runs					
CCCT technique for different GCM's - Intermediate climate - static runs					
Apsim technique for different GCM's - Intermediate climate - static runs					
CCCT technique for different GCM's - Intermediate climate - adaptation options included					
Apsim technique for different GCM's - Intermediate climate - adaptation options included					

The modelling results for Case Study 2 (20% start-up debt ratio) can be interpreted as follows:

- An average internal rate of return (IRR) of 7% is projected under the present climate scenario. When intermediate climate scenarios are imposed on the model, the IRR decreases to respectively 1% for the CCCT model and 1% for the APSIM crop model (ACM). The inclusion of adaptation strategies tends to have a positive effect on profitability with the IRR increasing to 10% (CCCT) and 2% (ACM). Intermediate climate projections will ultimately impact negatively on profitability and return on investment.

- A net present value (NPV) of R2.3 million is projected under present climate conditions. For intermediate climate conditions a negative NPV is projected for both the CCCT model (-R1.7 million) and ACM model (-R2.1 million). Both these projections are positively influenced by the inclusion of adaptation strategies in the model. A NPV of R8.5 million is projected for the CCCT model and a NPV of -R1.5 million for the ACM model.
- A cash flow ratio of 123% is projected under present climate conditions. This ratio, however, declines to 96% (CCCT model) and 85% (ACM) when intermediate climate scenarios are imposed on the model. Both models show an improvement in cash flow ratio when adaptation strategies are included in the model (CCCT model = 110%, ACM model = 88%). The intermediate climate projections will strain cash flow and repayment ability and may put the farming business in a financial position that falls outside the generally accepted financing norms. A cash flow ratio of less than 110% for a farming business is not attractive to any financier.
- A highest debt ratio of 36% is projected under present climate scenarios. When intermediate climate scenarios are imposed on the model, the highest debt ratio increases to 72% (CCCT model) and 133% (ACM model). The inclusion of adaptation strategies negatively influences the highest debt ratio to 90% and 166% for the CCCT model and the ACM model respectively. This is, however, due to expensive capital outlay forced into the model over a very short period of time. In order to be attractive to outside financiers, the highest debt ratio should not exceed 50%. It seems that without adaptation, intermediate climate projections will push the farming business outside this norm.
- A highest debt level of R1.7 million is projected under present climate conditions. This level increased to R3.2 million (CCCT model) and R5.5 million (CM model) when intermediate climate scenarios are imposed on the model. With the inclusion of adaptation strategies in the model, the highest debt level of R5.6 million (CCCT model) and R7.2 million (ACM model) is projected. It is clear that intermediate climate projections will ultimately increase debt levels.

- It is also significant to note that there is a strong correlation between the CCCT (expert opinions) and the Apsim model (crop model) approach. The results indicate that the CCCT methodology can be used with confidence.

6.3 Blyde River WUA

The following sections show a summary of the financial modelling results for the Blyde River WUA area.

6.3.1 Climate change impact on quality and yield of crops modelling results

There are no APSIM crop models (or any other crop model) for citrus and mangoes. For the Blyde River WUA area, the CCCT modelling technique (guided by expert opinions), was the only tool available to model the impact of projected climate change on the yield and quality of citrus and mangoes. The positive correlation between APSIM crop modelling results and CCCT modelling results in other areas increases confidence in the accuracy of the modelling outcome for the Blyde River WUA area.

6.3.1.1 CCCT modelling results

Table 6.7 shows the CCCT modelling results for the different GCMs for the present and intermediate future (2046 – 2065). The values are 20-year average values for the different models. Although only one out of five GCMs projects a decrease in yield for citrus, all models project a negative impact on quality. For mangoes the models project a negative impact on both yield and quality.

Table 6.7: CCCT modelling yield and quality projections for citrus and mangoes in the Blyde River WUA area

	Citrus						Mangoes					
	Grapefruit		Lemons		Valencia		Keitt		Kent		Tommy Atkins	
	Yield	Quality	Yield	Quality	Yield	Quality	Yield	Quality	Yield	Quality	Yield	Quality
CCC Pres	10	6	10	6	10	6	10	5	10	5	10	5
CCC Int	10	4	10	4	10	4	9	4	8	4	8	4
CRM Pres	10	5	10	5	10	6	10	5	10	5	10	5
CRM Int	10	3	10	3	10	4	8	4	7	4	8	4
ECH Pres	10	5	10	5	10	6	10	5	8	5	9	5
ECH Int	10	3	10	4	10	4	8	4	7	4	8	4
GISS Pres	10	6	10	6	10	6	11	6	10	5	10	6
GISS Int	8	4	9	4	9	4	9	4	8	4	8	4
IPS Pres	10	5	10	5	10	5	10	5	9	5	10	5
IPS Int	10	3	10	4	10	4	9	4	8	4	8	4
AVE Pres	**10**	**5**	**10**	**5**	**10**	**6**	**10**	**5**	**9**	**5**	**10**	**5**
AVE Int	**10**	**4**	**10**	**4**	**10**	**4**	**8**	**4**	**7**	**4**	**8**	**4**

Legend: Yield (% of base yield)

8	=	90%
9	=	95%
10	=	100%
11	=	105%
12	=	110%

Legend: Quality (% of base quality)

3	=	80%
4	=	90%
5	=	100%
6	=	110%
7	=	120%

6.3.2 Climate change impact on crop irrigation requirements results

Table 6.8 and Table 6.9 display the simulated irrigation requirements for citrus and mangoes for the current and intermediate future projected climates.

An 8% average annual increase in irrigation requirements is projected for citrus for intermediate future climates in order to obtain the same yield as with present climates (Table 6.8).

Table 6.8: SAPWAT3 simulated irrigation requirements for citrus for the present and intermediate future projected climates

Citrus - present														
Case study region	**Irri01**	**Irri02**	**Irri03**	**Irri04**	**Irri05**	**Irri06**	**Irri07**	**Irri08**	**Irri09**	**Irri10**	**Irri11**	**Irri12**	**Total**	
Hoedspruit_CCC_PR3	105	90	105	100	82	54	97	99	110	114	96	110	**1,162**	
Hoedspruit_CRM_PR3	64	44	64	84	88	62	105	111	111	98	70	74	**975**	
Hoedspruit_ECH_PR3	100	78	83	75	85	58	96	103	109	112	102	74	**1,075**	
Hoedspruit_GISS_PR3	101	92	99	86	82	49	89	95	94	83	90	88	**1,048**	
Hoedspruit_IPS_PR3	89	84	92	90	79	58	108	105	107	107	99	84	**1,102**	
Average	**92**	**78**	**89**	**87**	**83**	**56**	**99**	**103**	**106**	**103**	**91**	**86**	**1,072**	
Citrus - intermediate future														
Case study region	**Irri01**	**Irri02**	**Irri03**	**Irri04**	**Irri05**	**Irri06**	**Irri07**	**Irri08**	**Irri09**	**Irri10**	**Irri11**	**Irri12**	**Total**	**% change**
Hoedspruit_CCC_INT	105	100	114	100	96	63	102	98	127	122	104	108	**1,239**	7%
Hoedspruit_CRM_INT	80	54	67	73	91	71	108	120	131	108	72	86	**1,061**	9%
Hoedspruit_ECH_INT	102	85	81	75	91	70	105	114	122	113	98	113	**1,169**	9%
Hoedspruit_GISS_INT	107	91	108	99	94	60	104	101	99	100	98	109	**1,170**	12%
Hoedspruit_IPS_INT	83	83	102	90	90	63	96	111	103	121	103	90	**1,135**	3%
Average	**95**	**83**	**94**	**87**	**92**	**65**	**103**	**109**	**116**	**113**	**95**	**101**	**1,155**	**8%**

An 8% average annual increase in irrigation requirements is projected for mangoes for intermediate future climates in order to obtain the same yield as with present climates (Table 6.9).

Table 6.9: SAPWAT3 simulated irrigation requirements for mangoes for the present and intermediate future projected climates

Mangoes - present														
Case study region	**Irri01**	**Irri02**	**Irri03**	**Irri04**	**Irri05**	**Irri06**	**Irri07**	**Irri08**	**Irri09**	**Irri10**	**Irri11**	**Irri12**	**Total**	
Hoedspruit_CCC_PR3	122	112	116	89	65	99	99	105	128	128	107	122	**1,292**	
Hoedspruit_CRM_PR3	76	50	76	80	69	105	107	121	125	118	77	96	**1,100**	
Hoedspruit_ECH_PR3	112	86	99	73	67	96	101	116	122	133	110	95	**1,210**	
Hoedspruit_GISS_PR3	114	106	113	85	67	94	91	104	107	102	109	106	**1,198**	
Hoedspruit_IPS_PR3	99	103	100	85	64	107	104	119	121	121	115	98	**1,236**	
Average	**105**	**91**	**101**	**82**	**66**	**100**	**100**	**113**	**121**	**120**	**104**	**103**	**1,207**	
Mangoes - intermediate future														
Case study region	**Irri01**	**Irri02**	**Irri03**	**Irri04**	**Irri05**	**Irri06**	**Irri07**	**Irri08**	**Irri09**	**Irri10**	**Irri11**	**Irri12**	**Total**	**% change**
Hoedspruit_CCC_INT	120	116	129	98	75	108	101	117	134	141	121	125	**1,385**	7%
Hoedspruit_CRM_INT	96	70	79	69	77	115	121	135	139	118	88	105	**1,212**	10%
Hoedspruit_ECH_INT	116	114	93	74	74	118	119	120	130	130	116	120	**1,324**	9%
Hoedspruit_GISS_INT	130	106	126	90	75	108	97	110	117	116	113	119	**1,307**	9%
Hoedspruit_IPS_INT	99	98	120	83	75	105	103	115	112	141	119	106	**1,276**	3%
Average	**112**	**101**	**109**	**83**	**75**	**111**	**108**	**119**	**126**	**129**	**111**	**115**	**1,301**	**8%**

6.3.3 Climate change impact on the availability of irrigation water requirements

The Blyde River WUA is an irrigation area and dependent on irrigation water for production. The present and intermediate climate data for downscaled GCMs were used in the ACRU model to project future dam levels, which forms the base for calculating the annual allocation of irrigation water quotas to farmers. The projected total annual irrigation water quota (m^3) allocated to a farming system and monthly canal capacities are included in the DLP model as resource constraints.

The projection of the Blydepoort Dam level was done by UKZN, using the ACRU model. Figure 6.2 illustrates the historical and projected dam level of the Blydepoort Dam.

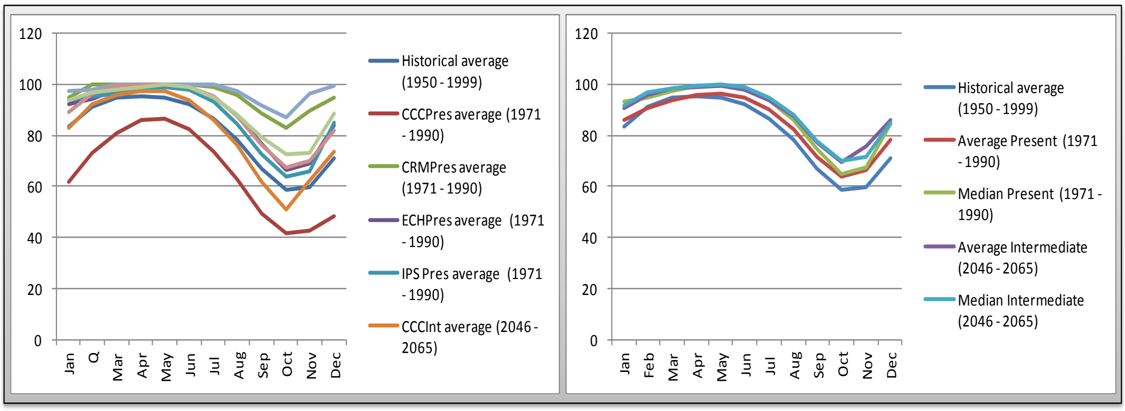


Figure 6.2: Historical and projected dam level for Blydepoort Dam

All indications are that the availability of irrigation water for the Blyde area irrigators (in terms of quota consistency) will not be negatively affected by the projected climate scenarios.

6.3.4 Adaptation strategies available

Increases in average temperatures and seasonal shifts are the biggest threats that the Blyde River WUA area faces. The following are problems associated with increased temperatures:

- Quality losses as a result of wind and sunburn (citrus and mangoes)
- Reduction in fruit set (citrus) as a result of sunburn
- Seedless cultivars are less tolerant to increased temperatures than seeded cultivars; the demand, however, is for seedless cultivars (citrus).

The only adaptation strategy that was identified to eliminate the threats associated with climate change to be included in the integrated model is the installation of shade nets over citrus and mango production areas

6.3.4.1 Shade nets

While water efficiency is a key concept to solve water-shortage problems in semiarid areas, shading nets structures in semiarid and arid environments can be considered as an intermediate solution for increasing water use efficiency and reducing plant water stress. It offer many advantages and environmental benefits, which is why an increasing area of crops, including citrus, is being grown under shading materials of various types. It was found that the use of the shading net reduces wind speed within the foliage and helps to decrease fruit dropping. The shade provided by the net does not affect yield and internal fruit quality (ratio of sugar to acid) but may increase fruit average weight and diameter (Abouatallah *et al*., 2012). Also refer to Section 6.2.4.3.

The panel of experts agreed that shade nets on citrus and mangoes can eliminate most threats associated with projected climate change and will have the following advantages:

- Improvement in fruit quality (less hail, wind and sun damage)
- Less stress on tree (more consistent yields)
- More effective use of irrigation water (less evapotranspiration).

6.3.4.2 Other adaptation strategies (not included in the model)

The following are a list of adaptation strategies debated but not included in the integrated climate change model:

- Mulching cover to conserve moisture
- More effective management of irrigation systems
- Cultivar development to increase natural heat resistance.

6.3.5 Financial vulnerability assessment results – Blyde River WUA case studies

6.3.5.1 Case Study 1

Table 6.10 summarises the financial ratios of the different climate scenarios that were modelled. The model assumes a 20% start-up debt ratio.

Table 6.10: Financial assessment results for Blyde River WUA Case Study 1

	IRR	NPV	Cash flow ratio	Highest debt ratio	Highest debt
Base run	14%	12,258,800	129%	43%	(3,419,599)
CCC Present (1971 - 1990)	18%	15,324,906	131%	56%	(4,439,923)
CRM Present (1971 - 1990)	19%	15,135,705	125%	35%	(2,759,573)
ECH Present (1971 - 1990)	13%	9,520,929	122%	46%	(3,638,295)
GISS Present (1971 - 1990)	19%	18,387,418	138%	42%	(3,342,224)
IPS Present (1971 - 1990)	13%	11,213,918	128%	56%	(4,446,420)
CCC Intermediate (2046 - 2065)	3%	(1,779,436)	97%	112%	(8,858,550)
CRM Intermediate (2046 - 2065)	-1%	(5,563,182)	79%	295%	(23,441,992)
ECH Intermediate (2046 - 2065)	0%	(4,800,209)	83%	235%	(18,687,659)
GISS Intermediate (2046 - 2065)	2%	(2,374,432)	94%	84%	(6,675,536)
IPS Intermediate (2046 - 2065)	3%	(1,426,069)	100%	76%	(5,958,340)
CCC Intermediate (2046 - 2065) Adaptions	7%	10,616,893	115%	177%	(28,995,741)
CRM Intermediate (2046 - 2065) Adaptations	7%	10,616,893	115%	177%	(28,995,741)
ECH Intermediate (2046 - 2065) Adaptations	7%	10,616,893	115%	177%	(28,995,741)
GISS Intermediate (2046 - 2065) Adaptations	7%	10,311,704	114%	175%	(28,350,214)
IPS Intermediate (2046 - 2065) Adaptations	7%	10,616,893	115%	177%	(28,995,741)
Colour code legend:					
Base run					
CCCT technique for different GCM's - Present climate - static runs					
CCCT technique for different GCM's - Intermediate climate - static runs					
CCCT technique for different GCM's - Intermediate climate - adaptation options included					

The modelling results for Case Study 1 can be interpreted as follows:

- An IRR of 16% is projected under the present climate scenario. When intermediate climate scenarios are imposed on the model, the IRR decreases to 1%. The inclusion of adaptation strategies tends to have a positive effect on profitability with the IRR increasing to 7%. Intermediate climate projections will ultimately impacts negatively on profitability and return on investment.
- A NPV of R13.3 million is projected under present climate scenarios. For intermediate climate scenarios a negative NPV (-R3.7 million) is projected. The inclusion of adaptation strategies in the modelling has a positive impact on profitability, to the extent that a NPV of R10.5 million is projected if adaptation strategies are included in the model.
- A cash flow ratio of 126% is projected under present climate conditions. This ratio however declines to 89% when intermediate climate scenarios are imposed on the model. The model shows an improvement in cash flow ratio when adaptation strategies are included in the model (cash flow ratio = 115%). The intermediate climate projections will strain cash flow and repayment ability and may put the farming business in a financial position that falls outside the general accepted financing norms. A cash flow ratio of less than 110% for a farming business is not attractive to any financier.

- A highest debt ratio of 47% is projected under present climate scenarios. When intermediate climate scenarios are imposed on the model, the highest debt ratio increases to 176%. To be attractive to outside financiers, the highest debt ratio should not exceed 50%. It seems that, without adaptation, intermediate climate projections will push the farming business outside this norm.
- A highest debt level of R3.7 million is projected under present climate conditions. This level increased to R14 million when intermediate climate scenarios are imposed on the model. It is clear that intermediate climate projections will ultimately increase debt levels.

6.3.5.2 Case Study 2

Table 6.11 summarises the financial ratios of the different climate scenarios that were modelled. The model assumes a 20% start-up debt ratio.

Table 6.11: Financial assessment results for Blyde River WUA Case Study 2

	IRR	NPV	Cash flow ratio	Highest debt ratio	Highest debt
Base run	18%	28,534,499	121%	31%	(5,490,201)
CCC Present Static (1971 - 1990)	27%	45,642,841	130%	45%	(7,854,056)
CRM Present Static (1971 - 1990)	23%	37,444,867	125%	22%	(3,946,723)
ECH Present Static (1971 - 1990)	20%	31,694,562	124%	24%	(4,270,149)
GISS Present Static (1971 - 1990)	30%	49,489,167	133%	24%	(4,161,145)
IPS Present Static (1971 - 1990)	17%	26,358,453	119%	24%	(4,237,474)
CCC Intermediate Static (2046 - 2065)	6%	4,868,599	106%	43%	(7,482,152)
CRM Intermediate Static (2046 - 2065)	2%	(5,044,555)	97%	55%	(9,772,454)
ECH Intermediate Static (2046 - 2065)	2%	(3,320,299)	102%	46%	(7,967,866)
GISS Intermediate Static (2046 - 2065)	4%	(467,839)	99%	40%	(6,955,239)
IPS Intermediate Static (2046 - 2065)	3%	(1,782,510)	104%	49%	(8,523,710)
CCC Intermediate(2046 - 2065) Adaptations	7%	17,291,478	104%	193%	(64,441,051)
CRM Intermediate (2046 - 2065) Adaptations	7%	17,291,478	104%	193%	(64,441,051)
ECH Intermediate (2046 - 2065) Adaptations	7%	17,291,478	104%	193%	(64,441,051)
GISS Intermediate (2046 - 2065) Adaptaions	7%	17,595,057	106%	186%	(60,869,250)
IPS Intermediate (2046 - 2065) Adaptations	7%	17,291,478	104%	193%	(64,441,051)
Colour code legend:					
Base run					
CCCT technique for different GCM's - Present climate - static runs					
CCCT technique for different GCM's - Intermediate climate - static runs					
CCCT technique for different GCM's - Intermediate climate - adaptation options included					

The modelling results for Case Study 2 (20% start-up debt ratio) can be interpreted as follows:

- An average IRR of 21% is projected under the present climate scenario. When intermediate climate scenarios are imposed on the model, the IRR turns negative. The inclusion of adaptation strategies tends to have a positive effect on profitability with the IRR increasing to 7%. Intermediate climate projections will ultimately impact negatively on profitability and return on investment.

- A NPV of R30.4 million is projected under present climate scenarios. For intermediate climate scenarios a negative NPV (-R8.8 million) is projected. The inclusion of adaptation strategies in the modelling has a positive impact on profitability, to the extent that a NPV of R17.2 million is projected if adaptation strategies are included in the model.
- A cash flow ratio of 119% is projected under present climate conditions. This ratio, however, declines to 81% when intermediate climate scenarios are imposed on the model. The model shows an improvement in cash flow ratio when adaptation strategies are included in the model (cash flow ratio = 97%). The intermediate climate projections will strain cash flow and repayment ability and may put the farming business in a financial position which falls outside the general accepted financing norms. A cash flow ratio of less than 110% for a farming business is not attractive to any financier.
- A highest debt ratio of 45% is projected under present climate scenarios. When intermediate climate scenarios are imposed on the model, the highest debt ratio increases to 246%. To be attractive to outside financiers, the highest debt ratio should not exceed 50%. It seems that without adaptation, intermediate climate projections will push the farming business outside this norm.
- A highest debt level of R7.9 million is projected under present climate conditions. This level increased to R43.4 million when intermediate climate scenarios are imposed on the model. It is clear that intermediate climate projections will ultimately increase debt levels.

6.4 Moorreesburg case study

6.4.1 Climate change impact on quality and yield of crops modelling results

6.4.1.1 APSIM crop modelling results

Figure 6.3 shows the projected yield for wheat for the intermediate future (2046 – 2065) in the Moorreesburg area, derived from APSIM calculations. The figures are expressed as percentage of the yield used in the base analysis.

Climate data from four GCMs were applied in the APSIM modelling to project intermediate future yield for wheat. The different GCM projections (20-year average) vary from a decrease of 4% to an increase of 4% compared to present yield. The overall average yield between the four models equals the average present yield.

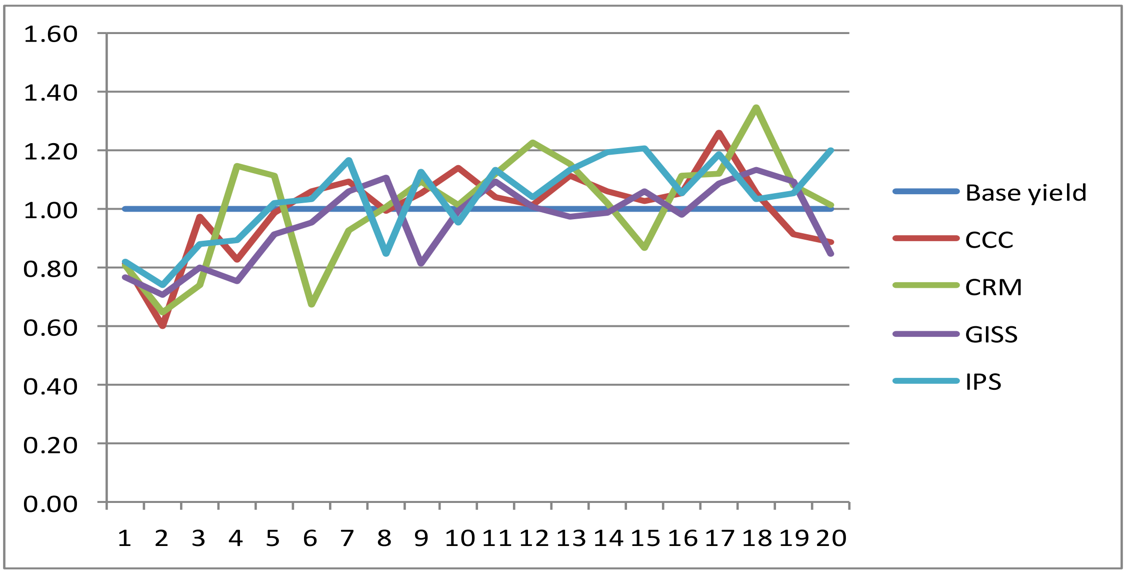


Figure 6.3: Projected yield (% of base yield) [2046 – 2065] for wheat in Moorreesburg area based on APSIM calculations

6.4.1.2 CCCT modelling results

Table 6.12 shows the CCCT modelling results for five different GCMs for the present and intermediate future (2046 – 2065). The values are 20-year average values for the different models. Despite relative small variances between the different GCM projections, no major changes in yield, from the present to the intermediate future, are projected. This result correlates with the APSIM crop modelling results, which increases confidence in the CCCT modelling technique.

Table 6.12: CCCT modelling yield projections for wheat in the Moorreesburg area

CCC Pres	CCC Int	CRM Pres	CRM Int	ECH Pres	ECH Int	GISS Pres	GISS Int	IPS Pres	IPS Int	AVE Pres	AVE Int
11	10	9	10	11	11	10	10	11	7	**10**	**10**

Legend: Yield (% of base yield)
8 = 90%
9 = 95%
10 = 100%
11 = 105%
12 = 110%

6.4.2 Adaptation strategies available

Adaptation options for the Moorreesburg area can be divided in two categories, namely changes in:

- Cropping systems
- Production practices

6.4.2.1 Cropping systems (crop rotation)

The benefit of crop rotation in reducing production risk involves three distinct influences that were described by Helmers *et al*. (2001). Firstly, rotations, as opposed to monoculture cropping, may result in overall higher crop yields as well as reduced production costs. Secondly, rotation cropping is generally thought to reduce yield variability compared with monoculture practices. Thirdly, crop rotation involves diversification, with the theoretical advantage that low returns in a specific year for one crop are combined with a relatively high return for a different crop. Drought, however, is usually detrimental to all crops, often preventing this advantage from occurring. An obvious benefit of diversification is the reduction of risk through the inclusion of alternative crops with relatively low risk (Nel and Loubser, 2004).

Higher yields associated with rotated crops will increase the per hectare cost of activities such as harvesting. On the other hand, weed and often pest control costs are less on rotated than monoculture crops, which will increase the net return. It is also known that nitrogen fertilization of grain crops can be reduced when grown in rotation with oil and protein rich crops without affecting the yield. The savings on inputs most probably outweigh the extra costs of harvesting higher yields, which suggests that the net returns and risk for the rotation systems are conservative estimates (Nel and Loubser, 2004).

The current cropping system for the case study is wheat-medics-wheat-medics combined with mutton and wool production. Other alternative cropping systems adapted for the region to be included in the model are:

- Wheat-medics-wheat-medics (with old man saltbush)
- Wheat-medics-medics-wheat
- Wheat-wheat-wheat-wheat (mono cropping system with no sheep)
- Wheat-lupin-wheat-canola (no sheep).

6.4.2.2 Production practices

In the past 15 years, successful adoption of conservation agriculture (CA) took place among grain and sugar farmers in Kwa-Zulu Natal, as well as among grain farmers in the Western Cape and Free State, but has remained rather slow in other production areas of South Africa. The main reasons for adopting CA relate to the improved water conservation properties and the ability to substantially lower production costs (Du Toit, 2007).

In 2004 it was reported that 45% of the total land cultivated in Brazil is estimated to be managed with no-till. In the case of land cropped by smallholder farmers (<50 ha), this figure is even reported to exceed 80% (Du Toit, 2012). Worldwide, a total of approximately 95 million hectares (ha) are currently being cultivated according to the principles of CA (Derpsch, 2005). The United Nations Food and Agriculture Organization, who has promoted the concept for the past ten years, states that CA has great potential in Africa, being the only truly sustainable production system for the continent (FAO, 2006).

Conservation agriculture (CA) is an integrated system built on the following basic principles (Nel, 2010; Du Toit, 2012):

- Minimum soil disturbance – conventional tillage methods are replaced by reduced or no-tillage and crops being planted by adapted planting equipment.
- Establishment and maintenance of an organic soil cover in the form of a mulch.
- Implementation of crop diversification and rotations, as opposed to mono-cropping.

The BFAP study (Du Toit, 2007) extensively researched conservation agriculture and concluded that it can definitely serve as an adaptation strategy. The study indicated significant economic and biological benefits, in the form of increased crop yields and net farm income, since starting with CA.

Adaptations options in terms of production practices for the Moorreesburg area include:

- Conservation agricultural production practices versus conventional production practices.

6.4.3 Financial vulnerability assessment results – Moorreesburg case study

Table 6.13 summarises the financial ratios of the different climate scenarios that were modelled. The model assumes a 20% start-up debt ratio.

Table 6.13: Financial assessment results for Moorreesburg case study

	IRR	NPV	Cash flow ratio	Highest debt ratio	Highest debt
Base run	5%	2,340,998	127%	17%	(3,871,160)
CCC Present (1971 - 1990)	6%	5,425,457	133%	17%	(3,871,160)
CRM Present (1971 - 1990)	5%	2,492,260	126%	14%	(3,871,160)
ECH Present (1971 - 1990)	6%	4,149,426	128%	14%	(3,871,160)
GISS Present (1971 - 1990)	5%	1,942,384	126%	10%	(3,871,160)
IPS Present (1971 - 1990)	7%	5,727,930	133%	7%	(3,871,160)
CCC Intermediate (2046 - 2065)	5%	2,197,053	126%	17%	(3,871,160)
CRM Intermediate (2046 - 2065)	5%	2,552,802	127%	12%	(3,871,160)
ECH Intermediate (2046 - 2065)	7%	5,499,782	133%	17%	(3,871,160)
GISS Intermediate (2046 - 2065)	5%	1,460,138	124%	22%	(4,281,636)
IPS Intermediate (2046 - 2065)	2%	(4,187,047)	112%	10%	(3,871,160)
CM CCC Intermediate (2046 - 2065)	5%	3,324,716	129%	23%	(4,417,363)
CM CRM Intermediate (2046 - 2065)	5%	3,418,428	129%	24%	(4,573,033)
CM GISS Intermediate (2046 - 2065)	4%	1,081,604	123%	23%	(4,401,884)
CM IPS Intermediate (2046 - 2065)	6%	4,204,177	131%	21%	(3,976,255)
CCC Intermediate (2046 - 2065) Adaptations	14%	24,560,173	159%	8%	(3,871,160)
CRM Intermediate (2046 - 2065) Adaptations	17%	24,332,290	158%	0%	(3,871,160)
ECH Intermediate (2046 - 2065) Adaptations	18%	28,973,417	167%	8%	(3,871,160)
GISS Intermediate (2046 - 2065) Adaptations	14%	23,437,682	156%	17%	(3,871,160)
IPS Intermediate (2046 - 2065) Adaptations	11%	14,254,306	139%	0%	(3,871,160)
CM CCC Intermediate (2046 - 2065) Adaptations	13%	22,798,326	158%	14%	(3,871,160)
CM CRM Intermediate (2046 - 2065) Adaptations	13%	23,072,360	159%	14%	(3,871,160)
CM GISS Intermediate (2046 - 2065) Adaptations	11%	19,347,228	153%	15%	(3,871,160)
CM IPS Intermediate (2046 - 2065) Adaptations	14%	24,985,717	161%	14%	(3,871,160)
Colour code legend:					
Base run					
CCCT technique for different GCM's - Present climate - static runs					
CCCT technique for different GCM's - Intermediate climate - static runs					
Apsim technique for different GCM's - Intermediate climate - static runs					
CCCT technique for different GCM's - Intermediate climate - adaptation options included					
Apsim technique for different GCM's - Intermediate climate - adaptation options included					

The modelling results for Moorreesburg case study (20% start-up debt ratio) can be interpreted as follows:

- An average IRR of 6% is projected under the present climate scenario. When intermediate climate scenarios are imposed on the model, the IRR decreases to respectively 5% for the CCCT model and 5% for the ACM. The inclusion of adaptation strategies tends to have a positive effect on profitability with the IRR increasing to 15% (CCCT) and 13% (ACM).

- A NPV of R3.9 million is projected under present climate conditions. For intermediate climate scenarios a NPV of R1.5 million for the CCCT model and R3 million for the ACM model are projected. Both these projections are positively influenced by the inclusion of adaptation strategies in the model. A NPV of R23 million is projected for the CCCT model and a NPV of R22 million for the ACM model. The impact of intermediate climate projections tends to be marginally negative on profitability and return on investment. The inclusion of adaptation strategies can ultimately put the farming system in a better position than the current conventional system under present climate scenarios.
- A cash flow ratio of 129% is projected under present climate conditions. This ratio, however, declines marginally to 124% (CCCT model) and 128% (ACM) when intermediate climate scenarios are imposed on the model. Both models show an improvement in cash flow ratio when adaptation strategies are included in the model (CCCT model = 155%, ACM model = 158%). The adoption of conservation agriculture principles seems to counter the negative effect of climate change completely in the Moorreesburg area.
- A highest debt ratio of 12% is projected under present climate scenarios. When intermediate climate scenarios are imposed on the model, the highest debt ratio increases to 16% (CCCT model) and 22% (ACM model). The inclusion of adaptation strategies positively influences the highest debt ratio to 7% and 14% for the CCCT model and the ACM model respectively. All these ratios are well within acceptable financing norms.
- A highest debt level of R3.8 million is projected under present climate conditions. This level increased to R4 million (CCCT model) and R4.3 million (ACM model) when intermediate climate scenarios are imposed on the model. With the inclusion of adaptation strategies in the model, the highest debt level of R3.9 million (CCCT model) and R3.9 million (ACM model) is projected. It is clear that neither the intermediate climate projections nor the inclusion of adaptation strategies will cause a significant increase in debt levels.
- The case study farm is already on a profitable crop rotation system (wheat-medics-wheat). With optimisation of the farming system there was no significant deviation in the crop rotation, except the inclusion of old man saltbush. Old man saltbush is commonly known as a drought strategy for small livestock farming in

South Africa. The results clearly indicate that changing to conservation agriculture is an efficient adaptation strategy for climate change in the Moorreesburg region.

6.5 Carolina case study

6.5.1 Climate change impact on quality and yield of crops modelling results

6.5.1.1 APSIM crop modelling results

Figure 6.4 shows the projected yield for maize for the intermediate future (2046 – 2065) in the Carolina area, derived from APSIM calculations. The figures are expressed as percentages of the yield used in the base analysis.

Climate data from four GCMs were applied in the APSIM modelling to project intermediate future yield for wheat. One model projects an average decrease of 25% while three models project an increase in average yield of approximately 10%.

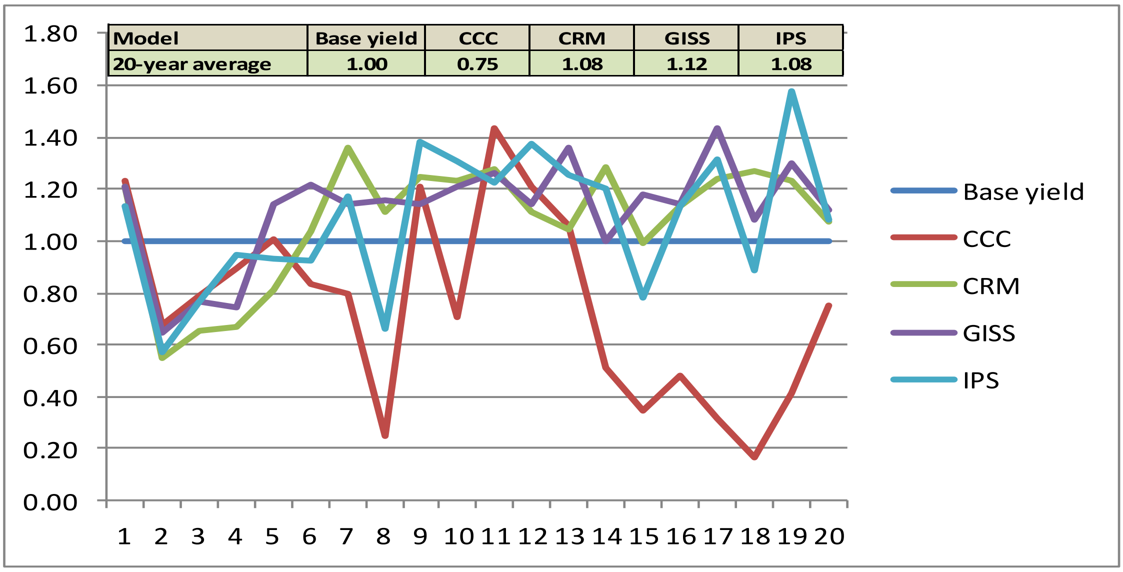


Figure 6.4: Projected yield (% of base yield) [2046 – 2065] for maize in Carolina area based on APSIM calculations

6.5.1.2 CCCT modelling results

Table 6.14 shows the CCCT modelling results for five different GCMs for the present and intermediate future (2046 – 2065). The values are 20-year average values for the different models. All five models project an average increase in yield of approximately 10%. This result correlates to a large extent with the APSIM crop modelling results where three out of four models projected similar increases in average yield.

Table 6.14: CCCT modelling yield projections for maize in the Carolina area

CCC Pres	CCC Int	CRM Pres	CRM Int	ECH Pres	ECH Int	GISS Pres	GISS Int	IPS Pres	IPS Int	AVE Pres	AVE Int
10	12	9	12	10	12	10	12	10	12	**10**	**12**

Legend: Yield (% of base yield)
8 = 90%
9 = 95%
10 = 100%
11 = 105%
12 = 110%

6.5.2 Adaptation strategies available

Adaptation options for the Carolina area can be divided in two categories, namely changes in:

- Cropping systems
- Production practices

6.5.2.1 Cropping systems (crop rotation)

For a detailed discussion on cropping systems refer to Section 6.4.2.1 (Cropping systems).

Current cropping systems are maize-soybeans-maize-soybeans and maize-sugar beans-maize-sugar beans combined with beef and mutton production. An alternative cropping system adapted for the region to be included in the integrated model is maize-maize-maize-maize (mono system).

6.5.2.2 Production practices

For a detailed discussion on production practices refer to Section 6.4.2.2 (Production practices).

Adaptations options include conservation agricultural production practices versus conventional production practices.

6.5.2.3 Other adaptation strategies (not included in the model)

The following are a list of adaptation strategies debated in the group discussions, but not included in the integrated climate change model:

- Narrower row width (for better moist conservation)
- More short growers (access to genetics is a problem)
- Moisture management is very important
- Grain sorghum and sunflower production as alternatives (to be researched).

6.5.3 Financial vulnerability assessment results

Table 6.15 summarises the financial ratios of the different climate scenarios that were modelled.

Table 6.15: Financial assessment results for Carolina case study

	IRR	NPV	Cash flow ratio	Highest debt ratio	Highest debt
Base run	5%	8,810,019	134%	16%	(17,600,000)
CCC Present (1971 - 1990)	5%	9,642,378	134%	14%	(17,600,000)
CRM Present (1971 - 1990)	4%	2,951,799	130%	15%	(17,600,000)
ECH Present (1971 - 1990)	5%	10,191,475	135%	16%	(17,600,000)
GISS Present (1971 - 1990)	5%	9,164,137	134%	16%	(17,600,000)
IPS Present (1971 - 1990)	5%	6,971,932	133%	14%	(17,600,000)
CCC Intermediate (2046 - 2065)	6%	19,911,856	142%	14%	(17,600,000)
CRM Intermediate (2046 - 2065)	6%	25,137,859	146%	15%	(17,600,000)
ECH Intermediate (2046 - 2065)	6%	19,456,349	141%	14%	(17,600,000)
GISS Intermediate (2046 - 2065)	6%	22,965,632	144%	14%	(17,600,000)
IPS Intermediate (2046 - 2065)	6%	21,677,866	144%	14%	(17,600,000)
CM CCC Intermediate (2046 - 2065)	4%	(2,984,864)	123%	11%	(17,600,000)
CM CRM Intermediate (2046 - 2065)	7%	38,604,274	158%	12%	(17,600,000)
CM GISS Intermediate (2046 - 2065)	8%	44,826,148	162%	12%	(17,600,000)
CM IPS Intermediate (2046 - 2065)	7%	38,858,886	158%	12%	(17,600,000)
CCC Intermediate (2046 - 2065) Adaptations	9%	51,182,114	160%	12%	(17,600,000)
CRM Intermediate (2046 - 2065) Adaptations	9%	56,165,104	165%	13%	(17,600,000)
ECH Intermediate (2046 - 2065) Adaptations	9%	50,892,980	160%	11%	(17,600,000)
GISS Intermediate (2046 - 2065) Adaptations	9%	52,960,065	164%	12%	(17,600,000)
IPS Intermediate (2046 - 2065) Adaptations	9%	52,083,487	164%	12%	(17,600,000)
CM CCC Intermediate (2046 - 2065) Adaptations	9%	46,472,120	157%	5%	(17,600,000)
CM CRM Intermediate (2046 - 2065) Adaptations	13%	104,039,509	194%	5%	(17,600,000)
CM GISS Intermediate (2046 - 2065) Adaptations	14%	113,484,946	198%	5%	(17,600,000)
CM IPS Intermediate (2046 - 2065) Adaptations	13%	103,346,315	193%	7%	(17,600,000)
Colour code legend:					
Base run					
CCCT technique for different GCM's - Present climate - static runs					
CCCT technique for different GCM's - Intermediate climate - static runs					
Apsim technique for different GCM's - Intermediate climate - static runs					
CCCT technique for different GCM's - Intermediate climate - adaptation options included					
Apsim technique for different GCM's - Intermediate climate - adaptation options included					

The modelling results for Carolina case study (20% start-up debt ratio) can be interpreted as follows:

- An IRR of 5% is projected under the present climate scenario. When intermediate climate scenarios are imposed on the model, the IRR increases to respectively 6% for the CCCT model and 7% for the ACM model. The inclusion of adaptation strategies tends to have a positive effect on profitability with the IRR increasing to 9% (CCCT) and 12% (ACM).

- A NPV of R7.8 million is projected under present climate conditions. For intermediate climate scenarios a NPV of R21.8 million for the CCCT model and R29.8 million for the ACM model are projected. Both these projections are positively influenced by the inclusion of adaptation strategies in the model. A NPV of R52 million is projected for the CCCT model and a NPV of R91 million for the ACM model. The impact of intermediate climate projections tends not to have a negative impact on profitability and return on investment. The inclusion of adaptation strategies can ultimately put the farming system in a better position than the current conventional system under present climate scenarios.
- A cash flow ratio of 133% is projected under present climate conditions. This ratio, however, declines marginally to 143% (CCCT model) and 150% (ACM) when intermediate climate scenarios are imposed on the model. Both models show an improvement in cash flow ratio when adaptation strategies are included in the model (CCCT model = 163%, ACM model = 186%). The adoption of conservation agriculture principles seems to contribute to profitability in the Carolina area.
- A highest debt ratio of 15% is projected under present climate scenarios. When intermediate climate scenarios are imposed on the model, the highest debt ratio increases to 14% (CCCT model) and 12% (ACM model). The inclusion of adaptation strategies positively influences the highest debt ratio to 12% and 5% for the CCCT model and the ACM model respectively. All these ratios are well within acceptable financing norms.
- A highest debt level of R17.6 million is projected under present climate conditions. This is the starting debt level for all scenarios and also the highest for the 20-year projection period.
- Similar to the Moorreesburg case study, the Carolina case study farm already converted to the more sustainable cropping system. The best adaptation strategy for the region is also to convert to conservation agriculture.

6.6 Chapter summary

Chapter 6 considers the integrated climate change modelling results for the selected case study areas. The modelling results are analysed in terms of climate change impact on:

- Quality and yield of crops (APSIM and CCCT modelling results).

- Crop irrigation requirements (for irrigation crops only – SAPWAT3 modelling results).
- The availability of irrigation water requirements (only for Blyde River WUA – ACRU modelling results).
- Financial vulnerability assessment results (for current and intermediate future climates).

The modelling results for the LORWUA case studies can be summarised as follows:

- Climate data from four GCMs was applied in the APSIM modelling. All the GCMs project a 20-year average decrease in yield, varying from 9% to 18%.
- Data from five GCMs was applied in the CCCT model. All five models project a decrease in yield for wine grapes, table grapes and raisins and a decrease in quality for table grapes.
- A 10% average annual increase in irrigation requirements is projected for table grapes for intermediate future climates in order to obtain the same yield as with present climates. For wine grapes and raisins, an 11% average increase in irrigation requirements is projected.
- The ACRU was not included in the integrated climate change modelling for LORWUA due to various reasons (see Section 4.2.1.4).
- Both climate change financial modelling techniques (APSIM crop modelling and CCCT modelling technique) indicate that intermediate climate scenarios from five different GCMs pose a threat to the financial vulnerability of farming systems in the LORWUA grape producing area.
- Several adaptation strategies to counter the impact of climate change on financial vulnerability were included in the model. These strategies include:
    - Shift wine grape cultivars towards cultivars that are more tolerant towards projected climate change
    - Increase raisin and table grape production
    - Install shade nets over table grapes production areas.
- The above adaptation strategies all seem to lessen the impact of climate change on financial vulnerability to a certain extent and seem worth further investigation.
- Adaptation strategies not included in the model, but worth investigation, include:
    - Irrigation at night to save water

    - Plastic or mulch cover to conserve moisture
    - Soil preparation and site selection for future plantings in order to ensure optimum production – rather scale down and eliminate marginal blocks.

The modelling results for Blyde River WUA case studies can be summarised as follows:

- Empirically downscaled climate values of five GCMs were applied in the CCCT model. Although, only one out of five GCMs projects a decrease in yield for citrus, all models project a negative impact on quality. For mangoes the models project a negative impact on both yield and quality.
- An 8% average annual increase in irrigation requirements is projected for both citrus and mangoes for intermediate future climates in order to obtain the same yield as with present climates.
- The projection of the Blydepoort Dam level was done by UKZN, using the ACRU model. All indications are that the availability of irrigation water for the Blyde River WUA area irrigators (in terms of quota consistency) will not be negatively affected by the projected climate scenarios.
- The CCCT modelling results indicate that intermediate climate scenarios from different GCMs pose a threat to the financial vulnerability of farming systems in the Blyde River mango and citrus producing area.
- The impact of intermediate climate scenarios on financial vulnerability will be more severe on farming systems that are highly geared (high debt levels).
- An adaptation strategy to counter the impact of climate change on financial vulnerability is to install shade nets over mango and citrus production areas. The installation of shade nets proves to lessen the impact of climate change on financial vulnerability to a certain extent and seems worthwhile to investigate further.
- Adaptation strategies not included in the model, but worth investigation, include:
    - Mulching cover to conserve moisture
    - More effective management of irrigation systems
    - Cultivar development to increase natural heat resistance

The modelling results for the Moorreesburg case study can be summarised as follows:

- Climate data from four GCMs were applied in the APSIM modelling to project intermediate future yield for wheat. The different GCM projections (20-year average) vary from a decrease of 4% to an increase of 4% compared to present yield. The overall average yield between the four models equals the average present yield.

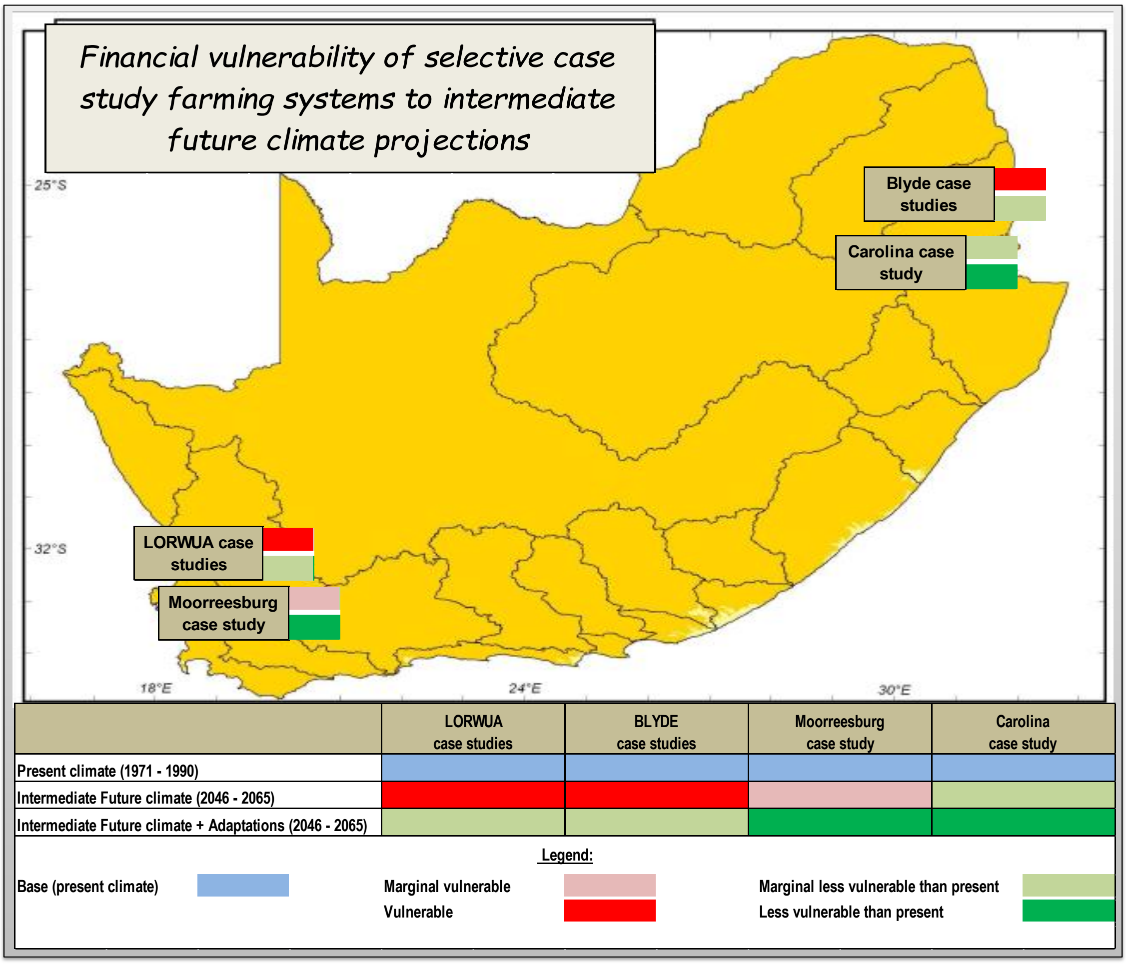
- Data from five GCMs was used in CCCT modelling. Despite relatively small variances between the different GCM projections, no major changes in yield, from the present to the intermediate future, are projected. This result correlates with the APSIM crop modelling results, which increases confidence in the CCCT modelling technique.
- Both climate change financial modelling techniques (APSIM crop modelling and CCCT modelling technique) indicate that intermediate climate scenarios from different GCMs pose a very marginal threat to the financial vulnerability of farming systems in the Moorreesburg dryland wheat producing area.
- The impact of intermediate climate scenarios on financial vulnerability will be more severe on farming systems that are highly geared (high debt levels).
- Adaptation strategies to counter the impact of climate change on financial vulnerability were included in the model. These strategies include:
    - Cropping systems
    - Production practices.
- The above adaptation strategies seem not only to counter the impact of climate change, but to positively impact on profitability.

The modelling results for the Carolina case study can be summarised as follows:

- Climate data from four GCMs was applied in the APSIM modelling to project intermediate future yield for maize. One model projects an average decrease of 25% while three models project an increase in average yield of approximately 10%.
- Data from five GCMs was used in CCCT modelling. All five models project an average increase in yield of approximately 10%. This result correlates to a large extent with the APSIM crop modelling results where three out of four models projected similar increases in average yield.
- Both climate change financial modelling techniques (APSIM crop modelling and the CCCT modelling technique) indicate that intermediate climate scenarios from five different GCMs pose no threat to the financial vulnerability of farming systems in the Carolina summer rainfall dryland area. Please note that abnormal climate events like storms, hail, etc., are not included in the climate modelling.

- Adaptation strategies to counter the impact of climate change on financial vulnerability were included in the model. These strategies include:
  - Cropping systems
  - Production practices.
- The above adaptation strategies seem to not only counter the impact of climate change, but to positively impact on profitability.

Figure 6.5 illustrates the mapping of selective case studies included in the study, viz. LORWUA, Blyde River WUA, Moorreesburg and Carolina. The map shows the location of the case studies and the financial vulnerability towards projected future climates. The colour coding legend indicates the degree of vulnerability to climate change, i.e. pink – marginally vulnerable, red – vulnerable, light green – marginally less vulnerable than present scenario, and green – less vulnerable than present scenario.



	LORWUA case studies	BLYDE case studies	Moorreesburg case study	Carolina case study
Present climate (1971 - 1990)	🟦	🟦	🟦	🟦
Intermediate Future climate (2046 - 2065)	🟥	🟥	▧	▨
Intermediate Future climate + Adaptations (2046 - 2065)	▨	▨	🟩	🟩

Legend:

Base (present climate)	🟦	Marginal vulnerable	▧	Marginal less vulnerable than present	▨
		Vulnerable	🟥	Less vulnerable than present	🟩

Figure 6.5: Mapping of selective case studies and their financial vulnerability to projected future climates

The LORWUA and Blyde River WUA are more vulnerable towards climate change than Moorreesburg and Carolina areas.

Chapter 7 follows with the summary, conclusions and recommendations.

CHAPTER 7 : SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

Chapter 1 describes the background, problem statement and objective of the study. The chapter demarcates the study area, defines the hypothesis that will guide the study, discusses the research method as well as the contribution of the research and the data used.

There is limited research on climate change and related impacts on livelihoods and the natural resources in some African countries (Environmental Alert, 2010; Louw *et al*., 2012). However, evidence from GCMs developed so far suggests that the agricultural sector in the Southern African region is highly sensitive to future climate shifts and increased climate variability (Gbetibouo *et al*., 2004). Therefore, Schulze (2011) suggests that, because of the complexity of South Africa's physiography, climate and socio-economic milieu, detailed local scale analyses are needed to assess potential impacts of climate change. In order to fill this gap, the challenge for this study was to develop an integrated climate change model to determine financial vulnerability of farming systems at farm level.

Chapter 2 summarises the literature review that was undertaken for this study. The chapter starts off by defining climate change followed by a brief history of climate change research. The impacts of climate change and global warming and more specifically, the likely consequences for agriculture, including bio-physical and socio-economic impacts, are discussed.

GCMs and the two downscaling approaches, viz. empirical and dynamical downscaling, are expounded. The CSAG, based at the University of Cape Town, South Africa, operates the pre-eminent empirically downscaled model for Africa and provides meteorological station level responses to global climate forcings for a growing number of stations across the African continent.

The empirical downscaling of values to climate station level used in this study was undertaken by the CSAG. Daily rainfall, as well as minimum and maximum temperature values, constitutes the output from five accredited GCMs from the IPCC (2007), in each case for two 20 year scenarios for present climate (1971 – 1990) and an intermediate future climate (2046 – 2065).

Chapter 2 also includes climate change projections for South Africa and more specifically for the case study areas. Warming for minimum and maximum temperatures is projected in respect of all four case study areas. Most projections favour an increase in rainfall for the summer rainfall areas. For the winter rainfall areas most projections point to a decrease in rainfall for early winter and a slight increase during springtime.

In the context of this study vulnerability means the inability of individual commercial farmers to respond to, or cope with, climate change effects on crop yields from a financial vulnerability point of view. Chapter 2 also defines the financial vulnerability assessment criteria that comprise a set of financial ratios, viz. IRR, NPV, cash flow ratio, highest debt ratio and highest debt.

Two main types of adaptation are autonomous and planned adaptation. In this study the focus was on autonomous adaptation, in other words, adaptation strategies that can be applied at farm level without support from other levels e.g. policies, etc. The success of adaptation strategies was evaluated by comparing the financial vulnerability criteria of different climate and management scenarios.

From the literature review it was clear that a gap exists in the research with reference to integrated economic modelling at farm level. This includes the linkages between changing projected climates, changing yield and quality of produce, hydrology (availability of irrigation water), changing crop irrigation needs (with new projected climates), financial vulnerability and financial sustainability of farming systems.

Chapter 3 gives an overview of the four case study areas, i.e. LORWUA, Blyde River WUA, Moorreesburg and Carolina, which broadly represent the summer and winter rainfall as well as irrigation and dryland crop production areas of South Africa.

The description of the case study areas include discussions on climate, natural resources, adapted crops for the region, crop irrigation requirements, crop cultivation practices and crop enterprise budgets. The critical climate thresholds for crops in the different regions, which form an integral part of the integrated climate modelling in this study, are also specified.

The different case studies were defined in terms of farm size, land use, irrigation water availability and valuation of assets and liabilities.

In Chapter 4 the development of the integrated climate change model is discussed. It comprises a layman's description of the integrated model and the four modules that form the pillars of the integrated climate model. These four modules are: (a) climate change impact modelling, (b) DLP model, (c) modelling interphases, and (d) the Financial Vulnerability Assessment model.

Climate change impact modelling comprises the modelling of empirically downscaled climate data that impact on crop yield and quality, changing crop irrigation requirements as a result of climate change and hydrological modelling to determine the availability of irrigation water due to changing weather patterns.

Chapter 4 outlines the role of GCMs, empirical downscaling, the APSIM crop modelling and the newly developed CCCT modelling technique. The contribution of the ACRU hydrological model and the SAPWAT3 model, as well as where the respective modelling outputs fit into the integrated climate model, are also described.

The objective, purpose and motivation for using the DLP modelling technique in the study are discussed in Chapter 4. The primary objective with the economic planning for a farming system is to establish the best choice between the alternative uses of limited resources to maximise return on capital invested. Independent of the scale of farming, five objectives must be reached:

- Establish which plan reflects the best use of land, water, capital and human resources.
- Establish the financial implications of the plan based on the expected future cash flow.
- Establish the capital required and the time when needed from own and borrowed sources.
- Analyse the complexity of marketing, financial and production management and the demands it will put on management capability.

- Analyse the financial incentive to put the plan into operation.

Mathematical programming techniques are pre-eminently suited to conducting the study of the financial vulnerability of farming systems without and with climate change adaptations.

The modelling interphases that link the output from the climate change modelling, hydrological modelling and crop irrigation requirements modelling are discussed and graphically illustrated.

Chapter 5 presents the design and the mathematical specification of the DLP and Financial Vulnerability Assessment models. The agricultural part of the model is to a large extent based on work done in Australia and applied in South Africa, by Louw (2001), who added several newly developed formulas and techniques to the model, to be applied at macro/regional level.

The interphases between the DLP model and other models that were developed in this study are unique and contribute to the existing DLP model. These interphases include:

- The APSIM crop model data whole-farm model interphase
- The CCCT yield model data whole-farm model interphase
- The CCCT quality model data whole-farm model interphase
- The ACRU hydrological model data whole-farm model interphase
- The SAPWAT3 crop irrigation requirements data whole-farm model interphase.

The link between the output of the DLP model and the Financial Vulnerability Assessment model also constitutes a new contribution to the DLP model.

The output of the DLP module is used as input to determine financial vulnerability of the farming system to future climates, evaluated by a set of financial ratios criteria, viz. IRR, NPV, cash flow ratio, highest debt ratio and highest debt. The comparison of financial vulnerability analysis results for present climates and projected future climates (with current cropping patterns and production practices) clearly illustrates the farming system’s financial vulnerability to climate change.

The value added by the DLP model is clearly illustrated in the next step when available adaptation options are included in the model and the calibration constraints are released, which enables the model to determine the optimal solution. This result ultimately illustrates the farming system's vulnerability to climate change with due consideration to adaptation strategies and technologies that are currently available.

The integrated climate change model proves to be a useful tool to model the impact of projected climate change on the financial vulnerability of farming systems. A unique feature of the CCCT modelling technique is its ability to also model the impact of climate on crop quality and not only on yield, as in the case of APSIM crop modelling.

The interphase between the ACRU hydrological model and the DLP model links projected climate change impact on availability of irrigation water and financial vulnerability at farm level.

A new approach was developed in this study by developing an interphase between the SAPWAT3 model and the DLP model to link projected impact of changing climates on crop irrigation water requirements and ultimately to financial vulnerability at farm level.

Chapter 6 considers the integrated climate change modelling results for the selected case study areas. The modelling results are analysed in terms of climate change impact on:

- Quality and yield of crops (APSIM and CCCT modelling results).
- Crop irrigation requirements (for irrigation crops only – SAPWAT3 modelling results).
- The availability of irrigation water requirements (only for Blyde River WUA – ACRU modelling results).
- Financial vulnerability assessment results (for current and intermediate future climates).

Possible adaptation strategies with their associated benefits and costs were identified during expert group discussions in the different regions. These adaptation options were brought into the DLP model as alternative options/activities available, which could be brought into the solutions when constraints are released during the second round of modelling.

The integrated modelling results for the case studies are summarised below:

LORWUA case studies

Both climate change financial modelling techniques (prototype APSIM crop model and CCCT modelling technique) indicate that intermediate climate scenarios from five different GCMs pose a threat to the financial vulnerability of farming systems in the LORWUA grape producing ara. Sensitivity analysis shows that the impact of intermediate climate scenarios on financial vulnerability will be more severe on farming systems that are highly geared (high debt levels).

Adaptation strategies to counter the impact of climate change on financial vulnerability include: (a) Shift wine grape cultivars towards cultivars that are more tolerant towards projected climate change, (b) increase raisin and table grape production, and (c) install shade nets over table grapes production areas. These strategies all seem to lessen the impact of climate change on financial vulnerability to a certain extent and seem worthwhile to further investigate.

Adaptation strategies that were not included in the model, but worth investigation, include: (a) Irrigation at night to save water, (b) plastic or mulch cover to conserve moisture, and (c) optimal site selection and soil preparation for future plantings in order to ensure optimum production (rather scale down and eliminate marginal blocks).

Blyde River WUA case studies

The modelling results from the CCCT modelling technique for the Blyde River WUA case studies indicate that intermediate climate scenarios from five GCMs pose a threat to the financial vulnerability of farming systems in the Blyde River WUA mango and citrus producing area. The impact will be more severe on highly geared farming systems.

The only adaptation strategy suggested by the expert group discussion to counter the impact of climate change on financial vulnerability is to install shade nets over mango and citrus orchards, which will offer the following advantages: (a) Improvement in fruit quality (citrus and mangoes) [less hail, wind and sun damage], (b) less stress on trees (citrus and mangoes) [more consistent yields], and (c) more effective use of irrigation water (citrus and mangoes) [less evapotranspiration].

Other adaptation strategies which could be investigated are: (a) Mulching cover to conserve moisture, (b) more effective management of irrigation systems, and (c) cultivar development to increase natural heat resistance.

Moorreesburg case study

The intermediate climate scenario modelling results from both climate change financial modelling techniques (APSIM crop modelling and CCCT modelling technique) point to a marginal threat to financial vulnerability of farming systems in the Moorreesburg wheat producing area, except for highly geared entities, for which the projected threats are more serious.

Alternative cropping systems (crop rotation) and alternative production practices (conservation agriculture) are adaptation strategies that not only counter the impact of climate change, but increase profitability.

Carolina case study

The APSIM crop modelling and CCCT modelling technique were applied to determine the financial vulnerability of the Carolina case study farming system to projected intermediate climates from five GCMs. The modelling results show that projected climates will not impact negatively on profitability of the farming system in the Carolina summer rainfall dryland area. All indications are that intermediate climate change scenarios will positively impact on the financial position of farming systems in the dryland maize and livestock producing area. However, it needs to be reiterated that abnormal climate events such as storms, hail, etc., are not included in the climate modelling.

The inclusion of crop rotation and conservation agriculture in the farming system has a positive impact on profitability.

Chapter 7 comprises the summary, conclusions and recommendations of the study. An integrated climate change model was successfully developed to quantify the financial vulnerability of different farming systems to projected climate change. This includes the integration of various models, viz. empirically downscaled climate models, whole-farm DLP models, ACRU hydrological model, SAPWAT3 model and Financial Vulnerability

Assessment model. The newly developed CCCT modelling technique and modelling interphase linkages are unique contributions to integrated climate change modelling at farm level.

7.2 Conclusions

This study sets out to develop an integrated climate change model to determine the financial vulnerability of different farming systems to climate change. The approach in this study successfully links a series of models, viz. empirically downscaled GCMs, whole-farm DLP model, APSIM and CCCT crop modelling techniques, ACRU hydrological model, SAPWAT3 crop irrigation requirements model and a Financial Vulnerability Assessment model.

Empirically downscaled climate data from five GCMs, all of which were applied in the IPCC's (2007) Fourth Assessment Report [AR4], served as basis for the APSIM, CCCT, ACRU and SAPWAT3 models. The modelling output from these models feed into the DLP model through a series of interphases. These modelling interphases are unique and for the first time successfully link the APSIM, CCCT, ACRU and SAPWAT3 model outputs to the DLP model at micro/farm level. The interphase that links the DLP model output to the financial assessment model is also a new contribution.

Extensive validation of climate models have been undertaken and while GCMs generally capture present climatic conditions adequately there are differences between the outputs of the various GCMs and especially individual events and extreme conditions are not captured as well as one would like. It is for this reason that ratio changes between future climatic conditions and present climatic conditions are made, rather than evaluating absolute outputs from the climate models. Uncertainty and the way in which to express it remain a challenge in climate change impact studies. At the time this project commenced the GCMs were the only credible tools that were available for climate change impact studies. Subsequently various downscaling attempts have been made, but the validation of these were not available for input in this project (Schulze, 2014; Johnston, 2014). Future research should take updated models into account.

The newly developed CCCT modelling technique proves to be a useful tool to determine the impact of projected climates on crop yield and quality. The APSIM crop modelling results and CCCT modelling results demonstrate similar trends for the two dryland case study areas, i.e. Moorreesburg and Carolina and also for the prototype APSIM model for grapes in LORWUA area. The similar trends in the results prove that, where APSIM crop models are not available, the CCCT modelling technique is suitable to quantify the impact of climate change on crop yield and quality. When interpreting crop modelling results the emphasis should be on changing trends in yield and quality projections rather than on absolute values.

No APSIM crop models exist for citrus and mangoes in the Blyde River WUA producing area and only the CCCT modelling technique could be applied to model the impact of projected climates on crop yield and quality. The crop modelling results and expected impact of projected climates on crop yield and quality were validated by expert opinions. A unique feature of the CCCT modelling technique is its ability to model the impact of projected climate change on both crop yield and quality as oppose to APSIM and other crop models that only model impact on yield. The value of this feature is underlined in the Blyde River WUA area for citrus where the projected impact of climate change will be more severe on quality than on yield.

The Financial Vulnerability Assessment model quantifies the economic and financial impact of changes in crop yield and quality as a result of changing climates. The model criteria provide for economic viability criteria (IRR and NPV) as well as for financial feasibility criteria, i.e. cash flow ratio and debt ratio, over a twenty year planning horizon. Not only does the model provide an accurate tool to quantify the financial impact of changing climates on farm level, but is also very useful to determine the economic viability and financial feasibility of adaptive strategies.

The empirically downscaled climate data from five GCMs applied in this study underline the correctness of those early predictions in the 1980s, that the world would become warmer. Increases in temperature for the intermediate future are projected for all four case study areas, varying from 1 °C to 2.5 °C with the highest projected increases (1.5 °C to 2.5 °C) in respect of the Carolina area.

This study clearly indicates the importance of biophysical factors and the capacity to adapt to climate change. The Moorreesburg as well as the Carolina case study results indicated that changing to conservation agriculture (more resilient cropping system) improves the adaptive capacity of the farming systems. In the Blyde River WUA case study, shade netting improves the biophysical adaptive capacity of mangoes and citrus (in terms of yield and quality). The LORWUA case study showed similar results for table grapes under shade nets.

For the Carolina case study, all five CCCT models project an average increase in maize yield of approximately 10%. This result correlates to a large extent with the APSIM crop modelling results where three out of four models projected similar increases in average yield and the findings of Du Toit *et al.* (2002). The study results show that, similar to Nelson *et al*. (2009), some regions will gain due to the impact of climate change and some will lose e.g. Blyde River WUA area (mangoes and citrus). The results of the study echoed those of Andersson *et al*. (2009), indicating that impacts of a changing climate could be considerable. Different regions of the country will likely be affected in many different ways. For this reason alone local scale analyses are needed to assess potential impacts (showing the importance of a micro scale integrated climate change modelling approach).

As already been pointed out by various studies, this study also clearly illustrates that, without the capacity to implement adaption strategies such as conservation agriculture (Moorreesburg and Carolina), shade netting (LORWUA and Blyde River WUA) and structural changes to land use patterns (LORWUA), the farming systems of the selected case studies will financially be extremely vulnerable to climate change (as indicated by reduction in IRR and NPV, higher debt ratios and decreasing cash flow ratios).

The high capital cost of certain adaptive strategies, e.g. shade nets would not be affordable to all farmers, especially on smaller operations and those that are highly geared. Systematic and timely implementation over a longer period of time can reduce the pressure on cash flow. This once again highlights the importance of strategic and long term planning, in which Government also could have a role to play. Timely research efforts should be implemented to determine the most appropriate adaptation strategies and communicate research findings on an ongoing basis to all role-players. For the sake of food security, regional socio-economic welfare, protection of much needed export earnings and to preserve land resources for generations to come, it may be worthwhile to investigate subsidies or green box grants in some instances to assist farmers to timeously adapt to projected climate change. The Scottish Government, for instance, has developed a policy initiative, “Farming for a better climate (FFBC)”, with the specific aim of mitigating climate change in agriculture. The FFBC has a communication programme that encourages farmers to adopt efficiency measures that reduce emissions, while at the same time having an overall positive impact on business performance. The purpose of such a body could not only be to identify and research the best practices, etc. but also to serve as communication channel to inform and keep role-players up to date with latest research, developments, etc.

This study shows the importance of research for cultivar development e.g. short grower cultivars (e.g. maize) for the summer rainfall area and more heat resistant cultivars for the Blyde River WUA area (citrus and mangoes). It also points out the importance of locality for future plantings and the projected switch to cultivars that are more tolerant to increasing temperatures (e.g. wine grape cultivars in the LORWUA area). The different results in terms of yield and quality projections for the four case study areas emphasise the importance of locality specific climate change research. In the summer rainfall area, for example, an increase in yield is projected for maize (Carolina case study) compared to a projected decrease in yield and quality for citrus and mangoes (Blyde River WUA area). The impact of projected climate change on yield and quality also differs in the winter rainfall area; the LORWUA grape producing area seems more vulnerable than the dryland wheat producing area of Moorreesburg.

In terms of vulnerability, the sensitivity in Moorreesburg is relatively low compared to e.g. the Blyde River WUA farming systems where adaptation strategies (shade nets) are more costly than adaptation strategies in Moorreesburg (converting to conservation agriculture and alternative cropping systems). The return on investment for implementing adaptation strategies is also more rapid for Moorreesburg compared to the Blyde River WUA area.

This study points out that citrus and mangoes in the Blyde River WUA area are extremely vulnerable to increasing temperatures. This is because prices of perishable produce depend to a large extent on quality grading and market requirements. The Moorreesburg and Carolina dryland mixed crop and livestock farming systems are less vulnerable.

This study achieved its primary and secondary objectives by filling the identified gap in climate change research, i.e. integrated economic modelling at micro or farm level and thereby making a contribution to integrated climate change modelling.

7.3 Recommendations

A number of recommendations for further research are presented as outcome of this study:

- In terms of the CCCT modelling technique the critical climate thresholds for crops should be further researched and refined. It could be worthwhile for future research to merge existing climate and existing yield data sets and deriving a variance-covariance matrix to test the assumption of independence and capture the interdependence of climate effects.
- The financial vulnerability assessment of farming systems to climate change should be executed throughout all production regions in South Africa. This will provide policy makers, industry leaders, input suppliers and researchers with valuable information for future strategizing.
- Adaptation options identified in this study should be further researched and validated. Research should focus on a number of items, viz. cropping patterns, production practices, cultivar development, optimal irrigation equipment and practices, soil water conservation techniques and shade nets.
- The development of crop models should be a high priority on the research agenda. Models that cover more crops and more accurate models will make a significant contribution to the integrated climate change impact modelling framework that was developed through this study.
- The role that Government, in particular Department of Environmental Affairs and Department of Agriculture, Forestry and Fisheries, could play in research and communication with regard to climate change research, adaptation treatments and implementation of adaptive interventions.

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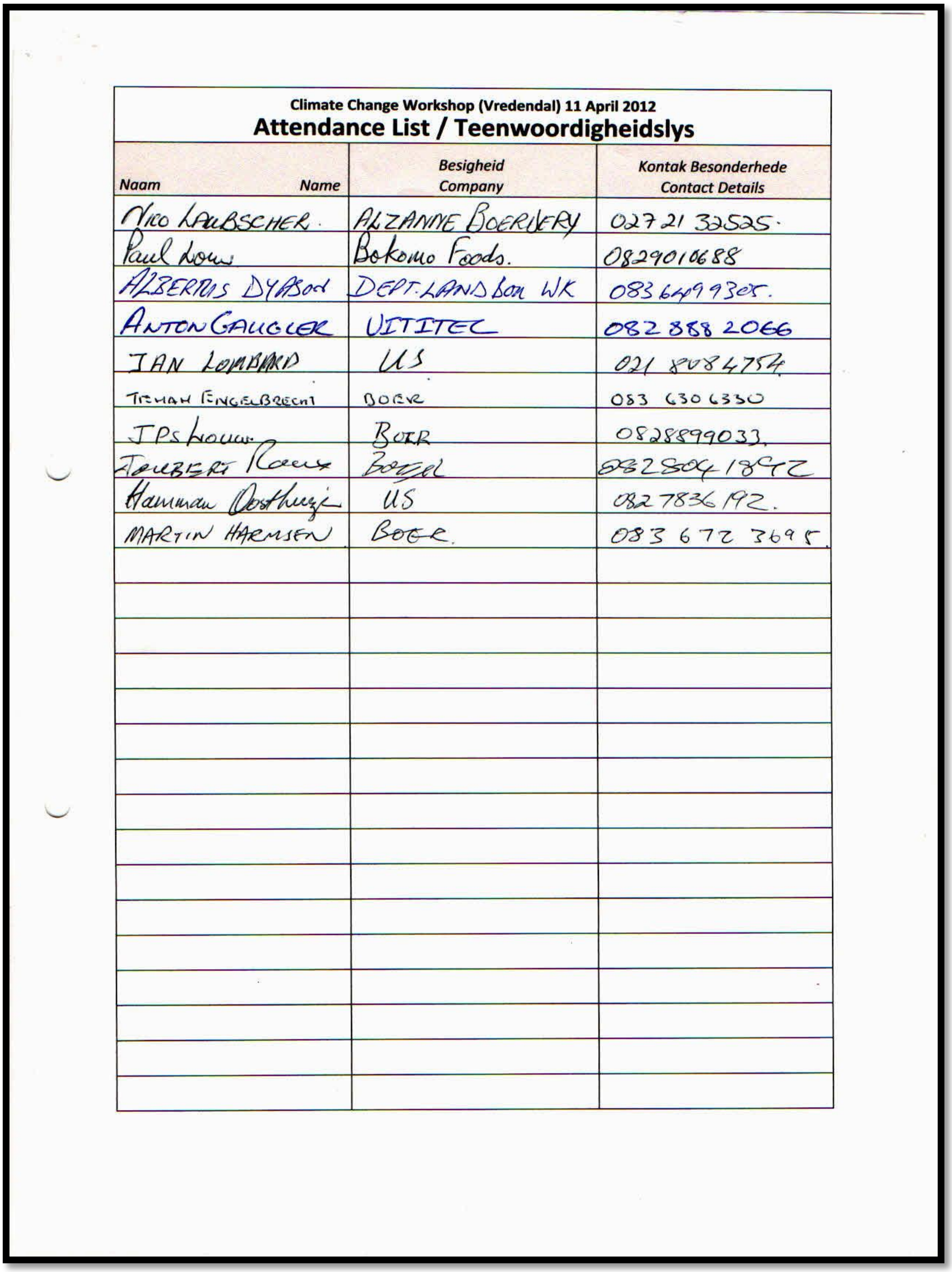
APPENDIX A: EXPERT GROUP DISCUSSIONS

Attendance registers for:

- LORWUA expert group discussions – 11 April 2012
- LORWUA expert group discussions – 17 September 2012
- Blyde River WUA expert group discussions – 16 April 2012
- Moorreesburg expert group discussions – 10 September 2012
- Carolina expert group discussions – 3 October 2012

LORWUA expert group discussions



Climate Change Workshop (Vredendal) 11 April 2012

Attendance List / Teenwoordigheidslys

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Nico LAUBSCHER.	ALZANNE BOERDERY	027 21 32525.
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IAN LOMBARD	US	021 8084754.
TIEMAN ENGELBRECHT	BOER	083 630 6330
JPS Louw	BOER	0828899033.
JOUBERT Roux	Boer	082804 1892
Hamman Oosthuizen	US	082 7836 192.
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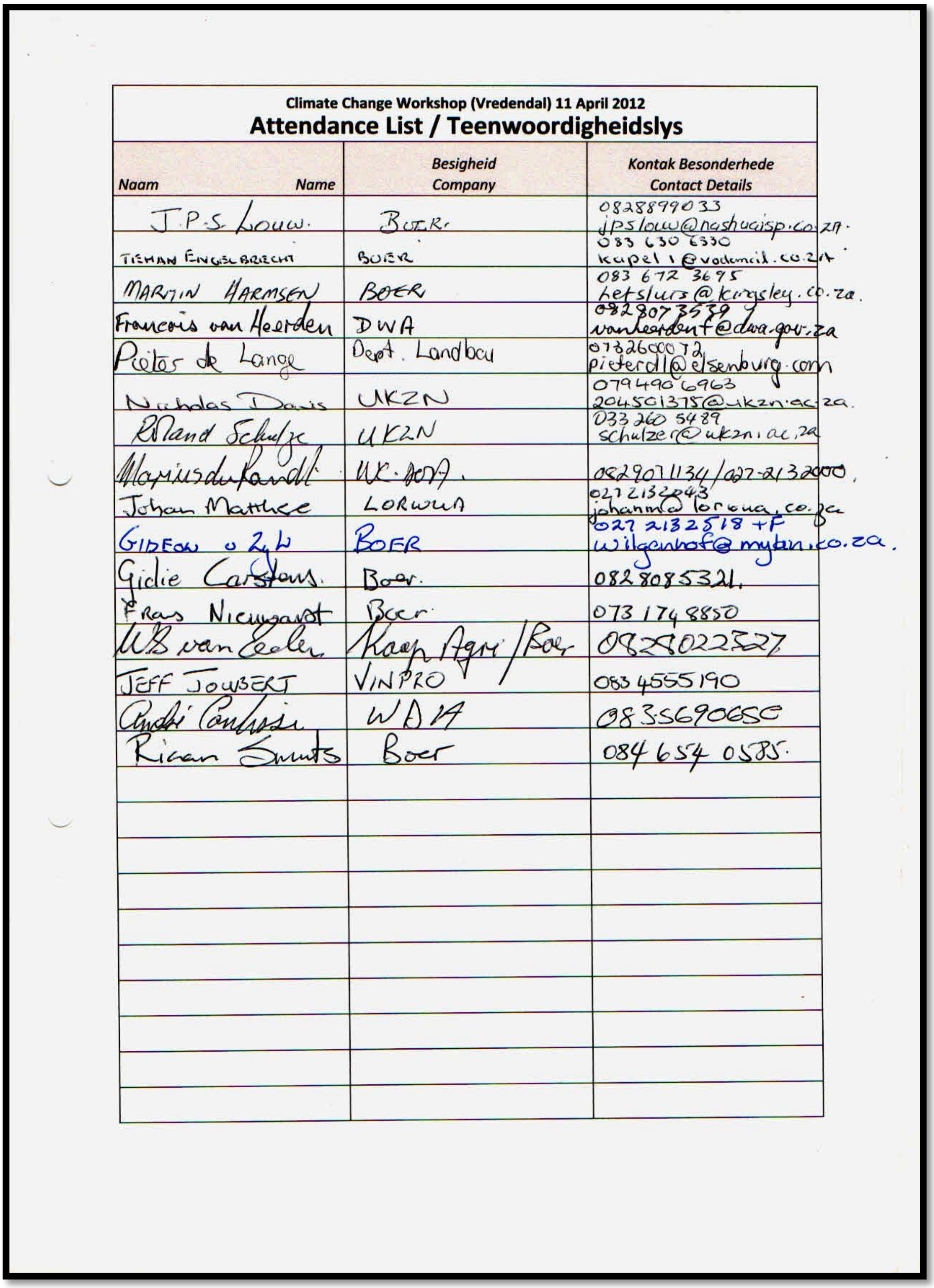

Climate Change Workshop (Vredendal) 11 April 2012

Attendance List / Teenwoordigheidslys

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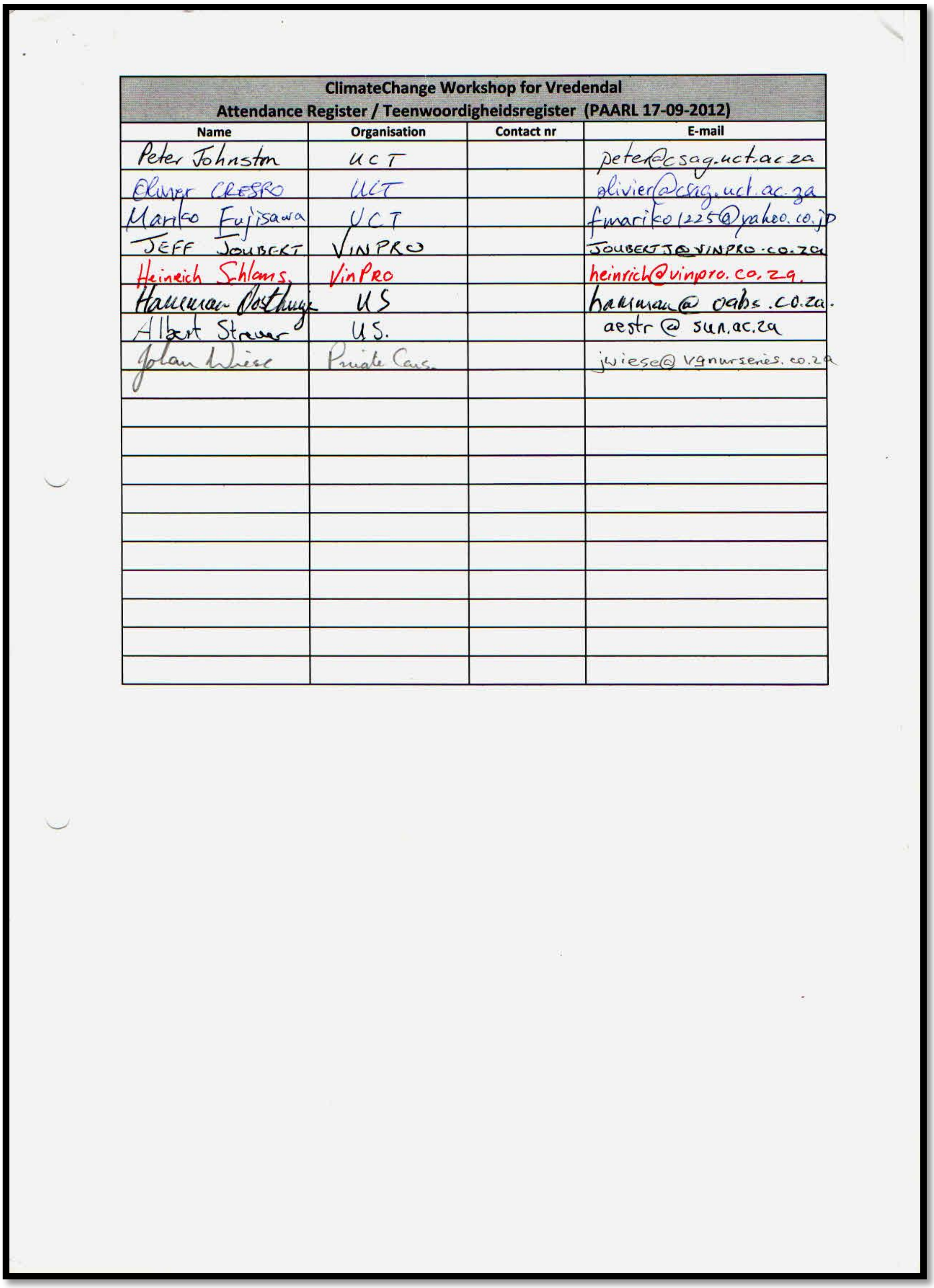

ClimateChange Workshop for Vredendal
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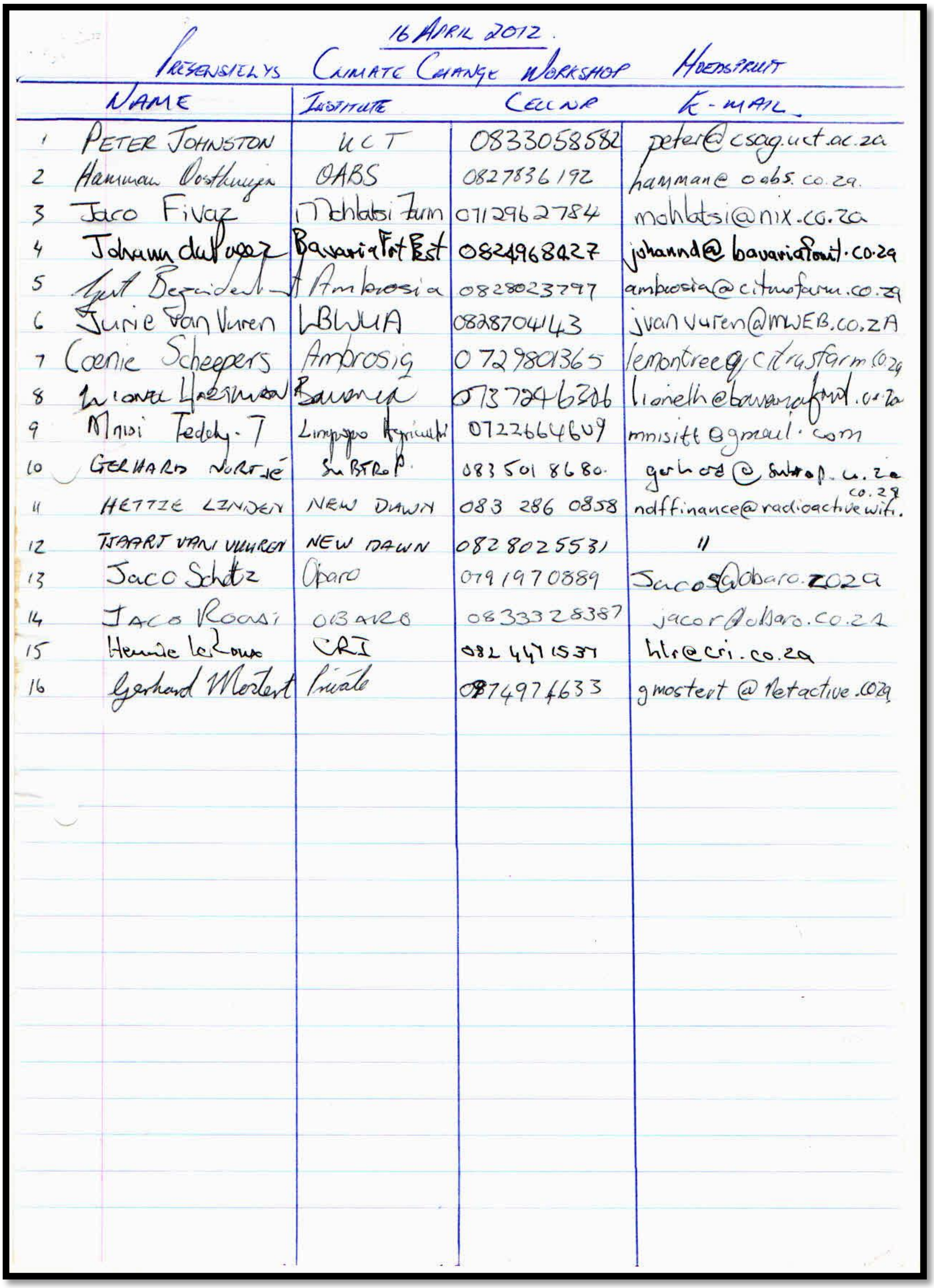
Blyde River WUA expert group discussions



16 APRIL 2012.

PRESENSIELYS CLIMATE CHANGE WORKSHOP HOEDSPRUIT

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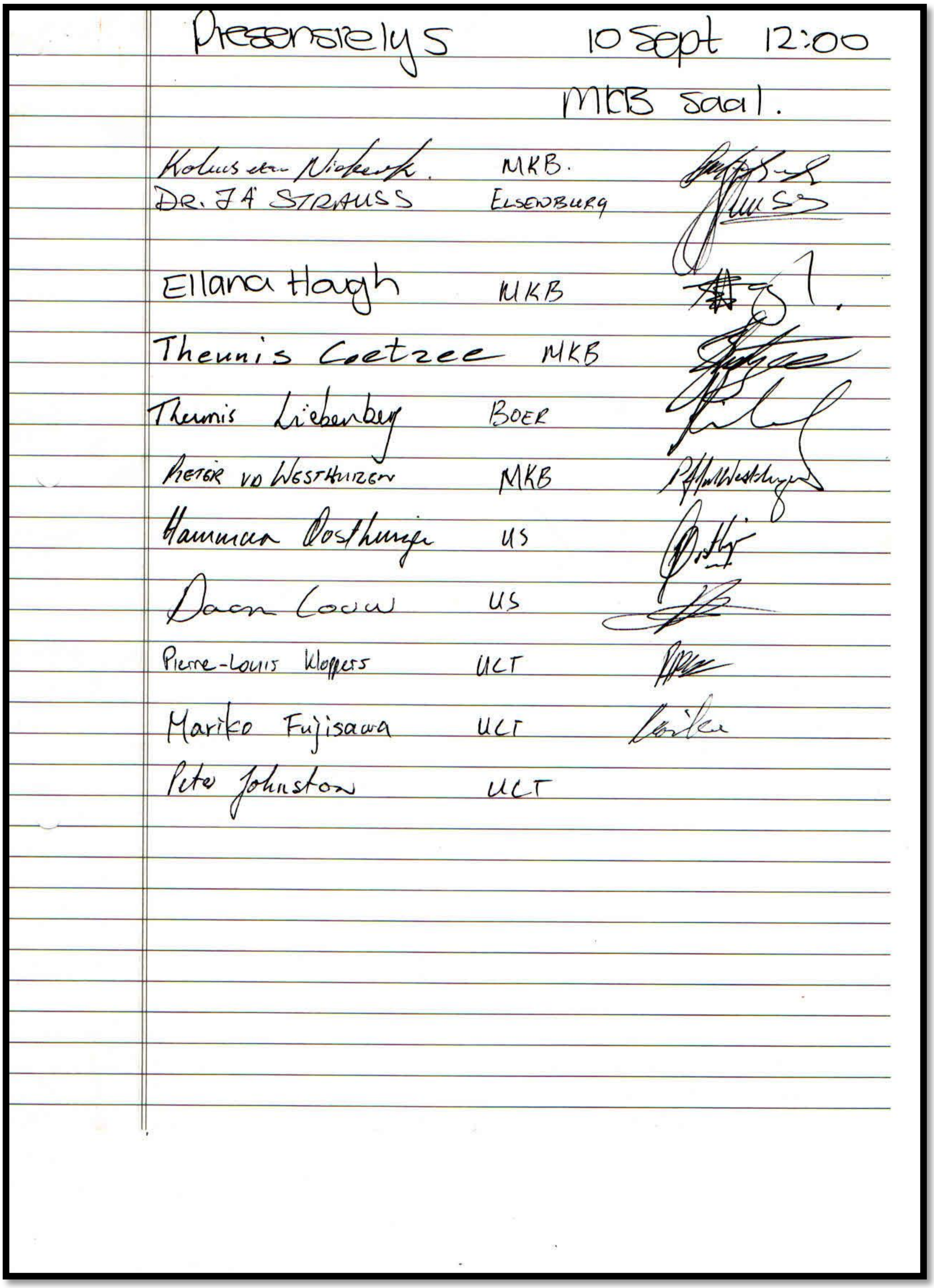
Moorreesburg expert group discussions



Presensielys 10 Sept 12:00

MKB saal.

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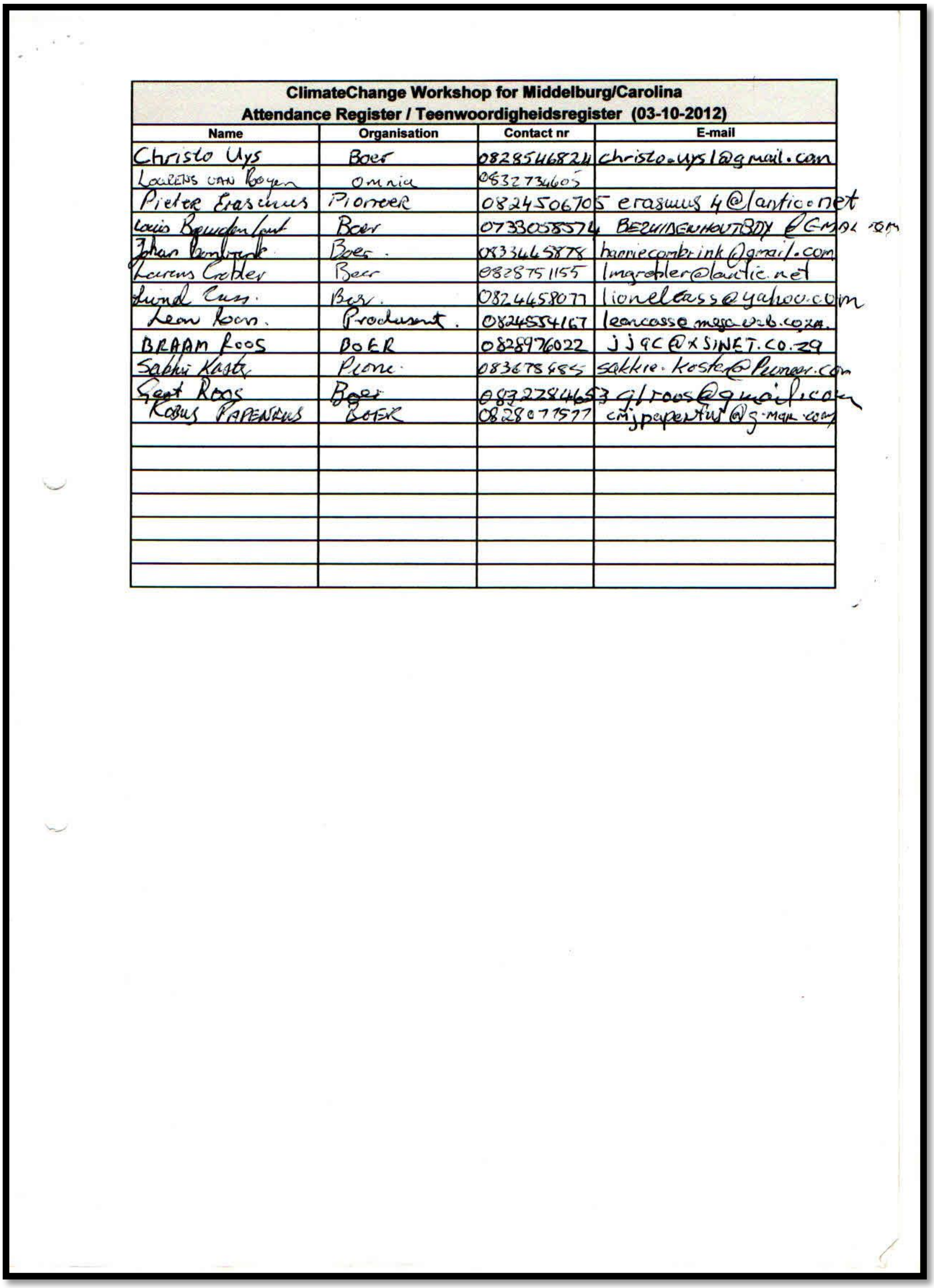
DR. JA STRAUSS	ELSENBURG
Ellana Haugh	MKB
Theunis Coetzee	MKB
Theunis Liebenberg	BOER
PIETER VD WESTHUIZEN	MKB
Hannica Oosthuizen	US
Daan Louw	US
Pierre-Louis Kloppers	UCT
Mariko Fujisawa	UCT
Peter Johnston	UCT

Carolina expert group discussions



ClimateChange Workshop for Middelburg/Carolina
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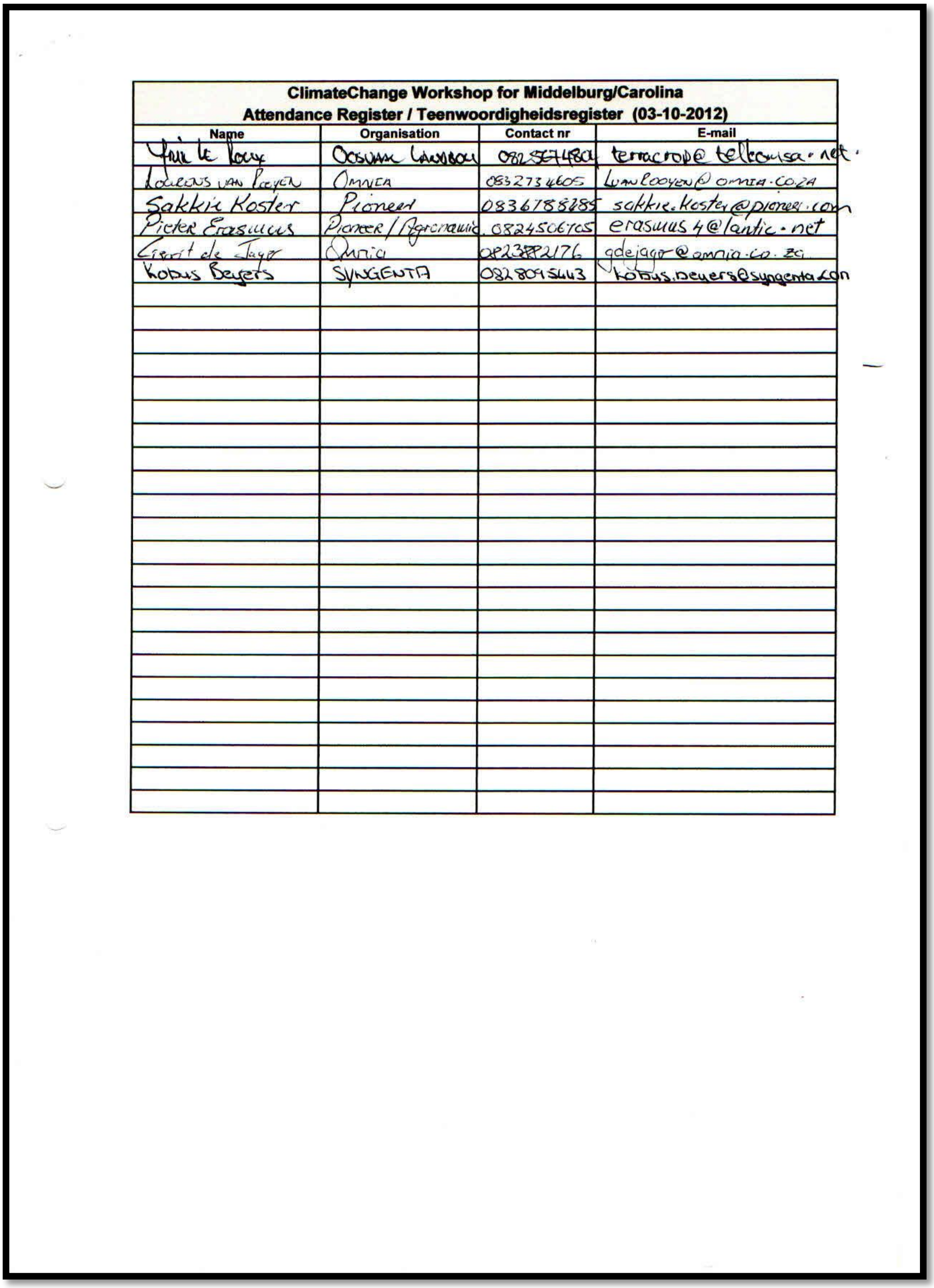

ClimateChange Workshop for Middelburg/Carolina
Attendance Register / Teenwoordigheidsregister (03-10-2012)

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APPENDIX B: SUMMARY OF CROP CRITICAL CLIMATE THRESHOLD BREACHES

Summary of crop threshold breaches – LORWUA case study area

Wine grapes	**Threshold Penalty weight - Yield**	**Threshold Penalty weight - Quality**	**Present climate (1971 - 1990)**							**Intermediate future climate (2046 - 2065)**						
			CCC	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**	**CCC**	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**
Tmxd > 38 °C for 5 days	-5%	0%	0	0	0	0	0	**0**	**0**	1	1	0	0	0	**2**	**0**
Tmxd> 45 °C in Nov	-5%	0%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Tmxd> 42 °C Nov - Dec	-5%	0%	1	0	1	0	2	**4**	**1**	32	14	8	2	7	**63**	**13**
Difference Tmax and Tmnd > 20 °C in Dec	-5%	0%	1	0	1	0	0	**2**	**0**	7	3	2	0	3	**15**	**3**
Tmnd <9 °C and Tmxd < 20 °C May - Jun	10%	0%	16	16	17	25	16	**90**	**18**	3	3	9	2	2	**19**	**4**
Average temperature < 22 °C in summer	10%	0%	3	2	2	0	0	**7**	**1**	0	0	0	0	0	**0**	**0**
5 days above 40 °C	-5%	0%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
> 33 °C for > 5 days with high Tmnd	0%	-5%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
5-10 mm rain Dec - Jan	0%	-5%	12	7	10	6	12	**47**	**9**	8	10	10	4	13	**45**	**9**
> 5 mm rain for 3 days Dec - Jan	0%	-5%	1	0	0	0	0	**1**	**0**	0	0	0	0	0	**0**	**0**
Any Rain from Dec to Apr = bursting/rotting	0%	-5%	20	19	20	17	20	**96**	**19**	20	20	20	17	20	**97**	**19**

Summary of crop threshold breaches – LORWUA case study area

Table grapes	Threshold Penalty weight Yield	Threshold Penalty weight Quality	Present climate (1971 - 1990)							Intermediate future climate (2046 - 2065)						
			CCC	CRM	ECH	GISS	IPS	**Total All models**	**Avg All models**	CCC	CRM	ECH	GISS	IPS	**Total All models**	**Avg All models**
Tmxd > 38 ^{o}C for 5 days	0%	-5%	0	0	0	0	0	**0**	**0**	1	1	0	0	0	**2**	**0**
Tmxd > 45 ^{o}C in Nov	-10%	-5%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Tmxd > 42 ^{o}C Nov - Dec	-10%	-5%	1	0	1	0	2	**4**	**1**	32	14	8	2	7	**63**	**13**
Difference Tmax and Tmnd > 20 ^{o}C in Dec	-10%	-5%	1	0	1	0	0	**2**	**0**	7	3	2	0	3	**15**	**3**
Tmnd < 9 ^{o}C and Tmxd < 20 ^{o}C May - Jun	10%	10%	16	16	17	25	16	**90**	**18**	3	3	9	2	2	**19**	**4**
Average temperature < 22 ^{o}C in summer	10%	10%	3	2	2	0	0	**7**	**1**	0	0	0	0	0	**0**	**0**
Difference Tmxd and Tmnd < 10 ^{o}C Oct - Nov	0%	-5%	75	55	93	25	69	**317**	**63**	62	64	69	35	100	**330**	**66**
> 33 ^{o}C for > 5 days with high Tmnd	0%	-5%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
5 - 10 mm rain Dec - Jan	0%	-5%	12	7	10	6	12	**47**	**9**	8	10	10	4	13	**45**	**9**
> 5 mm for 3 days Dec - Jan	-10%	-5%	1	0	0	0	0	**1**	**0**	0	0	0	0	0	**0**	**0**

Summary of crop threshold breaches – LORWUA case study area

Raisins	**Threshold Penalty weight Yield**	**Threshold Penalty weight Quality**	**Present climate (1971 - 1990)**							**Intermediate future climate (2046 - 2065)**						
			CCC	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**	**CCC**	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**
Tmxd > 38 ^{o}C for 5 days	-5%	0%	0	0	0	0	0	**0**	**0**	1	1	0	0	0	**2**	**0**
Tmxd > 45 ^{o}C in Nov	-10%	0%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Tmxd > 42 ^{o}C Nov - Dec	-5%	0%	1	0	1	0	2	**4**	**1**	32	14	8	2	7	**63**	**13**
Difference Tmax and Tmnd > 20 ^{o}C in Dec	-5%	0%	1	0	1	0	0	**2**	**0**	7	3	2	0	3	**15**	**3**
Tmnd < 9 ^{o}C and Tmxd < 20 ^{o}C May - Jun	10%	0%	16	16	17	25	16	**90**	**18**	3	3	9	2	2	**19**	**4**
Average temperature < 22 ^{o}C in summer	10%	0%	3	2	2	0	0	**7**	**1**	0	0	0	0	0	**0**	**0**
5 days above 40 ^{o}C	-10%	0%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
> 33 ^{o}C for > 5 days with high Tmnd	0%	-5%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
5 - 10 mm rain Dec - Jan	0%	-5%	12	7	10	6	12	**47**	**9**	8	10	10	4	13	**45**	**9**
> 5 mm for 3 days Dec - Jan	0%	-5%	1	0	0	0	0	**1**	**0**	0	0	0	0	0	**0**	**0**
Any Rain from Dec to Apr = bursting/rotting	0%	-5%	20	19	20	17	20	**96**	**19**	20	20	20	17	20	**97**	**19**

Summary of crop threshold breaches – Blyde River WUA case study area

Citrus Grapefruit	**Threshold Penalty weight - Yield**	**Threshold Penalty weight - Quality**	**Present climate (1971 - 1990)**							**Intermediate future climate (2046 - 2065)**						
			CCC	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**	**CCC**	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**
Tmxd > 40 °C and RH < 30% for 2 days Sept	-40%	0%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Tmxd >35 °C and RH < 30% for 2 days Sept	-40%	0%	0	0	0	0	1	**1**	**0**	0	0	0	7	1	**8**	**2**
Tmxd > 35 °C and RH < 20% for 2 days Sept	-40%	0%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Fruit drop (Nov/Dec) >7 days of Tmxd > 36 °C and RH < 40%	-30%	-10%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
2 °C warmer in May - colour deteriorates	0%	-4%	0	0	3	0	2	**5**	**1**	18	18	19	10	16	**81**	**16**
During picking temp > 36 °C - increase rind problems	0%	-1%	89	119	119	58	146	**531**	**106**	332	520	505	232	460	**2 049**	**410**
>14 days continuous rain during picking (autumn) causes leaf wetness and overripe fruit	0%	-10%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**

Citrus Lemons	**Threshold Penalty weight - Yield**	**Threshold Penalty weight - Quality**	**Present climate (1971 - 1990)**							**Intermediate future climate (2046 - 2065)**						
			CCC	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**	**CCC**	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**
Tmxd > 40 °C and RH < 30% for 2 days Sept	-25%	0%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Tmxd >35 °C and RH < 30% for 2 days Sept	-15%	0%	0	0	0	0	1	**1**	**0**	0	0	0	7	1	**8**	**2**
Tmxd > 35 °C and RH < 20% for 2 days Sept	-15%	0%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Fruit drop (Nov/Dec) >7 days of Tmxd > 36 °C and RH < 40%	-40%	-1%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
During picking temp > 36 °C - increase rind problems	0%	-1%	89	119	119	58	146	**531**	**106**	332	520	505	232	460	**2 049**	**410**
>14 days continuous rain during picking (autumn) causes leaf wetness and overripe fruit	0%	-15%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**

Citrus Valencia	**Threshold Penalty weight - Yield**	**Threshold Penalty weight - Quality**	**Present climate (1971 - 1990)**							**Intermediate future climate (2046 - 2065)**						
			CCC	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**	**CCC**	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**
Tmxd > 40 °C and RH < 30% for 2 days Sept	-25%	0%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Tmxd >35 °C and RH < 30% for 2 days Sept	-15%	0%	0	0	0	0	1	**1**	**0**	0	0	0	7	1	**8**	**2**
Tmxd > 35 °C and RH < 20% for 2 days Sept	-15%	0%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Fruit drop (Nov/Dec) >7 days of Tmxd > 36 °C and RH < 40%	-40%	-1%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
During picking temp > 36 °C - increase rind problems	0%	-1%	89	119	119	58	146	**531**	**106**	332	520	505	232	460	**2 049**	**410**
> 14 days continuous rain during picking (autumn) causes leaf wetness and overripe fruit	0%	-8%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**

Summary of crop threshold breaches – Blyde River WUA case study area

Mango Keitt	**Threshold Penalty weight - Yield**	**Threshold Penalty weight - Quality**	**Present climate (1971 - 1990)**							**Intermediate future climate (2046 - 2065)**						
			CCC	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**	**CCC**	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**
Average May Tmnd 3 °C warmer	-4%	0%	0	0	2	0	0	**2**	**0**	14	19	14	15	13	**75**	**15**
Tmnd < 2 °C Jul - Aug	-4%	0%	1	4	6	2	2	**15**	**3**	0	0	0	0	0	**0**	**0**
Sept - Dec (HU requirement 350 hours > 17.9 °C) cool temps averaging < 17.9 °C cause late maturation and market delivery delay	0%	-10%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Tmxd > 38 °C Dec - Jan	-1%	-1%	5	13	10	0	10	**38**	**8**	24	58	37	0	30	**149**	**30**

Mango Kent	**Threshold Penalty weight - Yield**	**Threshold Penalty weight - Quality**	**Present climate (1971 - 1990)**							**Intermediate future climate (2046 - 2065)**						
			CCC	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**	**CCC**	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**
Average May Tmnd 3 °C warmer	-8%	0%	0	0	2	0	0	**2**	**0**	14	19	14	15	13	**75**	**15**
Tmnd < 2 °C Jul - Aug	-8%	0%	1	4	6	2	2	**15**	**3**	0	0	0	0	0	**0**	**0**
Tmxd > 38 °C Sept	-1%	-1%	53	20	44	46	63	**226**	**45**	113	151	166	142	145	**717**	**143**
Sept - Dec (HU requirement 350 hours > 17.9 °C) cool temps averaging < 17.9 °C cause late maturation and market delivery delay	0%	-10%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Tmxd > 38 °C Dec - Jan	-1%	-1%	5	13	10	0	10	**38**	**8**	24	58	37	0	30	**149**	**30**

Mango Tommy Atkins	**Threshold Penalty weight - Yield**	**Threshold Penalty weight - Quality**	**Present climate (1971 - 1990)**							**Intermediate future climate (2046 - 2065)**						
			CCC	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**	**CCC**	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**
Average May Tmnd 3 °C warmer	-6%	0%	0	0	2	0	0	**2**	**0**	14	19	14	15	13	**75**	**15**
Tmnd < 2 °C Jul - Aug	-6%	0%	1	4	6	2	2	**15**	**3**	0	0	0	0	0	**0**	**0**
Sept - Dec (HU requirement 350 hours > 17.9 °C) cool temps averaging < 17.9 °C cause late maturation and market delivery delay	0%	-20%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Tmxd > 38 °C Dec - Jan	-1%	-1%	5	13	10	0	10	**38**	**8**	24	58	37	0	30	**149**	**30**

Summary of crop threshold breaches – Moorreesburg case study area

Wheat	**Threshold Penalty weight**	**Present climate (1971 - 1990)**							**Intermediate future climate (2046 - 2065)**						
		CCC	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**	**CCC**	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**
Mid May - Aug Tmxd > 20 °C	-10%	0	0	0	0	0	**0**	**0**	14	17	5	10	20	**66**	**13**
Tmxd > 25 °C in Sept	-10%	0	0	0	0	0	**0**	**0**	0	2	1	0	2	**5**	**1**
Rainfal May - less than 50 mm	-10%	6	9	8	10	8	**41**	**8**	5	5	7	8	13	**38**	**8**
Rainfal May - Sept < 200 mm	-30%	1	5	3	4	0	**13**	**3**	1	0	1	2	4	**8**	**2**
Rainfal May - Sept > 400 mm	20%	1	2	2	2	1	**8**	**2**	2	3	3	4	1	**13**	**3**
Rainfal May - Sept > 10 mm/week	33%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Rainfal Sept weeks 1 and 2 > 10 mm	10%	16	12	14	12	13	**67**	**13**	14	15	12	10	11	**62**	**12**
Rainfal Sept weeks 3 and 4 > 10 mm	10%	8	7	7	6	9	**37**	**7**	7	8	8	9	9	**41**	**8**
May-Jun no rain	-10%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Jun - Jul < 70 mm	-10%	1	3	5	2	2	**13**	**3**	1	4	0	1	0	**6**	**1**
Jul - Aug < 70 mm	-10%	4	4	2	2	1	**13**	**3**	1	5	1	2	2	**11**	**2**
Sept < 15 mm	-10%	4	6	2	3	6	**21**	**4**	2	1	3	6	3	**15**	**3**
Sept < 5 mm	-10%	0	0	0	1	1	**2**	**0**	0	1	1	3	2	**7**	**1**

Summary of crop threshold breaches – Carolina case study area

Maize	**Threshold Penalty weight**	**Present climate (1971 - 1990)**							**Intermediate future climate (2046 - 2065)**						
		CCC	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**	**CCC**	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**
Tmnd < -5 °C in Dec	-5%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Tmxd > 35 °C for 3+ days Jan - Feb	-5%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Tmnd < 12 °C in Nov	-1%	211	165	188	160	165	**889**	**178**	82	51	68	72	51	**324**	**65**
Rainfall < 40 mm in Oct	-5%	6	3	5	2	5	**21**	**4**	2	0	1	0	2	**5**	**1**
Rainfall < 60 mm in Nov	-5%	5	5	6	0	4	**20**	**4**	2	0	2	1	5	**10**	**2**
Rainfall < 80 mm in Dec	-5%	3	4	3	4	6	**20**	**4**	3	2	6	4	1	**16**	**3**
Rainfall < 100 mm in Jan	-15%	6	6	3	6	5	**26**	**5**	3	5	3	6	1	**18**	**4**
Rainfall < 60 mm in Feb	-5%	5	5	6	8	5	**29**	**6**	5	3	6	2	5	**21**	**4**
Rainfall > 80 mm in Feb	10%	12	10	10	10	10	**52**	**10**	10	13	9	13	14	**59**	**12**
Rainfall > 80 mm in Mar	10%	10	8	9	10	9	**46**	**9**	10	10	12	12	9	**53**	**11**
Rainfall > 160 mm in Feb - Mar	10%	13	8	10	10	11	**52**	**10**	11	14	14	15	8	**62**	**12**

Summary of crop threshold breaches – Carolina case study area

Soybeans	**Threshold Penalty weight**	**Present climate (1971 - 1990)**							**Intermediate future climate (2046 - 2065)**						
		CCC	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**	**CCC**	**CRM**	**ECH**	**GISS**	**IPS**	**Total All models**	**Avg All models**
Tmnd < -5 ^{o}C Oct - Jan	-50%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Tmxd > 28 ^{o}C for 3+ days in mid Jan - Feb	-5%	18	17	19	20	23	**97**	**19**	107	104	125	110	94	**540**	**108**
Average temperature > 25 ^{o}C in Nov	-10%	0	0	0	0	0	**0**	**0**	2	0	0	0	0	**2**	**0**
Tmxd > 35 ^{o}C Jan	-10%	0	0	0	0	0	**0**	**0**	0	0	0	0	1	**1**	**0**
Tmxd > 30 ^{o}C with low RH in Jan	-10%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Rainfall < 50 mm in Nov	-10%	5	5	6	0	4	**20**	**4**	2	0	2	1	5	**10**	**2**
Rainfall < 80 mm in Dec	-10%	3	4	3	4	6	**20**	**4**	3	2	6	4	1	**16**	**3**
Rainfall < 100 mm in Jan	-10%	6	6	3	6	5	**26**	**5**	3	5	3	6	1	**18**	**4**
Rainfall < 60 mm in Feb	-10%	5	5	6	8	5	**29**	**6**	5	3	6	2	5	**21**	**4**
Rainfall < 40 mm Jan	-10%	1	0	1	0	1	**3**	**1**	1	0	1	2	0	**4**	**1**
Rainfall > 60 mm and < 150 mm in Feb	5%	14	15	12	10	15	**66**	**13**	13	14	12	17	13	**69**	**14**
Rainfall > 60 mm and < 150 mm in Mar	5%	14	11	14	15	13	**67**	**13**	9	14	13	14	9	**59**	**12**
Rainfall > 120 mm and < 300 mm in Feb - M	5%	17	17	16	16	15	**81**	**16**	15	18	16	19	15	**83**	**17**

Summary of crop threshold breaches – Carolina case study area

Sugar beans	Threshold Penalty weight	Present climate (1971 - 1990)							Intermediate future climate (2046 - 2065)						
		CCC	CRM	ECH	GISS	IPS	Total All models	Avg All models	CCC	CRM	ECH	GISS	IPS	Total All models	Avg All models
Tmnd < -5 °C Oct - Jan	-50%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Tmxd > 26 °C for 3+ days in mid Jan - Feb	-10%	62	50	53	61	55	**281**	**56**	166	146	157	147	135	**751**	**150**
Tmxd > 30 °C with high RH in Jan	-10%	0	0	0	0	0	**0**	**0**	0	0	0	0	0	**0**	**0**
Tmxd > 30 °C during Jan	-10%	5	5	6	0	4	**20**	**4**	2	0	2	1	5	**10**	**2**
Rainfall < 50 mm in Nov	-10%	3	4	3	4	6	**20**	**4**	3	2	6	4	1	**16**	**3**
Rainfall < 80 mm in Dec	-10%	6	6	3	6	5	**26**	**5**	3	5	3	6	1	**18**	**4**
Rainfall < 100 mm in Jan	-10%	5	5	6	8	5	**29**	**6**	5	3	6	2	5	**21**	**4**
Rainfall < 60 mm in Feb	-5%	9	9	11	9	9	**47**	**9**	12	11	13	10	13	**59**	**12**
Rainfall > 140 mm in Jan	5%	8	7	7	4	9	**35**	**7**	9	8	7	8	5	**37**	**7**
Rainfall > 60 mm en < 100 mm in Feb	5%	10	8	10	9	9	**46**	**9**	5	8	6	6	8	**33**	**7**
Rainfall > 60 mm en < 100 mm in Mar	5%	13	11	10	10	11	**55**	**11**	10	11	7	10	13	**51**	**10**