
THE ECONOMICS OF CLIMATE CHANGE ADAPTATION STRATEGIES IN THE CERES REGION, WESTERN CAPE

BY ABIODUN AKINTUNDE OGUNDEJI

Submitted in accordance with the requirements for the degree
PHILOSOPHIAE DOCTOR

in the

PROMOTER: PROF. J.A. GROENEWALD

CO-PROMOTER: DR. H. JORDAAN

JULY 2013

FACULTY OF NATURAL AND AGRICULTURAL SCIENCES

DEPARTMENT OF AGRICULTURAL ECONOMICS

UNIVERSITY OF THE FREE STATE

BLOEMFONTEIN

DECLARATION

I, Abiodun Akintunde Ogundeji, hereby declare that this thesis work submitted for the degree of Philosophiae Doctor in the Faculty of Natural and Agricultural Sciences, Department of Agricultural Economics at the University of the Free State, is my own independent work, and has not previously been submitted by me to any other university. I furthermore cede copyright of the thesis in favour of the University of the Free State.

Abiodun Akintunde Ogundeji
Bloemfontein
July 2013

Date

ACKNOWLEDGEMENTS

“For I am confident of this very thing, that He who began a good work in me will perfect it until the day of Christ Jesus.”

Philippians 1:6

Firstly, I thank GOD, the Almighty for giving me the inner strength, wisdom and guidance to complete this study – there is none like You Lord.

I wish to thank the following people, who; in some way contributed to the successful completion of this study. In addition, everyone else in-between, whom because of space limitation, I may have omitted. To all of you, I'm eternally grateful.

Professional acknowledgements:

- My Promoter, Professor Jan Groenewald, for all his guidance, intellectual leadership, excellent supervision and motivation during the completion of this study.
- My Co-Promoter, Dr. Henry Jordaan, for his friendship, support and contributions. Your passion for research is truly inspiring and worth commending. I have learnt a lot from you.
- Prof Daan Louw, the initiator of this work. Thank you for sharing your knowledge with me and making all the relevant information needed available for the modelling exercise. The data and initial model on Ceres are appreciated.
- Prof. Johan Willemse, Chair of the Department of Agricultural Economics, University of the Free State, for his support, mentorship and interest in my overall development.
- Prof Bennie Grové, for his support and advice.
- My colleagues and friends at the Department of Agricultural Economics, University of the Free State for all their support throughout my studies and my academic career.
- A special word of appreciation to Mrs Louise Hoffman, Mrs Annely Minnaar, and Ms Ina Combrinck for their administrative support and encouragement.
- Mr. Pieter van Heerden of PICWAT consultancy for his guidance on how to use SAPWAT.

- Mr. Pieter Haasbroek of Agricultural Research Council for many discussions on the calculation of chill units.
- All the farmers (emerging and commercial), NGO's and other interested parties who attended our workshops to provide valuable information to improve our knowledge of the impact of climate change and possible adaptation strategies.
- The University of the Free State Water Management in Water-Scarce Areas Cluster, for their financial support.
- Lastly, the research presented in this thesis emanated from a research project that was funded by the International Development Research Centre (IDRC grant number: 104 150) entitled, **“Managing climate risk for agriculture and water resources development in South Africa: Quantifying the costs, benefits and risks associated with planning and management alternatives”** I would like to express my sincere appreciation to the IDRC for their financial contributions, and the Project team, Drr Mac Callaway, Peter Johnston, Mark Tadros, and Molly Helmuth, and Mr Trevor Lumsden, for their support during the course of the project.

Personal acknowledgements:

- My wife, Olawunmi, and children: Demilade and Tomisin for all their support and patience, especially during the final stages of my studies. I cannot ask for more from God as you are simply perfect, thank you for all your love. I am so blessed and honored to have you in my life.
- My parents, your unfailing love and encouragement made me who I am. I love you so much.
- My sisters, brothers and their families, for their unflinching love and support always. You are simply the best. Special thanks to Dr and Mrs E.O. Olaniyi for their guidance and support.
- Pastor Olu Oyewumi and Pastor Francis Boakye, for their spiritual upbringing.

ABIODUN AKINTUNDE OGUNDEJI

LIST OF ACRONYMS AND ABBREVIATIONS

ACRU	Agricultural Catchments Research Unit
BEWAP	BEsproeiings Water Bestuursprogram
BOCMA	Breede-Overberg Catchment Management Agency
BRDSEM	Berg River Dynamic Spatial Equilibrium Model
CCAA	Climate Change Adaptation in Africa
CDIM	Ceres Dynamic Integrated Model
CEEPA	Centre for Environmental Economics and Policy in Africa
CERES	Crop Environment Resource Synthesis
CIER	Centre for Integrative Environmental Research
CSIR	Centre for Scientific and Industrial Research
CTB	Ceres Tourism Board
CTC	Cape Town City
CU	Chilling Units
CWUC	Crop Water Use Change factors
DEA&DP	Department of Environmental Affairs and Development Planning
DEAT	Department of Environmental Affairs and Tourism
DLP	Dynamic Linear Programming
DNLP	Dynamic Non-Linear Programming
DP	Dynamic Programming
DWAF	Department of Water Agriculture and Forestry
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization of the United Nations Statistical database
FDLP	Farm-level Dynamic Linear Programming
GCM	Global Circulation Models
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IA	Integrated Assessment
IAM	Integrated Assessment Models
ICU	Infruitec Chill Units
IDRC	International Development Research Centre
IFR	In stream Flow Requirements
IPCC	Intergovernmental Panel on Climate Change
JJA	June, July, August
NAMC	National Agriculture Marketing Council
NDFI	Net Disposable Farm Income
NPC	National Planning Commission
PCU	Positive Utah Chill Units
PDC	Provincial Development Council

List of acronyms and abbreviations

RCM	Regional Climate Models
RCU	Richardson Chill Units
SAPWAT	South Africa Plant WATER
SWB	Soil-Water-Balance
UCT	University of Cape Town
UNESCO-IHP	United Nations Educational Scientific and Cultural Organization - International Hydrological Programme
UNESCO-WWAP	United Nations Educational Scientific and Cultural Organization - World Water Assessment Programme
US	United States
WC	Western Cape
WRC	Water Research Commission

TABLE OF CONTENTS

TITLE PAGE	i
DECLARATION	ii
ACKNOWLEDGEMENTS	iii
LIST OF ACRONYMS AND ABBREVIATIONS	v
TABLE OF CONTENTS	vii
LIST OF TABLES	xii
LIST OF FIGURES	xiii
ABSTRACT	xiv

CHAPTER 1

INTRODUCTION **1**

1.1	BACKGROUND AND MOTIVATION	1
1.2	PROBLEM STATEMENT	2
1.3	OBJECTIVES.....	4
1.4	ORGANISATION OF THE THESIS	6

CHAPTER 2

LITERATURE REVIEW **7**

2.1	INTRODUCTION.....	7
2.2	CLIMATE CHANGE AND EXTREME EVENTS.....	7
2.3	CLIMATE CHANGE IMPACTS	10
2.3.1	<i>IMPACT OF CLIMATE CHANGE ON WATER SECTOR</i>	11
2.3.2	<i>IMPACT OF CLIMATE CHANGE ON TEMPERATURE</i>	12
2.3.3	<i>IMPLICATIONS FOR AGRICULTURAL SECTOR</i>	13
2.4	MEASURING CLIMATE SENSITIVITY OF AGRICULTURE.....	15
2.4.1	<i>STRUCTURAL MODELLING APPROACH</i>	15
2.4.1.1	<i>Integrated assessment of climate change impacts</i>	15
2.4.1.2	<i>Integrated Assessment Models (IAM)</i>	17
2.5	COPING WITH CLIMATE CHANGE	19
2.5.1	<i>TYPES OF ADAPTATION</i>	20
2.6	THE ECONOMIC COST OF CLIMATE CHANGE IMPACTS AND ADAPTATION.....	21
2.6.1	<i>DECISION MAKING IN AGRICULTURE: APPLICATION OF DYNAMIC LINEAR PROGRAMMING (DLP) AND DYNAMIC PROGRAMMING (DP)</i>	22

2.6.2	APPLICATION OF DYNAMIC LINEAR PROGRAMMING IN CLIMATE CHANGE MODELLING	24
2.6.2.1	<i>International research</i>	24
2.6.2.2	<i>South Africa research</i>	25
2.7	CROP WATER MODELLING MODELS AND APPLICATION IN SOUTH AFRICA	26
2.8	CHILL UNIT ACCUMULATION MODELS IN SOUTH AFRICA	27
2.9	SUMMARY AND CONCLUSION	29

CHAPTER 3

OVERVIEW OF CERES ECONOMY **32**

3.1	INTRODUCTION	32
3.2	GENERAL DESCRIPTION AND LOCATION OF CERES	32
3.2.1	<i>CLIMATE AND SOIL</i>	34
3.3	THE KOEKEDOUW IRRIGATION SCHEME	35
3.4	DESCRIPTION OF THE CERES/KOEKEDOUW FARM STRUCTURE	36
3.4.1	<i>LAND CLASSIFICATION</i>	36
3.4.2	<i>CROP AREAS</i>	38
3.4.3	<i>WATER SOURCES</i>	40
3.5	CERES DECIDUOUS FRUITS AND CHILL UNITS REQUIREMENTS	40
3.6	IMPORTANCE OF THE AGRICULTURAL SECTOR IN THE REGIONAL ECONOMY	41
3.7	CONCLUSIONS	43

CHAPTER 4

METHODOLOGY **45**

4.1	INTRODUCTION	45
4.2	MODEL STRUCTURE	45
4.2.1	<i>DESCRIPTION OF THE MODULES OF THE MODEL</i>	47
4.3	CLIMATE PROJECTIONS AND EMISSIONS SCENARIOS	48
4.4	POST-PROCESSING OF ACRU OUTPUT FOR APPLICATION IN THE CERES FARM MODEL	49
4.5	ESTIMATION OF CROP WATER REQUIREMENT WITH SAPWAT	50
4.6	ESTIMATION OF CHILL UNIT REQUIREMENTS	52
4.7	CERES FARM MODEL	53
4.7.1	<i>CROP PRODUCTION POSSIBILITIES</i>	53
4.7.2	<i>IRRIGATION TECHNOLOGIES AND WATER USE INTENSITIES</i>	54

4.7.3	ALGEBRAIC TERMINOLOGIES	54
4.7.3.1	Set structure.....	55
4.7.3.2	Parameters.....	55
4.7.3.3	Variables.....	57
4.7.3.4	Agricultural Production Variables.....	58
4.7.3.5	Water use variables.....	59
4.7.3.6	Hydrology variables.....	59
4.7.3.7	Objective function.....	60
4.7.3.8	Equations.....	61
4.8	INTERTEMPORAL SPATIAL EQUILIBRIUM MODULE	63
4.9	THE URBAN DEMAND MODULE	69
4.10	INTEGRATED MODEL OUTPUT	70
4.11	CONCLUSION	70

CHAPTER 5

RESULTS

71

5.1	INTRODUCTION	71
5.2	IMPACT OF CLIMATE CHANGE ON CROP WATER REQUIREMENT	71
5.3	IMPACT OF CLIMATE CHANGE ON CHILL UNIT ACCUMULATION	74
5.4	COMPARISON OF BASE CLIMATE CHANGE SCENARIOS FROM THE INTEGRATED MODEL	77
5.4.1	<i>IMPACT OF CLIMATE CHANGE ON AREA - BASE COMPARISON</i>	77
5.4.2	<i>IMPACT OF CLIMATE CHANGE ON WATER USE - BASE COMPARISON</i>	80
5.4.3	<i>IMPACT OF CLIMATE CHANGE ON WELFARE – BASE COMPARISON</i>	81
5.5.4	<i>DISCUSSION– BASE ANALYSIS</i>	82
5.5	CLIMATE CHANGE ADAPTATION SCENARIO	83
5.5.1	FARM DAM AND WINTER WATER RIGHT ADAPTATION SCENARIO	83
5.5.1.1	<i>Impact on area</i>	84
5.5.1.2	<i>Impact on water use</i>	86
5.5.1.3	<i>Impact on welfare</i>	87
5.5.1.4	<i>Discussion</i>	88
5.5.2	WATER USE EFFICIENCY ADAPTATION SCENARIO	89
5.5.2.1	<i>Impact on Area</i>	89
5.5.2.2	<i>Impact on water use</i>	91
5.5.2.3	<i>Impact on welfare</i>	92
5.5.2.4	<i>Discussion</i>	93
5.5.3	INCREASE IN WATER TARIFFS SCENARIO	93
5.5.3.1	<i>Impact on Area</i>	94
5.5.3.2	<i>Impact on water use</i>	96
5.5.3.3	<i>Impact on welfare</i>	97

5.5.3.4	<i>Conclusion</i>	98
5.5.4	CONCLUSION	98

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS 101

6.1	INTRODUCTION.....	101
6.1.1	<i>BACKGROUND AND MOTIVATION</i>	101
6.1.2	<i>PROBLEM STATEMENT AND OBJECTIVES</i>	101
6.2	LITERATURE REVIEW	103
6.3	IMPACT OF CLIMATE CHANGE ON CROP WATER REQUIREMENT.....	104
6.4	IMPACT OF CLIMATE CHANGE ON CHILL UNIT ACCUMULATION.....	105
6.5	COMPARISON OF BASE CLIMATE CHANGE SCENARIOS FROM THE INTEGRATED MODEL.....	106
6.6	CLIMATE CHANGE ADAPTATION SCENARIO	107
6.6.1	<i>FARM DAM AND WINTER WATER RIGHT ADAPTATION SCENARIO</i>	107
6.6.2	<i>WATER USE EFFICIENCY ADAPTATION SCENARIO</i>	108
6.6.3	<i>INCREASE IN WATER TARIFF SCENARIO</i>	108
6.7	RECOMMENDATIONS.....	109
6.7.1	<i>POLICY RECOMMENDATIONS</i>	109
6.7.2	<i>RECOMMENDATIONS FOR FURTHER RESEARCH</i>	111

REFERENCES 112

APPENDICES 125

APPENDIX A: FARM MODEL CELL STRUCTURE.....	125
APPENDIX B: THE LAYOUT OF THE BULK WATER INFRAStructure	133

List of Tables

Table 2.1	Summary of observed and predicted climatic changes in the Western Cape	10
Table 2.2	Accumulation table for Richardson and Infruitec Chill Unit Models	28
Table 3.1:	Selected fruit types in Ceres and Richardson chill unit requirements	41
Table 3.2:	Fixed price multipliers for commodity and sector groupings	42
Table 4.1:	Summary of climate projections applied in hydrological modelling based on A2 emissions scenarios	49
Table 4.2:	Monthly reservoir factor	50
Table 4.3:	Future projected change in climate parameters for H10C station	52
Table 4.4:	Ceres crop production possibilities	54
Table 5.1:	Estimated Crop water requirement (m ³ /ha) for the base and future climate	72
Table 5.2:	Area under different irrigation intensities (Ha) – Base Comparison	78
Table 5.3:	The total average area under cultivation (Ha)	79
Table 5.4:	Area under different irrigation intensities (Ha)	84
Table 5.5:	The total average area under cultivation (Ha)	85
Table 5.6:	Area under different irrigation intensities (Ha)	89
Table 5.7:	The total average area under cultivation (Ha)	90
Table 5.8:	Area under different irrigation intensities (Ha)	94
Table 5.9:	The total average area under cultivation (Ha)	95

List of figures

Figure 2.1:	Integrated Framework for climate change ____	Error! Bookmark not defined.
Figure 3.1:	Map of Western Cape Province showing location of Ceres _____	33
Figure 3.2:	Actual monthly rainfall data from SAPWAT for the rainfall at H10C Weather station for years with low, average and good rainfall _____	35
Figure 3.3:	Ceres emerging farmers land use classification. _____	37
Figure 3.4:	Ceres commercial farmers land use classification _____	38
Figure 3.5:	Land utilisation according to crops by emerging farmers _____	39
Figure 3.6:	Land utilisation according to crops by commercial farmers _____	39
Figure 3.7:	Ceres farmers water supply sources _____	40
Figure 3.8:	Representation of socio economic linkages in the provincial economy __	43
Figure 4.1:	Ceres Dynamic Integrated Model (CDIM) Schematic Diagram _____	46
Figure 4.2:	Ceres region map showing the rivers, sub-catchments, quaternaries, towns and weirs. _____	51
Figure 5.1:	Comparison between the accumulated chill in the present and future climate using the Richardson Chill Unit Model _____	75
Figure 5.2:	Comparison between the accumulated chill in the present and future climate using the Infruitec Chill Unit Model _____	75
Figure 5.3:	Comparison between Richardson and Infruitec chill unit accumulation models _____	76
Figure 5.4:	Total average agricultural water use per annum _____	80
Figure 5.5:	Average annual crop water use per ha _____	81
Figure 5.6:	Net Disposable Farm Income – total over 20-years _____	81
Figure 5.7:	Total welfare – objective function value _____	82
Figure 5.8:	Total average agricultural water use per annum _____	86
Figure 5.9:	Average annual crop water use per hectare _____	87
Figure 5.10:	Net Disposable Farm Income – total over 20-years _____	87
Figure 5.11:	Total welfare – objective function value _____	88
Figure 5.12:	Total average agricultural water use per annum _____	91
Figure 5.13:	Average annual crop water use per ha _____	92
Figure 5.14:	Net Disposable Farm Income – total over 20 years _____	92
Figure 5.15:	Total welfare – objective function value _____	93
Figure 5.16:	Total average agricultural water use per annum _____	96
Figure 5.17:	Average annual crop water use per ha _____	96
Figure 5.18:	Net Disposable Farm Income – total over 20 years _____	97
Figure 5.19:	Total welfare – objective function value _____	98

ABSTRACT

The Western Cape (WC) region of South Africa, with its Mediterranean-type climate and predominantly winter rainfall, has been identified as highly vulnerable to projected climate change within both global and national contexts. The province will experience increasing temperatures and reductions in water supply in the future and these have to be adequately prepared for in order to mitigate these impacts.

The aim of this study is to develop and apply an integrated approach to quantify the economic impact of climate change on the agriculture and water resource sectors of Ceres, in Western Cape, South Africa. Although researchers have been able, to model, to a certain extent, the impact of climate change on the farm sector using integrated methodology, they have not yet included the impact of future change in crop water requirements as well as the impact of accumulated chill units. So currently, we do not have empirical knowledge of how the current and future change in crop water requirements and accumulated chill units will affect the farm structure. Thus in order to accurately quantify the impacts of different adaptation strategies at farm level, the existing models need to be adjusted and methodology developed to incorporate the impact of temperature.

SAPWAT was used to estimate crop water requirements for the base climate (1971-1990) and for the future climate (2046-2065). Results show that crop water requirements will increase as a result of projected climate change using the A2 climate change scenario. The water requirements for drip are less than that of Sprinkler, because of efficiency differences in the irrigation systems. The drip irrigation system is said to be a more efficient irrigation technology. It was also confirmed that future crop water requirements for drip irrigation system is still lower than the current water requirement under sprinkler. Accordingly, despite substantial increase in water requirements, under drip system, the total water requirement will be less under drip system compared to sprinkler system.

The Utah model (Richardson) and Daily positive Utah (Infruitec) chill unit accumulation model are used to test the hypothesis that winter chill will in Ceres reduce with climate change. Results from both models confirmed that climate change will result in reduction of future accumulation of chill units. The impact of climate change (projected temperature increase) on chill unit accumulation is more pronounced using Richardson model compared to Infruitec model. The result shows that it might be difficult to produce some fruit crops in the future in the Ceres region owing to insufficient chill that would be accumulated in the future. This will likely require growers' transition to different species or cultivars or develop management practices (planting density, pruning practices and irrigation regime) that can help overcome shortages in winter chill.

Results from crop water and chill unit models were incorporated into other models to develop the Ceres Dynamic Integrated Model. The model was used to simulate various climate change scenarios, and the results correspond with what can be expected from the prediction of impact on agriculture. The impact of climate change has resulted in changes in area, water use and welfare of the farmers in the future climate. Three different sets of adaptation strategies were evaluated using the developed integrated model. These three adaptation strategies include; availability of farm dam and water right; improving water use efficiency; and increase in water tariffs.

Farm dam capacity and winter water allocation seems to be the best adaptation strategy based on the results from this research. Giving farmers farm dam capacity alone, however will not improve the situation of the farmers, they also need water rights. Caution should be taken when considering such an adaptation option. Farm dam is a capital intensive infrastructure and if the farm dams don't fill up, it may worsen the situation of farmers since the high capital cost and resulting high unit cost of farm dam water will increase their financial vulnerability. Thus, giving farmers farm dam capacity and winter water right could be a good adaptation strategy but other issues surrounding its suitability should be considered. Increasing water use efficiency as an adaptation option according to analysis done in this study is also a good adaptation option for the Ceres farmers. Improved water management practices that increase the efficiency of irrigation water use may provide a significant adaptation potential under future climate change. Using water more efficiently improves the welfare of the farmers and also saves water for optimal irrigation usage. The model results indicate that increasing water tariffs as an adaptation strategy to climate change is less effective in the agricultural sector and can even result in a negative impact since farmers grow deciduous fruit crops which often use even more water irrespective of the tariff regime. Again, the price elasticity of demand for agricultural water is very inelastic since they cannot simply stop irrigating or change to deficit irrigation.

Therefore, using water more efficiently will be the best adaptation option based on the analysis done in this thesis to help the Ceres farmers cope with the future projected impact of climate change. Overall, a change in the farm profile in Ceres can be expected as a result of climate change and adaptation thereto.

INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Amongst the environmental issues facing the world today, climate change is arguably the most serious because of the severity of harms that it might bring. Many aspects of human society and well-being in developing countries, i.e. where we live, how we build, how we move around, how we earn our living, and what we do for recreation, still depend on a relatively benevolent range of climate conditions (Dessler and Parson, 2006). Many countries are vulnerable to this global climate phenomenon because of the potential impact on marginal natural resources balance and agricultural productivity (IPCC, 2001).

According to Kaiser and Drennen (1993), the unprecedented levels of climate change predicted will have tremendous implications for climate sensitive systems, such as forestry, other natural resources, and agriculture. With respect to agriculture, changes in temperature, precipitation and solar radiation will have an effect on the productivity of crop and livestock agriculture. Climate change will also have economic effects on agriculture, such as changes in farm profitability, prices, supply, demand, trade, and regional comparative advantage. In addition to this, the competitiveness of agriculture may be at risk (Darwin *et al.*, 1995).

Agricultural production, including access to food, in many Africa countries and regions is projected to be severely affected by climate variability and change. The area suitable for agriculture, the length of growing seasons and yield potential, particularly along the margins of semi-arid and arid areas, are expected to decrease (IPCC, 2007). Agricultural impact studies have shown that climatic changes could potentially alter crop yields at different locations or lead to changes in agricultural practices and crop combinations. The impacts of predicted climate changes over the next century on Southern Africa are likely to be very marked indeed (Meadows, 2006).

The Western Cape (WC) region of South Africa, with its Mediterranean-type climate and predominantly winter rainfall, has been identified as being highly vulnerable to projected climate change within both global and national contexts. Rising temperatures are already detectable and are predicted to increase by a further 1–2°C within the next 30 years, together with decreasing rainfall, especially in winter. Increases in temperature in the province may lead to an

increase in energy demand and water use, thereby competing with available irrigation water. In recent years, the economy of the region has received an added stimulus from tourism, with visits to Cape Town from Europe, Asia, and North America. Tourism also places stress on scarce resources, such as water. Increasing competition for water has resulted in the construction of a number of smaller water storage reservoirs in the last twenty years with limited number of sites left for further development. Thus, the WC will experience increasing temperatures and reductions in water supply in the future and these have to be adequately prepared for in order to mitigate these impacts.

1.2 PROBLEM STATEMENT

The projected increase in temperature will have an impact on water availability (Mimi and Jamous, 2010). Water resources are of more concern because changes in the water supply will affect the water availability for household use, water use in agricultural practices, and the vast industrial water demand. The water demand pressure, driven by population growth, degradation of water quality, lack of efficient water management and global temperature surges, accentuate water scarcity. According to an IPCC report (2007), by 2020 between 75 million and 250 million people are projected to be exposed to increased water stress owing to climate change. If coupled with increased demand, this will adversely affect livelihoods and aggravate related problems. In addition to the impact on water supply, climate change is also expected to affect future winter chill and thus could have a major impact on the fruit species with chilling requirements (FAOSTAT, 2009). All deciduous fruit trees require a certain amount of coldness to enter into dormancy (Sheard, 2001). Various fruit trees must fulfil a chilling requirement to break their winter dormancy and resume growth in spring (Luedeling and Brown, 2010). Insufficient winter chill can severely affect fruit yields and fruit quality when chilling requirements are not fulfilled (Dennis, 2003).

If winter chill decline occurs owing to climate change, production constraints are likely to occur, because many trees might not even fulfil their minimum chilling requirement (Luedeling *et al.*, 2009). It is therefore important to estimate, using different chilling models, the amount of chill units that will be accumulated in the future, based on the future climate projections. Such information can help farmers in the selection of appropriate cultivars of deciduous fruits to be planted in the future. The predicted change in climate is expected to have an impact on the viability of deciduous fruit production and hence on the livelihoods of the farmers in the Western Cape. Owing to the importance of agriculture in the Western Cape, the impacts of climate change could have large impacts on regional income, consumption and investment, employment and net exports. The reduction of these impacts by adaptation could be large or small, depending on the adaptation options available to the farmers. Both the impacts of climate change and the adjustments that farmers make to it to avoid climate change damages might

influence the flow of inputs, outputs and cash through the inter-industry structure of the Western Cape economy.

There have been a number of studies in South Africa focusing on the impacts of climate change at national level (Turpie, Winkler, Spalding-Fecher & Midgley, 2002; Gbetibouo & Hassan, 2004). Most studies on climate change adaptation have been conducted within the National Department of Environmental Affairs and Tourism (DEAT), through the National Response Strategy and the National Communication. The main focus of most studies was on the national impacts of climate change and the adaptation measures. The shortfall in the research addressed by past studies on the impacts of climate change is the lack of studies examining impacts at farm level. This needs to be addressed urgently as it is at this level that many people are directly affected by climate-induced impacts and it is at this level that institutional solutions can be introduced to target wide numbers of people.

Generally, the important part of the “solution” in the above research is to determine the extent to which adapting/adjusting to the predictable climate variability also reduces the adverse impacts of climate change and the economic value of these climate change damages. The aim is to translate the importance of these adaptation/adjustment options to resource-poor/emerging and commercial farmers to mitigate impacts on employment, the economy and their livelihood. This is because the large majority of the resource poor depend on agriculture for livelihood. Integrated models can be used to examine impacts either at the farm/activity level and this involves combining GCM (Global Circulation Models), RCM (Regional Climate Models)/downscaling to relevant spatial (and temporal) scales, Hydrology Models (Rainfall-runoff Models) to relate changes in climate to changes in (impacts on) runoff, surface water evaporation, plant evapotranspiration (water use) and return flows and economic models in order to translate the impacts of climate change on plants and humans directly into climate change damages and adaptation thereto.

Few studies in South Africa have estimated the benefits and costs of avoiding climate change damages. Notable among such studies is that of Callaway *et al.* (2008 and 2009). These studies were done at aggregate level and it was difficult to adequately model climate variable sensitivity at this level. Louw *et al.* (2012) have pointed out that there is a need for more research to increase the sensitivity of the farm models to climate change variables (temperature and water availability). This is of paramount importance since both temperature and water availability will have an impact on future farm structure in the Ceres region of Western Cape. Although researchers have been able to model, to a certain extent, the impact of climate change on the farm sector using integrated methodology, they have not yet included the impact of future change in crop water requirements, as well as the impact of reduction in accumulated chill units. So currently, we do not have empirical knowledge of how the current and future change in crop water requirements and accumulated chill units will affect the farm structure.

1.3 OBJECTIVES

The aim of this study is to develop and apply an integrated approach to quantify the economic impact of climate change on the agriculture and water resource sectors of Ceres, in Western Cape South Africa. Specific reference is made to the small scale/resource poor farmers and the commercial farmers because both groups of farmers will be affected by climate change. Such information will be useful for decision making in the planning and management of climate risk for agriculture and water resource development in Ceres, Western Cape, South Africa, and also for a wider application in Africa as a whole.

The main study aim will be achieved through pursuing the following objectives:

Objective 1: To estimate and compare the crop water requirement for the base climate (1971-1990) and future climate (2046-2065) in order to see how the projected change in climate will affect irrigation crop water requirements.

With climate change, it is hypothesised that the future crop water requirement is going to change for different irrigation technologies. SAPWAT (Van Heerden *et al.*, 2008) was used to estimate and compare the difference between the present and future crop water requirements. SAPWAT is a planning and management tool for the estimation of crop water irrigation requirements. The present irrigation crop water requirement was calculated using the already built-in weather data in SAPWAT. Since SAPWAT does not have future climate weather information, an artificial weather station was built into SAPWAT, based on the future climate projection. This enables one to estimate the future crop water requirement. The estimated irrigation crop water requirements for the base and future climate are used as an input in the whole farm-planning model of the Ceres region in a subsequent sub-objective to improve the sensitivity of the farm model.

Objective 2: To estimate and compare the accumulated chill units for the base climate and future climate in order to ascertain the impact of the projected change in climate on chill units accumulation.

Using daily minimum and maximum temperatures for the present climate, the Utah model of Richardson *et al.* (1974) and the Daily positive Utah (Infruitec) chill unit accumulation model of Linsley-Noakes *et al.* (1995) are used to calculate the accumulated chill for the present climate. In order to calculate the accumulated chill for the future climate, the present climate minimum and maximum temperatures were adjusted based on the future temperature climate change projection. The estimated chill unit for the base and future climate is also used as an input in the whole-farm planning model of the Ceres region in a subsequent sub-objective to improve the sensitivity of the farm model.

Objective 3: To develop an integrated methodology and apply the model to simulate physical impacts of climate change, and estimate the economic value of climate change damages.

In order to achieve objective 3, an integrated model encompassing climate, hydrology and farm module is developed. As part of the Climate Change Adaptation in Africa (CCAA) project, climate change scenarios of the University of Cape town are linked to the hydrological models (ACRU) of the University of KwaZulu-Natal and finally to the farm model of the Ceres region. Farm-level data and the typical farm constructed by Louw (2007) were updated and used in this study. The farm model was improved to adequately model the crop water and temperature relationship by incorporating into the farm model the irrigation crop water requirement estimated in objective 1 and the accumulated chill unit estimated in objective 2. The chill unit requirement and crop water requirement are sensitive to temperature; hence this overcomes the problems documented by Louw *et al.* (2011). Two different models, one representing the base and the other representing the future differentiated by time, are used. The comparison of the difference between the base and future models represents the impact of climate change in the future.

Objective 4: To quantify the potential impact of different adaptation strategies in order to design a farm structure that is more adaptable to mitigate the impact of climate change.

The integrated model developed in Objective 3 of this study is used to simulate the impact of different adaptation strategies in order to see how the farm structures will adjust with adaptation. The outcome from the simulations will give an indication of what the farm structure will look like in terms of water use, crop combination and welfare of the farmers in the future. Comparison between the future base model and the future model with different adaptation strategies represents what the farm structure will look like in the future.

1.4 ORGANISATION OF THE THESIS

This study is primarily concerned with the development of climate change adaptation strategies for farmers in Ceres. In order to sufficiently address this, a literature review of climate change impacts on agriculture and the water resource sector is provided in the next chapter. Specific reference is made to the impact of projected climate change on deciduous fruits, and in addition to this, issues related to the modelling approach of chill unit and crop water usage are also discussed.

In Chapter 3, an overview of the economy of Ceres and the Koekedouw irrigation scheme, which is the major source of water in the area, is presented. It includes the description of the topography, climate and general land use of the area. The data and methodology used to study the impact of climate change in the Ceres region is discussed in Chapter 4. The results of the base and future climate scenarios and the adaptation options are reported in Chapter 5. Chapter 6 firstly provides a summary of findings and secondly draws some conclusions and recommendations based on the results.

LITERATURE REVIEW

2.1 INTRODUCTION

Climate change and the impact upon already scarce water resources are important issues in the public debate of the world today (UNESCO-WWAP, 2009). Other issues, particularly the economic crisis gripping the world, are also receiving global attention, but the most important issue so far is climate change. Climate change has implications for peace and security, as well as serious implications for the environment, societies and economies. The fourth assessment report of the International Panel on Climate Change made the case fairly emphatically. Water managers all over the world are faced with the challenge of managing the year-to-year, month-to-month and even daily changes in the availability of water. This has significant effects on agriculture and other sectors of the economy where water availability is especially important. Scientists and economists from diverse disciplines have been working together to assess the potential impacts of climate change. Scientific evidence has now become overwhelming that human activities, especially the combustion of fossil fuels, are influencing the climate in ways that threaten the well-being and continued development of human society. The main objective of this chapter is to discuss the relevant literature that contributes to meeting the objectives of this study. Literature on the impact of climate change as it affects the water and agricultural sectors are reviewed. The concepts of adaptation and mitigation and its applicability to the water and agriculture sector are also examined. Various models that can be used to estimate irrigation crop water requirements, as well as models to calculate accumulated chill units, are reviewed. Lastly, a review of literature on mathematical programming and its application to climate change and adaptation is presented.

2.2 CLIMATE CHANGE AND EXTREME EVENTS

According to the IPCC, climate change refers to “a change in the state of the climate that can be identified by changes in the mean climatic variability of its properties and that persists for an extended period, typically decades or longer” (IPCC, 2007). Climate change may be due to natural internal processes or external forcing, or to persistent anthropogenic changes in the composition of the atmosphere or changes in land use (IPCC, 2007).

Climate change is no longer a likely future threat, rather the world is already experiencing the impacts of a changing climate and an increased incidence and changed prototype of extreme

weather events (Carraro and Sgobbi, 2008). Climate change is expected to increase the frequency and magnitude of many types of extreme events, including floods, droughts, tropical cyclones and wildfires (IPCC, 2007). New evidence also suggests that climate change is likely to change the nature of many types of hazards experienced in various places, such as landslides, heat waves and disease outbreaks, influencing not only the intensity but also the duration and magnitude of these events (O'Brien *et al.*, 2008).

The summary report of the 2009 Conference on Global Risks, Challenges and Decision pointed out that changes in climate are taking place at a more rapid rate than previously estimated. Many key climate indicators are already moving beyond the patterns of natural variability within which contemporary society and its economy have developed and thrived (Copenhagen synthesis report, 2009). These indicators include global mean surface temperature, sea-level rise, global ocean temperature, Arctic sea – ice extent, ocean acidification, and extreme climatic events. With unabated emissions, many trends in climate change will likely accelerate, leading to an increasing risk of abrupt or irreversible climatic shifts (Copenhagen synthesis report, 2009).

The Fourth IPCC report (IPCC, 2007 a, b, c) concludes that there is high evidence that the observed changes in the global climate systems are influenced by human activities. Despite efforts to abate the human causes, human-driven climate change will continue for decades and longer. In support of the conclusions of the IPCC Third assessment report (IPCC, 2001), the fourth assessment stresses how human-induced climate change will not only affect global temperature, but will lead to changes in the entire climate system, including precipitation patterns and intensity, wind patterns, sea level rise, frequency and intensity of extreme weather events. It also points out that the impacts of these changes will be felt differently in different regions of the world.

Globally averaged surface temperatures are estimated to rise by at least 1.8°C to 4.0°C by the end of the 21st century (IPCC, 2007b). If the increase in temperature occurs as projected, it most probably will have an important impact on water resources and agriculture. It is expected to alter precipitation and evapotranspiration, the prime drivers of water availability and agricultural production (Elgaali, 2005). Water supply and use in semi-arid lands are very sensitive to changes in precipitation and evapotranspiration, because the fraction of precipitation that runs off or percolates is small. Previous studies have also indicated that climate variability and extreme weather events are expected to be especially challenging for farming operations (Smit *et al.*, 2000; Bryant *et al.*, 2000; Schneider *et al.*, 2000 and Smit *et al.*, 1996).

For Southern Africa, sub-continental warming is predicted to be greatest in the northern regions (DEAT, 2004). Temperature increases in the range of between 1°C and 3°C can be expected by the mid-21st century, with the highest rises in the most arid parts of the region. Of greater

consequence for South Africa, as a semi-arid country, is the prediction that a broad reduction of rainfall in the range 5% to 10% can be expected in the summer rainfall region. This will be accompanied by an increasing incidence of both droughts and floods, with prolonged dry spells being followed by intense storms. A marginal increase in early winter rainfall is predicted for the winter rainfall region of the country (DEAT, 2004).

In the Western Cape region, there is little doubt that the region will face some degree of climate change in the 2030-2050 period. According to DEA&DP (2007), the application of a range of climate models to the Western Cape Province makes it possible to identify a number of stress factors, irrespective of local or global efforts to reduce greenhouse gas. Climate change is projected to cause an increase in the annual average temperature of at least 1°C by 2050. In addition to this, the IPCC Fourth Assessment Report shows an expected increase of between 3°C and 5°C by 2100.

Other effects are a possible increase in the frequency and intensity of extreme events, an increase in conditions conducive to wildfires (higher temperatures and increased wind velocity), and reduced rainfall in the western parts of the Western Cape, decreased water resources and reduced soil moisture due to an increase in temperature, coupled with a decrease in average precipitation. Temperature increases will also have impacts on crop activities – crop burn, drought, pests and microbes, resulting in yield reductions, and loss of rural livelihoods. Table 2.1 presents a summary of observed and predicted climate changes in the Western Cape. Of importance, according to the Table 2.1, is the projected increase in temperature and the resultant impact on crops and rural livelihood. According to Table 2.1, projected climate change will result in the reduction in soil moisture because of increases in temperature, coupled with a decrease in average precipitation. It will also give way to more summer rainfall from January onwards, especially inland and towards the eastern part of the Western Cape.

Table 2.1 Summary of observed and predicted climatic changes in the Western Cape

Observed trends
<ul style="list-style-type: none">❖ June – August (JJA) tendency for weaker pressure gradients - > More days with inversions (pollution/brown haze risks);❖ Increase in days with the berg wind during December, January and February (fire risk);❖ Rainfall in the mountain regions appears reasonably stable, possibly a slight increase. Rainfall on the coastal plain shows a slight negative drying trend.
Projected changes
<ul style="list-style-type: none">❖ More summer rainfall from January onwards, especially inland and towards the east ;❖ Reduction in early winter rainfall, especially towards the Southwest;❖ Temperature can be expected to rise everywhere, least on the coast and more as one move inland. Typical ranges to expect by 2050 are ~1.5° on the coast, and 2-3° inland of the coastal mountains. The absolute magnitude will depend on a number of factors and these values should be treated as median value within a range;❖ An increase in conditions conducive to wildfires (higher temperatures and increase wind velocity);❖ Reduced soil moisture from increase in temperature (evaporation) coupled with a decrease in average precipitation;❖ Temperature impacts on crop activities- crop burn, drought, pest and microbes resulting in yield reductions, and loss of rural livelihoods.

Source: Department of Environmental Affairs and Development Planning, Western Cape (2008) and CSIR (2005)

2.3 CLIMATE CHANGE IMPACTS

Extreme temperature events will have real impacts on the natural environment, as well as on human-made infrastructure and its ability to contribute to economic activity and quality of life. The anticipated impacts of climate change include rising sea levels, with stronger and more frequent storms. These impacts will vary across regions and sectors of the economy, leaving future governments, the private sector and citizens to face the full spectrum of direct and indirect costs accrued from increasing environmental damage and disruption (CIER, 2007).

Many sectors in the global economy will be affected by climate change and climate variability. Of importance in this study is the impact that climate change will have on water and temperature distribution, which has implication for the agriculture and water resource sectors of the Western Cape, South Africa. Some of the impacts of climate change on the water resource sector are discussed in the next session.

2.3.1 IMPACT OF CLIMATE CHANGE ON WATER SECTOR

Nicol and Kaur (2009) have divided the impacts of climate change on the water sector into knowns and unknowns. The knowns were further classified into supply and demand sides. Some of the supply-side impacts are changes in precipitation, changes in snow and ice melt, changes in evapotranspiration and soil moisture and changes in flooding and drought patterns. In addition to the supply side of the knowns, Nicol and Kaur (2009) also highlight the drivers changing the demand side as population growth, land use change, economic growth and technological change.

Water demand is also likely to increase as a result of changes in human settlements, caused either by the primary or secondary effects of natural change, or because of government-driven policy that shapes the pattern and density of future settlements (Nicol and Kaur, 2009). It is projected that the sea level rise and resource scarcity linked to climate change will drive increased rural-urban migration patterns, and will increase the cost of water supply and sanitation infrastructure as a result of more frequent flooding, salinisation of groundwater, and the increased need to re-use available water.

Apart from the knowns, there are also unknowns. Many aspects of the impact of climate change on water resource availability remain uncertain. This includes; system complexity (climate, hydrological and socio-economic); the coarsely-grained nature of many models and impact assessment methods; and the difficulty in weighing up relative cause and effect (Nicol and Kaur, 2009).

There are two broad trends in relation to climate change induced water stress which do not take into account adaptation (Nicol and Kaur 2009). Firstly, there will be an increase or decrease in water stress. This includes an increase or decrease in physical scarcity and/or the replacement of current areas of economic and social scarcity by physical scarcity. These changes will be driven directly by climate-induced impacts on the hydrological system. Secondly, there will be an increase in economic and social scarcity. These changes will be driven by the impact of climate change on demand for water.

Menzel *et al.* (2007) projected that the number of people living in regions with severe water stress will increase from 2.3 billion in 1995, to 3.8 – 4.1 billion in the 2020s, and to 5.2 – 6.8 billion in the 2050s. The main cause of increasing water stress will be growing water withdrawals as a consequence of growing population and improving economic conditions, rather than decreasing water availability. Without sufficient adaptation mechanisms in place to regulate supplies, increased runoff in the wet season may exacerbate flooding, whereas decreased runoff in dry seasons may precipitate a future increase in drought frequency and intensity (Arnell, 2004).

Climate change is expected to increase glacial melting, which will cause inland water levels to rise in the short term, followed by a downturn later, but the overall projected impact of climate change is that water scarcity will increase with time (Smith and Vivekananda, 2007). Surface and subsurface water flow and storage are already stressed by natural and anthropogenic causes. As a result, availability for human consumption, irrigation, energy production and industry may be reduced (Groisman *et al.*, 2004). Climate change will exacerbate existing and future stresses placed on supplies by continued economic and population growth (CIER, 2007).

2.3.2 IMPACT OF CLIMATE CHANGE ON TEMPERATURE

According to UNESCO-IHP (2011), higher temperatures and decreased precipitation would lead to decreased water supplies and increased water demands, and they might cause deterioration in the quality of freshwater bodies, putting strains on the already fragile balance between supply and demand in many countries. Even where precipitation might increase, there is no guarantee that it would occur at the time of year when it could be used; in addition, there might be a likelihood of increased flooding (UNESCO-IHP, 2011).

Changes in temperatures have also reduced snow cover, and glacier shrinkages have been observed around the globe (Oerlemans, 2005). Changes in the amount, timing, and distribution of rain, snowfall, and runoff are very probable, leading to changes in water availability, as well as in competition for water resources. Changes are also likely in the timing, intensity, and duration of both floods and droughts, with related changes in water quality. The most general impact on water quality will be through higher temperatures of surface water. Higher temperatures will increase microbial activities and bacterial and fungal population (Van Vliet and Zwolsman, 2008). This will be more severe in developing countries where there is lack of proper sanitation, and higher temperatures will increase the risk of water borne diseases.

The decrease in rainfall and the higher temperatures have caused an increase in drought frequency, particularly in the tropic and subtropics. Globally, the intensity and duration of droughts have increased since the 1970s (IPCC, 2007). This can lead to a significant drop in water availability for agriculture and can have severe negative financial consequences. It can also affect industrial and domestic water supply. However, an increase in temperature, coupled with raised CO₂ levels, may cause an increase in the rate of soil organic matter depletion from agro-ecosystems (Walker and Schulze, 2008). This means that larger quantities of artificial nutrient compounds will need to be used, or a shift be made in cultivars, to maintain productivity.

An increase in temperature to the predicted temperature range (between 0.2 – 6°C) will result in increased evapotranspiration which, together with the expected drying of ground water supplies, will require an increase in irrigation quantities, or a change in crop choice, both of which will

again have cost implications. In addition, climate change is expected to increase the quantity, variety and strength of pests, diseases and weeds species, and producers can therefore expect to alter farming practices to avoid major crop damage and losses (IPCC, 2001). The genetic variety of crops can assist in pest and disease resistance. Research has shown that certain varieties are less susceptible to drought, heat stress, pest infestations and diseases and are therefore more suitable for the predicted climate (IPCC, 2007).

2.3.3 IMPLICATIONS FOR AGRICULTURAL SECTOR

As identified in the literature, climate change will impact upon the availability of water resources for agriculture in the future through changes in precipitation, potential and actual evaporation, and runoff at the watershed and river basin scales. Both the demand for and supply of water for irrigation will be affected by changes in the hydrological regimes. There will be concomitant increases in future competition for water with non-agricultural users owing to population and economic growth (Strzepek *et al.*, 1999).

Agriculture is dependent upon the climate resources of temperature, sunlight, precipitation, and carbon dioxide. Efficient production depends upon optimum conditions of temperature and water supply. Changes in these projected climatic variables will adversely affect plant and animal systems over the next 10 – 30 years (Hatfield, 2008). The direct and indirect impacts of climate change on agriculture could have large impacts on agricultural production. Increasing variability in precipitation will cause uncertainty in the amount of water available during the year, which could negatively impact upon plant production and have a profound effect on pasture and hay supplies for cattle or grain supplies for all livestock (Hatfield, 2008).

Rising temperatures over the next 30 years will have an impact on crop yield because of the impacts of temperatures that are above optimal during the pollination stage in all crops (FAO, 2011). Occurrences of these temperatures will cause yield reductions which could be further decreased by shortages of water required for optimal plant growth. These effects will be noticeable in grain, forage, fibre, and fruit crops. In regard to fruit crops, climate change is likely to affect future winter chill and could have a major impact on the fruit species with chilling requirements (FAOSTAT, 2009). Insufficient winter chill can severely reduce fruit yields and fruit quality. When chilling requirements are not completely fulfilled, trees display irregular and temporally spread out flowering, leading to inhomogeneous crop development (Luedeling *et al.*, 2009). This process eventually results in altering fruit sizes and maturity stages at the time of harvest, which can substantially reduce yield amount and value (Saure, 1985).

In Southern Africa, more frequent and longer dry periods are expected in the future, again threatening crop failures. Climate change, therefore, is expected to worsen the food supply and hence exacerbate the widespread poverty in the region (CEEPA, 2002). According to CEEPA

(2002), the impact of these adverse climate changes on agriculture is exacerbated in Africa by the lack of adaptation strategies, which are increasing owing to the lack of institutional, economic and financial capacity to support such actions. Africa's vulnerability to climate change and its inability to adapt to these changes may be devastating to the agriculture sector, the main source of livelihood for the majority of the population. The utmost concern should accordingly be for a better understanding of the potential impact of the current and projected climate changes on African agriculture and to identify ways and means to adapt and mitigate the detrimental impact of climate change. Impacts on, and the adaptive capacity of, systems may vary substantially over the next decades and within countries because vulnerabilities can be highly dynamic in space and time. Consequently, there is a need to build resilient agricultural systems that have a high capacity to adapt to stress and changes and can absorb disturbances.

Fruit production in the Western Cape is under threat from the impact of climate change. Production of the Forelle pear (high chilling requirement), in particular, could be adversely affected by warming of the winter season owing to rising average temperatures and the consequent loss in chilling hours. Deciduous fruit need cold weather in which to rest and if it is not cold enough, this could lead to a decrease in production. According to Carbone and Schwartz (1993), insufficient chilling occurs when temperatures during the dormant season are anomalously high, thus inhibiting endodormancy. Lack of winter chilling gives rise to delayed foliation and the problem of production of small fruit of poor quality. Increased average maximum temperatures in January and February may result in poor colour development in "bicolour" fruits. The risk of sunburn is also increased (NAMC, 2007). An increase in temperature has already had an effect on certain crops. Early bud breaking has been seen on orange trees because of warmer weather. Early bud break can be devastating to farmers if the vulnerable buds are exposed to disease or if cold or frosty weather subsequently hits and destroys the crops (<http://ipsnews.net/africa/nota.asp?idnews=43255>).

Lack of effective chilling has an influence not only on tree development, but also on fruit quality as well (Luedeling and Brown, 2010). The buds remain dormant until they have accumulated sufficient chilling units of cold weather (Saure, 1985). When enough chilling units have accumulated, the buds are ready to grow in response to warm temperatures (Saure, 1985).

Apple and stone fruit trees develop their vegetative and fruiting buds in the summer and as winter approaches; the already developed buds go dormant in response to both shorter day lengths and cooler temperatures. These buds remain dormant until they have accumulated sufficient chilling units (CU) of cold weather. When enough chilling units have accumulated, the buds are ready to grow in response to warm temperatures. As long as there have been enough CUs, the flower and leaf buds will develop normally. According to Rana *et al.* (2009), if the buds do not receive sufficient chilling temperatures during winter to completely release dormancy, trees will develop one or more of the physiological symptoms associated with insufficient

chilling: 1) delayed foliation, 2) reduced fruit set and increased buttoning, and 3) reduced fruit quality. It also disrupts spring growth, causing inconsistent bud break and leaf development, and non-consistent fruit growth (Linville *et al.*, 1990). These physiological symptoms consequently affect the yield and quality of the fruit.

It can be concluded from the literature that increases in temperature will increase the vulnerability of the agricultural sector. It will lead to increases in the rate of evapotranspiration and can increase the demand for irrigation water. This will be in addition to competition for available water required for household water demand and industrial water demand. For instance, irrigation demand is projected to increase by 0.4% – 0.6% per year up to between 2030 and 2080, according to projections from the Food and Agriculture Organization (FAO). However, if the anticipated impacts of climate change are added, the projected demand will lead to an increase of between 5 – 20% by 2080. Adaptation is required in order to be able to contain the future impact of the projected climate changes. Given the expected impact of climate change on the agricultural sector, it is important to measure the sensitivity of the agricultural sector. Accordingly a discussion follows next on the measurement of the sensitivity of the agricultural sector.

2.4 MEASURING CLIMATE SENSITIVITY OF AGRICULTURE

Two main approaches have been identified in the literature to assess the sensitivity of the agricultural sector, i.e. to measure how agriculture will be affected if the particular components that make up the general climate of a region change by a certain amount (FAO, 2000). The approaches are namely; the structural modelling of agronomic responses, based on theoretical specifications and controlled experimental evidence; and the reliance on the observation of responses of crops and farmers perception of climate variations.

2.4.1 STRUCTURAL MODELLING APPROACH

The main objective of this approach is to improve the understanding of how crop management can be undertaken under different climatic conditions. It allows representative farms or crops to be modelled in a very basic way. There are two main types of structural modelling of agronomic response namely, integrated assessment models and crop growth simulation models. In this study more emphasis will be placed on the former.

2.4.1.1 Integrated assessment of climate change impacts

Assessment consists of social processes that bridge the domains of knowledge and decision – making, assembling and synthesising expert scientific or technical knowledge to advise policy or

decision-making (Parson and Fisher-Vanden, 1997; Parson, 1995; & Wayant *et al.*, 1996). An assessment process might seek to mine current knowledge to answer specific policy relevant questions, to identify policy relevant implications, or to help policy makers understand what questions they should be asking. Assessment is integrated according to the breadth of the expert knowledge it synthesises in advising on the issue at hand (Parson 1995; Wayant *et al.*, 1996; Rotmans and Dowlatabadi, 1998).

In the IPCC Third Assessment Report (IPCC, 2001c), integrated assessment was defined as an interdisciplinary process that combines, interprets, and communicates knowledge from diverse scientific disciplines from the natural and social sciences to investigate and understand causal relationships within and between complicated systems. Harremoes and Turner (2001) have stated that there are two main principles to integrated assessment, i.e. integration over a range of relevant disciplines; and the provision of information suitable for decision making. Integrated assessment can employ a range of methods, including scenario analysis, qualitative assessment and computer modelling. It is generally agreed that there are two main principles of integrated assessment, namely:

- (i) Integration of information obtained through a range of relevant disciplines, and,
- (ii) The provision of information suitable for decision making.

The integrated approach examines the societal impacts, and responses to climate change. The interactions within each sector and the interactions and feedback between sectors in the society are considered (Adams *et al.*, 1990; Rosenberg, 1993). It allows the identification of potentially important indirect interactions or mechanisms, the identification of important research gaps, and provides a means of integrating targeted research from a variety of disciplines into an enhanced understanding of the whole system (Chan *et al.*, 1999).

According to Morgan and Dowlatabadi (1996), the objective of the integrated assessment of climate change is to put available knowledge together in order to evaluate what has been learned, what the policy implications are and what the research needs are. It also serves as a tool for promoting a better understanding of, and more informed decisions on, how locales and regions contribute to, and are affected by, climate change (Yarnal, 1998). The main research activity in integrated assessment involves the development of methods for linking knowledge across domains or disciplines, particularly emphasising the role of important feedback mechanisms, nonlinearities and uncertainties (Easterlin, 1997).

Apart from the integrated assessment of climate change impacts, the impact and interaction approach can also be used (Elgaali, 2005). The impact approach is a straightforward linear analysis of cause and effect. Data from projected climate scenarios is used to determine the

responses of different biophysical systems to changes in climate. The interaction approach links climate change with other changes and with the feedback of a system affected by climate change. Integrated Assessment Models (IAM) are considered to be the main research tool for conducting an integrated assessment of climate change.

2.4.1.2 Integrated Assessment Models (IAM)

Integrated Assessment Models seek to combine knowledge from multiple disciplines in a formal integrated representation in order to inform policymaking, structure knowledge, and prioritise key uncertainties; and to advance knowledge of broad system linkages and feedbacks, particularly between socioeconomic and biophysical processes (Parson and Fisher-Vanden, 1997). They can combine simplified representations of the socioeconomic determinants of greenhouse gas emission, the responses of atmosphere and oceans, impacts on human activities and ecosystems, and potential policies and responses (Parson and Fisher-Vanden, 1997). A typical IAM model is presented in Figure 2.1. Figure 2.1 shows how the emission of greenhouse gases and their concentration in the atmosphere can lead to climate change, resulting in temperature rise, sea level rise, precipitation change and droughts and floods. According to indications in Figure 2.1, climate change will have an impact on human and natural systems and that adaptation can serve the purpose of reducing the impact on socio-economic development paths.

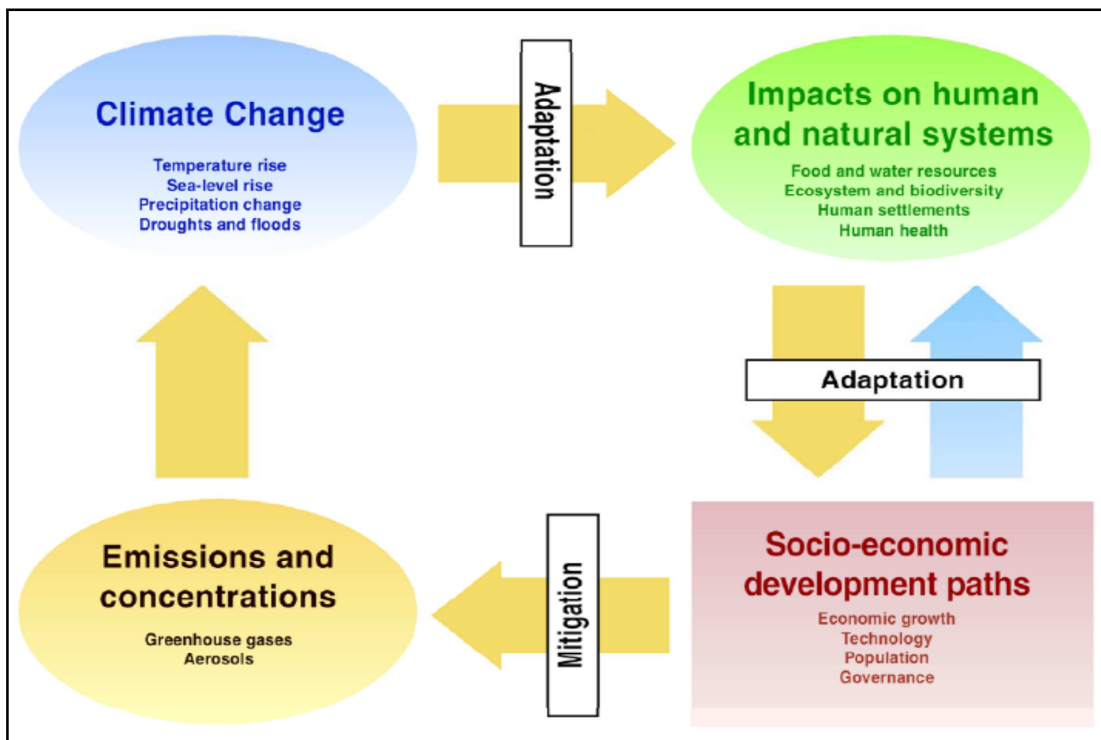


Figure 2.1: Integrated Framework for climate change

Source: Shukla (2002)

Many integrated assessment models of global climate change have been developed over the past decade and most of them have a focus on mitigation responses and costs (AGO, 2004). Many of these models have taken a 'top-down' approach, assessing damages at a regional or global level based on a global mean temperature change associated with a doubling of atmospheric CO₂ concentrations. Given this level of aggregation and the widely differing assumptions used in terms of the nature of associated impacts, it is not surprising to find that these studies have produced a very wide range of results (Cline 1992; Manne and Richels, 1992; Nordhaus, 1994 and Roughgarden and Schneider, 1999).

More recent 'bottom-up' IA models have sought to capture the individual direct effects of climate change at the local or regional level. Although these models have done a good job of capturing spatial and sectoral detail, they often contain so much detail that they are difficult to interpret. Further, they often lack sound damage estimates because they do not seek to estimate welfare effects and because they fail to account for adaptation, thus they are far from providing clear and careful damage estimates (Mendelsohn *et al.*, 2000).

The challenge, therefore, is to make use of the spatial and sectoral detail of 'bottom-up' models, while ensuring that:

- ❖ inter-regional and economy-wide effects and feedbacks are addressed;
- ❖ feedbacks arising from policy responses and adaptation measures are fully captured; and
- ❖ impacts are assessed on the basis of realistic scenarios of changes to future environmental, social-economic and land use conditions that are unrelated to climate change.

According to Parson and Fisher-Vanden (1997), four broad contributions have been claimed for integrated assessment (IA) modelling: evaluating potential responses to climate change; structuring knowledge and characterising uncertainty; contributing to broad comparative risk assessment; and contributing to scientific research. In principle, IA models can make any of these contributions; in practice, the work to date has served these purposes to different degrees, and the basic elements of structure and design of any particular IA model strongly influence which of these purposes it can serve and how well.

The use of integrated assessment models has not been widespread in the African context, although it is becoming an item on the agenda of several modelling groups and organisations (IPCC, 2007). More widespread use of integrated assessment models is a priority for the IPCC according to the Third Assessment Report, although it will require fundamental advances in the research literature. As a basis for integration, primary research on impacts on the potentially

most vulnerable sectors and regions must be conducted so that interactions among the many potential costs and benefits can be assessed and, where possible, quantified.

It has been identified in the literature that integrated assessment to climate change adaptation has the potential for incorporating different modules in one framework. The bottom-up approach is more relevant when adaptation at farm or regional level might have potential impact on provincial or national economy. An integrated assessment model, which combines scientific and economic aspects of climate change primarily for the purpose of assessing policy options for climate change adaptation, is required to properly understand the appropriate adaptation option to cope with the projected impact of climate change.

2.5 COPING WITH CLIMATE CHANGE

Mitigation and adaptation are two strategies that feature in the debate on coping with climate change and its impact. The IPCC has defined adaptation as adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderate harm or exploits beneficial opportunities. Similarly, Mitchell and Tanner (2006) have defined adaptation as an understanding of how individuals, groups and natural systems can prepare for and respond to changes in climate or their environment. According to them, it is crucial to reducing vulnerability to the impact of climate change.

Mitigation, on the other hand, is any action taken to permanently eliminate or reduce the long-term risk and hazards of climate change to human life and property. The IPCC defines mitigation as an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases. While mitigation tackles the causes of climate change, adaptation tackles the effects of the phenomenon.

Callaway (2004) has referred to adaptation as any adjustments that individuals, singly and collectively (in whatever organisational framework), make autonomously or policy makers undertake strategically to avoid (or benefit from) the direct and indirect effects of climate change. Individuals and organisations can do this autonomously in the sense that economic, social and political institutions with which they interact provide incentives for them to adjust “automatically” to climate change, without political intervention. Alternatively, they can adapt strategically through decisions made by governments. It is important to note that while adaptation can reduce impacts; it does not reduce them entirely (or rarely).

Adaptation and mitigation can be complementary, substitutable or independent of each other (IPCC, 2007b). Mitigation is defined as measures – policies, programmes, investments – to abate greenhouse gas emissions and thereby limit the level and rate of global warming. If complementary, adaptation reduces the costs of climate change impacts and thus reduces the

benefits of mitigation. Although adaptation and mitigation may be substitutable up to a certain point, they are never perfect substitutes for each other since mitigation will always be required to avoid 'dangerous' and irreversible changes to the climate system.

Callaway (2004) differentiates between mitigation and adaptation based on their qualitative differences: reducing emissions through mitigation changes climate and has the potential to reverse the impacts of climate change, while adaptation actions are simply adjustments to climate change and its associated impacts. Irrespective of the scale of the mitigation measures that are implemented in the next 10–20 years, adaptation measures will still be required owing to the inertia in the climate system. Both adaptation and mitigation depend on capital assets, including social capital, and both affect capital vulnerability and greenhouse gas (GHG) emissions (Rogner *et al.*, 2007).

Adaptation can involve both building adaptive capacity, thereby increasing the ability of individuals, groups, or organisations to adapt to changes, and implementing adaptation decisions, i.e. transforming that capacity into action. Both dimensions of adaptation can be implemented in preparation for or in response to impacts generated by a changing climate (Daw *et al.*, 2009). Therefore, adaptation is a continuous stream of activities, actions, decisions and attitudes that informs decisions about all aspects of life, and that reflects existing social norms and processes. It can be motivated by many factors, including the protection of economic well-being or improvement of safety (Adger *et al.*, 2005). It can be manifested in myriad ways: through market exchanges (Smit *et al.*, 2000), through extension of social networks (Adger, 2003), or through actions of individuals and organisations to meet their own individual or collective goals. It can be undertaken by individuals for their own benefit or it can be made up of actions by governments and public bodies to protect their citizens. These levels of actions take place within hierarchical structures such that the levels interact with each other.

Farmers need to be able to adjust to climate change and associated impacts singly or collectively. This will enable farmers to avoid the direct and indirect effects of climate change. Individual farmers can initiate adaptations at the farm level, which are referred to as autonomous, while other adaptations represent planning by larger public institutions or governments. In this thesis different adaptation options will be quantified at farm level with the aim of reducing the impact of the projected future climate change.

2.5.1 TYPES OF ADAPTATION

Adaptation has become of higher priority on the international climate change agenda. The increasing frequency of catastrophic weather events throughout the world makes it plain for all to see that adaptation must be addressed.

Delayed investment in adaptation will lead to large impacts, this is particularly critical for developing countries, where scientists predict the worst impacts will occur and where the greatest vulnerabilities lie (http://www.global-mechanism.org/dynamic/documents/document_file/ccesinfokit_web-1.pdf). Various types of adaptation can be distinguished, including anticipatory or proactive, autonomous or spontaneous and planned adaptation (IPCC, 2007).

- ❖ **Anticipatory adaptation:** Adaptation that takes place before impacts of climate change are observed. This is also referred to as proactive adaptation.
- ❖ **Autonomous adaptation:** Adaptation that does not constitute a conscious response to climatic stimuli but is triggered by ecological changes in natural systems and by market or welfare changes in human systems. Autonomous adaptation is the reaction of, for example, a farmer to changes in precipitation patterns, in that he or she changes crops or uses different harvest and planting/sowing dates. This is also referred to as spontaneous adaptation.
- ❖ **Planned adaptation:** Adaptation that is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state. For example, deliberate crop selection and distribution strategies across different agro climatic zones, substitution of new crops for old ones and resource substitution induced by scarcity (Easterling, 1996).

Depending on the type of adaptation considered or the combination of adaptations considered, adaptation should be able to completely offset most of the agricultural income loss, or if not, should leave an individual farmer with only a small loss. The farmer may be forced to lower profit expectations, but the farmer will remain solvent and flexible enough to be able to develop new production and marketing strategies for the future (Easterling *et al.*, 2004). At this level such an adaptation can be said to be successful. Thus, adaptation can be considered successful if it maintains services or welfare with a small or minimal loss.

2.6 THE ECONOMIC COST OF CLIMATE CHANGE IMPACTS AND ADAPTATION

Climate change impacts are defined as “the difference between conditions with and without climate change” (Ahmad and Warrick, 2001). They include all of the potential impacts of climate change from (direct) biophysical impacts through to (indirect) ecological and socio-economic impacts. Understanding past climate change patterns and monitoring climate change impacts is important for identifying vulnerable areas and designing appropriate adaptation measures. If no

action is taken, growing population in South Africa and economic growth in the coming years and decades will cause more greenhouse gas (GHG) emissions and hence causing global warming and other environmental damage. Projecting future climate change and its impact is therefore critical to the design of effective climate change policies and adaptation and mitigation actions. The need to develop appropriate adaptation strategies is an important consideration in the context of national, state and local government responses to the issue.

It is essential that economic assessments of climate change be framed in the context of a sound appreciation and understanding by decision-makers of all of the potential costs and benefits associated with climate change and climate change response. The assessment of costs of climate change impacts and net benefits of adaptation strategies is most appropriately undertaken as a two-staged process, with the focus in the first stage being on identifying the concepts, issues and methodologies appropriate for a robust analysis.

Once these concepts, issues and steps have been identified, decision-makers can then proceed with the more expansive and involved task of costing the impacts of climate change, under a range of scenarios, at the regional, sectorial and national levels. Once the costs of climate change impacts and net benefits of adaptation strategies are understood, decisions can be made about the most appropriate combination of adaptation measures.

2.6.1 DECISION MAKING IN AGRICULTURE: APPLICATION OF DYNAMIC LINEAR PROGRAMMING (DLP) AND DYNAMIC PROGRAMMING (DP)

The impact of linear programming models and methods on the practice of decision making is well known (Dantzig, 1963; Kantorovitch, 1965). Farming system analysis entails analysis on a whole-farm basis. One way that this can be done is through mathematical programming because the analysis is concerned with the performance and viability of alternative farming systems in the context of the farmer's constraints and objectives (Charry *et al.*, 1992). Linear programming has been a popular choice for modelling farmer decision making in response to technical and institutional innovations (Louhichia *et al.*, 2004; Elvio *et al.*, 2002; Thangata *et al.*, 2002; and Adeoti *et al.*, 2008). An extension of linear programming is the dynamic linear programming (DLP) method which is an optimisation approach that transforms a complex problem into a sequence of simpler problems.

Dynamic programming is an approach that takes a sequential or multistage decision process containing many interdependent variables and converts it into a series of single-stage problems, each containing only a few variables (Lohano and King, 2006). The technique is particularly suitable for obtaining numerical solutions to problems which involve functions which are non-linear and stochastic (Kennedy, 1986). According to McCarl and Spreen (2003) and Grove (2006), dynamic concerns arise when decisions makers face: (a) binding financial constraints

which change with time; (b) a production situation in which current actions impact the productivity of future actions; (c) a need to adjust over time to exogenous stimulus; (d) future uncertainty, and/or (e) an exhaustible base.

Dynamic programming and dynamic linear programming are not necessarily the same. According to Grove (2006), DLP is an alternative to capital budgeting in complex investment or development situations. It allows for simultaneous decisions to be taken, i.e. the choice of one or more items of irrigation systems and/or types of perennial cropping from a list of contenders; the timing of investments in relation to likely supplies of capital funds, either owned or borrowed; and/or the feasibility of any development or investment programmes in relation to existing supplies of fixed factors of production. Raes (1977) has stated that instead of preparing capital budgets to answer the above list of items of an investment programme, a dynamic linear programming model can be employed as a most efficient analytical procedure. Various authors (e.g. Backeberg, 1984; Minnaar, 1990; Nowers, 1991; Louw, 1996; Grove, 2006) have found that the DLP method is practical in simulating the farm system. It is a useful tool for analysing the interactions between management measures and production intensity on one hand, and farm income and environmental aspects on the other hand. Moreover, it is a useful tool for determining the implications of different policy options at farm level on economic and environmental aspects of farming (Acs *et al.*, 2007).

The time dependent processes of dynamic processes, such as a farming system, necessitate a dynamic approach to systems modelling (Louw, 1996). Farm investment decisions (e.g. as to perennial crops, livestock and/or irrigation investments) are more challenging to model than seasonal or annual (short term) cropping decisions (Grove, 2006). Biological processes change over time and this makes it impossible to accurately describe these systems without reference to the time dimension. Agricultural systems are dynamic, in the sense that they are in a constant state of change and evolution, whereby current events will affect their performance both financially and biologically in the future. The finances of the system are always dynamic, with future possibilities being affected by many different events, which influence the biological and economic efficiency of the farm. Therefore, DLP can be used to accurately model the complexity that can be encountered in the agricultural systems.

Whole-farm planning models are mostly developed with DLP; the reason for the development of whole-farm planning models with this technique was to enable agricultural economists to provide policy makers, as well as farmers, with a holistic (whole farm) answer on practical farm problems. It often happened in the past that the soil scientist, the animal scientist, the economist, etc. gave the farmer or policy maker their own isolated points of view on development or extension aspects without telling them the whole truth (Louw, 1996). Although whole-farm decision making is very complex, it is important for outsiders attempting to serve or influence farmers (e.g. through research or extension) to have some way of analysing and understanding whole-farm issues. Without this, any advice given may be incompatible with the

local farming practices, or may lead to lower, rather than higher, economic returns to farmer (Pannell, 1996).

2.6.2 APPLICATION OF DYNAMIC LINEAR PROGRAMMING IN CLIMATE CHANGE MODELLING

DLP has been widely used in different areas of agriculture. Most of the applications of DLP are recorded in the optimisations of agricultural water use. Application of DLP in climate change related research is a new application that has just erupted. Therefore, not many studies are available for review in this area. Most times, in climate change studies DLP is used in conjunction with other models in an integrated modelling framework. The discussion of the applications of DLP is divided into International and South African applications.

2.6.2.1 International research

As mentioned above, existing applications can be traced to agricultural water use optimisation. Several applications can be found in the review done by Conradie and Hoag (2004) concerning the application of mathematical programming models to determine irrigation water values.

Looking at climate change research, McCarl *et al.* (1999) used a multi-period, regional, mathematical programming economic model to evaluate the potential economic impacts of global climatic change on the U.S. forestry sector. A wide range of scenarios for the biological response of forests to climate change were developed ranging from small to large changes in forest growth rates. The response functions were used to characterise broad impacts of climate change on the sector. Results show that aggregate impacts (across all consumers and producers in the sector) are relatively small but that producers income and future welfare 30 – 40 years in the future are most at risk. The forest sector was found to adjust to mitigate climate change impacts, including interregional migration of production, substitution in consumption, and altered stand management.

John *et al.* (2005) used a whole-farm programming model, with discrete stochastic programming to represent climate risk and explore the consequences of several climate scenarios. The study provides a detailed analysis of these effects for an extensive dry land farming system in south-west Australia. Projected changes in climate would affect not only the profitability of agriculture, but also the way it is managed, including the way issues of land conservation are managed. Climate change may reduce farm profitability in the study region by 50% or more compared to the historical climate. Results suggest a decline in the area of crops on farms, owing to greater probability of poor seasons and lower probability of very good seasons. The reduced profitability of farms would likely affect the capacity of farmers to adopt some practices that have been recommended to farmers to prevent land degradation through dry land salinisation.

Shrestha *et al.* (2004) developed and applied a farm-level dynamic linear programming (FDLP) model to examine the impact of climate change on dairy farms in central England. The model was used to consider the effects of climate change on grass production and conservation. It aimed to determine whether these farms needed to change under future climatic conditions and if so, what type of adaptations would be the best for maximising their farm profits. The FDLP model was run again (Adaptation-run) for 2050 with any changes in farm activities in the Climate-run restricted to the Base-run values. The difference in net margin between the Adaptation-run and the Climate-run, if negative, showed that farmers' needed to change under future climatic conditions.

2.6.2.2 South Africa research

A few applications can also be found in South Africa. Callaway *et al.* (2006) developed the Berg River Dynamic Spatial Equilibrium Model (BRDSEM). It is a dynamic, multi-regional, non-linear programming (DNLP) model patterned after the 'hydro-economic' surface water allocation models developed by Hurd *et al.* (1999, 2004) for five major river basins in the US. It is a water planning and policy evaluation tool that was developed specifically to compare the benefits and costs and economic impacts of alternatives for coping with long-term water shortages in the Berg River Basin and Cape Town owing to climatic change.

More generally, the model was developed as a prototype to illustrate to basin planners how this type of model could be used in wider applications to assess the benefits and costs of alternatives for increasing water supplies and reducing water use with and without climate change. The core of BRDSEM consists of three modules, namely: The Intertemporal Spatial Equilibrium Module, the Urban Demand Module and the Regional Farm Module. These models are linked in an integrated methodology framework with Global Circulation Model data, a regional hydrologic model and inputs about policies, plans and technologies (see Callaway *et al.*, 2006, for further information about the model and development).

Louw *et al.* (2011) used the basic features of the BRDSEM to expand and improve the modelling framework for the CCAA project. The model was used to simulate different adaptation strategies to cope with climate change in Berg River catchments and parts of the Breede River. The Louw *et al.* (2011) model, which is an advancement of the Callaway *et al.* (2006) model, was also found not be sensitive to climate variables. It was pointed out that there is a need for more research to increase the sensitivity of the farm models to climate change variables (temperature and water availability).

Temperature is an important climate parameter which has been projected to increase in the future. This has implications for deciduous fruit production in the Western Cape, South Africa.

The majority of the agricultural crops produced in this area are deciduous fruits which require a certain degree of coldness (chill unit) for optimal production. If these requirements are not met, it could have serious implications for yield and crop combinations of the farmers. The impact of temperature on water availability and chill unit accumulation have to be adequately modelled in order to arrive at a valid conclusion regarding the adaptation scenarios considered both in the present and in the future.

2.7 CROP WATER MODELLING MODELS AND APPLICATION IN SOUTH AFRICA.

Singels *et al.* (2010) have provided a review on the development of water balance and crop models and the impacts of these models on production in South Africa. Models such as ACRU, BEWAB, CANE-GRO, CERES, PUTU, SAPWAT and SWB were considered in the review. Singels *et al.* (2010) highlighted the key characteristics and achievements of major South African modelling initiatives and their contribution to improving the sustainability and efficiency of South African crop production, as well as enhancing the science of crop production. Key factors necessary for successful crop water balance and future opportunity for model development and application were also presented. The research by Singels *et al.* (2010) provided a good overview of the characteristics of the different models and their application.

Of all the models mentioned above, SWB (Annandale *et al.*, 1999) and SAPWAT (Crosby and Crosby, 1999 & Van Heerdeem *et al.*, 2008) are two models that are locally available to estimate the crop water requirements of a variety of crops in South Africa (Grove, 2007). SWB is a very sophisticated crop growth simulation model that was specifically developed to improve real-time irrigation scheduling. The development of the model was in line with the old paradigm of determining when to irrigate and how much to irrigate to sustain maximum crop yield (Grove, 2007). The adoption of the model was relatively slow and the user base is still very small. Two of the reasons why irrigation managers do not adopt the model are that, until recently, it was cumbersome to set the model up and to simulate predefined irrigation schedules (Jordaan, Grové, Steyn, Benadé, Annandale and Pott, 2006). Accordingly, the usefulness of the model to evaluate the relative profitability of alternative irrigation schedules was hampered.

SAPWAT was developed as a planning and management tool for the estimation of crop water requirements by irrigation engineers, agriculturists, managers and farmers in South Africa (Crosby and Crosby, 1999). It is a further development of CROPWAT (Smith 1992) and can be used to estimate irrigation requirements of crops under varying crop production approaches and climates. SAPWAT has been fully adopted by the DWAF as a tool for determining irrigation water allocation in connection with the registering and licensing of agricultural water use.

SAPWAT has been widely used in South Africa to calculate crop water requirements. Several factors motivated the choice of SAPWAT over SWB by Grove (2007). Firstly, SAPWAT is founded on internationally accepted principles of estimating crop water requirements (FAO-56, Allan, Pereira, Raes and Smith, 1998) and is regarded as the standard in estimating crop water requirements in South Africa. As a result, the user base is large. Furthermore, government also sees it as a tool to benchmark lawful water use under the National Water Act (Act 56 of 1998). Secondly, it is easy to use the model because it is supplied with weather data and a unique set of crop parameters that is specific to South Africa. Thirdly, the model has a function to write the water budget equations to Excel[®]. From a research perspective, this is of benefit since the researcher does not need to have any experience in computer programming to evaluate the code in order to improve the model (Grove 2007). In addition to this, the crop varieties database in SAPWAT is extensive and it has provision for tree and deciduous crops which is not common in other models. SAPWAT uses the Koppen climate system (Koppen 1931; Strahler & Stralher 2002) for calculating crop coefficients and will therefore make it widely acceptable (Singels *et al.*, 2010).

2.8 CHILL UNIT ACCUMULATION MODELS IN SOUTH AFRICA

Temperature is a basic climatological parameter used frequently 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 (Schulze, 2012). Temperature during winter influences the growth and development of the buds of deciduous fruit, even though this might not be always visible from the outside during the dormant period. Winter temperatures also have a strong impact on flower quantity and quality and the timing and severity of flowering (Lötze and Bergh, 2012).

Agricultural scientists have developed mathematical models that are used by growers to select tree cultivars with chilling requirements that correspond to available chilling at a specific location. However, a grower's understanding of available winter chill is likely to reflect conditions of the past rather than those expected for a warmer future. Since orchards often remain in production for decades, consideration of future expected winter chill is necessary in times of imminent climate change. The accurate quantification of the 'coldness' of winter using phenological models can therefore assist farmers with a relatively complete assessment of how particular cultivars fare under the current conditions, which facilitates cultivar choice (Savage and Prince, 1972). Accurate models can also help researchers assess the effect of various climate change possibilities on fruit production in the fruit producing areas. The phenological models can also be used to predict maturity dates which improve the market delivery of fruits (Smith, 1985).

In South Africa two important monitoring systems for chill accumulation have been commonly used. The Utah or Richardson model (Richardson *et al.*, 1974), measuring “Richardson Chill Units (RCU)” and the Infruitec model (daily positive Utah model), measuring “Infruitec Chill Units (ICU)”. Other models as identified in the literature are the Dynamic model (Fishman *et al.*, 1987) and the Chilling hours model (sometimes referred to as Weinberger Model; Weinberger, 1950). It is important to note that some researchers refer to chill unit as chill hours. In effect, for the earlier low chill stone fruit, the accumulations are made in the months of May, June and July. For the pome fruits, August is also very important (Hacking, 2006). Studies on winter chill and chilling requirements often tacitly assume that the choice of the model is not important and that all models can be used interchangeably (Saure, 1985). As these models all rely heavily on the weighted values of hourly temperatures, predicted changes in temperature in winter will thus have a huge impact on these calculations. Especially if these changes occur in the region between 0°C and 18°C, the present values used for chilling unit accumulation at present, total accumulated chill units may change dramatically between seasons.

The Richardson and Infruitec models accumulate the same way, with the exception that the Infruitec model does not allow one to lose units when the temperature exceeds 16°C once these units have been “banked” by not being forfeited within the first 24 hours after accumulation. The accumulation table is set out in Table 2.2:

Table 2.2 Accumulation table for Richardson and Infruitec Chill Unit Models

Temperature °C	Richardson Units	Infruitec Units
< 1.4	0	0
1.5 – 2.4	0.5	0.5
2.5 – 9.1	1	1
9.2 – 12.4	0.5	0.5
12.5 – 15.9	0	0
16 – 18	-0.5	0
>18	-1	0

Source: (Hacking, 2006)

The Utah model of Richardson *et al.* (1974) was developed for peaches in areas with very cold winters, but it is now widely accepted for use in deciduous fruit growing areas worldwide. The Utah model (Richardson *et al.*, 1974) contains a weight function assigning different chilling efficiencies to different temperature ranges, including negative contributions by high temperatures. The model assigns chilling units for each hour at a given temperature, with temperatures between 2.5° and 9.2°C being the most favourable for chill unit accumulation (Table 2.2) because Richardson suggests that the full chill unit can be acquired when the temperature in an hour is between 2.5° and 9.2°C. This model has been adopted by the South

African deciduous fruit industry in the South Western Cape (Linsley-Noakes *et al.*, 1995). There are threshold temperatures which are important as some contribute to the chilling requirement and others do not. High temperatures do not contribute to the chilling requirement and temperatures below 0°C are also not considered effective for chilling. In some models higher temperatures counteract the positive effects of chilling and negative chill units are applied when temperatures exceed the threshold or when they are below threshold (Richardson *et al.*, 1974).

The Infruitec model calculates chill units by using the average temperature for each hour which is summed every 24 hours. If the total for the 24 hour period is negative it is counted as zero, but if the total is positive, it is added to the monthly total. These units were originally called “modified Utah chill units” (Linsley-Noakes, Allan and Matthee, 1994; Sheard, 2001), then Positive Daily Richardson Units (Allan *et al.*, 1995), and finally Daily Positive Utah Chill Units (PCUs) (Linsley-Noakes *et al.*, 1995). This model has been found to give a more accurate estimation of winter chilling in areas with mild winters, as well as areas experiencing very cold winters (Allan, 1999).

These models (Richardson and Infruitec) have been applied in South Africa (Midgley and Lötze, 2011 and Tharaga *et al.*, 2013) and have been found to produce good and consistent results, depending on the area.

2.9 SUMMARY AND CONCLUSION

Climate change is a reality. Given the climatic requirements of fruits, and the expected change in climatic conditions in the Western Cape, the fruit farmers are in for a rough ride. Farmers will have to adapt in order to remain in production. Depending on the type of adaptation considered or combination of adaptations considered, adaptation should be able to completely offset most of the agricultural income loss, or if not, will leave an individual farmer with a relatively small loss. The farmer may be forced to lower profit expectations, but the farmer should remain solvent and flexible enough to be able to develop new production and marketing strategies for the future (Easterling *et al.*, 2004). At this level, such an adaptation can be said to be successful. Thus, adaptation can be considered successful if it maintains services or welfare with a small or minimal loss.

It has been identified in the literature that an integrated approach to climate change adaptation has the potential for incorporating different modules in one framework. An integrated assessment model (IAM), which combines scientific and economic aspects of climate change, primarily for the purpose of assessing policy options for climate change adaptation, is required to understand the appropriate adaptation option to cope with the projected impact of climate change.

DLP can be used as an economic model in the framework of IAM. The DLP method proves to be appropriate in simulating the farm system. It is a useful tool for analysing the interactions between management measures and production intensity on one hand, and farm income and environmental aspects on the other hand. Moreover, it is a useful tool for determining the implications of different policy options at farm level on economic and environmental aspects of farming. Whole-farm planning models are mostly developed with DLP; the reason for the development of whole-farm planning models with this technique is to enable agricultural economists to provide policy makers, as well as farmers, with a holistic (whole-farm) answer to practical farm problems. Without this, any advice given may be incompatible with the local farming practices, or may lead to lower, rather than higher, economic returns to the farmer (Pannell, 1996).

A shortcoming of the existing model, nevertheless, is the fact that the impacts of temperature and crop water requirements are not properly modelled and this has an impact on the sensitivity of the model. Thus, researchers are unable to model the impact of temperature increases in the modelling framework which will have impact on the various adaptation options. In order to accurately quantify the economics of different adaptation strategies at farm level, the existing models need to be adjusted and a methodology developed to incorporate the impact of temperature.

Crop water requirements and chill unit requirements of various crops have been found to be dependent on temperature. Therefore, the impacts of temperature on crop water requirements and on chill unit accumulation have to be incorporated into the farm model in order to improve the sensitivity of the model to climate variables. Several models can be used to estimate crop water requirements in South Africa but SAPWAT has been fully adopted by the DWAF as a tool for determining irrigation water allocation in connection with the registering and licensing of agricultural water use. SAPWAT has been widely used in South Africa and is proved to be sufficient in the estimation of irrigation crop water requirements.

With respect to chill unit accumulation, two important monitoring systems for chill accumulation are mostly used in South Africa. The Utah or Richardson model (Richardson *et al.*, 1974), measuring "Richardson Chill Units (RCU)" and the Infruitec model (daily positive Utah model), measuring "Infruitec Chill Units (ICU)". Studies on winter chill and chilling requirements often tacitly assume that the choice of the model is not important and that all models can be used interchangeably. These models (Richardson and Infruitec) have been applied in South Africa and have been found to produce good and consistent results, depending on the specific area.

Based on the literature, an integrated assessment model (IAM) is important in the assessment of different adaption options to project impacts of climate change. It is required that such an integrated methodology be sensitive to climate variables in order to adequately simulate the impact of various adaptation strategies on farm systems. The inclusion of additional modules

will be essential in cases where the existing model is not sensitive enough for a valid conclusion to be made regarding the suitability of an adaptation strategy.

OVERVIEW OF CERES ECONOMY

3.1 INTRODUCTION

The main objective of Chapter 3 is to give an overview of the economy of Ceres and its relative importance to Western Cape economy. Firstly, a general description of Ceres and its location is presented. Thereafter, information will be given about the Koekedouw irrigation scheme which is the major source of irrigation water in Ceres. A description of the Ceres farm structure with specific reference to land use, crop areas, water sources and chill unit requirements of some deciduous fruit crops follows. The last section puts into perspective the importance of the agricultural sector in the regional economy.

3.2 GENERAL DESCRIPTION AND LOCATION OF CERES

Ceres is a town with about 46251 inhabitants in the Western Cape Province of South Africa (www.planyourholiday.co.za/western-cape/ceres). Figure 3.1 shows a map of the Western Cape indicating the location of Ceres and the surrounding towns. Figure 3.1 also shows that the Western Cape is bounded to the north by the Northern Cape Province and to the east by the Eastern Cape Province. Ceres is the administrative centre of the Witzenberg Local Municipality and it lies 130 kilometres to the north-east of Cape Town. It is an important agricultural town surrounded by affluent export-oriented fruit farmers (Umvoto Africa, 2010). It is one of the largest deciduous fruit and vegetable producing districts in South Africa. Fresh fruit produced in Ceres is marketed both locally and internationally, as well as other products such as fruit juices, dried fruit, potatoes and onions, just to mention a few. Major crops include apples, pears, peaches, and to a lesser extent, grapes, plums, nectarines, cherries, and for good measure, potatoes and onions. Ceres produces large quantities of fruit juices (the local juicing plant is the largest in the country).

The combined impact of the high topography, the distance from the sea, the high rainfall in winter and low rainfall in summer and the dry summers create a uniquely favourable climate for deciduous crops, especially for pears, apples and nectarines. Of the entire pear producing regions in South Africa, the Ceres region has the highest potential. The fact that Ceres

produces almost half of the total pear production in South Africa reflects these favourable conditions (Bester, 1991 and Louw, 2002).

Farmers from the Koue Bokkeveld (Olifants Doorn Catchment) and the Warm Bokkeveld (Breede Catchment) also use Ceres as a service centre (Umvoto Africa, 2010). Ceres thus is important to the economy of the Western Cape Province because of the strong agriculture-based industry and services.

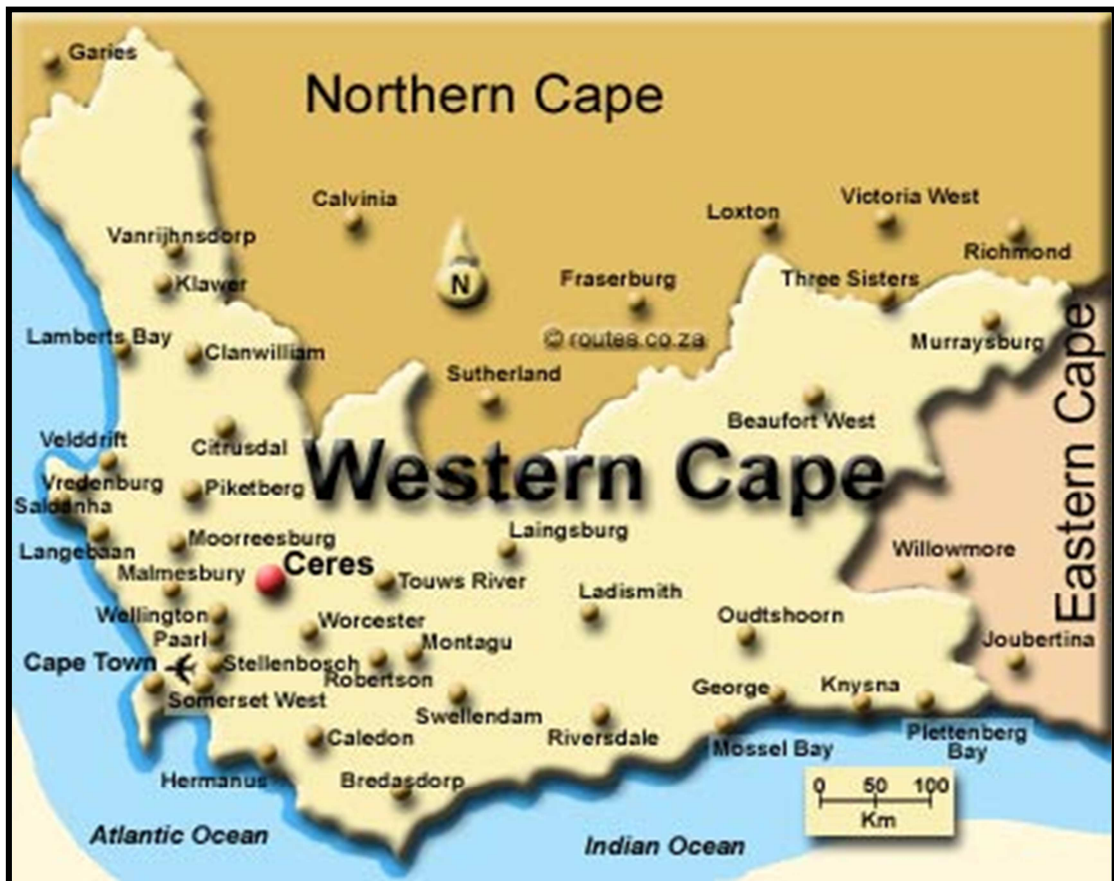


Figure 3.1: Map of Western Cape Province showing location of Ceres

Source: <http://routes.co.za/wc/ceres/>

Ceres serves as the hub of one of South Africa's most abundant fruit growing regions, a wide upland basin girded by the splendid mountains of the Witzenberg, Skurweberg and Hex River Mountain ranges. It is also known as the "Eden of Africa". Furthermore, according to the classification of towns in hierarchy, Ceres is classified as the second most important town in the Breede River region, next to Worcester. The region is fragmented internally by various mountain ranges with the result that no central service point exists in the spatial sense of the word. All the main routes from the north of the region join together in Ceres en-route to the Cape Metropole, which adds to the importance of the town.

The Ceres district consists of three diverse areas and each has its own unique charm and landscape. The Warm Bokkeveld is a wide fertile valley and is the centre of one of the richest agricultural regions of the Western Cape. Nine kilometres north of Ceres, at the foot of the Gydo Pass, is Prince Alfred's Hamlet – the hub of the potato and onion packing industry. Bo-Swaarmoed, east of Ceres, is famous for its cherry picking in season, snow during winter, proteas, and breath taking panoramic views of the valley. The Koue Bokkeveld is a mountainous area situated on a plateau. This is a fruit (apple and pear) and vegetable producing area. The Ceres fruit processors, which produces the largest quantity of apple and pear concentrates, is also located in Ceres (PDC, 2005).

As a result of the prominent mountain range, which forms a physical boundary between this area and the Cape Metropolis, a strong service sector has developed locally. Ceres receives its bulk water supply from the Koekedouw Dam, situated on the Koekedouw River, a tributary of the Dwars River, which flows into the Breede River (Umvoto Africa, 2011). The Ceres Koekedouw Dam was constructed to augment the water supply to the Ceres area. Water is supplied to a combined group of industrial and agricultural users and managed by the Ceres Koekedouw Management Committee, which is a joint enterprise between the Witzenberg Municipality and the Koekedouw Irrigation Board.

3.2.1 CLIMATE AND SOIL

The climate in Ceres is characterised by a major temperature variation between the summer maximums and the winter minimums. January and February are regarded as the hottest months of the year, with an average maximum of 29.9°C measured during February, while the average minimum of 2.4°C is measured during July (C TB, 2010).

Figure 3.2 shows the rainfall distribution pattern in the Ceres region on a monthly basis, generated from SAPWAT for years with low, average and good rainfalls. The average annual rainfall is 1 088 mm and the rain falls mainly during the winter months reaching a peak during May – July, depending on the distribution for the year. Snowfalls on the high mountain peaks are a common occurrence during winter and remain for up to 2 weeks at times. Summer rainfall is fluctuating and sporadic and is not considered for irrigation planning purposes.

The Warm Bokkeveld experiences large temperature fluctuations throughout the year, as well as on a daily basis. Maximum temperatures of more than 40 C are common whereas during the winter night temperatures can stay below 0C for long periods at a time. These climatic characteristics are favourable for deciduous fruit production (Bester, 1991). Relatively windless summers are also advantageous for fruit production since wind damage to fruit is reduced. The relatively low moisture content of soils, of between 55 and 60%, throughout the

year necessitate frequent irrigation and increase crop water requirements relative to other areas. On the other hand, the high summer temperatures are more tolerable for fruit trees compared to areas with high summer temperatures coupled to high humidity.

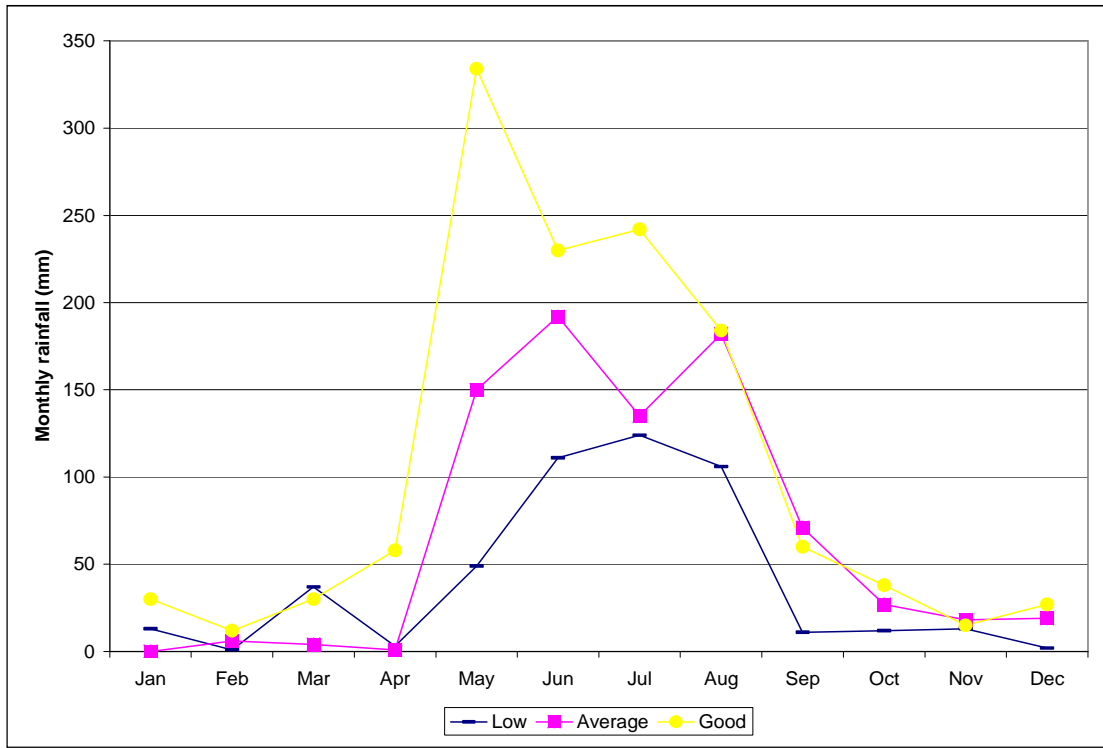


Figure 3.2: Actual monthly rainfall data from SAPWAT for the rainfall at H10C Weather station for years with low, average and good rainfall

Most of the soils in the Koekedouw irrigation region are sandstone soils. These soils are well trans-illuminated and deep, but have chemical imbalances. Bester (1991) gives a comprehensive report on the soil types and potential in the area.

3.3 THE KOEKEDOUW IRRIGATION SCHEME

The Koekedouw irrigation scheme is the major source of water supply to the Ceres region. The Koekedouw dam is approximately 2 kilometres north-east of Ceres on the Koekedouw River and was completed in 1998. It replaced the old concrete gravity arch dam at the same site which no longer had sufficient capacity and had also suffered earth quake during the 1969/90 period when severe damage to houses occurred at the nearby town of Tulbagh (Jones and White, 1999). Water from the dam is supplied to the town of Ceres, as well as Koekedouw Irrigation Board, for direct summer irrigation. The total average annual runoff is

22.5 million m³ with no upstream extraction: the dam was designed to supply 17 million m³/a at 85% assurance supply (BOCMA, 2010 & DWAF, 2003).

Ceres is entitled to 7 million m³/annum from the dam until 30 September 2017; whereafter the allocation will be increased to 10 million m³/a. The implication of this agreement is that Ceres encourages water consumption in order to be able to repay the investment into the dam (Umvoto Africa, 2011). In-stream flow requirements (IFR) of some 7 million m³/a (in a good year) and 4 million m³/a (in a dry year) are catered for prior to the supply of water to the above-mentioned two parties (DWAF 2003). A number of boreholes situated in shale formations can supply water. The boreholes target the Bokkeveld formation and the water is of poor quality. These are currently not utilised, as the town has sufficient water available from the Koekedouw Dam (Umvoto Africa, 2011). The water scheme is a pipeline distribution system situated on the western side of the Ceres Warm Bokkeveld region (see Appendix 1 for the layout of the bulk water infrastructure). The scheme distributes untreated water out of the dam from the distribution point, going in a northern and easterly direction to 41 farms mainly for irrigation purposes and to a lesser extent for household usage. The scheme consists of 12.36 kilometres of pipeline and 14 side lines with a total length of 19.65 kilometres. The total pipeline length is 32.01 kilometres (Bester, 2000).

3.4 DESCRIPTION OF THE CERES/KOEKEDOUW FARM STRUCTURE

Louw (2007) compiled notional representative farms for the Ceres district to establish a comprehensive business plan for the Koekedouw Emerging Farmers. These representative farms are adopted and used in this study. The Ceres farm region comprises both emerging (small-scale) and commercial farmers. The construction of notional representative farms from farm survey data is a common agricultural economic practice. Four representative farms (emerging, commercial small, commercial medium and commercial large) were constructed. The emerging farms surveyed were modelled as standalone farms in the farm model while the commercial farms were treated as representative farms. This was done in order to capture the differences in economies of scale and the extent of the area irrigated was used as basis to identify representative farms.

3.4.1 LAND CLASSIFICATION

Figures 3.3 and 3.4 represent the land use classifications for the Ceres farmers. A total of 626 ha of land is available to the emerging farmers, of which 240 ha are irrigable and 186 ha are actually irrigated. Dry land represents another 137 ha and the remaining area consists of other odd pieces.

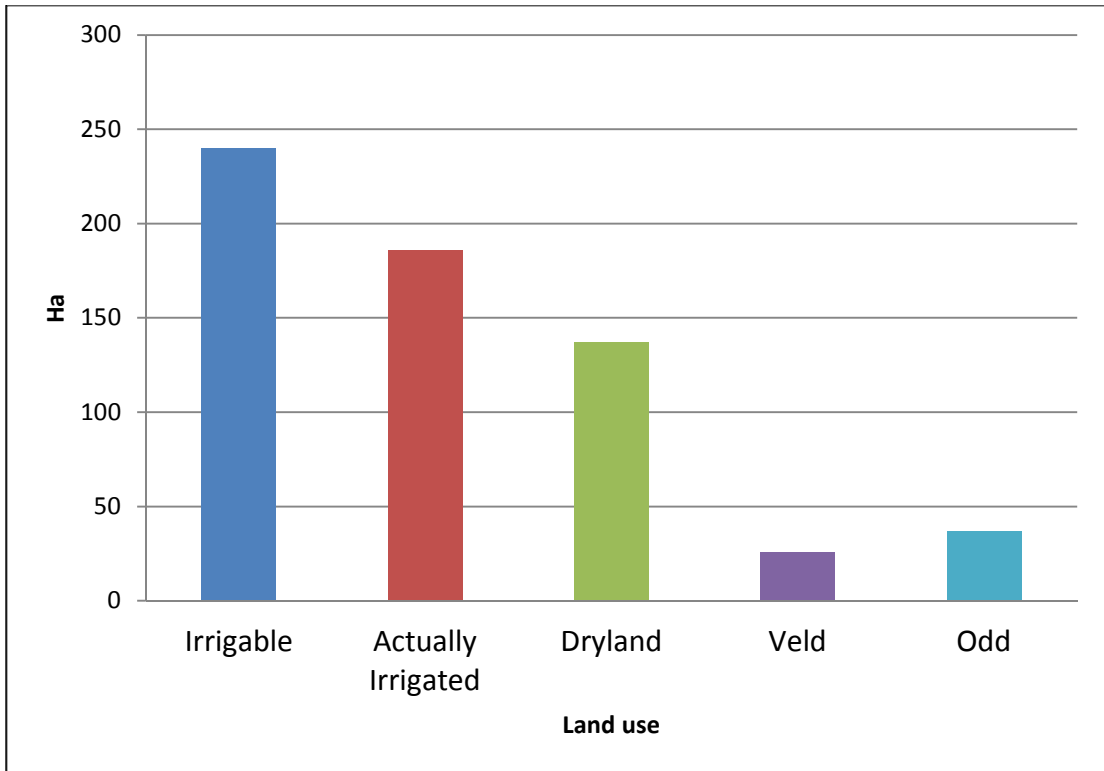


Figure 3.3: Ceres emerging farmers land use classification.

The commercial farmers land classification is presented in Figure 3.4. A total of 1 136 ha of land is available to the commercial farmers, of which 283 ha are irrigable and 267 ha are actually irrigated. Dry land represents another 266 ha and the remaining area consists of Odd and Veld.

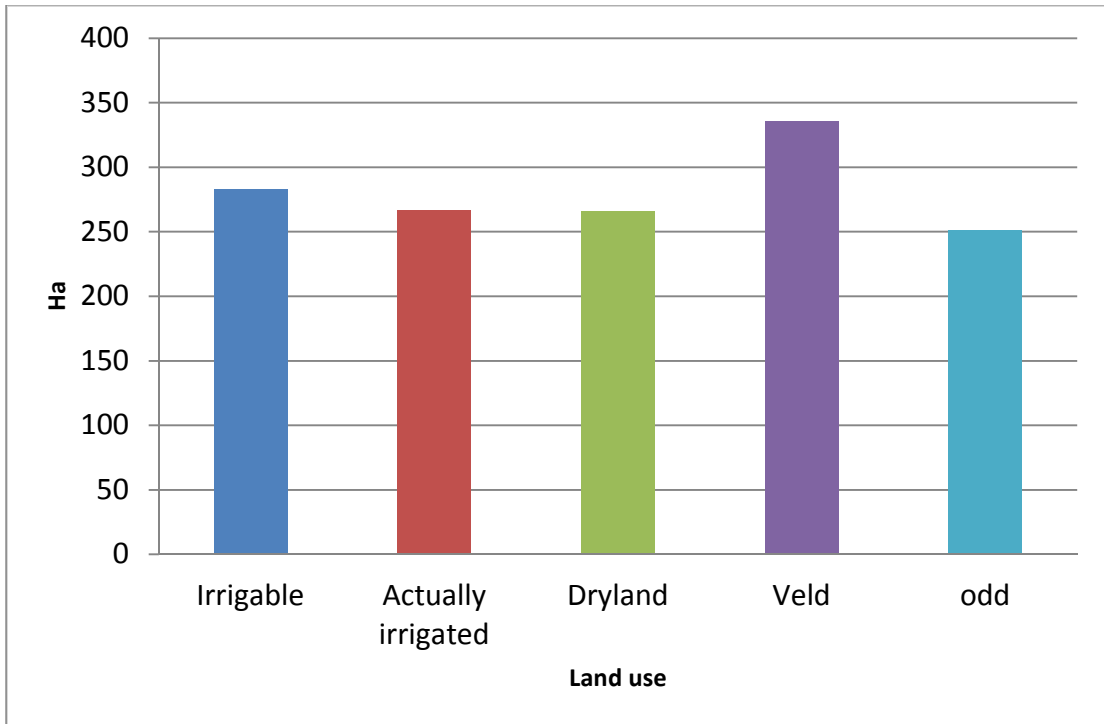


Figure 3.4: Ceres commercial farmers land use classification

It can be concluded from Figures 3.3 and 3.4 that a large hectarage of land is under irrigation agriculture. Therefore, the availability of irrigation water and access to irrigation water by both emerging and commercial farmers is crucial for agricultural production in Ceres.

3.4.2 CROP AREAS

Figures 3.5 and 3.6 represent the current utilisation of land by both the emerging and commercial farmers, respectively. Figure 3.5 shows that, for emerging farmers, wheat (dryland) is the dominating crop with 31% of the total land use. This is followed by long-term pastures (16%), peaches (13%), lucerne (11%) and butternuts (6%). Since this group of farmers are emerging farmers, they might not have access to capital to plant high-valued deciduous fruit crops in large scale, but as can be seen from Figure 3.5, such crops have been planted already. The area planted to deciduous fruits can be increased as capital and technical know-how has been provided to these groups of emerging farmers.

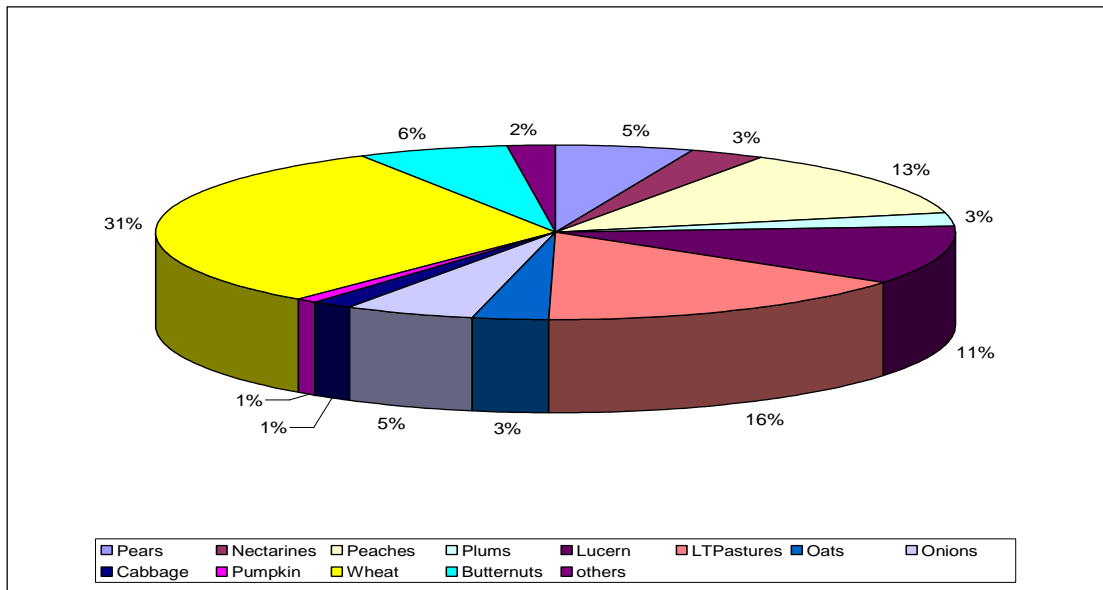


Figure 3.5: Land utilisation according to crops by emerging farmers

Figure 3.6 shows that peaches (34%), barley (25%) and plums (11%) are the major crops planted by the commercial farmers in the Ceres region. Commercial farmers thus produce more high-value crops which are destined for the export market and local consumption.

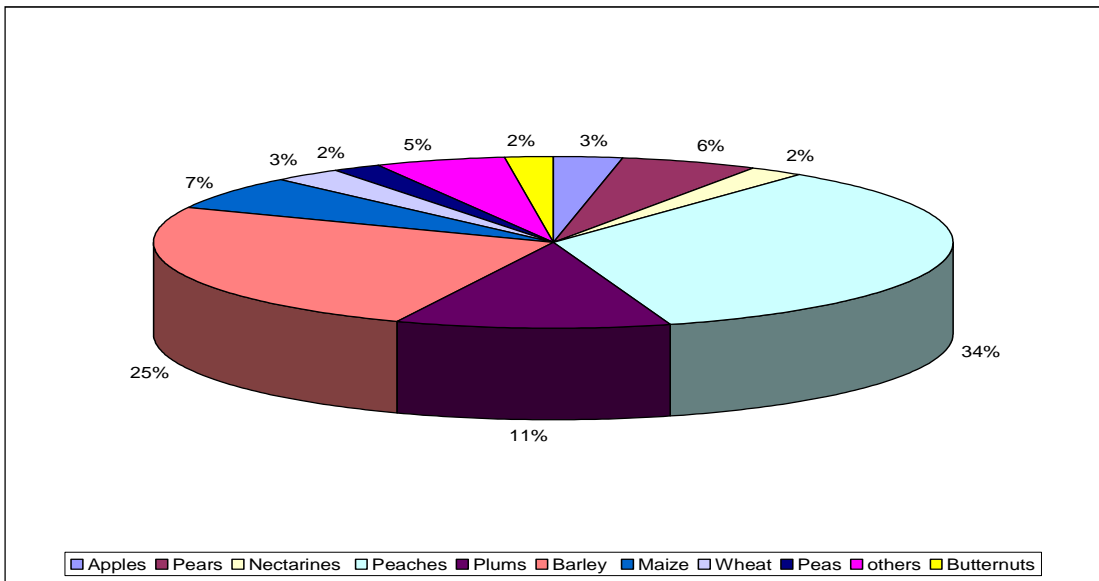


Figure 3.6 Land utilisation according to crops by commercial farmers

3.4.3 WATER SOURCES

Figure 3.7 shows the percentage contribution of different water resources to the total irrigation water for farmers in Ceres. Koekedouw water (summer and winter water) contributes approximately 43% to total water resources. This shows the importance of the Koekedouw irrigation scheme to the livelihood of the Ceres farmers. Farm dams are second largest source of water (natural runoff volume only), which represent 29% of the total volume, followed by boreholes (17%). Approximately 50% of the total farm dam capacity is filled up from natural runoff and the balance filled up with winter water sources (Koekedouw winter, Warm Bokkeveld, Dwarsriver, Boreholes, Rietvallei). Although boreholes are a relatively inexpensive source, pumping costs are approximately 14.5 cents per m³ of water or R1000 per ha irrigated. The Koekedouw summer water entitlement plays an important role in terms of security of water supplies during the summer.

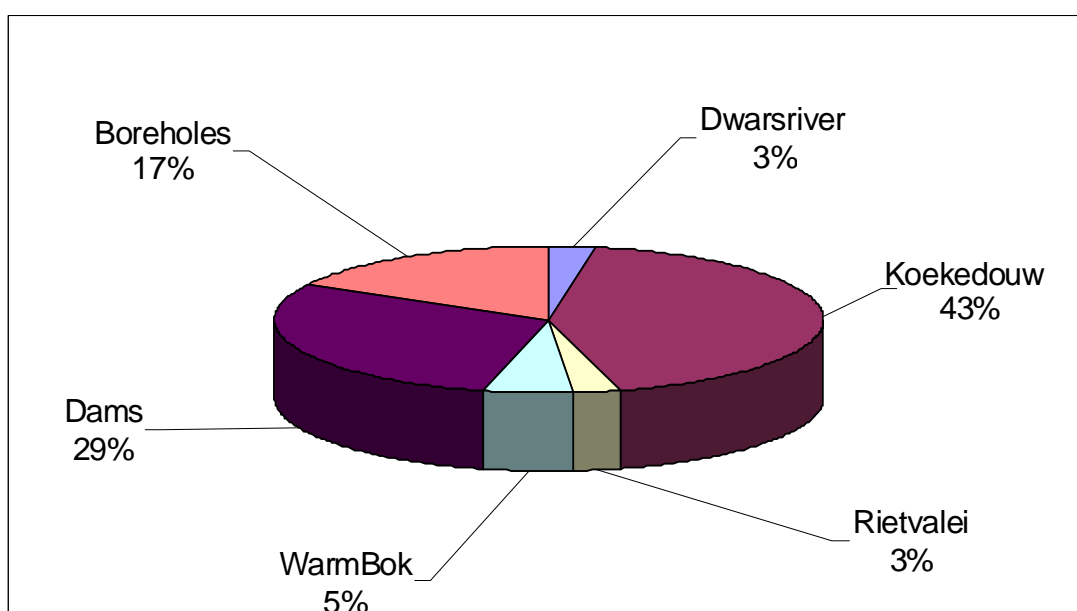


Figure 3.7 Ceres farmers water supply sources

3.5 CERES DECIDUOUS FRUITS AND CHILL UNITS REQUIREMENTS

All economically important fruit and nut tree species that originated in temperate and cool subtropical regions that are cultivated in South Africa have chilling requirements that have to be fulfilled each winter to ensure homogeneous flowering, adequate fruit set, and economically sufficient yields (Luedeling *et al.*, 2009). Total seasonal chill accumulation is nonetheless important in determining the progression of bud dormancy and a region's suitability for fruit production.

Table 3.1 presents four main cultivars of some deciduous fruit crops that are typically planted in the Ceres region, with their associated winter chill requirement. These indicated chill units represent the amount of coldness that is required for these deciduous fruits to break dormancy. The selection of these four main cultivars was based on a 2012 tree census. The tree census gives information about the different cultivars and area planted to those cultivars. The selected four cultivars for each fruit type are selected based on area cultivated.

Table 3.1: Selected fruit types in Ceres and Richardson chill unit requirements

Apples	RCU	Pears	RCU	Apricots	RCU	Nectarines	RCU	Plums	RCU
Golden Delicious	1400	Forelle	850	Soldonne	650	August red	650	Angeleno	400
Top red /starking	1400	Williams bon chretien	1200	Bebeco	700	Fantasia	600	Southern belle	600
Royal gala	1200	Packham's triumph	900	Ladisun	500	Flamekist	700	Fortune	400
Granny Smith	NA	Abate Fetel	850	Suaprieight	450	Summer Bright	550	African delight	250

Table 3.1 shows that the chill unit requirements for apple cultivars Golden Delicious and Top Red are 1400 RCU. Apples require more compared to the other deciduous fruit types presented in Table 3.1. Chill unit requirement for pear range between 850 – 1200 RCU. The Williams Bon Chretien pear cultivar has the highest chill unit requirement of 1200 RCU among the pear cultivars presented. Other deciduous fruits such as nectarines, apricots and plums have relatively moderate chill unit requirements. Considering the long life span of deciduous fruits compared with annual crops and the substantial investments required for their establishment, tree crop growers will be affected if the required chill unit is not accumulated. Farmers are sometimes forced to use artificial rest breaking chemicals, which translate to increases in production costs and hence have an impact on the profitability of such enterprises.

3.6 IMPORTANCE OF THE AGRICULTURAL SECTOR IN THE REGIONAL ECONOMY

Agriculture is a major economic contributor to the Western Cape economy. Although the province contributes only some 14% to the country's Gross Domestic Product, it generates almost 23% of the total value added by the agricultural sector in South Africa (Murray, 2010). The diverse production capacity of the province allows for at least 11 commodities to contribute significantly to agricultural production. Fruit, broiler poultry, eggs, winter grains (such as barley and wheat), hops, viticulture, ostriches and vegetables together contribute more than 75% of the total output.

The diversity of agricultural enterprises contributes to the provincial farming sector's general stability (Murray, 2010). The main industries in the sector include fruit, which contributes about R2.4bn; winter grain, some R1.8bn; white meat valued at R1,6bn; viticulture worth R1.6bn; and vegetables worth R1.4bn. The agricultural sector is critical for the Western Cape economy, accounting for 60% of regional exports.

The majority of the export potential for South African agriculture is concentrated in the wine grape producing areas of Worcester, Robertson and Stellenbosch; in the deciduous fruit areas such as Caledon, Paarl and Ceres; and in the citrus producing areas such as Citrusdal (McDonald & Punt, 2001). Eckert *et al.* (1997) have pointed out that agriculture plays a major role in the economy of the Western Cape. They used a social accounting matrix (SAM) to calculate the fixed price multipliers for agriculture in the Western Cape. These are presented in Table 3.2. Thus, R1.0 of additional demand for the horticultural sector's output will increase provincial value added by R1.40, require R0.2 of additional imports and contribute R0.24 to government revenue. In addition, 92.8 number of person-years employment will be created per extra R1.0 million final demands.

Table 3.2: Fixed price multipliers for commodity and sector groupings

	Employment^a	Value added^b	Imports^b	Government revenue^b
All Agriculture	82.8	1.29	0.21	0.26
Cereals	26.1	1.02	0.27	0.27
Other crops	70.8	1.36	0.19	0.25
Horticulture	92.8	1.40	0.20	0.24
Livestock	88.4	1.25	0.20	0.27
Agribusiness	39.7	1.02	0.26	0.2
Non-Agriculture	29.4	1.1	0.25	0.22

a Number of person-years employment created per R1.0 million final demand

b Rand value per additional R1.0 of final demand

Source: Eckert *et al.* (1997)

The agricultural sector contributes nearly 13% of the total formal sector jobs in the Western Cape. Horticultural enterprises dominate agriculture's contribution to provincial value added, employment, and employee remuneration. In descending order, viticulture, deciduous fruit, field scale vegetables and table grapes lead in this regard. All of these crops dominate in agricultural activities in the Koekedouw irrigation scheme.

Figure 3.8 is a simple representation of the economy of Ceres and the linkages between key socio-economic factors.

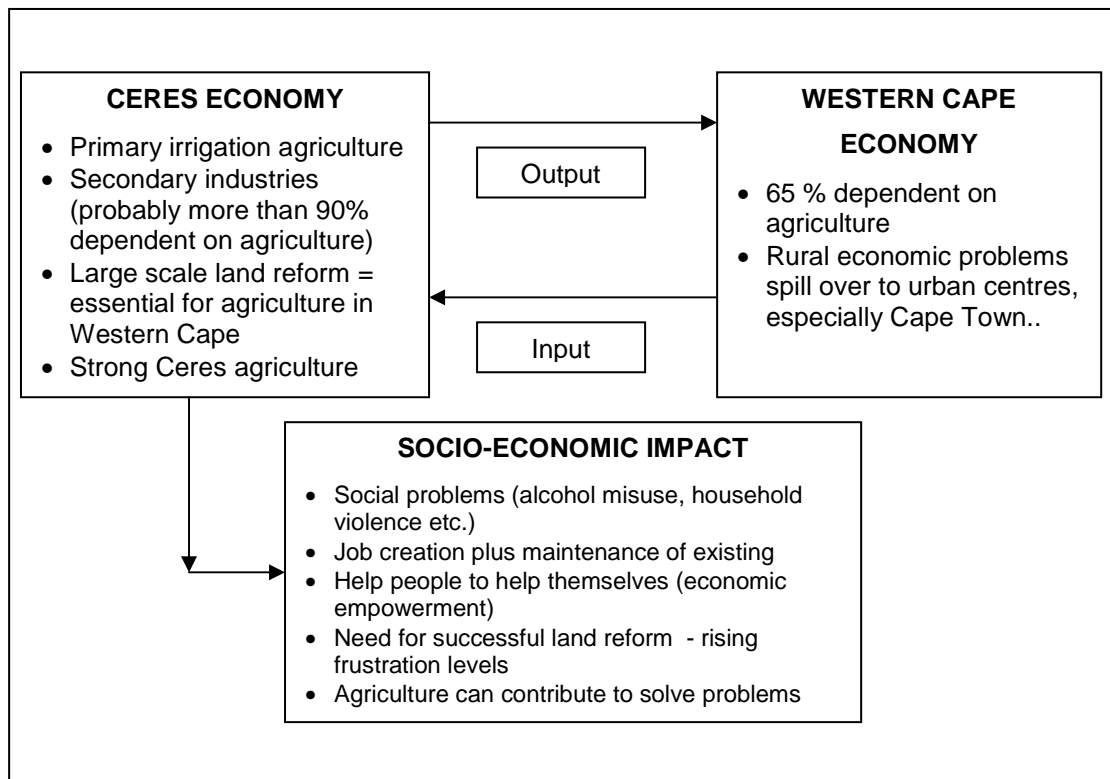


Figure 3.8 Representation of socio economic linkages in the provincial economy

Figure 3.8 shows that there is a close relationship between growth in the agricultural sector and its impact on growth in secondary industries, job creation, social problems and the spill over to the rest of the Western Cape economy, in particular the Cape metropolis.

3.7 CONCLUSIONS

The Ceres region is a well-endowed agricultural area in the Western Cape. Both the emerging and commercial farmers are situated in Ceres. Availability of irrigation water is especially crucial to the production of crops and the region produces high-value exportable crops for the international market. The chill unit requirements for the deciduous fruits produced in the Ceres region are fairly high. This coupled with the projected future increases in temperature could have impacts on the chill unit accumulations of certain crops, and consequently farmers might find it difficult to produce certain fruit crops in the future. The agricultural sector is a significant contributor to Ceres economy in terms of its contribution to the provincial agricultural GDP, the provision of jobs and the multiplier effect on the provincial

economy. Therefore, intervention at farm/area level will surely have an impact on the provincial economy because of the inter linkages that exist.

4.1 INTRODUCTION

The main objective of this chapter is to describe the procedure used to develop the integrated model used to simulate the impact of climate change and devise different adaptation strategies. The chapter commences by giving the structure of the integrated methodology and the various modules that were linked together to form the integrated model. The model includes a Ceres farm module, and an urban demand module embedded in an intertemporal spatial equilibrium framework. The modules are linked together in an integrated framework with inputs from a Global Circulation Model (GCM), the Agricultural Catchments Research Unit (ACRU), an irrigation crop water requirement module (SAPWAT) and a chill unit accumulation module. Lastly, the expected outputs were highlighted and conclusions were drawn based on the relevance of the new model developed from the existing ones.

4.2 MODEL STRUCTURE

Callaway *et al.* (2006) developed the Berg River Dynamic Spatial Equilibrium Model (BRDSEM). BRDSEM was developed specifically for this region to help water policy-makers and planners to examine the physical and economic impacts of rapid population growth and climate change; to assess the physical and economic benefits and costs of structural and non-structural measures for coping with both these problems; and to estimate the economic value of the physical damages that could be avoided by these options. Louw *et al.* (2011) used the basic features of the BRDSEM to expand and improve the modelling framework for the IDRC (International Development Research Centre) project. The model was used to simulate different adaptation strategies to cope with climate change in Berg River catchment and parts of the Breede River. Louw *et al.* (2011) concluded that there was a need for more research to increase the sensitivity of the farm models to climate change variables (temperature and water availability). In this present study an attempt was made to increase the sensitivity of the model in order to make valid policy recommendations and valid conclusions regarding different adaptation strategies available to the farmers at farm level. Two additional modules, namely the crop water module and chill unit accumulation module, were integrated with the models devised by Callaway *et al.* (2006) and Louw *et al.* (2011) to form the Ceres Dynamic Integrated Model (CDIM). The Louw *et al.* (2011) model was

developed at regional and aggregated level and accordingly the basic structure of the model was adopted to develop the Ceres model at farm level. In addition, the Ceres area was not considered in the previous modelling work that had been done on Western Cape.

A schematic diagram of the Ceres Dynamic Integrated Model is presented in Figure 4.1.

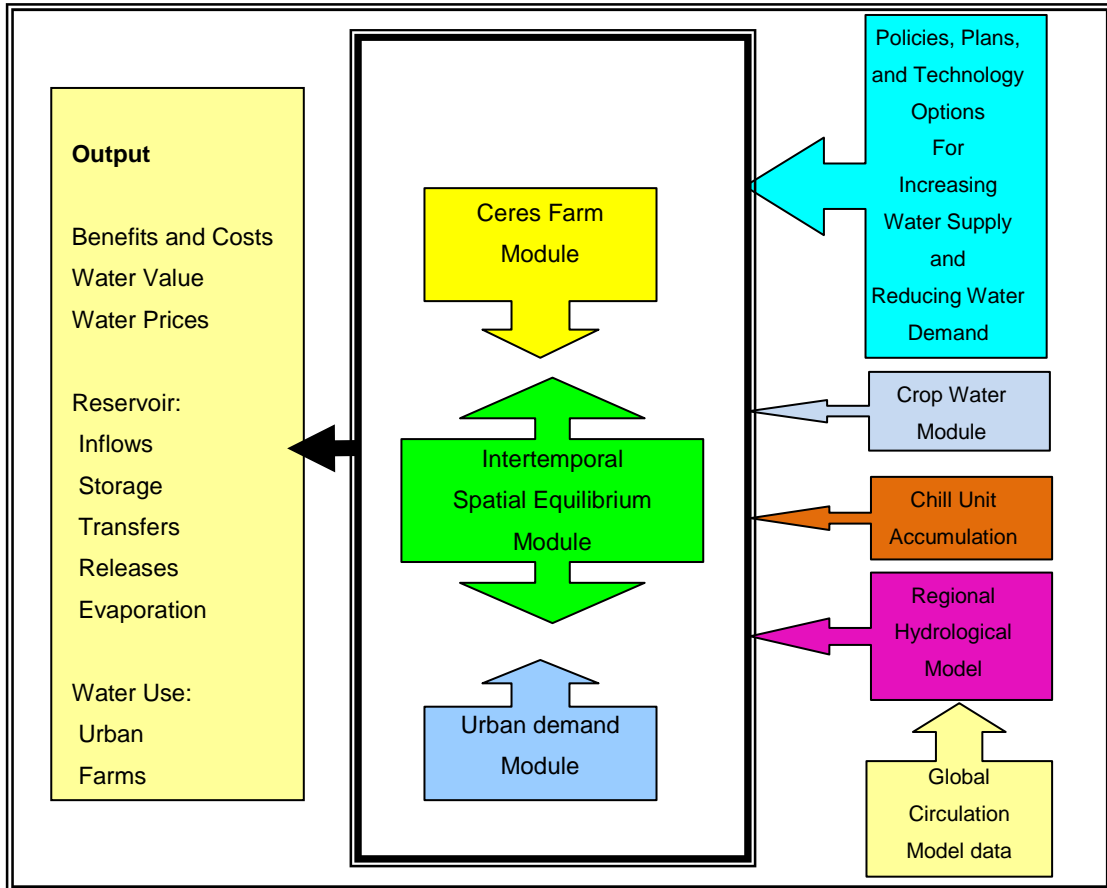


Figure 4.1: Ceres Dynamic Integrated Model (CDIM) Schematic Diagram

Source: Developed from Callaway *et al.* (2006) and Louw *et al.* (2011)

CDIM is an optimisation model that maximises the economic value of the net returns to water from urban and agricultural water users on a monthly basis over time. Runoff nodes, storage and farm reservoirs and water diversions are linked together by spatially differentiated flows consistent with basin hydrology. As presented in Figure 4.1, outputs from the GCM model of the University of Cape Town are linked to the Regional hydrological model (ACRU) of University of Kwazulu Natal to generate the data that is used in the Ceres farm model. Crop water requirements for base and future climate from SAPWAT and the accumulated chill unit from the Richardson and Infruitec chill unit models are also linked to the farm model.

4.2.1 DESCRIPTION OF THE MODULES OF THE MODEL

The Ceres Farm Module: This module consists of data from 11 emerging farmers and 3 representative commercial farmers. The model simulates the demand for agricultural water in the Ceres (Koekedouw) region. Included in the module are crop water relationships and different irrigation technologies (e.g. drip, micro and sprinkle), as well as chill unit requirements for deciduous fruit crops, to simulate the impact of climate change on water availability and farmers' crop combinations. The demand for agricultural water is a derived demand gauged from the demand for agricultural products. For each of typical farms there is a possibility of four possible water supply sources, one from the Koekedouw dam, farm dam, river or borehole (not necessarily for all).

The Intertemporal Spatial Equilibrium Module: The module was based on that of Callaway *et al.* (2006). It consists of a series of linear equations that characterise the water balances over time in specific reservoirs and the spatial flows of water in the basin, linking the runoff, reservoir inflows, inter-reservoir transfers and reservoir releases, to urban and irrigated agricultural demands for water. The module is basically the link between the hydrological (water supply) module and the economic model (dynamic programming model).

The Urban Demand Module: This module simulates the demand for urban water. The module was patterned along those of Callaway *et al.* (2006) and Louw *et al.* (2011).

The Ceres farm module and the urban demand module are linked directly to the storage and conveyance modules at different points of use in the basin and these three modules are then solved together as a dynamic programming model, using the inputs from the hydrology module.

The model has the ability to simulate reservoir operation and water allocation to urban and irrigated agricultural demands, based on the objective of economic efficiency, by regulation, or by a mixture of the two.

There are other important sources of information external to CDIM and they are:

- **Global Circulation Model data (Downscaling Global Climate Models):** This model supplies the hydrologic model with information about monthly temperature and precipitation at specific points in the basin for climate scenarios. The downscaling was done by the University of Cape Town climate research group as part of the input into the CCAA project. A detailed description of the methodology is available in Louw *et al.* (2011).
- **A Regional Hydrologic Model:** This model (ACRU) converts the monthly temperature and precipitation data from the regional climate model into monthly runoff at different runoff gauges for each climate scenario. The running and generation of output data from ACRU was done by University of Kwazulu Natal as part of the input into the CCAA project. A detailed description of the methodology is available in Louw *et al.* (2011). Output from ACRU is used in the Ceres Farm Model by the author. Detailed information about the processing of output from ACRU is presented later in this thesis.
- **Crop Water Requirement Model:** SAPWAT3 was used to estimate crop water requirements for both the present and future climate. This was based on the future climate projection information for Ceres supplied by Schulze (2012). The SAPWAT database was re-parametised to estimate future crop water requirements since such information is not readily available in SAPWAT.
- **Chill Unit Model:** This model estimates the accumulated chill units for a particular location based on temperature data. The Utah model of Richardson *et al.* (1974) and the Daily positive Utah (Infruitec) chill unit accumulation model of Linsley-Noakes *et al.* (1994) are used to estimate the chill unit requirements.
- **Inputs about Policies, Plans and Technologies:** This represents the sources of information that can be used to alter various parameters in the programming model to reflect alternative policies, plans and technologies for increasing water supply and reducing water use.

4.3 CLIMATE PROJECTIONS AND EMISSIONS SCENARIOS

The climate projections and associated emissions scenarios that were developed in the IDRC project and applied in hydrological modelling are given in Table 4.1. The projections were available at a daily level for rainfall as well as for maximum and minimum temperatures.

Table 4.1: Summary of climate projections applied in hydrological modelling based on A2 emissions scenarios

Period	UCT
Present (1971 - 1990)	IPSL-CM4 ("Low") ECHAM5/MPI-OM ("High")
Distant future (2046 - 2065)	IPSL-CM4 ("Low") ECHAM5/MPI-OM ("High")

Source: Louw *et al.* (2011).

The University of Cape Town (UCT) climate projections developed in the IDRC project were a regional downscaling of global projections derived from five IPCC coupled General Circulation Models (GCMs), namely, CGCM3.1(T47), CNRM-CM3, ECHAM5/MPI-OM, GISS-ER and IPSL-CM4 (the GISS-ER projections were later excluded owing to errors in the source GCM data). The climate projections applied in hydrological modelling were limited to a "High" (ECHAM5/MPI-OM) and "Low" (IPSL-CM4) GCM (based on projected changes in annual rainfall) to limit the number of hydrological and economic simulations to a manageable level. The present period selected for hydrological and economic modelling was shortened to 20 years (from the number of years available in the climate projections) to ensure that the present and distant future periods were of the same length (for comparison purposes).

4.4 POST-PROCESSING OF ACRU OUTPUT FOR APPLICATION IN THE CERES FARM MODEL

The hydrological outputs required as input to the economic modelling included:

- monthly time series of incremental runoff ($\text{m}^3 \times 10^6$) generated at dam, farm and exchange sites.
- monthly time series of dam evaporation "coefficients" (m^3 / ha) for major storage dams and representative farm dams.

To prepare the incremental runoff inputs for the economic modelling, the runoff outputs from ACRU were first accumulated from daily to monthly for each sub-catchment in the study area. Then, the sub-catchments contributing to each site were identified, and the runoff from those sub-catchments accumulated to provide the incremental runoff to each site (since incremental runoff was required, only runoff generated from the site immediately upstream was accumulated in this process). The dam evaporation "coefficients" were defined as the depth of water evaporated from an open water surface, expressed in units of m^3/ha . The ACRU model uses the A-pan as its reference potential evaporation and is estimated from temperature-based equations (in this case from the equation by Hargreaves and Samani, 1985).

The reference evaporation dataset as generated by ACRU for the base and future climate was used to calculate evaporation coefficients for both base and future climates. The evaporation coefficient was calculated using the formula:

$$\text{Evaporation coefficient (m}^3\text{/ha)} = (\text{reference evap (mm)} * \text{reservoir factor}) * 10$$

Where the reservoir factors for each month of the year are presented in the Table 4.2:

Table 4.2: Monthly reservoir factor

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Reference factors	0.73	0.73	0.74	0.72	0.70	0.67	0.63	0.62	0.63	0.66	0.68	0.69

4.5 ESTIMATION OF CROP WATER REQUIREMENT WITH SAPWAT

SAPWAT uses the basic methodology proposed in FAO-56 (Allan *et al.*, 1998) to calculate crop water requirements based on a reference evapotranspiration rate (ET_0) and the crop coefficient (K_c). K_c relates the water use of specific crops to ET_0 . The mathematical representation is given as:

$$ET_{\text{crop}} = K_c * ET_0$$

SAPWAT uses monthly or daily weather data as a basis for calculating daily Penman-Monteith reference evaporation (ET_0) values for a site, as described by Allan *et al.* (1998). Weather data in SAPWAT comes from five possible sources: CLIMWAT, manual weather stations, automatic weather stations, and user's own weather station data or imported data from external sources. SAPWAT included the full set of CLIMWAT data, as well as 50 years' daily data for each quaternary drainage region of the country (Schulze and Maharaj, 2006), and the daily value for some standard and automatic weather stations.

Using the already built-in weather data information, climate station, soil type and relevant irrigation technologies, the crop water requirement for the base period was estimated for different crops included in the farm model. Figure 4.2 shows different rivers, sub-catchments, and quaternaries in the Ceres region. The H10C quaternary weather station data was used for the estimation of crop water requirements. This weather station is the closest to the Ceres dam and to the farms in the region.

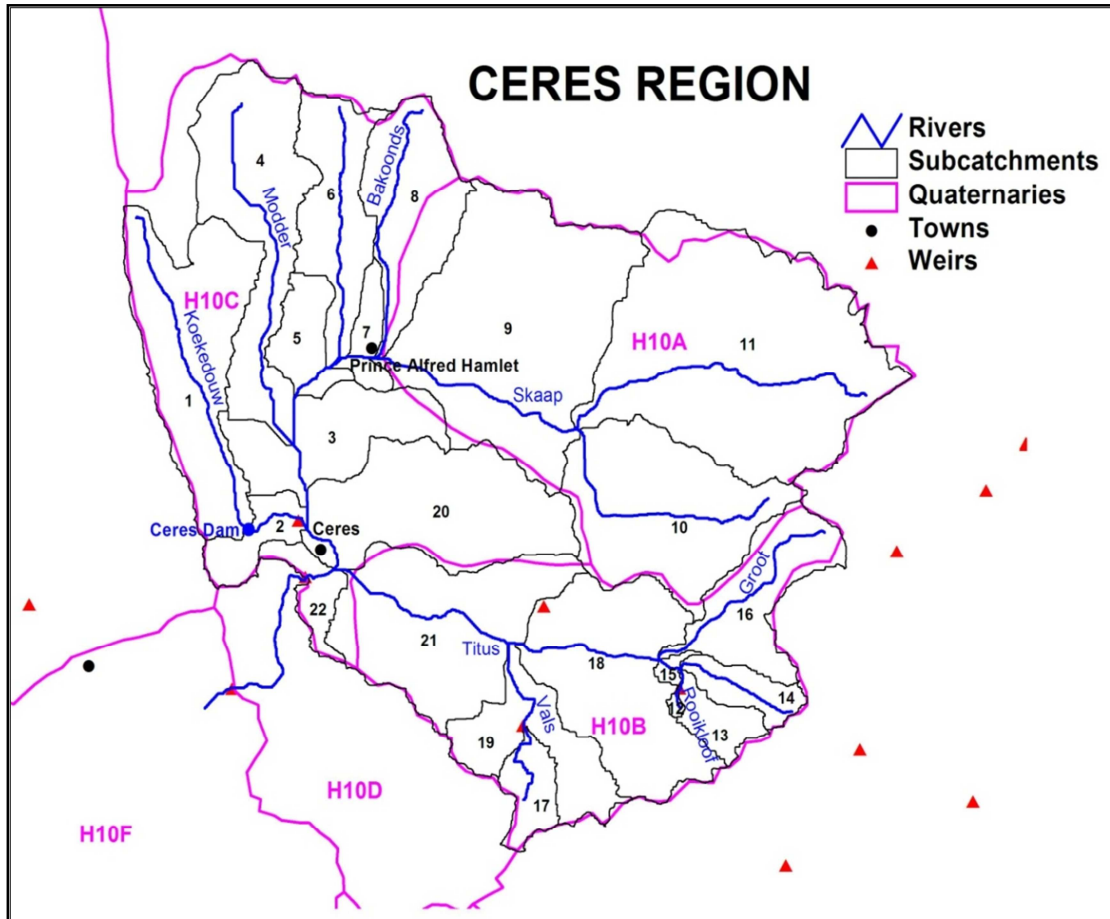


Figure 4.2: Ceres region map showing the rivers, sub-catchments, quaternaries, towns and weirs.

Source: ACRU

In order to estimate irrigation crop water requirements for the future, an artificial weather station called "H10C post climate" was created in SAPWAT. Future relative (%) changes in mean annual rainfall, mean annual temperature, and change in the Penman Monteith reference potential evaporation for the "High" and "Low" GCM, based on the A2 emission scenario by Schulze (2012), are used. These scenarios represent 2 of the 5 climate models ("High" = ECHAM5/MPI-OM; "Low" = IPSL-CM4) used in the "average of models" approach adopted in Schulze (2012). The future relative changes (%) are as presented in Table 4.3. Using the information presented in Table 4.3, the artificial weather station created was used to calculate crop water requirements for the future.

Table 4.3: Future projected change in climate parameters for H10C station

	Change in mean annual rainfall	Change in mean annual temperature	Change in Penman Monteith reference potential evaporation
Low	+10%	+20%	+11%
High	+8%	+12%	+7%

Source: Schulze (2012)

This study deviated from the usage of the crop water use change factors (CWUC) as used by Louw *et al.* (2011). Instead of using these factors, actual crop water requirements were estimated using SAPWAT for the future. This is to improve the sensitivity of the farm model since CWUC is a scaling factor (based on reference potential evaporation), which is applied to current crop water demand estimates (estimated elsewhere) to scale them to a future condition.

4.6 ESTIMATION OF CHILL UNIT REQUIREMENTS

As mentioned in Chapter 2 of this thesis, two different chill unit models are widely used in South Africa. The Utah or Richardson model (Richardson *et al.*, 1974), measuring "Richardson Chill Units (RCU)", and the Infruitec model (daily positive Utah model), measuring "Infruitec Chill Units (ICU)". Both models make use of hourly temperature data to calculate accumulated chill units. Hourly temperature data is not available for the base period. Available for use in this study is the daily maximum and minimum temperature. The sine curve mathematical formula is used to convert daily maximum and minimum temperature data to hourly data, meaning that it tries to simulate a sinus curve of hourly data, from daily maximum and minimum data values.

The shape of the temperature curve responds to the daytime solar cycle, and the temperature wave from sunrise to sunset can be described, according to Linvill (1990), as:

$$T(t) = (T_{\max} - T_{\min}) * \sin\left[\frac{(\pi)}{(D + 4)}\right] + T_{\min}$$

In order to define night-time cooling, starting at sunset, the Linvill (1990) mathematical expression can be used, which is given as:

$$T(t) = T_{ss} - \left[\frac{(T_{ss} - T_{mn})}{\ln(24 - D)} \right] \ln(t)$$

Where

- T(t) = temperature at time t after sunrise or at time t after sunset
- T_{max} = maximum temperature
- T_{min} = minimum temperature
- D = day length (hour)
- T_{ss} = temperature at sunset

The calculated T(t) is then used to estimate the accumulated chill units. Change in mean annual temperature, as presented by Schulze (2012), is used to adjust the base temperature for the estimation of future accumulated chill units. The base and future accumulated chill units are then used in the Ceres farm model. H10C quaternary weather station data in SAPWAT was extracted for calculation of accumulated chill units.

4.7 CERES FARM MODEL

The Ceres farm model is one of the important modules in the development of CDIM. The model simulates the demand for agricultural water in the Ceres (Koekedouw) region. Farm-level data and typical farms constructed by Louw (2007) were updated and used in this study. The farm model is dynamic in the sense that it takes into account not only the product markets for crops, but also the asset market for investment in the establishment, management, harvesting and re-establishment of perennial crops. The dynamic nature of the farm model requires that they include beginning inventories of the perennial crops previously planted, but still under cultivation, at the start of the planning horizon, and a terminal condition to reflect the net present value of future 'rotations' over an indefinite time horizon. As such, the models develop a long-term plan for the production of annual and perennial crops, both on dry and irrigated land.

4.7.1 CROP PRODUCTION POSSIBILITIES

The Ceres farm model contains production possibilities both for dry land crops and irrigated crops, as presented in Table 4.4. Crops are further classified on a short-term (vegetables and annual) and long-term (perennial) basis.

Table 4.4: Ceres crop production possibilities

Dry Land Crops	Irrigated Crops	
Wheat	Apples	Nectarines
Barley	Pears	Cabbage
Korog	Peaches	Cauliflower
	Plums	Carrots
	Apricots	Peas
	Pumpkins	Squash
	White wine	Butternuts
	Lucerne	Lettuce
	Long term pastures	Spinach
	Oats	Beetroot
	Potatoes	Sweetmellon
	Tomatoes	Maize
	Onions	Wheat
	Barley	Korog

Each crop has a crop budget associated with it that specifies crop yield per unit area, input requirements, input costs per unit, and crop price. For long-term crops (perennial crops) this same information by growth-stage, from the establishment of the crop to re-establishment, once the trees and vines have reached the maximum age at which they can be replanted.

4.7.2 IRRIGATION TECHNOLOGIES AND WATER USE INTENSITIES

There are three irrigation technologies reflected in the model, micro, sprinkle and drip, as well as three irrigation intensities, optimal, supplemental, and deficit. Monthly irrigation intensities (consumptive water use) used in the farm models are varied by crop, month, irrigation type, and growth stage for perennial crops and were calculated using SAPWAT.

4.7.3 ALGEBRAIC TERMINOLOGIES

Brooke *et al.* (1998), McCarl and Spreen (1997) and Louw (2001) have provided a detailed explanation of these components. The work of these authors can be consulted for a broader understanding of these components to avoid repetition here. The structure of these components as used in this study is therefore presented next.

4.7.3.1 Set structure

A set structure is formed by stating the set first and then the elements within each of the sets. If not in table format, the abbreviation for elements is provided in brackets. **C = set of all farm enterprises**, elements of which are denoted as **c**. The set structure, elements and subsets are presented in Appendix A.

4.7.3.2 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 (Louw 2001). In the description of the parameters, the sets are not always described in the sequence that they appear in the parameter. The Ceres whole-farm model has the following parameters:

TYPD _j	Defines the typical water users in region <i>j</i>
ALAND _{jl}	Availability of land resources <i>l</i> in region <i>j</i>
YEARSOC _i	Land occupation of crops <i>i</i>
AREAU _{im}	Monthly land requirement for land type of crop <i>i</i> in month <i>m</i>
IRINT _{ch}	Irrigation intensity possibilities <i>h</i> for crop <i>c</i>
OH _{b*}	Overhead and household expenses of a typical farm in region <i>b</i>
HH _{b*}	Household expenses of a typical farm in region <i>b</i>
MAXLOAN _{blo}	Maximum short-term loan <i>lo</i> of a typical farm in region <i>b</i>
LABCOST _b	Labour costs per annum of a typical farm in region <i>b</i>
DEPREC _b	Depreciation costs per annum of a typical farm in region <i>b</i>
LANDTAX _b	Land tax value to be taxed per annum of a typical farm in region <i>b</i>
INTST _{lo}	Real interest rate on short-term loans <i>lo</i> (12% and 5% inflation)
INTINV _{sa}	Real Interest rate on investments savings <i>sa</i> (7% and 5% inflation)
MAXC _b	Maximum own labour of a typical farm in region <i>b</i>
MAXR _b	Maximum labour rent capacities of a typical farm in region <i>b</i>
CASCOST	Cost of casual labour per unit
MAXOC _{bph}	Maximum own capital available of a typical farm in region <i>b</i> within the planning horizon <i>ph</i>
TYP _{cb}	Typology definition for a typical farm in region <i>b</i> and crop <i>c</i>

MAXAREA _{stc,b}	Fix aggregate level of short-term crops <i>stc</i> in the base year for a typical farm in region <i>b</i>
MAXGRCT _{b,*}	Maximum for a combination of vegetables for a typical farm in region <i>b</i>
MAXAREALT _{c,b,py}	Maximum area under long-term crops <i>c</i> in the previous years <i>py</i> for a typical farm in region <i>b</i>
CRBD _{i,gsl,*}	Budget information for crops <i>i</i> for the growing stage <i>gls</i> , Where * denotes casual labour (Clab), fixed labour (Flab), water (Water), yield (Yield) and present value of gross margins (PV)
YIELDCONV _{c,p}	Converts total yield of crop <i>c</i> to crop products <i>p</i>
PRICE _{i,p}	Price of cash crops <i>i</i> to crop product <i>p</i> per ton
TERMVAL _{i,gsl}	Terminal values of long-term crops <i>i</i> for the growth stage <i>gls</i>
WC _{i,m}	Water use in period <i>m</i> for crop <i>i</i>
WCRED _{i,m}	Reduced Water use in period <i>m</i> for crop <i>i</i>
IRINTSC _{m,h}	Irrigation intensity <i>h</i> scaling in period <i>m</i>
IRINCSC _{i,h}	Scaling of yield due to deficit irrigation intensity <i>h</i> for crop <i>i</i>
WDC _{b,q}	Allocation of water for irrigation for a typical farm in region <i>b</i> from water sources <i>q</i>
MIRC _{j,q}	Monthly water release capacity in for water users <i>j</i> from water sources <i>q</i>
MAXAWP _{j,q}	Maximum annual water availability for water users <i>j</i> from water sources <i>q</i>
MAXALLOC _{b,q}	Maximum initial volumetric allocation per ha entitlement for a typical farm in region <i>b</i> from water sources <i>q</i>
ALLOCTIME _{q,m}	Availability of water per month <i>m</i> from water source <i>q</i>
PUMPC _q	Pumping costs water sources <i>q</i>
ICW _{b,q}	Cost of water per ha for a typical farm in region <i>b</i> from water sources <i>q</i>
ICWV _{b,q}	Cost of water per volume of water for a typical farm in region <i>b</i> from water sources <i>q</i>
PREF _{c,b}	Preferences of farmers for crop <i>c</i> for a typical farm in region <i>b</i>
MAXFARMD _{j,fd}	Maximum annual dam capacity to be pumped from farm dam <i>fd</i> to water users <i>j</i>

DAMTOTCAP _{<i>j,fd</i>}	Natural inflow to farms dam <i>fd</i> to water users <i>j</i>
MAXFARMREL _{<i>j,fd</i>}	Maximum water release capacity of farm dam <i>fd</i> to water users <i>j</i>
DCAPS1 _{<i>dams</i>}	Reservoir storage capacity of the Koekedouw dam
RO _{<i>ros,m,ph</i>}	Runoff to Koekedouw dam
EVAPC1 _{<i>dams,m,ph</i>}	Evaporation coefficients for dams
EVINT1 _{<i>dams</i>}	Evaporation intercept for Koekedouw dam
EVSLOPE1 _{<i>dams</i>}	Evaporation slope for Koekedouw dam
EVAPC2 _{<i>b,m,ph</i>}	Evaporation coefficients for farm dams
EVSLOPE2 _{<i>b</i>}	Evaporation slopes for farm dams
EVINT2 _{<i>b</i>}	Evaporation intercept for farm dams
DIVCST _{<i>b</i>}	Cost of pumping water from river to farms
PUMPCST _{<i>b</i>}	Additional cost of pumping to farm storage
DCAPS2 _{<i>b</i>}	Farm dam capacity - million m ³
RFC _{<i>b</i>}	Return flow coefficients
MXURBALLO _{<i>u</i>}	Maximum urban allocation from Koekedouw
ELAST _{<i>g</i>}	Demand elasticities for water
BASEVOL _{<i>m,g</i>}	Household urban base monthly water use
URBMIN _{<i>m,g</i>}	Minimum Urban demand monthly water use
BASEPRICE _{<i>m,g</i>}	Urban base price per million m ³
ECRS _{<i>m</i>}	Ecological and reserve needs
VERDISKT _{<i>ph</i>}	Calculates NPV of cash flow (6%)
MANL _{<i>b,ph</i>}	Management level
ROS2 _{<i>Ea,m,ph</i>}	Runoff Section 2
RFC _{<i>b</i>}	Return flow coefficients

4.7.3.3 Variables

The Ceres whole-farm dynamic model contains several types of variables. They are described in terms of the variable contained in the objective function, agricultural production variables, water use variables and hydrology variables.

Variables included in the objective function

The following variables are included in the objective function:

Z	Total welfare (objective function value)
$dconst(g, m)$	Monthly urban demand constraint by sector
$urbdem(g, m, ph)$	Monthly urban demand by sector
$dslope(ph, g, m)$	Monthly urban demand slope by sector
$endb(b)$	End balance after redemption of loans.
$flowby(dams, m, ph)$	Dam spill
$fdflowby(ea, m, ph)$	Farm dam spill

4.7.3.4 Agricultural Production Variables

The agricultural production variables are the building blocks for the construction of the typical farms in the model.

$cf_{c,h,b,th}$	Area of crop c grown with irrigation intensity h on typical farm b for period th
$Totarea_{i,j,ph}$	Total long-term crop i area produced by water users j at a particular time ph
$TcropA_{i,h,b,th}$	Total crop area for Koekedouw/Ceres
$TLTopr_{r,b,ph}$	Total long-term crop area for Koekedouw/Ceres in any given year
$TotvegA_{b,ph}$	Total area of all vegetables
$TFCP_{c,p,b,ph}$	Typical farm b t annual production volume of crop i
$TCP_{i,p,ph}$	Total region production volume of crop i
$CS_{i,p,b,ph}$	Sell cash crops
$TCS_{i,p,b,ph}$	Total crop sales volume for Koekedouw/Ceres
$OC_{b,ph}$	Overhead costs for typical farm b
$HC_{b,ph}$	Household costs for typical farm b
$Owncap_{b,ph}$	Own capital contribution

TOTFAW _{<i>b,ph</i>}	Total annual water demand for typical farm <i>b</i>
TFMW _{<i>b,m,ph</i>}	Typical farm monthly water demand
Investmnt _{<i>b,Ph</i>}	Investment surplus for typical farm <i>t</i> in region <i>b</i> for year <i>ph</i>
Loanst _{<i>b,lo,ph</i>}	Short term loan for farm <i>t</i> in region <i>b</i> in year <i>ph</i>
Endb _{<i>b</i>}	End balance after redemption of loans
Prodcost _{<i>b,ph</i>}	Total direct production costs
Wcost _{<i>b,ph</i>}	Calculates water tariff per farm
Prodinc _{<i>b,ph</i>}	Total income from crop sales
Tvalues _{<i>b</i>}	Terminal values at the end of the planning horizon

4.7.3.5 Water use variables

Mwatertr _{<i>q,j,m,ph</i>}	Monthly transfer from schemes
AnualWU _{<i>j,ph</i>}	Annual water use
Wbal _{<i>j,q,ph</i>}	Balance of water remaining in sources after filling of farm dam
MWwatertr _{<i>q,j,ph,m</i>}	Monthly winter water extraction to fill farm dam
Damex _{<i>j,ph,m</i>}	Extraction from farm dam for irrigation
TotWSCH _{<i>q,j,ph</i>}	Total annual extraction from scheme for dam fill in winter plus direct use.

4.7.3.6 Hydrology variables

Urbdem _{<i>g,m,ph</i>}	Monthly urban demand by sector
Runoff _{<i>sites,sites, m, ph</i>}	Run off transfers
Transfers _{<i>sites,sites, m, ph</i>}	Releases from dams
Urbsup _{<i>sites, m, ph</i>}	Total urban supply
Stors1 _{<i>dams, m, ph</i>}	Reservoir storage Koekedouw
Flowby _{<i>dams, m, ph</i>}	Dam spill
Storstart _{<i>dams</i>}	Starting and ending storage
F _{<i>b,m,ph</i>}	Flow after diversion at each farm
Dtofld _{<i>b,m,ph</i>}	Diversion to fields on farms
Dtostor _{<i>bm ph</i>}	Diversion to farm storage

$Fstor_{bm,ph}$	Storage on farm reservoirs
$Fdflowby_{Ea,m,ph}$	Farm dam spill
$Stofld_{b,m,ph}$	Release from farm dams to fields
$Totdiv_{b,m,ph}$	Total diversion to fields and farm dam
$Cuse_{b,m,ph}$	Consumptive use by crops link to farm water use
$End_{ph,m}$	Ending flow
$Storstartf_b$	Starting and ending storage for farm dams
$KoekTrans_{Ea,Kw,m,ph}$	Volume of water transferred from Koekedouw scheme to farms

4.7.3.7 Objective function

The objective function of the model is to maximise the net present value of the economic returns to water. The model maximises an economic objective function, subject to constraints. As such, it simulates how water users and water managers would behave if they jointly maximise the net returns to water through actions under their control.

The objective function is specified as:

$$MaxZ = \sum_{g,m,ph} dconst_{g,m} * URBDEM_{g,m,ph} + \frac{1}{2} dslope_{ph,g,m} * sqr(URBDEM_{g,m,ph}) + \sum_b ENDB_b - \sum_{dams,m,ph} FLOWBY_{dams,m,ph} - \sum_{ea,m,ph} FDFLOWBY_{ea,m,ph}$$

Where:

$$dconst_{g,m} * URBDEM_{g,m,ph} + \frac{1}{2} dslope_{ph,g,m} * sqr(URBDEM_{g,m,ph})$$

represents the willingness-to-pay for water by the urban sector;

$$ENDB_b$$

is the end balance after redemption of loans;

$$FLOWBY_{dams,m,ph} \text{ and } FDFLOWBY_{ea,m,ph}$$

represents dam spill and farm dam spill, respectively.

The objective function is consistent with welfare maximisation by water consumers, farmers, and water managers and, thus, simulates the competition for water in efficient markets. Also, it is an accounting convention that measures the economic value of water. The objective

function is based on the assumption that farmers will maximise their long-term farm income, urban water users will maximise their willingness-to-pay for water, less the costs of water, and water managers will operate the system in order to satisfy these objectives at minimum cost.

4.7.3.8 Equations

The equations are used to set constraints for the model. The first section deals with the agricultural production equations, including land use and water use.

Agricultural production equations

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

Constraint 1: Restricts demand for land to available demand:

$$\sum_{i,h,th} cr_{i,h,b,th} \leq A_{land}_{bl}$$

Constraint 2: Calculates the total crop area for long-term crops in any given year:

$$\sum_{h,th} cr_{r,h,b,th} = Totarea_{r,b,ph}$$

Constraint 3: Calculates total crop area for Ceres in any year:

$$Cr_{i,h,b,th} = TcropA_{i,h,b,th}$$

Constraint 4: Calculates total long-term crop area for Ceres in any given year:

$$Totaarea_{r,b,ph} = TLTopp_{r,b,ph}$$

Constraint 5: Sums total area under all vegetables production:

$$\sum_{v,h} cr_{v,h,b,ph} = TotvegA_{b,ph}$$

Constraint 6: Calculates the total production of crops products in any given year:

$$TFCP_{i,p,b,ph} = \sum_{h,th,gl} cr_{i,h,b,th} * CRBD_{i,gl,"yield"} * IRINCSC_{i,h} * ManL_{b,ph} * Yieldconv_{i,p}$$

Constraint 7: Balance total production with total crop sales:

$$CS_{i,p,b,ph} = TFCP_{i,p,b,ph}$$

Constraint 8: Sums total crop sales from Ceres for all farms:

$$CS_{i,p,b,ph} = TCS_{i,p,b,ph}$$

Water use and balancing equations

The constraint equations in this group are designed to first calculate the water demand for each user and then to equate the demand with supply through the water entitlement and other water sources.

Constraint 9: denotes the water requirement of irrigation crops per typical farm in each of the irrigation regions and which cannot exceed the total availability of water for irrigation:

$$\sum_{k,h,th} cr_{k,h,b,th} * (to\ tan\ crwr_{k,h} / scalefact) - Totfaw_{b,ph} = 0$$

Constraint 10: Typical farm monthly water demand:

$$\sum_{k,h,th} cr_{k,h,b,th} * (WC_{k,m} * IRINTSC_{m,h} * IRINT_{k,h} * 10) / scalefact = TFMW_{b,m,ph}$$

Constraint 11: Equalise monthly with total irrigation use:

$$TOTFAW_{b,ph} = \sum_m TFMW_{b,m,ph}$$

Constraint 12: Maximum water right allocation to water users (Maxiallo_{b,ph}):

$$TOTFAW_{b,ph} \leq \sum_q (MIRC_{b,q} * Maxawp_{b,q}) / scalefact$$

Farm reservoir balances

Constraint 12: Starting reservoir balances:

$$FSTOR_{Ea,firstmo,firstyr} = STORSTARFT_{Ea}$$

Constraint 13: Intermediate reservoir balances:

$$FSTOR_{Ea,m+1,ph} = FSTOR_{Ea,m,ph} + DTOSTOR_{Ea,m,ph} - STOFD_{Ea,m,ph} - FDFLOWBY_{Ea,m,ph} - EVAPC2_{m,ph} * EVSLOPE2_{Ea} * FSTOR_{Ea,m,ph} + EVINT2_{Ea}$$

Constraint 14: Transition reservoir balances at the end of each year:

$$FSTOR_{Ea,firstmo,ph+1} = FSTOR_{Ea,lastmo,ph} + DTOSTOR_{Ea,lastmo,ph} - STOFD_{Ea,lastmo,ph} - FDFLOWBY_{Ea,lastmo,ph} - EVAPC2_{lastmo,ph} * EVSLOPE2_{Ea} * FSTOR_{Ea,lastmo,ph} + EVINT2_{Ea}$$

Constraint 15: Ending reservoir balances:

$$STORSTARTF_{Ea} = FSTOR_{Ea,lastmo,lastyr} + DTOSTOR_{Ea,lastmo,lastyr} - STOFD_{Ea,lastmo,lastyr} - FDFLOWBY_{Ea,lastmo,lastyr} - EVAPC2_{Ea,lastmo,lastyr} * EVSLOPE2_{Ea} * FSTOR_{Ea,lastmo,lastyr} + EVINT2_{Ea}$$

Constraint 15: Capacity constraint on farm reservoirs:

$$FSTOR_{Ea,m,ph} \leq DCAPS2_{Ea}$$

4.8 INTERTEMPORAL SPATIAL EQUILIBRIUM MODULE

The series of equations used in this module are based on the work of Callaway *et al.* (2005). Callaway *et al.* (2005) can be consulted for full information about the series of equations, and only relevant equations needed for the Ceres dynamic equilibrium model are presented here. This module is a matrix of linear equations and constraints in the mathematical programming model that characterises the water balances in the basin reservoirs – both storage and farm dams – and the spatially distributed physical linkages between runoff, water storage, and points of water use.

Constraint 16: Runoff Allocation Equations

These equations allocate the monthly runoff at each runoff gauge, the runoff from a single tributary can be diverted through a man-made conveyance structure or it can be allowed to continue downstream. The structure of the equations in this block follows the form:

$$\sum_{A1(ros.sites)} RUNOFF_{ros,sites,m,ph} = RO_{ros,m,ph}$$

where $RUNOFF_{ros,sites,m,ph}$ is a variable designating the allocated runoff at a specific site in month m and year ph from the runoff gauge ros ;

$RO_{ros,m,ph}$ is the monthly-annual runoff at gauge ros , as calculated in ACURU;

and $A1(ros, sites)$ is a convention (used throughout this thesis) to express a subset of ros and $sites$ that links runoff from specific gauges in the set ros to the major storage reservoirs, the Koekedouw site and Ceres urban demand in the set $sites$.

Constraint 17: Dynamic Storage Balances

These equations conserve the mass balance of water, over time, at the reservoir in the basin. For each reservoir there is: 1) an initial balance that specifies the level of starting storage in the first month of the first year, 2) intermediate balances that apply to the months January through to November of a given year; 3) end-of-year transitional balances that link water storage in December of one year to January in the next year; and 4) a terminal period balance.

Initial Balances

$$STORS1_{dams,firstmo,firstyr} = STORSTARTS1_{dams} \quad \text{for all dams,}$$

where $STORS1_{dams,firstmo,firstyr}$ is a variable for the starting storage for each dam in the first month of the first year of the planning horizon and $STORSTARTS1_{dams}$ is a variable that represents the starting and ending storage in each dam. The starting and ending storage is calculated endogenously, although the initial storage can also be set exogenously as a parameter to examine reservoir filling strategies, if that is necessary.

Intermediate Balances

$$STORS1_{dams,m+1,ph} = STORS1_{dams,m,ph} - EVAPCI_{(dams,m,ph)} * EVSLOPE_{(dams)} * STORS1_{(dams,m,ph)} + EVINT1_{dams} - FLOWBY_{dams,m,ph} + \sum_{A1(ros,dams)} RUNOFF_{ros,dams,m,ph} - \sum_{A2(dams,sites)} TRANSFERS_{dams,sites,m,ph}$$

for all dams, for month $m+1$ and all ph ,

where $EVAPCI_{dams,lastmo,ph}$ is the monthly annual evaporation coefficient from ACURU for each storage reservoir;

EV_{SLOPE}_{dams} and EV_{INT}_{dams} are parameters for the evaporation slopes and intercepts of the area-volume curves for each storage reservoir;

$TRANSFERS_{dams,sites,m,ph}$ is a variable that represents the possible transfers/releases from each reservoir to other dams and sites in the basin.

End of year transition balances

$$\begin{aligned} STORSI_{dams,firstmo,ph+1} = & STORSI_{(dams,lastmo,ph)} - EVAPCI_{(dams,lastmo,ph)} * EV_{SLOPE}_{dams} \\ & * STORSI_{(dams,lastmo,ph)} + EV_{INT}_{dams} - FLOWBY_{dams,lastmo,ph} + \sum_{A1(ros.dams)} RUNOFF_{ros,dams,lastmo,ph} \\ & - \sum_{A2(dams.sites)} TRANSFERS_{dams,sites,lastmo,ph} \end{aligned}$$

for all dams, for month m+1 and all ph,

Ending storage balance / Terminal balances

$$\begin{aligned} STORSTARTS_{dams} = & STORSI_{dams,lastmo,lastyear} - EVAPCI_{dams,lastmo,lastyear} * EV_{SLOPE}_{dams} \\ & * STORSI_{dams,lastmo,lastyear} + EV_{INT}_{dams} - FLOWBY_{dams,lastmo,lastyr} + \sum_{A1(ros.dams)} RUNOFF_{ros,dams,lastmo,lastyear} \\ & - \sum_{A2(dams.sites)} TRANSFERS_{dams,sites,lastmo,lastyear} \end{aligned}$$

for all dams in the last month of the last year.

Capacity Constraints

If the Koekedouw dam storage capacity is fixed, each reservoir in the upper basin has the following storage capacity constraints:

$$STORSI_{dams,m,ph} \leq DCAPS_{dams} \quad \text{for all dams, m and ph}$$

If the Koekedouw Dam storage capacity is determined endogenously in the model, the capacity equations become:

$$STORS1_{dams,m,ph} \leq DCAPS1_{dams}$$

for all m and ph

$$STORS1_{Koekdam,m,ph} \leq KOEKCAP \text{ for all } m \text{ and } ph,$$

where $DCAPS1_{dams}$ is a parameter denoting the storage capacity of the reservoirs and $KOEKCAP$ is a variable representing the endogenously determined capacity of the Koekedouw Dam.

Capacity Constraints on Transfers

There are a number of capacity constraints in the model to restrict releases from dams and to restrict the capacity of transfers in man-made conveyance structures between dams.

Constraint on transfer from Koekdam to Urb1

$$TRANSFERS_{koekdam,URB1m,ph} \leq TCAP1$$

Constraints for agricultural summer diversions from Koekdam

$$\sum_{SWM(M)} TRANSFERS_{Koekdam,Agric,M,ph} = TCAP4$$

Urban Linkage Equation

There are substantial losses in the delivery of water from urban waterworks to urban users. Accordingly, it was necessary to add an equation to characterise the impact of these features on the urban supply balance. At the same time, it was necessary to link the water demands in the urban module to the water supply in the dynamic spatial equilibrium model, a linkage that occurs through this equation. The urban linkage equations are:

$$\sum_{A5(sites)} (1 - LF) * URBSUP_{sites,m,ph} = \sum_g URBDEM_{g,m,ph}$$

for all m and ph ,

where LF is a fractional urban water loss parameter; and $URBDEM_{g,m,ph}$ is the demand for water by urban water sector g in month m and year ph .

Dynamic storage balances for on Farm reservoirs

Initial Balances / Starting reservoir balances

$$FSTOR_{Ea,firstmo,firstyr} = STORSTARFT_{Ea}$$

where $FSTOR_{Ea,firstmo,firstyr}$ is a variable representing the storage in farm dam Ea in January (first month) in the first year of the planning horizon and $STORSTARFT_{Ea}$ is a variable denoting the initial and terminal storage in each of the farm dams.

Intermediate reservoir balances

$$FSTOR_{Ea,m+1,ph} = FSTOR_{Ea,m,ph} + DTOSTOR_{Ea,m,ph} - STOFD_{Ea,m,ph} - FDFLOWBY_{Ea,m,ph} - EVAPC2_{Ea,m,ph} * EVSLOPE2_{Ea} * FSTOR_{Ea,m,ph} + EVINT2_{Ea}$$

for all Ea , $m+1$ and ph , where $EVAPC2_{Ea,m,ph}$ are the farm reservoir evaporation coefficients from ACUR and $EVSLOPE2_{Ea,m,ph}$ and $EVINT2_{Ea}$ respectively, are the slopes and intercepts of the volume-area equations for each farm dam.

End of the year transition balances

$$FSTOR_{Ea,firstmo,ph+1} = FSTOR_{Ea,lastmo,ph} + DTOSTOR_{Ea,lastmo,ph} - STOFD_{Ea,lastmo,ph} - FDFLOWBY_{Ea,lastmo,ph} - EVAPC2_{Ea,lastmo,ph} * EVSLOPE2_{Ea} * FSTOR_{Ea,lastmo,ph} + EVINT2_{Ea}$$

for all farms, for the first month of each $ph+1$.

Ending reservoir balances

$$STORSTARFT_{Ea} = FSTOR_{Ea,lastmo,lastyr} + DTOSTOR_{Ea,lastmo,lastyr} - STOFD_{Ea,lastmo,lastyr} - FDFLOWBY_{Ea,lastmo,lastyr} - EVAPC2_{Ea,lastmo,lastyr} * EVSLOPE2_{Ea} * FSTOR_{Ea,lastmo,lastyr} + EVINT2_{Ea}$$

For all dams in the last month of the last year.

Capacity constraint on farm reservoirs

The monthly–annual storage in the farm dams cannot exceed their capacity. Therefore, farm storage is constrained in each period, using the following equations:

$$FSTOR_{Ea,m,ph} \leq DCAPS2_{Ea} \text{ for all } Ea, m \text{ and } ph$$

Spatial Balances

This refers to the spatial balances between farms and the Koekedouw dam.

Initial flow balance on Koekedouw below dam

$$F_{firstfarm,m,ph} + DTOFLD_{firstfarm,m,ph} + DTOSTOR_{firstfarm,m,ph} \leq ROS2_{firstfarm,m,ph}$$

Intermediate balances linking farms

$$\begin{aligned} & -RFC_{Ea} * DTOFLD_{Ea,m,ph} + STOFD_{Ea,m,ph} - F_{Ea,m,ph} - ROS2_{Ea+1,m,ph} + DTOFLD_{Ea+1,m,ph} \\ & + DTOSTOR_{Ea+1,m,ph} + F_{Ea+1,m,ph} = 0 \end{aligned}$$

Last flow balance below dam

$$END_{ph,m} - RFC_{lastfarm} * DTOFLD_{lastfarm,m,ph} + STOFD_{lastfarm,m,ph} - F_{lastfarm,m,ph} = 0$$

Consumptive Use Balances

The farm models need a consumptive use supply variable to balance the crop water demands on irrigated areas in each farm region. The consumptive use balances links the two modules through a consumptive use variable for each regional farm. The consumptive use balances are:

$$CUSE_{Ea,m,ph} = (1 - RFC_{Ea}) * (DTOFLD_{Ea,m,ph} + STOFD_{Ea,m,ph})$$

for all Ea, m and ph

where $CUSE_{Ea,m,ph}$ is the amount of water used consumptively by crops on farm Ea in month m and year ph .

In stream Flow Constraints

In accordance with public policy, the in-stream flows in the lower portion of the Koekedouw must be maintained above critical levels to protect aquatic ecosystems.

These constraints are included in the model as:

$$F_{Ea,m,ph} \geq ECRS_m \quad \text{for all } Ea, m \text{ and } ph$$

where $ECRS_m$ is the monthly in-stream flow requirement for month m .

4.9 THE URBAN DEMAND MODULE

The urban demand water sector is based on two previous studies of the Berg River by Callaway *et al.* (2008, 2009) and Louw *et al.* (2011). Detailed information concerning the methods of estimation can be found in these studies. These demand functions play an important role in determining the net economic returns to water for two reasons. First, monthly water consumption and the shadow prices of urban water consumption (the price paid by water customers + the scarcity price) are calculated endogenously in the intertemporal spatial equilibrium model. Second, the integral of these demand functions appear in the objective function of the model and are the basis for calculating consumers' willingness to pay for water and consumer surplus (Louw *et al.*, 2011).

The demand function parameters were fit using the following equations:

$$DSLOPE_{ph,g,m} = \frac{pricefac * BASEPRICE_{g,m}}{BVFAC * (1 + POPGRO)^{ph} * BASEVOL_{g,m} * ELAST_g} \quad \text{for all } ph, g \text{ and } m.$$

$$DCONST_{g,m} = DSHIFT * (pricefac * BASEPRICE_{g,m}) * \frac{(ELAST_g - 1)}{ELAST_g} \quad \text{for all } g \text{ and } m.$$

$$MAXXDEM_{g,m,ph} = \frac{-DCONST_{g,m}}{DSLOPE_{ph,g,m}} \quad \text{for all } g, m \text{ and } ph.$$

where $DCONST_{g,m}$ is a calculated parameter that stands for the water demand function constant in urban sector g in month m ;

$DSLOPE_{g,m,ph}$ is a calculated parameter for the slope of the water demand function in sector g , in month m and year ph ;

$ELAST_g$ is the price elasticity of urban water demand in urban sector g from Louw (2001 and 2002);

and $BASEPRICE_{g,m}$ and $BASEVOL_{g,m}$ are the estimates of base water consumption and prices.

The expression $BVFAC_{g,m,ph} * (1 + POPGRO)^{ph}$, in the denominator of the *DSLOPE* equation, is used to shift the urban demand functions to the right to simulate exogenous population growth over time.

4.10 INTEGRATED MODEL OUTPUT

The output of the model is as depicted in Figure 4.1, although it is not limited to the ones listed therein. The important outputs for the purpose of this thesis include:

- annual crop mixes by farm and region;
- monthly water diversions and consumptive use by urban sector, farm regions and irrigated crops in each region;
- monthly reservoir storage, releases and transfers, and reservoir evaporation for main storage and farm reservoirs; and
- water prices, in urban and agricultural uses.

4.11 CONCLUSION

The purpose of this Chapter 4 was to describe the design of the Ceres Dynamic Integrated Model that was used to simulate the potential impact of climate change in the Ceres region of Western Cape. It is referred to as integrated framework because it linked different important modules together in a single unit. Although the existing model can be used to simulate different adaptation strategies to climate change, they are not sensitive to climate variables. Accordingly, there is need for further development of the model. Two additional modules (irrigation crop water requirement and chill unit accumulation module) were added to the existing framework to improve the sensitivity of the farm model. This is important because of the types of crops that are produced in the study area. The area is known for deciduous fruit production and these crops are sensitive to accumulated chill units.

This study deviated from the usage of crop water use change factors (CWUC), as used by Louw *et al.* (2011) to capture climate change impacts. Instead of using these factors, actual crop water requirements were estimated using SAPWAT for the future requirements. This is also believed to be able to improve the sensitivity of the farm model to climate variables. By extending the existing model, a more informed decision can now be made regarding the different adaptation strategies available to farmers and policy makers.

5.1 INTRODUCTION

The results of the respective analyses are presented and discussed in Chapter 5. The first part of this chapter reports the results of the crop water requirements estimated for the base period and the future climate, taking into consideration the climate change projection for the future. In the second part of this chapter, the results of the two chill unit accumulation models are presented and discussed. The base model results from the integrated model of the Ceres region are presented in the third part, and this is followed by the results of the various adaptation options tested in the future model to help farmers to adapt to the impacts of projected climate change on their farm businesses.

5.2 IMPACT OF CLIMATE CHANGE ON CROP WATER REQUIREMENT

SAPWAT3 (van Heerden *et al.*, 2008) was used to estimate crop water requirements for the base climate (1971-1990) and for the future climate (2046-2065). An artificial weather station was built into SAPWAT to calculate crop water requirements for the future because SAPWAT does not have information about the future climate. It is hypothesised that with climate change, crop water requirements are going to increase. Two different types of irrigation technologies, namely drip and sprinkler irrigation systems, were considered and analysed. These two irrigation systems are the most common type used by farmers in the Ceres region. Table 5.1 presents the results of the crop water requirements from SAPWAT. The crops presented here represent the crops included in the Farm model discussed in Chapter 4 of this thesis.

Table 5.5: Estimated Crop water requirement (m³/ha) for the base and future climate

Crop Option	Sprinkler			Drip			
	Base	Future	+	Base	Future	+	
			%			%	
Fruits							
Apples	Bud break: Mid spring	2980	3510	18	2110	2510	19
Apricot	Bud break: Early spring	2830	3400	20	1950	2320	19
Pears	Bud break: Late winter	3980	4690	18	2790	3320	19
Nectarine	Bud break: Mid spring	3480	4090	18	2350	2780	18
Peaches	Bud break: Mid spring	4130	4880	18	2900	3390	17
Grapes	Bud break: Mid spring	2870	3410	19	2170	2550	18
Plums	Bud break: Early spring	3390	3950	17	2180	2580	18
Vegetables							
Potatoes	Medium variety	4130	4650	13	2740	3080	12
Tomatoes	Table	4220	4860	15	2770	3190	15
Onion	Medium long day	7780	8680	12	2390	2770	16
Cabbage	Early varieties	3600	4020	12	2240	2530	13
Cauliflower	Early varieties	4300	4720	10	2840	3220	13
Carrots	Standard	3920	4390	12	2180	2490	14
Peas	Standard	4460	5050	13	2650	3050	15
Pumpkin	Standard	3460	3930	14	2260	2610	15
Squash	Baby	2980	3830	29	1990	2660	34
Butternut	Standard	4310	4570	6	2820	3070	9
Lettuce	Standard	3560	4450	25	1830	2510	37
Spinach	Standard	4520	5130	13	2570	2920	14
Beetroot	Standard	2790	3190	14	1970	2240	14
Melon	Early varieties	3740	4210	13	2580	2960	15
Pastures							
Pastures	Kikuyu	2260	2670	18	1750	2070	18
Lucerne	Standard	3290	3870	18	2480	2890	17
Cereals							
Korog	Winter cereals	3410	3950	16	1660	2040	23
Oats	Spring types	2790	3240	16	1400	1720	23
Maize	Short growers	3270	3850	18	2260	2670	18
Barley	Spring types	2790	3240	16	1400	1720	23

Water requirements will increase substantially for both types of irrigation technology. Table 5.1 shows that the crop water requirements for fruit crops range between 2830 and 4130 m³/ha for sprinkler irrigation in the base climate while that for the future climate ranges between 3400 and 4880 m³/ha. In the case of drip irrigation, the values are smaller with the base climate crop water requirement ranging between 1950 and 2900 m³/ha, while that for future climate ranges between 2320 and 3390 m³/ha. Of all the fruit crops considered, peaches use the most water under the two irrigation technologies, both in the present and future climates. The crop water requirements for vegetable crops range between 2790 and 7780 m³/ha using sprinkler irrigation technology in the base climate, while that of the future

climate ranges between 3 190 and 8 680 m³/ha. The requirement is slightly different in the case of drip system technology, with the base climate ranging between 1 830 and 2 840 m³/ha, while that for future climate ranges between 2 510 and 3 220 m³/ha. Of all the vegetables, onions are found to use more water, both in the base and future climate for the two irrigation technologies, although there is a substantial variation in the water usage in the sprinkler irrigation compared to drip irrigation system. Despite the high crop water requirement of onions, the Ceres region is known for onion production, with the Western Cape being the leading province in terms of onion production in South Africa. The Ceres region is also relevant in terms of the export of onions to the rest of the world.

The crop water requirements for cereals range between 2 790 and 3 410 m³/ha in the base climate, and between 3 240 and 3 950 m³/ha in the future climate for sprinkler irrigation technology, while that for drip technology ranges between 1 400 and 2 260 m³/ha for the base climate and 1 720 and 2 670 m³/ha for the future climate. Korog use more water under sprinkler technology (base and future) when all crops under the system are considered, while maize uses more water under the drip irrigation system, both in the base and future climates. In general, Table 5.1 shows that water use for drip irrigation are less than that of sprinkler irrigation because of efficiency differences in the irrigation systems. With the drip irrigation system less water is applied, with the figures presented in Table 5.1 confirming this.

It is important to state that crop water requirement (water use) is dependent on the cultivar of each crop chosen, as cultivar differences also play a major role. Table 5.1 shows that crop water requirements will increase as a result of projected climate change using the A2 climate change scenario. The change can be attributed to increase in temperature projected for the future. The crop with the highest deviation from the base climate in both irrigation systems is squash (29 and 34 %) while butternut (6 and 9 %) recorded the lowest deviation from the base climate for both sprinkler and drip irrigation technologies. Based on the findings presented in Table 5.1, an important adaptation strategy may be for farmers to make use of a more efficient irrigation system to mitigate the impact of increased water scarcity caused by climate change. Table 5.1 shows that future crop water requirements for drip irrigation systems are still lower than the current water requirements under sprinkler systems. Accordingly, despite a substantial increase in water requirements under drip irrigation, the total water requirement will be less under a drip system, compared to a sprinkler system.

With climate change resulting in an increase in crop water requirements in the future, coupled with limited available irrigation water and competition between agricultural, urban and industrial water usage, farmers should look into a more efficient way of using water. When addressing adaptation measures to be implemented to increase water use efficiency, a holistic approach that incorporates water productivity by crop, the use of water in the root zone for

transpiration and conversion into marketable product, as well as the efficiency of delivery of water from source to soil, should be considered.

The estimated crop water requirements for the base and future climates that were presented and discussed above will be used as input data in the Ceres Whole Farm Model to investigate how farmers should adjust their crop selection/combination as an adaptation to climate change, as is discussed in section 5.5. Further adaptation strategies will then be simulated for sustainability of the farm structure in the future. In the next section, the results from the application of chill unit models to determine the impact of climate change on chill unit accumulation is presented and discussed.

5.3 IMPACT OF CLIMATE CHANGE ON CHILL UNIT ACCUMULATION

The Utah model of Richardson *et al.* (1974) and the Daily positive Utah (Infruited) chill unit accumulation model of Linsley-Noakes *et al.*(1994) are used in this section to test the hypothesis that winter chill will reduce with climate change. The Richardson and Infruited models accumulate the same way, with the exception that the Infruited model there is no loss of chill units when the temperature exceeds 16°C. The climate variable of interest here is temperature. It is hypothesised that, as temperatures increase in the future owing to climate change, the accumulated chill units will reduce. The accumulated chill units reported in this section are calculated for the winter months (1st of May till 31st of August).

Figure 5.1 presents the accumulated chill units in Richardson units (RCU) from the Richardson model for the present (1971 – 1990) and future time (2046 – 2065). The mean accumulated chill for the present climate is 1291 RCU while that of future climate is 826 RCU. Figure 5.1 indicates that with increase in temperature, the accumulated chill units will reduce in the future.

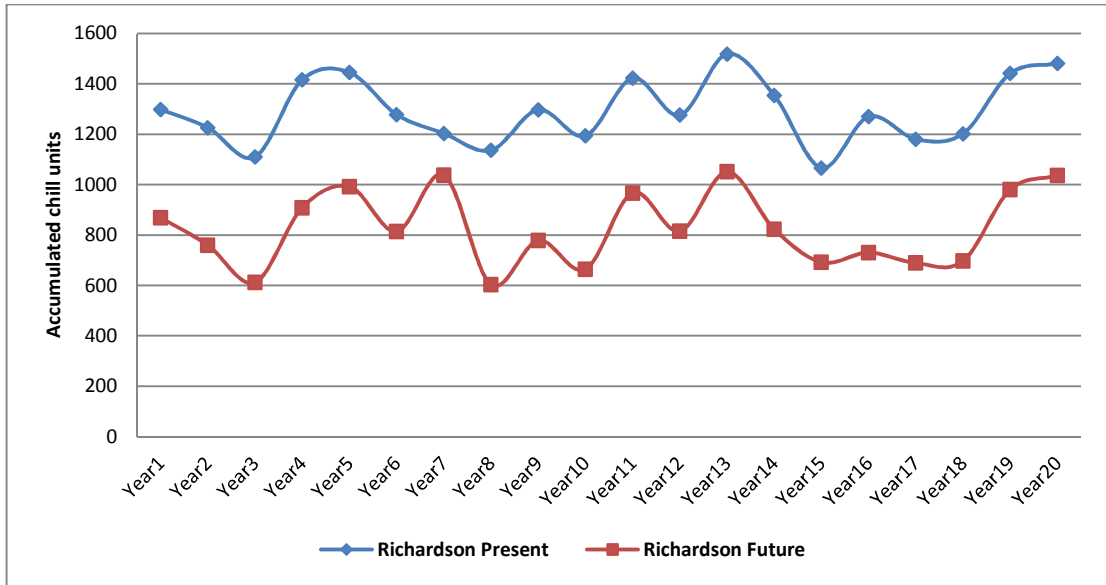


Figure 5.3: Comparison between the accumulated chill in the present and future climate using the Richardson Chill Unit Model

Figure 5.2 presents the accumulated chill units in Infruitec units (ICU) from the Infruitec model for the present (1971 – 1990) and future time (2046 – 2065). The mean accumulated chill for the present climate is 1319 ICU while that of future climate is 906 ICU. Similar to Figure 5.1, Figure 5.2 show that climate change has resulted in the reduction in accumulated chill on a year on year basis.

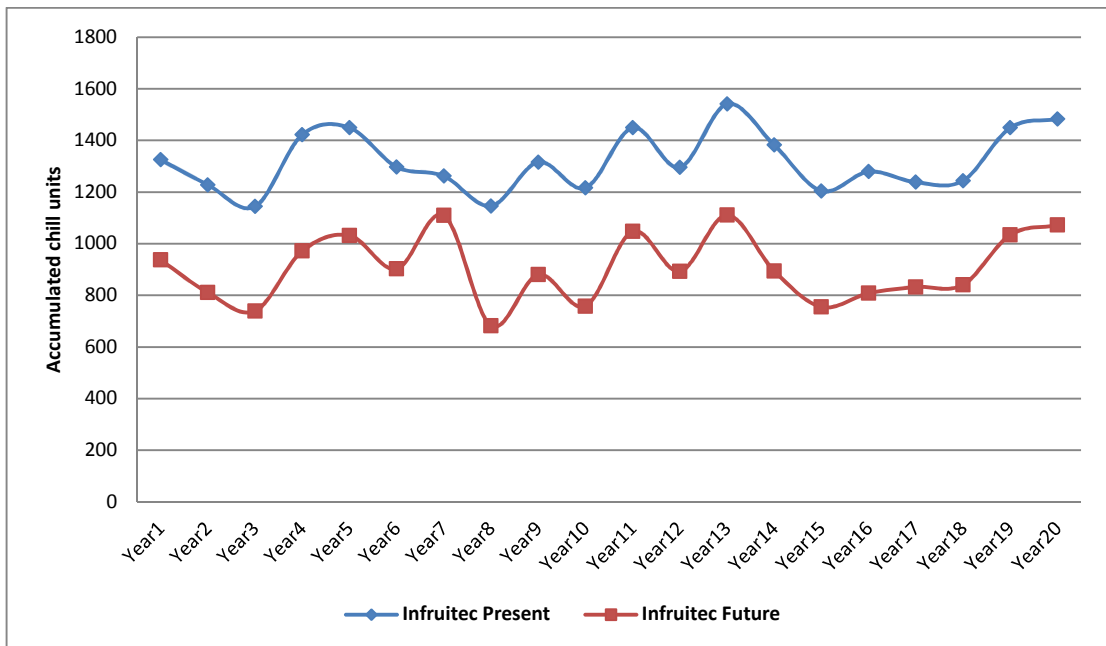


Figure 5.4: Comparison between the accumulated chill in the present and future climate using the Infruitec Chill Unit Model

Figure 5.3 compares the two models in terms of deviation from the base. The average deviation from the base for the Richardson model over the 20 year period is 36%, while that of Infruitec is 32%. These deviations from the mean were found to be statistically significant at 95% confidence interval ($\alpha = 0.05$). As can be seen from Figure 5.3, the impact of climate change (projected temperature increase) on chill unit accumulation is more pronounced using the Richardson model, compared to Infruitec model. The major difference between the two models, according to expert opinion, is in the interpretation of the models. The Richardson model gives the “quality” of the cold units while the Infruitec model is more about the “quantity” of the cold units (Peter de Vries, Hortec – Personal interview).

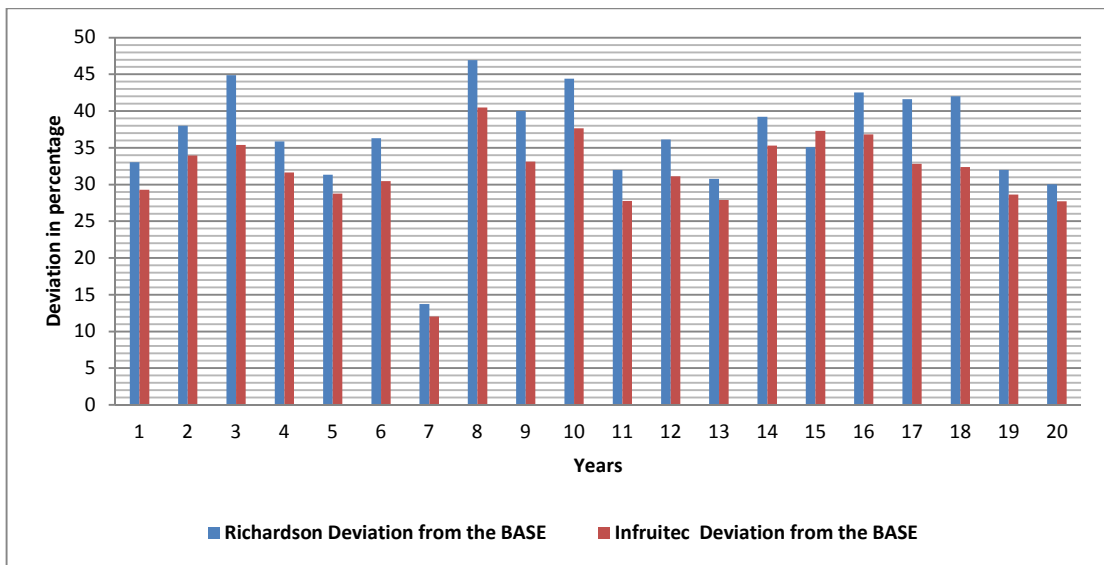


Figure 5.5: Comparison between Richardson and Infruitec chill unit accumulation models
Source: Own computation

The results presented show that it might be difficult to produce some fruit crops in the future in the Ceres region owing to the insufficient chill that would be accumulated in the future. Considering the long life span of deciduous fruit trees compared with annual crops and the substantial investments required for the establishment, tree crop growers will be more vulnerable to the long term effects of climate change than growers of annual crops. This will likely require a growers’ transition to different species or cultivars or the development of management practices (planting density, pruning practices and irrigation regime) that can help overcome shortages in winter chill. Climate change is also likely to severely challenge current production systems, some of which already rely on cultural measures such as rest-breaking chemicals and artificial defoliation. More research and development is required on cost-effective and safe rest-breaking products and programmes which are more suited to warmer conditions. The estimated chill units for the base and future climates will be used in the study for planning purpose in the Ceres whole-farm model discussed in Chapter 4. Since most of the crops are already established in the present climate, the projected future values can guide farmers in the selection of cultivars in the future when re-establishment of their orchard is to

be done. Otherwise, farmers will rely on the use of artificial rest breaking chemicals in cases of low accumulation. This will increase the production costs and hence have an impact on the profitability of such enterprise. In the next section, base results from the integrated model are discussed.

5.4 COMPARISON OF BASE CLIMATE CHANGE SCENARIOS FROM THE INTEGRATED MODEL

The previous chapter gave a description of the methodologies which were used to construct the integrated modelling framework. In this section the results of the scenarios are discussed. The objective of the modelling exercise was to demonstrate that it is possible to develop an integrated modelling framework for evaluating and making adaptation decisions related to agriculture and water resources in the Ceres area of Western Cape. This will enable one to predict what the farm structure will look like in the future and to be able to advise the farmers concerned. The integrated framework developed in this study has outputs that relate to both the agricultural and the urban sectors. For the sake of clarity, the focus of the discussion in this study will be on the agricultural sector. Sections that follow discuss the impact of climate change on area (irrigation intensities and crop combinations); water use (agricultural water demand and crop water use); and welfare (Net Disposable Farm Income (NDFI) and Total welfare).

5.4.1 IMPACT OF CLIMATE CHANGE ON AREA - BASE COMPARISON

Table 5.2 presents the average area under different irrigation intensities for the base scenarios. The average was calculated over a 20 year the planning horizon. Table 5.2 shows that there is no difference between UCT low and UCT high scenarios. For each of the low base climate scenarios, 591 ha of land are under optimal irrigation, while 57 ha and 16 ha are under deficit irrigation and dry land cultivation, respectively. This situation, however, changed in the base future scenarios with substitution taking place between optimal and deficit irrigation. About 23 ha of land were substituted from optimal irrigation with deficit irrigation, while area under dry land was halved in the future scenario. This is according to expectation because less water is expected to be available in the future based on the climate change projection and to account for this more land will have to be put under deficit irrigation.

Table 5.6: Area under different irrigation intensities (Ha) – Base Comparison

Technology	UCT Base Low	UCT Base Future Low	UCT Base High	UCT Base Future High
Optimal	591	568	591	568
Supplemental	0	0	0	0
Deficit	57	103	57	103
Dry land	16	8	16	8
Total (ha)	664	679	664	679

Table 5.3 shows the change in crop combinations for the base scenarios. Again, average area over the planning horizon is presented here. The general trend in both the high and low scenario is the substitution of high valued crops (fruits) with vegetables and annual crops in the future scenarios. For instance, Table 5.3 shows a reduction in the average area cultivated for apples, nectarines, peaches, wine grapes, and an increase in the cultivated area for onions, cabbage, cauliflower, beetroot, etc. This substitution might be the result of the increase in the cost of production (reduced profitability) of the high valued crop in the future. The increase in cost might be as a result of the increase in crop water requirement, as well as the reduction in chill accumulation. However, good management practices and rest breaking chemicals are available to help crops meet the chill requirement, albeit at a cost. Increases in temperature will indeed have impact on deciduous fruit production in the future.

Table 5.7: The total average area under cultivation (Ha)

Crops	UCT Base Low	UCT Base Future Low	UCT Base High	UCT Base Future High
Fruits				
Apples	9.7	4.9	9.7	4.9
Apricots	3.0	1.5	3.0	1.5
Pears	219.5	235.0	219.5	235.0
Nectarine	22.3	12.6	22.3	12.6
Peaches	117.0	58.5	117.0	58.5
Wwine	5.9	2.9	5.9	2.9
Plums	30.5	15.3	30.5	15.3
Total	407.9	330.7	407.9	330.7
Vegetables				
Potatoes	0.2	0.3	0.2	0.3
Tomatoes	0.2	0.4	0.2	0.4
Onions	96.8	142.4	96.8	142.4
Cabbage	51.1	74.1	51.1	74.1
Cauliflower	37.8	58.2	37.8	58.2
Carrots	0.1	0.1	0.1	0.1
Peas	0.4	0.6	0.4	0.6
Pumpkin	0.2	0.2	0.2	0.2
Squash	0.1	0.1	0.1	0.1
Butternuts	1.2	1.8	1.2	1.8
Lettuce	0.0	0.0	0.0	0.0
Spinach	0.1	0.0	0.1	0.0
Beetroot	47.7	60.1	47.7	60.1
Sweet melon	0.0	0.0	0.0	0.0
Total	49.3	62.2	49.3	62.2
Pastures				
LTPast	0.0	0.0	0.0	0.0
Lucerne	8.8	2.4	8.9	2.4
Total	8.8	2.4	8.9	2.4
Cereals				
Korog	0.0	0.0	0.0	0.0
Oats	0.4	0.5	0.4	0.5
Wheat	4.6	2.4	4.6	2.4
Maize	1.5	2.0	1.4	2.0
Barley	5.2	2.7	5.2	2.7
Total	11.7	7.6	11.6	7.6

5.4.2 IMPACT OF CLIMATE CHANGE ON WATER USE - BASE COMPARISON

The total average agricultural water use responds to the availability of water over the 20-year planning horizon. Figure 5.4 shows the total average agricultural water use per annum. If there is more water available, agriculture will respond by using more water through optimal irrigation intensities (and be more profitable), which will result in an overall increase in the demand for water. In the UCT Base High future scenario and UCT Base Low future, there is an increase in the average annual water use of almost 0.2 million m³ in Ceres.

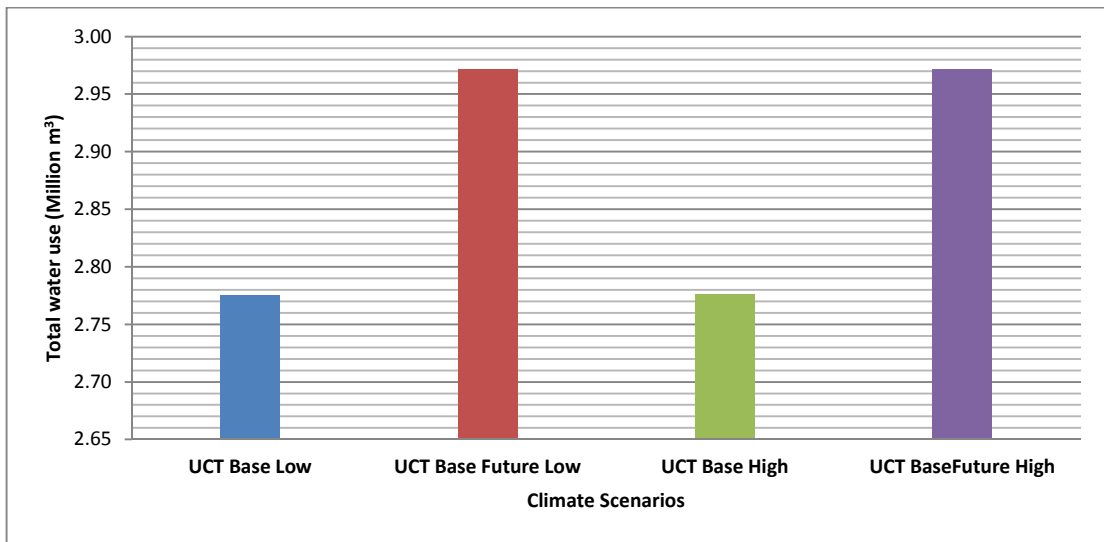


Figure 5.6: Total average agricultural water use per annum

The average annual water use per hectare is shown in Figure 5.5. The trend is almost identical to the total annual water use for agriculture shown in Figure 5.4. With climate change (increase in temperature) projected in the future, more water is expected to be used by crops because of the increased evaporation and evapo-transpiration that can accompany increases in temperature. On average, about 259m³ more water per hectare will be used in the future for both the high and the low climate base scenarios.

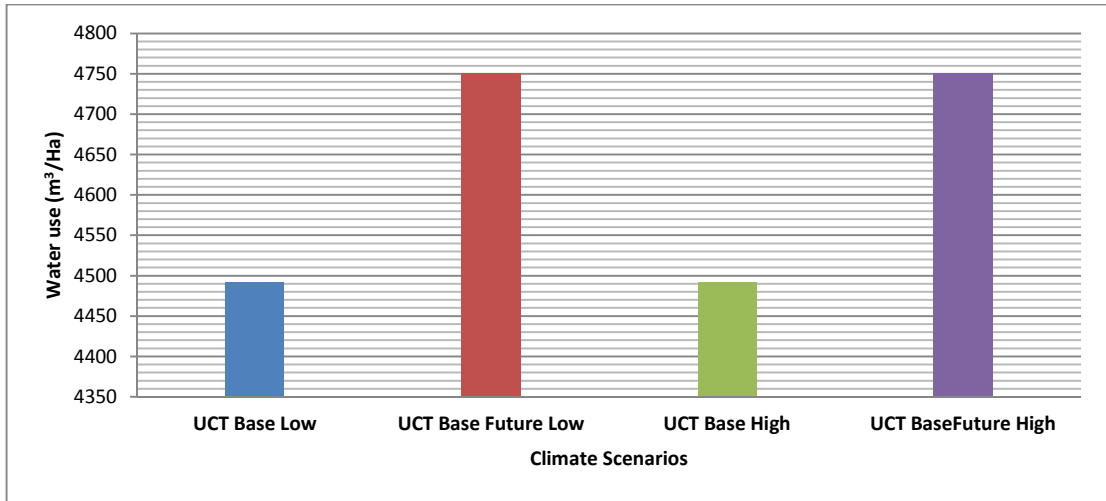


Figure 5.7: Average annual crop water use per ha

Figures 5.4 and 5.5 give an indication that more water will be required by the agricultural sector in the future with climate change and that necessary action/plans need to be put in place in order to adapt agriculture to this expected change to ensure sustainability of the sector in the Ceres region. Given the impact of climate change on irrigation practices and water requirements, the focus of attention next shifts to the consequent impact on the welfare of the farmers.

5.4.3 IMPACT OF CLIMATE CHANGE ON WELFARE – BASE COMPARISON

Figure 5.6 presents the average Net Disposable Farm Income (NDFI) for agricultural production for a period of 20 years. Figure 5.6 shows that NDFI increased considerably by a margin of R100 Million in the future scenario. This might be attributed to substitution that takes place in terms of crop combination in the future scenario.

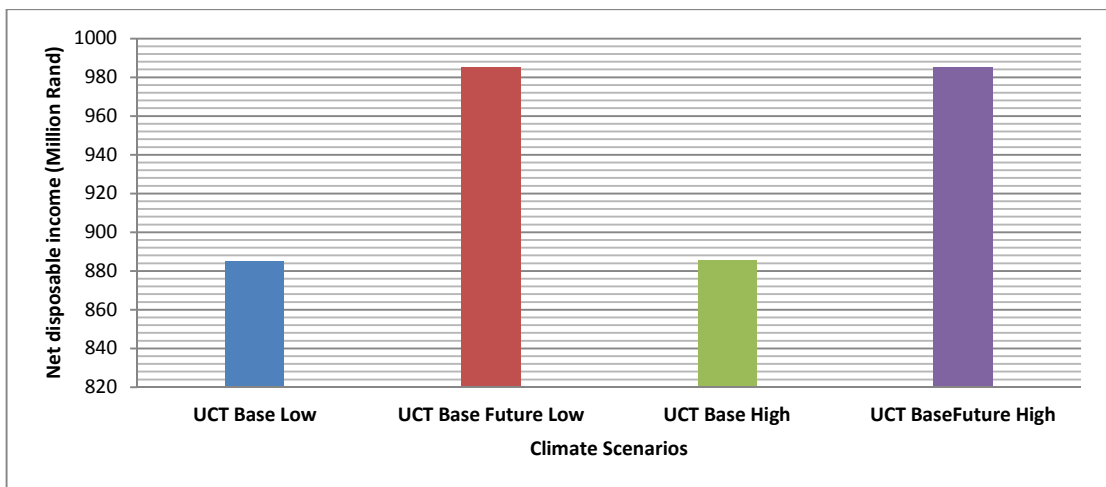


Figure 5.8: Net Disposable Farm Income – total over 20-years

Figure 5.7 shows the total welfare (or objective function value) for all sectors using the NPV of returns. The total welfare follows the same pattern as the NDFI. In general, the results show that the welfare of farmers improved in the future. Figure 5.7 shows that total welfare (objective function value) for the base period is R1 305 million while that for the future period is R1 336 million for both the low and high GCM base and future scenarios. The increase in welfare can also be attributed to the rational behaviour of farmers in substituting crops which incur higher costs of production with those of lower costs of production and hence will be more profitable.

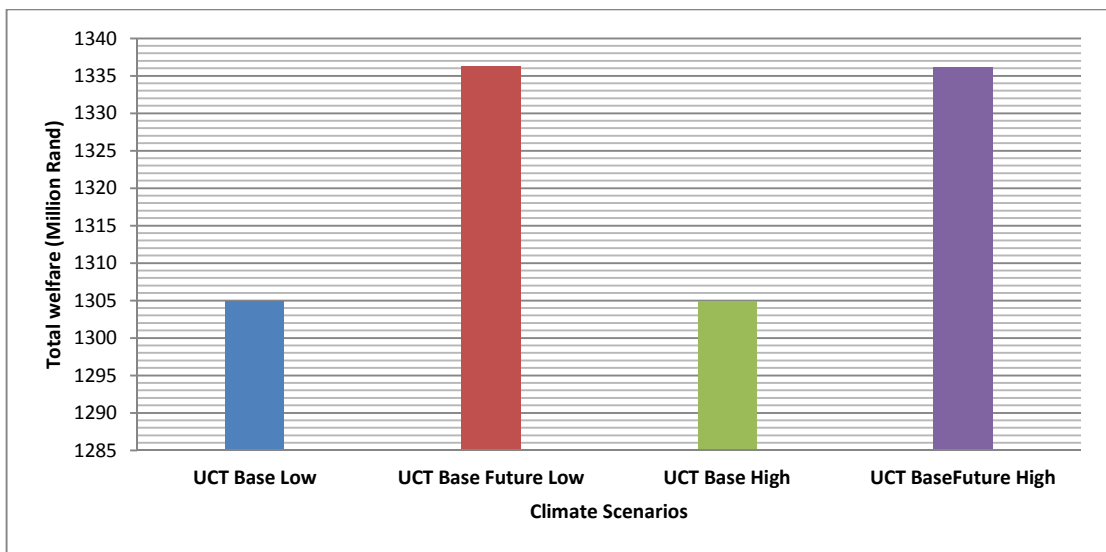


Figure 5.9: Total welfare – objective function value

5.5.4 DISCUSSION– BASE ANALYSIS

The findings which were described in this section show that the integrated modelling framework that was developed in Chapter 4 can be used to simulate various climate change scenarios, and that the results correspond with what can be expected from the farming systems. The impact of climate change has resulted in changes in area, water use and welfare of the farmers in the future climate. This is expected because farmers, like any other economic agent, seek to maximise profit and improve their welfare. With climate change, less area of land will be under optimal irrigation and high-value fruit crops will be substituted by other crops. This is because the fruit crops require optimal irrigation for good production and less water will be available in the future. The future sustainability of the agricultural sector in the Ceres region of Western Cape relies greatly on the type of adaptation strategy to be put in place by and for the farmers to cope with the projected impact of climate change. It is also observed that there is no noticeable difference between UCT high and low data. There seems to be some level of consistency in the data generated for the A2 high and low GCM data. Ultimately, the findings show that a substantial change can be expected in the profile of the

farming community in Ceres. The typical crops that are currently cultivated will have to be replaced by other crops that are less susceptible to the decrease in water availability and accumulated chill units. On a positive note, however, the changes seem to lead to an increase in welfare. In the next section, adaptation strategies that can further improve the welfare of the farmers are analysed and reported.

5.5 CLIMATE CHANGE ADAPTATION SCENARIO

In the next sections, the results of three different sets of adaptation strategies, which were evaluated using the integrated model developed in chapter 4 to evaluate how adaptation can improve the area, water use and welfare of the farmers in the future, are presented and discussed. These three adaptation strategies include the availability of farm dam and water rights, improving water use efficiency, and increases in water tariffs. Emerging farmers in the Ceres region do not have access to farm dam capacity and hence have no winter water rights, and accordingly this scenario will look at the impact of providing such facilities on the profile of the farmers. Secondly, using water efficiently has been identified in the literature as one of the adaptation strategies to climate change and this is empirically considered here. Lastly, the impact of increasing water tariffs on the behaviour of farmers and their profile is also considered.

5.5.1 FARM DAM AND WINTER WATER RIGHT ADAPTATION SCENARIO

Irrigation water plays a crucial role in the production of fruits, vegetables and grains in the Ceres region. The emerging farmers in this area do not have access to on-farm storage (farm dam) facilities to store water for use and hence they enjoy no winter water rights (water release for irrigation during winter months). In a set of scenarios (Scenario1 to Scenario5), we examine how the welfare of the farmers can be improved through the provision of farm dam storage and allocation of water rights. The potential impact of giving farmers farm storage facilities, with and without water rights, is first considered, and then an increase in water rights to the farmers follows. The scenarios are as follows:

Scenario 1: Farm dam capacity for emerging farmers, no winter water rights.

Scenario 2: Farm dam capacity for emerging farmers, with winter water rights.

Scenario 3: 20% increase in farm dam capacity for emerging farmers, winter water right allocation.

Scenario 4: 20% increase in farm dam capacity for emerging farmers, winter water right allocation increased by 20%.

Scenario 5: 30% increase in farm dam capacity for emerging farmers, winter water right allocation increased by 30%.

5.5.1.1 Impact on area

Table 5.4 shows the relative change in the area under different irrigation intensities relative to the base, considering different options from Scenario 1 through to Scenario 5. Table 5.4 shows that in Scenario 1, where farmers are given farm dam capacity without giving them winter water allocation, farming operations will not improve. There are no changes between the base and Scenario 1 results. This means that making a farm dam supply available to farmers without the ability to extract such water for usage is of no benefit to the farmers.

Table 5.8: Area under different irrigation intensities (Ha)

Technology	UCT Base Future Low	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Optimal	568.0	568.0	618.3	618.3	623.7	626.9
Supplemental	0.0	0.0	0.0	0.0	0.0	0.0
Deficit	102.9	102.8	78.1	78.1	76.4	73.2
Dry land	8.1	8.1	8.1	8.1	8.1	8.1
Total (ha)	678.9	678.9	704.5	704.5	708.2	708.2

When a winter water right allocation was given to the farmers in Scenario 2, farmers now have more water available for irrigation purpose and more land was also cultivated as the total area cultivated increased from 679 ha to 705 ha. The area under deficit irrigation also decreased from 103 ha in the base to 73 ha in Scenario 5. This can be as a result of the fact that farmers now have more water to irrigate and that high value crops which require optimal irrigation are under cultivation. Table 5.4 show that, as the farm dam capacity and winter water rights increase, a considerable change occurs in the irrigation intensity. This is an indication that a capital-intensive project, such as dam construction, will be of little or no value if the farmers are not also awarded the required winter water rights to allow them to irrigate during winter months.

Table 5.5 shows the crop combinations in the different scenarios. The area under fruit production increased, as did the area under vegetable production. More specifically, the area under pears and nectarines increased when farmers had farm dam capacity and legal access to winter water. Areas under pears increased to 246 ha in Scenario 5, compared to 235 ha in the base. Areas under onions and cauliflower also increased from 142 ha to 147 ha and 58 ha to 67 ha, respectively, under these scenarios. This is an indication that farm dam capacity accompanied by winter water rights will help the farmers adapt to the projected climate change impact.

Table 5.9: The total average area under cultivation (Ha)

Crops	UCT Base Future Low	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Fruits						
Apples	4.9	4.9	4.9	4.9	4.9	4.9
Apricots	1.5	1.5	1.5	1.5	1.5	1.5
Pears	235.0	235.0	245.8	245.8	245.8	245.9
Nectarine	12.6	12.6	13.1	13.1	14.0	14.1
Peach	58.5	58.5	58.5	58.5	58.5	58.5
Wwine	2.9	2.9	2.9	2.9	2.9	2.9
Plums	15.3	15.3	15.3	15.3	15.3	15.3
Total	330.7	330.7	342.0	342.0	342.9	343.1
Vegetables						
Potatoes	0.3	0.3	0.3	0.3	0.3	0.3
Tomatoes	0.4	0.4	0.4	0.4	0.4	0.4
Onions	142.4	142.4	146.9	146.9	146.9	146.9
Cabbage	74.1	74.1	72.6	72.6	71.9	71.7
Cauliflower	58.2	58.2	65.5	65.5	67.5	67.3
Carrots	0.1	0.1	0.1	0.1	0.1	0.1
Peas	0.6	0.6	0.6	0.6	0.6	0.6
Pumpkin	0.2	0.2	0.2	0.2	0.2	0.2
Squash	0.1	0.1	0.1	0.1	0.1	0.1
Butternuts	1.8	1.8	1.8	1.8	1.8	1.8
Lettuce	0.0	0.0	0.0	0.0	0.0	0.0
Spinach	0.0	0.0	0.0	0.0	0.0	0.0
Beetroot	60.1	60.1	63.3	63.3	64.8	64.9
Sweet melon	0.0	0.0	0.0	0.0	0.0	0.0
Total	338.3	338.3	351.8	351.8	354.6	354.3
Pastures						
LTPast	0.0	0.0	0.0	0.0	0.0	0.0
Lucerne	2.4	2.4	3.0	3.0	3.1	3.1
Total	2.4	2.4	3.0	3.0	3.1	3.1
Cereals						
Korog	0.0	0.0	0.0	0.0	0.0	0.0
Oats	0.5	0.5	0.5	0.5	0.5	0.5
Wheat	2.4	2.4	2.4	2.4	2.4	2.4
Maize	2.0	2.0	2.0	2.0	2.0	2.0
Barley	2.7	2.7	2.7	2.7	2.7	2.7
Total	7.6	7.6	7.6	7.6	7.6	7.6

5.5.1.2 Impact on water use

Figure 5.8 shows increases in agricultural water use: as more water is made available, the farmers respond by irrigating more. Figure 5.8 shows that more water is used in Scenarios 2, 3, 4 and 5, whereby farmers are given access to farm dam capacity and winter water allocation rights. Farm dam capacity without winter water rights (Scenario 1) shows no deviation from the base. This also confirms the fact that farm dam capacity without extraction rights will not be of benefit in improving the welfare of the farmers.

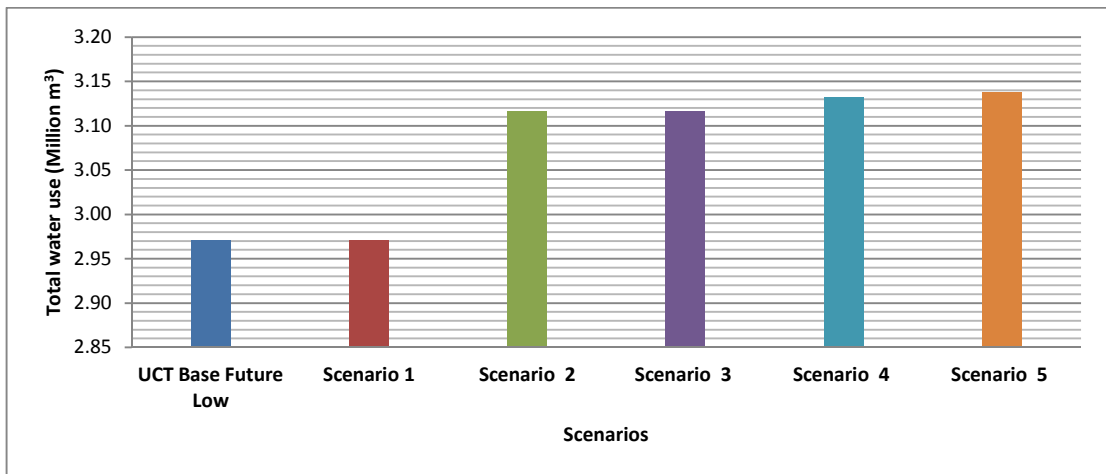


Figure 5.10: Total average agricultural water use per annum

The annual average crop water use presented in Figure 5.9 also shows an increase in water usage, relative to the base and Scenario 1. Crop water use increased by approximately 51 m³ per ha for all the scenarios, except Scenario 1, where it remains constant, and in Scenario 4 where it was 45 m³ per ha. The increase can be attributed to structural changes and higher temperatures which result in an increase in the crop water use requirements.

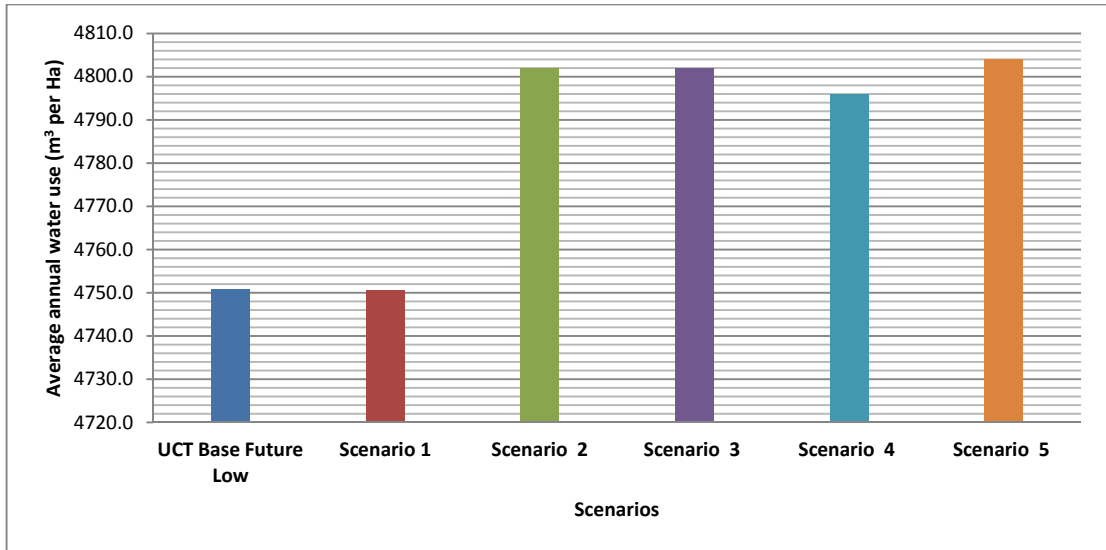


Figure 5.11: Average annual crop water use per hectare

5.5.1.3 Impact on welfare

Figure 5.10 presents the NDFI total for the period of 20 years. Under the adaptation scenario under consideration, the NDFI increased over the planning period. The increase in NDFI can be attributed to an increase in production of both high value crops and vegetables. The NDFI increased by an average of about R94 million from the base in Scenarios 2 to 5.

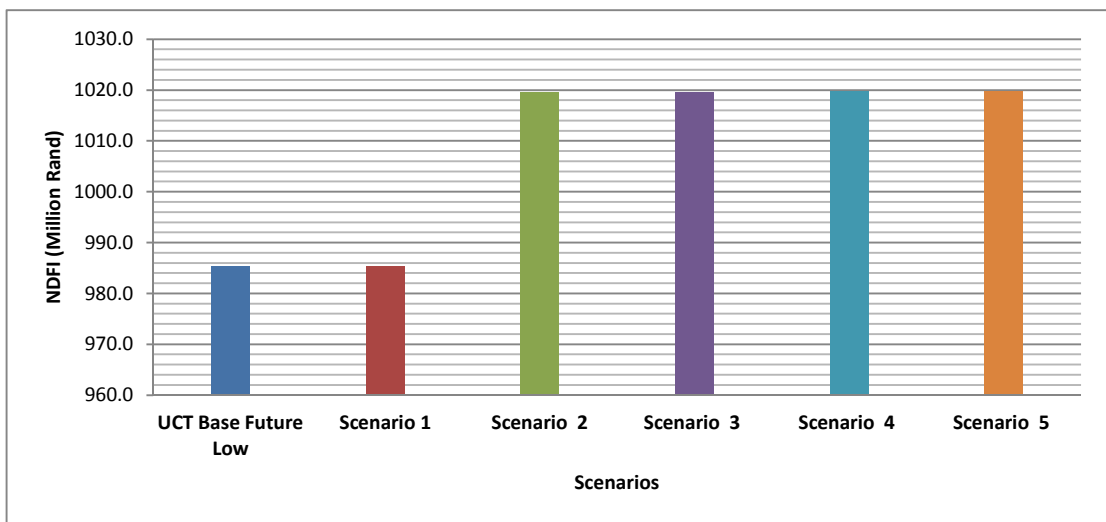


Figure 5.12: Net Disposable Farm Income – total over 20-years

Figure 5.11 shows the changes in the objective function as a result of provision of farm dam capacity and winter water allocation to the farmers. The results indicate that with the

exception of Scenario 1, farm dam availability and winter water allocation will be beneficial for all the farmers. The objective function increased at an average of R17 million from the base.

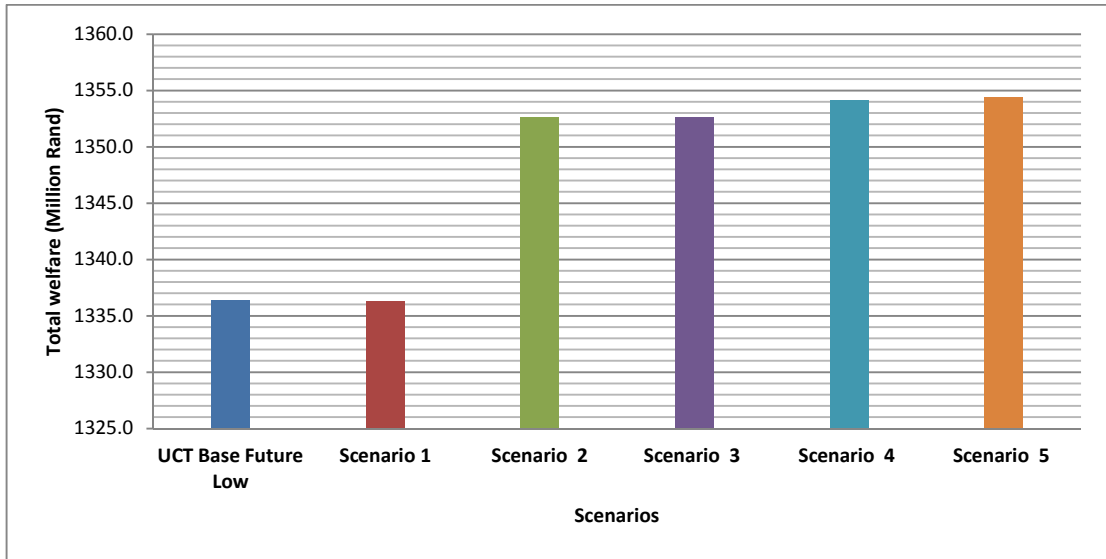


Figure 5.13: Total welfare – objective function value

5.5.1.4 Discussion

In this section, the impact of making farm dam supply and access to winter water available to the farmers as an adaptation strategy is evaluated and the result is compared to the base. The lack of availability of farm dam capacity has been recognised as one of the limiting factors to adaptation to climate change. The result confirms that making farm dam capacity available to farmers without also giving them the right to extract the water and use it during winter will be of no benefit to the farmers. However, their situation improved when the farmers had access to winter water. This is crucial in an area such as Ceres where the majority of the farmers are deciduous fruit farmers. The area is also known for some important vegetables, such as onions. Apart from serving as a source of water for both agricultural and urban water usage, a dam can also be used for other economic purposes. It is important to note that a farm dam is capital-intensive infrastructure and if the farm dams do not fill up, it may worsen the situation of farmers since the high capital cost and resulting high unit cost of farm dam water will increase their financial vulnerability. Louw *et al.* (2012) have analysed the bulk storage capacity of the main storage dams of the Cape Town City (CTC) and their storage levels from 2007-2011. Their analysis shows that in three of the five years under consideration the dams did not fill up to their maximum capacities. There is a large probability that increasing temperatures and reduced runoff will aggravate this situation in future. Thus, although the findings show that farm dam capacity and water rights during winter will improve the condition of the farmers in the future in the Ceres region, care should be taken in deciding

whether such an option is one to go by because of the investment involved and the possible limitation pointed out above.

5.5.2 WATER USE EFFICIENCY ADAPTATION SCENARIO

The second adaptation option to climate change is where water is used more efficiently. Here, water use efficiency is increased by 10%, 20% and 30% in Scenarios 6, 7, 8, respectively. The impact of this adaptation strategy will also be discussed in terms of the impact on area, water use and welfare.

5.5.2.1 Impact on Area

Table 5.6 shows the relative changes in the area under different irrigation intensities, considering the different options from Scenario 6 through to Scenario 8. Table 5.6 shows that using water more efficiently will result in more area under deficit irrigation being irrigated optimally. The efficient use of water makes more water available for irrigation purpose. The area under deficit irrigation decreased in Scenarios 6 through to 8, compared with the base, and the area under optimal irrigation increased across the board. This is an indication that efficient water usage as an adaptation strategy will translate to an increase in the cultivation of high value crops through optimal irrigation.

Table 5.10: Area under different irrigation intensities (Ha)

Technology	UCT Base	Future Low	Scenario 6	Scenario 7	Scenario 8
Optimal	568.0		631.9	649.8	672.3
Supplemental	0.0		0.0	0.0	0.0
Deficit	102.9		52.2	40.2	26.8
Dry land	8.1		8.1	8.1	8.1
Total (ha)	678.9		692.2	698.1	707.2

Table 5.7 shows the crop combination when water is used more efficiently. The area under fruit production increased, as did the area under vegetable production. More particularly, the area under pears increased from 235 ha in the base to 240, 242 and 246 ha, respectively, in Scenarios 6, 7 and 8. The areas under onions and cauliflower also increased, as can be seen in Table 5.7. The analysis shows that using water more efficiently will allow the farmers to save water and hence achieve a more profitable level of optimal irrigation.

Table 5.11: The total average area under cultivation (Ha)

Crops	UCT Base Future Low	Scenario 6	Scenario 7	Scenario 8
Fruits				
Apples	4.9	4.9	4.9	4.9
Apricots	1.5	1.5	1.5	1.5
Pears	235.0	239.6	242.3	246.0
Nectarine	12.6	12.4	13.0	12.8
Peaches	58.5	58.5	58.5	58.5
Wwine	2.9	2.9	2.9	2.9
Plums	15.3	15.3	15.3	15.3
Total	330.7	335.1	338.4	341.9
Vegetables				
Potatoes	0.3	0.3	0.3	0.3
Tomatoes	0.4	0.4	0.4	0.4
Onions	142.4	144.3	146.8	146.9
Cabbage	74.1	72.7	71.9	71.7
Cauliflower	58.2	60.3	60.0	64.4
Carrots	0.1	0.1	0.1	0.1
Peas	0.6	0.6	0.6	0.6
Pumpkin	0.2	0.2	0.2	0.2
Squash	0.1	0.1	0.1	0.1
Butternuts	1.8	1.8	1.8	1.8
Lettuce	0.0	0.0	0.0	0.0
Spinach	0.1	0.0	0.1	0.0
Beetroot	60.1	66.2	67.1	68.2
Sweet melon	0.0	0.0	0.0	0.0
Total	338.4	347.0	349.4	354.7
Pastures				
LTPast	0.0	0.0	0.0	0.0
Lucerne	2.4	2.6	2.8	3.0
Total	2.4	2.6	2.8	3.0
Cereals				
Korog	0.0	0.0	0.0	0.0
Oats	0.5	0.5	0.5	0.5
Wheat	2.4	2.4	2.4	2.4
Maize	2.0	2.0	2.0	2.0
Barley	2.7	2.7	2.7	2.7
Total	7.6	7.6	7.6	7.6

5.5.2.2 Impact on water use

Figure 5.12 shows a reduction in agricultural water use, as water is used more efficiently. Figure 5.12 shows that less water is used in Scenarios 6, 7 and 8 and this corresponds to 10%, 20% and 30% increases in water use efficiency. As the farmers use water more efficiently, the total agricultural water usage decreases. The available water can thus be used to increase the area under irrigation.

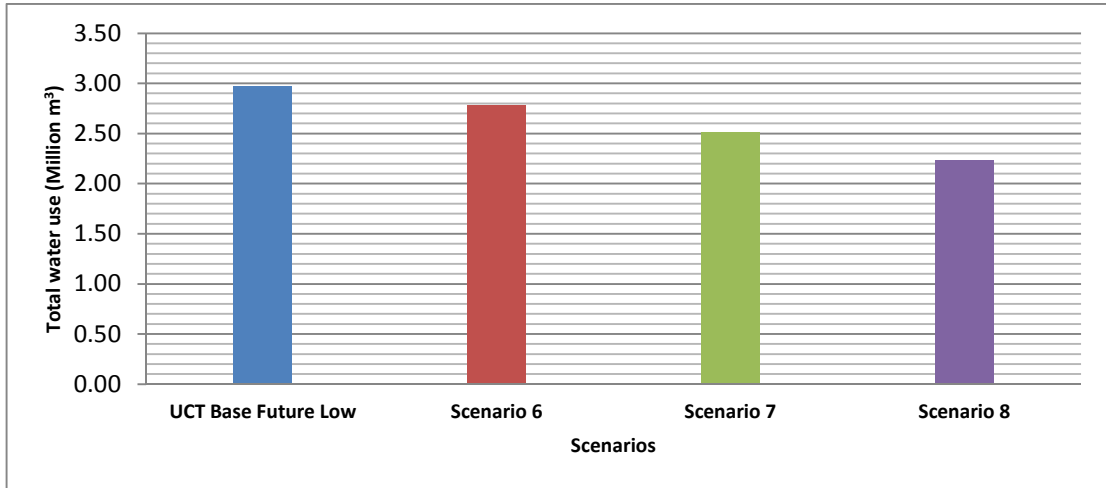


Figure 5.14: Total average agricultural water use per annum

The annual average crop water use is presented in Figure 5.13. The figure also shows a reduction in annual water usage compared to the base scenario. Crop water use decreased by approximately 391 m³, 850 m³ and 1321 m³ per ha, respectively. Corresponding to 10%, 20% and 30% increases in water use efficiency. The decreases can be attributed to a more efficient water use strategy by the farmers, thus making more water available to put more area under irrigation and for converting crops from deficit irrigation to optimal irrigation, especially fruit crops that need to be irrigated optimally for good harvest.

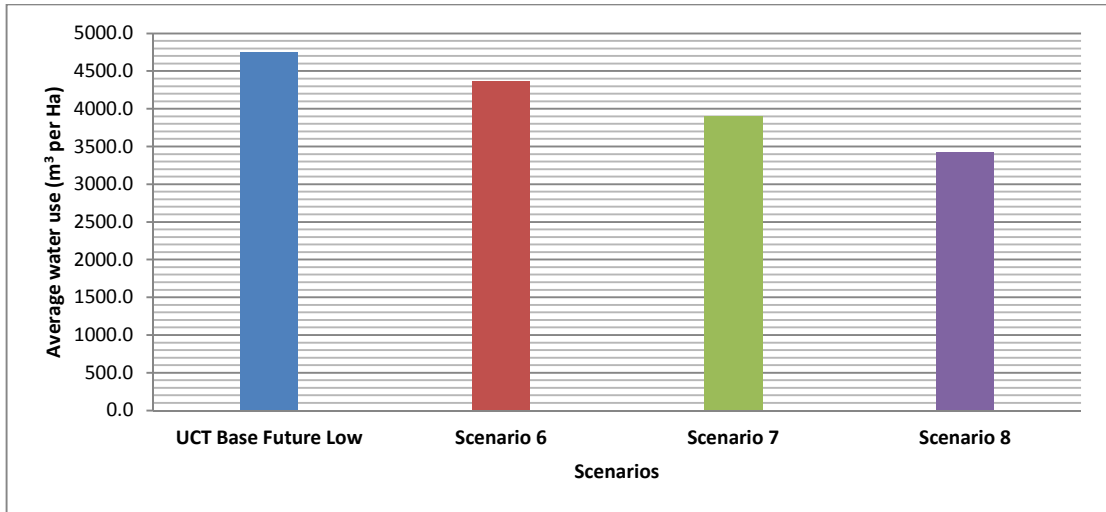


Figure 5.15: Average annual crop water use per ha

5.5.2.3 Impact on welfare

Figure 5.14 presents the NDFI total for the period of 20 years. Figure 5.14 shows that using water more efficiently will lead to an increase in NDFI over the planning period. The increase in NDFI can be attributed to the increase in production of both high value crops and vegetables. More efficient water use also reduced the production cost, increased production volumes and hence increased NDFI. The NDFI increased by an average of about R51 million from the base.

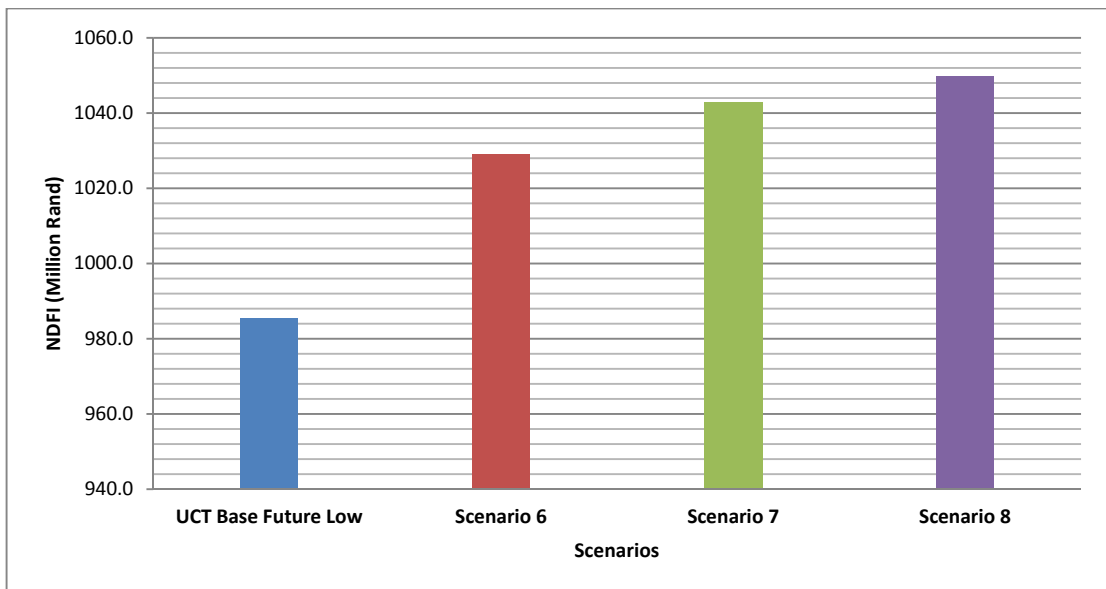


Figure 5.16: Net Disposable Farm Income – total over 20 years

Figure 5.15 shows the changes in objective function as a result of the increase in water use efficiency by the farmers. The results indicate that efficient water usage can substantially

improve the welfare of the farmers. The objective function increased by an average of R11 million compared to the base.

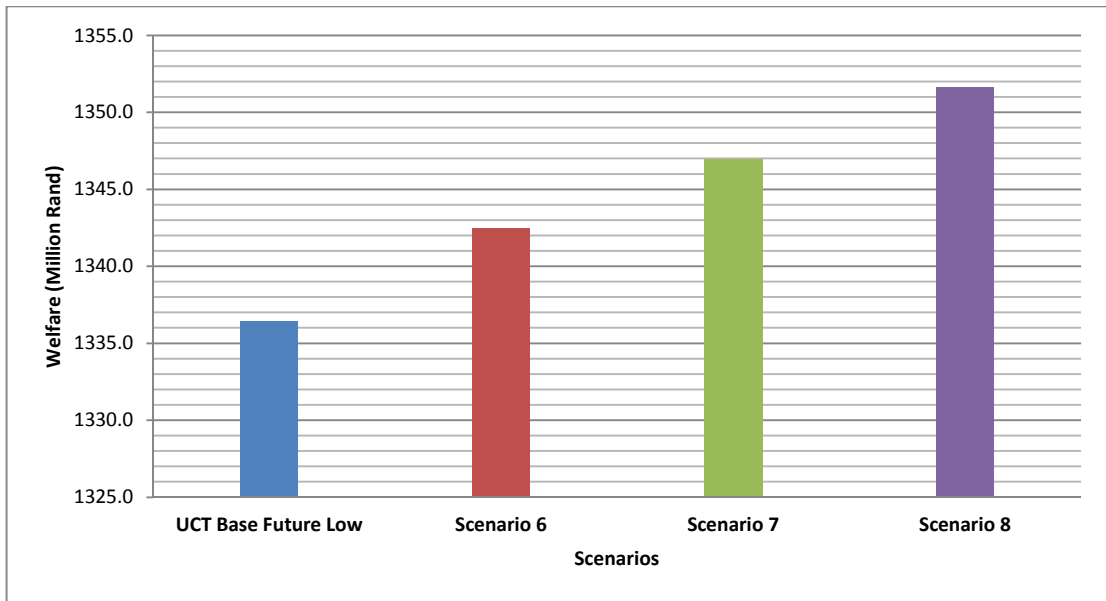


Figure 5.17: Total welfare – objective function value

Accordingly, using water more efficiently could be a favourable adaptation strategy to improve the welfare of the farmers in the Ceres region of the Western Cape.

5.5.2.4 Discussion

In this section, using water more efficiently is tested as an adaptation strategy to climate change. The result shows that the welfare of the farmers is improved when water is used more efficiently. Increasing irrigation efficiency would lead to saved water, which can either be used to augment crop yield (expand irrigated area), allow more water for downstream users or release water for other uses. In the context of this study, it led to more marginal land being used for production and an increase in the area under optimal irrigation. In the light of climate change, improving irrigation efficiency would be a plausible adaptive strategy. This could be achieved through the reduction of water leakages, changing to a more efficient irrigation system, irrigating during the night rather than day, the use of less thirsty crop cultivars and better water use monitoring.

5.5.3 INCREASE IN WATER TARIFFS SCENARIO

In this section, we investigated increases in water tariffs by 10%, 20% and 30%, as an adaptation option to climate change, in Scenarios 9, 10 and 11, respectively. An increase in

water tariffs is hypothesised to reduce water usage and also encourage farmers to use water economically.

5.5.3.1 Impact on Area

Table 5.8 shows the area under different irrigation intensities when water tariffs are increased. It is evident from this table that the status quo remains the same, as it was in the base. Increases in water tariffs would not induce farmers to bring marginal land into production and because the farmers are also careful in their irrigation intensity, they would not be able to increase the area under optimal irrigation because they would have to pay more for the water used.

Table 5.12: Area under different irrigation intensities (Ha)

Technology	UCT Base	Future Low	Scenario 9	Scenario 10	Scenario 11
Optimal	568.0		568.7	569.6	570.5
Supplemental	0.0		0.0	0.0	0.0
Deficit	102.9		102.8	102.5	102.1
Dry land	8.1		8.1	8.1	8.1
Total (ha)	678.9		679.6	680.1	680.7

Table 5.9 shows the crop combinations when water tariffs are increased. Table 5.9 shows that the increase in water tariffs would not change the existing crop combination from the base. Instead of removing productive land from production, the farmers maintained the status quo by paying more for water to maintain the farm structure. However, a slight increase in area under pears was observed but this dropped back to 233ha in Scenario 11 because the increment cannot be sustained. The analysis above is an indication that increasing the water tariffs is not a favourable adaptation strategy for the farmers in Ceres.

Table 5.13: The total average area under cultivation (Ha)

Crops	UCT Base Future Low	Scenario 9	Scenario 10	Scenario 11
Fruits				
Apples	4.9	4.9	4.9	4.9
Apricots	1.5	1.5	1.5	1.5
Pears	235.0	234.5	234.1	233.6
Nectarine	12.6	12.7	12.8	12.9
Peaches	58.5	58.5	58.5	58.5
Wwine	2.9	2.9	2.9	2.9
Plums	15.3	15.3	15.3	15.3
Total	330.7	330.3	330.0	329.6
Vegetables				
Potatoes	0.3	0.3	0.3	0.3
Tomatoes	0.4	0.4	0.4	0.4
Onions	142.4	142.4	142.4	142.4
Cabbage	74.1	74.5	75.0	75.4
Cauliflower	58.2	58.5	58.8	59.2
Carrots	0.1	0.1	0.1	0.1
Peas	0.6	0.6	0.6	0.6
Pumpkin	0.2	0.2	0.2	0.2
Squash	0.1	0.1	0.1	0.1
Butternuts	1.8	1.8	1.8	1.8
Lettuce	0.0	0.0	0.0	0.0
Spinach	0.0	0.0	0.0	0.0
Beetroot	60.1	60.3	60.5	60.7
Sweet melon	0.0	0.0	0.0	0.0
Total	338.3	339.2	340.2	341.2
Pastures				
LTPast	0.0	0.0	0.0	0.0
Lucerne	2.4	2.4	2.4	2.4
Total	2.4	2.4	2.4	2.4
Cereals				
Korog	0.0	0.0	0.0	0.0
Oats	0.5	0.5	0.5	0.5
Wheat	2.4	2.4	2.4	2.4
Maize	2.0	2.0	2.0	2.0
Barley	2.7	2.7	2.7	2.7
Total	7.6	7.6	7.6	7.6

5.5.3.2 Impact on water use

Figure 5.16 shows the trend in agricultural water use with increases in water tariffs as an adaptation strategy to climate change. Figure 5.16 shows that increases in tariffs did not allow the farmers to increase their agricultural water use. More importantly, it also did not cause a decrease in water use. This gives the reason why the farmers are not able to increase the area under fruit and vegetable production.

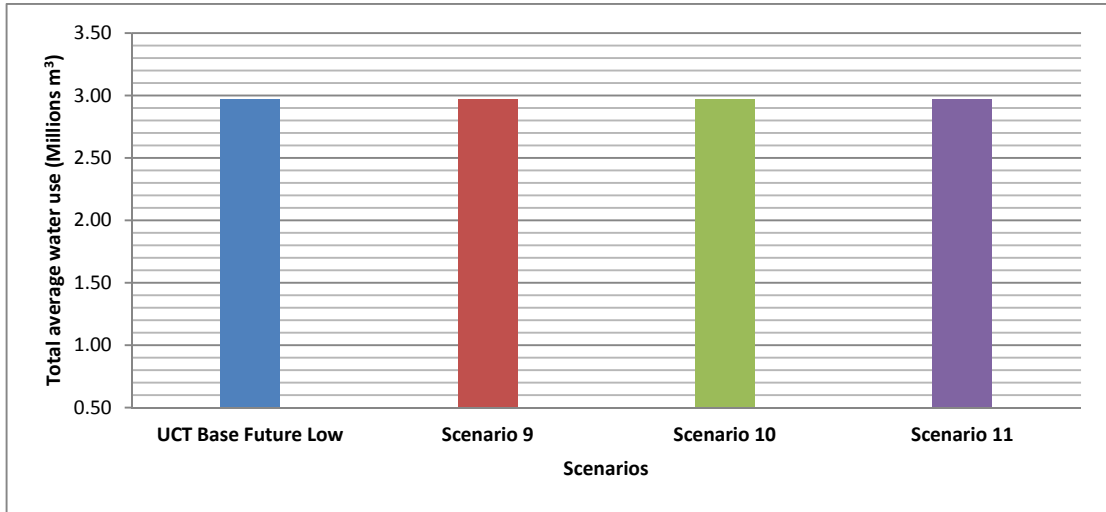


Figure 5.18: Total average agricultural water use per annum

In order to increase the areas under fruit and vegetable production, the farmers in return should be prepared to pay more for water. The annual average crop water use is presented in Figure 5.17. Figure 5.17 shows a decrease in average annual water usage as tariffs increase. Crop water use decreased by approximately 6 m³, 10 m³ and 15 m³ per ha, respectively, for 10%, 20% and 30% increases in water tariffs.

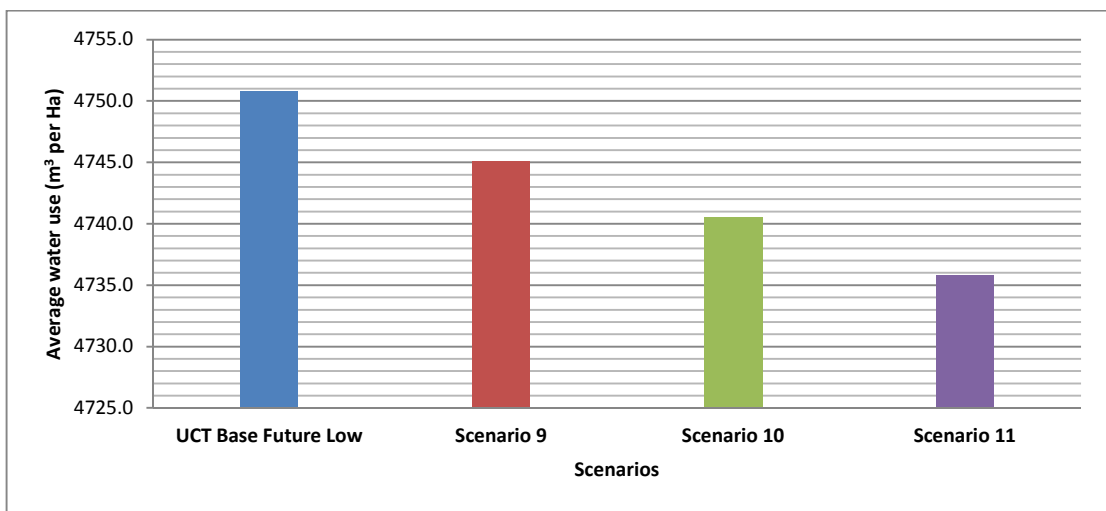


Figure 5.19: Average annual crop water use per ha

The decrease is the result of farmers cutting down on the expenses for water in the production cycle as a result of the increase in the costs of irrigation water. Such an adaptation strategy could impact negatively on the volume of production because water is an important input in the farming system. Despite decreases in per hectare usage of water, the total water usage remained the same.

5.5.3.3 Impact on welfare

Figure 5.18 presents the NDFI total for the period of 20 years. With increases in water tariffs, the NDFI decreased over the planning period. The decrease in NDFI can be attributed to increases in water tariffs that translated to increases in the production cost.

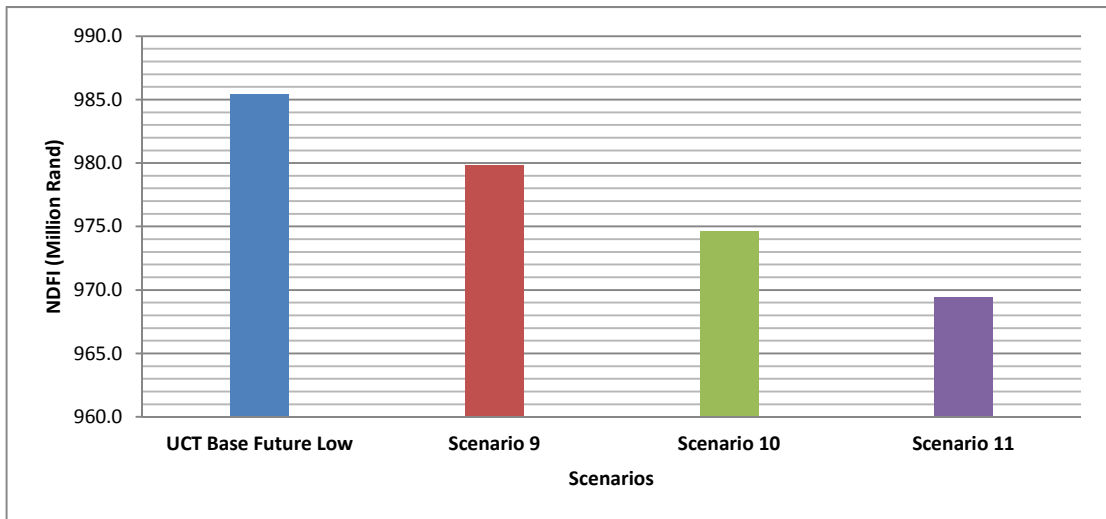


Figure 5.20: Net Disposable Farm Income – total over 20 years

Figure 5.19 shows the changes in the value of objective function as a result of increases in water tariffs. The results indicate that increases in water tariffs reduce the welfare of the farmers. The objective function decreased by an average of R1 million compared to the base. The increase in water tariffs scenario is found not to improve the welfare of the farmers.

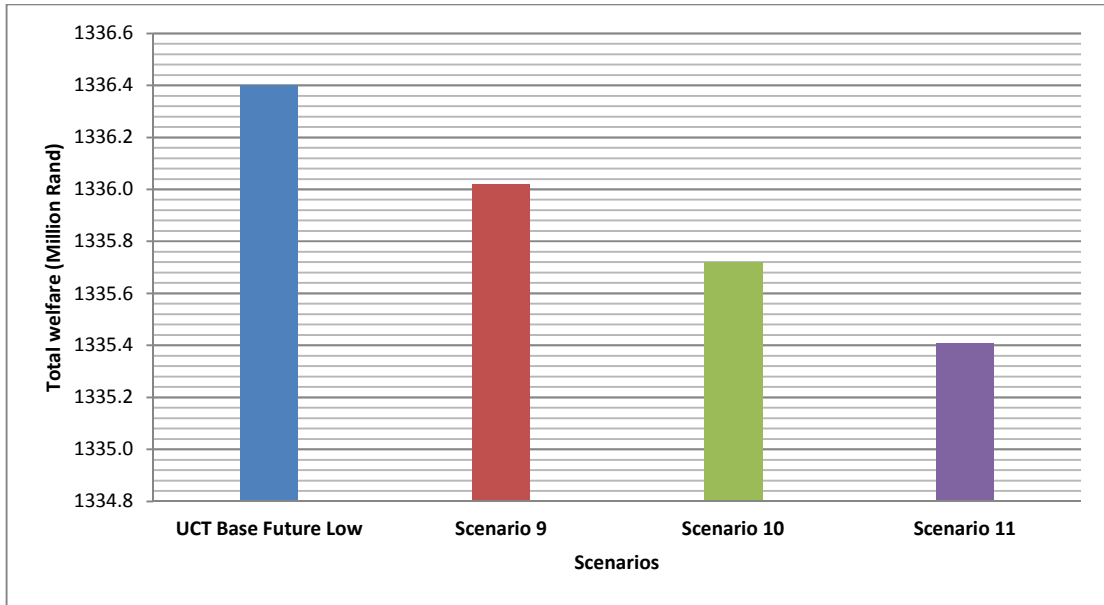


Figure 5.21: Total welfare – objective function value

5.5.3.4 Conclusion

The impact of increases in water tariffs as an adaptation strategy to climate change was analysed. The model results indicate that increasing water tariffs as an adaptation strategy to climate change is less effective in the agricultural sector and could even result in a negative impact, since farmers grow deciduous fruit crops which often require even more water, irrespective of the tariff regime. In addition to this, the vegetable crops planted in the Ceres area also require optimal levels of irrigation. Furthermore, the price elasticity of demand for agricultural water is very inelastic since farmers cannot simply stop irrigating or change to deficit irrigation. The production of fruit crops that must meet export market requirements requires that the farmers irrigate optimally and an increase in water tariffs, as seen in this section, will jeopardise production for such markets.

5.5.4 CONCLUSION

In this chapter, results from several models used in the study have been presented. It is evident that climate change will impact on future crop water requirements. Increased crop water requirements under a warming climate will place greater demands on available soil moisture and irrigation water supplies. Therefore, under climate change conditions, water could become a constraining factor for agriculture if not managed properly. Responding to the challenges of climate change impacts on water resources requires the use of adaptation strategies at local, regional, national and global levels. The adoption of crop varieties with increased resistance to high temperatures could help farmers cope with climate change because increased temperature increases evapo-transpiration and hence increases in crop

water requirements. In addition to this, the analysis shows that irrigation technology also has impacts on crop water requirements and consequently farmers should make use of more efficient irrigation technology systems. The initial investment might be large but the long-run impact of such an investment will be beneficial in the long run.

Climate change will also have an impact on the future chill unit accumulation in the Ceres area of the Western Cape, South Africa. The province is a producer of fruits in South Africa. The models used, Richardson and Infruitec, projected a reduction in the future chill unit accumulation. The deciduous fruit industry in the Western Cape will have to develop agricultural adaptation measures (e.g. low-chill varieties and dormancy-breaking chemicals) to cope with these projected changes. For some crops, production might no longer be possible. The usage of dormancy breaking chemical will, however, lead to increases in the cost of production of high value crops. Research and development is required on cost-effective and safe rest-breaking products to improve and increase fruit production in the Ceres region. Other adaptation strategies as identified in the literature include orchard cooling technologies, such as the use of evaporative cooling and kaolin-based particle film during autumn, to boost the early accumulation of chill units (Midgley and Lotze, 2011).

It was also demonstrated how the integrated modelling framework can be used to evaluate proposed adaptation strategies, such as an increase in farm dam storage capacities (the lack of which was identified as one of the key obstacles towards adaptation to climate change). Water use efficiency and increases in water tariffs as adaptation scenarios were also analysed. The analysis shows that increasing water tariffs is not a good adaptation strategy for farmers in the Ceres region. This increases the cost of production and thus reduces the welfare of the farmers. This is because high value crops and vegetables can only be produced under optimal irrigation. The irrigation demand for water is inelastic and it is unlikely that high water tariffs will reduce the level of water used for production.

Depending on the availability of funds to make farm dams available for emerging farmers, increasing access to farm dam capacity and winter water allocations seems to be the best adaptation strategy from the analysis presented in this thesis. However, simply giving farmers farm dam capacity alone will not improve the situation of the farmers, according to the analysis. Accordingly, caution should be taken when considering such an adaptation option. It is important to note that farm dams constitute capital intensive infrastructure and if the farm dams do not fill up, this might worsen the situation of farmers since the high capital cost and resulting high unit cost of farm dam water will increase their financial vulnerability. This can be a regretted option and countries are being urged to improve and consolidate their water resources management systems and to identify and implement “no regrets” strategies, which have positive development outcomes that are resilient to climate change. Therefore, giving

farmers farm dam capacity and winter water rights might be a good adaptation strategy, although other issues surrounding its suitability should be considered.

Increasing water use efficiency as an adaptation option, according to the analysis carried out in this study, is also a good adaptation option for the farmers. Improved water management practices that increase the productivity of irrigation water use may provide a significant adaptation potential under future climate change. Using water more efficiently improved the welfare of the farmers and also saved water for optimal irrigation usage. It can be referred to as a “no-regret” climate change adaptation option and could potentially make a substantial contribution towards increasing the water supply in the study region. Improvement in irrigation efficiency is crucial in ensuring the availability of water, both for food production and competing human and environmental needs. The findings from this adaptation scenario justify the investment that has been made by organisations, such as the Water Research Commission (WRC), towards water use efficiency in South Africa. Various research projects funded by the WRC have demonstrated how improvements can be made to efficiently manage water in South Africa (Reinders 2011, Annandale *et al.*, 2011, van Averbeké *et al.*, 2011). Therefore, using water more efficiently will be the best adaptation option based on the analysis done in this study to help the Ceres farmers cope with the future projected impacts of climate change. Overall, a change in the profile can be expected as a result of climate change and adaptation thereto. Given the role of agriculture and the contribution of Western Cape to the South African balance of payments in terms of exports, adaptation that will improve the welfare of both emerging and commercial farmers should be considered.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

6.1.1 BACKGROUND AND MOTIVATION

Climate change will have economic effects on agriculture, including changes in farm profitability, prices, supply, demand, trade, and regional comparative advantage. Many countries are vulnerable to this global climate phenomenon because of the potential impact on marginal natural resources balance and agricultural productivity (IPCC, 2001). The Western Cape (WC) region of South Africa, with its Mediterranean-type climate and predominantly winter rainfall, has been identified as highly vulnerable to projected climate change, within both global and national contexts. Increasing competition for water has resulted in the construction of a number of smaller water storage reservoirs in the last twenty years with limited number of sites left for development. The Western Cape will experience increased temperatures and reductions in water supplies in the future and these have to be adequately prepared for in order to ameliorate these impacts.

6.1.2 PROBLEM STATEMENT AND OBJECTIVES

The projected increase in temperature will have an impact on water availability (IPCC, 2001). Water resource is of most concern because changes in the water supply will affect water availability for household use, water use in agricultural practices, and the vast industrial water demand. In addition to the impact on water supply, climate change is also expected to affect future winter chill and thus could have a major impact on fruit species with chilling requirements (FAOSTAT, 2009). All deciduous fruit trees require a certain amount of coldness to enter into dormancy (Sheard, 2001). Insufficient winter chill can severely affect fruit yields and fruit quality when chilling requirements are not fulfilled (Dennis, 2003). If winter chill decline occurs owing to climate change, production constraints are likely to occur, because many trees might not fulfil their minimum chilling requirement (Luedeling *et al.*, 2009). Thus, climate change is expected to have a major impact on agricultural activities in the Western Cape.

There have been a number of studies in South Africa which have focused on the impacts of climate change at national level (Turpie *et al.*, 2002, Gbetibouo & Hassan 2004). The shortfall in the research addressed by past studies on the impacts of climate change is the lack of studies examining impacts at farm level. Thus, there is a need to quantify this impact at farm level.

Integrated modelling can be used to examine impacts either at the farm or activity level, and this involves combining GCM (Global Circulation Models), RCM (Regional Climate models)/downscaling to relevant spatial (and temporal) scales, Hydrology models (Rainfall-runoff models) to relate changes in climate to changes in (impacts on) runoff, surface water evaporation, plant evapo-transpiration (water use) and return flows and economic models in order to translate the impacts of climate change on plants and humans directly into climate change damages and adaptations thereto. Few studies in South Africa have estimated the benefits and costs of adapting to climate change. Notable among such studies are Callaway *et al.* (2008a, 2008b and 2009). These studies were done at aggregate level and it was difficult to adequately model climate-variable sensitivity at this level. Louw *et al.* (2012) have pointed out that there is a need for more research to be carried out to increase the sensitivity of the farm models to climate change variables (temperature and water availability). This is of paramount importance since both temperature and water availability will have an impact on future farm structure in the Ceres region of Western Cape. Although researchers have been able, to a certain extent, to model the impact of climate change on the farm sector using integrated methodology, they have not yet included the impact of future changes on crop water requirements, as well as the impact on accumulated chill units. Accordingly, we currently do not have empirical knowledge of how the current and future change in crop water requirements and accumulated chill units will affect the farm structure.

The aim of this study has been to develop and apply an integrated approach to quantify the economic impact of climate change on the agriculture and water resource sectors of Ceres, in the Western Cape Province of South Africa. Specific reference is made to the small-scale/resource poor farmers and to the commercial farmers because both groups of farmers will be affected by climate change. Such information will be useful for decision making in the planning and management of climate risk for agriculture and water resources development in Ceres, and for a wider application in Africa as a whole.

6.2 LITERATURE REVIEW

Climate change is a reality. Given climatic requirements of fruits, and the expected change in climatic conditions in the Western Cape, the fruit farmers are in for a hard time. Farmers will have to adapt in order to remain in production. Depending on the type of adaptation considered or a combination of adaptation considered, it should be able to completely offsets most of the agricultural income loss, if not, leaves an individual farmer with a small loss. The farmer may be forced to lower profit expectations, but the farmer remains solvent and flexible enough to be able to develop new production and marketing strategies for the future. Thus, adaptation can be considered successful if it maintains services or welfare with a small or minimal loss.

DLP can be used as an economic model in the framework of IAM. Several authors found DLP method appropriate in simulating the farm system. It a useful tool for analysing the interactions between management measures and production intensity on one hand, and farm income and environmental aspects on the other hand. Moreover, it is a useful tool for determining the implications of different policy options at farm level on economic and environmental aspects of farming. Whole farm planning models are mostly developed with DLP. The reason for the development of whole farm planning models with this technique was to enable agricultural economists to provide policy makers as well as farmers with a holistic (whole farm) answer on practical farm problems. Without this, any advice given may be incompatible with the local farming practices, or may lead to lower, rather than higher, economic returns to farmer (Pannell, 1996).

The shortcoming of the existing model is that the impacts of temperature and crop water requirements are not properly modelled and this has an impact on the sensitivity of the model. Thus, the researchers are unable to model the impact of temperature increases in the modelling framework which will have impact on the various adaptation strategies. Thus in order to accurately quantify the impacts of different adaptation strategies at farm level, the existing models need to be adjusted and methodology developed to incorporate the impact of temperature.

Crop water requirement and chill unit requirement of various crops has been found to be dependent on temperature. Therefore, the impact of temperature on crop water requirement as well as on chill unit accumulation can be incorporated into the farm model in order to improve the sensitivity of the model to climate variable. Several models are used to estimate crop water requirement in South Africa but SAPWAT has been fully adopted by the DWAF as a tool for determining irrigation water allocation in connection with the registering and licensing of agricultural water use. SAPWAT has been widely used in South Africa and is proved to be sufficient in the estimation of irrigation crop water requirement.

With respect to chill unit accumulation, two important monitoring systems for chill accumulation are mostly used in South Africa. The Utah or Richardson model (Richardson *et al.*, 1974), measuring “Richardson Chill Units (RCU)” and the Infruitec model (daily positive Utah model), measuring “Infruitec Chill Units (ICU). Studies on winter chill and chilling requirement often tacitly assume that the choice of the model is not important and that all models can be used interchangeably. These models (Richardson and Infruitec) have been applied in South Africa and have been found to produce good and consistent result depending on the area.

Based on the literature, an integrated assessment model (IAM), which combines scientific and economic aspects of climate change primarily for the purpose of assessing policy options for climate change adaptation, is required to properly understand the appropriate adaptation option to cope with the projected impact of climate change. It is required that such an integrated methodology be sensitive to climate variables in in order to adequately simulate the impact of various adaptation strategies on farm system. Addition of additional modules will be essential in case where existing model is not sensitive for a valid conclusion to be made regarding the suitability of an adaptation strategy.

6.3 IMPACT OF CLIMATE CHANGE ON CROP WATER REQUIREMENT

SAPWAT3 (van Heerden *et al.*, 2003) was used to estimate crop water requirement for the base climate (1971-1990) and for the future climate (2046-2065). Artificial weather station was built into SAPWAT to calculate crop water requirement for the future because SAPWAT does not have information about the future climate. Two different types of irrigation technologies, namely, drip and sprinkler irrigation system were considered and analysed. Water requirement will increase substantially for both types of irrigation technology. Results show that the water requirements for drip irrigation are less than that of Sprinkler, because of efficiency differences in the irrigation systems. The drip irrigation system is said to be a more efficient irrigation technology. It is important to state that the crop water requirement is dependent on the cultivar of each crop chosen as cultivar differences also play a major role.

Crop water requirement will increase as a result of projected climate change using A2 climate change scenario. The crop with the highest deviation from the base in both irrigation systems is squash (29 and 34 %) while butternut (6 and 9 %) recorded the lowest deviation from the base climate for sprinkler and drip irrigation technologies respectively. Based on the findings an important adaptation strategy may be if farmers were to make use of a more efficient irrigation system to mitigate the impact of increased water scarcity caused by climate change. It was also confirmed that future crop water requirement for drip irrigation system is still lower than the current

water requirement under sprinkler. So, despite substantial increase in water requirement under drip, the total water requirement will be less under drip compared to sprinkler.

With climate change resulting in increase in crop water requirement in the future and coupled with limited available irrigation water and competition between agricultural, urban and industrial water usage, farmers should look into a more efficient way of using water. When addressing adaptation measures to be implemented to increase water use efficiency, holistic approach that incorporate water productivity by crop, use of water in the root zone for transpiration and conversion into marketable product as well as efficiency delivery of water from source to soil should be considered.

6.4 IMPACT OF CLIMATE CHANGE ON CHILL UNIT ACCUMULATION

The Utah model of Richardson *et al.* (1974) and Daily positive Utah (Infruited) chill unit accumulation model of Linsley-Noakes *et al.*(1994) are used in this section to test the hypothesis that winter chill will reduce with climate change. The Richardson and Infruited models accumulate chill units the same way, with the exception that the Infruited model does not allow one to lose units when the temperature exceeds 16°C, unlike Richardson model which accumulate negative units above this temperature. The climate variable of interest here is temperature. It is hypothesised that, as temperature increases in the future due to climate change, the accumulated chill units will reduce. Results from both models confirmed that climate change will result in reduction of future accumulation of chill units. The impact of climate change (projected temperature increase) on chill unit accumulation is more pronounced using Richardson model compared to Infruited model. The major difference between the two models according to an expert opinion is in terms of the interpretation of the models. The Richardson model gives the “quality” of the cold units while the Infruited model is more about “quantity” of the cold units.

The average deviation from the base for Richardson model over the 20 years period is 36 % while that of Infruited is 32 %. These deviations from the mean were found to be statistically significant at 95 % confidence interval ($\alpha = 0.05$). The result shows that it might be difficult to produce some fruit crops in the future in the Ceres region due to insufficient chill that will be accumulated in the future. Considering the long life span of deciduous fruits compared to annual crops and the substantial investments required for the establishment, tree crop growers will be more vulnerable to the long term effect of climate change than growers of annual crops. This will likely require growers’ transition to different species or cultivars or to develop management practices (planting density, pruning practices and irrigation regime) that can help overcome shortages in winter chill. Climate change is also likely to severely challenge current production systems, some of which

already rely on cultural measures such as rest-breaking chemicals and artificial defoliation. More research and development is required on cost-effective and safe rest-breaking products and programs which are more suited to warmer conditions. Since most of the crops are already established in the present climate, the projected future values of chill units can guide the farmers in the selection of cultivars in the future when re-establishment of their orchard is to be done. Otherwise, farmers will rely on the use of artificial rest breaking chemicals in case of low accumulation. This will increase the production cost and hence have impact on the profitability of such enterprise.

6.5 COMPARISON OF BASE CLIMATE CHANGE SCENARIOS FROM THE INTEGRATED MODEL

The objective of the modelling exercise was to demonstrate that it is possible to develop an integrated modelling framework for evaluating and making adaptation decisions related to agriculture and water resources in the Ceres area of Western Cape. This will give an indication of changes in farm structure in the future and be able to advise the farmers on appropriate adaptation strategy.

The results confirmed that the Ceres dynamic integrated model developed in this study can be used to simulate various climate change scenarios, and that the results correspond with what can be expected from the farming systems. The impact of climate change has resulted in changes in area, water use and welfare of the farmers in the future climate. This is expected because farmers like any other economic agent, seek to maximise profit and improve its welfare. With climate change less area of land will be under optimal irrigation and more high value fruit crops are been substituted by other crops. This is because the fruit crops need optimal irrigation for good production and less water is projected to be available in the future. The future sustainability of agricultural sector in the Ceres region of Western Cape rely a lot on the type of adaptation strategy put in place by and for the farmers to cope with the projected impact of climate change. It is also observed that there is no noticeable difference between UCT high and low data. There seems to be some level of consistency in the data generated for the A2 high and low GCM data. Ultimately the findings show that a substantial change can be expected in the profile of the farming community in Ceres. The typical crops that are currently cultivated will have to be replaced by other crops that are less susceptible to the decrease in water availability and accumulated chill unit. On a positive note however, the changes seem to lead to increase in welfare.

6.6 CLIMATE CHANGE ADAPTATION SCENARIO

Some adaptation strategies that can further improve the welfare of the farmers are analysed and reported. Three different sets of adaptation strategies that were evaluated using the integrated model developed to evaluate how adaptation can improve the area, water use and welfare of the farmers in the future. These three adaptation strategies include; availability of farm dam and water right; improving water use efficiency; and increase in water tariff. Emerging farmers in the Ceres region don't have farm dam capacity and hence no winter water rights.

6.6.1 FARM DAM AND WINTER WATER RIGHT ADAPTATION SCENARIO

Irrigation water plays a crucial role in the production of fruits, vegetables and grains in the Ceres region. The emerging farmers in this area do not have access to on farm storage (farm dam) facilities to store water for use and hence no winter water rights (water release for irrigation during winter months). In this set of scenarios (Scenario1 to Scenario5) the aim was to examine how the welfare of the farmers can be improved through provision of farm dam and allocation of water rights. The scenarios are as follows:

Scenario 1: Farm dam capacity for emerging farmers, no winter water right.

Scenario 2: Farm dam capacity for emerging farmers, winter water right.

Scenario 3: 20% increase in farm dam capacity for emerging farmers, winter water right allocation

Scenario 4: 20% increase in farm dam capacity for emerging farmers, winter water right allocation increase by 20%

Scenario 5: 30% increase in farm dam capacity for emerging farmers, winter water right allocation increase by 30%

The results confirmed that making farm dam available to farmers without giving them the right to extract the water and use during winter will be of no benefit to the farmers. However, their situation improved when the farmers were allocated winter water rights to gain to water in winter. This is crucial in an area such as Ceres where majority of the farmers produce deciduous fruits. The area is also known for some important vegetables such as Onions. Apart from serving as a source of water for both agricultural and urban water usage a dam can also be used for other economic purposes. It is important to state that farm dam is a capital intensive infrastructure and if the farm dams don't fill up, it may worsen the situation of farmers since the high capital cost and resulting high unit cost of farm dam water will increase their financial vulnerability. Louw *et al.* (2012) presented the bulk storage capacity for the main storage dams of the Cape Town City

(CTC) and the storage levels from 2007-2011. The analysis shows that in three of the five years the dams did not fill up to their maximum capacities. There is a large probability that increasing temperatures and reduced runoff will aggravate this situation in future. Thus, although the findings above shows that farm dam capacity and water rights during winter will improve the condition of the farmers in the future in the Ceres region, care should be taken if such an option is to go by because of the investment involved and the possible limitation pointed at above.

6.6.2 WATER USE EFFICIENCY ADAPTATION SCENARIO

The second adaptation option to climate change was where water is used more efficiently. Here water use efficiency is increased by 10%, 20% and 30% in Scenarios 6, 7, 8 respectively. The results show that the welfare of the farmers is improved when water is used more efficiently. Increasing irrigation efficiency would lead to saved water, which can either be used to augment crop yield (expand irrigated area), allow more water for downstream users or release water for other uses. In the context of this study, it leads to more marginal land being used for production and increase in the area under optimal irrigation. In the light of climate change, improving irrigation efficiency could be a plausible adaptation strategy.

6.6.3 INCREASE IN WATER TARIFF SCENARIO

The last set of scenarios investigated the impact of increases in water tariff by 10%, 20% and 30% as an adaptation option to climate change as Scenarios 9, 10 and 11 respectively. An increase in water tariff was hypothesised to reduce water usage and also encourage farmers to use water economically. The model results indicate that increasing water tariffs as an adaptation strategy to climate change is less effective in the agricultural sector and can even result in a negative impact since farmers grow deciduous fruit crops which often use even more water depending irrespective of the tariff regime. In addition to this, vegetable crops that are planted in Ceres area also require optimal level of irrigation. Also, the price elasticity of demand for agricultural water is very inelastic since farmers cannot simply stop irrigating or change to deficit irrigation. Production of fruit crops that meet export market requirement requires that the farmers irrigate optimally and increase in water tariff as seen in this session will jeopardize production for such markets.

6.7 RECOMMENDATIONS

Based on the findings of this thesis, a number of recommendations can be made. For the purpose of discussion, the recommendations are divided into two main sections. The first section contains recommendations for policy makers which may contribute towards uplifting the welfare and sustainability of the agricultural sector in Ceres, and for application elsewhere. Following this, recommendations for future research will be made.

6.7.1 POLICY RECOMMENDATIONS

- Policies are required to facilitate government in meeting the responsibility of providing farmers with subsidised inputs/costs needed for adaptation. For instance, government might subsidise costs of farm dams for small/emerging farmers, costs of the installation of drip irrigation and of acquiring improved varieties of inputs necessary for production. Adoption of crop varieties with increased resistance to high temperature can help farmers cope with climate change because increase temperature increase evapo-transpiration and hence increase in crop water requirement. In addition to this, the analysis shows that irrigation technology also has an impact on crop water requirement; therefore farmers should make use of a more efficient irrigation technology system. The initial investment might be big but the long run impact of such an investment will be beneficial in the long run. NPC (2011) also recommends that a substantial increase be made in investment in water resources and irrigation infrastructure.
- Efforts should be directed towards making relevant and important information from climate change forecasts available to water resource managers. Such information should be integrated into water resources policy, planning and management in a systematic way for agricultural and human use in Africa. It will not be an easy ride to implement adaptation and mitigation strategies without institutional support. It has been demonstrated in this study that an integrated approach can provide a valid solution to the projected impact of climate change. South Africa stands at an advantage with a Water Act that makes provision for strong institutional governance directed at the river catchment level to manage water resources. Efforts should be directed towards integrating climate change strategies into water resources policy and planning at the catchment level.
- The Government can play a major role in supporting farmers and businesses to overcome some of barriers that can emanate from changing climate by creating an environment

conducive to the appropriate adaptation decisions. Evidence from our level of adaptation to current climate and the existence of barriers to adaptation demonstrates that self-interest will not always be sufficient, particularly as climate change will be much more rapid than previously experienced. Accordingly, adaptation strategies should not be politicised and a “no regret” adaptation strategy should be prioritised. For instance, in this study giving farmers farm dam capacity alone will not improve the situation of the farmers according to the analysis done. However, caution should be taken when considering such an adaptation option. It is important to state that farm dam is a capital intensive infrastructure and if the farm dams don't fill up, it may worsen the situation of farmers since the high capital cost and resulting high unit cost of farm dam water will increase their financial vulnerability. This can be a regret option and countries are being urged to improve and consolidate their water resources management systems and to identify and implement “no regrets” strategies, which have positive development outcomes that are resilient to climate change. Therefore, giving farmers farm dam capacity and winter water right could be a good adaptation strategy but other issues surrounding its suitability should be considered.

- More institutional support is necessary for farmers to enable them to adequately adjust and adapt to the projected impacts of climate change. The findings from this study show the importance of the investment that has been made by the organizations such as the Water Research Commission (WRC) in terms of water use efficiency in South Africa. Various research project funded by the WRC has demonstrated how improvements can be made to efficiently manage water in South Africa (Reinders 201, Annandale *et al.*, 2011, Averbek *et al.*, 2011). Therefore, using water more efficiently will be the best adaptation option based on the analysis in this thesis to help the Ceres farmers cope with the future projected impact of climate change. Overall, a change in the profile can be expected as a result of climate change and adaptation thereof. Farmers will require technical support to adequately cultivate improved variety of crops and apply new management practices on their farms. Given the role of agriculture and contribution of Western Cape to South Africa balance of payment in terms of export, adaptation that will improve the welfare of both emerging and commercial farmers should be considered.

6.7.2 RECOMMENDATIONS FOR FURTHER RESEARCH

- This research was carried out at aggregate crop level without taking cultivar differences into consideration. Further research needs to be done by breaking crops down into different cultivar categories in order to make a more informed policy recommendation to farmers about particular cultivars that will adapt well to projected impacts of climate change.
- A more sensitive integrated methodology has been developed in this study by extending the already existing models. This model can be tested and applied elsewhere in South Africa. There is also a need to do research similar to this in other regions and in different farming systems.
- In this study only the A2 emission climate scenario was considered. It is recommended that other emissions scenarios in near and distant future projections be considered to assess the full range of possible climate and runoff outcomes.
- It is important to note that world-wide climate change may result in world-wide changes in production patterns, and consequently in changes in product supplies and product markets. This could have a macro-economic impact on an economy. This means that new studies on product combinations – and policy – may have to be done fairly soon.
- There is a need for more research to be carried out, particularly on water use adaptation strategies, such as adaptation of cultivars and various facets influencing irrigation efficiency.

REFERENCES

- Acs, S., Berentsen, P.B.M. and Huirne, R.B.M. (2007). Conversion to Organic Arable Farming in the Netherlands: A Dynamic Linear Programming Analysis. *Agricultural Systems*, 94(2):405-415.
- Adams, R.M., Rosenzweig, C. Peart, R.M. Ritchie, J.T. McCarl, B.A. Glycer, J.D. Curry, R.B. Jones, J.W., Boote, K.J and Allen, L.H. (1990). Global climate change and U.S. agriculture. *Nature*, 345:219-224.
- Adeoti, A.I., Olayemi, J.K and Awoyemi, T.T. (2008). Optimal plans for fadama farming in the derived savannah zone of Nigeria: Application of dynamic programming. *Tropical and Subtropical Agroecosystems*, 8:37- 44.
- Adger, W.N.,(2003). Social capital, collective action and adaptation to climate change. *Economic Geography* 79:387–404.
- Adger, N.W, Arnell, N.W and Tompkins, E.L (2005). Successful adaptation to climate change across scales, *Global Environmental Change*, 15:77-86.
- Ahmad, Q.K. and Warrick, R.A. (2001). Methods and Tools. In climate change: Impacts, adaptation and vulnerability. Report of working group II of the Intergovernmental Panel on Climate change (ed. J. McCarthy). Cambridge University Press.
- Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998). Crop evapotranspiration. Guidelines for computing crop water requirements. Irrigation and Drainage Paper No 56. FAO. Rome, Italy.
- Allan, P. (1999). Measuring winter chilling in areas with mild winters. *Deciduous Fruit Grower* 49(10), S1-S10. Umvoto Africa, (2010). Reconciliation strategy for Cares. http://www6.dwa.gov.za/iwrp/DSS/UserFiles/IWRP/Documents/WC_DC2_WC022_CeresB_F.pdf. [Accessed 22 September 2012].
- Andrew Dessler and Edward A. Parson (2006). The Science and Politics of Global Climate Change: A guide to the debate. Cambridge University Press: ISBN:9780521539418.
- Annandale, J.G., Benadé, N., Jovanovic, N.Z., Steyn, J.M., and Du Sauto,y N. (1999). *Facilitating irrigation scheduling by means of the Soil Water Balance model*. Research Report

to the Water Research Commission. WRC Report No 753/1/99. Pretoria: Water Research Commission.

Annandale, J.G., Stirzaker, R.J., Singels, A., van der Laan, M. and Laker, M.C. (2011). Irrigation scheduling research: South African experiences and future prospects. *Water SA*, 37(5):751 -764

Barter, S. (1991). *Verslag en aanbevelings oor die voorgestelde nuwe Koekedou Besproeiingskema*.

Backeberg, G.R. (1984). *Besproeiingsontwikkeling in die Groot-Visriviervallei*. Ongepubliseerde M.Sc. (Agric)-verhandeling. Universiteit van Pretoria, Pretoria.

Bryant, C.R., Smit, B., Brklacich, M., Johnston, T.R., Smithers, J., Chiotti, Q. and Singh, B. (2000). Adaptation in Canadian agriculture to climatic variability and change. *Climatic Change*, 45(1):181–201.

BOCMA, (2010). *Breede-Overberg Catchment Management Strategy: Water Management Area Status Quo Summary Report*.

Carbone G.J. and Schwartz M.D. (1993). Potential impact of winter temperatures increase on South Carolina peach production. *Climate Res.*, 2:225-233.

Callaway, J.M. (2004). Adaptation Benefits and Costs: are they Important in the Global Policy Picture and How can we Estimate them? *Global Environmental Change*, 14: 273-282.

Callaway, J. M., Louw, D. B Nkomo, J. C. Hellmuth, M. E. and Sparks, D. A. (2006). 'The Berg River Dynamic Spatial Equilibrium Model: A new tool for assessing the benefits and costs of alternatives for coping with water demand growth, climate variability and climate change in the Western Cape', AIACC Working Paper No 31, International START Secretariat, Washington, DC.

Callaway, J.M., Louw D.B., Hellmuth M., Nkomo J.C. and Sparks D. (2008). Chapter 3: Benefits and costs of adapting water planning and management to climate change and water demand growth in the Western Cape of South Africa. In Neil Leary, Cecilia Conde, Jyoti Kulkarni, Anthony Nyong and Juan Pulhin (eds.). *Climate Change and Vulnerability and Adaptation*, Earthscan Books, London UK, pp. 53-70.

Callaway, J.M., Louw D.B. and Hellmuth M. (2009). Chapter 2: Benefits and Costs of Measures for Coping with Water and Climate Change: Berg River Basin, South Africa. In Fulco Ludwig, Pavel Kabat, Henk van Schaik and Michael van der Valk (eds.). *Climate Change Adaptation in the Water Sector*. Earthscan Books, London, UK, pp. 191-212.

Carraro, C and Sgobbi, A. (2008) "Climate Change Impacts and Adaptation Strategies In Italy. An Economic Assessment". Assessed on: <http://www.feem.it/userfiles/attach/Publication/NDL2008/NDL2008-006.pdf>. [Accessed 10 October 2011].

CEEPA (2002). Center for environmental economics and policy in Africa: Facts about Africa agriculture climate. Available online at http://www.ceepa.co.za/Climate_Change/. [Accessed 15 January 2010].

Ceres. www.planyourholiday.co.za/western-cape/ceres [Accessed 10 December 2012]

Copenhagen synthesis report (2009). Climate change. Global Risks, Challenges & Decisions. University of Copenhagen. Accessed on: www.climatecongress.ku.dk. [Accessed 22 September 2010].

CIER (2007). The US Economic Impacts of Climate Change and the Costs of Inaction. A Review and Assessment by the Centre for Integrative Environmental Research (CIER) at the University of Maryland.

Chan, N.Y., Ebi, K.L., Smith, F., Wilson, T.F. and Smith, A.E. (1999). An integrated assessment framework for climate change and infectious diseases. *Environmental Health Perspectives*, 107: 329-337.

Charry A, Daramola A.G and Dillon J.L. (1992). Application of mathematical programming in farming systems research and extension. *Agricultural Systems in Africa*, 2: 31-37.

Cline, W.R. (1992). The Economics of Global Warming. Washington D.C.: Institute for International Economics.

Conradie B.I. and Hoag D.L., 2004. A review of mathematical programming models of irrigation water values, *Water SA*, 30(3): 287-292.

Crosby, C.T and Crosby, C.P. (1999). *SAPWAT - a Computer Program for Establishing Irrigation Requirements and Scheduling Strategies in South Africa*. Report No. 624/1/99. Water Research Commission.

CTB (2010). Ceres Tourism Board Website.

Dantzig G. B. (1963). *Linear Programming and Extension*, Princeton University Press.

Daw, T., Adger, W.N., Brown, K., Badjeck, M.C. (2009). Climate change and capture fisheries: potential impacts, adaptation and mitigation. In K. Cochrane, C. De Young, D. Soto and T. Bahri (eds). Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper. (530):107-150.

Darwin, R., Tsigas, M., Lewandrowski, J. and Ranases, A. (1995). "World Agriculture and Climate Change: Economic Adaptations." Agricultural Economic Report 703, U.S. Department of Agriculture, Economic Research Service, Washington, DC.

Dennis, F.G. (2003). Problems in standardizing methods for evaluating the chilling requirements for the breaking of dormancy in buds woody plants. *HortSci.*, 38: 347-350.

Department of Water Affairs And Forestry (1998). National Water Act. Act No 56 of 1998. 20 August 1998.

Department of Water Affairs and Forestry (2003). Directorate of Water Resource Planning. Breede River Basin Study Main Report.

Department of Environmental Affairs and Tourism (2004). A national climate change response strategy for South Africa.

Department of Environmental Affairs and Development Planning (2007). A climate change strategy and action plan for the Western Cape. www.capegateway.gov.za/eadp. [Accessed 05 November 2010].

Easterling, W.E.: (1996), Adapting North American Agriculture to Climate Change in Review, *Agricultural and Forest Meteorology*, 80(1):1-54.

Easterling, W.E. (1997). Why regional studies are needed in the development of full scale integrated assessment modeling of global change processes. *Global Environmental Change*, 7(4): 337-356.

Easterling, W.E., Hurd, B.H. and Smith, J.B. (2004). Coping with Global Climate Change: The Role of Adaptation in the United States. Pew Center on Global Climate Change, Washington, DC.

Eckert, J.B., Liebenberg, G.F. and Troskie, D.P. (1997). Commercial agriculture in the Western Cape: Macroeconomic analysis with a social accounting matrix. *Agrekon*, 36(3): 302-324.

Elgaali, E. A. (2005) Modeling Regional Climate Change Impacts on Available Water for Agriculture. Ph.D. dissertation, Colorado State University, Fort Collins, Colorado.

Elvio Giasson, Ray B. Bryantb and Nelson L. Billsc (2002). Environmental and economic optimization of dairy manure management: a mathematical programming approach. *Agronomy Journal*, 94:757-766.

FAOSTAT (2009). Statistical database of the Food and Agriculture Organization of the United Nations.

Fishman, S., Erez, A. and Couvillon, G.A. (1987). The Temperature-Dependence of Dormancy Breaking in Plants -Computer-Simulation of Processes Studied under Controlled Temperatures. *Journal of Theoretical Biology*, 126: 309-321.

Gbetiobouo, G.A. and Hassan R.M., (2004). Measuring the economic impact of climate change on major South African field crops: a Ricardian approach, *Global and planetary change* 2004:47, pp. 143-152.

Groisman, P.Y., Knight, R.W., Karl, T.R., Easterling, D.R., Sun, B. and Lawrimore, J.H. (2004). Contemporary Changes of the Hydrological Cycle over the Contiguous United States: Trends Derived from In Situ Observations. *Journal of Hydrometeorology*, 5(1):64-85.

Grove B. (2006). Generalised whole-farm stochastic dynamic programming model to optimise agricultural water use. Report to the Water Research Commission. WRC Report No 1266/1/06. Pretoria: The Water Research Commission.

Grove, B. (2007). Stochastic efficiency optimisation analysis of alternative agricultural water use strategies in Vaalharts over the long- and short-run. Unpublished PhD thesis, Department of Agricultural Economics, University of the Free State, Bloemfontein, South Africa.

Hargreaves, G.H and Samani, Z.A. (1985). Reference crop evapotranspiration from temperature. *Transactions of the American Society of Agricultural Engineers*, 1:96-99

Hacking, A. (2006). An overview of the South African low chill fruit industry. Available online: http://www.lowchillaustralia.com.au/items/286/Session%205_Hacking%20SA%20Low%20Chill%20Industry.pdf. [Accessed 14 February 2010].

Harremoës, P., and Turner, R., (2001). Methods for integrated assessment. *Reg Environ Change*, 2: 57-65.

Hatfield, J.L. (2008). How will Climate Change Affect Agriculture over the Next 10-30 Years [CD-ROM]. In: 84th Agricultural Outlook Forum, Washington DC.

Hatfield, J.L., Boote, K. J., Kimball, B. A., Ziska, L. H., Izaurralde, R. C., Ort, D., Thomson, A. M. and Wolfe, D. (2011): Climate impacts on agriculture: Implications for crop production. *Agronomy Journal*, 103: 351-370.

Hurd, B. J. Callaway, P. Kirshen, and J. Smith. (1999). 'Economic Effects of Climate Change on US Water Resources' in Mendelsohn, R. and J. Neumann (eds.), *The Impacts of Climate Change on the US Economy*. Cambridge University Press, Cambridge, UK.

Hurd Brian H., Mac Callaway, Joel Smith, and Paul Kirshen. (2004). Climatic Change and US Water Resources: From Modeled Watershed Impacts to National Estimates. *Journal of the American Water Resources Association*, 2:130-148.

IPCC (2001), *Climate Change: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge, Cambridge University Press.

IPCC (2007). *Climate change: Synthesis Report*. Contribution of working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds)].

IPCC, (2007a). *Climate Change: The Physical Science Basis*. Summary for Policymakers. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

IPCC (2007b). *Climate Change -Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the IPCC Cambridge, Cambridge University Press.

IPCC (2007c). *Climate change: Impacts, Adaptation and Vulnerability*. Working Group II Contribution to the IPCC.

John, M., Pannell, D. and Kingwell, R. (2005) Climate change and the economics of farm management in the face of land degradation: Dryland salinity in Western Australia. *Canadian Journal of Agricultural Economics*, 53: 443–459

Jordaan, H., Grové, B., Steyn, M., Benade, N., Annandale, J.G and Pott, A. (2006). *Development of a decision support system to evaluate the profitability of alternative irrigation schedules taking risk into account*. SANCID symposium, Blyde River Canyon, Swadini Resort.

Jones, G.A and White, A.C. (1999). Geotechnics for developing Africa, Wardle, Bright and Fourie (eds), Balkema Rotterdam, ISBN: 9058090825.

Kaiser, H.M and Drennen T. (1993). *Agricultural Dimensions of Global Climate Change*. St. Lucie, FL: St. Lucie Press.

Kantorovich, L.V (1965). *The Best Use of Economic Resources*. Harvard University Press.

Kennedy, J. O. S. (1986). *Dynamic programming: applications to agriculture and natural resources*. London, Elsevier Applied Science.

Köppen, W., (1931). *Grundriss der Klimakunde*. Walter de Gruyter, Berlin, Germany.

Linsley-Noakes, G.C., Allan, P. and Mathee, G., (1994). Modification of rest completion prediction models for improved accuracy in South African stone fruits orchards. *Journal of the Southern African Society for Horticultural Sciences*, 4: 13-15.

Linsley-Noakes, G.C., Louw, M. and Allan, P. (1995). Estimating daily positive Utah chill units using maximum and minimum temperatures. *J. S. Afr. Soc. Hort. Sci.*, 5(1):19-24.

Linville, D.E. (1990). Calculating chilling hours and chill units from maximum and minimum temperature observations. *HortSci.*, 25: 14-16.

Lötze, E. and Bergh, O. (2012). Are chilling unit calculations still relevant for the SA fruit industry? *fresh notes* (64).

Lohano, H.D and King, R.P. (2006). Accuracy of Numerical Solution to Dynamic Programming Models. Staff Paper P06-3. Department of Applied Economics, College of Agricultural, Food, and Environmental Sciences, University Of Minnesota.

Louw, D.B. (1996). Die ontwikkeling van 'n geheelboerderybeplanningsmodel met behulp van dinamiese lineêre programmering vir die vee-kleingraan- weidingsgebiede van die Suid-Kaap. M.Sc. Universiteit van Stellenbosch, Stellenbosch.

Louw, D.B. (2002). Socio economic viability of the Koekedouw irrigation scheme – Ceres district

Louw, D.B. (2007). Business plan for the Koekedouw emerging farmers- Ceres district. Unpublished project report.

Louw, D.B., Johnston, P., Tadros, M., Schulze, R., Lumsden, T., Callaway, M and Helmuth, M. (2011). Managing climate risk for agriculture and water resources development in South Africa: Quantifying the costs, benefits and risks associated with planning and management alternatives. Unpublished project report.

Louhichia Kamel, Véronique Alaryb and Patrice Grimaudb (2004). A dynamic model to analyse the bio-technical and socio-economic interactions in dairy farming systems on the Réunion Island. *Animal Research*, 53: 363- 382

Luedeling, E., Zhang, M. and Girvetz, E. H. (2009). Climatic changes lead to declining winter chill for fruit and nut trees in California during 1950-2099. *PLoS ONE* (4): 1-9.

Luedeling, E. and Brown P.H. (2010). A global analysis of the comparability of winter chill models for fruit and nut trees. *Int. Journal Biometeorol*, 55:411-421.

Manne, A.S. and Richels, R.G. (1992). *Buying Greenhouse Insurance: The Economic Costs of CO₂ Emissions Limits*. Cambridge, Mass: The MIT Press.

McCarl, B.A., Gowen, M. Hohenstein, W. and Schneider, U.A. (1999). The impact of carbon permit prices on the U.S. agricultural sector. Prepared for Climate Change Policies and Programs Division, Office of Policy and Program Evaluation, U.S. Environmental Protection Agency (EPA), Washington, D.C.

McCarl, B.A and Spreen, T.H. (2003). *Applied mathematical programming using algebraic systems*. Texas A&M University.

McDonald, S. and Punt, C. (2001). The Western Cape of South Africa: Export Opportunities, Productivity Growth and Agriculture. Paper prepared for the 4th Global Economic Analysis Conference, Global Trade Analysis Project, Purdue University.

Meadows, M.E. (2006). Global change and southern Africa. *Geographical Research*, 44:135–145.

Mendelsohn, R, Morrison, W, Schlesinger, M.E and Andronova, N.G. (2000). Country-specific market impacts of climate change. *Climatic Change*, 45: 553–569.

Menzel, L., Florke, M., Matovelle, A. and Alcamo, J. (2007). Impact of socio-economic development and climate change on water resources and water stress. Center for Environmental Systems Research (CESR), University of Kassel.

Midgley, S.J.E. and Lötze, E. (2011). Climate Change in the Western Cape of South Africa: Trends, Projections and Implications for Chill Unit Accumulation. Proc. IXth IS on Orchard Systems.

Mitchell, T. and Tanner, T. (2006). Adapting to Climate Change: Challenges and Opportunities for the Developing Community. A Publication of Tearfund, UK.

Minnaar, H.A & Groenewald, J.A. (1990). Livestock production systems in a high rainfall diversified farming area: the Northern Drakensberg grazing region. *Agrekon*, 29(4):319-323.

Mimi Z.A and Jamous S.A. (2010). Climate change and agricultural water demand: Impacts and adaptations. *African Journal of Environmental Science and Technology*, 4(4):183-191

Morgan, M. G. and Dowlatabadi, H. (1996). 'Learning from Integrated Assessment of Climate Change'. *Climatic Change*, 34: 337-368.

Mqadi, (2005). Production function analysis of the sensitivity of maize production to climate change in South Africa. An unpublished Master's thesis submitted to the Department of Agricultural Economics, University of Pretoria.

Murray (2010). Key trends in the agricultural economy of the Cape Winelands District Municipality. Implications for farm workers and dwellers.

Nicol, A., and Kaur, N. (2009). Adapting to Climate Change in the Water Sector. Background Note, March 2009. Overseas Development Institute, London, UK.

Nordhaus, W.D. (1993). Reflections on the Economics of Climate Change. *Journal of Economic Perspectives*, 7(4):11-25.

O'Brien, K., Sygna, L., Leichenko, R., Adger, W., Barnett, J., Mitchell, T., Schipper, L., Tanner, T., Vogel, C. and Mortreux, C. (2008). Disaster risk reduction, climate change adaptation and human security, global environmental change and human security (GECHS) project, Oslo.

Oerlemans J. (2005): Extracting a climate signal from 169 glacier records. *Science*, 33: 675-677

Parson, E. A. (1995). Integrated assessment and environmental policy making. *Energy Policy*, 23:463-475.

Parson, E.A. and Fisher-Vanden, K. (1997). Integrated assessment models of global climate change. *Annu Rev Energ Environ*, 22:589–628.

Pannell, D.J. (1996). Lessons from a decade of whole-farm modelling in Western Australia. *Review of Agricultural Economics*, 18: 373-383.

PDC (2005). The agriculture and agri-business sector of the Western cape. A consensus on land reform, economic development, environment, food security, sustainable livelihoods and the desired intervention strategies.

Rana, R.S., Bhagat, R.M., Kalia, V. and Lal, H. (2009). 'Impact of Climate Change on Shift of Apple Belt in Himachal Pradesh', proceedings of workshop on Impact of Climate Change on Agriculture, ISPRS, http://www.isprs.org/proceedings/XXXVIII/8-W3/b2/10-B10-179_ISRO%20F.pdf (accessed 21 January 2011). [Accessed 22 September 2012].

Rea, A.N. (1977). Crop management economics. Crisby Lockwood Staples, London.

Reinders, F.B. (2011) "Irrigation methods for efficient water application: 40 years of South African research excellence" *Water SA*, 37(5): 765 -770.

Richardson, E.A., Seeley, S.D. and Walker, D.R. (1974). A model for estimating the completion of rest for 'Redhaven' and 'Alberta' peach trees. *HortScience*, 9:331-332.

Rotmans, J., and Dowlatabadi, H. (1996). Integrated assessment of climate change: Evolution of methods and strategies. In Human Choices and Climate Change: A State of the Art Report. Richland, Wash.: Battelle Pacific Northwest Laboratories.

Rosenberg, N. J. (1993). Towards an Integrated Impact Assessment of Climate Change: The MINK Study. Dordrecht, Boston, London: Kluwer Academic Pub.

Roughgarden, T. and Schneider, S.H., (1999). Quantifying uncertainties for damage from climate change. *Energy Policy*, 27: 415–429.

Rogner, H.-H., Zhou, D., Bradley, R., Crabbé P., Edenhofer, O., Hare B., Kuijpers, L., Yamaguchi, M., (2007). Introduction. In Climate Change: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press.

Saure, M.C.(1985). Dormancy Release in Deciduous Fruit Trees. *Horticultural Reviews*, 7: 239–300.

Savage, E.F. and Prince V.E. (1972). Performance of peach cultivars in Georgia. USDA and Univ of Georgia col. Agr. Expt. Sta Res. Bul. 114, Athens, GA.

Schneider, S.H., Easterling, W.E., and Mearns, L.O. (2000). Adaptation: sensitivity to natural variability, agent assumptions and dynamic climate changes. *Climatic Change*, 45(1): 203–221.

Schulze, R.E. (2012). A 2011 Perspective on Climate Change and the South African Water Sector. WRC Report TT 518/12, Water Research Commission, Pretoria, RSA.

Sheard, A.G. (2001). Measuring winter chilling in the south west region of KwaZulu-Natal during 2001 and its implications for deciduous fruit production: KZN Agri-Report No. N/A/2002/02.

Shrestha, S.K., Gibbons, J.M. and Ramsden, S.J (2004). Dairy farms in central England under climate change in 2050: do they need to change? Division of Agricultural and Environmental Sciences, School of Biosciences, University of Nottingham, Sutton Bonnington Campus, Loughborough, Leicestershire LE12 5RD, UK.

Shukla, P.R. (2002). Introduction to Integrated Environment Assessment Models. APEIS Capacity Building Workshop on Integrated Environment Assessment in the Asia-Pacific Region, Hotel Grand Inter-Continental, New Delhi.

Singels A, Annandale, J.G., De Jager, J.M, Schulze, R.E., Inman-Bamber, N.G., Durand, W., VAN Rensburg, L.D., Van Heerden, P.S., Crosby, C.T., Green, G.C and Steyn, J.M. (2010). Modelling crop growth and crop water relations in South Africa: Past achievements and lessons for the future. *S. Afr. J. Plant Soil*, 27: 49-65.

Smith, R. (1985). Predicting the dates of first commercial harvest of selected Ontario peach cultivars. *J. Amer. Soc. Hort. Sci.*, 110: 650-654.

Smit, B., McNabb, D. and Smithers, J. (1996). Agricultural adaptation to climate change. *Climatic Change*, 33: 7–29.

Smit, B., I. Burton, R.J.T. Klein, and J. Wandel, (2000): An anatomy of adaptation to climate change and variability. *Climatic Change*, 45: 223–251.

Smith, D. and Vivekananda, J. (2007). A climate of conflict: The links between climate change, peace and war. London: International Alert.

Smith, M. (1992). *CROPWAT, A Computer Programme for Irrigation Planning and Management*. FAO Irrigation and Drainage Paper no 46. FAO. Rome, Italy.

Strzepek, K.M., Major, D.C., Rosenzweig, C., Iglesias, A., Yates, D.N., Holt, A. and Hillel, D. (1999). New methods of modeling water availability for agriculture under climate change: The U.S. Cornbelt. *J. Amer. Water Resources assoc.*, 35:1639-1655.

Strahler, A.H. and Straler, A.N., (2002). *Physical Geography: Science and Systems of the Human Environment*. John Wiley and Sons, Inc. New York, USA.

Thangata P, Hildebrand P, and Gladwin C. (2002). Modelling agroforestry adoption and household decision making in Malawi. *African Studies Quarterly* 6 (1-2): <http://web.africa.ufl.edu/asq/v6/v6i1a11.htm>. [Accessed 10 May 2008].

Turpie, J., Winkler, H., Spalding-Fecher, R. and Midgley, G. (2002). Economic impacts of climate change in South Africa: A preliminary analysis of unmitigated damage costs. Southern Waters Ecological Research & Consulting & Energy & Development Research Centre. University of Cape Town.

UNESCO-WWAP (2009). *Climate change and water: An overview from the world water development report 3: water in a changing world. A world water assessment programme special report SC-2010/WS/5.*

UNESCO-IHP, (2011).The impact of climate change on water resources: The response of UNESCO's International Hydrological Programme. <http://unesdoc.unesco.org/images/0019/001922/192216e.pdf>. [Accessed 22 April 2013].

Van Averbeke, W., Denison, J. and Mnkeni, P.N.S (2011). Smallholder irrigation schemes in South Africa: A review of knowledge generated by the Water Research Commission. *Water SA*, 37(5): 797 -808

Van Heerden, P. S., Crosby, C. T., Grove, B., Benade, N., Theron, E., Schulze, R. E. and Tewelde, M. H. (2008). Integrating and upgrading of SAPWAT and PLANWAT to create a powerful and user-friendly irrigation water planning tool. Water Research Commission, Report number: TT391/08, Pretoria.

Van Vliet, M.T.H, and Zwolsman, J.J.G. (2008). Impact of summer drought on the water quality of the Meuse River. *Journal of Hydrology*, 353: 1-17.

Walker, N. J., and Schulze, R.E. (2008). "Climate change impacts on agro-ecosystem sustainability across three regions in the maize belt of South Africa" *Agriculture, Ecosystems and Environment*, 124: 114-124.

Weinberger, J.H., (1950). Chilling requirements of peach varieties. *Proceeding of the American Society for Horticultural Science*, 56:122-128.

Weyant J., Davidson O., Dowlatabadi H., Edmonds J., Grubb M., Richels R., Rotmans J., Shukla P., Cline W., Fankhauser S., and Tol R. (1996). Integrated assessment of climate change: an overview and comparison of approaches and results. In: Bruce JP, Lee H, Haites EF (eds) *Climate change 1995—economic and social dimensions of climate change. Contribution of working group III to the second assessment report of the intergovernmental panel on climate change (IPCC)*. Cambridge University Press, Cambridge.

Yarnal B. (1998). Integrated regional assessment and climate change impacts in river basins. *Climate Research*, 11(1): 65-74.

APPENDIX **A**

FARM MODEL SET STRUCTURE

A.1: Elements of the set C

Description	Element	Description	Element
Apples	Apples	Cabbage	Cabbage
Pears	Pears	Cauliflower	Cauliflw
Nectarines	Nect	Carrots	Carrots
Peaches	Peach	Peas	Peas
Plums	Plums	Pumpkins	Pumpkin
White wine	Wwine	Squash	Squash
Lucerne	Lucerne	Beetroot	Beetr
Oats	Oats	Sweet melon	Sweetmel
Potatoes	Potatoes	Wheat	Wheat
Tomatoes	Tomatoes	Maize	Maize
Onions	Onions	Barley	Barley
Apricots	Apricots	Triticale	Korog
Butternuts	Butternuts	Long term Pasture	LTPast
Lettuce	Lettuce	Spinach	Spinach

I = Set of all crop enterprises, elements are denoted as *i*. I is a subset of C. Elements and subsets of I are listed in Table 4.6. Enterprises are grouped into subsets:

- I_{stc} is the set of all short term crops
- I_{sto} is the set of short term crops excluding vegetables
- I_v is the set of vegetables
- I_{past} is the set of all the pastures
- I_{Epast} is the set of all long term crops excluding pasture
- I_{vegA} is the set of mainstream vegetables
- I_{vegB} is the set of Rankgewasse
- I_{vegC} is the set of all other vegetables
- I_r is the set of all other long term crops
- I_{rr} is the set of key long term crops
- I_k is the set of all irrigated crops
- I_d is the set of all dry land crops

A.2: Elements and subsets of I

Item Description	Element	Subsets of I												
		I _{stc}	I _{sto}	I _v	I _{pas} t	I _{Ep} ast	I _{ve} gA	I _{ve} gB	I _{ve} gC	I _r	I _{rr}	I _{rtes} t	I _k	I _d
Apples	Apples					*				*	*	*	*	
Pears	Pears					*				*	*	*	*	
Nectarines	Nect					*				*	*		*	
Peaches	Peach					*				*	*		*	
Plums	Plums					*				*	*		*	
White wine	Wwine					*				*	*		*	
Lucerne	Lucerne				*					*			*	
Oats	Oats	*	*										*	
Potatoes	Potatoes	*		*			*					*	*	
Tomatoes	Tomatoes	*		*			*					*	*	
Onions	Onions	*		*			*					*	*	
Apricots	Apricots					*				*	*		*	
Butternuts	Butternuts	*		*				*					*	
Cabbage	Cabbage	*		*			*						*	
Cauliflower	Cauliflw	*		*				*					*	
Carrots	Carrots	*		*				*					*	
Peas	Peas	*		*				*					*	
Pumpkins	Pumpkins	*		*				*					*	
Squash	Squash	*		*				*					*	
Beetroot	Beetr	*		*				*					*	
Sweet melon	Sweetmel	*		*				*					*	
Wheat	Wheat	*	*									*	*	*
Maize	Maize	*	*									*	*	*
Barley	Barley	*	*									*	*	*
Tricale	Korog	*	*										*	*
Long term	LTPast				*					*			*	
Pasture														
Spinach	Spinach	*		*				*					*	
Lettuce	Lettuce	*		*				*					*	

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

Irrigation land (Irrig)

Dryland (Dryland)

Sites= set of sites denoted as *sites*. There are 19 sites in the model.

U-site= set of urban sites denoted as *u-site*. There is only one site:

Urban site (URB1).

UA= Set of Urban and Agricultural site denoted a *ua*. There are two sites:

Urban site (URB1);

Agric sites (Agric).

AS = set of Agric site denoted as *as*. There is only one site:

Agric sites (Agric).

Dams = set of Dam site denoted by *dams*. There is only one main storage dam:

Dams sites (Koekdam).

Ros = set of runoff sites denoted by *ros*. There are two main runoff sites:

Ros (C1, C2).

J = set of all water user types with elements denoted by *j*. There are 11 emerging farmers, 3 representative commercial farmers and one urban region in the model:

KD1 to KD11;

KC1 to KC3;

Urb1.

Irrigation water users (J_b is the irrigation user subset):

KD1 to KD11

Emerging farmers

KC1 to KC3

Commercial farmers.

Existing Irrigation Users (Ea_b is the Existing irrigation areas):

KD1 to KD11;

KC1 to KC3.

Emerging farmers (Eme_b is the emerging farmers):

KD1 to KD11.

Commercial farmers (Cf_b is the commercial farmers):

KC1 to KC3.

FirstFarm(Ea) is a subset of Ea representing the first farm.

LastFarm(Ea) is a subset of Ea representing the last farm.

U_j is a set of urban users

Urban users

Urb

G = set of urban sector users, elements of which are denoted as *g*.

Household user

ihh

FW_g = Demand sector receiving free water (FW_g is urban sector user subset):

Household user

ihh

P = is a set denoting the destination of crop products, element of which is denoted as *p*.

There is only one destination which is the market.

SA = is a set of saving, element of which is denoted by *sa*:

Invest

LO = is a set of debt, element of which is denoted as *lo*:

Stloan

OF= is a set of Overhead factors, denoted as of:

Vegetables	Vegies,
Long term crops	LTcrops,
Dryland crops	Drcrops

GLS = is a set denoting the growth stage, element of which is denoted by gls:
g01 to g40

TH = is a set denoting total time series, element of which is denoted by th:
Y2017 to Y2065

Planning horizon (ph_{th} is a total time series subset) :
Y2046 to Y2065

Previous years (py_{th} is total time series subset) :
Y2017 to Y2045

FirstYr ($FirstYr_{ph}$ is planning horizon subset) :
First year

LastYr ($LastYr_{ph}$ is planning horizon subset) :
Last Year

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

wwm_m = Winter months (wwm_m is months subset):
April, May, June, July, August, September

swm_m = Summer months (swm_m is months subset):
October, November, December, January, February, March

$FirstMo_m$ = Frist month ($FirstMo_m$ is month's subset):
First Month

$LastMo_m$ = Last month ($LastMo_m$ is month's subset):
Last Month

Q=set of water sources, elements of which are denoted as q:

Koekedouw summer (KkdouwS)

Koekedouw winter (KkdouwW)

Warm Bokkeveld (WarmBW)

Bore holes (Boreh)

ww_q = Winter water (ww_q is water sources subset):

Koekedouw winter (KkdouwW)

Warm Bokkeveld (WarmBW)

Bore holes (Boreh)

kw_q = Koekedouw water (kw_q is water sources subset):

Koekedouw summer KkdouwS

Koekedouw winter KkdouwW,

ow_q = All other sources (ow_q is a subset of water sources):

Warm Bokkeveld WarmBW,

Bore holes Boreh

wp_q = Pump water schemes (wp_q is a water sources subsets):

Bore holes Boreh

FD= is a set of farm dams, elements of which are denoted by **fd**.

Farm dams FDams

A1(ROS,SITES) = is a set relating run off to sites

C1 .Koekdam

C2.Koekdam

A2(DAMS, SITES) = is a set relating dam to sites

Koekdam.URB1

Koekdam.Agric

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

Optimal irrigation (Opt)

Supplemental irrigation (Supp)

Deficit irrigation (Defc)

Dryland (Dry)

Louw (2001) has referred to supplemental irrigation 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 of applying supplemental or deficit irrigation on some crops. For example, it is 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)

kw_to_A6(kw,A6) = set relating Koekdam to Agric allocation

(KkdouwS, KkdouwW).Koekdam

IT= set of irrigation technology, elements of which are denoted by 'it'. There are three irrigation technologies:

Micro

Drip

Sprinkle

Alias statements

Alias statements are a convenient way of giving another name to a previously declared set. It is useful for sets where there are interactions between the elements within the same set. The following alias statements were used.

Alias (j,jp);

Alias (l,lp);

Alias (h,hp);

Alias (b,bp);

APPENDIX **B**

**THE LAYOUT OF THE BULK WATER
INFRASTRUCTURE**

