AIACC Final Reports

Estimating and Comparing Costs and Benefits of Adaptation Projects: Case Studies in South Africa and The Gambia

A Final Report Submitted to Assessments of Impacts and Adaptations to Climate Change (AIACC), Project No. AF 47

(Page intentionally left blank)

Estimating and Comparing Costs and Benefits of Adaptation Projects: Case Studies in South Africa and The Gambia

A Final Report Submitted to Assessments of Impacts and Adaptations to Climate Change (AIACC), Project No. AF 47

Submitted by Jabavu C Nkomo
University of Cape Town, Cape Town, South Africa
and
Bernard Gomez
Department of Water Resources, The Gambia

2006

Published by
The International START Secretariat
2000 Florida Avenue, NW
Washington, DC 20009 USA
www.start.org

Contents

List of Tables

List of Figures

About AIACC

Assessments of Impacts and Adaptations to Climate Change (AIACC) enhances capabilities in the developing world for responding to climate change by building scientific and technical capacity, advancing scientific knowledge, and linking scientific and policy communities. These activities are supporting the work of the United Nations Framework Convention on Climate Change (UNFCCC) by adding to the knowledge and expertise that are needed for national communications of parties to the Convention.

Twenty-four regional assessments have been conducted under AIACC in Africa, Asia, Latin America and small island states of the Caribbean, Indian and Pacific Oceans. The regional assessments include investigations of climate change risks and adaptation options for agriculture, grazing lands, water resources, ecological systems, biodiversity, coastal settlements, food security, livelihoods, and human health.

The regional assessments were executed over the period 2002-2005 by multidisciplinary, multi-institutional regional teams of investigators. The teams, selected through merit review of submitted proposals, were supported by the AIACC project with funding, technical assistance, mentoring and training. The network of AIACC regional teams also assisted each other through collaborations to share methods, data, climate change scenarios and expertise. More than 340 scientists, experts and students from 150 institutions in 50 developing and 12 developed countries participated in the project.

The findings, methods and recommendations of the regional assessments are documented in the *AIACC Final Reports* series, as well as in numerous peer-reviewed and other publications. This report is one report in the series.

AIACC, a project of the Global Environment Facility (GEF), is implemented by the United Nations Environment Programme (UNEP) and managed by the Global Change SysTem for Analysis, Research and Training (START) and the Third World Academy of Sciences (TWAS). The project concept and proposal was developed in collaboration with the Intergovernmental Panel on Climate Change (IPCC), which chairs the project steering committee. The primary funding for the project is provided by a grant from the GEF. In addition, AIACC receives funding from the Canadian International Development Agency, the U.S. Agency for International Development, the U.S. Environmental Protection Agency, and the Rockefeller Foundation. The developing country institutions that executed the regional assessments provided substantial in-kind support.

For more information about the AIACC project, and to obtain electronic copies of AIACC Final Reports and other AIACC publications, please visit our website at www.aiaccproject.org.

Summary Project Information

Regional Assessment Project Title and AIACC Project No.

Capacity Building in Analytical Tools for Estimating and Comparing Costs and Benefits of Adaptation Projects (AF47)

Abstract

The broad objective of AIACC project 47 was to develop the capacity to estimate and compare the benefits and costs of projects in natural resource sectors that reduce the expected damages from climate change in Southern and West Africa. There are two parts to this project. The first consists of using well-established principles from economic benefit-cost analysis to develop a framework to estimate the economic benefits and costs associated with the expected climate change damages avoided by a development project that does not take climate change into account. Then, these benefits and costs can be compared to the case where planners incorporate expected climate change into the project assessment. The second part consists of demonstrating this methodology in two project case studies, one in The Gambia and the other in South Africa.

The South African case study examines the benefits and costs of avoiding climate change damages through structural and institutional options for increasing water supply in the Berg River Basin in the Western Cape Province. The Gambian study, on the other hand, focuses on the agricultural sector, particularly on millet, the predominant crop in the country. To facilitate analysis, the Gambian study uses a detailed water–crop model, defines and explores adaptation strategies with the model and uses the results to carry out an economic analysis. The South African project develops and applies a Berg River Dynamic Spatial Equilibrium Model as a water planning and policy evaluation tool to compare benefits and costs and economic impacts of alternatives for coping with long-term water shortages due to climatic change. Results from the study will contribute to the development of international climate change policies and programs, particularly in regard to adaptation activities in developing countries under the United Nations Framework Convention on Climate Change (UNFCCC).

Administering Institution

Energy Research Centre, University of Cape Town, Cape Town. South Africa

Participating Stakeholder Institutions

The Department of Environment and Trade (DEAT), based in Pretoria, serves as the UNFCCC and GEF focal point for South Africa and as an appropriate stakeholder for the South African study. DEAT hosts the National Committee on Climate Change (NCCC) meetings in South Africa, with membership including the Department of Environment and Tourism, the Department of Minerals and Energy, the Department of Foreign Affairs, the Department of Agriculture, the Department of Water Affairs and Forestry, the Department of Trade and Industry, the Department of Science and Technology, and some NGOs. For Gambia, the Department of Water Resources in Banjul hosts the First National Communication (FNC). FNC is largely based on climate change studies undertaken by the National Climate Committee (NCC). The NCC brings together people of different professional backgrounds from government, non-governmental organisations and private sector institutions. It has a current membership of around 50 institutions from both national and regional level institutions.

Countries of Primary Focus

South Africa, The Gambia

Case Study Areas

South Africa: Water (Berg River Basin case study)

The Gambia: Agriculture (adaptation strategies for millet)

Sectors Studied

South Africa: Water

The Gambia: Agriculture

Systems Studied

Regional Economy

Project Funding and In-kind Support

Funding for the AIACC project was received from the following sources:

AIACC – TWAS	US $150 000.00
Additional funding: AIACC (ERC)	US $10 000.00
AIACC Supplementary Grant (Gambia: Peter Droogers + travel)	US $13 874.00
START	US $47 000.00
Riso (John M Callaway and Molly Hellmuth + travel)	US $199 000.00

Investigators

Principal Investigators: Jabavu C. Nkomo**.** Zimbabwean. Principal Research Officer, Energy Research Centre, University of Cape Town, P Bag Rondebosch, Cape Town. South Africa. Email**:** jabavu@erc.uct.ac.za and Bernard E. Gomez, Global Change Research Unit, Department of Water Resources, The Gambia. Email: be63gomez@yahoo.co.uk

Other Investigators: *South African Case Study*: Debbie Anne Sparks University of Cape Town, South Africa; John M. Callaway, UNEP Riso Centre, Roskilde, Denmark; Molly Hellmuth, UNEP Riso Centre, Roskilde, Denmark; Daniel Louw, University of Free State, South Africa; *The Gambian Case Study*: Bubu P. Jallow, Department of Water Resources, The Gambia; Momodou Njie, Department of Water Resources, The Gambia; John M. Callaway, UNEP Riso Centre, Roskilde, Denmark; Molly Hellmuth, UNEP Riso Centre, Roskilde, Denmark; Peter Droogers, FutureWater, The Netherlands.

Executive Summary

Research problem and objectives

The issue of adaptation project funding under the United Nations Framework Convention on Climate Change (UNFCCC) has taken on increasing importance over the last few years. However, very little formal work has been done by either the Climate Secretariat or by any bilateral or multilateral agencies on this issue to develop a framework or the analytical tools for evaluating and funding adaptation projects, comparable to that, which currently exists for mitigation projects.

There are reasons to justify development of a costing framework for adaptation projects. In the Third Assessment Report, the IPCC predicts that Africa will suffer the most severe impacts from climate change, and African policy-makers need to carefully examine the trade-offs between the benefits and costs of adaptation projects, as well as mitigation costs and adaptation costs. Such analysis cannot be performed without knowledge of the adaptation costs of projects in their locality.

This study develops the capacity to estimate and compare the benefits and costs of projects in natural resource sectors that reduce the expected damages from climate change in South Africa (the water sector) and The Gambia (the agricultural sector). There are two parts to this project. The first consists of using well-established principles from economic benefit-cost analysis to develop a framework to estimate the economic benefits and costs associated with the expected climate change damages avoided by a development project that does not take climate change into account. Then, these benefits and costs can be compared to the case where planners incorporate expected climate change into the project assessment. The second part consists of demonstrating this methodology on a selected adaptation project. Our ultimate objectives are to examine the benefits and costs of avoiding climate change damages (i) through structural and institutional options for increasing water supply using the Berg River Basin in the Western Cape Province in South Africa as a case study; and (ii) by examining adaptation strategies for millet in The Gambia.

Part I. Adaptation to Climate Change: The Berg River Basin Case Study

Runoff from the Berg River Basin constitutes the major source of water supply for the Cape Town metropolitan region and for irrigating 15 000 hectares of high value crops, the bulk of which is exported and represents an important part of the regional and national economy. In the last three decades, urban water consumption has increased by roughly three-fold in metropolitan Cape Town and promises to continue to grow at a rapid rate due both to the in migration of poorer households and economic development. As a result, the competition for water is increasing in the region and is expected to continue for the foreseeable future. This is further exacerbated by fairly high inter-annual variability in rainfall and runoff in the basin. This was illustrated by a recent drought that left the reservoir at about thirty% of average at the start of the irrigation season in 2004-2005.

Water planners in the region are currently in the process of assessing a variety of new supply sources and demand-side options to take the pressure off the existing supply sources. One such option is the Berg River (Skuifraam) Dam, which was finally approved after a lengthy and heated public discussion and construction began in 2004 (during the course of this study). However, they have not taken the possibility of climate change into account.

In that general context, the objectives of this study are to develop and implement the necessary analytical tools to:

- estimate the potential impacts of alternative climate change scenarios on water supply and demand in the basin through changes in runoff, evapotranspiration and surface evaporation;
- translate these physical impacts into monetary losses (or gains) for different groups of farmers and urban water users; and

- estimate and compare the benefits costs of the storage and water market options of avoiding climate change damages, with and without accounting for expected climate change in the planning for these options.

Method of estimation

To achieve these objectives we 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 for this study to compare the benefits and costs and economic impacts of alternatives for coping with long-term water shortages due 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.

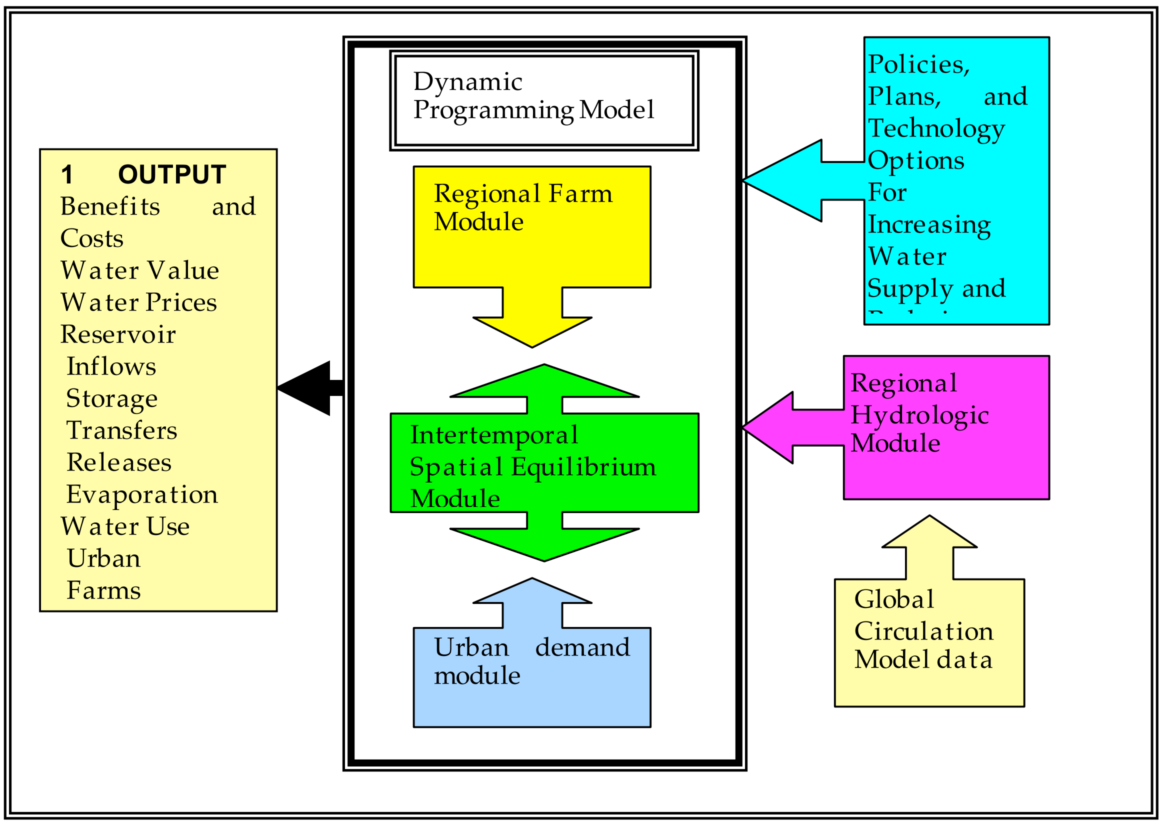


Figure 1.1: Berg River Spatial Equilibrium Model (BRDSEM) Schematic Diagram

The core of BRDSEM, shown in Figure 1.1, is made up of three linked modules:

- *The Intertemporal, Spatial Equilibrium Module* consists of a series of linear equations that characterise both the water balances over time in specific reservoirs and the spatial flow of water in the basin, linking runoff, reservoir inflows, inter-reservoir transfers and reservoir releases, to urban and irrigated agricultural demands for water.

- *The Urban Demand Module* simulates the demand for urban water for seven urban water uses.

- *The Regional Farm Module* consists of seven regional dynamic linear farm models (one for each farm region) that simulate the demand for agricultural water in the Upper-Berg River.

There are three sources of external sources of information to BRDSEM:

- *A Global Circulation Model*: This model supplies the hydrologic model with information about monthly temperature and precipitation at specific points in the basin for climate scenarios.

- *A Regional Hydrologic Model*: This model (WATBAL) converts the monthly temperature and precipitation data from the regional climate model into monthly runoff at different runoff gages for each climate scenario.

- *Inputs about Policies, Plans and Technologies*: This represents the source 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.

We estimated the economic value of the net returns to water for the following three climate change hydrology scenarios, two different levels of urban water demand, and four different policy regimes for allocating water, with and without the possibility of optimal storage capacity behind the Berg River Dam:

- Climate-Hydrology Scenarios
    - CSIRO SRES B2 REF Case (REF[1]): 1961 – 1990.
    - CSIRO SRES B2 Near Future Case (NF): 2010 – 2039.
    - CSIRO SRES B2 Distant Future Case (DF): 2070 – 2099, but applied for the period 2010 – 2039.
- Urban Water Demand Scenarios
    - No urban demand growth from current levels – no changes in the parameters of the urban water demand functions.
    - High urban demand growth – slopes of urban demand functions reduced consistent with 300% increase in water demands over thirty years.
- Water Allocation Policy Regimes
    - Option 1 – Adequate water supplies for urban and agricultural water demand (upper and lower bounds fixed on urban water demands and water diversions by regional farms).
    - Option 2 – Adequate supplies for agriculture (upper and lower bounds on water diversions by regional farms, only).
    - Option 3 – Adequate supplies for urban water use (upper and lower bounds on urban water demands).

---

1 The designation for each scenario, as used in the text, is in parentheses.

- Option 4 – Efficient water markets (no bounds on urban water demand or agricultural diversions).

We also used a framework developed by Callaway et al. (1998) and Callaway (2004a and 2004b) to estimate the benefits and costs associated with adapting to climate change for Option 1B (Option 1 with the possibility for Berg River Dam storage) and Option 4B (Option 4 with the possibility for Berg River Dam storage), under three different climate changes (REF-NF, REF-DF, NF-DF). These economic measures were as follows:

- Climate change damages – The ex ante value of the economic losses in the basin caused by climate change without adjustments in the storage capacity of the Berg River Dam to cope with climate change.
- The net benefits of adaptation – The ex ante net value of the climate change damages associated with adjusting the storage capacity of the Berg River Dam to be optimal for the change in climate.
- The imposed damages of climate change – The ex ante value of the climate change damages that can not be avoided, once optimal storage capacity adjustments are made.
- The costs of caution – The net economic losses experienced ex post, if one plans ex ante for a less severe climate change than actually occurs.
- The costs of precaution – The net economic losses experienced ex post, if one plans ex ante for a more severe climate change than actually occurs.

The previous set of measures apply to storage capacity adjustments made in anticipation of climate change for individual water allocation regimes, not for changes in the regimes themselves. We used the same framework to estimate the 'partial' net adaptation benefits associated with both: a) substituting a system of efficient water markets in Option 4B for the most highly constrained allocation system, represented by Option 1B and b) the addition of optimal reservoir capacity on top of the change in allocation systems. This was done for the climate changes REF-NF and REF-DF only. This analysis is important because ex ante reservoir storage decisions are subject to ex ante climate risks (i.e., by planning for the wrong climate change), while changing water allocation systems is a 'no regrets' measure, not subject to climate risk.

Main conclusions for Berg river study

The important conclusions from our study are as follows:

1. From a benefit-cost perspective, construction of the Berg River Dam at capacity levels that were optimal for the climate scenarios used in this analysis looks to be justified on the basis of economic efficiency.
2. From a benefit-cost perspective, the implementation of an efficient system of water markets, with or without construction of the Berg River Dam, resulted in the highest net returns to water compared to other simulated allocation systems under all climate and urban demand scenarios.
3. Agricultural water use was very robust to the simulated changes in climate, urban water demand assumptions, and the presence or absence of the Berg River Dam compared to urban water use and water allocation policies.
4. Urban water consumption, by contrast, fluctuated much more in response to both climate change and changes in water allocation policy.
5. Simulated climate change damages were relatively and absolutely much greater under our representation of the current allocation regime (Option 1B) than under the efficient water market regime (Option 4B) at high urban demand levels.

6. The impact of adaptation by adjusting reservoir capacity from partial to full adjustment was relatively small in both Options 1B and 4B.
7. The most significant reductions in climate change damages came from instituting a system of efficient water markets in Option 4B for our representation of the current allocation regime (Option 1B).
8. Overall, the analysis of the costs of caution and precaution did not provide any unambiguous results that would allow one to determine if it would be less costly to anticipate climate change or plan cautiously.
9. Finally, substituting markets for the existing allocation system substantially increased the simulated marginal cost of water to urban water users and led to reduced consumption on their part. This would have adverse consequences for poor households in the Cape Town Metropolitan region.

Part II. Adaptation to Climate Change for Agriculture in The Gambia: An explorative study on adaptation strategies for millet

The project developed an adaptation benefit-cost framework as well as analytical tools and procedures, and then applied these on the predominant crop in the Gambia – millet (*Pennisetum typhoides*) in a rainfed environment. Rainfall in the Gambia is characterised by significant variability on both the temporal and spatial scales, with the somewhat frequent occurrence of drought-related situations of greater concern. The choice of millet stems from its ability to withstand low moisture situations, such that any significant drop in yield linked to moisture stress, is expected to have a greater impact on the other crops.

Method of estimation

The study used observed climatological data from the Meteorological Services of the Gambia (rainfall & temperature), the Climatic Research Unit data set of the University of East Anglia, UK (solar radiation, relative humidity and wind speed) to characterise the reference climate (1961-1990). For the future climate, the study uses the Max Plank ECHAM4 and the Hadley Center HADCM3 Global Circulation Models for the A2 and B2 IPCC SRES scenarios. Whilst ECHAM4 predicts increases in rainfall and temperature for the Gambia, HADCM3 predicts increases in temperature, but a reduction in precipitation. Statistical downscaling technique was used to obtain rainfall, and minimum and maximum temperatures from the GCMs to specific locations in The Gambia, for the near future (2010 – 2039) and the distant future (2070 – 2099).

To assess the impact of future climate on millet production, the study used the Soil-Water-Atmosphere-Plant (SWAP) model. This is an integrated physically based simulation model for water, solute and heat transport in the saturated-unsaturated zone in relation to crop growth. The simulation of the reference period revealed average rainfall and crop yield of 976 mm and 1115 kg^{-1} respectively with a coefficient of variation (cv) of 30% for both parameters. Using the results of the HADCM3 ('no regrets'), average rainfall and yield for the near future, was 882 mm and 1141 kg^{-1}, with a cv of 33% for both parameters, whilst for the distant future, the average rainfall was 510 mm and yield of 243 kg^{-1}, with cv of 52 and 123% respectively.

In response to the projected negative impact of climate change on millet production, SWAP explored the use of 'no adaptation', introducing 'new crop variety', 'fertiliser application', 'irrigation', and 'supplemental irrigation' options. With the exception of the 'no adaptation' option all the other options showed increases in yields as compared to the base case (1141 kg^{-1}) ranging from 9 to 37%. The cv was also highest in the 'no adaptation' situation and lowest on the 'irrigation' option. This led to the consideration of the irrigation option in the benefit-cost analysis, though in practice, irrigation of upland cereals is not the norm in the Gambia.

In the economic analysis, costs and benefits are first identified, and then evaluated in monetary terms as far as possible. This leaves out intangible costs and benefits, which cannot be expressed in monetary terms. In this study, however, costs associated with land rental and fertility treatment, pest control, seed purchase, operation and/or maintenance of farm machinery/animals, etc., are omitted. This is more to do with expediency than principle.

Major considerations in the cost study include the (a) identification of water sources; (b) assessment of crop water requirements; (c) selection of irrigation method; and (d) costing of structural works, activities, and inputs, indispensable to irrigation water delivery. Annual costs are obtained by summing up investment, operation, maintenance, and replacement costs. These are derived from price and economic life data provided by suppliers and developers, a discount rate of 9% and a project horizon of 60 years.

On a percentage basis, operation and maintenance, and distribution costs represent the two largest components. For both surface and groundwater, and independent of scale, they account for 80 – 90% of total cost of irrigation using diesel-based water-lifting technologies. The corresponding value for solar pumping is 25%, whilst labour accounts for 2 – 5% of costs.

Main conclusions for the Gambia study

The study evaluates the benefits of adaptation (i.e., irrigation) under current climate $S(C_0, M_1)$, compared to no adaptation $S(C_0, M_0)$. Only direct benefits, which consist of increased farm production and income, are considered.

The detailed economic analysis shows that whilst preliminary results indicate substantial benefits from irrigation at a macro economic level, increased income from irrigation is not matched by costs incurred by farming households, suggesting the need for further policy measures to support irrigation. This is all the more relevant given the deteriorating economic situation, triggered mainly by low exports and increasing imports. Also, given the potential impacts of climate change and extreme weather on countries with surplus production, and the risk of those countries reverting to scarcity economics, especially in low production years, low GDP countries like Gambia are better of growing their own food than expecting to meet their demand from imports. Social impacts of re-vitalised agricultural production on employment generation, alleviation of poverty (increased income, improved nutrition of women and children), rural re-generation/development, etc., cannot be over-emphasised.

Capacity building outcomes and remaining needs

AIACC organized several well timed workshops that added a new dimension to learning, experience and skills, exposed the AF47 team to leading professionals in adaptation, and totally improved the team's approach to the adaptation project. The workshops increased the capacity and ability of the AF 47 team to analyse technical issues, to appreciate the multi-disciplinary nature of adaptation and to work in this context, and to apply some of the techniques and skills learned. Case studies and presentations, given the diversity of participants and projects, were very enriching. Workshops became a forum for new and innovative ideas, networking, information sharing and for exploring avenues for collaboration with other groups. We are now better able to supervise post-graduate students in adaptation, conduct more research in the area, monitor adaptation projects for other agencies, and even offer short courses on adaptation.

The AF 47 team has been able to develop a dynamic model which takes into it runoff sources for all reservoirs and includes irrigated agricultural production. Our models require refinement and constant updating if we are to meaningfully explore policy options further. Second, affordability and availability of latest software for GAMS would have helped find solutions in a much quicker time. This, in turn, would have enabled the team to be better able to probe further on the area studied, to teach other members of the team about the packages used, to develop a broader range of scenarios, to work closely with other regional modellers, and to pass on the skill to others.

The important thing for the team is now to test and apply the model developed to other river basins, and to further develop it as a standard tool that is easy to apply and interpret for estimating costs and benefits of adaptation to avoid climate change damages.

National communications, science-policy linkages and stakeholder engagement

The Department of Environment and Trade is South Africa's focal UNFCCC and GEF point, and hosts the National Committee on Climate Change (NCCC) meetings. The NCCC membership includes several government departments/ministries, some Non-governmental Organisations and interested researchers from various universities. As a member of NCCC, the Energy Research Centre attends and participates in regular meetings organized, and had been able to share research findings on adaptation.

The Department of Water Resources in The Gambia hosts the First National Communication (FNC). FNC is largely based on climate change studies undertaken by the National Climate Committee (NCC) under the chair of GCRU-DWR, and is the source of adaptation options/measures identified. The NCC brings together people of different professional backgrounds from government, non-governmental organisations and private sector institutions.

GCRU-DWR in collaboration with UNEP, has finalised its project proposal for the implementation of the National Adaptation Programme of Action (NAPA) under the auspices of the UNFCCC. All the adaptation options/measures that NAPA intends to examine originate from the First National Communication. It is expected that experience gained in the AIACC project would be very useful in implementing the NAPA.

Policy implications and future directions

Based on our experience in this study, we have basic recommendations for future research:

Extend the BRDSEM model to characterise the entire Boland Region in the Western Cape. To do this, the following modifications have to be made to BRDSEM:

Include the runoff sources for, and the dynamic water balances in, all of the reservoirs in the area including those on Table Mountain, which provide water for Cape Town, those downstream of the regional farms, and those north of the study area in the Boland region, and include linear programming representations for the irrigated agricultural production in the lower Berg River Basin below the regional farms and north of the current study region.

Conduct research to gather data and estimate the parameters of sector-level monthly water demand and waterworks supply (cost) functions for the Metropolitan Cape Town Region. We have already noted in Section 3.0 that the estimates of the parameters of the urban water demand functions used in BRDSEM are not strongly supported by adequate data. In addition, we dropped the urban water works supply function that was in Louw's static model, because this could not be supported by empirical cost data and the use of arbitrary elasticity assumptions heavily biased the results. However, such an undertaking could be supported by the WRC, DWAF, or the CCT in the larger context of alternative urban water pricing policies, nationally, regionally, or just in Cape Town. Such a study is important to assist public and private sector policy makers and planners to address the alternatives for balancing the principles of equity and economic efficiency in urban water pricing in South Africa.

Add additional storage and non-storage capacity options for increasing water supplies and water use efficiency and reducing water losses in the basin. The current version of BRDSEM also needs to be updated by including the possibility for additional storage capacity in the region, based on proposed plans and estimated costs. In addition, the water supply and cost data needs to be updated for wastewater recycling and desalinisation of seawater. Finally, we need to include possibilities for reducing water losses and the associated costs of these options in the delivery of water to users by the Cape Town water authority and for the conveyance systems used to deliver irrigation water to the regional farms.

Improve the representation of water market transfers and include the costs of water market transactions. In the current study, simply removing constraints on agricultural water diversions and urban water demand simulates efficient water markets. The structure of BRDSEM is such that, by removing these constraints, the solutions for the endogenous variables in the model are consistent with the implementation of efficient markets. However, this does not take into account how the current ownership of water rights and existing allocation of entitlements can be changed by specific transfers, nor does it include the transactions costs associated with these transfers. Modelling specific transfers is made a little difficult in BRDSEM because of the presence of return flows below each regional farm. However, it will still be possible to add many of the institutional features of water market transfers by including transfer balances in the model to represent existing entitlements and water rights and, after modifying them to take into efficient markets, looking at the impacts on downstream water users.

Develop a broader range of policy scenarios to blend efficient water markets with equity objectives in meeting the needs of the urban poor. The efficient market scenarios (Option 4A and B) led to high urban water prices and reduced urban water consumption by all households under the high urban water demand and climate change scenarios (NF and DF). We need to more fully explore the policy options and consequences of modifying water market policies to meet the basic needs of the urban poor.

Work closely with regional climate modelers in South Africa to implement BRDSEM using stochastic climate scenario data to generate downscaled distributions of monthly average temperature and precipitation data and transform this into stochastic runoff. As indicated in several places in the text, this study is deterministic, with climate change risk introduced in an ex ante – ex post framework. The climate scenarios used in this analysis are based on the downscaled results of just three runs for the CSIRO SRES B2 REF, NF and DF scenarios. We do not know where these time series results lie in the over-all joint and partial distributions of monthly temperature and precipitation for the region. Thus, it is fundamentally misleading to characterise climate change using the deterministic approach and not very helpful for water resources planners. However, the model and methods we have developed and implemented in this study can easily be transferred to a stochastic environment. This approach would be implemented through the following steps:

Estimate key parameters of the joint and partial distributions of monthly temperature and precipitation for selected climate change scenarios at different locations in the Berg River Basin using a regional climate model (RCM).

Validate RCM simulations of precipitation and temperature for the existing climate in the Berg River Basin against observed records and use these data to estimate the distributions of the errors.

Using this information, calibrate an existing water balance model, such as WATBAL stochastically, to simulate the joint and partial distributions of runoff and evaporation at selected runoff gages in the basin and the distributions of forecast errors associated with the runoff distributions.

Use BRDSEM, stochastically, to propagate the distributions of key variables in the model and their associated forecast, such as monthly reservoir storage, urban and agricultural water demand, water releases, and various economic welfare components.

Assess the impact of the forecast errors on Type I and Type II ex-ante, ex-post planning decisions.

Develop an analytical tool and associated databases to automate the generation of stochastic climate forecasts and error propagation for the RCM, for general use in the region.

Modify and automate an existing water balance model to generate stochastic runoff forecasts using stochastic climate forecasts.

Such a study represents an important step in bridging the communication and data gap between climate scientists and water planners, allowing water planners to work with climate change data on essentially the same basis they work with observed geophysical records, while taking into account inherent reliability problems in existing global and regional models to reproduce the 'historical' climate.

For Gambia, the most promising adaptation option(s) has to be implemented and successive studies should look into whether these adaptation strategies can be adopted through market forces, whether the government should impose these by subsidies or tax regulations, or whether bi-lateral aid should focus on this in an effort to minimise risks of food shortages.

PART I: Adaptation to Climate Change – The Berg River Basin Case Study

Jabavu C.Nkomo (Principal Investigator). Energy Research Centre, University of Cape Town, P Bag Rondebosch, Cape Town. South Africa.

Debbie Anne Sparks. Energy Research Centre. University of Cape Town.

John M. Callaway, PhD. Senior Researcher, UNEP Riso Centre, Roskilde, Denmark.

Molly Hellmuth. UNEP Riso Centre, Roskilde, Denmark.

Daniel Louw. Consultant and Associate Professor, Department of Agricultural

Economics, University of Free State, South Africa.

1 Introduction

1.1 Introduction

The issue of adaptation project funding under the United Nations Framework Convention on Climate Change (UNFCCC) has taken on increasing importance over the last few years. However, very little formal work has been done by either the Climate Secretariat or by any bilateral or multilateral agencies on this issue to develop a framework or the analytical tools for evaluating and funding adaptation projects, comparable to that, which currently exists for mitigation projects.

Several important reasons explain why the costing framework for mitigation projects is difficult to apply conceptually to adaptation projects (see Callaway, et al (1999)). First, whereas the mitigation costs of projects in different countries and sectors can be compared on the basis of cost-effectiveness, it is almost impossible to develop a consistent measure of the physical accomplishments (i.e. benefits) of adaptation projects, such as tons of carbon equivalent emissions. This problem is due to the fact that adaptation measures offset the physical impacts of climate change, which are qualitatively different from country to country (or even place to place within a country), by sector, and by type of project. Therefore, if adaptation costs are to be estimated and compared on a cost-effectiveness basis, a consistent basis for measuring the physical benefits of different projects must be found.

The second problem, which stems directly from the first, is that to measure the physical benefits of adaptation projects we must be able to measure how an adaptation project offsets the physical damages of climate change. This is not necessary for the mitigation-costing framework in which project accomplishments, as indicated, are measured in terms of reductions of carbon equivalent emissions. The final problem is that the base case used to measure the costs and accomplishments is conceptually different from the base case used to measure mitigation costs. For adaptation projects, the reference case is not based on 'business as usual' GHG emissions, but instead upon a projection of climate change impacts that would occur if the climate changed, but no additional adaptation actions were taken. This may sound, conceptually, very close to the base case approach used for mitigation projects, but it is not. This is because individuals, households and firms have an economic incentive to adapt 'autonomously' to climate change, but have no such incentive to mitigate GHG emissions.

There are further reasons to justify development of a costing framework for adaptation projects. In the Third Assessment Report, the IPCC predicts that Africa will suffer the most severe impacts from climate change, and African policy-makers need to carefully examine the trade-offs between the benefits and costs of adaptation projects, as well as mitigation costs and adaptation costs. Such analysis cannot be performed without knowledge of the adaptation costs of projects in their locality.

The purpose of this study is to develop the capacity to estimate and compare the benefits and costs of projects in natural resource sectors that reduce the expected damages from climate change in South Africa. There are two parts to this project. The first consists of using well-established principles from economic benefit-cost analysis to develop a framework to estimate the economic benefits and costs associated with the expected climate change damages avoided by a development project that does not take climate change into account. Then, these benefits and costs can be compared to the case where planners incorporate expected climate change into the project assessment. The second part consists of demonstrating this methodology on a selected adaptation project. Under Part I and Part II we report case studies which examine the benefits and costs of avoiding climate change damages through structural and institutional options for (i) increasing water supply using the Berg River Basin in the Western Cape Province as a South African case study; and (ii) conducting a study on adaptation strategies for millet production in the Gambia.

1.2 Background

The Berg River Basin is located in the Western Cape region of South Africa. The upper Berg River Basin is an economically important water supply system in the Western Cape that provides the bulk of the water for household, commercial and industrial use in the Cape Town metropolitan region. It also provides irrigation water to cultivate roughly 15,000 hectares of high value crops, primarily deciduous fruits, table and wine grapes and vegetables both for domestic and export use with strong multiplier effects in the domestic and national economy. Since the early 1970s water consumption in municipal Cape Town has grown by around three hundred%, fueled largely by the in migration of poor households to the Cape Town flats area. As the population of the Metropolitan Cape Town region grows the competition for water in the basin has become even more intense and farmers have responded by dramatically improving their irrigation efficiencies and shifting even more land into the production of high value export crops.

This has had an important impact on the value of water for irrigation. Recent studies by Louw (2001 and 2002) have shown that the marginal value product of irrigation water in the basin is higher than the prices by being paid by urban water users for water. The government of South Africa, on the other hand, has committed itself to a policy of equitable water use, by providing 6000 liters of water per month, without cost, to poor households in the country. This policy has had the obvious effect of intensifying the competition for water still further and, in the absence of other measures, will make it much harder for farmers to compete for water on the basis of economic efficiency unless the population growth in Cape Town slows, or other measures are adopted.

Recently, the government of South Africa commissioned a new dam in the Berg River basin, in an effort to alleviate the problem of an increasingly scarce water supply for the Cape Metro Region, while maintaining adequate supplies of water for irrigated agriculture. The commissioning of the new Berg River Dam was a controversial and lengthy process, focused largely on the adverse environmental consequences of the dam to riparian habitats. As a result, strict reserve requirements have been imposed on future storage behind the Berg River Dam to provide adequate water to preserve these habitats during summer months, when irrigation demand is highest. The government is also moving towards the creation of competitive markets for water in the basin (and elsewhere) under the new National Water Act (1998). Meanwhile, planners in the basin are searching both for new sites for water storage and new technologies, such as waste-water recycling and desalinisation to ease the water supply problems in the region.

The water resources supply picture in the region is further complicated by relatively high inter-annual variability in runoff in the Berg River Basin (Hellmuth and Sparks 2005). This was illustrated most recently by a sharp decline in runoff in the winter of 2004-2005 that resulted in a dramatic reduction in reservoir storage at the beginning of the irrigation season, when storage capacity in regional dams serving both urban and agricultural water users was about thirty% of the average capacity at this time of year. This has prompted the introduction of water use restrictions in Cape Town and other municipalities in the region and the outcome for farmers is uncertain, but at the current time, experts are predicting a thirty to forty% reduction in agricultural production, with attendant consequences for the regional and national economies that rely heavily on the income from the sale of export crops in the region.

Planning for the Berg River Dam and other water supply and demand options in the basin has, up until this point, failed to take into account the possibility that the build-up of greenhouse gases in the global atmosphere is affecting and will continue to affect the regional climate, potentially reducing existing runoff in the Basin. In a recent interview, a leading climatologist in the region, Bruce Hewitson (2004), has warned that the government should take a long-term view of changing climate conditions, or face potential consequences that could 'seriously compound' the existing challenges facing South Africa. According to Hewitson, 'We are still building society around what is considered to be normal climate, in for example water usage and infrastructure. But we increasingly need to take the changing characteristics of climate into consideration.'

Hewitson's concerns about climate change in the region are slowly gaining momentum in the planning process of the Western Cape's provincial government. In a recent statement (Essop and Phillip 2005), Premier Rasool indicated that 'We are in for long-term climatic changes, therefore this province will have to drive a process to lay the basis for long-term alternatives.' As a result, the provincial government has allocated an amount of R2 million to conduct an urgent investigation into alternative water resources, including the evaluation of desalination and other aquifers as a response to the impact global warming is having. In the meantime, concern over the consequences of the recent drought has sharpened the provincial government's focus on better adapting the water resources supply and demand systems in the basin to greater climate variability and climate change.

1.3 Overview of Objectives and Methods Used in this Study

1.3.1. Objectives

As indicated above, the context for this paper has three main elements:

- increasing competition for water between urban and agricultural water users;
- the threat of climate change to exacerbate that competition;
- the planning and policy responses to these issues.

In that general context, the objectives of this study are to develop and implement the necessary analytical tools to:

- estimate the potential impacts of alternative climate scenarios on water supply and demand in the basin through changes in runoff, evapotranspiration and surface evaporation;
- translate these physical impacts into monetary losses (or gains) for different groups of farmers and urban water users;
- estimate and compare the benefits and costs of the storage for the Berg River Dam and water market Options of avoiding climate change damages, with and without accounting for expected climate change in the planning for these Options.

1.3.2 Methods

The study team has extensively modified an existing static partial equilibrium model of the Berg River Basin (Louw, 2002) for use in an integrated environmental-economic assessment of climate change. The current model, known as the Berg River Dynamic Spatial Equilibrium Model (BRDSEM) is a dynamic spatial equilibrium model that includes all of the major water supply sources in the basin, as well as detailed farm-level irrigation water uses for important crops and livestock, and urban water demand in the Cape Town Metropolitan region. The most important modifications to the model consist of the following:

- Incorporating the inter-temporal features of reservoir storage for both major storage reservoirs and on-farm water storage, so that the model can be used to assess climate change impacts over time.
- Creating a hydrologically realistic, but simplified spatial representation of the physical and man-made water-supply system in the basin.
- Improving the hydrologic aspects of the model to allow
    - incorporation of stochastic stream flow ensembles from the WatBal rainfall-runoff model (Yates, 1996) and
    - calculation of return flows, reservoir evaporation and conveyance losses.
- Addition of an investment function for new reservoir capacity for the Berg River Dam.

- Development of on-farm water-use intensity estimates for different temperature regimes.

- Development of scenarios to reflect changes in water demand over time due to population and agricultural commodity market developments.

For this study, BRDSEM was used to assess the physical and economic effects of a number of alternative runoff scenarios, associated both with the historical climate, recent climate anomalies, and equally plausible changes in climate for the Basin. Each of these scenarios will be run for the following options:

- No water markets, no additional storage.

- Water markets, plus additional storage (both planned and optimal).

- Additional storage (both planned and optimal), no water markets.

- Both water markets and additional storage (both planned and optimal).

The results from these sets of simulations make it possible to estimate both the monetary value of the climate change damages without the various options and the monetary value of the benefits and costs of avoiding these damages through the various alternatives. This information can then be used to isolate the benefits and costs of planning for expected climate change, versus not planning for it, over a range of subjective probabilities for each climate scenario. One can also extend this approach (as shown in Callaway, 2004a and 2004b) to analyse the variation in optimal reservoir storage capacity over the same range of probabilities and then find the ex ante reservoir capacity that leads to the minimum level of regret, both in terms of planning for climate change that does not happen ex post and not planning for climate change that does occur ex post.

1.4 Relationship to Previous Studies on Climate Change and Water Resources

The literature on adaptation, such as it is, are summarised in the contributions of Working Group II to the *IPCC Second Assessment Report* (IPCC 1996) and the *IPCC Third Assessment Report* (2001). Callaway *et al.* (1998) called attention to the shortcomings of the literature reviewed in the *Second Assessment Report*, noting the following:

- limited focus on autonomous adaptation, as opposed to strategic adaptation;

- over-emphasis on adaptation by means of technological solutions and under-emphasis on changes in human behaviour;

- limited focus on quantifying adaptation costs, except for technological costs, and practically no emphasis on the quantification of adaptation benefits.

Just after the publication of the *Second Assessment Report*, Tol *et al.* (1998), nicely summarised the treatment of adaptation in the existing literature, by identifying four different approaches to modelling adaptation:

- **No adaptation.** A number of studies assume that humans are passive in the face of climate change and do not change their behaviour at all. This concept is unworkable or unrealistic in most impact areas, as most economic agents will have some incentives to adapt to climate change, even if governments do not intervene. However, as we will see, this type of assumption is useful as a reference point for measuring adaptation benefits and costs.

- **Arbitrary adaptation.** Some studies assume that adaptation of some kind will take place, but that the levels of adaptation, both autonomous and additional, are selected arbitrarily by individuals (autonomous) or governments (additional).

- **Observed adaptation.** This involves the use of either spatial or temporal analogues to examine how different societies (spatial) have adapted to climate variability in the present or past (temporal). The problem with this approach is that, while temporal analogues may be useful for predicting the scope of physical impacts, differences in social and economic conditions vary so greatly over time and space that these analogues can only be suggestive of the scope of human actions, and cannot serve as the basis for projection or prediction.

- **Modelled adaptation.** This approach utilises behavioural models, usually economic market models, to predict how humans will behave when climate changes. However, most of these studies fall short of quantifying adaptation costs and benefits.

Most of the studies in the last category fall under the heading of *Optimal Adaptation*. This approach to adaptation is based on economic efficiency and involves using models to project the behaviour of economic agents who adjust to climate change by equating marginal benefits (however defined) and marginal costs. The authors view this as the 'ideal' approach to assessing adaptation because it can be used to project[2] the economically efficient (their definition of optimal) levels of private (autonomous adaptation) and public (additional adaptation) action given specific changes in climate.

There is a growing body of literature about the value of the economic impacts of climate change, which falls short of specifically estimating either the cost or benefits of adaptation, and usually both. This literature is best represented by studies of the economic value of damages due to climate change due to sea level rise by Yohe *et al*. (1996), in the US agricultural sector by Adams *et al*. (1993), and for a number of economic sectors in the US (including water resources) by Mendelsohn *et al.* (1999).

These studies, and others like them, share in common the use of economic market models that contain supply and/or demand curves that are linked to climate variables, such as monthly precipitation and temperature, so that changes in the values of these variables induce changes in relative prices of inputs and outputs. This, in turn, affects the relative profitability of various goods and services in markets and leads to different levels of input use and commodity production. The resulting levels of profits, after these adjustments occur, are higher than if they did not occur (in other words, if economic agents acted as if relative prices had not changed, and acted just as they did prior to climate change). The adjustments that occur in input and output production levels in response to climate-induced changes in relative prices are in the broadest sense 'adaptive responses' to climate change. These responses can be very broad in scope, ranging from changing planting dates of crops to changing the type of technology used to treat wastewater.

As a rule, these studies do not explicitly report adaptation costs. Rather, they report the imposed costs of climate change, measured as the difference between net social benefits (i.e., welfare), with and with out climate change, assuming optimal adaptation to the existing climate (without climate change) and the altered climate (with climate change). While these studies take into account a wide range of normal market adjustments to climate change in response to relative price changes in inputs and outputs, they do not generally include estimates of both the benefits and costs associated with making the switch in adaptation from one climate to the other. However, in some cases, for example sea level rise (Titus *et al.*,

[2] 'Optimal' is a normative term, referring to how economic agents would behave if they equated marginal benefits to marginal costs in making consumption and production decisions. A normative model does not forecast actual behaviour, if economic agents base their decisions on other objectives, or there are market imperfections.

1991; Fankhauser, 1997; Yohe *et al*., 1996; and Yohe *et al*., 1999), the cost of specific adaptation measures – sea walls and retreat – is estimated.

Perhaps more importantly, none of these studies quantify the benefits of adapting to climate change. Instead, they at best provide economic estimates of the damages associated with and without climate change. Typical of this treatment is the study on water resources in Mendelsohn *et al.* (1999) by Hurd *et al.* (1999). This study estimates the economic value of the losses that can occur in four large river basins in the US by comparing an estimate of economic welfare in each basin under different parametric changes in average annual temperature and precipitation relative to current conditions with economic welfare under current climatic conditions. The resulting changes in economic welfare include the benefits and costs of adaptation, to be sure, but the authors of this study do not decompose their estimates sufficiently to identify the climate change damages without adaptation, the climate change damages avoided by adaptation, and the residual climate change damages that can not be avoided by adaptation. The results they show are simply the residual climate change damages after adaptation has taken place.

Since these papers were written, Callaway (2004a and 2004b) has published two papers that show how it is possible to isolate all three components of the economic effects of climate change in the framework of optimal adaptation – climate change damages, the net benefits of adaptation and the imposed damages of climate change. This framework is summarized in Section 3.0 of this paper. The important contribution of this study is that it is the first empirical application of this framework, making it possible to decompose the various benefits and costs of climate change and adaptation. The decomposition that is achieved includes not only technology and capital costs, but also costs and benefits associated with behavioural adjustments as economic agents (i.e., water users and water managers) make both short- and long-run adjustments to climate change. Finally, the application of this framework makes it possible to identify the net benefits of adaptation not only due to changes in investment in new technology and infrastructure aimed specifically at adapting to climate change and climate variability, but also due to the implementation of 'no regrets' measures, such as efficient water markets, which improve economic efficiency in water allocation and use for reasons unrelated to climate variability or changes in climate.

1.5 Organization of the Report

This study is divided into seven sections. Following the Introduction in Section 1, Section 2 provides an overview of the study area in terms of the hydrologic characteristics and the water supply and demand situation in the basin. Section 3, in turn, outlines in detail the conceptual methodology for estimating the economic losses due to climate change, the benefits of avoiding these damages through adaptation, and the climate change damages that cannot be avoided. It also shows how this same framework can be used to assess the costs of making planning mistakes when the climate for which a structural measure was designed does not occur. Section 4 introduces the BRDSEM model, which was developed for this project, while Section 5 presents the various scenarios and assumptions that were used in implementing BRDSEM and shows how they were organised to estimate the various benefits and costs associated with climate change and adaptation, under four alternative sets of options for allocating water, with and without construction of a Berg River Dam. This is followed in Section 6 by a presentation and discussion of the results of the scenario-options analysis. Finally, Section 7 summarises the study as a whole; presents the major conclusions; and discusses future improvements to BRDSEM and to the assessment methodology to improve data and model limitations. The study also has one appendix, Appendix A. This contains the GAMS code for the dynamic spatial equilibrium part of the model and for the regional farms.

2 The Study Area

The purpose of this Section is to provide an in depth overview of the water balance, agricultural production areas, irrigation practices and typical farms in the Berg River Basin study area. The following section will provide a description of the topography, climate and general land use of the area. This will be followed by a complete description of the water supply and demand conditions for the area.

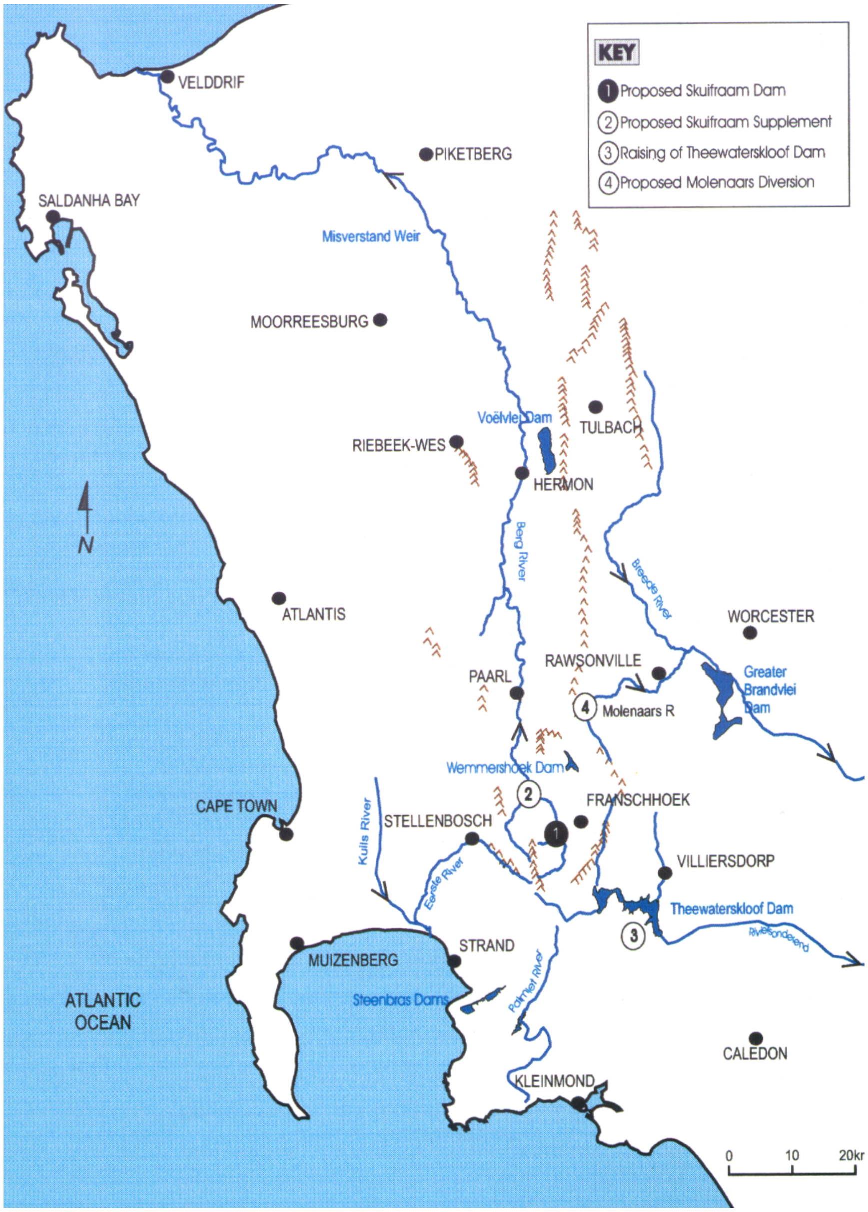
2.1 The Berg River and its Tributaries

The Berg River has its source in the high-lying mountainous area of the Groot Drakenstein Mountains. From here it flows in a northerly direction and joins the Franschhoek Valley. The flow continues towards Paarl, before which two tributaries join it. The first, situated to the east, is the Wemmershoek River, which is impounded by the Wemmershoek Dam, and the other is the Banhoek River. The Banhoek River has its source in the Groot Drakenstein and Jonkershoek mountains. It joins the Berg River from the west approximately halfway between Franschhoek and Paarl. The Berg River flows through Paarl and Wellington, where the Krom River from the east joins it.

This tributary has its source in the Limietberge, and drains the valley above Wellington. Flowing northwards, the Berg River is joined by various other tributaries. The larger ones are the Kompanjies River, the Klein Berg River and Twenty Four Rivers. Also situated to the east is the Voëlvlei Dam. See Figure 2.1 for a visual representation of the Berg River, its tributaries and dams.

The Klein Berg River has its source in the high lying Winterhoek Mountains in the northeast of the Tulbagh Valley. Further south the Boontjies River joins it. From here, it flows westwards, between the Obiekwa and Voëlvlei mountains into the Berg River Valley, and joins the Berg River to the west of Saron. Approximately 3 km north is the confluence of the Twenty Four Rivers and the Berg River. This river drains the high lying mountainous area of the Groot Winterhoek. After a further 10 to 15 km, the Berg River flows over the Misverstand Weir. Upstream of the Weir, it is joined by tributaries that drain the areas north of Porterville and Morreesburg. From here onwards, the river flows in a north-westerly direction and drains into the Atlantic Ocean at Velddrift (DWAF, 1993e).

As we pointed out in Chapter 1, the Berg River basin was chosen as a case study because of its complex nature, the fact that it supplies, amongst others, water to the Cape Metropolis and also because of its strategic importance for highly valued summer crops in the winter rainfall region of the Western Cape. As also pointed out in Section 1.5 this research is only concerned with the Upper-Berg River, which is the area from the source of the river to a farm called Sonquasdrift, situated near to the Voëlvlei Dam. The Voëlvlei Dam supplies the Lower Berg River irrigation area with water.



Source: DWAF (1997a)

Figure 2.1: Visual Description of the Study Area

2.2 Natural Features of the Berg River

The natural features of the Berg River are discussed in terms of the topography, climate and land-use in this section.

2.2.1 Topography

The upper region of the Berg River Basin is surrounded by high mountain ranges (RL 1500 m) to the south, east and west. The river basin is fairly narrow (10-15 km) between the sources (Groot Drakenstein) and Wellington. Northwards of Wellington, the Limietberg continues to bound the valley to the west. In the east, the basin levels out and the river valley widens to approximately 25 km (DWAF, 1993e).

2.2.2 Climate

The climate which prevails in the Berg River Basin is typical of the Western Cape Region. This region's climate is classified as Mediterranean, experiencing winter rainfall together with high summer evaporation. Precipitation is from cold fronts approaching the area from the northwest. As a result of the topographical influence of the mountains, a large spatial variability is experienced in the mean annual precipitation (MAP). In the high lying areas of the Groot Drakenstein, the MAP is around 2 600 mm, while further northwards, where the Berg River Basin levels out, the MAP drops to below 500 mm (DWAF, 1993e).

The area is characterised by a significant seasonal variation in monthly evaporation, which is typically 40 to 50 mm in winter, and 230 to 250 mm in the summer months. The mean annual evaporation throughout the basin shows less spatial variability than the mean annual precipitation. The high rainfall/low evaporation during winter and low rainfall/high evaporation during summer is an important climatic feature of the Western Cape Region (DWAF, 1993e).

2.2.3 Land use

Land in the Upper Berg River area is primarily used for wine farming and to a lesser extent, for fruit farming. A portion of the land is irrigated with water either collected in farm dams or abstracted directly from the river and its tributaries. Lucerne, vegetables and other crops are also grown, but only in small amounts. Forestry is found throughout the Berg River Basin, but predominates in the high altitude and rainfall areas.

In the Lower Berg River areas, towards the north, land utilisation changes from wine farming to dry land grain farming. Apart from crops and forestry, indigenous 'fynbos' vegetation is found in most areas. This growth varies from dense concentrations in gullies to sparse coverings on rocky mountain slopes (DWAF, 1993e). Land use for different crops in the Upper-Berg River Basin in 1992 and 1999 are presented in Figure 2.2 and Figure 2.3 respectively.

It is clear from the two figures that a significant change in agricultural land use has occurred since 1992, i.e. away from wine grapes towards fruit production. This change was induced by favourable conditions on export markets during the early 1990s.

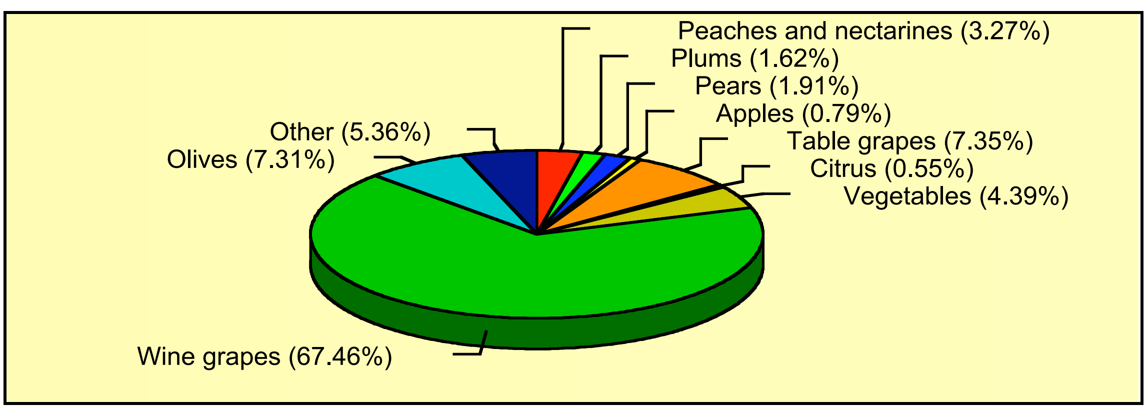


Figure 2.2: Irrigated Land Use in the Upper Berg River (1992)

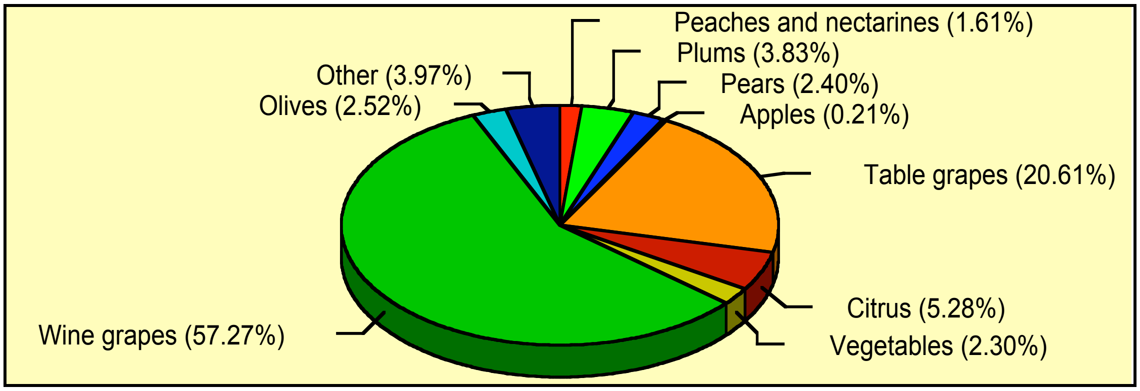


Figure 2.3: Irrigated Land Use in the Upper Berg River (1999)

2.3 Water Supply and Demand Characteristics of the Berg River

In order to construct a water balance for the Upper-Berg River the water supply sources and water demand for the urban and agricultural water use sectors are discussed. The water supply to the urban sector is treated separately from the supply of water for irrigation purposes. All the water supply sources to the urban sector are discussed. The Berg River, the Theewaterskloof Dam and farm dams are the major sources of water for the irrigation sector and are also discussed here. The Theewaterskloof Dam is the only source in this study, which faces potential competition between urban and agricultural water users. A short discussion of the Theewaterskloof Dam follows.

2.3.1 The Theewaterskloof dam

According to the DWAF (1992a) the Theewaterskloof Dam (see Figure 2.1) has a capacity of 480.4 million m^3 and regulates the water flow in the Riviersonderend River. This source is supplemented by water abstraction at diversion weirs on the Wolwekloof and Banhoek streams, which are tributaries of the Berg River, and at Kleinplaas Dam on the Eerste River. Kleinplaas, which has a capacity of 0.376 million m^3 per annum, also serves as a balancing reservoir for the tunnel system. Two diversion weirs feed flows into the tunnel for distribution, as required, to the tunnel outlets at Robertsvlei near Franschhoek or to the Theewaterskloof Dam. The firm yield of the system has been calculated from historical flow sequences covering 60 years to be 207 million m^3 per annum.

The City of Cape Town (CCT) is entitled to a supply of 83 million m^3 per annum from the scheme, and in addition it uses the 7 million m^3 per annum allocation of Paarl Municipality ceded in return for the 7 million m^3 per annum that the CCT supplies from Wemmershoek Dam. Stellenbosch Municipality has an allocation of 3 million m^3 per annum, bringing the total allocation for urban use to 93 million m^3 per annum (DWAF, 1992a). The remaining water is allocated for agricultural use but because the agricultural demand has grown less than anticipated when the scheme was planned, the CCT has received a temporary additional allocation of 93 million m^3 per annum. The total urban allocation from the Theewaterskloof Dam is therefore 186 million m^3 per annum.

However, these allocations are theoretical as the real amount of water that the CCT as well as the agricultural sector receives is highly dependent on the amount of water in the storage dams at the beginning of the season. For instance during the 1999/2000 season the CCT only received 145 million m^3 of water and in the 2000/2001 season (due to low levels in the storage dams) only 123 million m^3 of water was allocated to the CCT (DWAF, 2000). With the provisions of the National Water Act, 1998, these allocations may change again as the unused water rights presently allocated for agriculture may be reallocated.

2.3.2 Urban water supply

The Water Service Authority (WSA) referred to in this study is the City of Cape Town (CCT). The Water and Waste Directorate within the CCT is responsible for the provision of bulk water services. The CCT utilises water from various dams within the Cape Metropolitan Area (CMA) and also from dams outside the CMA. Table 2.1 shows the water supply sources for the CCT (CMC, 2000).
Some of the dams are operated and controlled by the CCT, whilst the other dams are operated and controlled by the Department of Water Affairs and Forestry. The CCT obtains approximately 70 to 75% of its raw water requirements from DWAF and the remainder from its own sources. Approximately 15% of the raw water requirements are obtained from sources within the CMA.

The yield of these supply sources is theoretical. For example the water budget for 2000/2001 indicated that only about 330 million m^3 would be available. This is the reason for the water restrictions that were imposed during November 2000 (DWAF, 2000). The growth in urban demand is so rapid, that it is believed that demand management will not stem growth in demand sufficiently and that it would be necessary to provide additional supplementary water sources.

Dams/rivers	*Owned and operated by*	*Approximate % of total supply requirements*	*Allocation/yield Million m^3*
Theewaterskloof Dam	DWAF	47.7 %	186
Voëlvlei Dam	DWAF	16.9 %	66
Palmiet River	DWAF	5.8 %	22.5
Wemmershoek Dam	CMC	14.4 %	56
Steenbras Upper and Lower Dam	CMC	9.7 %	38
Simon's Town Lewis Gay Dam and Kleinplaas	CMC	0.5 %	1.85
Land en Zeezicht Dam (From Lourens River)	CMC	0.1 %	0.5
Table Mountain: Woodhead Hely-Hutchinson De Villiers Dam Victoria Dam Alexandra Dam	CMC	1,3 %	5
Other sources: Atlantis Boreholes Nantes Dam Berg Pumpstation Land en Zeezicht Jonkershoek stream Antoniesvlei	 Western Cape RSC Paarl Paarl Somerset West Stellenbosch Wellington	 % % 0.6 % % 1.4 % 0.1 %	 4.4 0.5 2.5 0.5 5.5 0.5
TOTAL		**100 %**	**389.8**

Source: DWAF (1992a and 2000)

Table 2.1: Water Supply Sources for the CCT

The DWAF (1997a) recommended six sources for further investigation. These are shown in Table 2.2 (also see Figure 2.1 for the location of Skuifraam (now referred to as the Berg River) and Molenaars schemes). The Berg River Dam is the next major dam to be constructed in the Western Cape, and construction started in 2004. The envisaged cost of the Berg River Scheme was originally estimated at R780 million or R0.57/m3 in March 1999 and it is envisaged that the CCT would be responsible for repaying a large portion of this capital investment (DWAF, 1992a). The building of this dam is highly controversial due to the possible loss of riparian habitat due to low flows on the lower Berg River in summer months. As a result, strict regulations will be imposed on low flows during these months. However, the exact nature of the restrictions is still being debated.

Scheme	*Scheme Yield m^3 x 10^6*	*Commissioning Year*	*Relative cost of water*
Palmiet1*	31	1998	1
Voëlvlei/Lorelei 1	15	2000	1.3
Skuifraam Dam (Berg River Dam)	72	2001	2.4
Molenaars Diversion to Skuifraam	37	2005	1.9
Lourens River Diversion	20	2006	1.8
Cape Flats Aquifer	18	2008	2.2
* *Already in operation. Base for index of relative cost comparison.*			

Source: DWAF (1992a)

Table: 2.2: Possible Sequence of Schemes Suggested by the Western Cape System Analysis (WCSA)

2.3.3 Urban water demand

It is estimated that approximately 4 million people live within the Western Province and approximately 2.56 million within the CMA. The population growth rate is approximately 2.5% per annum. In 1996, the total population of South Africa was over 40 million. The interim population estimate of the CMA for 1998 based on the 1996 Census data is approximately 2.9 million. The age distribution reveals a young population with 26% (or ± 750 000 people) under the age of 15 (CMC, 2000). The CMA has a structurally diverse economy, with key sectors being manufacturing, tourism, services and trade. The key growth sectors include financial services, construction, service and industrial niches such as food processing and high technology. Major factors affecting the economic development in the CMA have been the growth in the tourism industry and strong foreign investment interest. The CMA is the primary economic centre of the Western Cape Province, with a 75% share in the provincial gross domestic product (GDP) and more than a 10% share in the national gross domestic product. The GDP of the CMA is approximately R60 billion. A list of the customers to which the CMC supplies bulk water and the share of total amount of water they consumed during the 1998/99 financial year is shown in Table 2.3.

Water service authority	*Estimated consumption (m□) July '98 to June '99*	*% of total consumption July '98 to June '99*
City of Cape Town	88 681	28.9%
City of Tygerberg	76 461	24.9%
South Peninsula Municipality	55 782	18.2%
Blaauwberg Municipality	26 857	8.8%
Oostenberg Municipality	24 477	8.0%
Helderberg Municipality	14 506	4.7%
Paarl Municipality	15 308	5.0%
Wellington Municipality	3 095	1.0%
Winelands District Council	1 636	0.5%
Total	306 803	100%

Source: CMC (2000)

Table 2.3: Water Demand of Urban Users Supplied by the CMC

The Water Department monitors water consumption of the average peak week consumption in summer and compares actual consumption with that which was predicted. This is done to determine when new schemes have to be implemented to meet the annual water demand as well as when a new water treatment plant has to be constructed to meet peak demands. The planning for the implementation of new schemes is carried out in conjunction with the Department of Water Affairs and Forestry and Ninham Shand Consulting Engineers, using the Western Cape System Analysis Planning Model (CMC, 2000).

The historic growth in water demand has averaged between 3 and 4% per annum over the last 30 years. Whereas previously bulk water schemes were constructed to meet the growth in annual water demand, the emphasis has now shifted to limit the growth in water demand by implementing Water Demand Management (WDM) measures. WDM is essential as there are a limited number of feasible water supply schemes available and the cost to implement new schemes gets increasingly higher, both financially and environmentally (CMC, 2000).

The CCT has already announced its intention to reduce predicted water demand by the year 2010 by 10%. The predicted water demand figures are based on a study carried out in 1991 by the Institute for Futures Research, and the CCT has been using the Second World Growth Scenario as its projected demand growth scenario. The water demand per sector during 1998/1999 is shown in Figure 2.4 (CMC, 2000).

Source: CMC (2000)

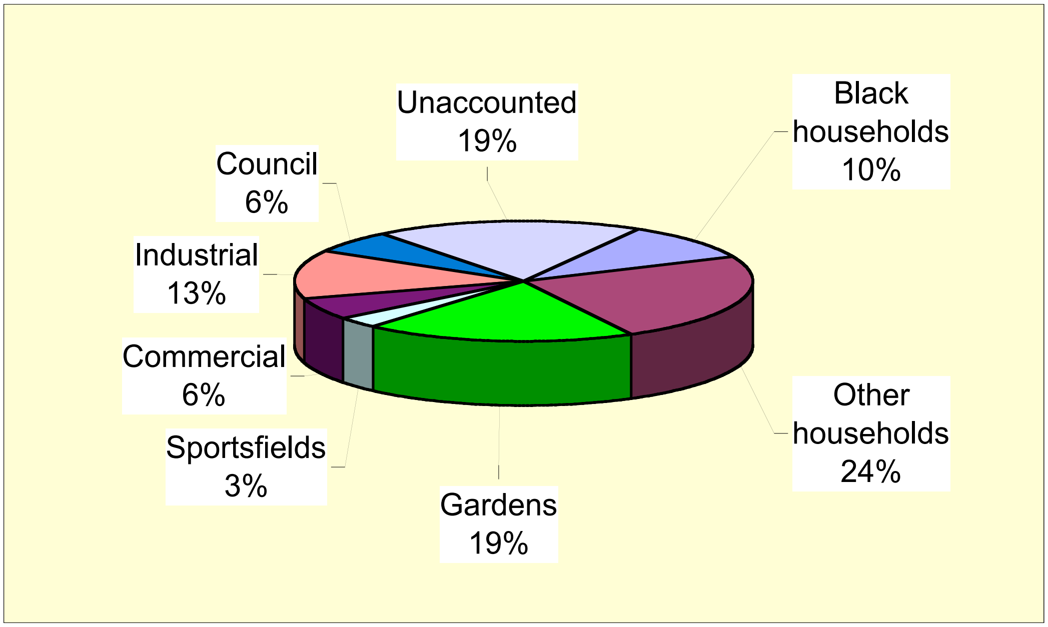


Figure 2.4: Urban Water Consumption Breakdown for the CCT

The expected growth in demand at an average growth rate of 3% (water demand management strategies not included) per annum is shown in Figure 2.5. It is clear that the water demand will outstrip water supplies in 2005 (if there are droughts in between, even sooner). This highlights the water shortages that will face the CCT and the irrigators along the Berg River in the not so distant future. Even if the Berg River Dam can be completed within the next four years, the demand will already have reached such levels that the new capacity will only last for another four to five years before it is also outstripped by demand. If water demand management strategies can be implemented successfully this picture will not be so bleak (CMC, 2000).

The problem is aggravated by the fact that the urban demand is also highly seasonal and that the peak demand coincides with the peak agricultural demand and the driest time of the year. This is shown in Figure 2.6. The water demand of the urban sector nearly doubles from the months of June, July and August, reaching a peak during December and January. This period also coincides with the peak summer tourist period when tourists from the northern parts of the country and from overseas come to Cape Town by the thousands.

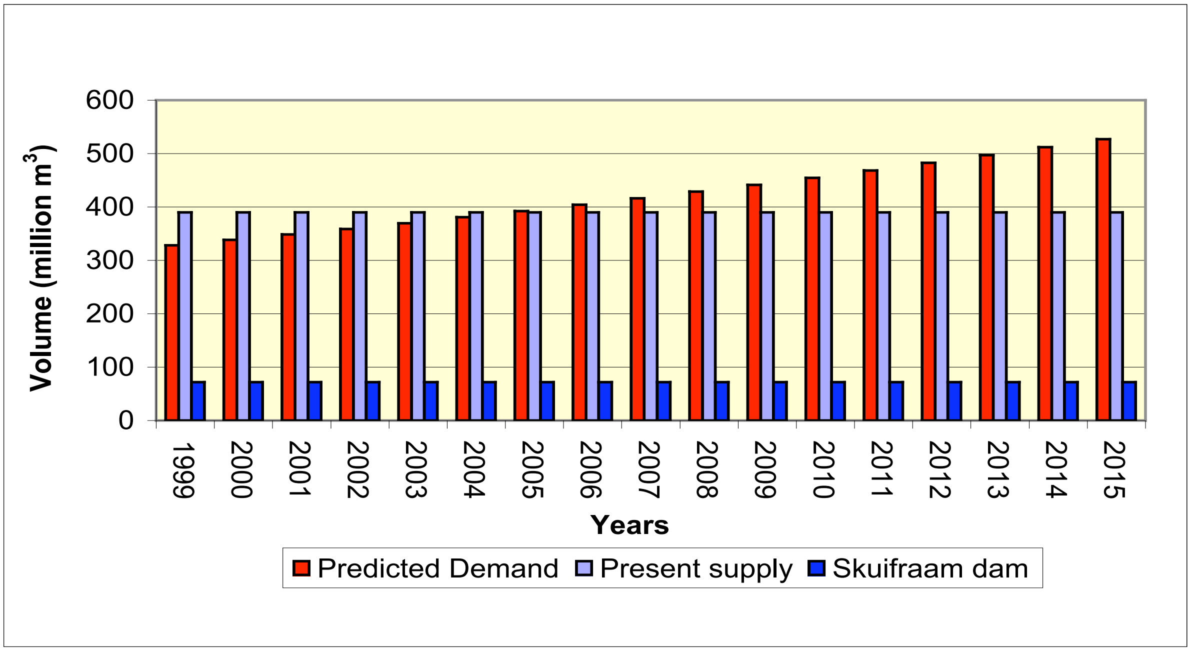
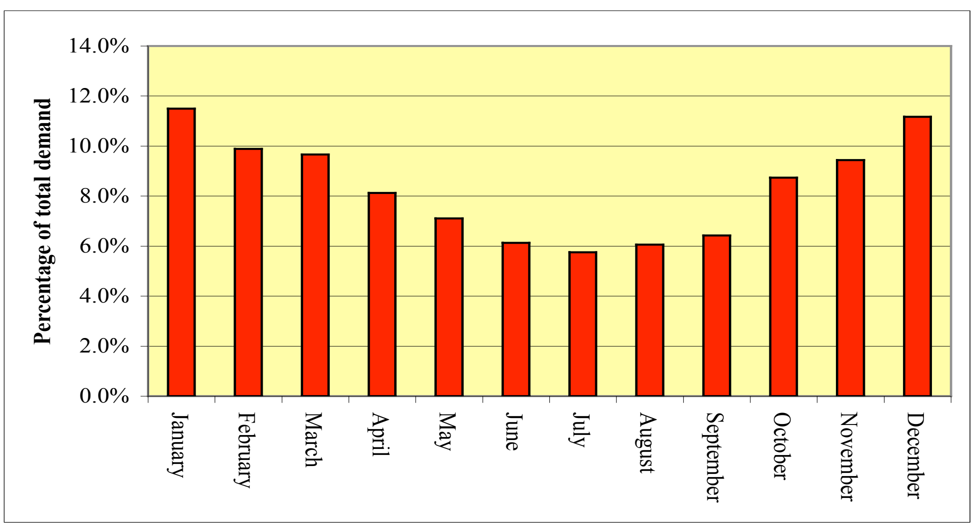


Figure 2.5: Expected Growth in the Urban Demand for Water in the CMC 1999-2015



Source: CMC (2000)

Figure 2.6: Seasonal Demand for Urban Water

2.3.4 Agricultural water supply

According to the Government Gazette (1983) the maximum quantities of water, if available, may be provided annually in respect of each hectare of land for the following areas:
Four thousand (4 000) m^3 of water for the properties from the Franschoek Forest Reserve up to and including the farms Sandkliphoogte 835 on the left bank and Fraaigelegen 841 on the right bank of the Berg River. Referred to as Berg1 in this study.

Five thousand (5 000) m^3 of water for the properties from Erf 8442, Paarl, on the left bank and Hartebeestekraal 844 on the right bank up to and including the farm Zeekoeigat 80 on the left bank and Olyvenboom 83 on the right bank of the Berg River. Referred to as Berg2 in this study.

Six thousand (6 000) m^3 of water for the properties from Hazekraal 58 on the left bank and Olyvenboom 56 on the right bank up to and including Portion 2 of Sonquas Doorndrift 648 on the left bank and the Remainder of Sandleegte 201 on the right bank of the Berg River. Referred to as Berg3 in this study.
The supply of water for irrigation purposes consists of allocation water from the Theewaterskloof Dam, natural runoff in the winter (April-September) and farm dams. Although the total allocation from the Theewaterskloof Dam to the Upper-Berg River is 75 million m^3 (14 985 ha) of water, the average use has varied between 30 million m^3 and 40 million m^3 since 1997. According to the latest figures released by the DWAF the water budget allocated for the Upper-Berg River is 42 million m^3. The remainder of the agricultural water allocation, 33 million m^3, is already used by the CCT in order to meet their demands (DWAF, 2000).

During the winter months riparian users are permitted to pump an unspecified amount of water from the river. The normal practice is to fill up farm dams during the winter for use during the dry summer months. In a normal year it is not necessary to irrigate crops in the winter months. Some of the other water users have so-called winter water rights. These users may pump a specified volumetric amount of water per ha during the winter and are mostly situated on irrigation board pumping schemes away from the river. At present these allocations consist of:

- Riebeek-Wes: 75 ha with an allocation of 6 000 m^3 per ha.
- Riebeek-Kasteel: 220 ha with an allocation of 6 000 m^3 per ha.

The Perdeberg, Noord-Agter Paarl and Suid-Agter Paarl irrigation regions do not have any winter water rights.

The farm dam capacity varies for different parts of the river and tends to be more important in the lower parts of the Upper-Berg river (see Figure 2.7). It is clear from Figure 2.7 that the irrigators on the irrigation board schemes, Suid-Agter Paarl (SAP), Noord-Agter Paarl (NAP), Perdeberg (PB) and Riebeek-Kasteel (RK), are more dependent on farm dams than the riparian irrigators (Berg 1, Berg 2 and Berg 3). It is virtually impossible to make an accurate assessment of the total farm dam capacity of the Upper-Berg River. However, it has been estimated by the DWAF (1993c) that during 1990 conditions the total capacity of farm dams was 37.858 million m^3. It has been shown by the DWAF (1993c) that from 1980 the farm dam capacities increased less rapidly, indicating that the basin is reaching full development. In order to calculate a water balance it was assumed that the total farm dam capacity for the Upper-Berg River is 40 million m^3.

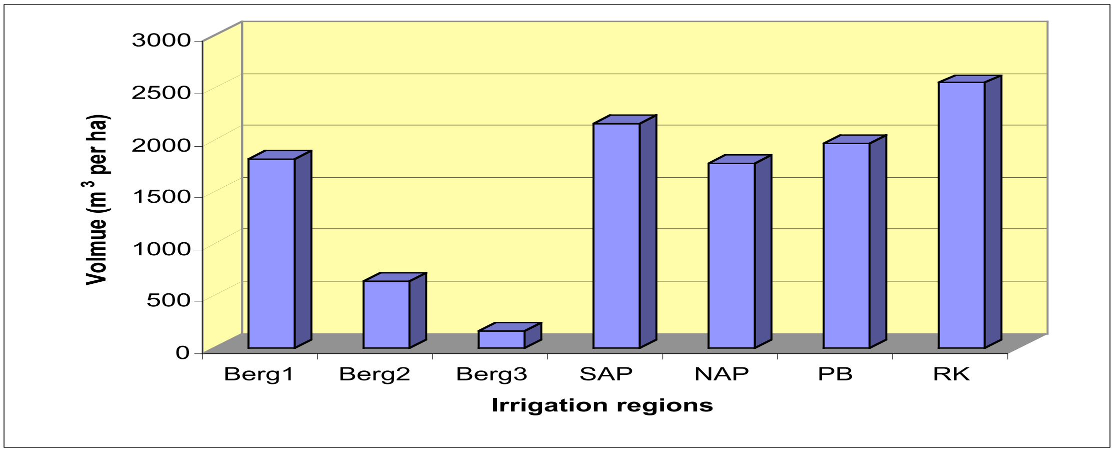


Figure 2.7: Regional Farm Dam Capacity

2.3.5 Agricultural water demand

According to the DWAF (1992b) the demand for the irrigation sector was forecasted to increase from 30 million m^3 in 1995 to 70 million m^3 per annum in 2010. However, it should be noted that there has been a moratorium on further allocation of irrigation water since 1995. This moratorium slowed the rate of water demand growth, although trading of unused water rights continued. DWAF (1992b) assumed that the need for irrigation water will be determined by:

- the market potential for products (mainly deciduous fruit, vegetables, wine grapes and citrus);
- the availability of land for production; and
- the relative production-economic competitiveness of the area.

Figure 2.8 shows the actual annual withdrawals by the Berg River Irrigation Board from the Theewaterskloof Dam for the 1993/94 to 1999/2000 water years. Although withdrawal varies between water years it is clear that the forecasts of 1995 were, to a great extent, overestimates.

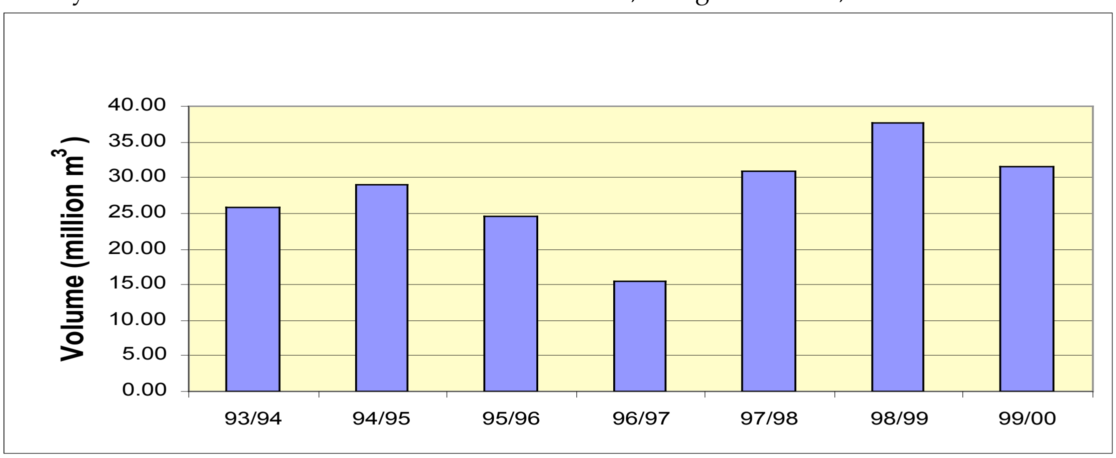
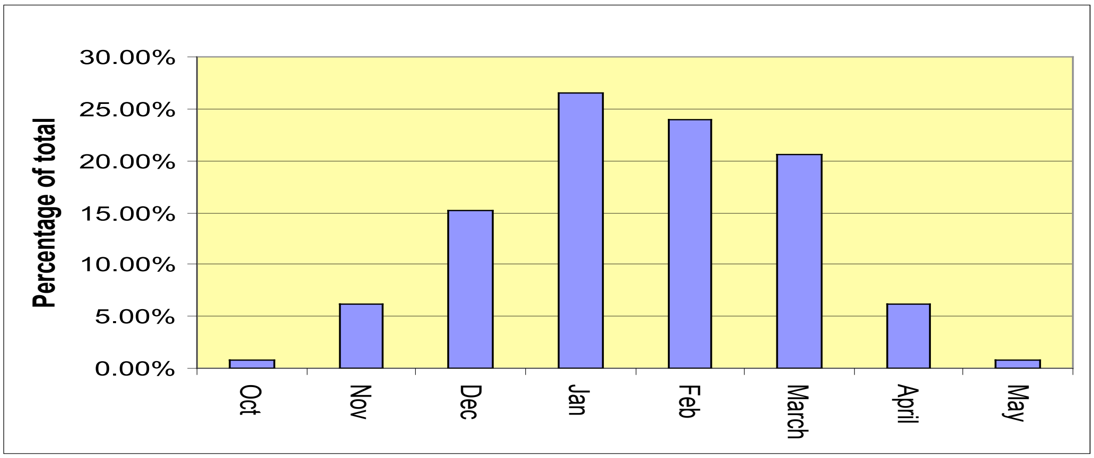


Figure 2.8: Annual Water Release for Agricultural Use (1993/94 – 1999/00)

Figure 2.9 shows the highly seasonal demand for irrigation water from the Berg River. The high demand coincides with high summer temperatures, high evapotranspiration and therefore high crop demands. One of the most critical periods is the after-harvest (usually March-May) irrigation needed to enable crops to build up reserves for the next season. During years when the rainy season starts late, a shortage of irrigation water for this important period in the crop cycle is often experienced.



Source: Berg River Irrigation Board (2000)

Figure 2.9: Seasonal Demand for Irrigation Water for the Upper-Berg (1993-2000)

Unfortunately there is no accurate estimate of land use available for the Upper-Berg River. Most of the statistics are either for the whole Berg River or for districts within the Berg River. The DWAF (1993c) estimated the total area under irrigation in the Upper-Berg River during 1980 at 7686.3 ha. The DWAF (2000) estimated that approximately 80% of the total entitlement (15 019 ha) area is used for irrigation purposes. The survey results of this study found that this percentage is closer to 82.75%. The total estimated area under irrigation is, according to the survey results, therefore 12 429 ha. The growth in the area irrigated since 1980 was therefore approximately 62% or an average of 3.1% per annum. From these results it can be derived that the average growth in water demand for the agricultural sector was also approximately 3% per annum. However, the DWAF (1992a) indicated that growth has also slowed down since 1995 and given the uncertainties at present with regard to the future availability of water and the depressed fruit and wine markets it is expected that, at least for the near future, growth will slow down even further. The estimated crop distribution for 1999/2000 is presented in Table 2.4.

The crops presented above use approximately 38 million m^3 of water from the Theewaterskloof Dam. The percentage of water from natural runoff to fill the farm dams varies between the different irrigation areas (65 to 90%), as the rainfall becomes lower further away from the mountains. The survey results indicated that on average 70% of the capacity of the dams are filled up from natural runoff. If the DWAF (1993c) estimate of the farm dam capacity (40 million m^3) is assumed to be correct, the 12 429 ha is irrigated with 38 million m^3 from the Theewaterskloof Dam plus 28 million m^3 water from farm dams natural inflow plus 12 million m^3 winter water extraction from the river (mostly to fill up farm dams for use in the summer). This amounts to an average availability of 66 million m^3 of water or 5 310 m^3 per ha per annum.

Irrigation crops	*Hectare*	*% of total*
Vineyard	7 245	53.0%
Table grapes	2 982	24.0%
Plums	485	3.9%
Soft citrus	568	4.6%
Olives	267	2.1%
Vegetables	339	2.7%
Pears	297	2.4%
Citrus	231	1.9%
Peaches	155	1.2%
Other	529	4.3%
Total	**12 429**	**100%**

Table 2.4: Estimated Crop Distribution in the Berg River Irrigation Area (1999/2000)

2.4 Concluding Remarks: Implications for Modelling

The Berg River 'System' is very complicated both from a hydrologic and water use perspective. In modeling the system as a whole (Section 4.0) we have tried to retain the major physical elements of the climate, the natural hydrologic system and the water balance in the basin. On the other hand, we decided to make some important simplifications in our representation of man-made systems in the basin.

Most importantly, we decided to model only the main sources of water supply in the Upper Berg River Basin – Theewaterskloof, Wemmershoek, and the Berg River (Skuifraam) Dams. These are the major sources of water supply storage in the basin for both urban and agricultural water use. The water balance in the dams in the lower Berg River Basin and the dams on Table Mountain and other sources of supply that feed directly into urban water demand was modeled parametrically as a single source of supply that could vary by month, based on historical patterns, and by climate scenario.

We also did not include the full range of alternative supply sources as was done by Louw (2001 and 2002), as shown in Table 2.2. However, we did include the Berg River Dam, wastewater recycling and desalinisation of seawater as options for providing additional water supplies in the region.

These simplifications were based on our limited computational capacity, the resources available to the project, and the fact that the primary objectives of the project were to demonstrate a methodology for estimating the values of the economic damages that could be caused by climate change and the benefits of reducing these damages by adding additional storage capacity in the form of the Berg River Dam and by switching the water allocation methods, discussed here, to a system of efficient water markets.
In the future, we plan to build a more complete model of the Boland Region as a whole that will include a more faithful representation of all of the existing and potential supply sources in the area.

3 A Framework for Estimating the Benefits and Costs of Adapting to Climate Change

Callaway (2004a, 2004b) and Callaway et al. (1998) have developed a framework for estimating the benefits and costs of adapting to climate change both in the case of development projects and other kinds of 'no-regrets' projects whose primary objective is something other than adapting to climate change. The rationale for this focus is two-fold. First, 'no-regrets' projects may reduce climate change damages without any modification and, second, modifications can be made to make these projects more robust in the face of climate change.

The framework is developed around a planning approach in natural resource sectors that places special emphasis on two important features of long-range planning. The first is the role of investment in adjusting to climate variability and climate change under risk and uncertainty. The second is due to the fact that planners must make investment decisions that, once made, cannot usually be undone. Since they are planning under uncertainty about the precise nature of climate variability and climate change over a long period, their future predictions can turn out to be 'wrong'. Thus, in addition to looking at the benefits and costs of their investments if the climate they are planning for turns out to be true, they also have to weigh the costs of being wrong about their climate expectations.

3.1 The Conceptual Framework[3]

A main theme in the framework is that planning for climate change is conceptually not very different from planning for climate variability. The fundamental similarity between the two is that the objective of both types of actions is to avoid the damages of meteorological conditions that adversely affect human behaviour and economic activity, when these conditions are at least partly random and predicting them is subject to error. Both types of adjustments (i.e., to climate variability and climate change) have the potential to create benefits when they make society better off than it would have been if no adjustments had taken place. Both also involve the need to make *ex ante* decisions (i.e., prior to their implementation) under risk in making long-run investments in capital stocks, leading to more or less 'robust' and 'flexible' investments, depending on the extent of climate variability in the existing or expected climates. In addition, both types of adjustments, especially those involving investments in capital stocks are subject to making 'bad decisions', *ex post* (once they have been implemented), by making the wrong adjustments (including no adjustment). Finally, both types of decisions involve re-allocating scarce resources to make these adjustments, *ex ante*, quite apart from the issue of whether the adjustment decision turns out to have been a bad one, *ex post*.

The major differences between the two types of adjustment are:

- Climate variability is, by definition, a stationary process, while climate change is a non-stationary process, and this makes it harder to detect and characterise.

[3] The theory behind the framework is spelled out mathematically in Callaway (2004b).

- To plan for climate change planners need to explicitly introduce the climate variability associated with 'alternative climates', while climate variability planning involves only the variability in the existing climate.
- Planners consider the historical records of geo-physical processes that they use to adjust to climate variability to be more reliable than the results of climate models, particularly at the temporal and spatial scales they ordinarily use to make *ex ante* planning decisions.
- The climate is changing slowly and, for a given local climate, it is more difficult to detect changes in a transient process than a stationary one.

Thus, even though planners in climate-sensitive industries and government have the right (i.e., existing) tools for assessing the costs and benefits of a variety of options for adjusting to climate change, they have little guidance about how to characterise climate change in ways that are useful to them. At the same time, they do not feel statistically or psychologically comfortable enough to integrate the existing information they have from the climate change community into their planning process. This leaves planners caught between the extremes of no action, on the one hand, and invoking the precautionary principle, on the other.

However, it is quite likely that society is already adjusting to climate change, even if it is hard to detect or cannot be detected at all. That is because individuals and firms are able to at least partially adjust to climate changes that affect weather patterns, and are treated as 'strange' weather – to which they can adjust in some cases – and not as climate change. For example, a few years of abnormally late frosts will usually convince fruit growers they need to take some sort of inexpensive protection measures, without even knowing if this pattern is due to climate change or existing climate variability. If the pattern continues, fruit growers may make more substantial investments in protection measures, or even go out of business, without having information about climate change. These types of decisions can be attributed to normal profit maximising behaviour, without any indication that there has been a statistically significant change in the distribution of early frosts. When the climate change signal is finally detected, this will lead to other adjustment decisions, involving more fundamental changes in farming investments. To better understand how individuals and governments adjust to climate change we want to sketch out, conceptually, a three-stage adjustment process to both climate variability and climate change that we believe characterises the way individuals acting singly or collectively are currently adapting to climate change.[4]

To illustrate the economic aspects of this framework, we introduce the idea of an objective function that quantitatively measures the contribution of various actions to the objectives of the planner in a climate sensitive industry. For example, in the planning of a reservoir, the main objectives of the planner might be to maximise the reliability of the reservoir given fixed demands for water or, in a market framework, to maximise the net returns to water subject to a given level of reliability. Either way, the objective function would look something like: $Z[X(C_i, K_i), K(C_i)]$, where K represents the long-run investment in reservoir storage capacity and is a function of climate; X stands for short-run reservoir management actions that depend on reservoir capacity, after it is fixed; C represents the exogenous

[4] This process is presented in a stochastic, *ex ante - ex post* framework in the original workshop paper (Callaway, 2003).

climate variables that directly affect the storage capacity of the reservoir and reservoir management, and i = 0, 1 represents the climate 'state' that characterises the joint and partial distributions of the meteorological variables. Note that both X and K are functions of C, since we are assuming in this simple model that climate is the only exogenous variable in the planning problem.
Using this objective function and Table 3.1, we can trace out a simultaneous and continuous adjustment process to climate variability and climate change between any two transient climate states, i = 0 (current climate state), 1 (new climate state) along two different paths:

Management (X, K)	*Existing Climate (C_0)*	*Changing Climate (C_1)*
Adjustment to Climate Variability	Industry is adapted to existing climate through $X(C_0)$ and $K(C_0)$.	Industry adjusts to 'new' climate variability, without detecting climate change, through short run adjustments in management input $X(C_1)$, but does not change its institutions or capital stocks substantially, $K(C_0)$.
Adaptation to changing climate	Industry decides to take precautionary actions and adapts to climate change through long run investments $K(C_1)$ even though climate change can't be detected.	Industry detects climate change and adapts to climate change so that both management inputs $X(C_1)$ and capital stocks are optimal for the climate, $K(C_1)$.

Source: Modified from Fankhauser (1997), Callaway et al. (1998) and Callaway (2004b)

Table 3.1: Stages of Adjustment to Climate Variability and Climate Change for a Climate-Sensitive Industry

The first path starts in the top-left cell of Table 3.1 (or in between the top left and top-right cells) and represents adjustment to current climate variability, or the Base Case. In this stage, society is adapted to the current climate (or as close as possible to it, given existing information) both in terms of the allocation of management inputs, capital stocks and institutions. The objective function in this stage is equal to:

$$Z[X(C_0, K_0), K(C_0)].$$

The next stage in the first path, in the top-right cell of Table 3.1, represents the 'partial adjustment' to climate change. In this stage, the climate is changing, but it cannot be detected reliably, and therefore there are no climate-related incentives to re-plan the optimal level of investment in capital, privately or publicly. In this case, industries cope with climate change they cannot detect by treating it as if it were climate variability and changing their use of variable inputs (to the extent they can). For example, a reservoir operating authority might be able to partially adapt to a drier climate at the start of a water season by adjusting its reservoir operating policy, based on recent climate 'anomalies', while later on it might have to rely on water use restrictions to cope with water shortages. However, the reservoir authority probably will not enlarge existing reservoirs or plan new ones because the cost of doing this, if the observed 'anomalies' do not represent a permanent change in climate, could be very large. And if the climate information that is available is not reliable, the risks are even higher. Thus, the value of the objective function in this stage will be:

$$Z[X(C_1, K_0), K_0]$$

where the bold letters denote that the capital stock is fixed from the previous stage.

The range of partial adjustments that can occur can be quite large. For example, the water authority may be able to anticipate some 'anomalies', such as the El Niño and La Niña phenomena and adjust its allocation policy well in advance of the water season. In general, the capacity of an industry to adjust to climate change it cannot detect reliably is a function of the flexibility that is built into the existing level of the capital stock, as a result of existing climate variability, the 'overlap' between climate variability and climate change, and of course its ability to predict the weather in the short- and medium-term.

The third stage in the first path is full adjustment to climate change, shown in the lower-right cell of Table 2.1. The most important element of this stage is that climate change can either be detected in some way and/or forecasts about the nature of climate change are made useful for making planning decisions *and* they are deemed reliable enough to use for risk planning in climate-sensitive industries and activities, privately and publicly. This will create climate-related incentives to re-plan investment in capital stocks in the *ex ante* planning stage and may also be helpful in *ex post* planning, once climate change risk is built into meso-scale and weather forecasting models. Whether the model results from the *ex ante* part of the model are acted upon will be a normative decision, based on whatever criteria are used to evaluate private and public investments. But the important thing about this stage of the adjustment process, analytically, is that it can to lead to both long-run and short-run adjustments to both climate change and climate variability and this, in turn, has the potential to make people better off than they would be under partial adjustment. The value of the objective function in this stage is equal to:

$$Z[X(C1, K1), K(C1)].$$

The second path is what we consider precautionary adaptation to climate change. This includes anticipatory (Smith and Lenhart, 1996) pro-active adaptation (Hitz and Smith, 2004), both of which are based on 'no-regrets' principles, as well as actions that are based on the precautionary principle, to avoid irreversible effects. It involves moving, first, from the Base Case in the upper-left cell, to the lower-left cell, where individuals intentionally make changes to institutions and new climate-avoiding investments in capital stocks to cope with climate change that cannot be detected. No regrets actions can be viewed as optimal from society's perspective for reasons other than climate change, while actions based on the precautionary principle are rooted in risk management. The final stage in this path is full adjustment just as it was along the previous path.

The following economic measures can be used to characterise the welfare losses and gains in monetary terms along the first adjustment path (Callaway, 2004a and 2004b):

Climate change damages: The net loss in net welfare due to the physical damages of climate change compared to the Base Case, taking into account partial adjustment to climate change, but not specific actions to adapt to climate change. This is measured by: $Z[X(C_1, K_0), K_0] - Z[X(C_0), K(C_0)]$.

Net benefits of adaptation: The net reduction in climate change damages due to making capital investments that are perceived to be 'optimal' for climate change. This is measured by $Z[X(C_1,K_1), K(C_1)] - Z[X(C_1, K_0), K_0]$. This measure can, in turn, be decomposed into the following parts:[5]

Climate change benefits: The reduction in climate change damages avoided by specific adaptation actions.

Climate change costs: The cost of the real resources used by society to adapt to climate change.

The imposed damages of climate change: The residual climate change damages that are not avoided by specific adaptation actions. This is measured by $Z[X(C_1), K(C_1)] - Z[X(C_0, K_0), K(C_0)]$.
In a risk-planning framework, one can use information from both paths to calculate two important pieces of information to guide decisions about preparing (or not preparing) for climate change. In planning for climate change on an *ex ante* basis, planners face two kinds of risks. They can assume the climate is changing, and make capital investments based on this assumption, but *ex post* it may turn out that climate is not changing or that the climate change that is occurring or will occur is much less severe than they assumed. This kind of 'mistake' will have cost consequences, because the investment that was made *ex ante* is not optimal *ex post*. Alternatively, planners can assume *ex ante* that the climate is not changing and take no action, but find out *ex post* that the climate has changed. This 'mistake' also has cost consequences, because their actions were not optimal. Given the possibility for these kinds of *ex ante – ex post* planning mistakes one can define two additional costs:

The cost precaution: This is the cost of assuming, *ex ante*, that the climate will change from C_0 to C_1, and making the capital investment $K_{j,}$ when climate does not change, *ex post*: $Z[X(C_0, K_1), K_1] - Z[X(C_0, K_0), K(C_0)]$.

The cost of caution: This is the cost of assuming, *ex ante*, that climate will not change from C_0 to C_1, and thus not changing the level of investment in K_i (i.e., take no action), when in fact climate does change, *ex post*: $Z[X(C_1, K_0), K_0] - Z[X(C_1, K_1), K(C_1)]$.

This information can then be developed, for example, using a two-stage stochastic programming approach at the sector (Gillig *et al*., 2001) or project level (Callaway, 2004B) to determine how robust various management strategies (under partial adjustment) and capital investments (under full adjustment) are under the various mixed climate distributions.

Given the current level of risk associated with using the results from global and regional climate models, the subjective probabilities assigned to the various mixed distributions in such an assessment would be highly speculative, as would be the determination of dominant management strategies or investments for any combination of subjective probabilities across these mixed distributions. However, even at this stage when our ability to detect and forecast climate change is so poor, this type of

[5] The calculations are not shown because they require decomposing the net welfare function into its benefit and cost components.

sensitivity analysis can be a useful guide to point out the potential costs and benefits of a range of management and investment decisions under partial and full adjustment. This is better than nothing, and in some cases we may well find precautionary actions that come very close to being 'no regrets' actions under a wide range of climate alternatives and subjective probabilities.
The conceptual framework outlined above considers only two climate states and is perhaps a little too general to be understood in terms of its application to an actual planning situation. Therefore, in the next section we provide an example that applies specifically to our own research and involves planning under uncertainty for a number of different climate scenarios.

3.2 The Application of the Framework

Here we focus on its application to planning under risk and uncertainty. We consider a case where a river basin planning agency in a developing country wants to build a water supply reservoir to meet growing urban demands, while trying to maintain adequate water supplies for high valued agricultural crops. This is exactly the case in the Berg River Basin. The agency has a model that estimates the contribution of reservoir capacity to the objectives of the agency, given information about the expected magnitude of urban and agricultural water demands and the effects of climate on runoff. The model is forward looking over a long-term planning horizon and solves for the optimal storage capacity (and short-run management variables), given assumptions about future population growth and water demands.

The agency also has historical information about the observed climate and a number of scenarios ($j = 0, 1, \ldots, N$) that depict how the climate might look in the future. Unfortunately, the agency does not know how accurately these models can forecast the current climate (i.e., how reliable the models are) because thorough model validation exercises have not been completed. It also does not know the probabilities associated with the occurrences of the different climate scenarios, since these are based on different assumptions about global population growth and economic development – factors that are very hard to predict. Nevertheless, the agency wants to try to factor climate change into its reservoir capacity plans because the climate has been behaving strangely in recent years (even though a climate change, *per se*, cannot be detected using the historical record), provided that it has a good idea about the future consequences of building too big or too small a reservoir.

Table 3.2 shows the information that the agency has developed as a result of its climate change assessment. It is like Table3.1, but has more than two climate states. It also does not include a short-run management variable, although adjustment of this variable is assumed, since no matter what the climate is, the reservoir operating authority has the ability to alter reservoir management and water allocations in the short-run. Each cell entry measures the value of the agency's objective function (Z) as a function of the reservoir capacity (K_i in each row) and climate scenario (C_j in each column). The climate scenarios are arranged in the table so that, as one moves from left to right, the climate changes become more adverse. In this example, we will assume that the agency's objective can be measured in monetary terms as the net returns to water in the basin (as is true for BRDSEM[6]), but this does not have to be the case.

The bold cell entries in italics along the diagonal of Table 3.2 represent the optimal, or 'full adjustment' values of the agency's objective function for each climate scenario. This means that any change in the optimal reservoir capacity (K_i) will result in a smaller value of Z for that climate scenario. If the objective is to maximise the net returns to water in the basin, then at the optimal value of K_i for a particular climate scenario, the marginal benefits of the last unit of storage capacity will just equal the marginal costs of providing that capacity. So, in that context, ***Z(C_0, K_0)*** is an *ex ante* estimate of the maximum net returns to water, given the current climate, C_0, and this is achieved by building a reservoir with a capacity of K_0. ***Z(C_1, K_1)*** is the optimal value of the objective function for climate $C_{1,}$ if the agency builds a reservoir with a capacity of C_1, and so on, all the way down to ***Z(C_N, K_N)***. Finally, because the climate becomes more adverse as we move from left to right in the table, ***Z(C_0, K_0)*** > ***Z(C_1, K_1)*** > … ***Z(C_N, K_N)***.

Reservoir Capacity	*Climate Scenarios*			
	C_0	*C_1*	*C_2*	*C_N*
K_0	**Z(C_0, K_0)**	Z(C_1, K_0)	Z(C_2, K_0),…,	Z(C_N, K_0)
K_1	Z(C_0, K_1)	**Z(C_1, K_1)**	Z(C_2, K_1),…,	Z(C_N, K_1)
K_2	Z(C_0, K_2)	Z(C_1, K_2)	**Z(C_2, K_2),…,**	Z(C_N, K_2)
K_N	. . . Z(C_0, K_N)	. . . Z(C_1, K_3)	. . . Z(C_2, K_N)	. . . **Z(C_N, K_N)**

Table 3.2: Reservoir Capacity and Objective Function Values for Full and Partial Adjustment under Alternative Climate Scenarios

It is important to keep in mind that the reservoir capacity is being determined before a climate change can either be detected or, if it has not happened yet, before it actually occurs. Thus, these estimates of optimal reservoir capacity and optimal economic returns to water are *ex ante* estimates. If the planner guesses right about climate change, then these estimates will also be the *ex post* net returns to water, but this cannot be determined until climate change is detected or takes place, presumably after the reservoir is built, unless waiting to build the reservoir turns out to be the best strategy.

The objective function values in the off-diagonal cells are estimated by holding the optimal value of reservoir storage constant for each climate scenario and re-running the model for each climate scenario.

---

6 The Berg River Dynamic Spatial Equilibrium Model was introduced in Section 1.0 and will be fully discussed in Section 3.0.

These values are associated with the 'partial adjustment' scenarios. That is to say: they depict a situation in which the management of the reservoirs and the allocation of water can change in response to climate change, but the reservoir capacity cannot. These off-diagonal elements (and the partial adjustment scenarios that underlie them) have an important meaning to the planning problem, both in terms of *ex ante* and *ex post* planning.

In row 1, as we have already stated, the optimal *ex ante* strategy under the current climate is to build a reservoir with a capacity of K_0. But what will happen if the reservoir is built and the agency later finds out what the true climate is, or the climate changes to C_1? In that case, our *ex ante* assessment is that the objective function value will fall[7] from $\boldsymbol{Z(C_0,\ K_0)}$ to $Z(C_1, K_0)$, and if the climate under which the reservoir will operate is correctly characterised C_2, then the objective function will fall even farther to $Z(C_2, K_0)$, and so on. The same holds true for all of the upper diagonal elements in Table 3.1. For example, if the *ex ante* climate expectation is C_2, then it would be optimal to build a reservoir with a capacity of K_2, but if the true climate is actually C_N, then the highest value of the objective function that can be achieved, holding the reservoir capacity at K_2 is $Z(C_N, K_2)$. Given this meaning, the information in each row of the table on and above the diagonal elements can be used by the agency to construct *ex ante* estimates of the damages caused by climate change if it does not correctly adjust to it, the net benefits of correctly adjusting from one expected climate to the other, and the residual damages after the adjustment, whether or not it knows which climate scenario is the most likely.

We can redefine the construction of these various benefit and cost estimates both more generally to a wider range of climate scenarios and more narrowly in terms of water resources planning than was done in Section 3.1 as follows:

Climate Change Damages (ex ante): This is an ex ante measure of the economic losses that the agency expects to occur if the climate changes from its currently perceived 'state', C_i, to another climate state, C_j, when the agency does not build a reservoir with the storage capacity K_j. For example, if under the climate, C_0, the optimal capacity of the reservoir is $K_0 = 0$, then the ex ante value of climate change damages associated with the occurrence of climate state C_2 is equal to $Z(C_2, K_0) - Z(C_0, K_0)$. This definition works for any pair-wise comparison of climate states. For example, if the current climate state is C_2, and the climate is expected to change to C_N, then the climate change damages are equal to $Z(C_N, K_2) - Z(C_2, K_2)$ More generally,

$$\text{Climate Change Damages} = Z(C_j, K_i) - Z(C_i, K_i) \qquad \text{EQ 3.1}$$

where i is an assumed current climate state and j is an alternative climate state.

Net Benefits of Adaptation (ex ante): This is an *ex ante* measure of the net benefits of adjusting from a state of partial to full adjustment to climate change. This is the same thing as saying it is a measure of the climate change damages avoided by adapting to climate change. In the previous example, the economic loss associated with not adjusting to climate change is equal to $Z(C_2,\ K_0) - \boldsymbol{Z(C_0,\ K_0)}$. However, building a reservoir with a capacity that is optimal for C_2 results in estimated returns to water worth $\boldsymbol{Z(C_2,\ K_2)}$,

[7] We know that Z will fall based on the ordering of the climate scenarios and the application of the LeChatelier principle (Silberberg, 1978).

which must be greater than the value $Z(C_2,\ K_0)$[1]. Thus, the *ex ante* benefits of adjusting (adapting) to climate change in this example are $\boldsymbol{Z(C_2,\ K_2)}$ – $Z(C_2,\ K_0)$ and this will hold true for any pair-wise comparison of climate states. For example, the net benefits of adaptation associated with a current climate C_2 and an expected climate of C_N are $\boldsymbol{Z(C_N,\ K_N)}$ – $Z(C_N,\ K_2)$. The more general definition[8] is:

$$\text{Net Benefits of Adaptation} = Z(C_j, K_j) - Z(C_j, K_i) \qquad \text{EQ 3.2}$$

Imposed Climate Change Damages (ex ante): This is an *ex ante* measure of the climate change damages that are not avoided by adaptation. But one must be careful about the way this is expressed, because it may or may not be physically possible to avoid all climate change damages. In many cases, it will not be, because adaptation is usually not a perfect substitute for mitigation (Callaway, 2004a). What matters in this definition is that it is not 'optimal' to avoid all the climate change damages, based on the objectives of the planning agency. In our previous example, the total value of climate change damages is equal to $Z(C_2,\ K_0)$ – $\boldsymbol{Z(C_0,\ K_0)}$ to which we can add the net benefits of adaptation, leaving the residual: $Z(C_2,\ K_0) - \boldsymbol{Z(C_0,\ K_0)} + [\boldsymbol{Z(C_2,\ K_2)} - Z(C_2,\ K_0)] = \boldsymbol{Z(C_2,\ K_2)} - \boldsymbol{Z(C_0,\ K_0)}$. For the case where the current climate is C_2 and the expected climate is C_N, imposed climate change damages are equal to $\boldsymbol{Z(C_N,\ K_N)} - \boldsymbol{Z(C_2,\ K_2)}$ or more generally:

$$\text{Imposed Climate Change Damages} = Z(C_j, K_i) - Z(C_i, K_i) + \qquad \text{EQ 3.3}$$

$$Z(C_j, K_j) - Z(C_j, K_i) = Z(C_j, K_j) - Z(C_i, K_i)$$

As stated in the previous section, there are two additional definitions that can be derived from Table 3.1. By appealing to the *ex post* meaning of the cell entries we can compare *ex ante* plans with *ex post* outcomes and look at the costs of making planning 'mistakes', either as a result of acting too cautiously or not cautiously enough.

These off-diagonal cell entries on both sides of the diagonal have an important *ex post* meaning to the agency's planning problem. Consider, first, the meaning of the cell entries that lie above the diagonal, as they relate to the agency taking a cautious approach to climate change, given the uncertainty in the available information about climate change. For example, let us assume that the agency acts cautiously and decides to build a reservoir best suited to the current climate, but later on it turns out that the true climate is characterised by C_2. In this case, $Z(C_2,\ K_0)$ represents the *ex post* net returns to water under partial adjustment. However, if the agency had correctly guessed the 'right' climate scenario (C_2), it would have built a reservoir with a capacity of K_2 and net returns of $\boldsymbol{Z(C_2,\ K_2)}$, which is higher than the partial adjustment value $Z(C_2,\ K_0)$. Thus, by comparing the objective function values for the right and wrong adjustments, it can get an idea of the *ex post* cost of acting too cautiously. These *ex ante – ex post* definitions do not necessarily depend upon defining a current climate, but can apply more broadly to any *ex ante* planning 'mistake' when viewed from an *ex post* perspective. For example, if the current climate is characterised by C_0 and the agency builds a reservoir expecting C_2, but C_N actually occurs, then evaluating the cost of acting too cautiously involves the comparison of $Z(C_N,\ K_2)$ with $\boldsymbol{Z(C_N,\ K_N)}$, which is the greater of the two.

---

8 The net benefits of adaptation can be decomposed into benefits and costs as shown in Callaway (2004B).

The cell entries below the diagonal tell a different *ex post* story. Let's suppose the agency had some reason to expect climate scenario C_2 and built the reservoir accordingly with a capacity of K_2 for which the *ex ante* returns to water were ***Z(C₂, K₂)***, but later on, *ex post*, the agency was not able to detect any climate change at all. So, the *ex post* returns to water are $Z(C_0, K_2)$, which are actually higher than $\boldsymbol{Z(C_2, K_2)}$. While this may sound like a win-win situation and justify the application of the precautionary principle to adaptation, this is not really the case. Why not? Because, had the agency correctly guessed (on an *ex ante* basis) the right *ex post* climate, it would have built the reservoir with a capacity of K_0, leading to net returns to water equal to $\boldsymbol{Z(C_0, K_0)}$, which is higher than the value $Z(C_0, K_2)$. Again, by comparing the objective function values for the right, $\boldsymbol{Z(C_0, K_0)}$, and wrong, $Z(C_0, K_2)$, climate state, the agency can gain valuable information about acting too precautiously (i.e., not cautiously enough) in its capacity planning. This also works for any partial comparison of climate states. For example, if the current climate is characterised by C_0 and the agency, expecting C_N to occur, builds a reservoir with the capacity of K_N, but C_2 occurs *ex post*, then the costs of acting too precautiously can be estimated by comparing $Z(C_2, K_N)$ with $\boldsymbol{Z(C_2, K_2)}$, which is the larger of the two.

These two features of the information gathered by the agency make it possible to define two additional 'costs' related to adaptation planning. These measures combine *ex ante* expectations about climate with the *ex post* results of making the wrong decision and so are called *ex ante – ex post* measures. They are:

The Cost of Caution (ex ante – ex post): This is a measure of the economic losses that will occur *ex post* if planners take *ex ante* actions consistent with an expected climate, C_i, but a worse climate change occurs, *ex post*, as characterised by C_j. A formal definition for expected *ex ante* climate state (i) and the actual *ex post* climate state (j) is:

$$\text{The Cost of Caution} = Z(C_j, K_i) - Z(C_j, K_j), \qquad \text{EQ 3.4}$$

which turns out to be the same measure as for the net benefits of climate change with a negative sign in front of it since it represents a cost, not a benefit.

The Cost of Precaution (ex ante – ex post): This is a measure of the economic losses that will occur if planners assume, *ex ante*, the climate will change to C_j and build a reservoir with the capacity K_j, when in fact the *ex post* climate turns out to be C_i, which is less adverse than C_j. A formal definition, given expected *ex ante* climate state (j) and the actual *ex ante* climate state (i) is:

$$\text{The Cost of Precaution} = Z(C_i, K_j) - Z(C_i, K_i) \qquad \text{EQ 3.5}$$

In the BRDSEM, the objective function is couched in terms of the net economic returns to water in the basin. Given that construction, the five benefit and cost definitions are illustrated in an economic market framework for water in Figure 3.1, taken from Callaway (2004b). The downward sloping line, Dem, indicates the aggregate demand curve for water in the basin. In fact the demand curve for water will also be influenced by climate change, but showing these changes complicates the graphic analysis. Therefore in this figure, we assume for the sake of simplicity that D does not respond to climate change. The effects of climate change on the availability of water in the basin are illustrated by shifts in the aggregate supply curve for water in the basin S(C, K). The supply curve for water depends on the reservoir capacity, (K) and the climate (C). Thus, each supply curve corresponds to one of the four scenario boxes in Table 2.1. The indexing of both climate and storage are consistent with the above analysis. For the *ex ante* measures, i stands for the initial climate and j stands for the expected climate change. For the *ex ante – ex post* measures, i stands for the expected climate, *ex ante*, while j stands for the actual climate that occurs, *ex post*.

There is economic logic in the way the four aggregate water supply curves are arranged in Figure 3.1. The supply curve, $S(C_i, K_i)$ lies below all the rest if we assume that climate change has the effect of reducing water supply and that subsequent adjustments to climate change either require building a larger reservoir or and/or avoiding climate change damages by adjusting the reservoir operating policy.

The supply curve $S(C_i, K_j)$ must lie above $S(C_i, K_i)$ since adaptation by means of the adjustment from K_i to K_j is no longer optimal for the current climate. The supply curve $S(C_j, K_j)$ must also lie above $S(C_i, K_i)$ since adaptation cannot completely eliminate the adverse effects of climate change.[9] Finally, the supply curve $S(C_j, K_i)$ must lie above $S(C_j, K_j)$, since the adaptation to climate change under the former is not complete.

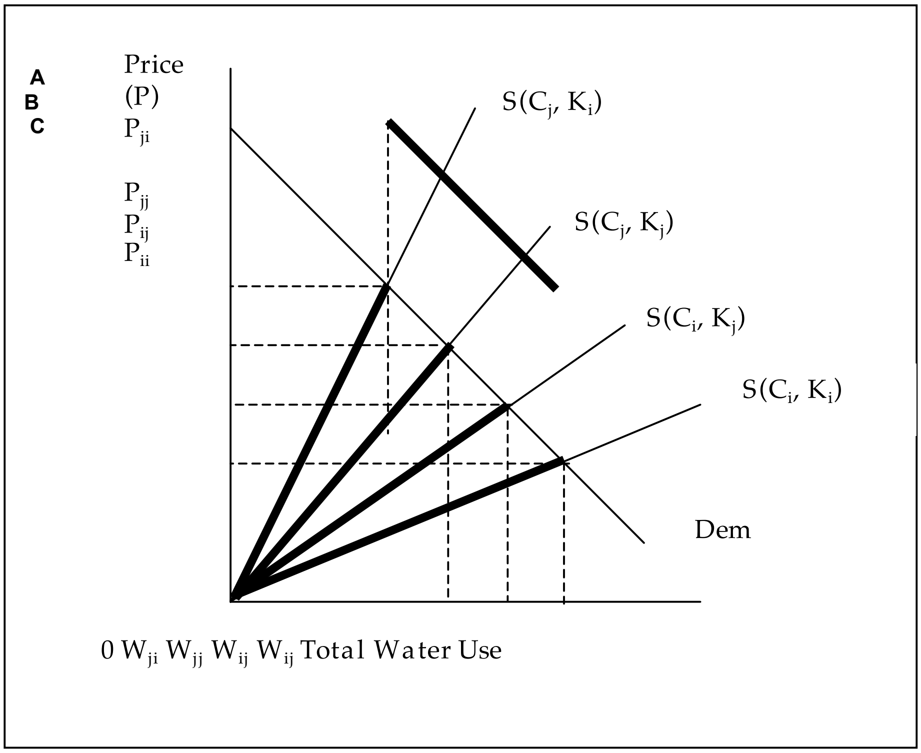


Figure 3.1: Illustration of Benefit and Cost Measures in a Water Market

For each demand and supply curve intersection, the resulting water price[10] (P) and aggregate consumption are shown on the price (vertical) and quantity (horizontal) axes of the figure. In this

---

[9] The relationship between $S(C_i, K_j)$ and $S(C_j, K_j)$, as shown in Fig. 3.1, implies that adapting to climate change that does occur is more costly than adapting to climate change that does not occur; however, this is an empirical issue, strictly speaking, since long-run investments made to adapt to climate change may preclude or limit adjustments in variable inputs that would have occurred in the absence of climate change and adaptation.

[10] Here price stands for the marginal value of water in use.

diagram, the net returns to water are calculated as the sum of Consumers' and Producers' Surplus, which is an economic welfare measure that is often used to characterise the economic value of a good or an asset in a market (Silberberg, 1978 and Just *et al*., 1982). The heavily outlined rectangles between the supply curves are measures of changes in the net value of water, due to shifts in the supply curve.

In this diagram, the area **A**+**B**+**C** equals $Z(C_j, K_i) - Z(C_i, K_i)$, which is the loss in the sum of consumers' and producers' surplus associated with *climate change damages*. The area **A** equals $Z(C_j, K_j) - Z(C_j, K_i)$, which is the gain in the sum of consumers' and producers' surplus associated with the positive *net benefits of adaptation. The imposed climate change damages*, or $Z(C_j, K_j) - Z(C_i, K_i)$, are represented by loss of consumer and producer surplus indicated by area **B**+**C.** In the *ex-ante – ex-post* framework, the negative value of the area **A**, or $Z(C_j, K_i) - Z(C_j, K_j)$, represents the loss in consumers' and producers' surplus as a result of making a 'wrong' planning decision that is too cautious. This is *the cost of caution*, while the area **C**, or $Z(C_i, K_j) - Z(C_i, K_i)$, represents *the cost of precaution*. This is the cost the agency will face if it acts too aggressively in the face of expected change and the expected change does not occur.

An important question to ask is: 'How can this information be used to make decisions about investing in measures to avoid climate change damages when the information about climate change is so uncertain?' The answer to this question is that even without reliable information about expected climate scenarios or the probabilities associated with their occurrences we can still calculate *ex ante* measures of the net benefits of building a reservoir for different expected climate states and compare these with the costs of acting too cautiously or too precautiously, if the expected climate state does not materialise. This is exactly what we will examine in the Berg River Basin by developing and applying BRDSEM in just the way outlined in the example.

This is just a first step. In our analysis, we work with deterministic scenarios that represent no more than a single run of a climate model. To better implement an *ex ante – ex post* assessment we would prefer to have two additional pieces of information that currently are not available for the region:
estimates of the parameters of the joint and partial distributions of monthly temperature and precipitation at different weather gauges in the region for each scenario; and
estimates of the forecast error for the regional climate model from regional validation trials that will tell us how reliable the model is in the first place.

With this information, we can propagate the joint and partial distributions of runoff in the basin and the distributions of the parameters of the forecast errors in the climate model. These distributions can in turn be propagated through BRDSEM to reflect distributions of the important output variables in the model, such as the net returns to water, water consumption by different sectors, reservoir storage, etc., and the forecast errors around them. Making the analysis fully stochastic in this way will help planners in the region to look at the physical and economic consequences over the entire distribution of runoff values in a particular climate scenario. Additional information about the errors around the forecasts of these variables will help planners to better understand the risks of making Type I and Types II errors given the quantifiable uncertainty in the climate models. This will also help climate modellers to better grasp the need for the kind of information that planners need in all natural resource sectors and hopefully provide additional guidance for making the models both more useful and reliable.

4 The Berg River Dynamic Spatial Equilibrium Model

4.1 Model Overview

BRDSEM 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 for this AIACC project 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 due 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. Figure 4.1 is a schematic diagram of BRDSEM and the models that feed information to it.

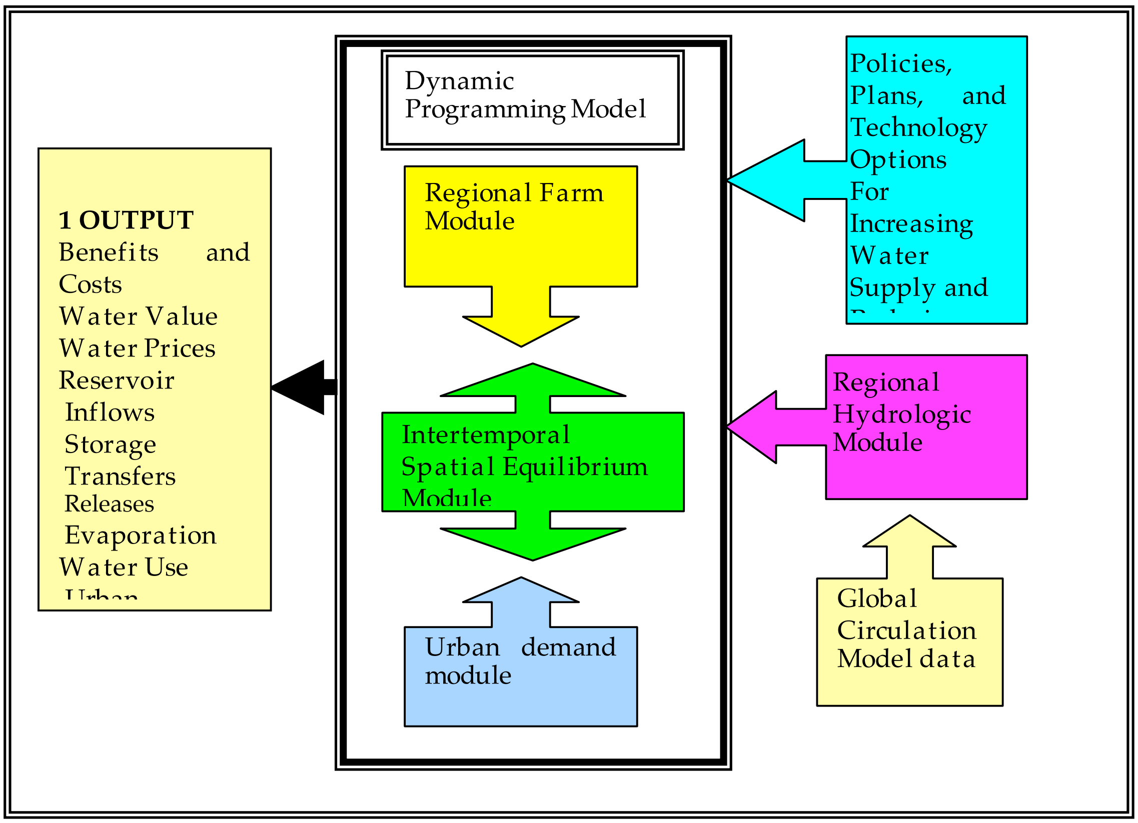


Figure 4.1: Berg River Spatial Equilibrium Model (BRDSEM) Schematic Diagram

Parts of BRDSEM, primarily the regional farm models, were originally developed by Louw (2001, 2002) in the context of a static, non-spatial model, to examine alternative sources of supply and allocation systems in the study area. The model has been significantly modified for this project; however, the core data remains the same.

The core of BRDSEM, shown in the box labelled 'Dynamic Programming Model' consists of three linked modules. The three 'modules' are interconnected in the framework of a dynamic non-linear programming model, which was constructed using the General Algebraic Modelling System (GAMS) and solved using the MINOS and CONOPT solvers. Each module can be developed and modified separately, with only minor adjustments to other modules and elements in the non-linear programming model. These modules are:

The Intertemporal Spatial Equilibrium Module: This module consists of a series of linear equations that characterise a) the water balances over time in specific reservoirs and b) the spatial flow of water in the basin, linking runoff, reservoir inflows, inter-reservoir transfers and reservoir releases, to urban and irrigated agricultural demands for water.

The Urban Demand Module: This module simulates the demand for urban water for seven urban water uses.

The Regional Farm Module: This module consists of seven regional dynamic linear farm models (one for each farm region) that simulate the demand for agricultural water in the Upper-Berg River.[11]
These last two modules are linked directly to the storage and conveyance module at different points of use in the basin and these three modules are then solved together as a dynamic, non-linear programming model, using the inputs from the hydrology module. An important feature of the model is that the capacity of the Berg River Dam can be determined endogenously based on the criteria of economic efficiency or it can be fixed exogenously. More generally, the model can 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.
The output of the model consists of (but is not limited to):

- measures of the economic value of water based on the welfare for water users, broken down by urban sector and farm region;
- water prices, in urban and agricultural uses;
- monthly reservoir storage, releases and transfers, and reservoir evaporation for main storage and farm reservoirs;
- monthly water diversions and consumptive use by urban sector, farm regions and irrigated crops in each region;
- annual crop mixes by farm region; and
- return flows by farm region, low flows by farm regions, and various system losses due to conveyance losses.

Figure 4.1 shows three external sources of information to BRDSEM:

Global Circulation Model data: This model supplies the hydrologic model with information about monthly temperature and precipitation at specific points in the basin for climate scenarios.

11 The BRDSM model is an improvement on previous static model developed by Louw (2002) for the South African Water Research Commission (WRC).

A Regional Hydrologic Model: This model (WATBAL) converts the monthly temperature and precipitation data from the regional climate model into monthly runoff at different runoff gages for each climate scenario.

Inputs about Policies, Plans and Technologies: This represents the source 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.

A schematic overview of the Intertemporal Spatial Equilibrium module, showing the physical relationships between runoff points, major storage reservoirs and water users in BRDSEM is presented in Figures 4.2A and 4.2B. A more detailed hydrologic representation of both the upper and lower sections of the Berg River Basin can be found in Hellmuth and Sparks (2005).

Figure 4.2A characterises the runoff, storage and transfers of water in the 'upper' basin. There are six 'sites' in the upper basin of BRDSM. Three of these sites constitute the major dams in the model, each associated with a storage reservoir: Theewaterskloof (TWAT), Wemmershoek (WMRS), and the Berg Dam (BERG). The final site is the Berg Supplemental Site (BERGSUP), which is a pumping station below the Berg River Dam that collects runoff below the dam and pumps it to the Berg Reservoir.
Table 4.1 shows the runoff sources for, the deliveries from other sites, and the deliveries to other sites for each of the four upper basin sites as depicted in Figure 4.1A.

Site	*Runoff sources From WATBAL*	*Possible Deliveries from*	*Possible Deliveries to*
TWAT	H6H007-8, H6R001-2, G1H019, G1H038	NONE	URB1 via WMRS waste treatment, and URB2
WMRS	G1R002	NONE	URB1 via WMRS waste treatment
BERG	G1H004, G1H038	TWAT, BERGSUP	BERGSUP
BERGSUP	G1H019, G1H003	TWAT, BERG	BERG, LOWERBERG
URB1	NONE	WMRS, TWAT	Urban demand - Municipalities
URB2	OUTSIDE	TWAT	Urban demand – Cape Town

Table 4.1: Upper Basin Sites, Including Runoff Sources, and Deliveries from and to Other Sites

TWAT receives monthly runoff from three measured at the gauges numbered H6H007, H6H008, H6R001, and H6R002. It also can receive a portion of the runoff from two additional sources, as measured at gauges G1H038 and G1H019. TWAT can release water to URB2, which in turn is connected to urban demand in Cape Town and to the municipalities in the region through the Wemmershoek Waste Treatment plant. It can also release water to the Berg Dam.

WMRS receives monthly runoff from a single source, as measured at gauge G1R002. It can make monthly deliveries to URB1, local urban demand, and through the waste treatment plant and to a point below BERG and BERGSUP.

BERG receives monthly inflows from runoff measured at gauge G1H004 and a portion of the runoff from G1H038 that is not taken by TWAT. The runoff allocation from G1H038 can be fixed or determined endogenously within the model. BERG can receive transfers from TWAT and BERGSUP.

BERGSUP receives monthly runoff from G1H003 and the unallocated portion of G1H019. It can receive transfers from both WMRS and BERG and it can transfer water it collects from the other sources back to BERG for storage or send this water downstream to the 'lower' section of the Berg River.

URB1 receives water from WMRS and TWAT via the Wemmershoek waste treatment plant and sends water to the local municipalities.

URB2 receives water from TWAT and from a supply site labelled 'OUTSIDE' and delivers this water to Cape Town.

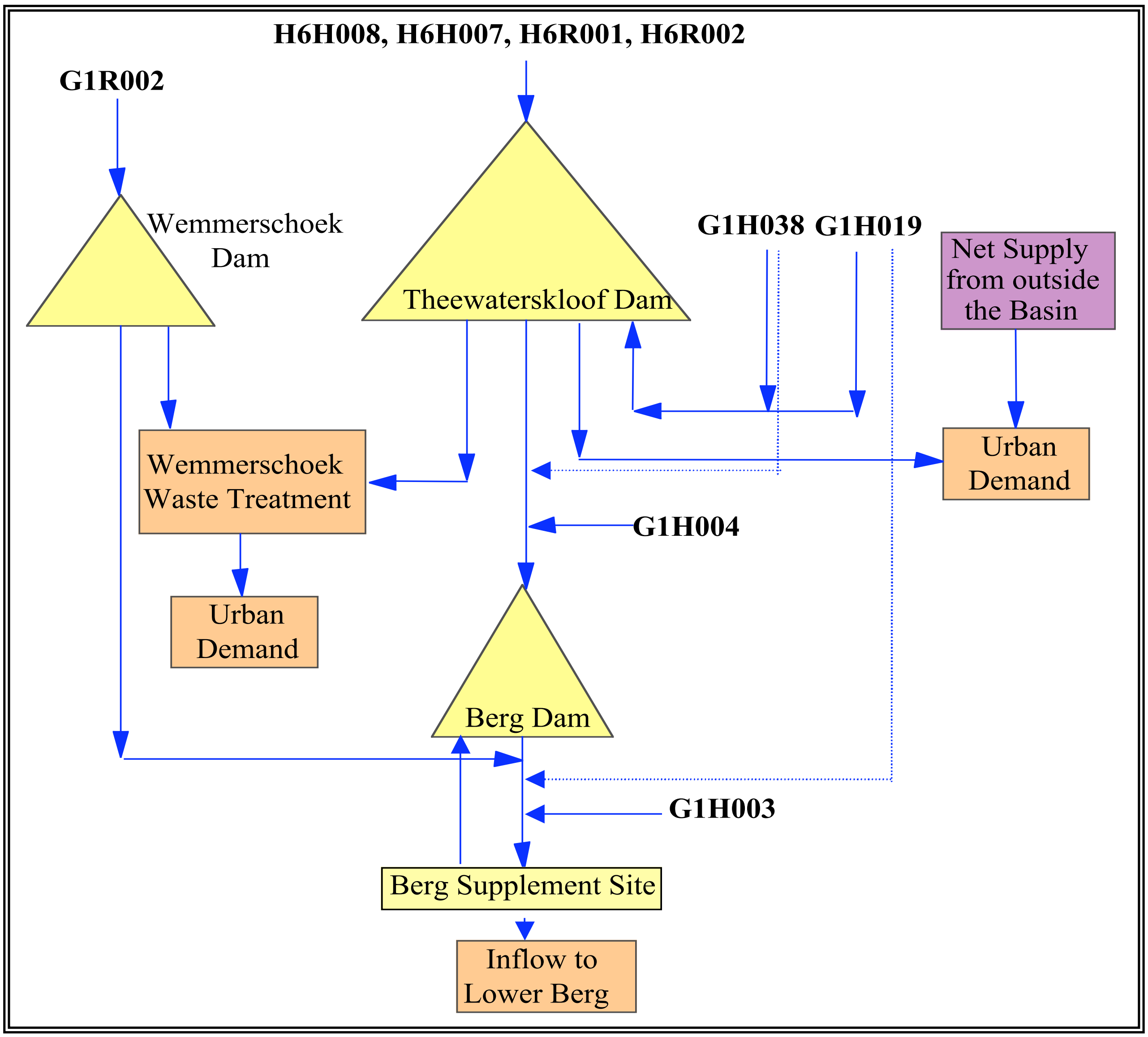


Figure 4.2 A: Schematic Diagram of Upper Berg River as Depicted in BRDSEM

OUTSIDE represents the supply of water available to Cape Town from water supply reservoirs sources not explicitly characterised in the model. As stated in section 2.4, these supplies are fixed over each year, but vary by month according to historical patterns and climate scenario. The decision not to model the runoff into these reservoirs and the operation of these reservoirs in detail was a strategic one, based on a comparison of the extra effort involved to include them and the resources available to the project. This represents an important limitation in the model. Figure 4.2B is a schematic representation of the 'lower' part of the Berg River Basin, below BERGSUP.

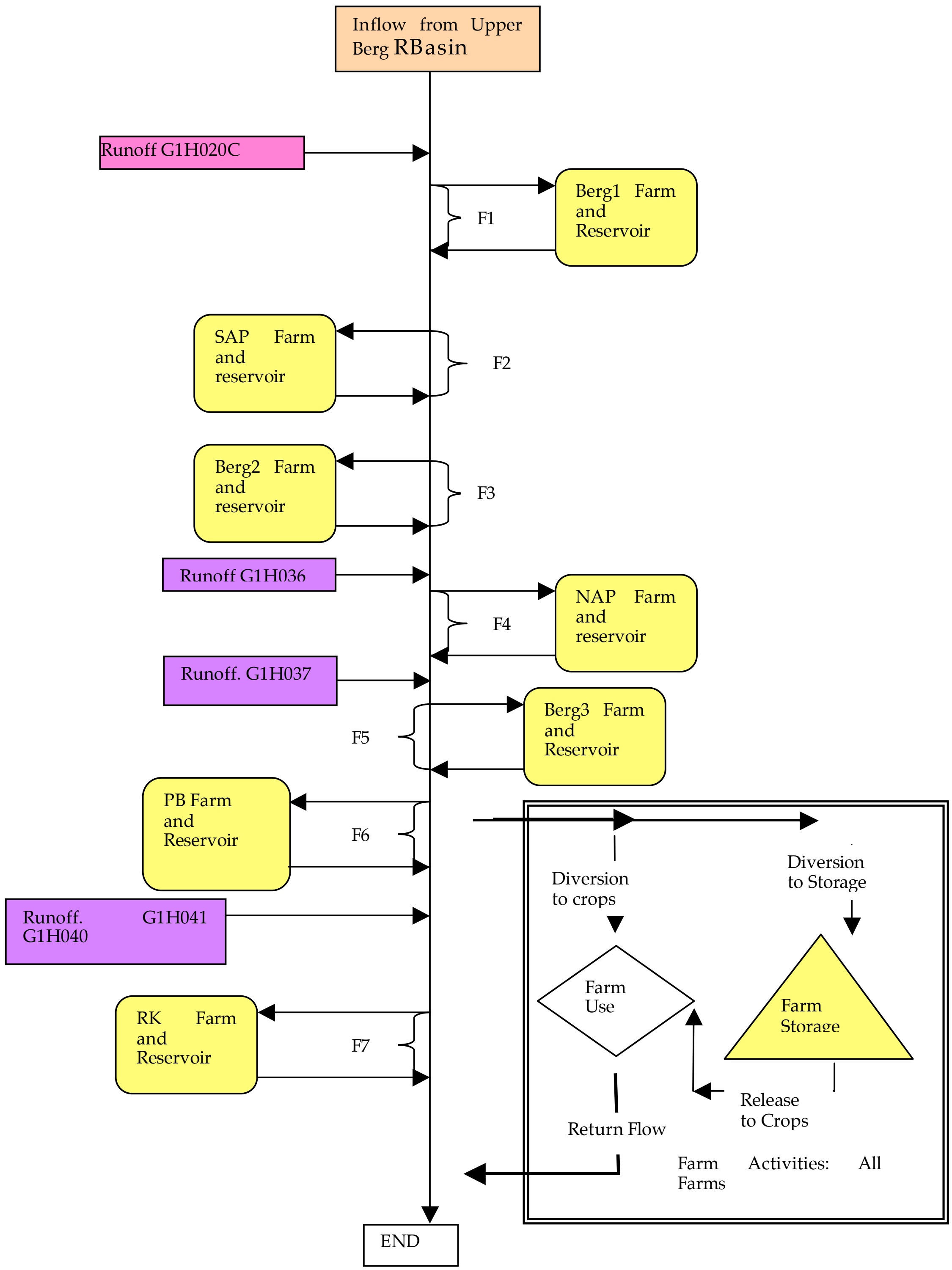


Figure 4.2B: Schematic Diagram of the Lower Berg River as Depicted in BRDSEM

The lower basin consists of the main stem of the Berg River, and the major sources of runoff from tributary waters that flow directly into the mainstem. The monthly runoff from these five tributaries, as generated by WATBAL, is measured at the runoff gauges G1H020C, G1H036, G1H037, G1H041 and G1H040 (combined). There are seven farm regions in the model, BERG1, SAP, BERG2, NAP, BERG3, PB and RK, arrayed in that order along the mainstem. The use of water by each farm is depicted in the box in the lower right of the diagram. Each farm has the following options for using water. It can divert and pump water directly from the river to irrigate crops or divert it and transfer it to a farm dam for irrigation use later in the season. Part of the water that is used to irrigate crops, whether it comes directly from diversions or farm dam storage, is used consumptively by crops as determined in the regional farm models and part returns to the river as return flow. The flows in the Figure designated F1 through F7 represent the monthly instream flows at each farm region. These are constrained using low flow bounds during the summer months to protect aquatic ecosystems.

4.2 Technical Description of BRDSEM

BRDSM falls into a class of economic models that has the following five main features:

- Dynamic – the model maintains mass balances for water at each reservoir discretely over time (months and years), as well as investment irrigated agricultural land.
- Multi-regional (spatial) – the model simulates the flow of water over space between runoff nodes, storage reservoirs, and water use.
- Non-linear programming – the model maximizes the discounted net sum of consumers' and producers' surplus subject to flow and storage constraints (shown in the two schematic diagrams) and various restrictions on water transfers and conveyances; part of the objective function of the model is non-linear, capturing the willingness-to-pay of urban water users by sector.
- Partial-equilibrium – the model simulates an intertemporal and spatial price equilibrium (Takayama and Judge, 1971) for a number of water using sectors within the study area, but the flow of goods and services in these sectors is not linked to other sectors in, and outside, the region.
- Ex-ante, ex-post – investment decisions in the capacity of the Berg River Dam and irrigated agricultural land are made ex-ante in the model, based on ex-ante, rational expectations about population growth and climate in the future, which may not be realised, ex-post.
- Perfect foresight – the model solves simultaneously in all periods, implying that economic agents in the model have rational expectations and follow them in making production and investment decisions.

As previously discussed, BRDSEM consists of three modules, linked together in a mathematical programming framework. For presentation purposes, the structure of the programming model must be broken down a little differently into four linked components, as follows:

- A non-linear (quadratic) objective function that characterises the normative objectives of the agents in the model.
- An intertemporal, spatial equilibrium module/matrix that characterises the spatially distributed flow of water and water storage in the basin.
- An urban water demand module/model that is linked directly to the objective function, and the intertemporal spatial equilibrium matrix.
- Regional farm/irrigation module/demand model that is linked directly to the objective function and the intertemporal spatial equilibrium matrix.

4.2.1 The objective function

The objective function of the model is to maximise the net present value of the returns to water in the basin over thirty 12-month periods. In this form, the objective function serves two purposes. First, it is consistent with welfare maximisation by water consumers, farmers, and water managers and, thus, simulates the competition for water in efficient markets. Second, it is an accounting convention that measures the economic value. The first function of the objective function can be partially or completely

over-ridden by constraining the allocations of water to reservoirs and from reservoirs to water users, depending on how 'tight' the constraints are on the allocations. However, even when these constraints are in place, the objective function still provides a measure of the net economic value of water in the basin.
The returns to water in BRDSEM are defined as the sum of the following benefits of water use minus the costs of water use:

Benefits

- Willingness-to-pay for water by urban consuming sectors in Cape Town and the municipalities in the basin.
- Long-term farm income for the seven regional farms.

Costs

- Long-term (investment and production costs) for the seven regional farms.
- The capital cost of the Berg River Dam.
- The costs of operating the reservoirs and delivering water to both municipalities, and consumers and the seven regional farms and pumping costs.[12]

Objective Function for Urban Users (Includes both Benefits and Costs)

The economic measure for the total welfare for urban water consumers is the net present value of the monthly willingness-to-pay for water in five urban demand categories over the planning horizon, less the costs of water to the water utility[2]. These demand categories include: lower income households (IHH), higher income households (LHH), garden and lawn water use (Gar), industrial consumers (Ind), Commercial water users (Com), and public sector water use (Cou). Consumer's willingness-to-pay for water is defined as the maximum amount of money a consumer would be willing to pay for the water he/she uses, rather than do without it (Silberberg 1978). This measure is derived from the demand curves of urban water users, the construction of which will be discussed later.

The concept of consumer willingness-to-pay for water is illustrated in Figure 4.3, which depicts a linear demand curve (Dem) for a 'representative' urban water user or industry.

---

12 One of the limitations of the current model is that it does not include urban water works and waste treatment costs due to lack of data.

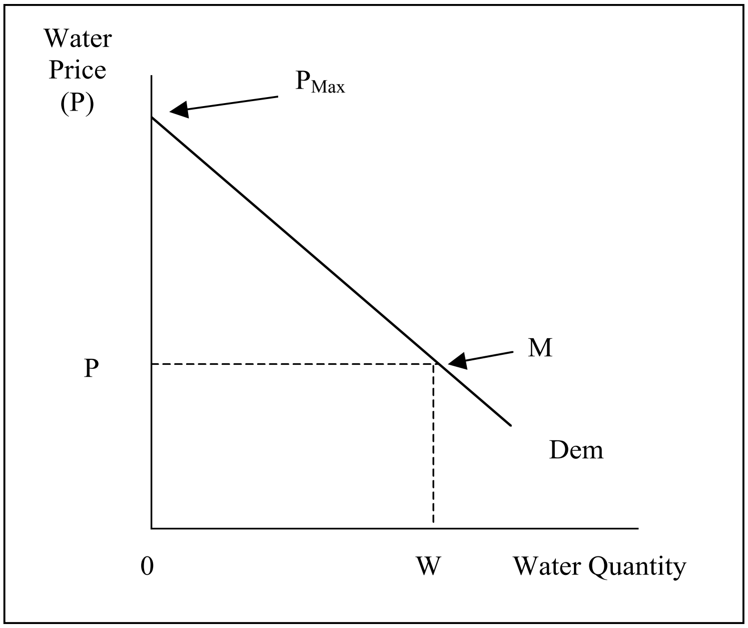


Figure 4.3: Explanation of Consumer Willingness-to-Pay for Water and Consumers' Surplus in Urban Water Demand

The development of the urban demand curves for water in BRDSEM will be discussed later on in this section. Each point on the demand curve represents the maximum amount of money the consumer is willing to pay (measured on the water price axis) for the last unit of water he/she consumes (measured on the water quantity axis). The demand curve for water is downward sloping based on the assumption that consumers derive less and less utility as they consume more and more water. The point where the demand curve intersects the water price axis (P_{Max}) is known as the choke price, because at that price water use is zero. This is the maximum amount the consumer is willing to pay for the first unit of water rather than do without it. As the user consumes more and more water (moving to the right on the water quantity), he/she derives correspondingly greater welfare as the price of water falls and the quantity consumed increases. In other words, at the price below P_{Max}, the water user receives a welfare 'surplus' from not having to pay P_{Max}. At the price P, where the urban consumer uses W units of water, his/her willingness-to-pay for water is measured by the area under the demand curve between P_{max} and W, or the area $0P_{max}$ MW. If we take into account the price the consumer pays for water, P, (as we do in a separate part of the objective function) then by deducting the cost of the water (P*W=0PMW) from the willingness-to-pay for water, we arrive at a net welfare measure, known as consumers' surplus, which is measured by the area $PP_{max}M$. Consumers' surplus is formally defined as the maximum willingness-to-pay by the consumer for water, rather than go without it, less the amount paid for the water (Silberberg 1978).

The Objective Function for Regional Farms (Includes both Benefits and Costs)

This part of the objective function for the seven regional farms is derived from the dynamic income balance in the regional farm models. The development of the regional farm models will be discussed later in this section. The objective for each of the seven representative farms is to maximise the aggregated long-term net farm income (NDI). NDI consists of the following income and cost elements, calculated on an annual basis over the planning horizon (except as noted):

Income

- Income from crop sales for both irrigated and non irrigated crops, including both annual and perennial crops (seventeen crops in all).
- Short-term loans, at the time the loan is incurred.
- Interest on investments.
- Terminal net market value of the perennial crops calculated at the end of the planning horizon over an infinite future period (future investment, and production costs are subtracted from expected crop sales).

Costs

- Direct allocateable production costs for both annual and perennial crops.
- Investment costs in land establishment for perennial crops.
- Overhead costs (all costs not directly allocateable) with the exception of water costs per region per year.
- Water costs, including water tariff and pumping costs where applicable.
- Paid interest on short-term loan of the previous year plus payback of capital amount per region per year, at the time the loan is paid back.
- Household expenses per year.

Capital Costs of the Berg River Dam

The model can be run, either by setting the capacity of the Berg River Dam exogenously, or by determining the capacity of the reservoir (BERGCAP) endogenously, based on a comparison of the time stream of discounted marginal benefits of the reservoir with the marginal cost. In order to make that comparison, the objective function must contain a cost function for the Berg River Dam as a function of the reservoir capacity. The parameters of this cost function were estimated using data from the original design study. The best fitting 'well-behaved' cost function[13] was linear:
Berg Capital Cost = 3.36425*BERGCAP.

4.2.2 Intertemporal spatial equilibrium module (Matrix)

This module is actually a matrix of linear equations and constraints in the mathematical programming model that characterises the water balances in the basin reservoirs – both storage and regional farm dams – and the spatially distributed physical linkages between runoff, water storage, and points of water use. This matrix was depicted schematically in Figures 4.2A and B.
There are eleven blocks of equations in the matrix:

- Runoff allocation equations (2520 Equations).
- Dynamic storage balances for the three major storage reservoirs (1016 Equations).

---

13 The marginal cost for this function must be positive and non-decreasing, over the feasible range of the storage capacity variable. The linear function was the best fitting function, explaining 98% of the variance between BERGCAP and the capital cost.

- Capacity constraints on these reservoirs (720 Equations).
- Static balances for the Berg Supplemental site and two urban demand sites (720 Equations).
- Capacity constraints on man-made conveyance structures and reservoir releases (1800 Equations).
- A static link between the two urban demand sites and urban consumption (360 Equations).
- Static lower basin flow balances for the regional farms (2520 Equations).
- On farm consumptive use balances (5040 Equations).
- Capacity constraints on instream flows (2520 Equations).
- Dynamic storage balances for the on-farm reservoirs (2534 Equations).
- Capacity constraints on the on-farm reservoirs (2520 Equations).

Runoff Allocation Equations

These equations allocate the monthly runoff at each runoff gauge, in WATBAL, plus outside sources of supply to Cape Town to specific reservoirs, the Berg Supplemental site and Cape Town urban demand. In two cases (G1H019 and G1H038), 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:

$$\sum_{A1(ros.sites)} RUNOFF_{ros,sites,m,ph} = RO_{ros,m,ph} \qquad \text{for all ros, m, ph} \qquad \text{EQ 4.1}$$

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 WATBAL; and A1(ros.sites) is a convention (used throughout this paper) to express a subset of ros and sites that links runoff from specific gages in the set ros to the major storage reservoirs, the Berg Supplemental site and Cape Town Urban demand in the set sites.

Dynamic Storage Balances

These equations conserve the mass balance of water, over time, at each of the three major reservoirs 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 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 ***EQ 4.2.1***

$$STORS1_{dams,January,firstyear} = STORSTARTS1_{dams} \qquad \text{for all dams,}$$

where $STORS1_{dams,January,firstyear}$ 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; however, the initial storage can also be set exogenously as a parameter to examine reservoir filling strategies, if that is necessary.

Intermediate Balances ***EQ 4.2.2***

$$\begin{aligned} STORS1_{dams,m+1,ph} &= STORS1*(1-EVAPC1_{dams,m,ph})*EVSLOPE1_{dams} \\ &- EVAPC1_{dams,m,ph}*EVINT1_{dams} + \sum_{A1(ros.dams)} RUNOFF_{ros,dams,m,ph} \\ &- \sum_{A2(dams.sites)} TRANSFERS_{dams,sites,m,ph} + \sum_{A3(sites.dams)} (1-DLOSS_{sites,dams})*TRANSFERS_{sites,dams,m,ph} \end{aligned}$$

for all dams, for month m+1 and all ph,
where $EVAPC1_{dams,m,ph}$ is the monthly annual evaporation coefficient from WATBAL for each storage reservoir; $EVSLOPE_{dams}$ and $EVINT_{dams}$ 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 upper basin, when

controlled over the subset A2(dams,sites) and possible transfers to each reservoir from other dams and sites in the upper basin, when controlled over the subset A3(sites, dams); and $DLOSS_{sites,dams}$ is a parameter that represents the fractional system losses in transfers from other sites and dams, as controlled over the subset A3(sites, dams).

End of Year Transitional Balances **EQ 4.2.3**

$$STORS1_{dams,january,ph+1} = STORS1 * (1 - EVAPC1_{dams,december,ph}) * EVSLOPE1_{dams} - EVAPC1_{dams,december,ph} * EVINT1_{dams} + \sum_{A1(ros.dams)} RUNOFF_{ros,dams,december,ph} - \sum_{A2(dams.sites)} TRANSFERS_{dams,sites,december,ph} + \sum_{A3(sites.dams)} (1 - DLOSS_{sites,dams}) * TRANSFERS_{sites,dams,december,ph}$$

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

Terminal Balances **EQ 4.2.4**

$$STORSTARTS1_{dams} = STORS1 * (1 - EVAPC1_{dams,december,lastyear}) * EVSLOPE1_{dams} - EVAPC1_{dams,december,lastyear} * EVINT1_{dams} + \sum_{A1(ros.dams)} RUNOFF_{ros,dams,december,lastyear} - \sum_{A2(dams.sites)} TRANSFERS_{dams,sites,december,lastyear} + \sum_{A3(sites.dams)} (1 - DLOSS_{sites,dams}) * TRANSFERS_{sites,dams,december,lastyear}$$

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

Upper Basin Capacity Constraints

If the Berg River Dam storage capacity is fixed, each reservoir in the upper basin has the following storage capacity constraints:

$$STORS1_{dams,m,ph} \leq DCAPS1_{dams}$$ for all dams, m and ph EQ 4.3.1

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

$$STORS1_{A6,m,ph} \leq DCAPS1_{A6}$$ EQ 4.3.2

for the subset A6(TWAT and WMRS), for all m and ph

$$STORS1_{Berg,m,ph} \leq BEGCAP$$ for all m and ph, EQ 4.3.3

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

Static Balances for the Non-Reservoir Sites in the Upper Basin

BRDSEM contains three sites BERGS, URB1 and URB2 that have no real storage capacity. However, these sites receive water from runoff and the reservoirs in the region and, in the case of BERGS it actually has the possibility of transferring a limited amount of runoff in the winter months back to the Berg Dam for storage and summer releases. Therefore it was necessary to include the following static mass balance at each of these sites.

EQ 4.4

$$\sum_{A1(ros.sites)} RUNOFF_{ros,sites,m,ph} + \sum_{A2(dams.sites)} (1 - DLOSS_{dams,sites}) * TRANSFERS_{dams,sites,m,ph} = \sum_{A3(sites.dams)} TRANSFERS_{sites,dams,m,ph} + \sum_{A4(sites)} TOBERG_{sites,m,ph} + \sum_{A5(sites)} URBSUP_{sites,m,ph}$$

for each of the non-storage sites (BERGS, URB1 and URB2) and all m and ph, where $TOBERG_{sites,m,ph}$ is a variable that represents the flow released past the Berg Supplemental site to the lower basin in month m and year ph and $URBSUP_{sites,m,ph}$ is a variable that represents the flow of water released to the two urban demand sites in each month and year.

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. These are based on information supplied by Ninham Shand[14]. The structure of these constraints varies widely and we do not include the specific functions in our discussion, here.

Urban Linkage Equation

There are substantial losses in the delivery of water from urban waterworks to urban users and there are also additional sources of water (desalinisation and recycling) that are included as alternative supply options. Therefore 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 urban module to the water supply in the dynamic spatial equilibrium model, a linkage that occurs through this equation. The urban linkage equations are:

EQ 4.5

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

for all m and ph,
where LF is a fractional urban water loss parameter; $NPSOURCE_{p,m,ph}$ is a variable that represents the monthly supply of water available from alternative source p (water recycling and desalinisation) in year ph; and $URBDEM_{g,m,ph}$ is the demand for water by urban water sector g in month m and year ph.

Lower Basin Flow Balances

These equations balance the flow of water released from the upper basin as it moves through the lower basin, accounting for farm diversions and return flow and augmentation through runoff from tributary sources. There are three sets of equations in this block: 1) an initial balance for the first regional farm (BERG1), 2) intermediate balances for the rest of the farms, and 3) an end-of system balance.

Initial Balances

$$\sum_{A4(sites)} TOBERG_{sites,m,ph} * (1-CLOSS) + ROS2_{Berg1,m,ph} = F_{Breg1,m,ph} + DTOFLD_{Berg1,m,ph} + DTOSTOR_{Berg1,m,ph}$$

EQ 4.6.1

for all m and ph,
where CLOSS is a parameter that captures water manager's best guess about the amount of water lost due to seepage, phreophytes and conveyance loss in the lower Berg basin; $ROS2_{Berg1,m,ph}$ is the runoff into the lower basin from a tributary above Berg1, calculated in WATBAL; $F_{Berg1,m,ph}$ is a variable that represents the instream flow at Berg1 after the diversion is taken out in each month and year; $DTOFLD_{Berg1,m,ph}$ is a variable that represents the diversion by Berg1 to irrigate crops in each month

[14] Information as a result of conversations between Mike Shand, Molly Hellmuth and Daan Louw.

and year and $DTOSTOR_{Berg1,m,ph}$ is the amount of water in each month and year at Berg1 that is pumped into the farm reservoir for later use.

Intermediate Balances

$$RFC_b * (DTOFLD_{b,m,ph} + STOFLD_{b,m,ph}) + F_{b,m,ph} = DTOFLD_{b+1,m,ph} + DTOSTOR_{b+1,m,ph} + F_{b+1,m,ph} \quad \textbf{EQ 4.6.2}$$

for all farms (b), m and ph after Berg1,
where RFC_b is the fractional amount of water returned to the system as return flow by farm b and $STOFLD_{b,m,ph}$ is the flow of water that diverted from storage to irrigate crops in each month and year.

End of System Balance

$$RFC_{RK} * (DTOFLD_{RK,m,ph} + STOFLD_{RK,m,ph}) + F_{RK,m,ph} = END_{m,ph} \quad \text{EQ 4.6.3}$$

for the last farm, RK, and all m and ph,
where $END_{m,ph}$ is a variable that characterises the monthly-annual flow at the end of study area.

Consumptive Use Balances

Because we have included the possibility for return flows in the model, there is a need to ensure that consumptive use plus return flows equals the total amount of water applied to irrigated crops. In addition, the farm models need a consumptive use supply variable to balance the crop water demands on irrigated area 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:

$$CUSE_{b,m,ph} = (1 - RFC_b) * (DTOFLD_{b,m,ph} + STOFLD_{b,m,ph}) \quad \text{EQ 4.7}$$

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

Instream Flow Constraints

As a matter of public policy, the instream flows in the lower portion of the Berg River must be maintained above critical levels to protect aquatic ecosystems. These constraints are included in the model as:

$$F_{b,m,ph} \geq ECRSL_m \quad \text{for all b, m and ph} \quad \text{EQ 4.8}$$

where $ECRSL_m$ is the monthly instream flow requirement for month m, which was set at 4.0 $10^6 m^3$ for this study in the summer months.

Dynamic Storage Balances for on-Farm Reservoirs

BRDSEM maintains the water balance in the seven lower-basin regional farm reservoirs in the same way, generally, as in the upper basin.

Initial Balances

$$FSTOR_{b,January,firstyear} = STORSTARTF_b \quad \text{for all b,} \quad \text{EQ 4.9.1}$$

where $FSTOR_{b,January,firstyear}$ is a variable representing the storage in farm dam b in January in the first year of the planning horizon and $STORSTARTF_b$ is a variable denoting the initial and terminal storage in each of the farm dams.

Intermediate Balances

$$FSTOR_{b,m+1,ph} = FSTOR * (1 - EVAPC2_{b,m,ph}) * EVSLOPE2_b - EVAPC2_{b,m,ph} * EVINT2_b + DTOSTOR_{b,m,ph} - STOFLD_{b,m,ph} \quad \textbf{EQ 4.9.2}$$

for all b, m+1 and ph,
where $EVAPC2_{b,m,ph}$ are the farm reservoir evaporation coefficients from WATBAL and $EVSLOP2_{b,m,ph}$ and $EVINT2_{b,m,ph}$, respectively, are the slopes and intercepts of the volume-area equations for each farm dam.

End of Year Transitional Balances

EQ 4.9.3

$$FSTOR_{b,Januray,ph+1} = FSTOR * (1 - EVAPC2_{b,December,ph}) * EVSLOPE2_{b}$$
$$- EVAPC2_{b,December,ph} * EVINT2_{b} + DTOSTOR_{b,December,ph} - STOFLD_{b,December,ph}$$

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

Terminal Balances

$$STORSTARTSF_{b} = FSTOR * (1 - EVAPC2_{b,December,lastyear}) * EVSLOPE2_{b}$$
$$- EVAPC2_{b,December,lastyear} * EVINT2_{b} + DTOSTOR_{b,December,lastyear} - STOFLD_{b,December,lastyear}$$

EQ 4.9.4

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

Capacity Constraints for the 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:

$$FSTOR_{b,m,ph} \leq DCAPS2_{b}$$ for all b, m and ph EQ 4.10.

4.2.3 The urban demand module

Urban demand for water functions does not exist for Cape Town or the municipalities in the region, nor are there any estimates for the price elasticity of demand for water in Cape Town or the region. Estimating new demand functions for BRDSEM was not possible due to limited project resources. This is an important limitation of the current model.

The urban demand module in the original version of the model (Louw 2001, 2002) was significantly modified and simplified for this project. The original module was based on a non-linear model of urban demand and supply that was calibrated to observed consumption data using PMP (Howitt, 1995). We chose to simplify the model for four basic reasons. First, the non-linear demand functions were local, Cobb-Douglas approximations that contained no choke price and the approximation of consumer surplus using this approach grossly understated true consumer surplus. This meant that price elasticity of demand was always constant, even when prices increased. Second, the lack of a choke price (demand intercept) made it difficult to systematically shift the demand curves out over time to simulate demand growth in a manner that was consistent with aggregating the demands over representative agents in each demand sector at given prices (i.e., horizontal aggregation of demands). Third, the use of PMP made the model inflexible for simulating demand growth that was significantly greater than observed consumption. This is because the shadow prices that were introduced into the demand formulation penalised consumption that was greater than in the observed consumption data to which the demand and supply equations were calibrated. Finally, lacking any information on waterworks costs, the water works supply curve was based on an assumed and undocumented supply elasticity and both the slope and intercept of this function were fit using this information by means of PMP. Thus, the water works supply function played an important role in establishing urban water prices that was out of proportion to the data available to estimate its parameters.

Thus, we decided to create an urban demand module that was more transparent and had the following properties:

- Linear demands with an intercept that acted as a choke price for demand, which would also allow the price elasticity of demand to increase at higher urban water prices.
- A mechanism for shifting out the demand functions over time that was consistent with horizontal aggregation of representative demand curves.
- Allowed prices to be determined on the basis of scarcity (through interaction with lower basin agricultural water demands) and the cost of water to the urban waterworks.
- Was flexible enough to allow the introduction of an urban waterworks supply function at a later date, when and if further information became available on water works costs.

The demand functions developed for BRDSEM are based on two pieces of information developed by Louw (2001, 2002) estimates of the price elasticities of water demand for six consumer classes (lower income households, higher income households, lawn watering, industrial, commercial, and public sector) and 2) estimates of base consumption and price data for the period 1972-2003.
The demand function parameters were fit using the following equations:

$$DCONST_{g,m} = BASEPRICE_{g,m} \frac{(ELAST_g - 1)}{ELAST_g} \qquad \text{for all g and m} \quad \text{EQ 4.11.1}$$

$$DSLOPE_{g,m,ph} = \frac{BASEPRICE_{g,m}}{BVFAC * (1 + POPGRO)^{ph} * BASEVOL_{g,m} * ELAST_g} \qquad \text{EQ 4.11.2}$$

for all g, m 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; ELASTg 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 EQ 4.11.2 is used to shift the urban demand functions to the right to simulate exogenous population growth over time. This will be discussed in greater detail below.

The slope and intercept parameters, above, are consistent with the inverse urban water demand functions:

$$DCONST_{g,m,ph} + DSLOPE_{g,m,ph} * URBDEM_{g,m,ph} = DPRICE_{g,m,ph} \qquad \text{EQ 4.12.1}$$

for all g, m, and ph, and the willingness-to-pay functions in the objective function:
EQ 4.12.2

$$WTP_{g,m,ph} = DCONST_{g,m,ph} * URDEML_{g,m,ph} + .5 * DSLOPE_{g,m,ph} * URBDEM^2_{g,m,ph}$$

for all g, m, and ph.
where $DPRICE_{g,m,ph}$ is the urban water price for demand sector g in month m and year ph and $WTP_{g,m,ph}$ is the corresponding willingness-to-pay for water.

The expression in the denominator of EQ 4.11.2, $BVFAC * (1 + POPGRO)^{ph}$, deserves special attention, because it serves the function of simulating exogenous demand growth over time. BVFAC is a scalar that can be used to shift out the urban demand functions to the left by a fixed amount in proportion to the base demand levels, while the second term $(1 + POPGRO)^{ph}$ is used to shift the demand functions at a constant annual rate of growth (i.e., POPGRO) for each year in the planning horizon. Thus, for any given population growth scenario, one can adjust BVFAC to reflect the base demand in the initial year and then increase demand by the rate POPGRO for each additional year.
Figure 4.4 shows how this works. In the figure there are two urban demand curves, Dem_0 and Dem_1. The demand curve Dem_1 has been shifted to the right using, for example, BVFAC. (Both expressions have

the same partial effect on the demand slope). Using the shift formulation we have developed, $W_1 = W_0$*BVFAC (or $W_1=W_0$* $(1+POPGROW)^{ph}$ for the demand price P. This applies for any given demand price, from the choke price, P_{Max}, to the point where P=0. This formulation has two desirable features. First, it provides for consistent aggregation across representative agents in each demand sector. That is to say, if one agent consumes W_0 at price P, then two of them will consume $W_1=2*W_0$ at the same price. Second this approach correctly aggregates willingness-to-pay, such that $WTP_1=2*WTP_2$ at any given water price.[15]

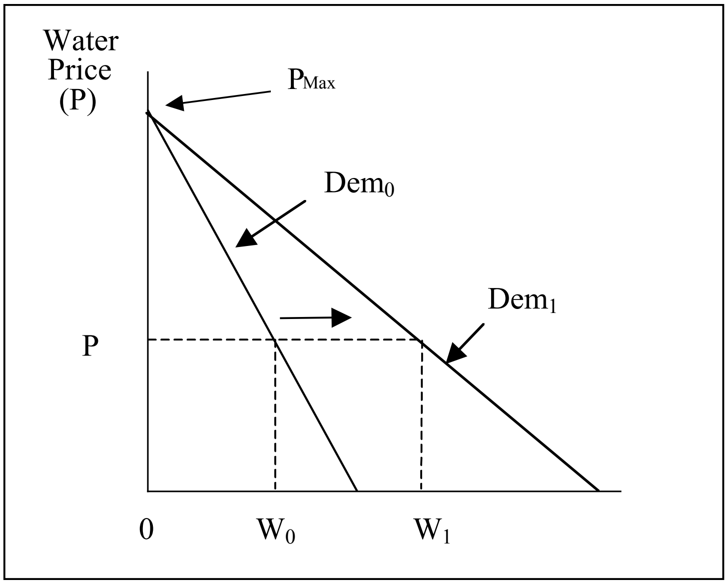


Figure 4.4: Illustrated Demand Shifts due to Population Growth in BRDSEM

This approach does not, however, capture technological change that may make the demand curves more elastic for any given level of water consumption, due to greater technical efficiency in the use of water. How increases in water use efficiency in urban sectors affect urban demand functions is a complicated topic that we were unable to address.

As previously stated, we did not include an urban waterworks supply function due to lack of data to estimate these parameters. We did, however, experiment with this using the following formulation to fit the constants and slopes of monthly waterworks supply functions:

---

[15] Both kinds of consistency are NOT achieved if one uses the following formulation: BVFAC*(DCONST*W+. 5*DSLOPE*W^2) as this approach increases both the slope and the intercept, making the intercept higher and the slope steeper.

$$SCONST_m = Max(BASEPRICE_{g,m})\frac{(SELAST-1)}{SELAST} \quad \text{for all m} \qquad \text{EQ 4.13.1}$$

$$SSLOPE_m = \frac{Max(BASEPRICE_{g,m})}{\sum_g BASEVOL_{g,m} * SELAST} \quad \text{for all m} \qquad \text{EQ 4.13.2}$$

where $SCONST_m$ and $SSLOPE_m$ are, respectively the fitted monthly intercepts and slopes of a monthly waterworks supply function and SELAST was an assumed price elasticity of monthly water supply. This gives the monthly inverse waterworks supply and cost functions as:

EQ 4.14.1

$$SCONST_m + SSLOPE_m * (\sum_{sites} URBSUP_{sites,m,ph}) = SPRICE_{m,ph} \quad \text{for all m and ph}$$

EQ 4.14.2

$$COST_{m,ph} = SCONST_m * \sum_{sites} URBSUP_{sites,m,ph} + .5 * SSLOPE_m (\sum_{sites} URBSUP_{sites,m,ph})^2$$

for all m and ph. Including this formulation had the very desirable effect of forcing urban demand and supply prices to increase as demands were shifted out. However, the choice of a supply elasticity was both arbitrary and highly influential on the balance between urban and agricultural water use. The elasticity assumptions have a direct effect on the excess demand functions for water. Increasing the supply elasticities (above 1) reduces both the intercepts and the slopes of the excess demand functions, making them steeper. This, in turn, has a strong determining effect on the re-allocation of water between agriculture and urban demands. When the water supply is reduced as in the climate scenarios, increasing (or reducing) the monthly urban supply elasticities has the effect of increasing (or reducing) urban water losses relative to agriculture[16].

While our experiments yielded useful information about the effects of marginal urban waterworks costs on urban demand in Cape Town, we decided to drop the waterworks supply function from the model for the time being, until better data became available to fit empirical supply functions.

4.2.4 The regional farm module

The regional farm module was based on the linear programming regional farm formulation in Louw (2001, and 2002). The farm models are fully documented in these two sources. For that reason we include what is basically a non-mathematical overview of the structure of these models and the modifications made to them for BRDSEM.

There are basically seven dynamic farm linear programming models in the agricultural sector of BRDSEM, one for each of the following regions (see Hellmuth and Sparks (2005) for a hydrologic overview of the spatial relationships between these regions):

16 The governing first-order condition for water allocation is to set the excess demand prices (demand price – supply price) equal in both sectors.

- Berg 1
  Suid-Agter Paarl (SAP)
- Berg 2
  Noord-Agter Paarl (NAP)
- Berg 3
  Perdeberg (PB)
  Riebeek-Kasteel (RK)

Each farm model is dynamic in the sense that it takes into account not only the product market for crops, but also the asset market for investment in the establishment, management and harvesting and re-establishment of perennial crops, principally – but not limited to – deciduous fruits, such as table and wine grapes and apples. In point of fact, the 'rotation' length of perennial crops from establishment to re-establishment is fixed in the model, greatly reducing model size. However, the amount of dry and irrigable land given over to perennial crops can change in the model, once the trees and wines reach their maximum age (but not before). The dynamic nature of the farm models require 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.

The fact that the farm models are dynamic added a complicating factor to BRDSEM. In the case of a static farm model, demand functions for water can be derived by parametric programming methods (Vaux and Howitt, 1984, Kelso et al 1973). In the case of a dynamic farm model, water use in a single period is linked to past water use and expected future use over the planning period. This makes the use of parametric programming computationally burdensome due to the need to make the farm water demands in any given period conditional on past and future use. For this reason, it was necessary to include entire farm models for each region within the structure of BRDSEM. These farm models are reduced and simplified versions of those developed by Louw (2001, 2002).

For the sake of clarity it is useful to provide a very brief mathematical overview of the models used in BRDSEM. In its simplest form a regional farm type model can be formally described as a linear optimisation problem under linear constraints:

$$
\begin{aligned}
&\textit{Maximize } Z = \sum_{r,p} Supply_{r,p}\ Price_{r,p} - \sum_{r,f,t} C_{r,f,t}(Levl) \\
&\textit{Subject to}: \quad (a)\, Supply_{,\cdot p} = \sum_{f,t} Levl_{r,p,f,t}\ Yield_{r,p,f,t} \\
&\qquad (b) \sum_{p} Levl_{r,p,f,t}\ a_{r,p,f,t,res} \leq b_{r,f,t,res} \quad \lambda_{r,f,t,res} \\
&\qquad (c) \sum_{p,t} Levl_{r,p,f,t}\ a_{r,p,f,t,res} \leq b_{r,f,\text{"all"},res} \quad \lambda_{r,f,\text{"all"},res}
\end{aligned}
\qquad \text{EQ 4.15}
$$

where Supply defines the quantity produced of product p in region r, C is a variable cost function in activity levels (acreage), constraints (a) defines quantities produced as a sum of activity levels Levl multiplied with fixed yields Yield per farm type f and technology t (rain or irrigation), (b) define that resource usage cannot exceed resource endowment b r region, farm and technology whereas (c) define binding resources across technologies as cash flow constraints. λ's are the shadow values associated with the resource constraints.

The objective function of the farm models was outlined briefly in a previous section. Here, we provide an overview of the activities in the model and the resource constraints.

Activities

Production Possibilities

Each regional model contains production possibilities for seven dry land, and nine irrigated crops. Crops are further broken down on a short-term (annual) and long-term (perennial) basis. The possible crops in each regional model are (perennial crops are shown in italics):

Dry Land Crops	***Irrigated Crops***	
Red wine grapes	Red wine grapes	Nectarines
Wheat	*White wine grapes*	Vegetables
Oats	Table grapes	Pasture
Canola	*Plums*	
Lucerne	Citrus fruits	
Olives	Olives	
Pasture	Peaches	

Each crop has a crop budget associated with it that specifies crop yield per unit area, input requirements per unit area, input costs per unit, and crop price. Long-term crops (perennial crops) include 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 cultivated. The crop prices and input costs are expressed in terms of constant rand in the year 2000 (R2000).

Irrigation Technologies and Water Use Intensities

There are three irrigation technologies in the model: regular, supplemental, and deficit. Monthly irrigation intensities (consumptive water use) used in the farm models varied by crop, month, irrigation type, and growth stage (for perennial crops, except pasture) and were taken directly from Louw (2001, 2002). A monthly-annual adjustment was made for climate change, using crop factors (Hellmuth and Sparks, 2005) based on the potential evapotranspiration of each crop under higher/lower temperatures for each climate scenario. The rationale for this adjustment is that as temperatures increase, relative to the base case, the monthly crop water requirements for each crop will increase relative to the reference case, to achieve a given yield. Thus crop yields were held constant and the water requirements adjusted according to the calculation of monthly crop factors developed for each climate scenario.

Resource Restrictions (Equations)

Each regional farm model contains eleven blocks of resource allocation equations and four flexibility constraints. Resource equations are normally fixed and can only be changed at a cost. The resource allocation equations in each regional farm model include:

- Monthly land requirement for dry land crops.
- Monthly land requirement for irrigation crops.
- An equation to sum the total area of long term crops per region.
- An equation to sum the total area of short term crops per region.
- An equation to sum the total crop production volume per region.
- An equation to calculate the regional monthly water demand.
- An equation that links the farm models water demand to the water supply generated in the hydrological module of the full model.
- An equation that forces the 'Overhead costs' activity into the solution (must be paid).
- An equation that forces the 'Household costs' activity into the solution (must be paid).
- An equation that allocates short term loans to specific activities and calculates the maximum on short term loans (calculated as 30% of the value of fixed assets).
- An equation that calculates the long-term net farm income per region per annum.

Each farm model also includes flexibility constraints, required to set the upper and lower bounds from observed crop production areas. Theses restrictions are in some way also there to provide for risk since it is impossible to capture individual farmers risk behaviour in such an aggregated model. However, these restrictions – particularly the lower bounds – can also have the effect of preventing re-allocation of water from farm to urban areas as water becomes more scarce. Therefore the lower bounds on both long-term crop area and short-term crop area were reduced in the climate scenario simulations to 10% of the land available for cultivation. Since almost all of the possible land that can be cultivated in the basin is currently under cultivation there was no need to change the upper bounds on crop area.

4.3 A Final Word About the Use and Misuse of BRDSEM

There are two important things to keep in mind about the characteristics of BRDSEM. The first is that it is a planning and policy model, not a forecasting model. It is a model to be used by policy makers and planners to compare alternatives for increasing water supply and reducing water use in the basin on an *ex ante* or *ex ante – ex post* basis, recognising that the long-term future rarely turns out like we think it will. The fact that the model estimates water use, water allocation, and reservoir storage over a planning horizon is for planning purposes, not predictive purposes. When making long term policy and planning decisions on an *ex ante* basis that will carry on into the future and which may be hard (or nearly impossible) to reverse, planners and policy makers need to have an idea about future water supply and demand conditions. One of the advantages of BRDSEM is that much of this planning future is determined endogenously by the model, so that planners and policy makers do not have to make as many assumptions as they would in a bottom-up engineering model. However, that does not change the fact that the estimates of variables in the future by BRDSEM are still *ex ante* estimates, needed to assess policies and plans that are implemented in the present over a longer time horizon. Thus, anyone who treats the future results that come out of BRDSEM as forecasts is misusing the model. The model is intended to be used to assess policy and planning decisions, not to act like a crystal ball.

The second feature, related to the first, is that BRDSEM is a 'normative' model. That is to say: 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. By tightening the policy constraints on the model that govern water allocations to users, one can deviate from the economic optimum to satisfy various policy approaches for re-allocating water. However, the objective function in BRDSEM is still 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.

The fact that BRDSEM contains these normative assumptions about how water users and water behave does not in any way preclude the use of the model to analyse water allocation policies that are not market oriented. If one wants, as a matter of public policy, to introduce an allocation system that is based strictly on distributive or equity principles one can easily do that, and this will effectively change one set of objectives for water managers, but the objective of achieving such policies at minimum cost will not change. What cannot be done in the current BRDSEM is to alter the motivation of water users, for example to make them act altruistically such that, say, urban water users can increase their willingness-to-pay by transferring water to agriculture. Thus any policy reallocation of water from higher to lower valued uses will create a welfare loss compared to a market-oriented policy. However, policy makers are still free to make their own judgements about whether these economic losses can be justified on public policy grounds.

Thus, when analysing alternative policies and plans for increasing water supplies, reducing water use, or achieving public policy objectives, the model always provides an economic yardstick, based on the assumption that water consumers and water managers behave rationally. What the model does not supply, and what public policy must, is whether the economic gains or losses experienced by the agents in the model as a result of comparing two policy scenarios are greater or less than the non-economic gains or losses that the model does not put in economic terms. Thus, BRDSEM is just one piece – but arguably an important piece – of a larger public policy puzzle that public officials must solve given all the information available to them.

5 Scenarios and Methods

We used BRDSEM to conduct two different, but related types of assessments. The first assessment represents a combination of traditional benefit-cost analysis and sensitivity analysis, while the second was an analysis of full and partial adjustment for one of the benefit-cost options. The latter analysis is not comprehensive, but was used to demonstrate the methodology for calculating climate change damages, net adaptation benefits, imposed climate change damages and the costs of caution and precaution.

The remainder of this section describes the two types of analysis that were conducted and discusses the climate, allocation policy and urban water demand growth scenarios that were used in different parts of the analysis.

5.1 Benefit-Cost/Sensitivity Analysis

This part of the analysis focused on exploring the effects of the following four factors on the net returns to water and water allocations between urban and agricultural users:

- Existing water entitlements on agricultural diversions.
- Maintaining adequate levels of urban water consumption.
- Efficient water markets.
- The Berg River Dam.

For this part of the study, we analysed eight different options under three different climate-hydrology scenarios (see Section 5.4) and two different urban water demand growth scenarios (See Section 5.5) for a total of forty-eight different simulations. The eight basic options, as defined for this study, are shown below in Table 5.1.

Option 1A: Upper and lower bounds were imposed on monthly water diversions (not consumptive use) by the regional farms in summer and winter months to reflect existing entitlements (see Section 5.6). Monthly urban water demand, by sector, was also constrained by both upper and lower bounds to reflect our assumptions about 'adequate use' (see Section 5.6). The storage capacity of the Berg River Dam was set to zero. In this option, the lower bounds on both agricultural water diversions and urban water use must be satisfied, first. After that, the two sectors compete for water in efficient water markets, up to the point where the upper bounds in both sectors are satisfied, if possible. The reservoirs are operated on a monthly basis to achieve a least-cost allocation. This is true for all the options.

Option 2A: Upper and lower bounds were imposed on monthly water diversions in the summer and winter months to reflect existing entitlements and the storage capacity of the Berg River Dam was also set to zero. However, monthly urban water demand, by sector, was not constrained at all. This means that water is allocated to agricultural users until the lower bounds on agricultural diversions are satisfied. After that, urban and agricultural water users compete for water in efficient markets, up to the maximum level for allowable diversions by agricultural users. If these upper bounds are reached, then urban users can continue to use water until the marginal benefits equal marginal costs.

Option	*Agricultural Entitlements*	*Adequate Urban Water Use*	*Berg River Dam*	*Description*
1A	Yes	Yes	No	Existing farm entitlements must be met Adequate urban water use ensured No Berg River Dam
2A	Yes	No	No	Existing farm entitlements must be met Adequate urban water use is not assured No Berg River Dam
3A	No	Yes	No	Adequate urban water use ensured Farm entitlements are not binding No Berg River Dam
4A	No	No	No	Efficient markets allocate water to all users No Berg River Dam
1B	Yes	Yes	Yes	Existing farm entitlements must be met Adequate urban water use ensured Berg River Dam is optimal for this option
2B	Yes	No	Yes	Existing farm entitlements must be met Adequate urban water use is not assured Berg River Dam is optimal for this option
3B	No	Yes	Yes	Adequate urban water use ensured Farm entitlements are not binding Berg River Dam is optimal for this option
4B	No	No	Yes	Efficient markets allocate water to all users Berg River Dam is optimal for this option

Table 5.1: Options in the Benefit-Cost/Sensitivity Part of the Analysis

Option 3A: For this option, upper and lower bounds are imposed on monthly urban water demand, by sector, and not on agricultural diversions. This means that water is first allocated to urban users until the lower bounds on urban water demand are satisfied. After that, the two sectors compete for water in efficient markets until the upper bounds on urban water use are reached. If there is still enough water available after that point, then the regional farms can divert as much water as is economically justified. Finally, the storage capacity of the Berg River Dam was set to zero.

Option 4A: For this option, there are no restrictions on agricultural diversions or on urban water use. Water is allocated based strictly on efficient market principles. The storage capacity of the Berg River Dam is zero.

5.2 No Adjustment and Full and Partial Adjustment of the Berg River Dam

Storage Capacity

All of the 'B' Options in the benefit-cost/sensitivity analysis were conducted by allowing full adjustment of the storage capacity of the Berg River Dam. We selected *Options 1B* and *4B* for conducting a comparison of full and partial adjustment to climate change. These two options were selected for two reasons. First, *Option 1B* most nearly reflects the current allocation situation in the basin, while *Option 4B* is a full market option. Thus, differences in the way water users and managers can partially and fully adjust to climate change has policy significance. Second, *Option 1B* is the most highly constrained option, while *Option 4B* is the least constrained. We wanted to explore how water users and water managers partially and fully adjusted to climate change under these two extremes. Our a priori assumption was that a competitive market policy would produce lower climate change damages and lower net adaptation benefits compared to the current allocation rules. The reasoning behind this is that the change to markets would not only avoid more climate change damages than the current allocation system due to the fact that it involved fewer constraints on demand; the 'partial' change to efficient water would also create much greater partial adaptation benefits (i.e., due to moving from the highly constrained policy to efficient markets, holding reservoir capacity at zero for both systems) than adjustments of reservoir capacity from partial to full adjustment under efficient markets.

Table 5.2, below, is patterned after Table 3.2, and applies specifically to the combination of *Option 1B* and *Option 4B*, involving all three types of adjustment to climate change (none, full and partial).

Reservoir Capacity	*Climate Scenarios*		
	REF	*NF*	*DF*
No Berg (Option 1A and 4A)	$Z(C_{ref}, K=0)$	$Z(C_{nf}, K=0)$	$Z(C_{df}, K=0)$
Berg Optimal (Option 1B and 4B) K_{ref}	$\boldsymbol{Z(C_{ref}, K_{ref})}$	$Z(C_{nf}, K_{ref})$	$Z(C_{df}, K_{ref})$
K_{nf}	$Z(C_{ref}, K_{nf})$	$\boldsymbol{Z(C_{nf}, K_{nf})}$	$Z(C_{df}, K_{nf})$
K_{df}	$Z(C_{ref}, K_{df})$	$Z(C_{nf}, K_{df})$	$\boldsymbol{Z(C_{df}, K_{df})}$

Table 5.2: Reservoir Capacity and Objective Function Values for No Adjustment and Full and Partial Adjustment under Three Climate Scenarios, Holding Urban Water Demand Growth and Water Allocation Regime Constant

This part of the analysis was conducted in four steps. First, we started by running BRDSEM with the reservoir capacity of the Berg River Dam fixed at zero for all three-climate-hydrology scenarios, for both urban water demand growth scenarios and for the 'adequate urban water use' scenario. This is shown in the first row of Table 5.1. We did this to establish a 'no adjustment' Base Case. These no adjustment cases are the same as *Options 1A and 4A*. [17]

Second, for *Options 1B* and *4B,* we simulated six full adjustment scenarios for each option (12 in all) – one for each climate-hydrology scenario and urban water demand growth scenario, always imposing the 'adequate urban water use' constraints on urban demands. We did this by making the capacity of the Berg River Dam (BERGCAP) an endogenous decision variable in the model, and allowing it to calculate the optimal reservoir storage consistent with the climate change and urban water demand growth assumptions. This internal calculation is based on comparing the present value of the marginal cost of the Berg River Dam with the present value of the marginal returns to water for the last unit of storage capacity. These full adjustment simulations are denoted by the objective function values in bold, italic print in Table 5.2.

The third step, conducted for *Options 1B* and *4B*, involved simulating the partial adjustment scenarios for each climate change hydrology scenario and each urban water demand scenario, while maintaining the 'adequate urban water use' constraints on urban demands. In these runs, the storage capacity of the Berg River Dam was held constant at its optimal value, as determined in the previous set of full adjustment simulations. Then, BRDSEM was used to simulate how water consumers and reservoir operators would adjust to the three climate-hydrology scenarios, under both urban water demand growth scenarios, if the dam was already built at its *ex ante* storage capacity level and water could be re-allocated using efficient water markets.

Finally, we used the information gathered in steps two and three to estimate the various values for climate change damages, net adaptation benefits, the imposed climate change damages and both the cost of caution and precaution for *Options 1B* and *4B*. How these estimates were constructed was explained previously in Section 3.2 of this paper. In doing this, we had to decompose the effects of climate change, dam construction and urban water demand growth on the estimates of these measures. To do so, we had to run a total of eighteen scenarios. Decomposing these effects is important since demand growth, even when consumption per capita is reduced, can result in returns to water that are greater than the damages caused by climate change.

5.3 Climate – Hydrology Scenarios

For all of the options, we used three deterministic, transient climate scenarios. A detailed explanation of the climate scenarios and how they were used to develop inputs for the economic model is discussed in detail in Hellmuth and Sparks (2005). For this assessment, we used information provided by WATBAL for the following climate-hydrology scenarios:

---

17 This was done in the benefit-cost/sensitivity analysis.

- CSIRO SRES B2 REF Case (REF[18]): 1961 – 1990;
- CSIRO SRES B2 Near Future Case (NF): 2010 – 2039;
- CSIRO SRES B2 Distant Future Case (DF): 2070 – 2099.

Each of these scenarios is time dependant (or transient), as indicated above, applying to specific years. The wide time spans encompassed by these scenarios, i.e., 1961 – 2099 creates some complications for long-term planning studies. There are two main reasons for this. First, they would necessitate incorporating arguably large structural and technological changes into the modelling of the urban and agricultural demand for water in BRDSEM. These types of changes are very hard to predict over a 100-year period with any degree of reliability and we also lacked the resources and computational capacity to bound these possible changes by a sensitivity analysis of a number of the parameters in the model that might be expected to change over that time period. The second reason is that, given current demand growth for water in Cape Town, around 3% per year over the last 25 years) we would have had to model a number of alternative new sources of water supply in a dynamic-spatial framework. The resources and computational capacity available to the project, again, limited this.

As a result, we decided to retain the transient character of the scenarios in that they depict the hydrologic effects of climate change over time; however, we ran the NF and DF scenarios for the same time period, 2010 – 2039. This changes the meaning of the DF scenario and, effectively, turns it into a more adverse climate scenario, with lower runoff and higher evaporation, compared to NF for the same time period. This allows us to demonstrate the method for calculating the various benefit and cost measures without having to adjust for structural and technological changes that occur in different time periods. Adjusting for the effects of urban water demand growth over two different time periods in the REF case and the two climate-hydrology scenarios, NF and DF proved difficult enough.

For each of the three scenarios, the following climate-sensitive information was passed to BRDSEM:

- Monthly runoff for 30 years at upper basin runoff gauges (see Fig. 3.1A).
- Monthly runoff for 30 years at lower basin runoff gauges (see Fig. 3.1B).
- An adjustment for monthly runoff from outside the basin, based on runoff from gauge G1H019.
- Monthly reservoir evaporation coefficients for 30 years for the three major storage reservoirs in the upper basin (see Fig. 3.1A).
- Monthly reservoir evaporation coefficients for 30 years for seven of the on-farm reservoirs in the lower basin (see Fig. 3.1B).
- Monthly consumptive water use adjustment factors for 30 years for each of the seven farm regions (see Fig. 3.1B).
- An annual adjustment for dry land crop yields, based on a linear relationship between runoff and dry land wheat (from simulations of the ACRU model for wheat only).

5.4 Urban Water Demand Growth Scenarios

The agricultural area in the basin has been relatively stable for the last half-decade and is not expected to grow much more due to limited land availability (Louw 2001 and 2002). However, urban

[18] The designation for each scenario, as used in the text, is in parentheses.

water demand in the basin has been growing rapidly, mainly due to the growth of Cape Town, and there is therefore a need to include urban water demand growth in BRDSEM.

For all of the options, we used two different urban water demand growth scenarios to bound the increases in urban water demands that could be expected in the region from 1961 – 2039, the total time period between the start of the reference case (REF) and the end of the two climate-hydrology scenarios (NF and DF). The two demand growth scenarios were: a) no growth after 2010 and b) 300% growth over the two time periods. A discussion of the approach used to shift the urban demand curves for water in the high (i.e., 300%) growth scenario is contained in Figure 5.4. We were provided with urban demand data for the City of Cape Town that allowed us to fix the average five-year water demand for 1961-1964 using the parameter BVFAC (see EQ 3.11.2) and to estimate the average annual rate of growth of urban demand for the period 1961 – 1990. We used that annual average rate to shift the monthly urban base demand in each urban sector by means of the parameter POPGRO, and with it the entire demand curve to the right, on an incremental basis year-by-year (see EQ 3.11.2) from 1961 to 1990. We followed the same procedure for shifting out the demand curves in the two climate-hydrology scenarios, by fixing the starting demand curve for 2010 and then shifting it out incrementally over a thirty-year period, on a year-by-year basis from 2010 – 2029. The rate of change (300% over thirty years) was the same for both periods. Thus, the incremental character of the demand shifts is consistent with the incremental hydrologic changes in each of the three climate change–hydrology scenarios.

5.5 Water Allocation Scenarios

This section describes the way in which agricultural and urban water demands were constrained to reflect, respectively, existing entitlements and 'adequate urban water use'.

5.5.1 Agricultural entitlements

We wanted to estimate the net benefits of different water allocation regimes and to decompose the net benefits of adaptation to climate change due to different water allocation regimes. To do this on the agricultural side, we used information from Louw (2001 and 2002) regarding the summer and winter entitlements to, and allowable winter pumping of water from, the Berg River by the regional farms in the basin. These constraints were imposed for Options 1 and 2. This data is shown in Table 5.3.

FarmRegion	*Summer Entitlements*	*Winter Entitlements*	*Allowable Winter Pumping*
Berg1	9.051	0.000	5.90
SAP	3.870	0.000	1.90
Berg2	3.861	0.000	1.71
NAP	8.196	0.000	1.41
Berg3	22.304	0.000	0.33
PB	8.065	0.000	1.75
RK	8.738	1.771	1.771[1]
[1] Includes Winter Entitlement, since it is also 'allowed'			

Table 5.3: Summer and Winter Entitlements to Divert Water and Allowable Winter Pumping to Farm Dams from the Berg River by Regional Farm (m^3 x 10^6)

We imposed these constraints in BRDSEM through the following equations:

$$\sum_{Summer} TOTDIV_{b,m,ph} \geq ENTITLES_b \quad \text{for all b and ph} \quad \text{EQ. 5.1}$$

$$\sum_{Winter} TOTDIV_{b,m,ph} \geq ENTITLEW_b \quad \text{for all b and ph} \quad \text{EQ. 5.2}$$

$$\sum_{Winter} TOTDIV_{b,m,ph} \leq ALLOWINT_b \quad \text{for all b and ph} \quad \text{EQ. 5.3}$$

where TOTDIV, as previously defined, represents diversions from the Berg River and ENTITLES, ENTITLEW, AND ALLOWINT are, respectively, the lower bounds for summer and winter entitlements and the upper bounds for allowable diversions from the Berg River.

These constraints turned out to be the source of infeasible solutions that occurred under the high urban demand growth and DF climate-hydrology scenarios. Nevertheless, we decided to retain these constraints because this is the type of information that policy makers need in order to design more robust allocation systems.

5.5.2 Adequate urban water use

We also decided to constrain urban water demand by sector in some for *Options* 1 and 3. We did this for two reasons. First, in early trials, we discovered that, under adverse climatic conditions with high urban demands, water use in the two household sectors was forced to very low, unsustainable, values. When we attempted to reserve water for just the household sectors, based on current South African policies, water use in other urban sectors was driven to zero. Therefore, we used estimates of minimum sustainable water use developed by Louw (2001 and 2002) as lower bounds on monthly urban water demand, by sector. Second, because the empirical validity of the urban demand functions in the model is weak, we also placed upper bounds on monthly urban water use, by sector. The upper bounds were equal to the base volumes of water used in the estimation of the parameters of the demand functions. These two sets of constraints form our working definition of 'adequate urban water use'. These lower and upper bounds are shown in Tables 5.4 and 5.5.

Month	*Urban Demand Sector*					
	Ihh	*Ohh*	*Lawn use*	*Commercial*	*Industrial*	*Public Sector*
January	2.47	5.94	2.33	1.48	3.22	0.64
February	2.13	5.11	2.01	1.28	2.77	0.55
March	2.26	5.42	2.13	1.36	2.94	0.58
April	1.75	5.20	1.65	1.05	2.27	0.45
May	1.53	3.67	1.44	0.92	1.99	0.39
June	1.32	3.17	1.24	0.79	1.72	0.34
July	1.24	2.97	1.17	0.74	1.61	0.32
August	1.30	3.13	1.23	0.78	1.70	0.34
September	1.38	3.32	1.30	0.83	1.80	0.36
October	1.88	5.51	1.77	1.13	2.44	0.48
November	2.03	5.88	1.92	1.22	2.64	0.52
December	2.40	5.77	2.27	1.44	3.12	0.62

Table 5.4: Lower Bounds on Monthly Urban Water Demand by Sector $m^3 \times 10^6$

These upper and lower bounds were included in BRDSEM as follows:

$$URBDEM_{g,m,ph} \geq MINVOL_{g,m} \qquad \text{for all g, m, and ph} \qquad \text{EQ. 5.4}$$

$$URBDEM_{g,m,ph} \leq BASEVOL_{g,m} \qquad \text{for all g, m, and ph} \qquad \text{EQ. 5.5}$$

where URBDEM as previously defined is monthly urban demand in each sector, MINVOL is a parameter, reflecting the minimum allowable urban demand, the data for which is contained in Table 5.4 and BASEVOL, as previously defined, is a parameter, the data for which is contained in Table 5.5

Month	*Urban Demand Sector*					
	Ihh	*Ohh*	*Lawn use*	*Commercial*	*Industrial*	*Public Sector*
January	3.53	8.48	7.77	2.12	5.59	2.12
February	3.04	7.3	6.69	1.82	3.95	1.82
March	3.23	7.75	7.1	1.94	5.20	1.94
April	2.50	6.00	5.5	1.50	3.25	1.50
May	2.19	5.25	5.81	1.31	2.84	1.31
June	1.89	5.53	5.15	1.13	2.45	1.13
July	1.77	5.25	3.89	1.06	2.30	1.06
August	1.86	5.47	5.10	1.12	2.42	1.12
September	1.97	5.74	5.34	1.18	2.57	1.18
October	2.69	6.45	5.91	1.61	3.49	1.61
November	2.90	6.97	6.38	1.74	3.77	1.74
December	3.43	8.24	7.55	2.06	5.46	2.06

Table 5.5: Upper Bounds on Monthly Urban Demand by Sector $m^3 \times 10^6$

5.6 Scenario Limitations

There are a number of limitations in the construction of the scenarios. Those that we have already discussed include:

- compression of the DF scenario to fit the NF time period due to problems in modelling structural and technological changes that will affect water demands in the next 100 years;
- fairly simple urban water demand growth scenarios that do not account for technological change, but are based on empirically observed increases in demand over recent years;
- Some data limitations regarding the response of dry land crops to climate change; and
- Simplification of the existing method of allocating water to users in the basin.

However important these limitations are the most important limitation has not yet been touched on. This is, namely: that the climate scenarios are deterministic, representing just one simulation from a family of simulations by the CSIRO GCM. As such, each scenario contains the intra-seasonal and inter-annual variability associated with just one GCM trial and this does not necessarily reflect the intra-seasonal or intra-annual variability associated with the change in climate. That is to say that these climate scenarios may come from a hotter-drier series of years than the average for a specific climate change state or they may come from a colder-wetter series of years. No such information was provided. What we would have liked to have done and what we hope to do in the future is to gather enough information about the joint and partial distributions of temperature and precipitation in the basin and use this information to estimate the parameters of these distributions. With that information in hand, it will be possible to propagate the resulting distributions of hydrologic variables used in BRDSEM through WATBAL using Monte Carlo or other, more efficient sampling methods. That variability can then be further propagated through BRDSEM using the same methods, allowing us to develop distributions of the important output variables from BRDSEM.

This type of information and analysis is vitally important for water planners and policy makers because having it will make the risks associated with planning much more manageable. In point of fact, we are a year or so away from being able to do this in South Africa due to the current state of regional climate modelling. The computational resources required to do this are also quite large, especially in terms of propagating runoff and evaporation distributions through BRDSEM, but they are not beyond reach.

For the time being, the scenarios that have been constructed for this project and paper are extremely useful for demonstrating the use of BRDSEM as a policy and planning tool to provide information that will make adapting to climate change more manageable and less risky. However, the deterministic nature of the analysis needs to be bridged so that water resource planners can begin to treat climate data with a level of certainty (or uncertainty) approaching that which exists in their observed climate records.

6 Results

This section contains the results of the scenario analysis as described in Section 4.0. The discussion is divided into two parts. Section 6.1 covers the benefit-cost analysis and also includes a general discussion of the scenario results, while Section 6.2 covers the assessment of climate-related benefits and costs. Section 6.3 presents the results for the costs of caution and precaution and Section 6.4 looks more carefully at the so-called 'partial' adaptation benefits of the efficient water markets. Finally, Section 6.5 touches on the limitations of conducting deterministic assessments such as this one.

6.1 Results for the Benefit-Cost Analysis and General Discussion of Results

The results of the benefit-cost analysis are contained in Table 6.1. This table is divided into four parts. The first part shows the reduction in average annual runoff for the three different climate-hydrology scenarios, which is the same under both urban water demand scenarios. Average annual runoff in the NF scenario is roughly 11% lower than the REF scenario, while average annual runoff for the DF scenario is 22% lower than in the REF scenario.

The second part of Table 6.1 presents the estimates for the net returns to water for the eight different options across the three climate-hydrology scenarios and the two urban water demand scenarios. These estimates are just the value of the objective function of BRDSEM for each of the scenarios. The net returns to water are estimated as net present values, in which the annual returns to water are discounted at 6% over thirty years, relative to the first year of each scenario. We do not display the results for alternative discount rates since the results are fairly transparent, with higher (or lower) discount rates resulting in lower (or higher) values for the net returns to water and smaller (or larger) investments in the storage capacity of the Berg River Dam.

Our a priori expectations were that, according to the Le Chatelier principle, the value of the net returns to water would decrease as more constraints to water use were added. Thus, following our discussion in Section 4.0, we assumed: net returns (Option 4) > net returns (Option 2) and net returns (Option 3) > net returns (Option 1). This set of a priori expectations was borne out in all of the scenarios. For both the A and B Options, the unconstrained (i.e., efficient water markets) values in Option 4 for the estimated net returns to water were always higher than the values for the fixed farm allocation (Option 2) and adequate urban water (Option 3) Options, and the estimated net returns to water for Options 2 and 3 were always higher than for Option 1, which was the most highly constrained.

We had no a priori expectations regarding the relationship between Option 2 (fixed farm allocations and Option 3 (adequate urban water), but the results are interesting. In all of the cases, the net returns to water in Option 2 (fixed farm allocations) dominate those in Option 3 (adequate urban water supply), and these differences are largest for the high urban water demand scenarios, both without and with a Berg River Dam with optimal storage capacity. This is interesting because it implies that the value of water at the margin is generally higher in irrigated agricultural use than in the various urban demand sectors, when one or the other is constrained. This is consistent with the results obtained by Louw (2002).

	Climate Scenarios No Urban Demand Growth			*Climate Scenarios High Urban Demand Growth*		
	REF	*NF*	*DF*	*REF*	*NF*	*DF*
Ave. Annual Runoff (m^3 x 10^6)	75.501	67.443	58.892	75.501	67.443	58.892
Options	Net Returns to Water[1] Under Full Adjustment ($R10^6$)					
1A. Fixed farm allocations Adequate urban water No Berg Dam	58 724	55 752	52 820	74 920	58 006	44 897[2]
2A. Fixed farm allocations No Berg Dam	59 797	56 220	52 895	90 881	82 621	75 035
3A. Adequate urban water No Berg Dam	58 754	55 797	52 041	79 594	63 935	48 410
4A. Market allocation No Berg Dam	59 847	56 343	53 135	91 959	83 936	76 516
1B. Fixed farm allocations Adequate urban water Berg Dam	58 724	55 790	53 564	90 116	76 892	62 673
2B. Fixed farm allocations Berg Dam	59 807	56 772	54 371	96 250	89 624	83 192
3B. Adequate urban water Berg Dam	58 754	55 818	53 636	90 181	76 996	63 826
4B. Market allocation Berg Dam	59 850	56 802	54 427	96 315	89 705	83 479
Options	Optimal Berg River Dam Capacity m^3 x 10^6					
1B	0	15	69	151	272	240
2B	12	88	116	141	132	188
3B	0	10	70	140	222	206
4B	6	84	109	138	128	178
Benefit-Cost Comparison	Difference in Net Returns to Water[1] Under Full Adjustment $R10^6$)					
Substitute markets for **1A** (**4A** compared to **1A**)	1 123	591	314	17 039	25 930	31 619
Add dam only to **1A** (**1B** compared to **1A**)	0	38	744	15 196	18 887	17 777
Add markets to dam (**4B** compared to **1B**)	1 126	1 012	863	6 199	12 813	20 805
Add dam + markets to **1A** (**4B** compared to **1A**)	1 126	1 050	1 607	21 395	31 700	38 582

All monetary estimates are expressed in present values for constant Rand (R) for the year 2000, discounting over 30 years at a real discount rate of 6%.

This case was infeasible. Lower bounds on urban water use were re-set at 95% of the minimum values (lower bounds) to make the case feasible.

Table 6.1: Benefit-Cost Results for Four Planning Options, Under Three Alternative Climate Scenarios and Two Urban Water Demand Growth Scenarios

In fact, as we will see later, the marginal value of urban water, when constrained in Options 1 and 3 under the low urban demand scenarios was artificially high compared to agricultural demands, since urban water prices fell and urban water consumption rose when these constraints were removed. In the high urban water demand cases, urban water prices were artificially low when urban water consumption was constrained and these prices rose and urban water consumption fell when the constraints on urban water demands were removed. Thus, the picture is a little more complicated than Louw discovered, but the conclusion is a bit darker for the future with regard to the urban sectors, since as we shall see climate change plus high urban water demands lead to much more drastic curtailments in urban than agricultural water use under Options 2 and 4.

On the other hand, as we acknowledged in Section 3.0, the formulation of the urban demand functions in BRDSEM is based on relatively weak empirical evidence compared to the formulation of the on-farm water demands. Thus, this result may be partially an artefact of the urban water demand functions in the model and calls further attention to the need to conduct additional research to better estimate urban demand and waterworks supply functions for Cape Town. This point cannot be made too strongly.

We also assumed that the net returns to water for the B scenarios, which allowed for the endogenous determination of the storage capacity of the Berg River Dam, would always dominate the net returns to water in the A scenarios, as long as the dam was built. If this were not true then there would be no economic rationale for building the dam. As expected, this turned out to be true in every case. Except for Options 1B compared to 1A and 3B compared to 3A, in which the optimal capacity of the Berg River Dam was zero (and therefore the net returns to water did not change under the B Options, the net returns to water were higher when the dam was constructed based on economic efficiency considerations.

The third part of Table 6.1 shows the optimal storage capacity for the four B Options. We had two a priori assumptions regarding the effects of climate change and higher urban demand on the storage capacity of the Berg River Dam. Our first assumption was that, as runoff decreased, the optimal storage capacity of the Berg River Dam would increase in each of the B Options. This assumption was found to be true for all four options under the low urban water demand scenario. However, this assumption did not hold true for any of the B scenarios, where capacity varied widely as runoff was reduced.

There are several possible reasons for this. The first is computational, owing to the structure of the model. Within BRDSEM, there are many different 'routes' that water can take in the basin from some of the runoff point to some of the demand points at the same or virtually identical costs. As a result, in simulating the various options, we found multiple local optima for some of the cases, as well as many points where the solver 'stalled' due to this problem[19]. It turned out that the endogenous storage capacity of the Berg River Dam was very sensitive to small changes in the objective function. While we believe that most of the optima we eventually found are global (or at least very close to global), the resulting uneven pattern in storage capacities shown in Table 6.1 could be due in part to this feature of the model.

[19] We solved this problem by adding small additional transfer costs on some 'routes' that were unlikely and by repeatedly re-starting the model at different starting points. This was time consuming, as many of the solutions took three hours, even when starting from an existing feasible basis at a local optimum.

Second, our assumption regarding the relationship between average annual runoff and the optimal storage capacity of the Berg River Dam was not a strong one, since changes in optimal storage capacity can depend as much on the relative changes in monthly runoff by month and the variance of monthly runoff as on changes in average annual runoff. We did not investigate this issue fully, but we did find that the coefficient of variation for runoff in the winter months was higher in the NF scenario than in the REF and DF scenarios and this could partly explain why the optimal storage capacity of the Berg River Dam is higher in some of the NF scenarios than under the DF scenarios.

Third, the location of runoff points in the basin and the relative changes in runoff at these different points on a monthly basis can have an important effect on changes in optimal storage capacity. In the case of the Berg River Basin, only the regional farms have access to the runoff in the lower basin, while both the farms in the lower part of the basin and urban demands can be satisfied by runoff in the upper basin. (We should note in this context, that as the climate scenarios became more severe, there were substantial increases in the use of the Berg River Supplementary site to pump water back into the Berg River Dam). Since the storage capacity of the Berg River Dam tended to be higher for the NF scenarios than for the DF scenarios (under high urban water demands) for only those options involving upper and lower bounds on urban water consumption, it is possible that the additional water needed in the upper basin to satisfy the lower bound on urban water consumption, also explains part of this pattern.

Fourth, we found that filling the Berg River Dam becomes a problem under the DF scenario relative to the NF scenario, and this problem is most severe under the high urban water demand scenarios when runoff that could be used to fill the Dam must be diverted to satisfy urban water needs. This further helps to explain why the relationship between the severity of climate change and optimal storage capacity did not follow our a priori expectations, especially for those options where adequate urban water is required in Options 1B and 3B.

Finally, the ultimate determinate of the optimal capacity of the Berg River Dam in BRDSEM for each option and scenario is economic: the net returns to water of the last cubic meter of storage are equal to the marginal cost of the last unit storage. Thus, both runoff and demand considerations are factored into the equation through the marginal net returns to water. Ultimately, the main conclusion we can draw from this analysis is that the optimal capacity of the Berg River Dam is highly sensitive to economic considerations embodied in allocation regimes and the relative timing and relative location of reductions in monthly runoff.

Our second a priori assumption regarding optimal storage capacity size was that the simulated storage capacity of the Berg River Dam would be extremely sensitive to the allocation regime that was assumed for each option. This turned out to be true, and can be seen by looking down each column in the third part of the table. More specifically, we assumed that efficient water markets in Option 4B would reduce the need for storage capacity relative to the other allocation systems. This proved not be true under the low urban water demand scenarios for Options 1B and 3B (where optimal storage capacity was lower than for Options 2B and 4B), but was true for all the remaining Options and scenario combinations. The reason for the anomaly in Options 1B and 3B under low urban water demands is that the simulated urban water consumption was considerably lower for these options than for Options 2B and 4B (see Table 6.2). This means that when urban demand was close to, or at, its upper bound in these cases, either there was no need or the price of urban water was not high enough to justify the building of the dam. However, in the high urban water demand scenarios urban consumption was large enough at its lower bound in Options 1B and 3B to require large increases in the storage capacity of the Berg River Dam, relative to Options 2B and 4B. When the constraints on urban demand are eliminated entirely in Options 2B and 4B, simulated urban water prices were free to increase, urban water consumption falls, and the optimal storage capacity of the Berg River Dam was reduced. Thus, our general conclusion is that efficient water markets for water are generally a substitute for storage capacity in the Berg River Basin, especially at high urban demand prices.

In the last four rows of Table 6.1, we show some benefit-cost comparisons that underscore the value of instituting a system of efficient water markets in the Basin. If we compare the net returns to water for the efficient market case, without a dam (4A), with the most highly constrained allocation policy (1A), we found net benefits ranging from R1.1 billion to R31.6 billion, depending on the assumed climate-hydrology and urban water demand scenarios. This means that simply instituting a system of efficient water markets in the basin will, by itself, create substantial net benefits compared to the existing allocation regime and others that we simulated.

Now what would happen if an optimally sized Berg River Dam was built and the allocation regime was not changed from Option 1A? The answer is shown in the comparison between Options 1B and 1A. In all but one case (DF + low urban water demand), the net benefits associated with just building the dam (1B) compared to the no dam Option (1A), were lower than the net benefits of instituting a system of efficient water markets and not building the dam (4A compared to 1A).

In the next row, we simulate substituting a system of efficient water markets for the existing allocation regime and estimate the net benefits with the substitution of the water markets including the dam for each of the three climate scenarios. This is shown in the comparison between Options 4B and 1B. The net benefits range from R1.1 billion to R20.8 billion, depending on the assumed climate-hydrology and urban water demand scenario. These results mean that even when the Berg River Dam is built at its optimal storage capacity, the net benefits of replacing the existing allocation system with a system of efficient water markets are substantial under each climate-hydrology scenario.

In the final row of the table, we compare the net returns to water for Option 4B relative to1B. Doing so provides an estimate of both adding an optimally sized reservoir and substituting a system of efficient water markets for the existing allocation regime. The net benefits in each column of this comparison are equivalent to the sum of the columns for the two previous rows (i.e., net returns [(1B) – (1A)] + net returns [(4B) – (1B)] = net returns [(4B) – (1A)]). The net benefits of building the dam and substituting a system of efficient water markets range from R1.1 – R38.6 billion, suggesting that this is the best of the options from a benefit-cost perspective.

These results underscore the importance of water markets in adapting to climate change. However, the benefit-cost comparisons presented here do not in any way represent the adaptation benefits of substituting water markets for other allocation systems. This is because these benefit-cost comparisons were made for each climate-hydrology scenario. To fully understand the benefits of substituting a system of efficient markets for the other allocation schemes, one must also vary the climate. We will focus on this issue in Section 6.4.

Table 6.2 contains estimates of the average annual consumption by the urban and agricultural demand sectors for the various Options and scenarios.

	Climate Scenarios No Urban Demand Growth			*Climate Scenarios High Urban Demand Growth*		
	REF	*NF*	*DF*	*REF*	*NF*	*DF*
Option 1A – Fixed Farm Allocations and Adequate Urban Supply (No Dam)						
Urban Consumption	310.0	309.6	291.6	522.5	522.5	496.4
Agricultural Consumption	66.2	67.5	69.0	64.9	66.1	65.9
Option 2A – Fixed Farm Allocations (No Dam)						
Urban Consumption	379.2	339.5	298.8	425.6	365.3	309.0
Agricultural Consumption	66.2	67.5	69.0	65.3	66.6	67.6
Option 3A – Adequate Urban Supply (No Dam)						
Urban Consumption	310.0	309.9	297.3	522.5	522.5	522.5
Agricultural Consumption	66.2	66.8	68.8	42.5	35.7	23.9
Option 4A – Efficient Water Markets (No Dam)						
Urban Consumption	382.4	345.9	307.1	445.1	388.3	330.8
Agricultural Consumption	66.2	66.8	68.8	57.2	56.5	57.5
Option 1B – Fixed Farm Allocations and Adequate Urban Supply (Dam)						
Urban Consumption	310.0	310.0	308.0	522.5	522.5	522.5
Agricultural Consumption	66.2	67.5	69.6	66.2	66.8	67.9
Option 2B – Fixed Farm Allocations (Dam)						
Urban Consumption	386.1	384.9	358.7	491.7	447.3	396.3
Agricultural Consumption	66.2	67.5	69.6	66.0	66.9	68.6
Option 3B – Adequate Urban Supply (Dam)						
Urban Consumption	310.0	310.0	309.5	522.5	522.5	522.5
Agricultural Consumption	66.2	67.5	69.5	66.1	66.7	65.6
Option 4B – Efficient Water Markets (Dam)						
Urban Consumption	386.2	385.0	360.3	495.8	447.9	398.9
Agricultural Consumption	66.2	67.5	69.6	66.2	66.9	69.3
[1] Urban consumption includes 19% system losses.						

Table 6.2: Simulated Average Annual Water Consumption by Urban[1] and Agricultural Users and Average Annual Storage in the Upper and Lower Basins

The estimates of urban consumption include a nineteen% loss factor, which means that actual consumption, excluding losses, is nineteen% lower than shown in the table. Agricultural consumption, as shown in this table, measures the direct consumptive use of water and is not to be confused with water diversions, which can be pumped directly to fields or to farm storage for later field applications[20].

The most obvious differences in this table are those between the low and high urban water demand scenarios. The high urban water demand scenarios all have higher water consumption (including losses) than the low water demand scenarios. What may seem surprising, at first, is that none of the values for estimated urban water consumption under the high urban water demand scenarios are three times higher than the corresponding values for the low water demand scenarios. There were two reasons for this. The first is that while the demand curves were shifted out by a factor of three times base level consumption, the urban sector water prices could still rise (or fall) along the new demand curves, just as they could for the low urban water demand scenarios. The second reason is that, when adequate urban water supplies were ensured in Options 1 (A and B) and 3 (A and B) under the low urban water demand scenarios, annual average urban water consumption was always at, or close to, its upper bound (310 10^6 m^3), while in the high urban water demand scenarios average annual urban water consumption was at, or close to, its lower bound (522.5 10^6 m^3). Thus, when these bounds were relaxed in Options 2 an 4, urban water prices fell and urban water consumption increased along the demand curves, under the low urban water demand scenarios. But, under the high urban water demand scenarios, urban water prices increased and urban water consumption fell along the demand curves.

This last factor helps to explain another potential anomaly in Table 6.2, that simulated urban water consumption for Options 2 (A and B) and 4 (A and B) was higher than simulated urban water consumption under Options 1 (A and B) and 3 (A and B) for all of the low urban water demand scenarios. However, under the high urban water demand scenarios, this pattern was completely reversed. The explanation for this reversal in pattern is fairly straightforward. In the low urban water demand cases, urban water consumption was at, or close to, its upper bound. Removing the constraints on urban water consumption simply allowed urban consumption to increase because it was price-competitive with agricultural demands for water, even when urban water prices fell. Under the high urban water demand scenarios, on the other hand, urban water consumption was always at, or close to, its lower bound. Thus, eliminating the upper and lower bounds on urban water demand had the effect of increasing urban water prices, which drove urban water consumption down below the previous lower bounds.

On the whole, agricultural water consumption was more robust than urban water consumption both to changes in climate and changes in the allocation system. In Option 3A, with high urban demands, meeting the lower bound on urban water consumption caused sharp cutbacks in agricultural water consumption. This occurred, to a lesser extent, under Option 4A. However, the cutbacks in both urban and agricultural consumption in this Option must also be judged on the basis of their economic efficiency. Despite the fact that water consumption in this option fell for both sectors, relative to the highest values in other options, the net returns to water in Option 4A was higher than in any of the other non-

---

[20] System efficiency losses in delivering water to the regional farms were deducted from the upper basin supply after BERGSUP, not at the points of use or diversion.

dam (A) Options. When the Berg River Dam storage capacity was added to the Options (B), agricultural water consumption varied very little compared to urban water consumption under all of the B Options with both low and high urban water demands.

The general conclusions that one can draw from Table 6.2 are, nevertheless, quite clear. If urban population continues to grow at current rates and one does not build a Berg River Dam with sufficient capacity, it will be very hard to maintain current per capita urban water consumption under any allocation system with currently available supplies and water use efficiencies. This will be true even if the climate does not change, and things will get relatively worse if it does. The implementation of allocation systems that favour urban over agricultural consumers will lead to relatively sharp declines in agricultural water use and irrigated agricultural production. Furthermore, even if the Berg River Dam is built, as is the case now, additional supplies or increases in water use efficiency will still be needed to bring per capita water consumption close to current levels, under all of the allocation systems we simulated. Finally, if increased growth in urban water demands, combined with climate change, does tend to favour the agricultural sector, as our results show, policy measures that artificially increase water consumption would probably have dire consequences for irrigated agriculture in the region.[21]

6.2 Results for the Analysis of Climate-Related Benefits and Costs Under Full and Partial Adjustment

This part of the assessment combines the results of the full and partial adjustment scenarios for Options 1B and 4B. Tables 6.3 and 6.4 present the basic results for the full and partial adjustment simulations conducted for Options 1B and 4B. The rows in each table represent the climate-hydrology scenario used to plan the storage capacity of the Berg River Dam. The columns indicate the climate-hydrology scenario under which full or partial adjustment occurs. The diagonal elements (in bold) in each table represent the optimal (full-adjustment) values for the net returns to water in the three climate scenarios. They are the same as the row entries in Table 6.1 for Options 1 and 4. Each off-diagonal element represents the partial adjustment value for the net returns to water under the column climate scenario, holding storage capacity fixed at the level indicated in the row climate scenario.

We can give an example to better explain the construction of the two tables. In Table 6.2, the optimal net returns to water under full adjustment are R58.724 billion for Option 1B under the low urban water demand scenario. The optimal storage capacity for this Option and climate and demand scenario is 0.0 million cubic meters. If we simulate the climate as in NF and hold the storage capacity of the Berg Dam at zero, the net returns to water under partial adjustment fall to R55.752 billion. Simulating the climate as DF, and holding storage capacity of the Berg River Dam at zero, results in net returns to water of R52.82 billion, and so on. The net returns to partial adjustment, in theory, can never be higher in any given column than the full adjustment value in that column.

---

21 We did not simulate any policies that forced current per capita urban water under high urban water demands to be at current levels, but the conclusion still seems inescapable.

Climate scenario used in planning and storage capacity (10^6 m^3)	*Climate Scenarios*		
	REF	*NF*	*DF*
	No Urban Water Demand Growth		
REF – 0	58 724	55 752	52 820
NF - 15	58 674	55 790	53 146
DF – 69	58 493	55 694	53 564
	High Urban Water Demand Growth		
REF – 151	90 116	76 683	62 475
NF - 272	89 912	76 892	62 615
DF – 240	89 974	76 860	62 673

Table 6.3: Net Returns to Water Under Optimal and Partial Adjustment for Option 1B (R10^6)

Climate scenario used in planning and storage capacity (10^6 m^3)	*Climate Scenarios*		
	REF	*NF*	*DF*
	No Urban Water Demand Growth		
REF – 6	59 850	56 417	53 284
NF – 84	59 724	56 802	54 376
DF – 109	59 675	56 772	54 427
	High Urban Water Demand Growth		
REF – 138	96 315	89 704	83 444
NF - 128	96 307	89 705	83 421
DF – 178	96 255	89 688	83 479

Table 6.4: Net Returns to Water Under Optimal and Partial Adjustment for Option 4B (R10^6)

This is just common sense, since the full adjustment value for the net returns under any given climate scenario will always be the highest. Changing the reservoir storage capacity for that climate will produce a constrained result with a lower value for the net returns to water. Thus, if one looks at the DF column for Option 1B with low urban water demands, the highest value is for full adjustment (R53.564 billion) and the remaining two column values above it (for the storage capacity levels of 69 and 15 million cubic meters, respectively) are smaller than this – R53.146 billion and R52.820 billion.

The simulated results in Tables 6.3 and 6.4 are all we need to calculate climate change damages, the net benefits of adaptation, the imposed damages of climate change and the costs of caution and precaution for scenarios 1B and 4B. Note: these values are conditional on the two water allocation systems for which they are estimated. None of these values captures the ‘partial’ benefits of substituting Option 4 (efficient water markets) for Option 1 (adequate water supply for both sectors).

We estimated climate change damages, the net benefits of adaptation and the imposed climate change damages for three different adverse climate changes from full adjustment.[22] They are:

- REF-NF: A change from the initial climate-hydrology scenario, REF, to the more adverse terminal climate-hydrology scenario, NF scenario.
- REF-DF: A change from the initial climate-hydrology scenario, REF, to the more adverse terminal climate-hydrology scenario, DF scenario.
- NF-DF: A change from the initial climate-hydrology scenario, NF, to the more adverse terminal climate-hydrology scenario, DF scenario.

Estimates of climate change damages, the net benefits of adaptation and imposed climate change damages are presented, together, in Table 6.5 for Option 1B and Table 6.6 for Option 4B.

6.2.1 Climate change damages

Climate change damages were previously defined in this paper as the *ex ante* economic losses that are projected to occur if the climate changes when economic agents only partially adjust to the climate change. In the context of the Berg River Basin, this means that water users and managers are free to adjust water consumption and reservoir operation, but not the storage capacity of the Berg River Dam.

For any of the three above climate changes, climate change damages can be estimated as the negative row difference between the net returns to water for the initial full adjustment climate-hydrology scenario (REF or NF) on the diagonal of Tables 6.3 and 6.4 and for the partial adjustment case under the terminal climate-hydrology scenario (NF or DF) in that same row.

[22] We estimated only the climate change damages, net benefits of adaptation and imposed damages of climate change for departures from full adjustment that involved more adverse climate change. There are similar measures for the beneficial climate changes: DF-NF, DF-REF and NF-REF.

Benefit and Cost Measures	*Climate Changes*		
	REF-NF	*REF-DF*	*NF- DF*
	No Urban Water Demand Growth		
Climate Change Damages (% Decrease relative to initial climate)	-2 972 (-5.01)	-5 904 (-10.05)	-2 644 (-4.74)
Net Benefits of Adaptation (% of Climate Change Damages)	38 (1.28)	744 (12.61)	418 (15.82)
Imposed Climate Change Damages	-2 934	-5 159	2 226
	High Urban Water Demand Growth		
Climate Change Damages (% Decrease relative to initial climate)	-13 433 (-14.91)	-27 640 (-30.67)	-14 277 (-18.57)
Net Benefits of Adaptation (% of Climate Change Damages)	209 (1.56)	198 (0.01)	58 (0.004)
Imposed Climate Change Damages	-13 223	-27 442	-14 219

Table 6.5: Estimates for Climate Change Damages, Net Benefits of Climate Change and Imposed Climate Change Damages for Option 1B ($R10^6$)

Benefit and Cost Measures	*Climate Changes*		
	REF-NF	*REF-DF*	*NF- DF*
	No Urban Water Demand Growth		
Climate Change Damages (% Decrease relative to initial climate)	-3 433 (-5.74)	-6 566 (-10.97)	-2 426 (-4.27)
Net Benefits of Adaptation (% of Climate Change Damages)	386 (11.23)	1 143 (17.41)	51 (0.02)
Imposed Climate Change Damages	-3 048	-5 423	-2 375
	High Urban Water Demand Growth		
Climate Change Damages (% Decrease relative to initial climate)	-6 611 (-6.86)	-12 871 (-13.36)	-6 284 (-7.01)
Net Benefits of Adaptation (% of Climate Change Damages)	1 (0.0002)	34 (0.003)	57 (0.009)
Imposed Climate Change Damages	-6 610	-12 837	-6 227

Table 6.6: Estimates for Climate Change Damages, Net Benefits of Climate Change and Imposed Climate Change Damages for Option 4B ($R10^6$)

Thus, to estimate the climate change damages associated with the REF-NF climate change for the low urban water demand scenario in Option 1B, one takes the negative difference in Table 6.3: R55 752 (partial adjustment for NF in the REF row) minus R58 724 (full adjustment for REF in the REF row) = –R2 972 million, and so on. This means that, for Option 1B with low urban water demands, R2.972

billion-worth of economic damages will be experienced if there is no adjustment to the storage capacity of the Berg River Dam when the climate changes from REF to NF.

6.2.2 Net benefits of adaptation

The net benefits of adaptation were previously defined in this paper as the *ex ante* economic value of the climate change damages that can be avoided by planning for climate change. In the context of the Berg River Basin, this means that water users and managers are free to adjust water consumption and reservoir operation, as well as the storage capacity of the Berg River Dam.

For any of the three above climate changes, the net benefits of adaptation that are achieved by optimally adjusting the capital stock can be estimated from Tables 6.3 and 6.4 as the positive column difference between the net returns to water in the full adjustment case for the terminal climate (NF or DF) on the diagonal and the partial adjustment cases in that same column (NF or DF). Thus, to estimate the net benefits of adaptation associated with optimally adjusting the storage capacity of the Berg River Dam from REF to NF for the low urban water demand scenario in Option 1B, one takes the negative difference: R55 790 (full adjustment for NF in the NF row) minus R55 752 (full adjustment for REF in the REF row) = R38 million, and so on. This means that, for Option 1B with low urban water demands, building the Berg River Dam with the optimal storage capacity for the NF climate-hydrology scenario avoids R38 million-worth of the roughly R3 billion-worth of climate change damages in this climate change (REF-NF).

6.2.3 Imposed climate change damages

The imposed damages of climate change were previously defined in this paper as the *ex ante* economic value of the climate change damages that cannot be avoided both by changes in water consumption and reservoir operation and by planning for climate change. In the context of the Berg River Basin, this means that, even after water users and managers adjust water consumption, reservoir operation and storage capacity of the Berg River Dam, there are still some climate change damages that cannot be avoided. These are the imposed damages of climate change.

For any of the three above climate changes, the imposed damages of climate change can be estimated from Tables 6.3 and 6.4 as the negative difference between the net returns to water in the full adjustment case for the terminal climate (NF or DF) on the diagonal and the full adjustment case for the initial climate (REF or NF), also on the diagonal. Thus, to estimate the imposed damages of climate change (after optimally adjusting the storage capacity of the Berg River Dam from REF to NF) in the low urban water demand scenario for Option 1B, one takes the positive difference:
R55 790 (full adjustment for NF in the NF row) minus R58,724 (partial adjustment for NF in the REF row) = R– 2 934 million, and so on. This means that, for Option 1B with low urban water demands, there are still R2.934 billion-worth damages even after building the Berg River Dam with the optimal storage capacity for the NF climate-hydrology scenario.

6.2.4 Discussion of results

Perhaps the most striking results from this analysis (Tables 6.5 and 6.6) are the relative magnitudes of climate change damages when compared to the full adjustment net returns to water under the initial climate. These economic losses range from about 5-11% in the low urban water demand scenarios for both options and from around six to as high as 30% for the high urban water demand scenarios, with the largest relative economic losses taking place for Option 1B under the high urban water demand scenario. If these climate-hydrology scenarios are indicative of future climate change in the basin, then the inescapable conclusion is that the economic losses due to climate change, without increasing dam size, will be severe, even when at high urban demand levels, per capita water consumption in the urban sector will be reduced from current levels.

There are two additional sets of conclusions to be drawn from this analysis. First, if we look at the differences within each option, it can be seen that climate change damages and the imposed climate change damages are larger in the high urban water demand scenarios than the low demand scenarios. At the same time, the net benefits of adaptation are all relatively (and in all but one case, absolutely) lower in the high urban water demand scenarios than the low demand scenarios. This stands to reason, since water is effectively both more valuable and scarcer under the high urban water demand scenarios and there is less room for adjusting reservoir operation in the partial adjustment cases. As a result, under partial adjustment, water prices rise substantially, especially in the urban sector, and water consumption decreases. Thus, changing the capacity of the reservoirs to get back into full adjustment through adaptation has a relatively small effect on the net returns to water. This situation is reversed in the low urban water demand scenarios, where water price adjustments still take place, but changing the storage capacity also plays an important role in adapting to climate change.

Looking at the differences between the two options shows two things. First of all, the results for the low urban water demand scenarios do not show any marked differences in climate change damages, the net benefits of adaptation and the imposed damages of climate change. This was a little surprising, at first, but what it means is that at low urban demand levels, the type of water allocation system used in the basin does not really affect economic performance, at least in aggregate terms. However, under the high urban water demand scenario, there are some sharp differences in the results. The most notable of these is the reduction in the total and relative values of climate change damages for the system of efficient water markets (Option 4B) compared to the much more highly constrained allocation system (Option 1B). In these high urban demand cases, climate change damages are 50-60% lower for the system of efficient water markets than the corresponding climate change damages for Option 1B. And this is true, even despite the fact that the net returns to water under full adjustment (from which the reductions in the net returns to water under partial adjustment are measured) are always higher for Option 4B than 1B.

But, interestingly enough, the net adaptation benefits for the efficient water market Option (4B) are smaller in both absolute and relative terms than for Option 1B in the high urban water demand scenario. The fact that climate change damages and net adaptation benefits are lower for the system of efficient water markets than for the more highly constrained allocation system, at least under high urban water demands, was expected. It means that this type of allocation system is more robust to climate change and that being out of full adjustment does not impose as high an economic penalty on water users as does a more highly constrained allocations system. The full logic of this conclusion will be expanded upon in Section 6.4, where we estimate the net adaptation benefits of changing *both* the water allocation regime and the climate.

Our main conclusion for this part of the analysis is that, if climate changes and urban water demands continue to grow at current rates, climate change damages will be relatively large and the adaptation benefits associated with changing storage capacity to get back into full adjustment will be relatively small, leaving still-relatively large residual damages. However, this analysis did not estimate the 'partial' adaptation benefits of switching allocation systems from Option 1 to Option 4 and then adjusting storage capacity relative to the reference case in Option 1A. This will be covered in Section 6.4.

6.3 Results for the Costs of Caution and Precaution

As discussed in Section 3.0, planning for climate change involves two kinds of climate-related risks. These risks are associated with making *ex ante* planning decisions, based on expectations about climate change, that turn out to be 'wrong' on an *ex post* basis. First there is the risk of planning for no climate change or a less severe change in climate than actually occurs (or already exists, but cannot be detected). Second, there is the risk of planning for a more severe change in climate than actually occurs, or exists.

The first type of error is associated with caution; the second with precaution. In both cases, being wrong means that the storage capacity of the reservoir planned and built under *ex ante* climate expectations is not optimal for the *ex post* climate. As a result, in both cases, the net returns to water will be lower than if planners had correctly anticipated the true change or no change in climate.

Now, the problem is: water resource planners do not have a crystal ball when it comes to predicting how the climate will change. Moreover, the currently available information water resource planners do have about climate change that is relevant to their planning decisions either does not exist or is subject to large uncertainties.

In spite of these problems, planners can still estimate the value of the economic losses that will be incurred if they act too cautiously or precautiously based on the information they do have. In some – but not all circumstances – this type of analysis may provide sufficiently clear information for them to act either cautiously or precautiously in their planning.

Tables 6.7 and 6.8 contain 'regrets' matrices for Options 1B and 4B. We use the term 'regrets' because it is frequently applied in the water resources planning literature to characterise the risks of making *ex ante – ex post* 'mistakes', such as we are characterising here. The rows in these tables indicate the *ex ante* climate expectations used in planning the storage capacity of the Berg River Dam, while the rows indicate the *ex post* climate that actually occurs. (Of course, planners do not know with certainty which climate will occur; these are just the possibilities under review).

The results in each cell of these two tables were estimated using the information in Tables 6.3 and 6.4 as follows. For each ex post climate scenario (in the columns of Tables 6.3 and 6.4), there is one full adjustment estimate for the net returns to water and two remaining entries for the net returns to water. The cell entries in Tables 6.7 and 6.8 are the negative column differences between the full adjustment values for the net returns to water and the partial adjustment values in that column. Thus, the diagonal cell entries are all zero. The cell entries in the upper diagonal elements of these two tables represent our estimates of the cost of caution. They will look familiar because they are the same as the net benefits of adaptation, with the sign reversed. This stands to reason: the costs of caution can be avoided by adaptation. For example in Table 6.3 under Option 1B with low urban water demands, the estimate of – R744 million (cell REF, DF) is the reduction in the net returns to water if planners believe that climate change is characterised by the REF climate-hydrology scenario (and do not build the Berg River Dam), but the climate change that actually occurs is characterised by the DF scenario.

The lower diagonal elements in each table represent the costs of precaution. If, for example, water resource planners in the basin decided to act precautiously and plan for the DF climate (by building a reservoir with a storage capacity of 69 million cubic meters) under Option 1B, assuming low water demands, but the climate did not change from the REF scenario, then the resulting cost of precaution would be – R231 million. Thus, by comparing the costs of caution for REF-DF and the costs of precaution for DF-RED, we can conclude that acting cautiously will cost basin water users and water providers as a whole about 3.2 times more than acting precautiously, and this is an indication that planning for the DF climate change may not be a bad idea, since it will be less costly. But, keep in mind that this conclusion only applies for this combination of climate scenarios.

Assumed ex ante climate scenario and storage capacity (10^6 m^3)	*Ex Post Climate Scenario*		
	REF	*NF*	*DF*
	No Urban Water Demand Growth		
REF – 0	0	-38	-744
NF – 15	-50	0	-418
DF – 69	-231	-96	0
	High Urban Water Demand Growth		
REF – 151	0	-209	-198
NF – 272	-204	0	-58
DF – 240	-141	-32	0

Table 6.7: Regrets Matrix for Option 1B: Changes in Net Returns to Water ($R10^6$)

The arrows in the top part of Table 6.6 indicate the relevant pair-wise comparisons of climate changes for the two options and urban demand assumptions.[23] By comparing these cases, planners can gain a clearer picture of the costs of planning mistakes to further inform their policy and capacity planning decisions. In general, for any given ex-ante, ex-post combination of scenarios (for example REF-DF and DF-REF) a high negative value for the cost of caution and a low negative value for the cost of precaution gives an indication that planning for a given climate change, and being wrong, is much less costly than not planning for it and being wrong. As such, this provides additional support for acting precautiously and sizing the reservoir optimally for the DF climate. Conversely, a high negative value for the cost of precaution and a low negative value for the cost of caution gives an indication that planning for a given climate change, and being wrong, will cost much more than not planning for it, and being wrong. Thus, this provides a partial indication that acting cautiously and not changing the capacity of the reservoir from its optimal REF value may be the best strategy.

23 If we assume that the REF climate is the true current climate then only the comparisons associated with the top two arrows make sense: (REF-NF and NF-REF) and (REF-DF and DF-REF).

Assumed ex ante climate scenario and storage capacity (10^6 m^3)	*Ex Post Climate Scenario*		
	REF	NF	DF
	No Urban Water Demand Growth		
REF – 6	0	-386	-1 143
NF – 84	-126	0	-51
DF – 109	-175	-30	0
	High Urban Water Demand Growth		
REF – 138	0	-1	-34
NF - 128	-8	0	-57
DF – 178	-60	-18	0

Table 6.8: Regrets Matrix for Option 4B: Changes in Net Returns to Water ($R10^6$)

Table 6.9 attempts to summaries the results from Tables 6.7 and 6.8 to show which pair-wise comparisons indicate that it is less risky to plan for climate change, and be wrong, than not plan for it, and also be wrong. Admittedly, the results in this table are simply too ambiguous to draw any firm conclusions about which option and which planning choice within each option is the dominant one from the standpoint of avoiding regrets.

Climate Change Pairs	*Indicated Action*
Option 4B, low urban demand	
REF-NF, NF-REF	No clear dominance
REF-DF, DF-REF	Plan for DF
Option 1B, high urban demand	
REF-NF, NF-REF	No clear dominance
REF-DF, DF-REF	No clear dominance
Option 4 B, low urban demand	
REF-NF, NF-REF	Plan for NF
REF-DF, DF-REF	Plan for DF
Option 4B, high urban demand	
REF-NF, NF-REF	No clear dominance
REF-DF, DF-REF	No clear dominance

Table 6.9: Comparisons of Costs of Caution and Precaution to Indicate Possible Actions

On the other hand, one fairly powerful and consistent conclusion that emerges from this part of the analysis as a whole is that the regrets associated with Option 4B, under the high urban water demand scenario, are substantially lower than those in 1B. That is to say, a system of efficient water markets reduces the costs of being cautious, and being wrong, as well as the costs of acting precautiously, and being wrong. Combined with the earlier results from the partial adjustment analysis in Section 6.2, this strengthens the case for using a system of efficient water markets as an important line of defence against climate change.

6.4 Measuring the Net Adaptation Benefits of No Regrets Policies: The Case for Efficient Water Markets

Planning for climate change by changes in reservoir storage is subject to climate risk, as we have shown above. However, adopting a system of efficient water markets is not subject to climate risk, since, as we showed in Section 6.1 the net returns to water were always higher under Options 4A and 4B compared to the other A and B Options. That is to say, efficient water markets will improve welfare in the basin whether or not the climate changes, and whether or not planners correctly anticipate the 'right' climate change. In Section 6.3, we estimated the net adaptation benefits for each of the B Options associated with adjusting the reservoir storage capacity of the Berg River Dam for various climate changes. The question is: how can we estimate the net adaptation benefits of substituting water markets for the other allocation systems?

To answer this question, we must take the analysis in Section 6.3 one step further, by looking at *both* changes in climate and changes in the water allocation regime. Callaway (2003) illustrated one way to estimate the benefits of water markets by decomposing changes in the net returns to water into the partial net benefits associated with adding optimal reservoir storage and efficient water markets. To do this, we need to compare the net returns to water for the following general cases:

- REF climate + No dam + No water markets (for Options 1A, 2A and 3A in the REF climate).
- Climate Change (NF or DF) +No Dam + No water markets (for Options1A, 2A and 3A in the NF or DF climate scenarios).
- Climate change (NF or DF) + Water markets (for Option 1B in the NF or DF climate scenarios).
- Climate change (NF or DF) + Dam + Water markets (Full adjustment for Option 4B to the NF or DF climate).

The negative differences in the net returns to water between Case 1 and Case 2 are the partial climate change damages for Options 1, 2 and 3, without adding a dam. The positive differences in the net returns to water between Case 2 and Case 3 are the partial net benefits of adaptation to the climate scenarios NF and DF by substituting water markets (but not dams) in Option 4A for the allocation systems in Options 1, 2 and 3. The positive differences between Case 3 and Case 4 are the partial net benefits of adaptation to the climate scenarios NF and DF by adding optimal storage capacity in Option 4B to the water markets. The partial imposed damages of climate change are equal to the differences between Case 4 and Case 1. When the net returns to water in Option 4B, under full adjustment, for the NF and DF cases are higher than the net returns to water in the REF scenario for Options 1A, 2A and 3A, the imposed damages of climate change will actually be positive, indicating that the benefits of adding storage capacity and markets are greater then the total climate change damages without storage capacity and efficient water markets. This result occurs simply because the net returns to water for Option 4B in some of the climate change scenarios are greater than the net returns to water under the REF climate for the other options.

All of these measures can be constructed directly from Table 6.1. However, the size of the table required to produce all these partial results is very large. Therefore, we only show the results for Option 1 relative to Option 4, consistent with the rest of the tables in this section.

Table 6.10 shows the results of the partial decomposition of climate change related benefits, starting in the REF Scenario for Option 1 without any reservoir storage in the basin (Option 1A) and ending with adaptations associated with adding optimal storage capacity and efficient water markets for the NF and DF scenarios (Option 4B). This happens to be one of those cases in which the terminal net returns to water, under full adjustment, for Option 4B in some of the NF and DF scenarios are greater than the net returns to water for Option 1A in the REF scenario. Therefore, the total sums of the partial net adaptation benefits of adding both optimal storage capacity and efficient water markets are greater in some cases than the partial climate change damages and hence the partial imposed climate change damages are positive in these cases.

Benefit and Cost Measures	*Climate Changes*	
	REF-NF	*REF-DF*
	No Urban Water Demand Growth	
Partial Climate Change Damages	-2 972	-5 904
Partial Net Benefits of Adaptation Due to substituting water markets	591	315
Partial Net Benefits of Adaptation Due to Adding Storage Capacity	459	129
% Contribution of Water Markets to Total Partial Net Benefits	56.25	19.57
Imposed Climate Change Damages	-1 922	-4 297
High Urban Water Demand Growth		
Partial Climate Change Damages	-16 914	-30 023
Partial Net Benefits of Adaptation Due to substituting water markets	25 930	31 619
Partial Net Benefits of Adaptation Due to Adding Storage Capacity	5 769	6 963
% Contribution of Water Markets	81.80	81.95
Imposed Climate Change Damages	14 785	8 558

Table 6.10: Estimates for Partial Climate Change Damages, Net Benefits of Climate Change for Adding Storage Capacity and Water Markets and the Imposed Climate Change Damages, Comparing Options1 and 4 ($R10^6$)

The results in this table underscore the important contribution of substituting efficient water markets for the more highly constrained allocation system represented in Option 1A and B. In three of the four cases, substituting this type of allocation system contributes at least half of the partial net adaptation benefits. Most noteworthy is the fact that in the high urban water demand scenarios, water market substitution accounts for over eighty% of the total partial net adaptation benefits. Furthermore, in both these climate scenarios with high urban water demands, water market substitution alone is greater than the value of climate change damages. This is not to downplay the importance of adding storage capacity, which account for about eighteen% of the total partial net adaptation benefits in the NF and DF climate scenarios under high urban water demands. However, the point that needs to be stressed is that adding storage capacity is subject to the climate risks shown in Tables 6.7 and 6.8, while water markets will perform equally well under any climate once they are implemented in an effective manner.

6.5 Concluding Remarks: Limitations of Deterministic Benefit-Cost Assessments

It is important to keep in mind that, given the data available, the climate-hydrology scenarios used in this analysis are deterministic. In the future, we hope to be able to conduct a fully stochastic analysis when information is available from CSIRO to estimate the parameters of the distributions of monthly temperature and precipitation for the SRES-2B scenario. At that point, we will be in a position to estimate the distributions of the cell entries in Table 6.1. But, for now, these results are simply point estimates, derived from three climate model runs that do not capture the underlying variability in the SRES-2B Scenario.

A further limitation in these results is that we have no information to estimate the probability of the occurrence of any of the three scenarios, either in relation to the simulations we have used for the SRES-2B scenario or other scenarios. A fully stochastic analysis requires both pieces of information. The reason for this is that we ultimately want to estimate the expected values of both the net returns to water and the optimal storage capacity of the Berg River Dam, not only for the SRES-B2 scenario, but other scenarios as well. By doing this, we can uncomplicate the presentation of the results and, instead of presenting a single deterministic value for each scenario run, provide the reader with expected values of the net returns to water and optimal storage capacity, under different policy options. In the first instance – that is with just the distributions of the SRES-B2 scenario – these expected values would be conditional on the occurrence of that scenario, while in the second instance – using information about the probabilities of occurrence of other scenarios – these would be either conditional on the probabilities selected or else, unconditional, if we believed the available scenario information reflected all possible states of future climate (which is unlikely). In any of these cases, the analysis would be much improved and much more helpful to water resource planners.

7 Main Conclusions and Recommendations for Future Research

7.1 Main Conclusions

The important conclusions from our study are as follows:

From a benefit-cost perspective, construction of the Berg River Dam at capacity levels that were optimal for the climate scenarios used in this analysis looks to be justified on the basis of economic efficiency. Under the low urban water demand assumptions, the optimal storage capacity of the reservoir ranged from zero (Option 1B –REF climate and 3B) to 116 10^6 m^3 (Option 2B – DF climate). Under the high urban water demand scenario, the optimal storage capacity ranged from 138 10^6 m^3 (Option 4B – REF climate), depending on the climate scenario used to 240 10^6 m^3 (Option 1B – REF climate), depending on the climate scenario used. Overall, the efficient market option (1B) required the smallest storage capacity levels for both low and high urban water demand scenarios.

From a benefit-cost perspective, the implementation of an efficient system of water markets, with or without construction of the Berg River Dam, resulted in the highest net returns to water compared to other simulated allocation systems under all climate and urban demand scenarios. Under the low urban water demand scenario, efficient water markets produced only slightly higher net returns to water compared to the other allocation systems – of the order of one billion Rand or less compared to the other allocation schemes. This represents welfare improvements of the order of two%, or less. Under the high urban water demand assumption, the system of efficient water markets outperformed other allocation methods by as much as 31%.

Agricultural water use was very robust to the simulated changes in climate, urban water demand assumptions and the presence or absence of the Berg River Dam than urban water use and water allocation policies. In the forty-eight benefit-cost simulations (4 water allocation options, 2 urban water demand assumptions, 3 climate scenarios, and 2 Berg River Dam options – 0 capacity and optimal capacity), annual average agricultural water consumption remained around 66 – 69 10^6 m^3 in all but six cases and all of these cases were without the Berg River Dam.

Urban water consumption, by contrast, fluctuated much more in response to both climate change and changes in water allocation policy. Part of this fluctuation was due, of course, to the assumed increases in Cape Town population in the high urban water demand scenario. However, it is important to note that, under the low urban water demand assumption, annual average urban water consumption was always at, or above the upper policy bound used to represent adequate urban water supply, while under the high urban water demand assumption, annual average urban water consumption was at or below its lower policy bound. Also, when the upper and lower bounds on urban water demand were relaxed in Options 2B and 4B under the high urban water demand scenario, annual average urban water use dropped sharply, depending on the climate. These decreases ranged from roughly five – twenty-five below the lower bound on urban water used, imposed in the other water allocation scenarios, Options 1B and 3B.

Simulated climate change damages were relatively and absolutely much greater under our representation of the current allocation regime (Option 1B) than under the efficient water market regime (Option 4B) at high urban demand levels. These were the only two options for which climate change damages were calculated and compared. For Option 1B, estimated climate change damages, under the low urban water demand scenario, ranged from roughly three – six billion Rand (a 5-10% reduction in the net returns to water), depending on the severity of the climate change. Under the high urban water demand scenario, these losses increased to roughly thirteen – twenty-seven billion Rand (a 15-31% reduction in the net returns to water), depending on the severity of the climate change. For Option 4B, estimated climate change damages under the low urban water demand scenario were about the same absolute and relative order of magnitudes as for Option 1B. However, under the high urban water demand scenario, these losses were reduced – compared to Option 1B – to roughly seven – thirteen billion Rand (a 7-13% reduction in the net returns to water), about half the value of the climate change damages experienced in Option 1B.

The impact of adaptation by adjusting reservoir capacity from partial to full adjustment was relatively small in both Options 1B and 4B. These were the only two options for which these benefits were calculated. Moreover, the net benefits of adaptation for Options 1B and 4B both declined when urban water demand was increased and the net adaptation benefits for Option 4B were quite small, when urban water demands were at high levels. For Option 1B, the estimated net adaptation benefits, under the low urban water demand scenario, ranged from about 0.04 – 0.7 billion Rand (a 1-15% reduction in climate change damages), depending on the severity of the climate change. Under the high urban water demand scenario, the net adaptation benefits in Option 1B decreased to around 0.05 – 0.2 billion Rand (less than or equal to a 1.5% reduction in climate change damages). For Option 4B, the estimated net adaptation benefits, under the low urban water demand scenario, ranged from about 0.05 – 1.1 billion Rand (less than or equal to a 17% reduction in climate change damages), depending on the severity of the climate change. Under the high urban water demand scenario, the net adaptation benefits in Option 4B decreased much more than in Option 1B to around 0.001 – 0.03 billion Rand (less than or equal to a 0.009% reduction in climate change damages).

The most significant reductions in climate change damages came from instituting a system of efficient water markets in Option 4B for our representation of the current allocation regime (Option 1B). Conclusion 6 indicates the adaptation benefits of the two water allocation policies, once these policies are adopted. It does not take into account the partial adaptation benefits associated with: a) substituting a system of efficient markets for the current allocation system and b) changing the optimal storage capacity of the Berg River Dam, from the current allocation system to a system of efficient markets. Under the low urban water demand scenarios, we found that the substitution of efficient markets in Option 4A under the NF and DF climate scenarios for the current allocation system in Option 1A under the REF climate explained 55% and 20%, respectively, of the change in the net returns to water from Option 1A (REF climate) to Option 4B (NF or DF climates). Under the high urban water demand scenarios, this figure rose to roughly 82% for both the REF to NF and REF to DF climate changes. The remainder of the changes in the net returns to water from Option 1A (REF climate) to Option 4B (NF or DF climates) could be explained by storage capacity adjustments associated with moving from Option 4A to 4B, holding the climate constant at NF or DF.

Overall, the analysis of the costs of caution and precaution did not provide any unambiguous results that would allow one to determine if it would be less costly to anticipate climate change or plan cautiously.

7.2 Recommendations for Future Research

Based on our experience in this study, we have basic recommendations for future research:

- Extend the BRDSEM model to characterize the entire Boland Region in the Western Cape. To do this, the following modifications have to be made to BRDSEM:
- Include the runoff sources for, and the dynamic water balances in, all of the reservoirs in the area including those on Table Mountain, which provide water for Cape Town, those downstream of the regional farms, and those north of the study area in the Boland region.
- Include linear programming representations for the irrigated agricultural production in the lower Berg River Basin below the regional farms and north of the current study region.

Sufficient data currently exist to make these modifications. Acquiring and implementing the CPLEX QIP solver for GAMS can easily overcome the problems we experienced with long solution times in this study. In some trials by Arki Consulting in Denmark, solution time for BRDSEM was reduced by a factor of 1000 by using this solver instead of the current versions MINOS or CONOPT.

Conduct research to gather data and estimate the parameters of sector-level monthly water demand and waterworks supply (cost) functions for the Metropolitan Cape Town Region. We have already noted in Section 3.0 that the estimates of the parameters of the urban water demand functions used in BRDSEM are not strongly supported by adequate data. In addition, we dropped the urban water works supply function that was in Louw's static model, because this could not be supported by empirical cost data and the use of arbitrary elasticity assumptions heavily biased the results. The current study team does not possess the adequate econometric skills to estimate these functions. However, such an undertaking could be supported by the WRC, DWAF, or the CCT in the larger context of alternative urban water pricing policies, nationally, regionally, or just in Cape Town. Such a study is important to assist public and private sector policy makers and planners to address the alternatives for balancing the principles of equity and economic efficiency in urban water pricing in South Africa.

Add additional storage and non-storage capacity options for increasing water supplies and water use efficiency and reducing water losses in the basin. The current version of BRDSEM also needs to be updated by including the possibility for additional storage capacity in the region, based on proposed plans and estimated costs. These options would be implemented in BRDSEM in the same way the Berg River Dam was included in the model. In addition, the water supply and cost data needs to be updated for wastewater recycling and desalinisation of seawater. Finally, we need to include possibilities for reducing water losses and the associated costs of these options in the delivery of water to users by the Cape Town water authority and for the conveyance systems used to deliver irrigation water to the regional farms.

Improve the representation of water market transfers and include the costs of water market transactions. In the current study, simply removing constraints on agricultural water diversions and urban water demand simulates efficient water markets. The structure of BRDSEM is such that by removing these constraints, the solutions for the endogenous variables in the model are consistent with the implementation of efficient markets. However, this does not take into account how the current ownership of water rights and existing allocation of entitlements can be changed by specific transfers, nor does it include the transactions costs associated with these transfers. Modelling specific transfers is made a little difficult in BRDSEM because of the presence of return flows below each regional farm. However, it will still be possible to add many of the institutional features of water market transfers by including transfer balances in the model to represent existing entitlements and water rights and, after modifying them to take into efficient markets, looking at the impacts on downstream water users.

Develop a broader range of policy scenarios to blend efficient water markets with equity objectives in meeting the needs of the urban poor. The efficient market scenarios (Option 4A and B) led to high urban water prices and reduced urban water consumption by all households under the high urban water demand and climate change scenarios (NF and DF). We need to more fully explore the policy options and consequences of modifying water market policies to meet the basic needs of the urban poor.

Work closely with regional climate modelers in South Africa to implement BRDSEM using stochastic climate scenario data to generate downscaled distributions of monthly average temperature and precipitation data and transform this into stochastic runoff. As indicated in several places in the text, this study is deterministic, with climate change risk introduced in an ex ante – ex post framework. The climate scenarios used in this analysis are based on the downscaled results of just three runs for the CSIRO SRES B2 REF, NF and DF scenarios. We do not know where these time series results lie in the over-all joint and partial distributions of monthly temperature and precipitation for the region. Thus, it is fundamentally misleading to characterise climate change using the deterministic approach and not very helpful for water resources planners. However, the model and methods we have developed and implemented in this study can easily be transferred to a stochastic environment. This approach would be implemented through the following steps:

- Estimate key parameters of the joint and partial distributions of monthly temperature and precipitation for selected climate change scenarios at different locations in the Berg River Basin using a regional climate model (RCM).
- Validate RCM simulations of precipitation and temperature for the existing climate in the Berg River Basin against observed records and use these data to estimate the distributions of the errors.
- Using this information, calibrate an existing water balance model, such as WATBAL stochastically, to simulate the joint and partial distributions of runoff and evaporation at selected runoff gages in the basin and the distributions of forecast errors associated with the runoff distributions.
- Use BRDSEM, stochastically, to propagate the distributions of key variables in the model and their associated forecast, such as monthly reservoir storage, urban and agricultural water demand, water releases, and various economic welfare components.
- Assess the impact of the forecast errors on Type I and Type II ex-ante, ex-post planning decisions.
- Develop an analytical tool and associated databases to automate the generation of stochastic climate forecasts and error propagation for the RCM, for general use in the region.
- Modify and automate an existing water balance model to generate stochastic runoff forecasts using stochastic climate forecasts.

Such a study represents an important step in bridging the communication and data gap between climate scientists and water planners, allowing water planners to work with climate change data on essentially the same basis they work with observed geophysical records, while taking into account inherent reliability problems in existing global and regional models to reproduce the 'historical' climate.

PART II: ADAPTATION TO CLIMATE CHANGE FOR AGRICULTURE IN THE GAMBIA

Bernard E. Gomez (Principal Investigator). Department of Water Resources. The Gambia.
Bubu P. Jallow. Department of Water Resources. The Gambia
Momodou Njie. Department of Water Resources. The Gambia.
John M. Callaway, PhD. Senior Researcher, UNEP Riso Centre, Roskilde, Denmark.
Molly Hellmuth. USA. UNEP Riso Centre, Roskilde, Denmark.
Peter Droogers

8 Introduction

A significant amount of effort has been focused on identifying and estimating the costs of undertaking actions that will reduce the expected magnitude of climate change, by reducing emissions of greenhouse gases (GHGs) or by expanding the size of carbon sinks. This body of work has been documented by the IPCC in their various assessment reports and the general framework and the analytical tools for evaluating the costs of GHG mitigation projects is not only widely accepted, but also have been integrated into the language of the Kyoto Protocol.

The relationship between adaptation projects and sustainable development has received very little attention, outside of the implicit linkages between anticipatory adaptation and market liberalisation policies in developing countries. Particularly lacking in this regard is a framework for distinguishing between project benefits and costs that are development-related and those that are climate change-related and for evaluating the climate-related benefits of 'no regrets' adaptation measures.

In addition, in the recently published Third Assessment Report, the IPCC predicts that Africa will suffer the most severe impacts from climate change, and African policy-makers need to carefully examine the trade-offs between the benefits and costs of adaptation projects, as well as mitigation costs and adaptation costs.

In previous research on adaptation costs, Callaway *et al.* (1999) identified several important reasons why the costing framework for mitigation projects is difficult to apply conceptually to adaptation projects, as follows:

- Whereas mitigation costs of projects in different countries and sectors can be compared on the basis of cost-effectiveness, it is almost impossible to develop a consistent measure of the physical accomplishments (i.e. benefits) of adaptation projects.
- To measure the physical benefits of adaptation projects we must be able to measure how an adaptation project offsets the physical damages of climate change. This is not necessary for the mitigation-costing framework in which project accomplishments, as indicated, are measured in terms of reductions of carbon equivalent emissions.
- The base case used to measure the costs and accomplishments is conceptually different from that used to measure mitigation costs.

8.1 Objectives

To help build and strengthen the institutional capacity within Africa to develop and implement analytical tools for estimating and comparing the costs and benefits of adaptation projects in key natural resource sectors.

Ensure that results from the study will contribute to the development of international climate change policies and programmes, particularly in regard to adaptation activities in developing countries under the UNFCCC.

8.2 Methodology

The broad approach taken on this project will focus on the following major areas:

Development of adaptation benefit-cost framework: The project builds upon the earlier adaptation cost framework developed by Callaway *et al.* (1999) and Fankhauser (1997) to define and develop the relevant metrics for estimating and comparing the costs and benefits of the adaptation projects to be developed. The framework will be developed in a manner to make it possible to isolate development- and climate-related benefits and costs of individual projects and to assess the sensitivity of adaptation benefits and costs to the uncertainty inherent in regional climate change scenarios.

Development of analytical tools and procedures: The project will develop general procedures and specific analytical tools for consistently measuring the costs and benefits of adaptation projects in the agriculture sector in Africa. These procedures and tools will be developed to allow multi- and by-lateral development institutions to evaluate the benefits and costs specifically related to climate adaptation 'add-ons' to sustainable development projects.

Application of analytical tools and procedures: The project will apply these procedures and analytical tools to estimate the benefits and costs of a well-defined adaptation project in the agricultural sector in the West African region.

These objectives and methodologies have been tested and applied for The Gambia focusing on the agricultural sector, particularly on the predominant crop in the country: millet. A detailed water-crop model has been setup and applied for a reference period and for future projected climates. Adaptation strategies have been defined and explored with the model and an economic analysis has been applied on the results.

9 Overview of The Gambia

9.1 General Description

The Gambia is the smallest country on the African continent and shares a land border on the north, east and south with Senegal whilst the western façade opens up to the Atlantic Ocean. The country has a land area of 11 000 km^2, and a population of 1.33 million, estimated to be growing at 4.1% annually. With a population density of 130 per square kilometre, The Gambia is among the five most densely populated countries in Africa. More than 62% of the population lives in the rural areas. The Gambia has about 500 000 hectares of forests and woodlands, which constitutes about 48% of the total land area. The average annual rate of deforestation is estimated to be 1%.

Agriculture is the mainstay of The Gambian economy, employing about 75% of the labour force. The GDP per capita is $1 100. Industry, agriculture and services account for 12%, 21% and 67% of GDP, respectively. However, the growth rate in the agricultural sector at 2.7% has been lagging behind the service sector, which is 4.3%.

The Gambia is one of the poorest countries in the world with a GNP per capita of US$340. It was ranked 149 out of 161 in the United Nations Development Programme (UNDP) Human Development Index, 2001. About 64% of the total population live below the national poverty line, whereas 59% of the population live below US$1 per day, and 83% live below US$2 per day. Poverty, environment and natural resources are very closely related. Of those who are extremely poor, 91% work in agriculture.

Life expectancy in The Gambia is about 53 years overall, 52 years for men and 55 for women. Infant mortality was 73 per 1000 babies born in 2000, down from 159 per 1000 babies born in 1980. The under-five mortality rate is about 110 per 1000 children. Prevalence of malnutrition declined to 30% in 2000. About 62% of total population, 53% of the rural population and 80% of the urban population have access to safe water supply. Sanitation services are available to 37% of the total population, 35% of the rural population and 41% of the urban population.

Fuel wood is the predominant source of energy in The Gambia and accounts for 79% of total energy consumption. Electricity is generated entirely from petroleum based fuels.

The total road network in The Gambia is 2,700 km long, of which 956 km are paved. The Gambia has 400 km of waterways, which include the Gambia River, the most navigable river in West Africa.
The Gambia has a coastline 80 km long. The coastline is mainly composed of sandy beaches and the main developments include residential, commercial and fish landing facilities as well as beach hotels. Results of a recently commissioned study on the causes of erosion revealed that they were partly due to human activities (sand mining) and partly natural (inundation and sea level rise).

9.2 Climate

9.2.1 Overview

The Gambia's climate can be classified as sub-tropical with distinct dry and rainy seasons. The dry season is from November to May the following year, with average temperatures around 21-27°C and the Harmattan wind (dusty wind from the Sahara) keeping the humidity low. The rainy season is from June to October with high humidity and average temperatures around 26-32°C. Generally, there is considerable cooling off in the evening. Temperatures are mildest along the coastline and the amount and duration of rainfall lessens inland. Rainfall is on average about 800 mm y^{-1} (1960-1990), but considerable differences exist between years.

9.2.2 Variation in precipitation

Considerable year-to-year variation in precipitation occurs in The Gambia. In addition, due to the effect of latitude and the influence of large water bodies, spatial variation in precipitation occurs where the general pattern is that the western part of the country receives the highest amount of rain, followed by the eastern part and the middle receiving the least rainfall. For the main meteorological stations (Figure 9.1), annual precipitation over the period 1950-2002 has been plotted. It is clear that considerable variation between years occurs and the devastating droughts in the early 1970's and the mid 1980's are clearly visible. The difference between the meteorological stations shows that in most years Yundum receives most precipitation (1037 mm y^{-1} over the period 1950-2002), followed by Basse (924 mm y^{-1}) and by Janjanbureh (848 mm y^{-1}).

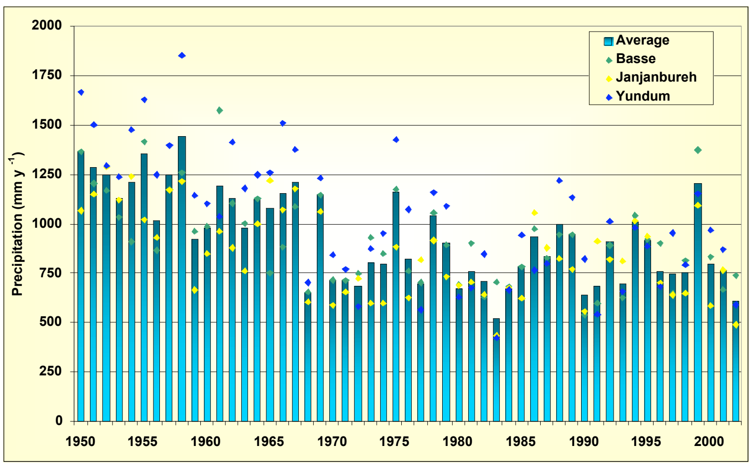


Figure 9.1: Observed Annual Precipitation Over the last 50 Years for three of the Main Meteorological Stations

From Figure 9.1 it is clear that temporal variation is much higher than the spatial variation considering the annual total precipitation. In other words, droughts are not very localized and if one part of the country is experiencing dry spells the entire country is suffering.

9.2.3 Gridded climate data

It is clear that it is essential to take into account this spatial and temporal variation in further analysis of climate change and the impact of climate on crop production. Detailed spatial interpolation techniques, such as kriging, can be employed to cover this spatial variation and weather generators can be used to expand the observed temporal variation over non-observed periods. For this study we have selected to use an existing global dataset of gridded climate parameters: the so-called CRU dataset.

The CRU TS 2.0 dataset is provided by the Climatic Research Unit (CRU) of the University of East-Anglia, UK, (Mitchel *et al.*, 2003). The CRU dataset provides interpolated gridded precipitation, temperature, cloud cover and humidity values based on observations for global land surfaces, between 1901 and 2000 on a 0.5° x 0.5° grid at monthly intervals. Since the dataset was developed at a global scale, care should be taken in using the dataset at smaller scales. Nonetheless, the dataset provides an excellent alternative for the tedious process of interpolation and collecting more difficultly obtainable data such as sunshine hours, radiation and relative humidity.

A quick comparison between the observed rainfall and the gridded rainfall shows that averages for the entire country match very well (Figure 9.2). Plotting the long-term average precipitation patterns reveals that, according to the CRU-dataset, the north-south gradient is more profound than the east-west one, which explains, taking into account the shape of The Gambia, the driest regions being in the middle of the country.

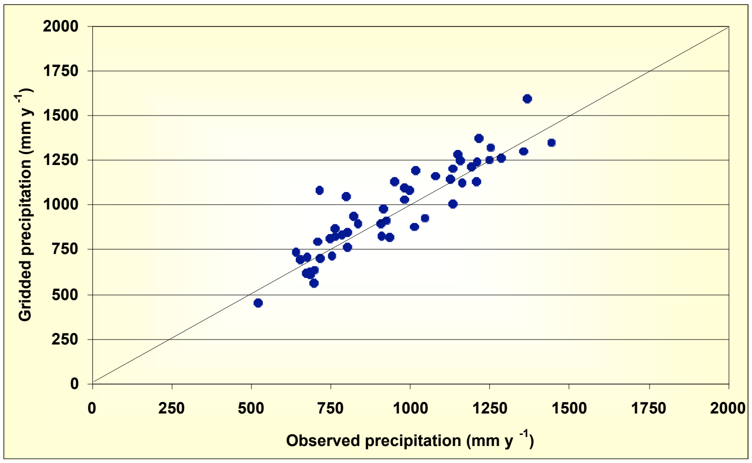


Figure 9.2: Observed and Gridded Annual Precipitation for the Entire Country over the Period 1960-2000

Observed data is the average for the stations Yundum, Basse and Janjanbureh, gridded data are the average for the 14 CRU-grids covering The Gambia.)

9.3 Agriculture

The Gambia remains predominantly an agrarian economy. The sector contributes up to 20% of the country's GDP, generates about 40% of total export earnings, employs over half of the labour force, and provides an estimated two-thirds of total household income. Typical sub-sectoral contributions in the agricultural sector are 15% from crops and 5% from livestock. The economy continues to rely heavily on a single cash crop, groundnut, for foreign exchange earnings. The main crops grown are millet, sorghum, maize, rice (upland & lowland), groundnut, cotton and sesame, whilst livestock reared are cattle, sheep, goats, poultry and pigs.

Despite its primary role, agriculture's share in most key socio-economic indicators has been on the decline in the last three decades. The decline is attributed to a combination of adverse climatic conditions, declining international agricultural commodity prices, and inadequate domestic policy and institutional support to the sector.

Domestic grain production meets only 50% of the national food grain requirement. Rice is the staple food and attracts substantial imports. Local rice production is constrained by dry season salinity along most stretches of the River Gambia. Despite an increase in horticultural production, and the introduction of sesame, diversification of the production base in the agricultural sector has been slow, reflecting competitiveness and risk in local and international markets. A concentrated period of intense rainfall followed by a long dry period makes it difficult for producers, particularly in the absence of irrigation infrastructure in most parts of the country.

Household production systems are characterised by subsistence rain-fed grain production, traditional livestock rearing, semi-commercial groundnut, limited horticulture, cotton, and sesame production. The population pressure on agricultural land (550,000 hectares is of arable potential) is high. Agro-industrial activity is mainly limited to cereal processing, dairy production, cotton ginning, and groundnut and sesame oil extraction.

Overall, agricultural production and productivity levels are low. Farming systems are risk adverse, minimising the use of capital inputs. At this stage of development, a low risk, low input form of mixed farming based on small production units has evolved, giving rise to low production and marketed output, and low land and labour productivity. Risk aversion, low productivity and incomes are thus locked in a vicious circle. Livestock production systems are predominantly traditional, although a growing number of modern livestock enterprises exist.

There is a gender division of labour between upland and lowland crops. Whilst upland crops (mainly coarse grains and groundnut) are generally the responsibility of men, lowland crops, especially rice are tended by women. In the livestock sub-sector, gender divisions of labour and management responsibility in relation to livestock exist, with cattle managed by males and small stock often by females.

10 Drought Index

10.1 Introduction

Due to the high dependence of the Gambian agricultural sector and rural communities on rainfed agriculture, the occurrence of drought has direct impacts on food security and household economies. Indirect impacts include malnutrition, further entrenchment of poverty, higher food import bills and loss of revenue at the national level, rural-urban migration, increased vulnerability of the economy to external shocks, etc.

Drought, in an agricultural context is characterised by shorter growing periods due to delayed onset and/or early cessation of rains; extended dry spells during the crop growing season; or low rainfall in exceptional cases. Given the trend towards global warming, attributed to increased atmospheric concentrations of CO_2 and other greenhouse gases, crop water requirements are expected to increase in response to higher temperatures and rates of photosynthesis.

10.2 Defining Drought

10.2.1 Rainfall

Situated in the tropical, semi-arid region of Africa, rainfall in The Gambia is highly variable, from year-to-year, requiring thus investigation its long-term behaviour, if pertinent conclusions are to be reached. Daily data from the Department of Water Resources dataset were therefore compiled from all the rainfall measuring stations in the country from the date they started operating to the year 2002. Although the vast majority of rainfall measuring stations started in the early 1970s, there is a high prevalence of data gaps.

Only data from 4 out of 23 stations, viz., Yundum (13º 21´ N, 16º 38´ W), Yallal (13º 33´ N, 15º 43´ W), Janjanbureh (13º 32´ N, 14º 46´ W), and Basse (13º 19´ N, 14º 13´W), situated in different agro-ecological zones, had the required record length, with the exception of Yallal, in which kriging (average area of 5km x 5km) was used to fill a 10-day (1 - 10 August 1990) data gap in the Yallal time series. Pair-wise and multiple correlation between daily rainfall at Yallal and three adjoining stations which form a triangle within which Yallal is located, i.e., Kerewan (42 km to the west), Jenoi (18 km to the south-east), and Ngeyen Sanjal (32 km to the north-east), resulted in low correlation coefficients, apparently due to the localised nature of most rainfall events[24].

10.2.2 Water balance

With the rainfall situation described above, we reason that an attempt to define agricultural drought should show the balance between crop water demand and moisture availability. In order to avoid getting trapped in another, multi-parameter interpolation exercise, the search for an appropriate

---

24 Rainfall occurred on the same day in all four stations only 12% of the time.

computation method, requiring minimum and readily available data as inputs led to the Frere and Popov (1979) monitoring and forecasting model adopted by the FAO.
The water balance for a period (i) is expressed as:

$$P_{(i)} = Ra_{(i)} + S_{i-1} - Et_{(i)} - Ru_{(i)} - Dr_{(i)}$$

Where

$P_{(i)}$ is the soil moisture,
$Ra_{(i)}$ is the total rainfall during the period (i),
$S_{(i-1)}$ is the soil moisture storage in the previous time step,
$Et_{(i)}$ is the evapotranspiration,
$Ru_{(i)}$ is the runoff,
$Dr_{(i)}$ is the drainage into the subsoil.

Inputs to this model are rainfall, potential evapotranspiration (Penman-Monteith), crop coefficients (according to length of crop cycle), and soil moisture holding capacity. Whilst rainfall must be current for the season under examination, evapotranspiration is the computed long-term averages, thus the historic values for the period of 1951 – 1980, compiled under the CILSS AGRHYMET Programme. The soil moisture holding capacity is set at 100 mm for the rooting zone (Williams, 1979).
The main output of this model is the cumulative water satisfaction index (WSI), with runoff/drainage and total water requirements as secondary outputs.

Since drought is mainly associated with low moisture availability, we decided to restrict water balance analyses to the lowest tercile (the Yallal meteorological station) and for the 'Early Millet' (*Pennisetum typhoides)* crop. The choice of early millet stems from its ability to withstand low moisture situations, such that any significant drop in yield linked to moisture stress, is expected to have a greater impact on the other crops grown in The Gambia, namely, maize (*Zea mays*), sorghum (*Sorghum bicolor* (L. Moench)), rice (*Oryza sativa*) and groundnut (*Arachis hypogea*). We recall that grain production at national level only meets about 50% of domestic grain requirement reflecting the fragility of the Gambian economy vis-à-vis stressors in the food production chain.

In order to reflect risk management strategies adopted by different Gambian farmers, three sowing dates were selected for each growing season. The different sowing dates (June 11-20, June 21-30, and July 1-10) resulted in WSI values of 87%, 87% and 96%, respectively, which are further averaged to derive a representative WSI for a growing season.

Contrary to expectations, an attempt to correlate seasonal WSI with millet yields obtained from the sample surveys, conducted by the Department of Planning (Agriculture) using simple regression techniques proved unsatisfactory. A close look at the model outputs (WSI) showed little variation in the index over the successive rainy seasons, suggesting that the model may not be fully capturing the inter-annual seasonal variation.

Also, since yield figures are averaged over an administrative division, rather than the more refined village/town level to which WSI refers to, it is thought that the spatial mismatch could be a factor for the low correlation.

10.2.3 Drought characterisation

Figure 10.1 shows a significant correlation between seasonal rainfall and yield. In conformity with expectation, the figure shows that in general, assuming management options and crop pests and diseases situations remain fairly similar over the period under review, low rainfall is associated with poor yields. Maximum yields occur with rainfall amounts of between 800 to 1200 mm, whilst rainfall above the latter does not necessarily translate into high yields. From the above, it would appear that both annual rainfall and its temporal distribution are the key determinants of yield in this environment, as could seen from Figure 10.1, where the 1991 seasonal rainfall of 544 mm, gave average yields (1027 kg ha^{-1}), whereas the 1997 seasonal rainfall of 956 mm, culminated in below average yield (620 kg ha^{-1}).

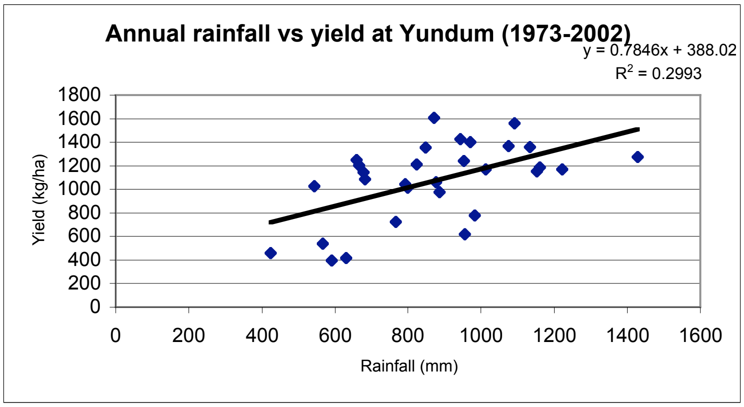


Figure 10.1: Regression Plot of Seasonal Rainfall and Yield at Yundum

A drought in the Gambian agricultural context could therefore be grossly characterised as a season with less than 600 mm of rainfall. Except in cases of good temporal distribution, amounts below this threshold are likely to result in poor yields. For amounts above this threshold, it can be expected that the cumulative rainfall over the whole season would somehow compensate for poor temporal distribution, and at least result in average yields.

An operational definition could be obtained by further analysis of the temporal distribution of low rainfall seasons. Also, it might be more reasonable to develop a threshold per rainfall environment as it prevails in the country.

11 Water-Crop Simulation Model

11.1 SWAP

SWAP (Soil-Water-Atmosphere-Plant) is an integrated physically based simulation model for water, solute and heat transport in the saturated-unsaturated zone in relation to crop growth. A detailed description of the model and all its components is beyond the scope of this paper, but can be found in Van Dam et al. (1997), Kroes et al. (1999), and Van Dam (2000). For this study, the water transport module and the detailed crop growth module WOFOST were used. The first version of the SWAP model was already written in 1978 (Feddes et al., 1978) and from then till now the program has undergone a number of modifications. The version used for this study is SWAP 2 and has been described by Van Dam et al. (1997).

The SWAP model has been applied and tested for many different conditions and locations and has proven to produce reliable and accurate results (SWAP, 2003). It (SWAP model) has also been used extensively in climate change related studies. A study in Sri Lanka focused on adaptation strategies to climate change for rice cultivation, where the SWAP model was incorporated with a basin scale model to ensure that upstream—downstream processes of water resources were considered (Droogers, 2003). The SWAP model was also applied in an adaptation study across seven contrasting basins in Africa, Asia, America, and Europe to explore how agriculture can respond to the projected changes in climate (Droogers and Aerts, 2003).

The next two sections describe the soil water and crop growth modules in the SWAP model relevant to this study.

11.2 Soil water module

The core part of the soil water module (see Figure 11.1) is the vertical flow of water in the unsaturated-saturated zone, which can be described by the well-known Richards' equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z} + 1\right) - S(h)\right] \qquad \text{EQ 4.1}$$

where, θ denotes the soil water content ($cm^3\ cm^{-3}$), t is time (d), h (cm) the soil matric head, z (cm) the vertical coordinate, taken positive upwards, K the hydraulic conductivity as a function of water content ($cm\ d^{-1}$). S (d^{-1}) represents the water uptake by plant roots (Feddes et al., 1978), defined for the case of a uniform root distribution as:

$$S(h) = \alpha(h)\frac{T_{pot}}{|z_r|} \qquad \text{EQ 4.2}$$

where, T_{pot} is potential transpiration ($cm\ d^{-1}$), z_r is rooting depth (cm), and α (-) is a reduction factor as function of h and accounts for water deficit and oxygen deficit. Total actual transpiration, T_{act}, was calculated as the depth integral of the water uptake function S.

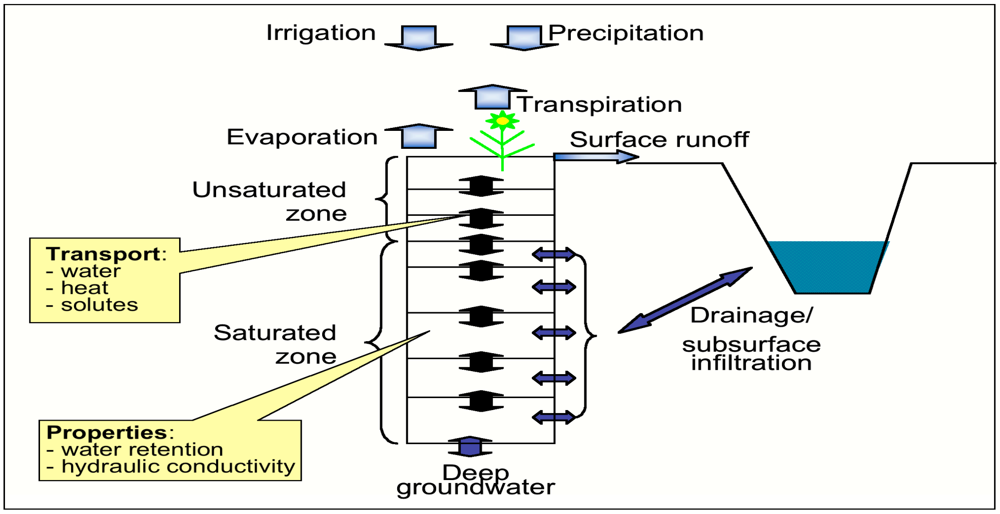


Figure 11.1: Overview of the Main Processes Included in the Soil-Water-Crop Module of SWAP-WOFOST

The partitioning of potential evapotranspiration into potential soil evaporation and crop transpiration is based on the leaf area index (LAI). Actual crop transpiration and soil evaporation are obtained as a function of the available soil water in the top layer or the root zone, respectively. Actual crop transpiration is also reduced when salinity levels in the soil water are beyond a crop specific threshold value.

Irrigation processes can be modelled as well and irrigation applications can be prescribed at fixed times, scheduled according to different criteria, or by using a combination of both.
As mentioned earlier, SWAP contains three crop growth routines: a simple module, a detailed module, and the detailed module attuned to simulate grass growth. Independent of external stress factors, the simple model prescribes the length of the crop growth phases, leaf area, rooting depth and height development. The detailed crop module is based on WOFOST 6.0 (Supit et al., 1994; Spitters et al., 1989).

11.3 Crop growth module

A brief overview of the detailed crop growth module used to compute the maximum obtainable (=potential) yield is given here. Figure 11.2 shows the main processes and relations included in WOFOST (World Food Studies). The WOFOST series has been developed and applied extensively in a wide range of geographical and climatological locations, either as a stand-alone, or integrated with SWAP.

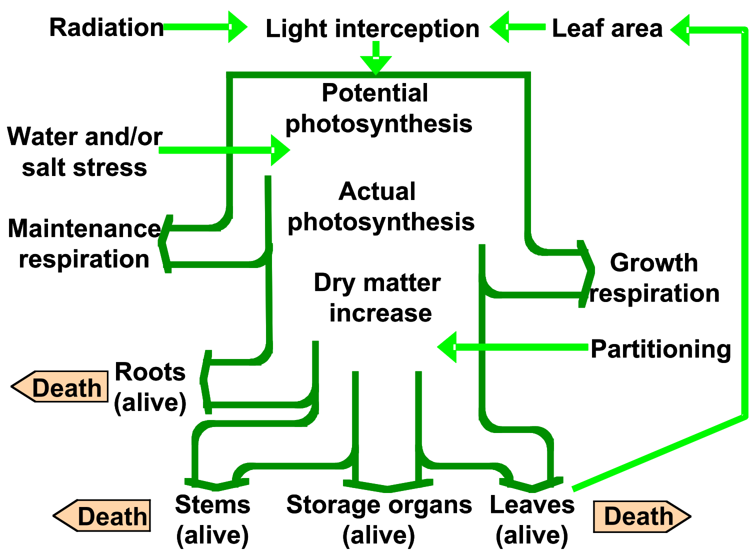


Figure 11.2: Overview of the Main Processes Included in the Detailed Crop Growth Module of SWAP-WOFOST

WOFOST computes incoming Photosynthetically Active Radiation (PAR) just above the canopy at three selected moments of the day. Using this radiation and the photosynthetic characteristics of the crop, the potential gross assimilation is computed at three selected depths in the canopy (Spitters et al., 1989). Gaussian integration of these values results in the daily rate of potential gross CO_2 assimilation (kg CO_2 ha^{-1} d^{-1}). This potential is the maximum that can be obtained given the crop variety, CO_2 concentration and nutrient status without any water stress, pest or diseases.

Part of the assimilates produced are used to provide energy for the plant maintenance processes. The rate of maintenance respiration is a function of the amount of dry matter in the various plant organs, the relative maintenance rate per organ and the ambient temperature. The remaining assimilates are partitioned among roots, leaves, stems and storage organs, depending on the phenological development stage of the crop (Spitters *et al.*, 1989). These remaining assimilates are converted into structural dry matter, and part of these assimilates are lost as growth respiration.

The net increase in leaf structural *dry matter* and the specific leaf area (ha kg^{-1}) determine leaf area development, and hence the dynamics of light interception, except for the initial stage when the rate of leaf appearance and final leaf size are constrained by temperature, rather than by the supply of assimilates. The dry weights of the plant organs are obtained by integrating their growth and death rates over time. The death rate of stems and roots is considered to be a function of development stage (*DVS)*. Leaf senescence occurs due to water stress, shading (high *LAI*), and also due to life span exceedence.

Some simulated crop growth processes, such as the maximum rate of photosynthesis and the maintenance respiration are influenced by temperature. Other processes, such as the partitioning of assimilates or decay of crop tissue, are steered by the *DVS*. Development rates before anthesis are controlled by day length and/or temperature. After anthesis only temperature will affect development rate. The ratio of the accumulated daily effective temperatures, a function of daily average temperature, after emergence (or transplanting in rice) divided by the temperature sum (*TSUM*) from emergence to anthesis, determines the phenological development stage. A similar approach is used for the reproductive growth stage (van Dam et al., 1997).

12 Climate Change Scenarios

Past climate change studies in The Gambia that have used Global Circulation Model (GCM) results to predict future climate change demonstrated a considerable variance and inconsistency in their projections, depending on the GCM (GOTG, 2003). In this study, more recent versions of two GCMs, the Max Planck ECHAM4 model and The Hadley Centre HadCM3 model for the A2 IPCC SRES scenarios (IPCC, 2000) were downscaled to the Gambia. These two models represent two plausible futures, but are inconsistent in precipitation projections.

This chapter is organised into three sections. Section I describes the downscaling process of the two GCM model scenarios to fit the Gambian context. This section begins with a description of the IPCC SRES scenarios, the selection of the two GCMs, and follows with a brief description of the climate datasets, meteorological stations, and required climate variables. Finally, section I finishes with a description and results of the GCM downscaling process. Section II describes the relationship of ENSO and precipitation in the Gambia. Finally, Section III describes the impact of carbon dioxide on crop growth.

12.1 Local Adjustment

The use of GCM climate data for modelling impacts on agriculture has been evolving over the past twenty years. In order to obtain information at spatial scales smaller than a grid-box in a GCM, it is necessary to 'downscale'. There are two broad approaches to downscaling, neither of which is inherently superior to the other, and either of which may be appropriate in a given situation. These approaches are:

- Statistical downscaling, where an equation is obtained empirically to capture the relationship between small-scale phenomena and the large-scale behaviour of the model. By far the majority of the studies into the effects of climate change on river flows at regional and catchment scales have used this technique, by applying large scale changes in climate to observed climate projected by GCMs input data to create perturbated climate series.
- Dynamical downscaling, where a high-resolution regional climate model (RCM) is embedded within a GCM. This technique is relatively recent and still subject to improvements. Major problems concern direct error propagation from the global GCM to the regional model. Resulting regional scenarios will have a higher spatial resolution, but still carry the same or even larger uncertainties as the global scenarios. Also excessive computing power is needed to generate longer data series
- Combination techniques, using regional models, statistical downscaling and observed regional climate data in so-called 'data assimilation' modelling. This highly specialised technique is currently under development and requires further research into its wider applicability.

For this study, we use statistical downscaling process, with particular effort to maintain the variability while simultaneously capturing the mean for the reference period 1961-1990 or 1990-1999 for HADCM3 and ECHAM4, respectively.

12.1.1 IPCC SRES scenarios and GCM models

For its Third Assessment Report (TAR), the IPCC prepared a total of 40 emission scenarios (IPCC Special Report on Emission Scenarios – SRES). The scenarios were based on the emission driving forces of demographic, economic and technological evolutions that produce greenhouse gas (mainly carbon dioxide) and sulphur emissions.

Four scenario 'storylines' were developed (the list below has been adapted from IPCC TAR, 2001, Working Group I Box 9.1, p. 532):

- Storyline A1: This scenario describes a future world of very rapid economic growth, global population that peaks in the mid 21st century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income.

- Storyline A2: The A2 scenario describes a very heterogeneous world. The underlying theme is self reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented than in other storylines.
- Storyline B1: The B1 scenario describes a convergent world with the same global population as the A1 scenario (population that peaks in mid-century and declines thereafter), but with rapid change in economic structures towards a service and information oriented economy, with reductions in material intensity and the introduction of clean and resource efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.
- Storyline B2: The B2 scenario describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with a continuously increasing global population, at a rate lower than that in the A2 scenario, with intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the B2 scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.
-

For the purpose of this study, the A2 and the B2 IPCC SRES scenarios were chosen. In conjunction with these storylines, several GCMs were run. As described above, we have chosen two GCMs from this group, based partially on the results of previous climate change studies of The Gambia (US Country Studies and National Communication to UNFCCC), and partially on information from current GCM indications of the Gambia. Since the magnitude and signal of climate change were highly variable and inconsistent dependent upon the GCM in past studies of The Gambia, we decided to select two GCMs which best capture the range of these model inconsistencies. From past studies, the Hadley Centre model, HCGG, represented a more extreme scenario of increased temperatures and a reduction in precipitation. The newer version of the model, HADCM3, maintains this trend, although the predictions are less 'extreme'. In past studies on The Gambia, the ECHAM4 model was not used, meanwhile, after consideration of the climate information provided by AIACC Group AF07, we chose this model as it predicted *increases* in precipitation and temperature for the Gambia.

12.1.2 Available climate information

As described before, the SWAP model requires daily climate time series of radiation, maximum and minimum temperature, humidity, wind speed, rainfall, and reference evapotranspiration (optional). These were chosen based on their location, and on the relative quality and availability of meteorological data.

Since there are some constraints in availability and quality of data in The Gambia, additional climatic information was obtained from the CRU TS 2.0 dataset (Mitchel *et al.*, 2003). The CRU[25] dataset provides interpolated gridded precipitation, temperature, cloud cover and humidity values based on observations for global land surfaces, between 1901 and 2000 on a 0.5° x 0.5° grid at monthly intervals.

For this modelling study, three parameters: precipitation, minimum temperature and maximum temperature were taken from the existing meteorological stations; while the remaining variables radiation, humidity, wind speed were taken from the CRU data set. Notice that the CRU data is given at a monthly time step, but the model requires daily data. The monthly data is distributed into daily values as described in Step 5, Section 12.1.3. The meteorological stations each lie within one of the CRU grid cells. In the case of missing station data, the CRU dataset was used to patch the missing values.
To minimise the number of results to be presented we selected to focus in the further analysis on one meteorological station: Yundum. Since the entire country falls in one GCM grid the actual precipitation amount will differ for the other stations due to the downscaling procedure, but the relative changes will remain constant.

12.1.3 Downscaling the GCM data

Three climate variables were downscaled: precipitation, and minimum and maximum temperature. The downscaling procedure was done at a monthly time period, which means that the three variables were downscaled for each of the climate scenarios, giving a total of six downscaled variables (3 climate variables * 2 GCM Scenarios) for three time periods: the reference period (1961 – 1990 (HADCM3) or 1990-1999 (ECHAM4)), the near future period 2010 – 2039, and the distant future period 2070 - 2099. The downscaling procedure is as follows:

STEP 1. ***Preparing the observed reference period data.*** The reference time period is set for all variables at 1961 – 1990 for the HADCM3 model, and 1990-1999 for the ECHAM4 model. The station data is daily, and will need to be converted first to monthly values (monthly precipitation is the sum of the daily precipitation for the corresponding month, monthly minimum and maximum temperature is equal to the average of the minimum and maximum temperatures for the corresponding months).
STEP 2. ***Computing the adjusted reference period GCM time series.*** The objective is to downscale the *unadjusted reference period* GCM data to fit the statistical characteristics of variability and mean of the corresponding *reference period* observed historical station data. Equation 12.1 was used to attain the corrected, or adjusted, climate parameter, thus creating the 'adjusted reference period GCM time series':

$$a'_{gcm,M} = \left(\frac{a_{gcm,M} - \overline{a_{gcm,M}}}{\sigma_{gcm,M}} \right) \cdot \sigma_{obs,M} + \overline{a_{obs,M}} \qquad \text{EQ 12.1}$$

where:

---

[25] Since the dataset was developed at a global scale, care should be taken in using the dataset at smaller scales. However, the dataset provides an excellent alternative for the tedious process of interpolation and collecting more difficult obtainable data such as sunshine hours, radiation and relative humidity.

a'_{gcm} is the corrected climate parameter (total precipitation or average temperature)
a_{gcm} the simulated climate parameter

$\overline{a_{gcm}}$ the average simulated climate parameter

σ_{gcm} the standard deviation of the simulated climate parameter
σ_{obs} the standard deviation of the observed climate parameter

$\overline{a_{obs}}$ the average observed climate parameter, and

M the subscript indicating that analyses were done for each month separately.
STEP 3. From this equation two adjustment factors, for each month considered, can be derived using the same time span for observations as well as GCM 'projections' (e.g. 1961-1990, and 1990-1999):

$$a_{adj,M} = \frac{\overline{a_{obs,M}}}{\overline{a_{gcm,M}}} \qquad \text{EQ 12. 2}$$

$$\sigma_{adj,M} = \frac{\sigma_{obs,M}}{\sigma_{gcm,M}} \qquad \text{EQ 12. 3}$$

STEP 4. ***Derive the adjusted GCM values for future projections*** (e.g. 2010-2039, 2070-2099). These above two adjustment factors (EQ 12.2 and 12.3) are used to derive the adjusted GCM values for future projections (e.g. 2010-2039, 2070-2099):

$$a'_{gcm,M} = \left(a_{gcm,M} - \overline{a_{gcm,M}}\right)\sigma_{adj,M} + \left(\overline{a_{gcm,M}} \cdot a_{adj,M}\right) \qquad \text{EQ 12. 4}$$

STEP 5. ***Creating a daily time series.*** Distribute the monthly-adjusted GCM time series in order to create an adjusted daily data time series. Take the distribution of the reference period observed time series, and apply it to the GCM time series.

12.2 ENSO and Precipitation in The Gambia

The Gambia exhibited a strong teleconnection with Sea Surface Temperatures (SSTs) in the Atlantic during the recorded 1982-83 and 1986-88 El Nino periods. During these two El Nino events, a significant reduction in precipitation was evident. We consider here whether this teleconnection is evident in other ENSO years, specifically whether or not positive and negative SST anomalies in the Atlantic are associated with dry and wet Gambian weather composites. This will determine whether El Nino Southern Oscillation (ENSO) indices, such as SSTs have some forecast potential in terms of rainfall in The Gambia.

We use three composites of the NINO3 SST index from December to February, as indications of El Nino, La Nina and non-ENSO years. The annual precipitation (effectively the cumulative monthly precipitation for the rainy season from June to October) for the CRU data grid corresponding to the Yundum meteorological station is compared to three different NINO3 SST composites for the months of December to February, for the years 1901-1999. The CRU dataset was chosen because of the length of the available climate record, but has been shown to be highly correlated to the Yundum meteorological station (Figure 9.2).

The three composites use the NINO3 SST index from December to February, and are defined as follows:
Composite 1 represents ENSO index values less than -0.75.
Composite 2 represents ENSO index values between -0.75 and 0.75.
Composite 3 represents ENSO index values greater than 0.75.

Higher magnitude, persistent positive SST anomalies represent warming, or El Nino events, and higher magnitude, persistent negative SST anomalies represent cooling, or La Nina events. The average annual rainfall for each of the composites is shown in Table 12.1.

Composite	*ENSO*	*Precipitation (mm y^{-1})*
1	La Niña	1042
2	Non ENSO	918
3	El Niño	867

Table 12.1: Average Annual Precipitation Values (mm) for the CRU Grid Data and ENSO Index Composite

There are 12 years of composite 1 ENSO values and 18 years of composite 3 ENSO values from the 99 years of data. There is a distinct difference in average precipitation values, as negative anomalies show higher precipitation values and positive anomalies result in lower precipitation values. There is no significant correlation between the ENSO index and precipitation (R^2 = .03). There appears to be a higher correlation in the Composite 3 correlation with precipitation (R^2 = .4) although not significant. There are two distinctly low-precipitation values associated with high composite values representing the 1982-83 and 1986-1988 El Nino years. There is little correlation for the Composite 1 with precipitation.

12.3 Impact of CO_2 on Crop Growth

Production potential of a crop is based on the fixation of solar energy in biomass, referred to as photosynthesis, according to the well-known process:

$$H_2O + CO_2 \xrightarrow{light} CH_2O + O_2$$

In this process, CO_2 from the atmosphere is transformed into glucose (CH_2O), resulting in the so-called gross assimilation of the crop. The required energy for this originates from (sun) light, or, more precisely from PAR. The amount of PARin the total radiation reaching the earth’s surface is about 50%. However, some part of the produced glucose is directly used by the plant through the process of respiration. The difference between gross assimilation and respiration is the so-called biomass production or crop production.

It is important in this process is to make a distinction between C3 and C4 plants. The difference being that they have different carbon fixation properties. C4 plants are more efficient in carbon fixation and the loss of carbon during the photorespiration process is also negligible for C4 plants. C3 plants may lose up to 50% of their recently-fixed carbon through photorespiration. This difference suggests that C4 plants will not respond positively to rising levels of atmospheric CO_2. Meanwhile, it has been shown that atmospheric CO_2 enrichment can, and does, elicit substantial photosynthetic enhancements in C4 species (Wand et al., 1999).

Examples of C3 plants are potato, sugar beet, wheat, barley, rice, and most trees except Mangrove. C4 plants are mainly found in the tropical regions and some examples are millet, maize, and sugarcane. A third category are the so-called CAM plants (Crassulacean Acid Metabolism) which have an optional C3 or C4 pathway of photosynthesis, depending on conditions: examples are cassava, pineapple and onions.

As a result, the maximum gross assimilation rate (A_{max}) is about 40 (20-50) kg CO_2 ha^{-1} h^{-1} for C3 plants and 70 (50-80) kg CO_2 ha^{-1} h^{-1} for C4 plants. This maximum is only reached if no water, nutrient or light (PAR) limitations occur. It is interesting to note that only about 1% of the plant species are in C4 category and these are mainly found in the warmer regions. The main reason is that optimal temperatures for maximum assimilation rates are about 20ºC for C3 plants and 35ºC for C4 plants.

Modelling studies based on detailed descriptions of crop growth processes also indicate that biomass production and yields will increase under elevated CO_2 levels. For example Rötter and Van Diepen (1994) showed that potential crop yields for several C3 plants in the Rhine basin will increase by 15 to 30% in the next 50 years as a result of increased CO_2 levels. According to their model the expected increase in yield for maize, a C4 plant, will be only 3%, indicating that their model was indeed based on the assumption that C4 species don't benefit from higher CO_2 levels.

In addition to these theoretical approaches, experimental data have been collected to assess the impact of CO_2 enriched air on crop growth. A vast amount of experiments have been carried out over the last decades, where the impact of increased CO_2 levels on crop growth has been quantified. The Center for the Study of Carbon Dioxide and Global Change in Tempe, Arizona, has collected and combined results from these kinds of experiments (CSCDGH, 2003).

For the SWAP model, the impact of elevated CO_2 levels, i.e., the so-called Light Use Efficiency (LUE) was adjusted to account for this. Bouman et al. (2001) derived the following equation based on extensive experimentation on rice:

$$LUE = LUE_{340} \cdot \frac{(1 - e^{-0.00305 \cdot CO - 0.222})}{(1 - e^{-0.00305 \cdot 340 - 0.222})}$$

where LUE is the Light Use Efficiency (kg ha^{-1} hr^{-1} (J m^{-2} $s)^{-1}$), LUE_{340} the Light Use Efficiency at CO_2 levels of 340 ppm, CO the CO_2 concentration (ppm). It is assumed that this equation is valid for all C3 plants, however information on C4 plants, like millet, is lacking. Somewhat arbitrarily we assume here, based on the CSCDGH dataset, that for C4 plants, the impact is 50% of that for C3 plants. The LUE for millet is 0.38 at current CO_2 levels and, based on this equation, will increase to 0.41 in 2025 and to 0.46 in 2085.

13 Impact of Climate Change on Crop Production

13.1 Reference Situation

The period 1961-1990 has been selected as reference to compare the impact of climate change on millet yields for Yundum. This reference is obtained by setting-up the SWAP model as described in the previous sections, using the observed precipitation and temperature from the meteorological station with some additional data from the CRU dataset (solar radiation, relative humidity, wind speed).
In Table 13.1 the average terms of the water balance and crop yields are given. Long-term average millet yields are 1115 kg ha^{-1}, which is slightly higher compared to the 1040 kg ha^{-1} as provided by the FAO statistics over the same period. In terms of variation in yields over the 30 years, the impact of drought is substantial, with very low yields for the years 1972, 1977, 1980 and 1983.

Water Balance					
In	*Avg*	*CV*	*Out*	*Avg*	*CV*
Precipitation	976	30	Transpiration	186	25
Storage	-5		Evaporation	341	18
			Percolation	441	57
Crop Yield					
	1115	30			

Note: Values are average (mm y^{-1}), Coefficient of Variation (%) and crop yields (kg ha^{-1}) over the period 1961-1990.)

Table 13.1: Water Balance for the Yundum Reference Situation

The average precipitation over the 30 years period is 976 mm and is used for crop transpiration, soil evaporation and percolation to the groundwater. Roughly speaking, half of the amount of precipitation is used as evapotranspiration and the other half percolates to the deep groundwater. Obviously, year to year variation occurs, depending on the amount of rainfall. The amount of water transpired by the crop and evaporated from the soil shows less variation than the amount of water percolating to the deep groundwater. The range of crop transpiration per season is between 105 and 250 mm y^{-1}, for soil evaporation 240 and 475 mm y^{-1}, while the range for percolation is between 40 and 925 mm y^{-1}. The relatively low values of crop transpiration are in years where crop growth is very sparse and one should also realise that the figures provided are the actual amount of water transpired by only the crop, so without the soil evaporation. The so-called crop water requirements (CWR) are therefore higher and should be obtained by adding the uncontrolled soil evaporation during the growing season.

Expressing the distribution of annual precipitation to the three main components of the water balance as percentages, can provide values higher than 100%, as the soil water storage is not constant and can be depleted or recharged during dry or wet years, respectively. For example, during the dry year 1983, a substantial amount of soil water storage is depleted (190 mm) which results in low percolation in 1984 as most of the rains that year were used for refilling the dry soil. Even during dry years about 100 mm of water percolates to the deep groundwater as some rainfall might occur outside the growing season or rainfall might be too intensive to be stored in the root zone.

In terms of strategies to use water more productively, it is important to realise that crop transpiration should be considered as a beneficial use of water, while soil evaporation should be considered as a real loss. The substantial amount of percolation guarantees that groundwater resources are secured and might be even exploited more intensively.

13.2 Impact of Climate Change

13.2.1 Near future (2010-2039)

The major impact of climate change on millet yields will be the projected changes in precipitation. As shown in Table 13.2, a reduction in rainfall of 10% can be expected in the period 2010-2039. The projected increase in temperature will have a minor impact on millet growth as such, since the optimum temperature for C4 plants is between 35 and 40ºC, depending on species and varieties. Besides the direct impact of increased temperatures on crop growth, the indirect impact will be that the crop water requirements (reference evapotranspiration) will increase, putting even more stress on the scarcer water resources. As discussed earlier, CO_2 fertilisation can have a positive impact on the photosynthesis process, although for C4 plants but less profound than for C3 plants. The entire process is therefore a complex system of positive and negative factors that are included in the model.

		1961-1990	*2010-2039*	*2070-2099*
Precipitation				
	Average (mm y^{-1})	976	882 (-10%)	510 (-48%)
	CV (%)	30	33	52
Yield				
	Average (kg ha^{-1})	1115	1141 (+2%)	243 (-78%)
	CV (%)	30	33	123
Note: percentages in brackets are changes relative to the reference period 1961-1990.				

Table 13.2: Impact of Climate Change on Precipitation and Millet Yields at Yundum

As shown in Table 13.2, the overall impact of these changes on millet is that the average yield over the period 2010-2039 is almost similar to the reference (1961-1990). However, the variation in yields between years has almost doubled as indicated by the Coefficient of Variation in the table. In terms of food security this can be seen as a real danger since an increase in extremes is harder to cope with than a gradual change.

Another important expected component of this increased variation is the clustering of dry and wet years. For subsistence farming systems, a low yield year followed by a normal year is something that can be overcome. However, a period of two or even more successive years of low yields are very hard to overcome and will trigger a negative spiral of hunger, poverty, low resistance, diseases, lack of seeds, etc. The number of successive years with low yields is expected to increase in the future. The devastating droughts in Sahelian Africa in the early 70's were somewhat less pronounced in The Gambia.

Adaptation strategies should be focused therefore on trying to minimise the years with low yields or to assure that sufficient resilience is built amongst people to overcome these years. In terms of reducing the low yields, adaptation options such as irrigation and the use of drought resistant varieties might be explored. Building resilience to crop and people can be done by a range of technical as well as socio-economic measures like loans and savings schemes, improved food storage capacity, integration of livestock farming with arable farming, and reservoir or groundwater storage capacity.

13.2.2 Distant future (2070-2099)

The projections according to HADCM3 for precipitation are dramatic. Precipitation is projected to go down by almost 60% at the end of this century. It is clear that this is an extreme in comparison to other GCMs (GOTG, 2003), but it is interesting to analyse the extreme as a worst scenario case.

Table 13.2 indicates, as expected, that under these low rainfall conditions, hardly any crop production is possible. However, as a result of the increased CO_2 levels, higher temperatures and solar radiation, the production potential of millet increases by almost 60% as compared to 1961-1990. The low rainfall, however, puts so much stress on the crop that this production potential is not met, except in four years where the rainfall was high.

It is obvious that the only adaptation to this extreme reduction in precipitation is shifting to irrigated agriculture. However, the lower rainfall means also that the recharge to the groundwater will be lower. It is known that some hydrological processes are highly non-linear, e.g. a reduction in precipitation by 50% might affect percolation much more than 50%. Model results show that for the reference period, average percolation is 440 mm and will reduce to only 30 mm over the period 2070-2099.

13.2.3 Yields according to the ECHAM4 projections

It has been made clear that the HADCM3 projections for Western Africa are somewhat drier than some of the other GCMs (GOTG, 2003). We have therefore selected to evaluate the impact of climate change on millet yields also for the ECHAM4 GCM using again the A2 SRES forcing. The models were set up similar as for the HADCM3 as described before, with only changing the meteorological input. Unfortunately, ECHAM4 'projections' start only from 1990 onwards, so the reference period selected was 1990-1999 instead of 1961-1990.

Table 13.3 shows the impact of the climate change projections according to ECHAM4. Average yields will go up, but a small increase in variation can be expected. The major reason for this increase is the combined effect of the CO_2 fertilisation, slightly more rainfall, and the increased solar radiation. However, higher temperatures increase the crop water requirements. The simulation model integrates all these factors in an integrated manner, resulting in the output as shown in Table 13.3.

	HADCM3 average (kg ha^{-1})	*CV (%)*	*ECHAM4 average (kg ha^{-1})*	*CV (%)*
Reference	1 115	30	923	23
Near Future (2010-2039)	1 141	33	1 046	24
Distant Future (2070-2099)	243	123	1 274	29

Note: Reference period for HADCM3 is 1961-1990, for ECHAM4 1990-1999.

Table 13.3: Impact of Climate Change on Millet Yields Explored with the Crop-Soil Model for the two GCMs Considered

Since changes in yields are much lower than according to the HADCM3 projections, it was decided to concentrate the adaptation strategies on the worst case only.

14 Adaptation Strategies

14.1 Definition of Adaptation Strategies

It is clear that considering the results of the impact assessment as presented in the previous section, adaptation strategies for the near future (2010-2039) should be different from those for the distant future (2070-2099). For the near future it is most important that adaptation be focused on reducing the expected increase in variation in yield, while for the distant future only the introduction of irrigated agriculture seems to be viable. Given the extreme reduction in precipitation as projected by the HADCM3 in comparison to other GCMs, and the fact that measures taken in the near future will be also beneficial for the longer term, we will concentrate here only on adaptation strategies for the near future (2010-2039).

In the First National Communication (GOTG, 2003) no adaptation strategies for the agricultural sector were explored, but only some potential measures were mentioned focusing on:

- crop breeding programs;
- soil fertility;
- planting dates;
- irrigation;
- integrated agricultural systems;
- early warning systems;
- advanced post harvest technologies.

Using these recommendations in combination with additional discussions and the objectives of this particular study, the following three adaptation strategies are explored: (i) improved crop variety, (ii) enhanced use of fertiliser, and (iii) introduction of irrigation.

14.2 Improved Crop Variety

The first adaptation strategy explored is the introduction of a millet crop variety adapted to the local conditions in The Gambia. Although the breeding as such will require substantial efforts, we assume here that the variety developed will be (i) more drought resistant, (ii) high yielding, and (iii) a decreased growing season from 100 days to 80 days. These three changes in crop characteristics were included in the SWAP model and simulations were run for the near future (2010-2039).

Actual millet yields will increase by about 25% and also a reduction in year-to-year variation will occur (Table 14.1). However, years with low yields will still occur as precipitation is still too low even for the drought resistant crops. As discussed earlier, projections of rainfall indicate that values can be as low as 310 mm y^{-1} according to the HADCM3 model.

		Yield	
	Average (kg ha^{-1})	*Change (%)*	*CV (%)*
No adaptation	1141		33
Crop variety	1294	+13	32
Fertiliser	1517	+33	25
Irrigation	1563	+37	11
Supplemental irr.	1247	+9	30

Note: Change indicates the change in yield compared to the no adaptation, CV is the year-to-year Coefficient of Variation in yields.

Table 14.1: Results of the Adaptation Strategies as Explored with the Model for the Near Future (2010-2039)

One of the major efforts of this adaptation strategy will be to breed these varieties that are adjusted to the local conditions in The Gambia. Although some of these varieties do exist already, the distribution of seeds is an even greater challenge. Normal farmer practice is that seeds from the previous year are used for the next year. So, this adaptation strategy should clearly go beyond the technical aspects of breeding and requires substantial efforts in terms of extension services and credit schemes.

14.3 Enhanced Fertilizer Use

It is well documented that the problem of Sub-Saharan Africa is not solely precipitation, but also nutrient shortages (e.g. Rockstrom, 2002). A shortage of nutrients is on the one hand having a direct impact on crop growth, but has also an indirect impact on soil water holding capacity. Soils in the Yundum region have reasonably high soil water holding capacities already, so the major benefit from an increased use of fertiliser will be on the crop. In terms of fertiliser, the approach we follow here is not specific in whether this will be by means of chemical or natural fertiliser. The SWAP model is not specific in the amount of fertiliser that will be applied, but assumes that the soil nutrient status goes from poor to good. In practical terms this can be translated to about 200 kg N ha^{-1}. A more detailed exploration focusing on this fertiliser use was done by the DSSAT model (GOTG, 2003).

The use of fertiliser will increase crop yields and reduce year-to-year variation (Table 13.3). However, since fertiliser will mainly play a role in terms of the production potential of the crop and only a minor role on drought resistance, still many years with low yields can be expected.

14.4 Irrigation

One of the most obvious adaptation strategies is the introduction of irrigation. Considering the decrease in rainfall as projected by the HADCM3 in the near and distant future, irrigation might be the only solution. As discussed earlier, the question at the moment is whether the long-term average rainfall will be sufficient to store water for irrigation purposes. For the near future, this will be the case too, but according to the HADCM3 projections, severe water shortage will occur at the end of this century. Storage of water in reservoirs might be difficult in The Gambia given the topography, so one should concentrate on either irrigation from groundwater or from river water. The latter requires a proper analysis of salt water intrusion, which can be up to 250 km upstream. Obviously, expected sea level rise and a reduction in runoff might increase this figure substantially.

The use of groundwater for irrigation purposes is certainly a viable option, given the fact that groundwater recharge is high and is also for the near-future, expected to be high. However, groundwater levels are somewhere between 10-30 m which will bring high costs to pump this water. We have therefore split this irrigation adaptation strategy in two sub categories: full irrigation and supplemental irrigation.

Table 14.1 shows that the full irrigation option has a substantial impact on crop yields and variation in yields. Yields will increase by almost 40% compared to the no adaptation case. The amount of irrigation required to obtain these higher yields vary between 0 to 500 mm y^{-1} depending on the amount of precipitation. The long-term mean annual irrigation requirements are 200 mm y^{-1}.

In terms of food security it is evident that the year-to-year variation should be low. For the business as usual strategy, the number of years where millet yields are below 1000 kg ha^{-1} is 9 out of 30. Applying the irrigation adaptation strategy reduces this to zero. This adaptation strategy is clearly worthwhile to pursue, but a proper economic analysis including benefit—costs analysis and the social and managerial implications should be analysed more in detail before concrete implementation plans are to be developed.

Given the constraints in terms of costs of irrigation, the so-called supplemental irrigation case was explored. The assumption was that the maximum amount of irrigation available for a single year was 150 mm, and as long as rainfall was not reducing crop yields too much no irrigation would be applied. In the SWAP model this was implemented assuming that a farmer starts to irrigate his field only if the soil moisture content at 50 cm depth was below pF 3. This strategy reduced the year-to-year variation and increased the average crop production by about 10%.

The supplemental irrigation as specified here is minimal and is sometimes referred to as survival irrigation: providing only one or two irrigations to ensure that the crop will not die. The difference between the two irrigation adaptation strategies is somewhat vague and the supplemental irrigation can be explored further by setting the threshold value of 150 mm to some higher levels.

15 Economic Assessment of Adaptation Strategies

15.1 Introduction

The previous chapters in this report have looked carefully at the use of crop yield models (SWAP in particular) to estimate not only the effects of climate change and CO_2 fertilisation on millet yields in The Gambia with and without climate change, but also the potential for some specific 'non-traditional' management (adaptation) options to reduce yield losses due to the net effects of climate change and CO_2 fertilisation. This section of the report focuses on the rationale for integrating an assessment of the additional costs of these management options into the crop yield assessment and presents an outline of economic analysis methodology and some preliminary results showing the relative profitability of irrigation as an adaptation option.

Studies by Rosenzweig et al. (1993, 1995), Rosenzweig and Parry (1994) and Parry et al. (1999) have assessed the global implications of various adaptation options (such as changing crop planting dates, increasing fertiliser use, adoption of new plant varieties and expanding irrigation) on the production of grain crops using a combination of crop yield models and a global trade model. For these investigations, the crop yield models were used to estimate the effects of various management (i.e., adaptation) options on small grain yields, with and without climate change. The yield estimates derived from these simulations were then used to change the crop yields in a global trade model, and the global trade model was used to explore the implications of climate change on crop production (including small grains) with and without climate change and the adaptation options. These studies generally have found that the adaptation options under investigation helped to offset grain production and GDP losses due to climate change.

The major limitation of this approach is that it only addresses the benefits of adaptation options (increased yields) without considering the possible additional costs of these options, and the impact of this cost on their comparative profitability. Implicitly, these studies assume that the adaptation options do not cost any more than traditional management options for the same crops. So, given higher yields associated with the adaptation options, they appear to be more profitable than the traditional management options. In a market setting this would lead farmers to adopt the adaptation measures through 'autonomous' adaptation and would, in turn, help to offset production losses due to climate change using traditional management methods.

But, what if adaptation is not free; and worse still, what if the production costs of the adaptation measure are higher than for traditional practices? How will farmers behave? The simple answer is that profitability of the adaptation strategies relative to traditional management will not be as great (and may even be negative) and, as a result of this, the economic incentives of farmers' to adopt these measures will be diminished, and less 'autonomous' adaptation will occur.

Figure 15.1 shows a series of inverse supply curves for a single crop. From the perspective of an individual farmer, these supply curves, S(C, M), trace out the minimum marginal cost (on the vertical axis) at which the farmer can supply increasing levels of output (on the horizontal axis). Holding output constant, the marginal cost at which this output can be produced is influenced by climate (C) and the management options chosen by the farmer (M). To keep the graphic analysis tractable, we assume that climate change does not affect the market price (P) of the commodity and that climate change increases the marginal cost of producing a given level of output of the commodity, holding management constant, due to yield reductions.

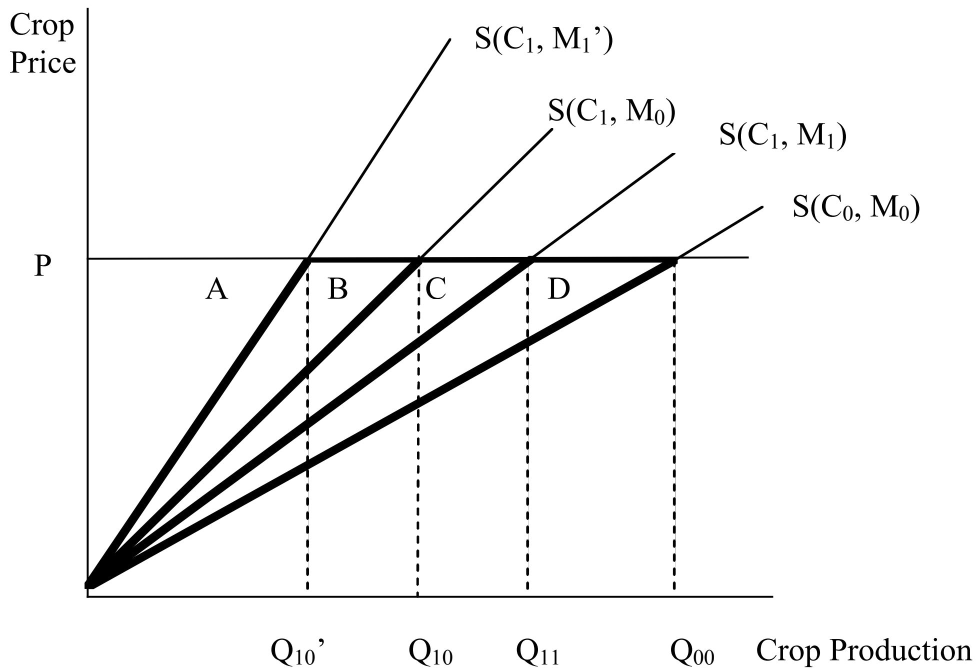


Figure 15.1: Illustrative Example of Inverse Supply Curves for a Single Crop

Under the current climate (C_0) the farmer uses management (M_0), and therefore the supply curve S(C_0, M_0) will govern the farmer's production decision. At the market price, P, the profit-maximising farmer will produce Q_{00} tons of the crop, on average, and the farmer's profit will be equal to the sum of the four triangular areas: A+B+C+D. Now, if we assume that climate changes from C_0 to C_1, and the farmer has three supply curve choices for adapting to climate change, each embodying a different type of management, and each with a different level of optimal output and implied profit at the market price. These choices are: S(C_1, M_0), which characterises production decisions, using the same management as under C_0, with an associated production level of Q_{10} and a profit equal to the sum of the areas A+B; S(C_1, M_1), which characterises production decisions using management M_1, with an associated production level of Q_{11} and a profit equal to the sum of the areas A+B+C; and S(C_1, M_1'), which characterises production decisions using management M_1', with an associated production level of Q_{11}' and a profit equal to the area A. As such, the latter two supply curves can be seen to characterise production decisions, using potential adaptation options. Which of the three management options (and supply curves) will govern the behaviour of the profit-maximising farmer? The answer is the supply curve with the lowest marginal costs, this being the supply curve that will produce the highest profit, namely S(C_1, M_1), and which also produces the smallest decrease in production and profit loss relative to production under the initial climate.

For The Gambia, we want to analyse the relative profitability of the various management options under consideration to find out if these options are likely to be adopted as a result of autonomous adaptation, because they are more profitable than current practices, or if they are less profitable than current practices we want to assess the costs of 'forcing' these options into the market for policy reasons using the instruments available to The Gambian government. But this task is complicated by the fact that much small grain production takes place at the household level and by the fact that many of the inputs used to produce small grains by the household are difficult to price in market terms. These are common problems which economists face when working with small farm holders in developing countries and which make it very difficult to develop supply curves for household producers.

As a way of getting around these two problems, we propose to assess the cost-competitiveness of the management options as measures a) to replace food aid during periods of extreme drought; and/or b) to replace small grain imports over a wider range of climatic conditions to achieve self-sufficiency in small grain production, and we propose to do this both under the historical climate and several climate change scenarios for The Gambia. Framing the problem in either of these two ways will allow us to estimate and compare the additional cost of each of the management options per mt of small grain production against a) the full cost per mt of providing food aid; and/or b) the import price of small grains. The results of this assessment will then make it possible to determine if the adaptation options are likely to be adopted through market forces (possibly aided by assistance to farmers to train them in the use of the management options), or the extent to which the government will need to subsidise farmers or tax imports to push these management options into practice.

In section 15.2 below, we give an illustrative example of benefit-cost analysis applied to irrigation using historical climate.

15.2 Methodology

In the process of economic analysis, costs and benefits are first identified, and then evaluated in monetary terms as far as possible. This leaves out intangible costs and benefits which cannot be expressed in monetary terms.

In the example given, we also omit costs associated with land rental and fertility treatment, pest control, seed purchase, operation and/or maintenance of farm machinery/animals, etc. This is more to do with expediency than principle, and does not detract from the generality of the analysis which focuses on the economics of irrigation water delivery.

15.2.1 Cost Study

Major considerations in the cost study include the (a) identification of water sources; (b) assessment of crop water requirements; (c) selection of irrigation method; and (d) costing of structural works, activities, and inputs, indispensable to irrigation water delivery.

Groundwater in the Gambia is of high quality, and, unlike surface water, is less constrained by seasonality, making it the natural choice for irrigation, especially for upland crops such as millet.
The downside to groundwater-based irrigation is high energy costs, which in effect constitute a major decision variable in the selection of water lifting technology (GITEC, 1992; UNDP, 1996).

Irrigation of upland crops is a relatively new addition to agricultural practices in the Gambia, and in the few places where it exist; sprinkling irrigation using labour-intensive methods is generally used. Whether this is the most cost-efficient way forward is yet to be proven, but the practice is quite understandable given the low costs of labour and technological sophistication required.

Cost element	*Groundwater*		*Surface water*	
	Solar	*Diesel*	*Diesel (1)*	*Diesel (2)*
Dam	n/a	n/a	13 488 178	0
Borehole/Intake	1 177	1 177	0	0
Modules/Panels	6 025	n/a	n/a	n/a
Pump and/or Inverter	2 057	1 285	3 213 656	3 213 656
Generator	n/a	219	547 732	547 732
Tower and tank	3 466	6 485	n/a	n/a
Distribution network	2 082	13 879	34 697 108	34 697 108
O&M costs	2 267	34 488	86 220 703	86 220 703
Unskilled labour	368	2 453	6 131 250	6 131 250
Total Cost	17 441	59 986	144 298 627	130 810 449
Cost per ha	5 814	2 999	2 763	2 494
Cost per m^3 water	0.53	0.27	0.25	0.23

Notes:

n/a = not applicable.

Water supplied per ha is 11,000 m^3/yr in all cases investigated

Infrastructure and other costs in columns 2, 3, and 4 relevant to irrigation areas of 3, 20, and 50,000 ha, respectively.

Diesel (1) 15% of the cost of dam construction is allocated to irrigation.

Diesel (2) 0% of the cost of dam construction is allocated to irrigation.

Table 15.1: Annualised Costs of Infrastructure Components and Manual Water Delivery (in US dollars)

Table 15.1 gives the cost build-up for irrigation water supply from different water sources, using different water-lifting technologies. Annual costs are obtained by summing up investment, operation, maintenance, and replacement costs. Costs are derived from price and economic life data provided by suppliers and developers, a discount rate of 9% and a project horizon of 60 years. In the case of irrigation using surface water, joint and separable costs probably applicable to irrigation development within the context of the OMVG (Interstate Organisation for the development of the Gambia River Basin) are considered. Further simplifications entail the assumption of zero terminal salvage value for infrastructure.

In this table, variations in the cost of the options presented are both technology- and scale dependent, with solar-based systems exhibiting the highest development cost per hectare or per cubic meter (m^3) of water.

On a percentage basis, O&M and distribution costs represent the two largest components. For both surface and groundwater, and independent of scale, they account for 80 – 90% of total cost of irrigation using diesel-based water-lifting technologies. The corresponding value for solar pumping is 25%, whilst labour accounts for 2 – 5% of costs. The assumption made here is that there is no scarcity of and competition for labour. According to Kargbo (1989), labour is the most important factor in the Gambian farming system, and if demand is not met by migrant labour, this component should see an increase in its overall share.

15.2.2 Benefit study

The benefit study uses output from SWAP-WOFOST in order to evaluate the benefits of adaptation (i.e., irrigation) under current climate $S(C_0, M_1)$, compared to no adaptation $S(C_0, M_0)$. Increased production arising from irrigation is hypothetically traded on the cereal market at constant dollar values of $150 per metric ton.

	Average Yield (mt/ha)	*Market value (US$)*
Without irrigation	1.1	165
With irrigation	3.1	465
Difference	2.0	300

Table 15.2: Annualised Benefit from Improved Yields (in US dollars)

Only direct benefits, which consist of increased farm production and income, are considered in this example. A fuller analysis would assign monetary values to off-farm agriculturally related activities, handling, marketing, and processing of produce. Table 15.2 shows that increased crop production yields a net return of $300/ha.

15.3 Benefit-Cost Analysis

The philosophy behind benefit-cost analysis and computational procedures are quite straightforward. Net benefit of adaptation is computed by subtraction of total costs (C) from total benefits (B), i.e., B – C.[26] Alternatively, a benefit-cost ratio, B/C, indicates the profitability or otherwise of a given adaptation option.

The most economical cost of water established in the cost study is used in the analysis, which examines sensitivity of results to discount rates. The value of 3% in Table 8.3 is a good approximation of net effective interest rate from 1961 to the late 1970ies, whereas 14% is a better reflection of interest rates on borrowed capital from Gambian commercial banks, and inflation during the decade 1981 – 1990.

A number of points emerge from Table 15.3. Under the assumptions used in this example, net benefits of irrigation development are negative, and translate to B/C values closer to zero than to 1. Table 15.3 further indicates the sensitivity of results to discount rates. Higher rates raise average costs and

[26] All benefits and costs are considered as incremental with reference to the situation without irrigation $S(C_0, M_0)$.

consequently depress B – C, or B/C ratios. It is quite understandable that inclusion of other production costs will worsen the B/C ratios, but on the other hand, operation of boreholes as dual-purpose infrastructure, will have the opposite effect. At $150 per metric ton, millet yields of 14 t/ha and 21.5 t/ha, totally unheard of, are needed in order to obtain positive economic returns, at 3% and 14% discount rates respectively. Even at $300 per metric ton, i.e., international market price of 100% broken Thai B rice at the end of the study period, positive net benefits remain an elusive target.

	Discount rate	
	3%	*14%*
Irrigation costs	2 171	3 233
Benefits	300	300
Net benefits (US$/ha)	-1 871	-2 933
B/C	0.14	0.09

Table 15.3: Net Benefit and Benefit-Cost Ratios Associated with Irrigation Water Delivery for Specified Market Price of Millet

A cereal balance for the Gambia is established for the period 1961- 1990 using nutritional requirements, population, cultivated area, yield data from SWAP-WOFOST, and agricultural statistics kept by the Department of State for Agriculture in the Gambia. The cereal balance is the difference between consumption (C) and production (P) adjusted for stock held at the start of the accounting period. In this figure, surplus cereal production shows up as positive P – C values, whilst negative values indicate shortfalls that need to be made up through commercial imports and/or food aid (see Figure 15.2)

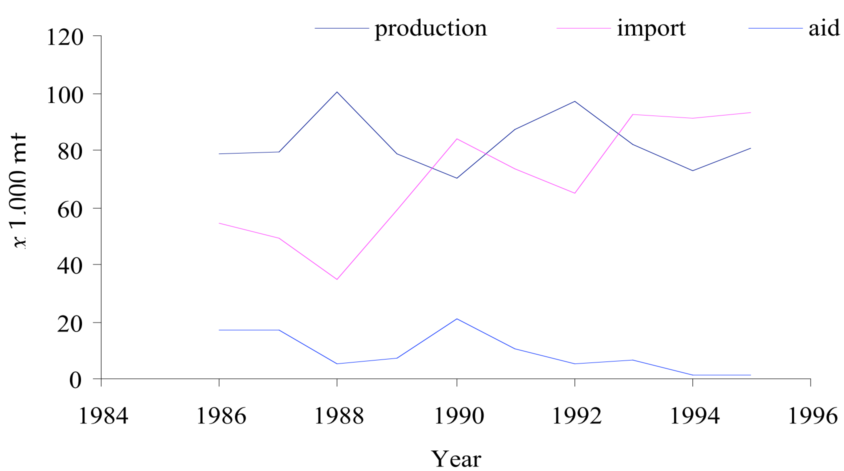


Figure 15.2: Time Series of Cereal Production, Imports, and Food Aid (1985-1995)

Observe the synchronicity between production shortfalls, higher imports, and food aid inflows and the downward trend in the latter (source: GOTG, 1996. Country Paper for the World Food Summit)
A major point of observation from Figure 15.2 is the increasing deficit in production, starting in the early 1970ies. Food production deficits/surpluses, i.e., P – C, depend on the prescribed per capita consumption

used in the analysis. Indeed, the absolute value of deficits only equals imports when a per capita consumption of 170 kg/person/year and STU of zero are assumed. We point out that this per capita consumption is very close to the value of 175 kg/person/year used by DOSA (2002), but both values yield results contradicting historical data on rice imports, the substitute cereal for millet and vice versa. We have therefore opted to use the value of 250-kg/person/day that is much closer to the average in CILSS countries.

Impact Measure	*STU = 0%*		*STU= 20%*	
	Without irrigation	*With irrigation*	*Without irrigation*	*With irrigation*
Commercial Import/Food Aid (mt)	49 196	0	52 601	0
Commercial Import/Food Aid (US$)	7 379 383	0	7 890 218	0
Crisis years	20	0	19	0
Foreign exchange savings (US$)	- 7 379 383	22 582 350	- 7 379 383	22 582 350

Notes:

n/a = not applicable.

All values except crisis years are averages over 30 years. Assumed per capita cereal consumption is 250kg/person/year.

Crisis years defined as years when food STU falls below the food security threshold set by policy is the total out of maximum of 30.

Table 15.4: Socio-Economic Impacts of Irrigation Under Different Food Security Policies for the Period 1961 – 1990

The most riveting observation from Table 15.4 is that increased production from irrigation for the period under study would eliminate the need for commercial cereal import/food aid. A second point of major significance that substantial foreign exchange savings could be made, and, wholly or partially re-invested in agricultural development. To fix some ideas, annual savings of roughly $22 million could fund the development of 7 500 ha of millet using diesel-pumped groundwater.

Differences between dollar values of commercial import/food aid and foreign exchange savings arises due to higher premium placed on food security when STU is set to 20% compared to 0%. On the other hand, foreign exchange savings under rain-fed and irrigated conditions are entirely based on computations using production deficits/surpluses and market price of cereals.

15.4 Concluding remarks

Traditionally, food production shortfalls are made up from commercial imports and/or food aid. In the 1960s and well into the 1970s, cheap food imports have had a significant influence on agricultural and trade policies (Carney, 1986). However, a deteriorating economic situation and consistently rising food prices at the rate of 14% per annum, starting in the mid-1980ies, has forced a rethink of both policies. Potential impacts of climate change and extreme weather on counties with surplus production (Parry et al., 1999), and the risk of those countries reverting to scarcity economics in years of low production, makes it extremely important for countries like the Gambia to increase their food production and concurrently decrease import volumes of staple food. Observe that these objectives have a positive impact on global food reserves whether or not the Gambia is/becomes a surplus food producer. Social impacts of re-vitalised agricultural production on employment generation, alleviation of poverty (increased income, improved nutrition of women and children), rural re-generation/development, etc., cannot be over-emphasised.

Currently, cereal imports account for 9% of the import bill, second only in dollar value to mineral fuel imports. Statistics on food aid reported in GOTG (1996) indicate relatively small and decreasing volumes (Figure 15.2), which perhaps reflect current donor emphasis on increasing national food production capacity. As a matter of fact, the Gambia government's 'Special Programme for Food Security', launched in 2002, is getting financial and technical support for crop production from the FAO, the government of Italy, the UN Human Security Trust Fund, amongst others (GOTG, 2004).

Whilst preliminary results shown above indicate substantial benefits from irrigation at a macro economic level, increased income from irrigation is not matched by costs incurred by farming household (i.e. dabadas), suggesting the need for further policy measures to support irrigation.

It should be noted that agricultural sector and related policies (water resources, energy, fiscal, social insurance/protection, trade, etc.) that translate into changes in the exchange value of production inputs, labour productivity, and market prices of crops, all have a potential to improve or degrade farm enterprise budgets. In general, economic policies that tax consumption whilst subsiding production have an overall positive impact on B/C ratios. It is also obvious that unattractive prices will ultimately undermine import substitution goals.

16 Conclusions and Recommendations

This study is aiming at the development of a framework for evaluating adaptation projects in the agricultural sector of The Gambia. The major steps taken were:

- collect base data and information;
- extract IPCC projections for The Gambia;
- downscale these projections to the local conditions for The Gambia;
- setup a crop-water model;
- evaluate the impact of climate change on yields;
- define adaptation strategies;
- evaluate the impact of these adaptation strategies; and
- evaluate the economics of these adaptation strategies.

In this study we have set up and applied this framework using data from two GCMs while concentrating on the most common grain crop in The Gambia: millet. In terms of adaptation strategies we selected some of the most relevant strategies: crop variety improvements, fertiliser applications and irrigation. However, the modelling framework as it is setup can be easily applied to other GCMs, SRES scenarios, crops, soils, or adaptation strategies.

From the analysis it is clear that the impact of climate change on millet yields depends highly on the GCM selected. The HADCM3 projections indicate a much drier future, while the ECHAM4 ones indicate somewhat more rainfall in the future. Considering the 'no-regret' principle, we decided to explore the adaptation strategies for the HADCM3 projections only.
Emphasis was put on the annual variation, and more specifically on the successive years of low yields. Introduction of irrigation appears to be the most successful adaptation strategy, yields will increase and, moreover, year-to-year variation decreases substantially.

The detailed economic analysis shows that whilst preliminary results indicate substantial benefits from irrigation at a macro economic level, increased income from irrigation is not matched by costs incurred by farming household (i.e. dabadas), suggesting the need for further policy measures to support irrigation. This is all the more relevant given the deteriorating economic situation, triggered mainly by low exports and increasing imports. Also, given the potential impacts of climate change and extreme weather on countries with surplus production, and the risk of those countries reverting to scarcity economics (as is the case this year), especially in low production years, low GDP countries like Gambia are better of growing their own food than expecting to meet their demand from imports.

Finally, the most promising adaptation option(s) has to be implemented and successive studies should look into whether these adaptation strategies can be adopted through market forces, whether the government should impose these by subsidies or tax regulations, or whether bi-lateral aid should focus on this in an effort to minimise risks of food shortages.

PART III: PROJECT OUTCOMES

17 Capacity Building Outcomes and Remaining Needs

Workshop empowered the AF47 team, and increased its capacity and ability to analyse technical issues, to appreciate the multi-disciplinary nature of our project and to work in this context, and to apply some of the techniques and skills learned. All these added a new dimension to learning and skills, and totally improved our approach to the adaptation project. Important lessons learned in workshops were in terms of framing adaptation science for policy making. This deepened our understanding of adaptation, especially along lines of: how it reduces impacts; the obstacles and barriers to better adaptation; adaptation priorities and how they are selected; the complimentarily between adaptation, climate change and vulnerability; how adaptation works for both measures and policy, and the linkage between adaptation and sustainable development. Our learning process was also enhanced by case studies or presentations by participants on different AIACC projects and our interaction with them. All these helped to put our work into proper perspective. Above all, workshops were also a forum for networking, information sharing and for exploring avenues for collaboration with other groups. We are now better able to supervise post-graduate students in adaptation, conduct more research in the area, and monitor adaptation projects for other agencies.

The AF 47 team developed a dynamic model which takes into it runoff sources for all reservoirs and includes all irrigated agricultural production in the lower Berg River Basin. First, the current version of the model needs to be updated, with water supply and cost data updated, and explore policy options further. Second, the team relied on MINOS or CONOPT versions which took much too long to arrive at solutions. Affordability and availability of latest software like the CPLEX QIP for GAMS would have helped find solutions in a much quicker time. This, in turn, would have enabled the team to be better able to probe further on the area studied, to teach other members of the team about the packages used, to develop a broader range of scenarios, to work closely with other regional modellers, and to pass on the skill to others.

Early 2004 we were given a slot in an NCCC meeting to present on adaptation, and not too long ago circulated our findings at this meeting. Apart from raising awareness on the project particularly given the diverse nature of NCCC membership, there has been keen interest on adaptation from various people, particularly as it applies to a contested area as the Berg River Basin. We have been able to share our ideas with NCCC members and to take into account their thinking in certain areas. Interest is continuing, and the study will add much to existing knowledge and bring into fore further questions to be explored. The important thing for the team is now to test and apply the model developed to other river basins, and to further develop it as a standard tool that is easy to apply and interpret for estimating costs and benefits of adaptation to avoid climate change damages.

18 National Communications, Science-Policy Linkages and Stakeholder Engagement

The Department of Environment and Trade is South Africa's focal UNFCCC and GEF point, and hosts the National Committee on Climate Change (NCCC) meetings. The NCCC membership includes various government departments, of note: the Department of Environment and Tourism, the Department of Minerals and Energy, the Department of Foreign Affairs, the Department of Agriculture, the Department of Water Affairs and Forestry, the Department of Trade and Industry, the Department of Science and Technology. Some Non-governmental Organisations and interested researchers from various universities also attend. The Energy Research Center is a member of NCCC, and attends meetings on a regular basis. We presented the project AF 47 at an NCCC gathering early in 2004, and our work has attracted a lot of interest from various parties since then. We circulated out findings at its last meeting and have been requested to give a presentation at the Climate Change & Biodiversity in Africa Conference to be held in Pretoria in October this year.

The Department of Water Resources in The Gambia hosts the FNC. FNC is largely based on climate change studies undertaken by the National Climate Committee (NCC) under the chair of GCRU-DWR, and is the source of adaptation options/measures identified. The NCC brings together people of different professional backgrounds from government, non-governmental organisations and private sector institutions. It has a current membership of around 50 institutions from both national and regional level institutions.

Towards the end of May 2003, GCRU-DWRpresented this project, particularly the selected, workable project to the Agriculture and Natural Resources Working Group (ANRWorking Group).[27] The feedback received was very favourable for the pursuit of the project, as it was felt that the expected results would be very useful in furthering current understanding of drought and its impacts on the socio-economic sectors of the country.

GCRU-DWRin collaboration with UNEP, has finalised its project proposal for the implementation of the National Adaptation Programme of Action (NAPA) under the auspices of the UNFCCC. All the adaptation options/measures that NAPA intends to examine originate from the First National Communication. Moreover, it is expected that experience gained in the AIACC project would be very useful in implementing the NAPA.

[27] The ANRWorking Group was established in 1995 and comprises of high level professionals in the agriculture and natural resource sectors, to provide policy guidance on the sectors to government. The Group is empowered to approve project proposals and, to monitor, evaluate, and take major decisions on all projects being implemented under the agriculture and natural resource sectors.

19 Outputs of the Project

Papers Published:

Callaway, John M. 2004a. '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, John M. 2004b. 'Chapter 4: The benefits and costs of adapting to climate variability and change' in OECD, The Benefits and Costs of Climate Change Policies: Analytical and Framework Issues. OECD, Paris, France.

This papers will benefit researchers, policy makers, researchers and planners working on adaptation and climate change. Analysis is quite rigorous and the works assume some understanding of economics. Copies can be obtained from: mac.callaway@risoe.dk

Other Papers:

J.C. Nkomo, D.B. Louw, D.A. Sparks, J.M. Callaway and M.E. Hellmuth 2004. Capacity Building in Analytical Tools for Estimating and Comparing Costs and Benefits of Adaptation Projects in the Berg River Basin, South Africa. Messages from Dakar. GEF/AIACC.

Momodou Njie, Molly Hellmuth, Peter Droogers, Bubu Jallow, John Mac Callaway, and Bernard Gomez. 2004. Adaptation of Gambian Agriculture to Climate Change: Novel or Re-discovered Strategies? Messages from Dakar. GEF/AIACC.

J M Callaway, M.E. Hellmuth, J.C. Nkomo, D.A. Sparks and D.B. Louw 2003. Estimating and Comparing the Benefits and Costs of Avoiding Climate Change Damages. AIACC Notes. November 2003. See also: http://uneprisoe.org/AIACC/BergRiverCaseStudy%20.pdf

Molly Hellmuth and Debbie Sparks. Modelling the Berg River Basin: an explorative study of the impacts of climate change on runoff. Working Paper submitted to AIACC.

Bernard Gomez, Momodu Njie, Bubu Jallow, Molly Hellmuth, John Mac Callaway, Peter Droogers. 2004. Adaptation to Climate Change forAgriculture in The Gambia: An explorative study on adaptation strategies for millet. Submitted as AIACC Working Paper

Hellmuth, M.E. and Sparks, D.A. 2005. An explorative study of the impacts of climate change on run-off in the Upper Berg and Riviersonderend River Basins, South Africa. Submitted to the South African Journal of Science.

Jabavu C Nkomo, John M Callaway, D Louw, M Hellmuth and D Sparks. Estimating benefits and costs of adapting to climate change: The Berg River basin case study. Draft paper being prepared for the Adaptation Systhesis book.

The target audience for this papers is: policy makers, researchers, academics and those with keen interest in adaptation and climate change. Papers (1) - (3) can be regarded as initial papers produced about the project meant for wide circulation, and mainly to report on the project itself and for awareness about the project activities. Items (4) and (5) serve as working papers, while (6) and (7) are papers under consideration for publication. For copies, contact: jabavu@erc.uct.ac.za.

AIACC Reports:

- JABAVU C NKOMO JULY 2003. 34 PAGES.
  HTTP://SEDAC.CIESIN.COLUMBIA.EDU/AIACC/PROGRESS/AF47_JULY03.PDF
- Jabavu C Nkomo, January 2004. 74 pages.
- http://sedac.ciesin.columbia.edu/aiacc/progress/AF47_Jan04.pdf
- Jabavu C Nkomo, July 2004. 76 pages
- Jabavu C Nkomo. January 2003. 25 pages

These are interim reports submitted to AIACC. They detail progress on the project as it was being undertaken, and report on project activities, tasks performed and output produced, difficulties encountered and lessons learned, interaction between project and preparation for National Communication, the remaining tasks to be performed, anticipated difficulties/challenges, and outputs produced at each stage. The reports are mainly of interest AIACC, and gave for intervention as was seen fit. Copies can be obtained from: jabavu@erc.uct.ac.za.

20. Policy Implications and Future Directions

20.1 Policy Implications

Part I Adaptation to Climate Change: The Berg River BasinCase Study

From a benefit-cost perspective, construction of the Berg River Dam at capacity levels that were optimal for the climate scenarios used in this analysis looks to be justified on the basis of economic efficiency. Under the low urban water demand assumptions, the optimal storage capacity of the reservoir ranged from zero (Option 1B –REF climate and 3B) to 116 10^6 m^3 (Option 2B – DF climate). Under the high urban water demand scenario, the optimal storage capacity ranged from 138 10^6 m^3 (Option 4B – REF climate), depending on the climate scenario used to 240 10^6 m^3 (Option 1B – REF climate), depending on the climate scenario used. Overall, the efficient market option (1B) required the smallest storage capacity levels for both low and high urban water demand scenarios.

From a benefit-cost perspective, the implementation of an efficient system of water markets, with or without construction of the Berg River Dam, resulted in the highest net returns to water compared to other simulated allocation systems under all climate and urban demand scenarios. Under the low urban water demand scenario, efficient water markets produced only slightly higher net returns to water compared to the other allocation systems – of the order of one billion Rand or less compared to the other allocation schemes. This represents welfare improvements of the order of two%, or less. Under the high urban water demand assumption, the system of efficient water markets outperformed other allocation methods by as much as 31%.

Agricultural water use was very robust to the simulated changes in climate, urban water demand assumptions and the presence or absence of the Berg River Dam than urban water use and water allocation policies. In the forty-eight benefit-cost simulations (4 water allocation options, 2 urban water demand assumptions, 3 climate scenarios, and 2 Berg River Dam options – 0 capacity and optimal capacity), annual average agricultural water consumption remained around 66 – 69 10^6 m^3 in all but six cases and all of these cases were without the Berg River Dam.

Urban water consumption, by contrast, fluctuated much more in response to both climate change and changes in water allocation policy. It is important to note that, under the low urban water demand assumption, annual average urban water consumption was always at, or above the upper policy bound used to represent adequate urban water supply, while under the high urban water demand assumption, annual average urban water consumption was at or below its lower policy bound. Also, when the upper and lower bounds on urban water demand were relaxed in Options 2B and 4B under the high urban water demand scenario, annual average urban water use dropped sharply, depending on the climate. These decreases ranged from roughly five – twenty-five below the lower bound on urban water used, imposed in the other water allocation scenarios, Options 1B and 3B.

Simulated climate change damages were relatively and absolutely much greater under our representation of the current allocation regime (Option 1B) than under the efficient water market regime (Option 4B) at high urban demand levels. These were the only two options for which climate change damages were calculated and compared. For Option 1B, estimated climate change damages, under the low urban water demand scenario, ranged from roughly three – six billion Rand (a five to ten% reduction in the net returns to water), depending on the severity of the climate change. Under the high urban water demand scenario, these losses increased to roughly thirteen – twenty-seven billion Rand (a fifteen to thirty-one% reduction in the net returns to water), depending on the severity of the climate change. For Option 4B, estimated climate change damages under the low urban water demand scenario were about the same absolute and relative order of magnitudes as for Option 1B. However, under the high urban water demand scenario, these losses were reduced – compared to Option 1B – to roughly seven – thirteen billion Rand (a seven to thirteen% reduction in the net returns to water), about half the value of the climate change damages experienced in Option 1B.

The impact of adaptation by adjusting reservoir capacity from partial to full adjustment was relatively small in both Options 1B and 4B. These were the only two options for which these benefits were calculated. Moreover, the net benefits of adaptation for Options 1B and 4B both declined when urban water demand was increased and the net adaptation benefits for Option 4B were quite small, when urban water demands were at high levels. For Option 1B, the estimated net adaptation benefits, under the low urban water demand scenario, ranged from about 0.04 – 0.7 billion Rand (a one to fifteen% reduction in climate change damages), depending on the severity of the climate change. Under the high urban water demand scenario, the net adaptation benefits in Option 1B decreased to around 0.05 – 0.2 billion Rand (less than or equal to a 1.5% reduction in climate change damages). For Option 4B, the estimated net adaptation benefits, under the low urban water demand scenario, ranged from about 0.05 – 1.1 billion Rand (less than or equal to a seventeen% reduction in climate change damages), depending on the severity of the climate change. Under the high urban water demand scenario, the net adaptation benefits in Option 4B decreased much more than in Option 1B to around 0.001 – 0.03 billion Rand (less than or equal to a 0.009% reduction in climate change damages).

The most significant reductions in climate change damages came from instituting a system of efficient water markets in Option 4B for our representation of the current allocation regime (Option 1B). Conclusion 6 indicates the adaptation benefits of the two water allocation policies, once these policies are adopted. It does not take into account the partial adaptation benefits associated with: a) substituting a system of efficient markets for the current allocation system and b) changing the optimal storage capacity of the Berg River Dam, from the current allocation system to a system of efficient markets. Under the low urban water demand scenarios, we found that the substitution of efficient markets in Option 4A under the NF and DF climate scenarios for the current allocation system in Option 1A under the REF climate explained fifty-five and twenty%, respectively, of the change in the net returns to water from Option 1A (REF climate) to Option 4B (NF or DF climates). Under the high urban water demand scenarios, this figure rose to roughly eighty-two% for both the REF to NF and REF to DF climate changes. The remainder of the changes in the net returns to water from Option 1A (REF climate) to Option 4B (NF or DF climates) could be explained by storage capacity adjustments associated with moving from Option 4A to 4B, holding the climate constant at NF or DF.

Overall, the analysis of the costs of caution and precaution did not provide any unambiguous results that would allow one to determine if it would be less costly to anticipate climate change or plan cautiously.

Part II Adaptation to Climate Change for Agriculture in The Gambia

From the analysis it is clear that the impact of climate change on millet yields depends highly on the GCM selected. The HADCM3 projections indicate a much drier future, while the ECHAM4 ones indicate somewhat more rainfall in the future. Considering the 'no-regret' principle, we decided to explore the adaptation strategies for the HADCM3 projections only.

Emphasis was put on the annual variation, and more specifically on the successive years of low yields. Introduction of irrigation appears to be the most successful adaptation strategy, yields will increase and, moreover, year-to-year variation decreases substantially.

21 Plans and Recommendations

Part I Adaptation to Climate Change: The Berg River Basin Case Study

Extend the BRDSEM model to characterize the entire Boland Region in the Western Cape. To do this, the following modifications have to be made to BRDSEM:

Include the runoff sources for, and the dynamic water balances in, all of the reservoirs in the area including those on Table Mountain, which provide water for Cape Town, those downstream of the regional farms, and those north of the study area in the Boland region, and

Include linear programming representations for the irrigated agricultural production in the lower Berg River Basin below the regional farms and north of the current study region.

Sufficient data currently exist to make these modifications. Acquiring and implementing the CPLEX QIP solver for GAMS can easily overcome the problems we experienced with long solution times in this study. In some trials by Arki Consulting in Denmark, solution time for BRDSEM was reduced by a factor of 1000 by using this solver instead of the current versions MINOS or CONOPT.

Conduct Research to gather data and estimate the parameters of sector-level monthly water demand and waterworks supply (cost) functions for the Metropolitan Cape Town Region. We have already noted that the estimates of the parameters of the urban water demand functions used in BRDSEM are not strongly supported by adequate data. In addition, we dropped the urban water works supply function that was in Louw's static model, because this could not be supported by empirical cost data and the use of arbitrary elasticity assumptions heavily biased the results. However, such an undertaking could be supported by the WRC, DWAF, or the CCT in the larger context of alternative urban water pricing policies, nationally, regionally, or just in Cape Town. Such a study is important to assist public and private sector policy makers and planners to address the alternatives for balancing the principles of equity and economic efficiency in urban water pricing in South Africa.

Add additional storage and non-storage capacity options for increasing water supplies and water use efficiency and reducing water losses in the basin. The current version of BRDSEM also needs to be updated by including the possibility for additional storage capacity in the region, based on proposed plans and estimated costs. These options would be implemented in BRDSEM in the same way the Berg River Dam was included in the model. In addition, the water supply and cost data needs to be updated for wastewater recycling and desalinisation of seawater. Finally, we need to include possibilities for reducing water losses and the associated costs of these options in the delivery of water to users by the Cape Town water authority and for the conveyance systems used to deliver irrigation water to the regional farms.

Improve the representation of water market transfers and include the costs of water market transactions. In the current study, simply removing constraints on agricultural water diversions and urban water demand simulates efficient water markets. The structure of BRDSEM is such that by removing these constraints, the solutions for the endogenous variables in the model are consistent with the implementation of efficient markets. However, this does not take into account how the current ownership of water rights and existing allocation of entitlements can be changed by specific transfers, nor does it include the transactions costs associated with these transfers. Modelling specific transfers is made a little difficult in BRDSEM because of the presence of return flows below each regional farm. However, it will still be possible to add many of the institutional features of water market transfers by including transfer balances in the model to represent existing entitlements and water rights and, after modifying them to take into efficient markets, looking at the impacts on downstream water users.

Develop a broader range of policy scenarios to blend efficient water markets with equity objectives in meeting the needs of the urban poor. The efficient market scenarios (Option 4A and B) led to high urban water prices and reduced urban water consumption by all households under the high urban water demand and climate change scenarios (NF and DF). We need to more fully explore the policy options and consequences of modifying water market policies to meet the basic needs of the urban poor.

Work closely with regional climate modelers in South Africa to implement BRDSEM using stochastic climate scenario data to generate downscaled distributions of monthly average temperature and precipitation data and transform this into stochastic runoff. This study is deterministic, with climate change risk introduced in an ex ante – ex post framework. The climate scenarios used in this analysis are based on the downscaled results of just three runs for the CSIRO SRES B2 REF, NF and DF scenarios. We do not know where these time series results lie in the over-all joint and partial distributions of monthly temperature and precipitation for the region. Thus, it is fundamentally misleading to characterise climate change using the deterministic approach and not very helpful for water resources planners. However, the model and methods we have developed and implemented in this study can easily be transferred to a stochastic environment. This approach would be implemented through the following steps:

- Estimate key parameters of the joint and partial distributions of monthly temperature and precipitation for selected climate change scenarios at different locations in the Berg River Basin using a regional climate model (RCM).
- Validate RCM simulations of precipitation and temperature for the existing climate in the Berg River Basin against observed records and use these data to estimate the distributions of the errors.
- Using this information, calibrate an existing water balance model, such as WATBAL stochastically, to simulate the joint and partial distributions of runoff and evaporation at selected runoff gages in the basin and the distributions of forecast errors associated with the runoff distributions.
- Use BRDSEM, stochastically, to propagate the distributions of key variables in the model and their associated forecast, such as monthly reservoir storage, urban and agricultural water demand, water releases, and various economic welfare components.
- Assess the impact of the forecast errors on Type I and Type II ex-ante, ex-post planning decisions.
- Develop an analytical tool and associated databases to automate the generation of stochastic climate forecasts and error propagation for the RCM, for general use in the region.
- Modify and automate an existing water balance model to generate stochastic runoff forecasts using stochastic climate forecasts.

Such a study represents an important step in bridging the communication and data gap between climate scientists and water planners, allowing water planners to work with climate change data on essentially the same basis they work with observed geophysical records, while taking into account inherent reliability problems in existing global and regional models to reproduce the 'historical' climate.

Part II Adaptation to Climate Change for Agriculture in The Gambia

The detailed economic analysis shows that whilst preliminary results indicate substantial benefits from irrigation at a macro economic level, increased income from irrigation is not matched by costs incurred by farming household, suggesting the need for further policy measures to support irrigation. This is all the more relevant given the deteriorating economic situation, triggered mainly by low exports and increasing imports. Also, given the potential impacts of climate change and extreme weather on countries with surplus production, and the risk of those countries reverting to scarcity economics (as is the case this year), especially in low production years, low GDP countries like Gambia are better of growing their own food than expecting to meet their demand from imports.

The most promising adaptation option(s) has to be implemented and successive studies should look into whether these adaptation strategies can be adopted through market forces, whether the government should impose these by subsidies or tax regulations, or whether bi-lateral aid should focus on this in an effort to minimise risks of food shortages.

22 References

Adams, R.M., R.A. Fleming, B. McCarl, and C. Rosenzweig. 1993. 'A Reassessment of the Economic Effects of Global Climate Change on US Agriculture,' *Climatic Change* 30:147-167.

Berg River Irrigation Board. 2000. Personal communication. Paarl, South Africa.

Callaway, J.M. 2003. 'Adaptation Benefits and Costs – Measurements and Policy Issues', Environment Directorate; Environment Policy Committee, OECD. ENV/EPOC/GSP (2003) 10/FINAL. Paris France.

Callaway, John M. 2004a. '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, John M. 2004b. 'Chapter 4: The benefits and costs of adapting to climate variability and Change' in OECD, *The Benefits and Costs of Climate Change Policies: Analytical and Framework Issues*. OECD, Paris, France.

Callaway, John. M., L. Ringius, and L. Ness. 1998. 'Adaptation Costs: A Framework and Methods' in Christensen, J. and J. Sathaye (eds.*), Mitigation and Adaptation Cost Assessment Concepts, Methods and Appropriate Use*. UNEP Collaborating Centre on Energy and Environment, Risø National Laboratory, Roskilde, DK.

Cape Metropolitan Council (CMC). 2000. Private communication with Mr. A. Singels, City Engineer, Cape Town.

Department of Water Affairs and Forestry, South Africa (DWAF). 1991. *Long-term urban water demand in the Western Cape Metropolitan region 1990-2020***.** Prepared by PH Spies and JB Barriage of the Institute for Futures Research at the University of Stellenbosch in association with Ninham Shand Inc. as part of the Western Cape System Analysis. Department of Water Affairs and Forestry Report No. PG000/00/1590, Pretoria, South Africa.

Department of Water Affairs and Forestry, South Africa (DWAF). 1992a. *Description of existing urban water supply infrastructure***.** Prepared by H.A Smit of Ninham Shand Inc. in association with BKS Inc. as part of the Western Cape System Analysis. Department of Water Affairs and Forestry Report No. PG000/00/1490**,** Pretoria, South Africa.

Department of Water Affairs and Forestry, South Africa (DWAF). 1992b. *Vooruitskattings van besproeiingswaterbehoeftes***.** Prepared by J Laubsher in association with F Ellis of the Department of Agricultural Economics, University of Stellenbosch as part of the Western Cape System Analysis. Department of Water Affairs and Forestry Report No. PG000/00/3091**,** Pretoria, South Africa.

Department of Water Affairs and Forestry, South Africa (DWAF). (1993a. Government Notice 966, Pretoria, South Africa.

Department of Water Affairs and Forestry, South Africa (DWAF). 1993b. *A review of the groundwater resources of the Western Cape***.** Prepared by G Dyke of Ninham Shand Inc. in association with BKS Inc. as part of the Western Cape System Analysis. Department of Water Affairs and Forestry Report No. PG000/00/2591, Pretoria, South Africa.

Department of Water Affairs and Forestry, South Africa (DWAF). 1993c. *Collection, storage and manipulation of data, Volume IV: Berg River Basin.* Prepared by G Howard of Ninham Shand Inc. in association with BKS Inc. as part of the Western Cape System Analysis. Department of Water Affairs and Forestry Report No. PG000/00/1190, Pretoria, South Africa.

Department of Water Affairs and Forestry, South Africa (DWAF). 1993e. *Hydrology of the Berg River Basin***.** Prepared by RRBerg of Ninham Shand Inc. in association with BKS Inc. as part of the Western Cape System Analysis. Department of Water Affairs and Forestry re Report No. PG000/00/2491, Pretoria, South Africa.

Department of Water Affairs and Forestry, South Africa (DWAF). 1994a. *Water requirements for the maintenance of the Berg River Estuary Volume 1: Report on Work Session***.** Prepared by S Granger of Ninham Shand Inc. in association with BKS Inc. as part of the Western Cape System Analysis. Department of Water Affairs and Forestry Report No. PG000/00/4993, Pretoria, South Africa.

Department of Water Affairs and Forestry, South Africa (DWAF). 1994b. *Water requirements for the maintenance of the Berg River Estuary Volume II: Compilation of papers by consultants.* Prepared by S Granger of Ninham Shand Inc. in association with BKS Inc. as part of the Western Cape System Analysis. Department of Water Affairs and Forestry Report No. PG000/00/4993, Pretoria, South Africa.

Department of Water Affairs and Forestry, South Africa (DWAF). 1994c. *Water Demand Management.* Prepared by PRLittle of Ninham Shand Inc. in association with BKS Inc. as part of the Western Cape System Analysis. Department of Water Affairs and Forestry Report No. PG000/00/4693, Pretoria, South Africa.

Department of Water Affairs and Forestry, South Africa (DWAF). 1996. *Skuifraam feasibility study: Berg River IFRrefinement workshop proceedings***.** Prepared by C. Brown of Southern Waters Ecological Research and Consulting cc. Department of Water Affairs and Forestry Report No. PG100/00/1296 Pretoria, South Africa.

Department of Water Affairs and Forestry, South Africa (DWAF). 1997a. *Skuifraam feasibility study: Main Report***.** Prepared by E van der Berg and R.B Martin of Ninham Shand Inc. Department of Water Affairs and Forestry Report No. PG100/00/0596, Pretoria, South Africa.

Department of Water Affairs and Forestry, South Africa (DWAF). 1997b. *Skuifraam feasibility study: Hydrology.* Prepared by E van der Berg and R.B Martin of Ninham Shand Inc. Department of Water Affairs and Forestry Report No. PG100/00/0797, Pretoria, South Africa.

Department of Water Affairs and Forestry, South Africa (DWAF). 2000. Private Communication. Mr. B. Van Zyl and Mr. B. Swart, Bellville, Cape Town.

Essop, Philda and Bulelani Phillip. 2005. 'Adapt or Die, Farmers Warned,' Cape Argus, January 21, 2005. Cape Town, South Africa.

Fankhauser, S. 1997. *The Costs of Adapting to Climate Change.* Working Paper Number 13. Global Environmental Facility, Washington, DC.

Gillig, D., B. A. McCarl, and C. C. Chen. 2001. 'Effects of Climatic Change on a Water Dependent Regional Economy: A Study of the Texas Edwards Aquifer,' Climatic Change, 49, 397-409.

Government Gazette. 1983. Notice 8693. State Printers Republic of South Africa, Pretoria.

Hewitson, Bruce. 2004. 'Scientist warns of climate change.' www.iafrica.com, 6 May, 2004. Cape Town, South Africa.

Hellmuth, Molly and Debbie Sparks. 2005. Modelling the Berg River Basin: An explorative study of he impacts of climate change on run off. Submitted as AIACC Working Paper.

Hitz, Sam and Joel Smith. 2004. 'Chapter 2: Estimating global impacts from climate change,' in OECD, *The Benefits and Costs of Climate Change Policies: Analytical and Framework Issues*. OECD, Paris, France.

Howitt, Richard. 1995. 'Positive mathematical programming'. *American Journal of Agric.Economics* 77:329-342.

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. 1996. *Climate Change 1995: Economic and Social Dimensions.* Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

IPCC. 2001. *Climate Change 2001: Impacts, Adaptation & Vulnerability*. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Just, Richard E., Darrell L. Hueth and Andrew Schmitz. 1982. *Applied Welfare Economics*. Prentice-Hall, Englewood Cliffs, New Jersey, USA.

Kelso, Maurice, William E. Martin and Lawrence E. Mack. 1973. *Water Supplies and Economic Growth in an Arid Environment: An Arizona Case Study*. University of Arizona Press, Tucson, Arizona, USA.

Louw, Daniël Bernard. 2001. *Modelling the Potential Impact of a Water Market in the Berg River Basin*. Ph.D. thesis. University of the Orange Free State, Bloemfontein, South Africa, January 2001.

Louw, Daniël Bernard. 2001. *The Development of a Methodology to Determine the True value of Water and the Impact of a Potential Water Market on The Efficient Utilisation of Water in the Berg River Basin*. Water Research Commission Report (WRC) No. 943/1/02, Pretoria, South Africa.

Mendelsohn, R. and J. Neumann, eds. 1999*. The Impacts of Climate Change on the US Economy*. Cambridge University Press, Cambridge, UK.

National Water Act 1998. Act no 36 of 1998. Republic of South Africa. www.dwaf.pwv.gov.za/Documents/Legislature/nw_act/NWA.doc

Yates, D.N. 1996. 'WatBal: An integrated water balance model for climate impact assessment of river basin runoff', *Water Resources Development* 2:121-139.

Silberberg, Eugene. 1978. *The Structure of Economics: A Mathematical Analysis*. McGraw-Hill, New York, New York, USA.

Smith J.B. and S. S. Lenhart. 1996. 'Climate Change Policy Adaptation Options,' Climate Policy 6:193-201.

Takayama, T. and G.G. Judge. 1971. Spatial and Temporal Price and Allocation Models. North Holland, Amsterdam, The Netherlands.

Titus, J.G., R.A. Park, S.P. Leatherman, J.R. Weggel, M.S. Greene, P.W. Mausel, S. Brown, C. Gaunt, M. Trehan and G. Yohe. 1991. 'Greenhouse Effect and Sea Level Rise: The Cost of Holding Back the Sea,' *Coastal Zone Management* 19:172-204.

Tol, R., J. Smith, and S. Fankhauser. 1998.'The scope for adaptation to climate change: what can we learn from the impact literature?' *Global Environmental Change* 8:109-123.

Vaux, H.J. and R.E. Howitt. 1984. 'Managing water scarcity: An evaluation of interregional transfers', *Water Resources Research* 20:785–92.

Yohe, G.W., J.E. Neumann, P.B. Marshall, and H. Ameden. 1996. 'The economic cost of greenhouse induced sea level rise for developed property in the United States', *Climatic Change* 32:387-410.

Yohe, G., J. Neumann, and P. Marshall, 1999: The Economic Cost of Greenhouse Induced Sea Level Rise in the United States in Mendelsohn, R. and J. Neumann (eds.), *The Impacts of Climate Change on the US Economy,* Cambridge University Press, Cambridge, UK.

Part II. Adaptation to Climate Change for Agriculture in The Gambia: An explorative study on adaptation strategies for millet

Bouman and Tuong, 2001. Oriza: rice crop simulation model. Publication International Rice Research Institute, Philippines.

Carney, J. A., 1986. The social history of Gambian rice production: An analysis of food ecurity strategies, Ph.D dissertation, University of Iowa, 221p.

Doorenbos, J. and A. H. Kassam. 1979. Yield response to water. *Irrigation and Drainage Paper 33*. FAO, Rome, 193 pp.

DOP, 2001. Statistical Yearbook on Gambian agriculture for the year 2000. Annual Report. Department of State for Agriculture. Banjul. 47p.

DOSFEA, 2004. Estimates of Revenue and Expenditure for 2004 (approved Version).

Droogers, P. 2000. Estimating actual evapotranspiration using a detailed agro-hydrological model. J. of Hydrology 229: 50-58.

Droogers, P. 2002. Global high-resolution map of soil hydraulic characteristics. IWMI Working Paper (in preparation).

Droogers, P. 2003. Adaptation to climate change to enhance food security and preserve environmental quality: example for Southern Sri Lanka. Agricultural Water Management (in press).

Droogers, P. and J. Aerts. 2003. Adaptation strategies to climate change and climate variability: a comparative study between seven contrasting river basins. Physics and Chemistry of the Earth. (submitted)

FAO. 2002. Digital soil map of the world and derived soil properties on CD-rom. http://www.fao.org/ag/agl/agll/dsmw.htm.

Feddes R.A., Kowalik P.J. & Zarandy H. 1978. Simulation of field water use and crop yield. Simulation Monographs. Pudoc. Wageningen, The Netherlands.

GITEC, 1992. Feasibility study for a rural water supply programme. Main report and appendices.

Consultancy report prepared for MNRE. Banjul.

GOTG, 1996. Country Paper for the World Food Summit.

GOTG, 2003. First national communication of the Republic of The Gambia to the United Nations Framework Convention on Climate Change. Government of The Gambia, United Nations Development Program, Global Environment Facility (GOTG, UNDP, GEF).

GOTG/UNDP, 1996. Rural Water Supply and Sanitation Project Agreement (GAM/93/003 &

GAM/92/C01), Banjul.

IPCC, 2003. Intergovernmental Panel on Climate Change. Data Center: http://www.ipcc.ch.

IPCC, 2000. Special Report on Emission Scenarios (SRES) of the Intergovernmental Panel on Climate Change. Nakicenovic, N. and R. Swart (Eds.), Cambridge University Press, Cambridge, UK, 570 pp.

Kargbo, A. M., 1989. An economic analysis of rice production systems and production organisation of rice farmers in the Gambia, Ph.D dissertation, University of Michigan, 303p.

Kroes, J.G., J.C. van Dam, J. Huygen, and R.W. Vervoort, 1999. User's Guide of SWAP version 2.0. Simulation of water flow, solute transport and plant growth in the Soil-Water-Atmosphere-Plant environment. *Technical Document 48*, Alterra Green World Research, Wageningen, *Report 81*, Department of Water Resources, Wageningen University and Research, Wageningen, The Netherlands, 127p.

Parry, M., C. Rosenzweig, A. Iglesias, G. Fischer, and M. Livermore. 1999. 'Climate Change and World Food Security: A New Assessment,' Global Environmental Change, 9, S51-S67.

Rosenzweig, C., M. Parry, and G. Fischer. 1995. 'World Food Supply' in Strzepek, K.M. and J.B. Smith (eds.). As Climate Changes: International Impacts and Implications, Cambridge, UK: Cambridge University Press.

Rosenzweig, C., M. Parry. 1994. 'Potential Impacts of Climate Change on World Food Supply', Nature, 367, 133-138.

Rosenzweig, C., M. Parry, G. Fischer, and K. Frohberg. 1993. Climate Change and World Food Supply. Research Report No. 3. Oxford University Environmental Change Unit. Oxford, England.

Rötter, R.P., and C.A. van Diepen. 1994. Rhine basin study: Land use projections based on biophysical and socio-economic analyses. Volume 2. Climate change impact on crop yield potentials and water use. Wageningen, DLO Winand Staring Centre, Report 85.2, 152 p.

Spitters, C.J.T., H. Van Keulen and D.W.G. van Kraalingen, 1989. A simple and universal crop growth simulator: SUCROS87. *In*: R. Rabbinge, S.A. Ward and H.H. van Laar (Eds.). *Simulation and systems management in crop protection.* Simulation Monographs. Wageningen, Pudoc, The Netherlands, 147-181.

Supit, I,; A.A. Hooijer and C.A. Van Diepen (Eds.), 1994. System description of the WOFOST 6.0 Crop Growth Simulation Model implemented in CGMS. *Volume 1: Theory and algorithms.* European commission, Luxembourg. 146 pp.

SWAP, 2003. http://www.wau.nl/SWAP

Van Dam, J.C., J. Huygen, J.G. Wesseling, R.A. Feddes, P. Kabat, P.E.V. VanWalsum, P. Groenendijk, and C.A. van Diepen, 1997. Theory of SWAP version 2.0. Wageningen Agricultural University and DLO Winand Staring Centre. Technical Document 45.

Van Diepen, C.A., J. Wolf, H. Van Keulen, and C. Rappoldt, 1989. WOFOST: a simulation model of crop production. Soil Use and Management 5: 16-25.

Wand, S.J.E., Midgley, G.F., Jones, M.H. and Curtis, P.S. 1999. Responses of wild C4 and C3 grass (Poaceae) species to elevated atmospheric CO2 concentration: a meta-analytic test of current theories and perceptions. Global Change Biology 5: 723-741.

Williams, J.B., 1979. Soil Water Investigation in The Gambia. Technical Bulletin 3. Land Resources Development Centre. Ministry of Overseas Development, Surrey, England.

Yates, D., S. Gangopadhyay, B. Rajagopalan, and K. Strzepek. 2003. A technique for generating regional climate scenarios using a nearest-neighbor algorithm. Water Resources Research, Vol. 39, No. 7, 1199.

23 Abbreviations and Acronyms

AIACC Assessment of Impacts and Adaptations to Climate Change
BERG Berg Dam
BERGCAP Berg River Dam capacity of the reservoir
BRDSEM Berg River Dynamic Spatial Equilibrium Model
BERGSUP Berg supplementary site
CCT City of Cape Town
CSIRO Commonwealth Scientific and Industrial Research Organisation
CMA Cape Metropolitan Area
CMC Cape Metropolitan Council
Com Commercial water users
Cou Public sector water use
CRU Climatic Research Unit
CSCDGH Center for the Study of Carbon Dioxide and Global Change
CSIRO Commonwealth Scientific and Industrial Research Organisation
CWR Crop water requirements
DVS Development stage
ENSO El Nino Southern Oscillations
FAO Food and Agricultural Organisation
FNC First National Communication
GAMS General Algebraic Modelling System
Gar Garden and lawn water use
GCM Global Circulation Model
GDP Gross domestic product
GHG Greenhouse gas
GOTG Government of The Gambia
DNLP Dynamic non-linear programming
DWAF Department of Water Affairs and Forestry
IHH Higher income households
Ind Industrial consumers
IPCC Intergovernmental Panel on Climate Change
LAI Leaf Area Index
LHH Lower income households
NAP Noord-Agter Paarl
NCC National Climate Committee
NDI Long-term net farm income
OVMG Interstate Organisation for the Development of The Gambia
PAR Photosynthetically active radiation
PB Perdeberg
RCM Regional Climate Model
RK Riebeek – Kasteel
SAP Suid –Agter Paarl
SPES Special Report on Emissions Scenario
SWAP Soil water atmosphere plant
TWAT Theewaterskloof
UNFCCC Assessment of Impacts and Adaptation to Climate Change
WATBAL Water balance model
WCA Water Systems Authority
WCSA Western Cape System Analysis
WMRS Wemmershoek

WRC	Water Research Commission
WOFOST	World Food Studies

(Page intentionally left blank)

For copies of final reports from the AIACC project and other information about the project, please contact:

AIACC Project Office
The International START Secretariat
2000 Florida Avenue, NW, Suite 200
Washington, DC 20009 USA
Tel. +1 202 462 2213
Fax. +1 202 457 5859
Email: aiacc@agu.org

Or visit the AIACC website at:
www.aiaccproject.org