CAPACITY BUILDING IN ANALYTICAL TOOLS FOR ESTIMATING AND COMPARING COSTS AND BENEFITS OF ADAPTATION PROJECTS IN AFRICA
(AIACC AF 47)

JANUARY 2004 SEMI-ANNUAL REPORT

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Acronyms

DEAT	*Department of Environmental Affairs and Trade*
ERC	*Energy Research Centre (Formely EDRC and ERI)*
FAO	*Food and Agriculture Organisation of the United Nations*
FNC	*First National Communication*
GCM	*Global Circulation Model*
GCRU-DWR	*Global Change Research Unit, Department of Water Resources*
GEF	*Global Environment Facility*
UCCEE	*UNEP Collaborating Centre*
UNEP	*United Nations Environment Programme*
UNFCCC	*United Nations Framework Convention on Climate Change*
WSI	*Water Satisfaction Index*

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CONTENTS

1.0 INTRODUCTION

This project aims to develop 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 Africa and West Africa. An economic benefit-cost analysis is used to develop a framework to estimate the economic benefits and costs associated with the expected climate change damages avoided by a development project not taking into account climate damages. This methodology is demonstrated in two project case studies as follows:

- The South African case study, which 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,
- Adaptation to climate change for agriculture in the Gambia

Teaming together for the project are three organisations: Energy Research Centre (ERC), University of Cape Town; the Global Change Research Unit, Department of Water Resources (GCRU-DWR) in Banjul, Gambia; and UNEP Collaborating Centre on Energy and Environment and Development (UCCEE) in Riso, Denmark.

This report covers the period July to December 2003. It is broken into three parts: the progress report by ERC during the period, project progress by GCRU – DWR, and the expenses report.

2.0 PROGRESS REPORT

2.1 EDRC

2.1.1 PROJECT ACTIVITIES

The study team is currently modifying an existing spatial equilibrium model of the Berg River Basin for use in an integrated environmental-economic assessment of climate change. The current model 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:

- 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 stochastic streamflow ensembles from the WatBal rainfall-runoff model and calculation of return flows, reservoir evaporation and conveyance losses,
- Addition of investment functions for new reservoir capacity,
- Development of on-farm water-use intensity estimates for different temperature regimes, and
- Development of scenarios to reflect changes in water demand over time due to population and agricultural commodity market developments.

Once modified and verified, the model will be 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 four options:

Options	***No additional storage***	***Plus additional storage***
No water markets	*Ö*	*Ö (planned and optimal)*
Water markets	*Ö(planned and optimal)*	*Ö(planned and optimal)*

The simulated results will be used 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.
- isolate the benefits and costs of planning for expected climate change, versus not planning for it.
- 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.

2.1.2 TASKS PERFORMED AND OUTPUT PRODUCED

Meetings/Conferences/Workshops

Table 2.1.1 shows conferences/workshop attended during the reporting period.

Table 2. 1.1 Conferences/Workshops.

Meeting	***Venue***	***Date***	***Attendance***	***Outcome***
South African Global Change Symposium	*Cape Town*	*October 27 – 29*	*Delegates from all over South Africa. About 50 presentations with a wide attendance*	*Presented a paper on Estimating and Comparing the Costs and Benefits of Adaptation Projects*
COP-9 (Two EDRC members gratefully sponsored by the Wuppertal Institute Org)	*Milan, Italy*	*December 7 - 11*	*Over 5000 participants from 166 governments, 4 observer states, 312 intergovernmental, non governmental and other observer organisations*	*Various and Adaptation day*

Travelling

In Table 2.1.2 we report the project related travelling done during the period.

Table 2.1.2. Travelling

Date	***Venue***	***Attendance***	***Purpose***	***Outcome***
	Paarl (Western Cape)	*JC Nkomo* *D Louw*	*To contract part of the project to D Louw*	*Signing of project tasks*
		J C Nkomo *D Sparks* *D Louw*	*Meeting with D Louw to clarify project tasks.*	*Project clarification* *Teleconference*
12 – 16 October	*Paarl (Western Cape)*	*Mac Callaway* *M Hellmuth* *JC Nkomo* *D Sparks* *D Louw*		*Economic model and hydrological model detail*
22 October	*Cape Town*	*D Sparks* *M Hellmuth* *M Shand* *D Louw*	*To gather information on the Berg River for calibration and operation the*	*Useful data provided on disc, and access to relevant library reports provided*

			hydrological model	

2.1.3 DIFFICULTIES ENCOUNTERED AND LESSONS LEARNED

One of the important factors behind our project selection was that Daan Louw's work on the Berg River Basin was closest to what we seek to do. The objective then was to modify Louw's model and implement the Upper Berg River spatial equilibrium model. The model could then be used to compare adaptation benefits associated with water markets and/or additional storage capacity of the Berg River Basin. Our main problem has been to move with speed. Outstanding items are on the approach to take, fitting the farms into a spatial equilibrium code and converting Daan's model directly into a spatial equilibrium model, and them implementing this for a full set of activities with limited hydrology. Once this part of the project is done, we should be able to move relatively fast to meet deadlines for the other tasks.

2.1.4 INTERACTION BETWEEN PROJECT AND PREPARATION FOR NATIONAL COMMUNICATION

The Department of Environmental Affairs and Tourism (DEAT) is the focal UNFCCC and GEF points of SA, and have been informed in their official capacity as a focal point of the project. Contact has been made with the main focal point person. We expect to give a presentation at a stakeholder's meeting at DEAT before long.

2.1.5 TASKS TO BE PERFORMED OVER THE NEXT EIGHT MONTHS

Major tasks to be performed the next eight months are outlined below:

Task	**Milestone/Deliverables**
Development of Hydrologic Model and Climate Hydrology Interface	● Calibrate hydrologic model ● Development of hydrologic model outputs to conform to economic model requirements.
Verification of interlinked model performance	● Test and verify model performance
Implement Integrated Economic/Water Resources Model to estimate benefits and damages	● Climate scenarios (including current climate), in combination with ● Economic options scenarios to estimate damages/benefits with and between (including interactions): 1. Partial and full adjustment 2. Existing capacity vs. optimal additional investment in storage capacity 3. No water markets vs. water markets

2.1.6 ANTICIPATED DIFFICULTIES/CHALLENGES

In terms of the future, our immediate anticipated problems relate to having sufficient time to complete our tasks in order to achieve our goals and deadlines. We have made contact with our National Communications focal point, and have abandoned attempts of getting World Bank funding as was the initial understanding. Although there may be some unexpected problems as the project is executed, we are now in a position of forging ahead with the project to its completion.

Obvious challenges facing us are to produce high quality technical assessments and to meet the deadlines set.

Valuable lessons we are learning are: planning ahead to mitigate undesirable effects, and active sharing of information with other projects.

2.1.7 OUTPUTS PRODUCED

Outputs produced are as follows:

- Appendix 1. 'Estimating and Comparing the Benefits and Costs of Avoiding Climate Change Damages in Natural Resource Sectors in Developing Countries'. Paper presented at the South African Global Change Symposium in Cape Town, October 27- 29
- Appendix 2. Article on 'Estimating and Comparing the Benefits and Costs of Avoiding Climate Change Damages'. Published in AIACC Notes November 2003, Vol. 2 Issue 2.
- Appendix 3. Working document on hydrology by Molly Hellmuth.

2.2 GCRU-DWR

2.2.1 SUMMARY OF PROJECT ACTIVITIES

Technical Activities

Liaison and consultation with partners

GCRU-DWR in consultation with UCCEE and EDRC, applied for a supplementary grant from the AIACC Secretariat, to secure the services of a crop modelling expert to help build the capacity of the team. The grant was approved by AIACC, and the commencement of implementation was scheduled for the last week of November, but time constraints led to its postponement to the second week of January (precisely January 9 - 16, 2004).

Though no solid outputs can be claimed from mid-November to the end of December 2003, it is worthy of mention that a lot of information exchange has taken place between GCRU-DWR, UCCEE and Futurewater (consultancy firm), in preparation for the consultant's visit. The intense information exchange led to the production of working paper (see Appendix 4) during the consultant's visit.

Specific tasks

During the previous reporting period, one of the tasks carried out was to fill a 10-day data gap in the rainfall series of Yallal. This obstacle was solved using ordinary kriging on an average area of 5 km x 5 km grid.

Using the krigged dataset for Yallal, our work would now be based on three stations, namely Yundum, Yallal and Basse, with a common observation period of 30 years (1973 - 2002). It must however, be noted that due to the fact that the rainfall value obtained by the kriging method is contributed (in the correlational sense) from rainfall elsewhere, more rainy days, as well as lower/attenuated intensities were apparent in the kriged dataset.

Progress made so far is reported in the next section.

2.2.2 TASKS PERFORMED AND OUTPUTS PRODUCED

With the daily rainfall data of the past 30 years, we argue that an attempt to define agricultural drought should show the balance between crop water demand and soil moisture availability. In order to avoid getting trapped in another, multi-parameter interpolation exercise, the search for an appropriate computation method, requiring minimum and readily available data as inputs, led to the Frere and Popov's monitoring and forecasting model (1979), adopted by the FAO.

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, here the historic values compiled under the CILSS AGRHYMET Programme for the period of 1951 – 1980. A soil moisture holding capacity of 100 mm for the rooting zone is obtained from infiltration and drainage studies in different parts of the country.

The main output of this model is the cumulative Water Satisfaction Index (WSI), with runoff/drainage and total water requirements as secondary output.

Since drought is mainly associated with inadequate moisture, we decided to confine water balance analyses to the lowest tercile (§ table 1) 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 susceptible to be caused by a shortage of moisture 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*). It is worthy of mention that grain production at national level only meets about 50% of domestic grain requirement and thus shows the fragility of the Gambian economy vis-à-vis stressors in the food production chain.

Three sowing dates were selected for each of the sites and for each season, in order to better simulate sowing conditions in farmers' fields, from where the yield figures were obtained. Millet yield figures are obtained from the various annual National Agricultural Sample Surveys, conducted by the Department of Planning for the study sites (i.e., average for the administrative division, rather than the more detailed district level yield figure that is preferable when spatial variability of the rainfall is important and the country as a whole.

Contrary to expectations, an attempt to correlate yields with WSI using simple regression techniques proved unsatisfactory. A close look at the model outputs (WSI) showed little variation in the index over the successive seasons, suggesting that the model may not be fully capturing the inter-annual seasonal variation. Since the model did not include a yield component, the original idea of linking one to the above model was abandoned because of the poor correlation.

This has put a brake on the progress of the team, which currently lacks expertise in modelling in this area, and prompted to call for external advice.

2.2.3 DIFFICULTIES ENCOUNTERED AND LESSONS LEARNT

One major difficulty is identified. The spatial mismatch between WSI and yield figures. Whilst WSIs were computed for location specific weather monitoring stations, crop yield data were averaged over an administrative division covering more than 1000 km^2.

2.2.4 TASKS TO BE PERFORMED IN THE NEXT EIGHT-MONTH PERIOD

With the intervention of the consultant on crop modelling, GCRU-DWR will continue to use the SWAP (Soil-Water-Atmosphere-Plant) model (Van Dam et al., 1997) to explore the impacts of drought and adaptation options at the three sites.

From the work contained in the working paper, the team would be in a position to move into accomplishing the following tasks:

- Provide a working definition of 'drought' as it relates to the three ecologies in The Gambia;
- Determine the nature and frequency of droughts under a changed climate using more GCMs;
- Assess the impact of drought in a changed climate on crop production;
- Assess adaptation strategies; and
- Examine economic models that could be used to develop the framework for the benefit cost analysis of the project.

The team will also explore the possibility of discussing the project's findings with a wider group of national stakeholders, in order to test the acceptability of the results.

2.2.5 ANTICIPATED DIFFICULTIES IN THE NEXT EIGHT-MONTH PERIOD

Anticipated difficulties or rather the risks of non-completion of specific tasks/activities remain, largely linked to external factors. The GCRU-DWR may therefore need considerable leverage to secure, on time, external expertise, data and models needed to carry out its work.

If the delay in accessing project funds persists, tasks requiring the input of resources, might prove difficult to accomplish on time.

2.2.6 CONNECTIONS BETWEEN AIACC PROJECT AND FNC

The Gambia launched its First National Communication on November 20, 2003. The ceremony was presided over by the Vice President of The Republic of The Gambia, Her. Excellency, Madam Isatou Njie Saidy. Other dignitaries included the Secretaries of State for Fisheries, Natural Resources and the Environment (Focal Policy institution for the Convention on Climate Change), and Finance and Economic Affairs.

During the presentation of the Communication to the audience, the importance of the AIACC project was fully elaborated upon as a mechanism to build national capacity in developing understanding on adaptation issues. This project was well received and the results highly awaited.

The SWAP and WSBM models seem to respond quite well to both the current and future needs of the project and as such the team highly appreciates acquiring skills in their setting up, operation and interpretation of outputs. A training session on the models for members of the National Climate Committee (taskforce responsible for implementing the Convention on Climate Change) is envisaged, in preparation for the Second National Communication.

2.2.7 OUTPUTS PRODUCED

Appendix 4. ‘Adaptation to Climate Change for Agriculture in the Gambia: An Explorative study on adaptation strategies for millet’. Draft document to be submitted as AIACC Working Paper.

Appendix 1

(South African Global Change Symposium Conference Slides)

Estimating and comparing the benefits and costs of adaptation projects

J.C. Nkomo[1], D.A. Sparks[1], J.M Callaway[2], M.E.Hellmuth[2] and D.B. Louw[3]

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[2]UNEP Collaborating Centre on Energy and Environment, Risø, Denmark
[3]Deciduous Fruit Producers' Trust, Paarl

1. Outline

- Background on AIACC projects
- Project objectives
- The Berg River Case Study
- Conclusion

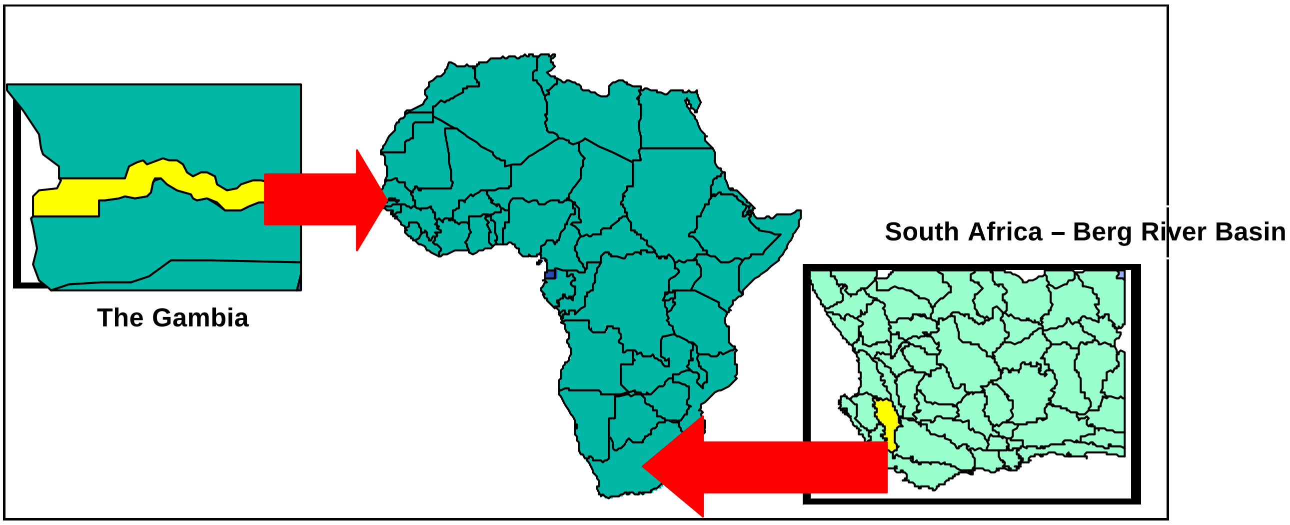
2. Background on AIACC projects

- Assessment of Impacts and Adaptation to Climate Change (AIACC) is a global initiative with UNEP/WMO and IPCC, funded by GEF.
- It involves 23 regional studies involving over 40 countries.
- Projects are being investigated in Latin America, Asia, Small Island States and Africa.
- This project is one of 10 African projects.

3. Project Objectives

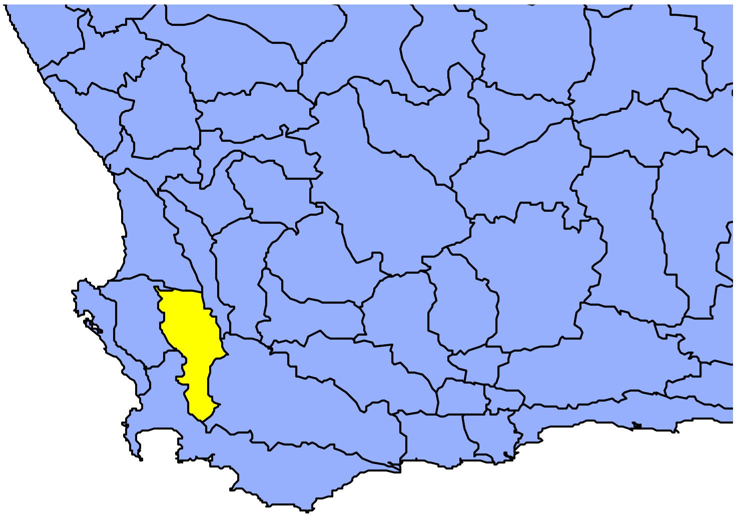
- The project aims to develop capacity to estimate and compare the benefits and costs of projects in natural resource sectors that reduce the expected damages from climate change (CC) in South and West Africa.
- An economic benefit-cost analysis is used to develop a framework to estimate the economic benefits and costs associated with the expected CC damages avoided by a development project not taking into account CC damages.

- The methodology is demonstrated in two case studies – The Gambia and South Africa.
- We report here on the SA case study in the Berg River Basin.



4. The Berg River Case Study

- The project examines the benefits and costs of avoiding CC damages through structural and institutional options for increasing water supply in the Berg River Basin in the Western Cape.



Strategic And Developmental Importance

- The Upper Berg is an economically important water supply system in the W. Cape and provides the bulk of the water for household, commercial and industrial use in the Cape Town metropolitan region.
- It provides irrigation water to cultivate approx. 15 000 hectares of high value crops e.g. deciduous fruits, table & wine grapes and vegetables for domestic and export use, with strong multiplier effects in the domestic and national economy.

- Provides water to ecology and reserves.

- Competition for water in the Basin has become intense, since farmers have shifted production to highly valued export crops, while urban demand has grown with the expanding population.

Policy Developments

- A new dam has been commissioned in the Berg River Basin in an effort to alleviate the increasingly scarce water supply.

- The government is also moving towards creating a competitive market for water under the new National Water Act (1998).

- Planning until now has not accounted for the build-up of GHG in the atmosphere, which will continue to affect the climate and potentially reduce runoff in the Basin.

Case Study Objectives

- Estimate the potential impacts of alternative CC scenarios on water supply and demand in the Basin, through changes in runoff, evapotranspiration and surface evaporation.

- Translate these physical impacts into money losses (or gains) for different groups of farmers and urban water users.

- Estimate and compare the benefits and costs of storage and water market options of avoiding CC damages, with and without expected CC in the ex ante planning for these options.

Methods

→ Upper Berg River Spatial Equilibrium Model (Louw, 2002):

- Links farm LP models to simulate water demand for agriculture and urban water users.
- Has been applied specifically to the Upper Berg River Basin to consider the impact of a water market and can be modified to be dynamic.

→ WatBal hydrologic model (Yates, 1996):

- Rainfall-runoff model.
- Provides hydro-related inputs to Spatial Equilibrium Model.

Some of the modifications to be made are:

- Incorporating intertemporal features of reservoir storage for major reservoirs and farm dams so CC can be assessed over time.
- Creating a hydrologically realistic, but simplified representation of the physical and man-made water supply system in the Basin.
- Improving the hydrological aspects of the model to allow stochastic streamflow ensembles from the WatBal Model, and calculation of return flows.
- Addition of investment functions for new reservoir capacity.
- Development of on-farm water use intensity estimates for different temperature regimes.

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

Implementation

- Once modified and verified the model will be used to assess the physical and economic effects of a number of alternative runoff scenarios associated with historical climate, recent climate anomalies and plausible future climate changes for the Basin.
- Each of the scenarios will be run for the following four options…

	No additional storage	**Additional storage**
No water markets	✓	✓
Water markets	✓	✓

The simulated results will be used to:

- Estimate the monetary value of CC damages without the various options and the monetary value of the benefits and costs of avoiding these damages through various alternatives.
- Isolate benefits and costs of planning for expected CC versus not planning for it.
- Find the reservoir capacity that leads to the minimum level of regret in terms of planning for CC that doesn't happen and not planning for CC that does occur.

5. Conclusion

- The methodology being used is not new, but has been used in one form or another to evaluate natural resource development projects under risk and uncertainty associated with historical climate variability.

- But, planners in natural resource sectors are often mystified about how to incorporate uncertainty associated with CC into their current projects.

- Hence, this project will hopefully demystify the problem and demonstrate how existing tools and approaches can be modified to integrate CC into the assessment of natural resource development investments.

Appendix 2

(Paper in AIACC Notes. November 2003. Vol.2, Issue 2)

Estimating and Comparing the Benefits and Costs of Avoiding Climate Change Damages in Natural Resource Sectors in Developing Countries

J.M. Callaway[1], M.E. Hellmuth[1], J.C. Nkomo[2], D.A. Sparks[2] and D.B. Louw[3]

Project Objectives

The broad objective of AIACC project 47 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 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. This framework is reported in Callaway (2003). The second part consists of demonstrating this methodology in two project case studies, one in The Gambia and the other in South Africa. This paper reports on the South African case study, which is examining 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 Berg River Case Study

The upper Berg River 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. As the population of the Metropolitan Cape Town region grows the competition for water in the basin has become even more intense as farmers have shifted production toward highly valued export crops and the government searches for solutions to make good on its promise to provide a minimum amount of “free” water to all households to meet minimum daily requirements.

Recently, the government of South Africa commissioned a new dam in the Berg River basin, in effort to alleviate the problem of increasingly scarce water supply for the Cape Metro Region. The commissioning of the new Berg Dam was a controversial and lengthy process. 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). Planning for both options 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.

The AIACC AF47 group is collaborating with regional grower’s associations in the Berg River, as well as with the Department of Water Affairs and Forestry (DWAF). Both groups have shown considerable interest in the project as the explicit costs and benefits of adjustment measures to climate change have not been previously examined in the region.

Case Study Objectives

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

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- 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,
- 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 ex ante planning for these options.

Methods

The study team is currently modifying an existing spatial equilibrium model of the Berg River Basin (Louw, 2002) for use in an integrated environmental-economic assessment of climate change. The current model 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:

- 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 streamflow ensembles from the WatBal rainfall-runoff model (Yates, 1996) and
    - Calculation of return flows, reservoir evaporation and conveyance losses,
- Addition of investment functions for new reservoir capacity,
- Development of on-farm water-use intensity estimates for different temperature regimes, and
- Development of scenarios to reflect changes in water demand over time due to population and agricultural commodity market developments.

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Implementation

Once modified and verified, the model will be 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, and
- Both water markets and additional storage (both planned and optimal).

The results from these sets of simulations will 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 change scenario. One can also extend this approach (as shown in Callaway, 2003) to analyze 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.

Conclusion

The methodology being used in this study – ex ante, ex post planning – is not new. It has been used in one form or another to evaluate natural resource development projects under risk and uncertainty associated with historical climate variability. Nevertheless, planners in natural resource sectors often seem mystified about how to incorporate the uncertainty associated with climate change into their current projects. One of the most important benefits of this project hopefully will be to de-mystify the problem by demonstrating how existing tools and approaches can be modified slightly to integrate climate change into the assessment of natural resource development investments in South Africa and The Gambia. While the South African case study will consider a relatively developed watershed, with competing urban and agricultural users, the Gambian case study focuses primarily on evaluating the effectiveness of a variety of agricultural adaptation options in reducing the vulnerability of a spectrum of rural farmers to climate changes.

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Appendix 3
(Working document by Molly Hellmuth)

Hydrological aspects of the Berg River Basin

Section I. Introduction

This document outlines the calibration of the Upper Berg River Basin and the Upper Breede River basin for the purposes of providing flow data to the Berg Spatial Equilibrium (BSE) model. This paper is divided into 4 parts:

- Section I. Begins with a brief description of the watersheds, showing the spatial location of the representative farms, the rivers and gauges within the basins.
- Section II. Describes how the flow network fits into the BSE model
- Section III. Gives the details for the calibration of each of the flow points, including:
    i. Sub-watershed information;
    ii. Details of met demands;
    iii. Details of farm storage;
    iv. Assumptions;
    v. Calibration parameters;
    vi. Statistics of calibrated versus naturalized incremental flows;
- Section IV. Gives details of the storage characteristics that will be required in the BSE model
- Section V. Gives details of data sources used.

Throughout this document, all **ASSUMPTIONS and all implications for the BSE** model are highlighted. Particularly important **QUESTIONS** are highlighted.

The Upper Berg (light blue) and Breede (light green) River basins are shown in Figure 1, below. The original representative farm regions as indicated by Daan are shown highlighted in green. Red crosses indicate the gauging stations which were used in the Ninham Shand study of the Upper Berg River[4]. These stations will be used in this study as incremental runoff location points into the BSE model. See Section V for a list of data sources.

ASSUMPTION: As you can see from the highlighted representative farm regions, the PB, RK and SAP regions overlap into the neighboring watershed. *The water from this outside source (neighboring watershed) is assumed to be not significant*, so the

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[4] The decision to use the information from the NS study was taken because the data has undergone extensive quality analysis: the precipitation stations have been patched, the gauges have been patched, and the flow network has been naturalized taking into account met upstream demands. Note that I am calibrating to the patched observed incremental naturalized flow (1959- 1993) which has been generated from NS Calibration—this facilitates the use of the WB model to be easily used with the Spatial Equilibrium model. Downstream of gauge G1H020, information from the WCSA study will be used, as well as existing flow data from DWAF (http://www.dwaf.gov.za/hydrology/cgi-bin/his/cgihis.exe/station). The hydrologic model will be calibrated to these' stations. Below station G1H020, existing flow stations will be used.

locations of these representative farms were modified to lay within the Berg River basin (see maroon outline) in order to simplify the hydrology of the study.

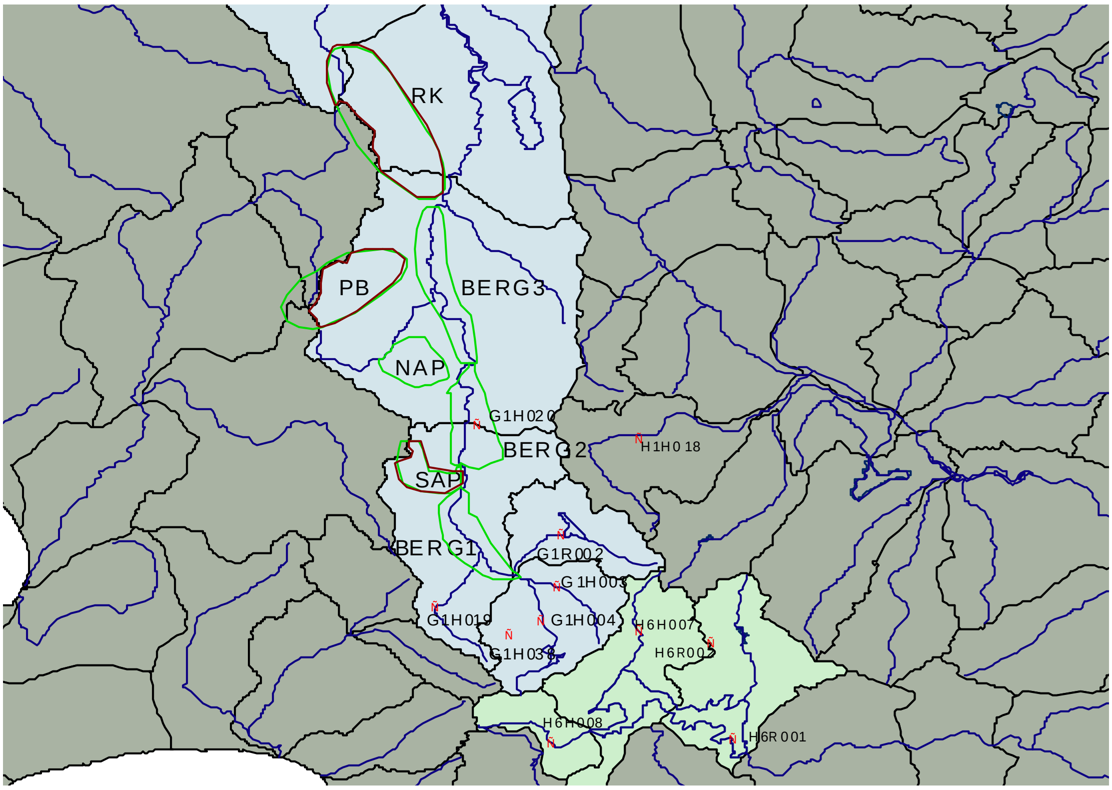


Figure 1. The watersheds, gauges, rivers, representative farms. Red gauges indicate those used in calibration (correspond with those in the Ninham Shand study).

Section II. The flow network diagram for BSE model reference

Figure 2 shows the schematic of the flow network, and how the flow will enter into the BSE model. Missing from this schematic at this point: FARM DAMS.

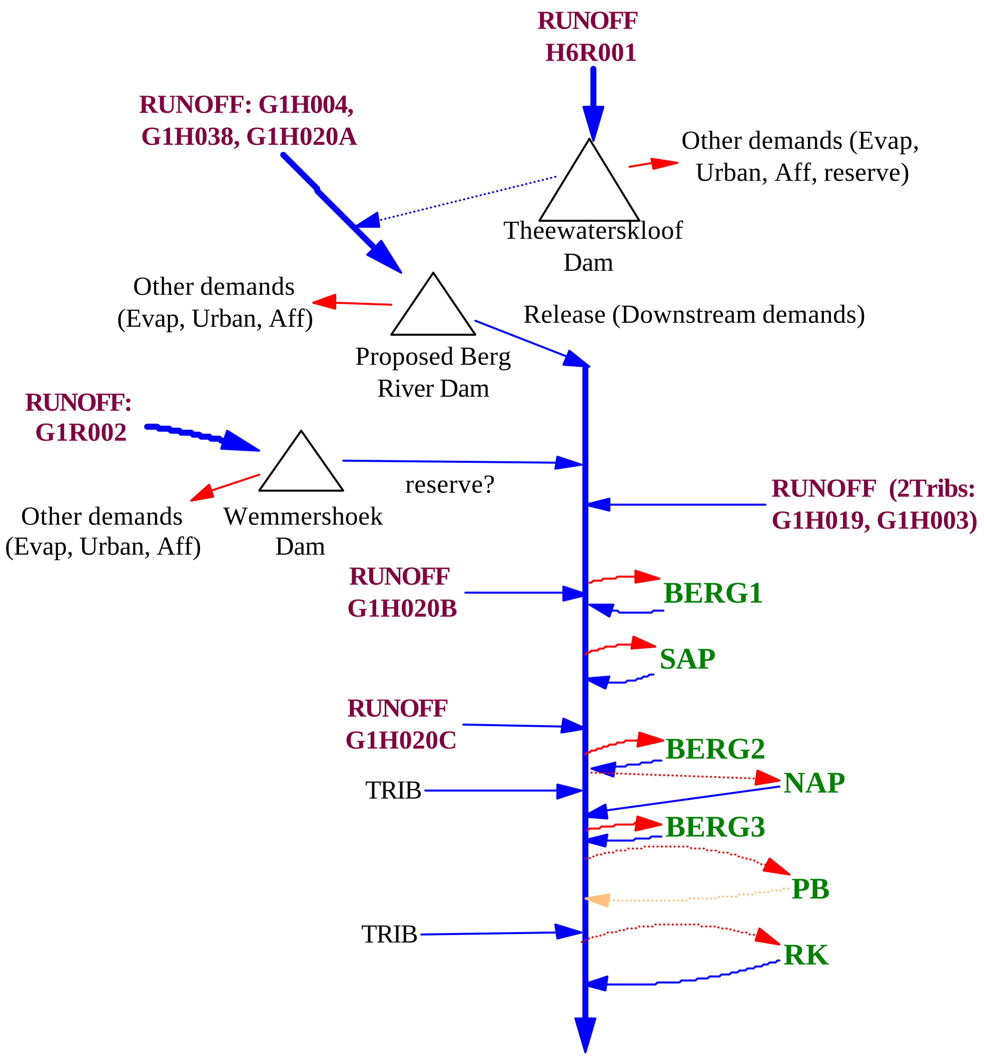


Figure 2. Schematic of the flow network. Marroon BOLD represent flow inputs from hydrologic model.

QUESTION to Daan: Notice the **dotted** lines in Figure 2, above. Do the NAP, PB, and RK representative farms pump their water from the Berg river? You and Mac will want to consider how return flows are modeled—especially in the case of region PB (orange dotted line above).

The following text explains this schematic in more detail.

1. BERG1.
    a. Flow above Berg1 is composed of incremental runoff from 6 upstream gauges and water-imports from the Theewaterskloof dam.
        i. There are two impoundments upstream of BERG1 region (Wemmershoek and (*potentially*) Berg dams).

ii. Two tributaries (G1H019, G1H020B) flow into the middle of the Berg 1 region. We **assume** this flow is available to entire BERG1 region.
iii. Three sources flow into the Berg dam: G1H004, G1H038 and G1H020A + water imports from Theewaterskloof.
iv. One source G1R002 flows into the Wemmerschoek.
v. BSE model implications:
    1. Role of reverse valves (**BSE model**)—either we can hardwire rules into the BSE model, or the water will need to be allocated by the model. It may be easier to make some assumptions (i.e. concerning rules about water transfers from inlets in the mountains), as the hydrology can get tricky with shifting hydraulic heads.
    2. **QUESTION:** Wemmershoek Dam is currently used as a supply source for urban areas. Do we need to model this in BSE model s.t. overflow and reserves are captured? *Can we make assumptions that released flow is negligible?*
    3. Consideration of farm dams (for **inclusion in BSE** model)—one virtual farm dam is assumed to exist for each representative region.
    4. Return flows (included in **BSE** model)

PROVIDED to the BSE model: Incremental monthly flow series for each gauge. These may be aggregated by node where it is more convenient.

2. SAP
    a. Unused flows upstream of BERG1 and BERG1 return flows **assumed** available. (in **BSE** model) Reserve will need to be accounted for.

3. BERG2
    a. SAP/BERG1 unused and return flows available (**BSE model**)
    b. Incremental runoff at G1H020C (note this gauge is in the middle of the BERG2 region). We **assume** this flow is available to entire BERG2 region.

[In terms of calibration of the river basin, I am here (January 7, 2004). I will need more information to proceed]

4. NAP
    a. **QUESTION**: NAP lies off the main stem. Does the return flow from NAP make it to the stream?
    b. NAP lies on a tributary, this tributary will be modeled and incremental runoff is **assumed** available to NAP

5. BERG3
    a. Trib flow **assumed** to come in above NAP? (It intersects NAP and BERG3, NAP being upstream).
    b. Return flows from NAP.

6. PB
    a. PB lies off the main stem. **QUESTION**: Water source—pumped from Berg River (into farm dams)? Return flows available to RK?

7. RK
    a. RK lies off the main stem. **QUESTION:**
    b. What about the other trib?
    c. Is water pumped from berg into farm dams?

Section III. Detailed notes on calibration of gauges

This section provides detailed calibration information for the gauges. It is broken into 3 parts: Part 1: Upper Berg River Basin; Part 2: Lower berg River Basin; Part 3: Above Theewaterskloof dam. Part 2 is pending more information.

In order to derive incremental naturalized flows, met demands were added and water transfers (or supplementations from other basins) were subtracted.

PART 1. Upper Berg River

1. NODE 1: Tributary G1H038, Wolwekloof River. (1 of 5 tributaries of the Berg river to be modeled upstream of BERG1 region).

Sub catchment area	13.1	km^2
MAP:	2470	mm
MAE (S-PAN):	1302	mm
Afforested area	0.49	km^2
Incremental Naturalized MAR	22.6	MCM
NO IRRIGATION		
NO FARM DAMS		

Table 1. Properties of G1H038.

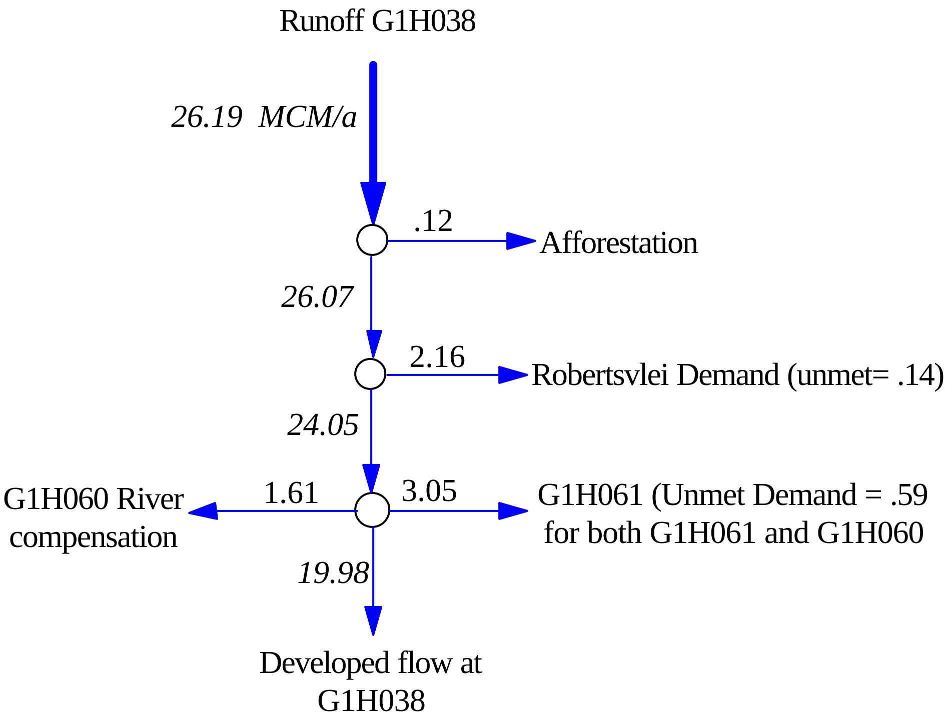


Figure 3. From naturalized to Developed flow at G1H038.

Calibration Notes:

This basin contains the abstraction point for the transfer of water to Theewaterskloof dam (Gauge G1H061), as well as, an abstraction point called river compensation (G1H060). The data at gauge G1H061 is very poor. For calibration purposes, the **assumption** that there is **no** transfer of water to Theewaterskloof dam in the summer time was made (for purposes of determining the naturalized flow).

Also, S-Pan evaporation numbers were converted to A-pan for calibration.

BSE requirements: I have calibrated to incremental naturalized flow, thus the following need to be **accounted for in the BSE model**:

- the transfer properties of the pipeline to Theewaterskloof (transfer amounts to be determined by BSE model). (Historically about 3.05 MCM/a is transferred)
- Set river compensation flow to 1.02 MCM/a (this amount was determined by subtracting the historical (1.61 MCM/a from the unmet demand .59 MCM/a. Note this unmet demand was for both G1H060 and G1H061, but I am suggesting we account for it at once).
- **met** demands need to be accounted for in the BSE model: forestry (.12 MCM/a), Robertsvlei demand (.168 MCM/mo)

Calibration Results:

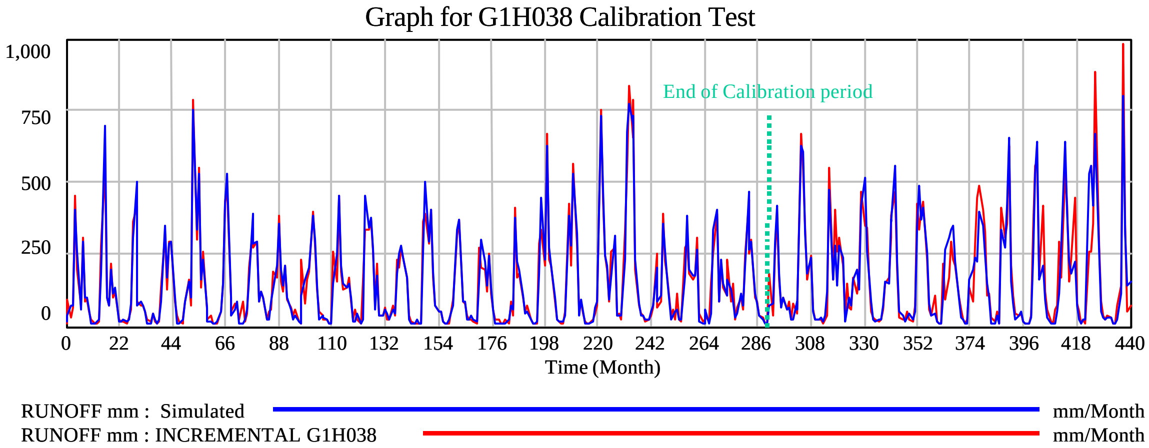


Figure 4. Calibration of Runoff for G1H038.

The first two-thirds of the simulated incremental naturalized record (1950- 1974) was used to calibrate the data, and the final third (1975-1993) was used to test the calibration.

NOTES: The mean runoff for the calibration period was matched, resulting in: 21.78 MCM/a
For the entire period (1950-1993) the simulated average annual value was: 23.4 MCM/a, versus 23.6 MCM/a actual.

2. NODE 2: Tributary G1H004—Gauge on the Berg River

	HIGH MAP	LOW MAP	Total	
Sub catchment area	39.9	16.21	56.11	km^2
MAP:	2726	2287	2599	mm
MAE (S-PAN):	1302	1302	1302	mm
Afforested area	4.90	7.38	12.28	km^2
Irrigation Area	0	0.15	.15	km^2
Incremental Naturalized MAR	112.8			MCM
NO FARM DAMS				

Table 2. Properties of G1H004.

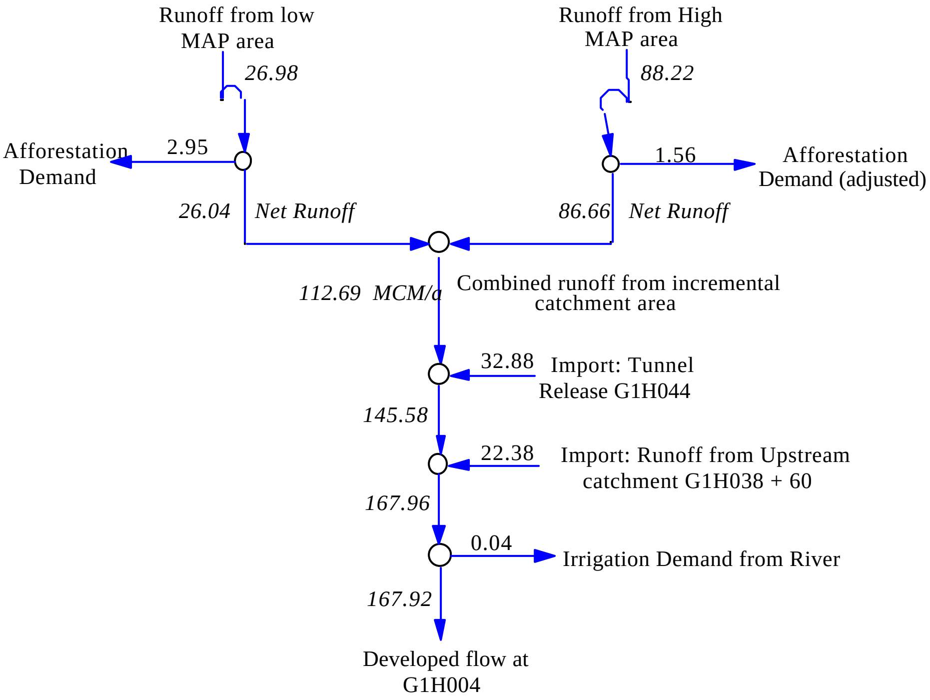


Figure 5. From naturalized to developed flow at G1H004.

Notes:

The NS work divided the regions into low and high MAP because of requirements for the WSSP model, I will use the combined total for calibration.

BSE requirements: I have calibrated to naturalized flow, thus the following need to be **accounted for in the BSE model**:

- the transfer properties of the pipeline from Theewaterskloof G1H044 (transfer amounts to be determined by BSE model). (Historically about 32.88 MCM/a is transferred)

- **met** demands need to be accounted for in the BSE model: forestry (3.51 MCM/a), irrigation demand (.04 MCM/a) [note this irrigation demand is upstream of BERG1 region]

Calibration Results:

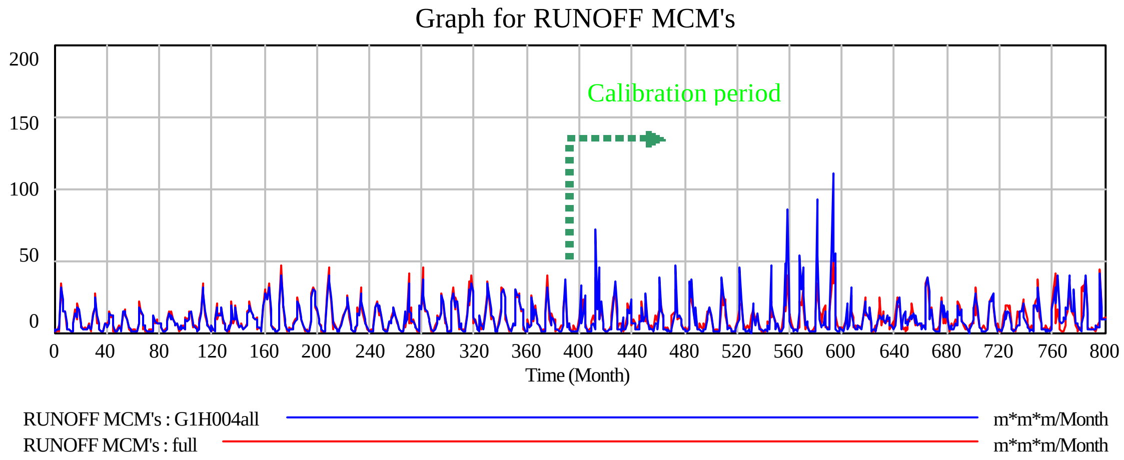


Figure 6. Calibration of Runoff for G1H004. Series G1H004all represents the entire series, while series full represents the simulated series. The beginning of the calibration period (1959 –1983) is shown on the graph.

Calibration of this basin proved difficult. The initial “automatic” calibration failed to capture the mean (15% lower than the patched observed flow). Similarly, when the calibration was tested against the longer record, the simulated mean was about 15% less than observed. This is due to the inability of the model to capture the peak flows. Because of the nature of this study, the mean statistic was considered important to capture. Thus the value of one of the calibration parameters (epsilon) was adjusted slightly to tend towards the mean. Mean runoff calibration test, observed = 119 MCM/a, simulated = 113 MCM/a. Mean runoff full period, ‘observed’ = 113 MCM/a, simulated = 111 MCM/a.

3. NODE 3: Sub catchment G1H003 (Franschoek River)

Sub catchment area	46.34	km^2
MAP:	1006	mm
MAE (S-PAN):	1266	mm
Afforested area	4.9	km^2
Irrigation Area	4.94	km^2
FARM DAM Capacity	.397	MCM
Incremental Naturalized MAR	23.15	MCM

Table 3. Properties of G1H038.

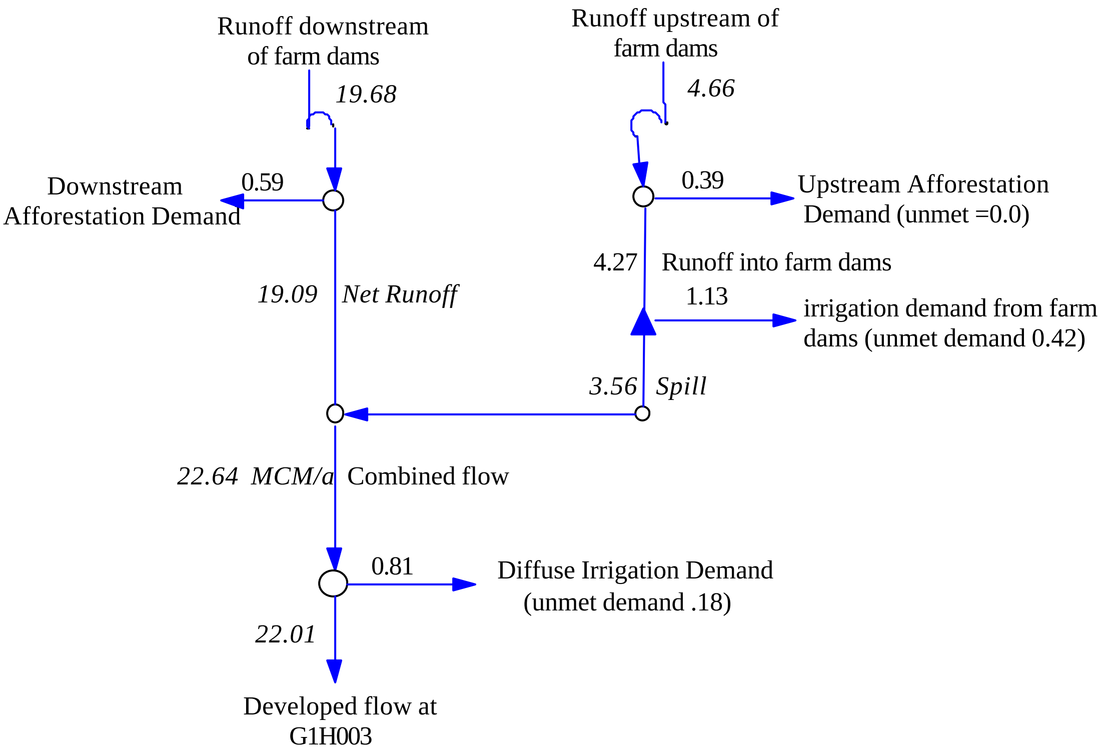


Figure 7. From naturalized to developed flow at G1H003

Notes:

BSE requirements: I have calibrated to naturalized flow, thus the following need to be **accounted for in the BSE model**:

- **met** demands need to be accounted for: forestry (.98 MCM/a), irrigation demand (1.34 MCM/a) [note this irrigation demand is upstream of BERG1 region]
- **farm dam not modeled—but the met demands taken out of downstream flow (part of irrigation demand see above).**

Calibration:

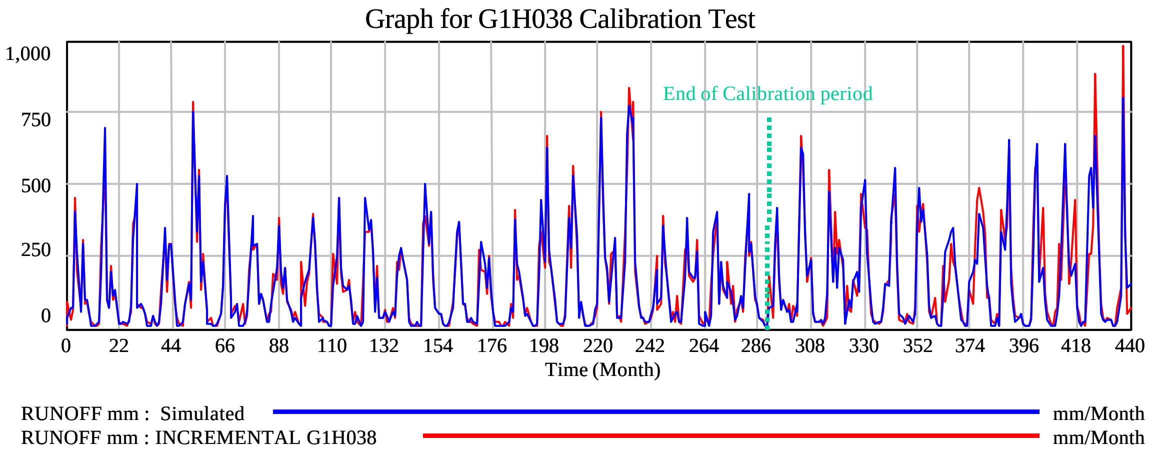


Figure 8. Calibration G1H003

4. NODE 4: Calibration of G1H019 Banhoek River

Sub catchment area	22.8	km^2
MAP:	1805	mm
MAE (S-PAN):	1302	mm
Afforested area	2.43	km^2
Irrigation area	.57	km^2
FARM DAM capacity	.202	MCM
Incremental Naturalized MAR	22.65	MCM

Table 4. Properties G1H019

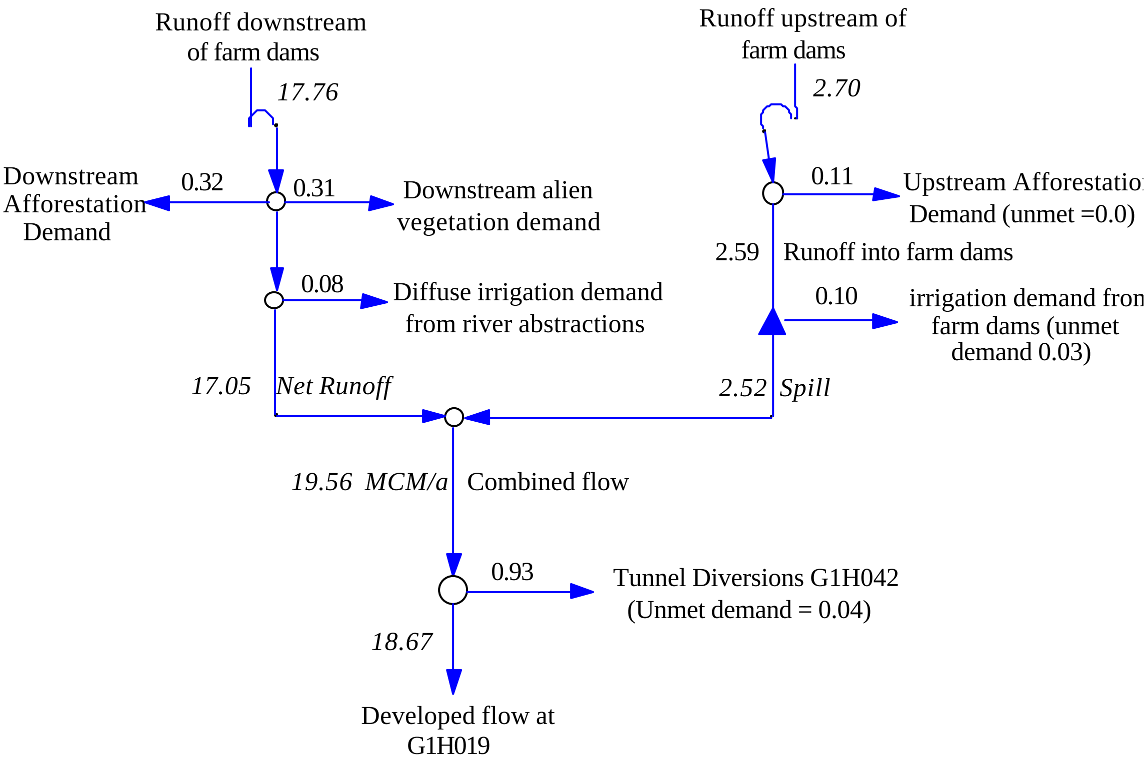


Figure 9. Schema G1H019

Notes:
The tunnel diversions are taken from NS, recommend we leave the diversions constant.

BSE requirements: I have calibrated to naturalized flow, thus the following need to be **accounted for in the BSE model**:

- **met** demands need to be accounted for: forestry (.43 MCM/a), alien vegetation (.31 MCM/a), irrigation demand (.15 MCM/a) [note this irrigation demand is upstream of BERG1 region], tunnel diversions (.89 MCM/a)
- **farm dam not modeled—but the met demands taken out of downstream flow (part of irrigation demand see above).**

Calibration:

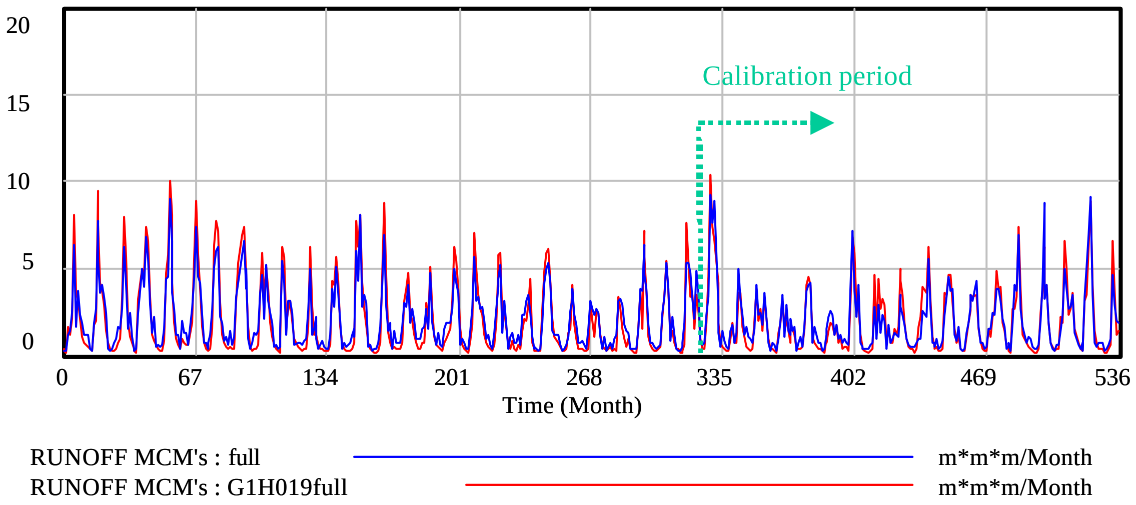


Figure 10. Calibration test of G1H019. Calibrated to the period of 1977-1993, run from 1950.

The mean of 21.6 MCM/a was met for the’ period of 1977-1993, for the entire period the mean was slightly higher (23.4 MCM/a vs 22.9 MCM/a).

5. NODE 5: Model Calibration G1R002: Wemmershoek River

Sub catchment area	85.25	km^2
MAP:	1382	mm
MAE (S-PAN):	1266	mm
Afforested area	5.04	km^2
Irrigation area	0	km^2
FARM DAM capacity	0	MCM
Incremental Naturalized MAR	74.09	MCM

Table 5. Properties G1R002

NOTE: This is the amount of water going into the DAM. This was modeled only to get a sense of how the inflow would change under climatic changes.

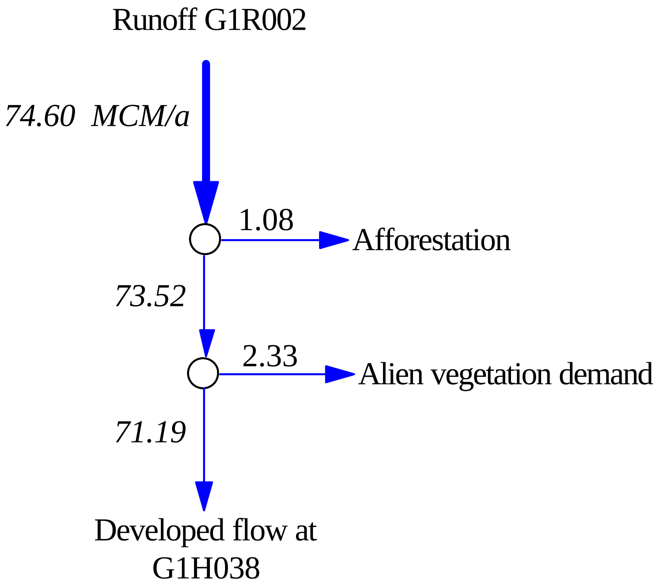


Figure 11. Schematic of G1R002

Notes:

- **BSE requirements**: None, I will make a model with storage to simulate the effects that cc has on water availability for Cape Town.

Calibration:

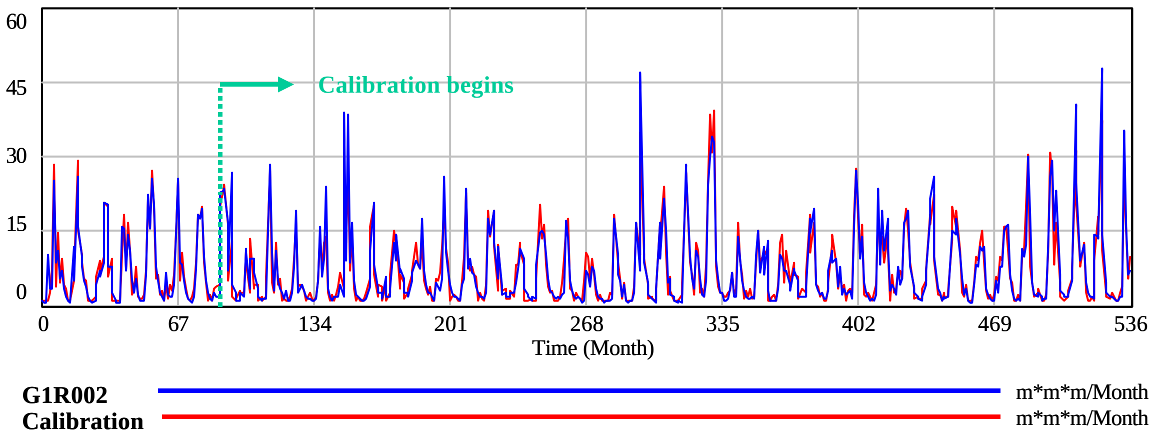


Figure 12. Calibration of G1R002

6. NODE 6: Calibration of Gauge G1H020

Sub catchment area	399.59	km^2
MAP:	979	mm
MAE (S-PAN):	1529	mm
Afforested area	57.32	km^2
Irrigation area	28.42	km^2
FARM DAM capacity	16.509	MCM
Incremental Naturalized MAR	157.62	MCM

Table 6. Properties G1H020

Notes:
Watershed G1H020 was calibrated, and then the. Flow was broken into 3 different nodes, in order to get the correct flow available upstream of the BERG RIVER dam, and BERG1 region (see figure 2, above).

The incremental flow factors are as follows:
G1H020A = .038 (5.99 MCM/a)
G1H020B = 0.474
G1H020C = 0.488

Note, this is important because the produced flow will be allotted to different representative farms (see figure 2, above).

The following table gives the demands which need to be accounted for from each Node in the **BSE MODEL**.

NODE	G1H020 A	G1H020 B	G1H020 C	TOTAL	
Afforested demand	1.92	8.06	3.51	13.49	MCM
Alien Veg	0.0	.73	.06	.79	MCM
Irrigation from river	0.0	1.21	2.82	4.03	MCM
FARM DAM irrigation	0.	1.53	5.72	7.25	MCM
Winter abstractions for filling dams	0.0	.62	.24	0.86	MCM
Paarl Abstraction	-	-	-	.35	MCM

Table 7. met demands by node.

*** Note: The irrigation demands will be different based on what the BSE model requires.**

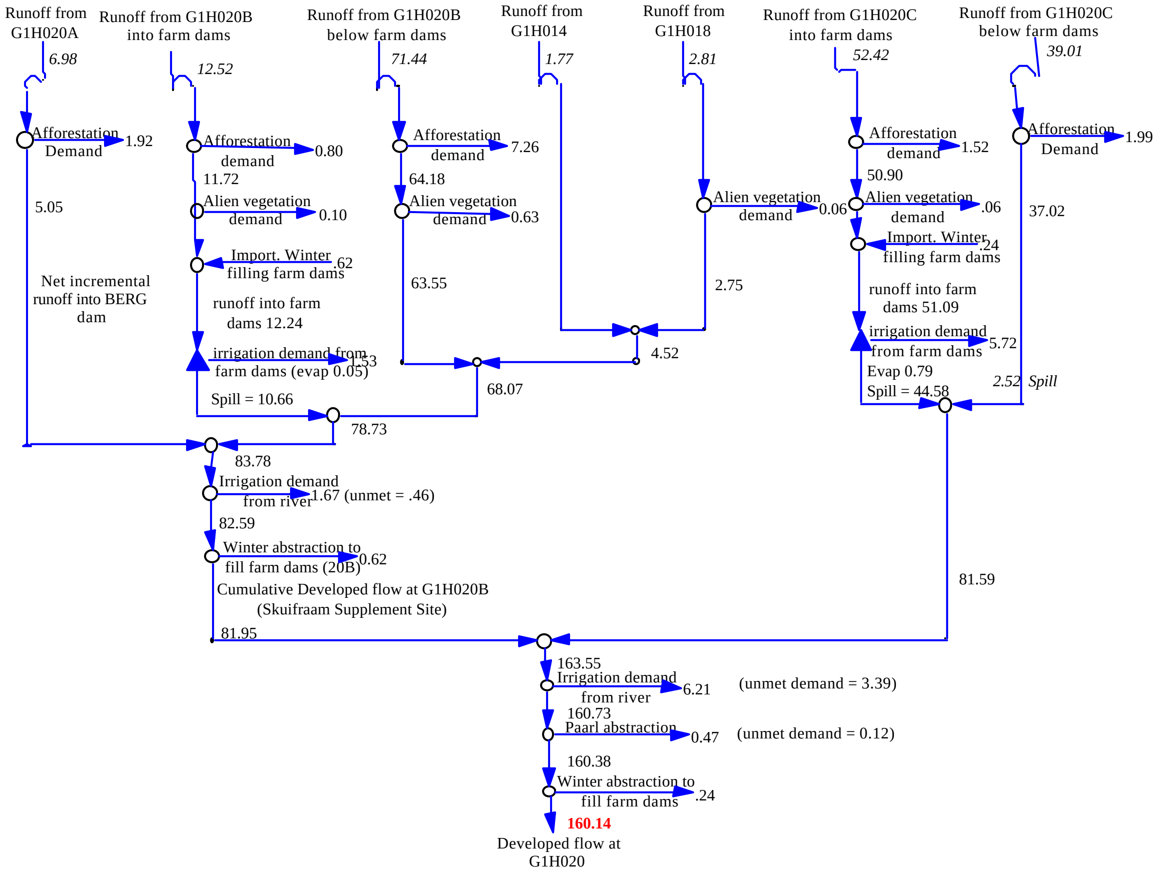


Figure 13. Model configuration sub catchment G1H020

Calibration:

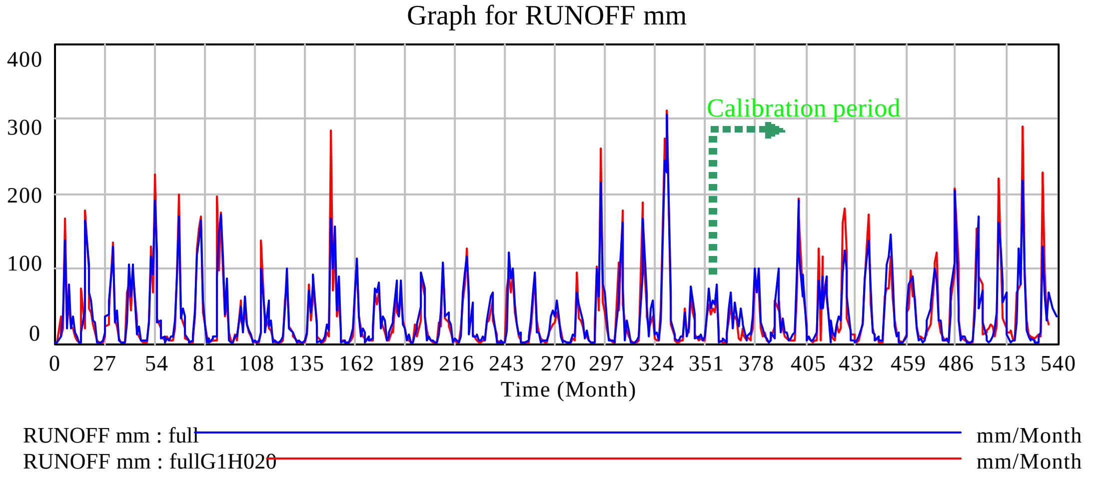


Figure 14. Calibration and test for G1H020. Calibration was done over the last 14 years (1980 –1994)

PART THREE: ABOVE THEEWATERSKLOOF DAM

1. NODE 7: H6H007, Du Toits River

Sub catchment area	46	km^2
MAP:	1445	mm
MAE (S-PAN):	1288	mm
Afforested area	0	km^2
Irrigation area	0	km^2
FARM DAM capacity	0	MCM
Incremental Naturalized MAR	42.01	MCM

Table 8. Properties H1H007

Notes:
The model calibration is relatively easy as there is no development of the basin—the only demand to subtract is that of alien vegetation.

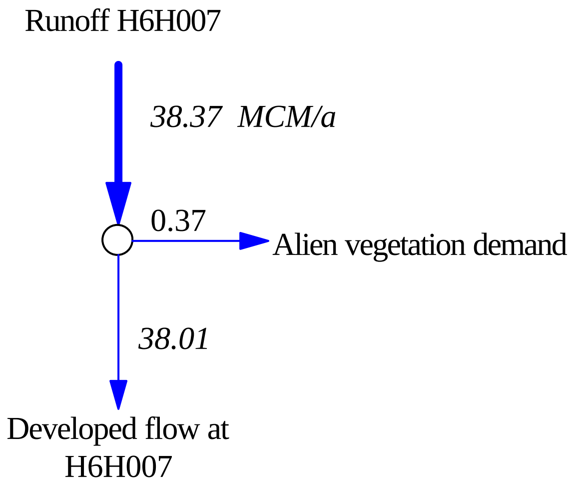


Figure 15. Model configuration of H6H007

Calibration results:

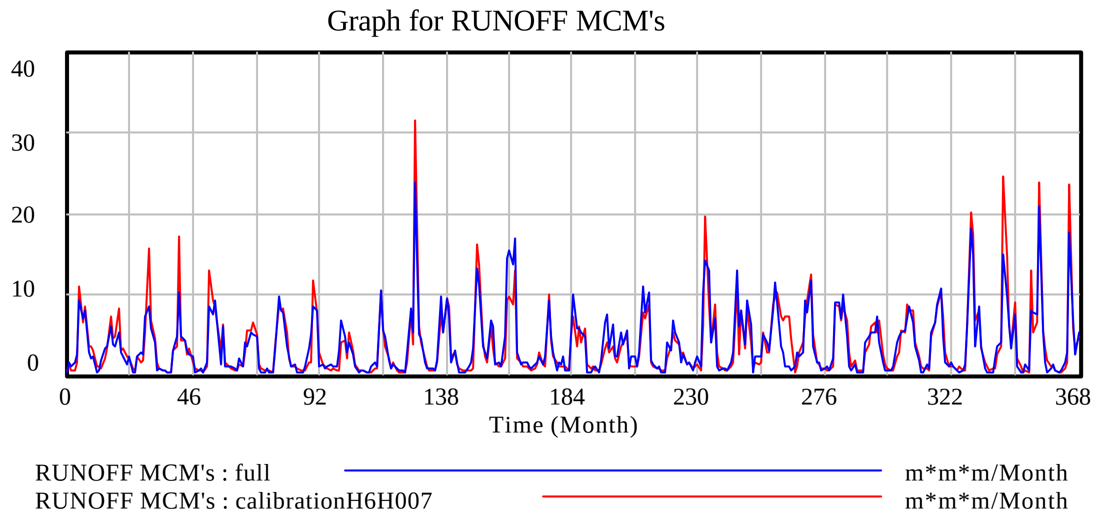


Figure 16. calibration from 1964-1991.

Full series (Figure x, below) uses different temperature series (CRU series)

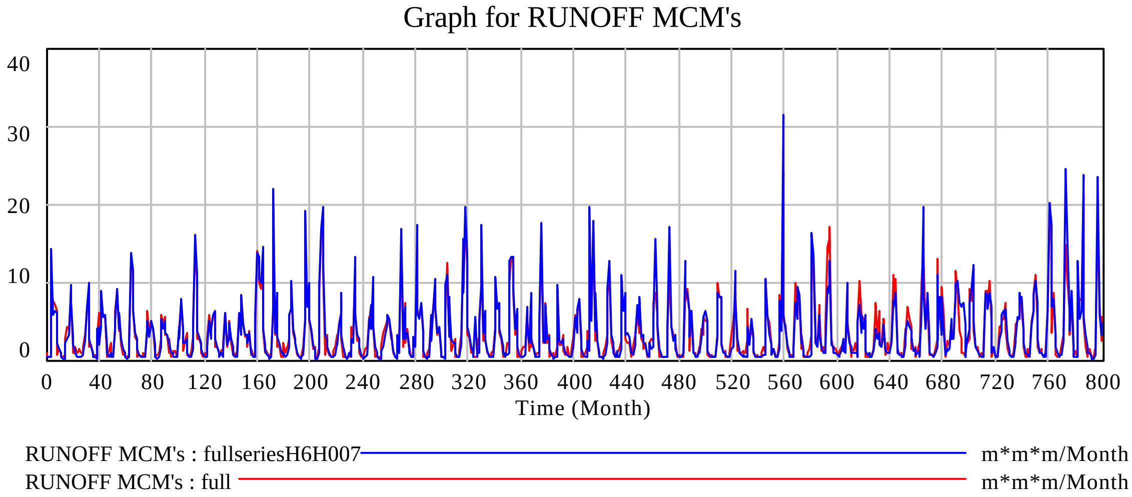


Figure 17. Full series 1927-1993.

2. Node 8: H6H008, Riviersonderend

Sub catchment area	38.57	km^2
MAP:	2314	mm
MAE (S-PAN):	1175	mm
Afforested area	0	km^2
Irrigation area	0	km^2
FARM DAM capacity	0	MCM
Incremental Naturalized MAR	60.85	MCM

Table 9. Properties H6H008

There are no demands, so the configuration is as follows:

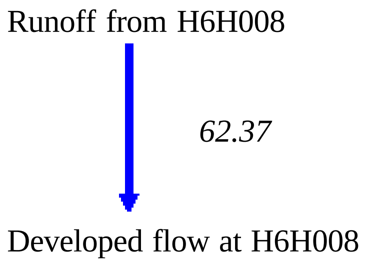


Figure 18. Schematic of developed flow for gauge H6H008.

Calibration:

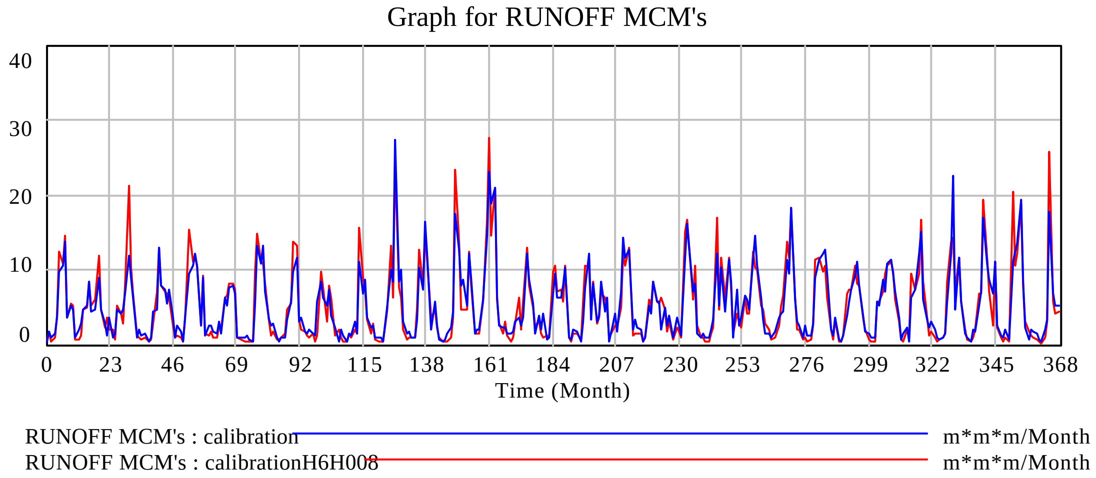


Figure 19. Calibration of H6H008.

3. Node 9: H6R002, Elands River

Sub catchment area	50.2	km^2
MAP:	1165	mm
MAE (S-PAN):	1160	mm
Afforested area	1.478	km^2
Irrigation area	4.90	km^2
Alien veg	.29	km^2
FARM DAM capacity	1.481	MCM
Incremental Naturalized MAR	23.43	MCM

Table 10. Properties H6H008

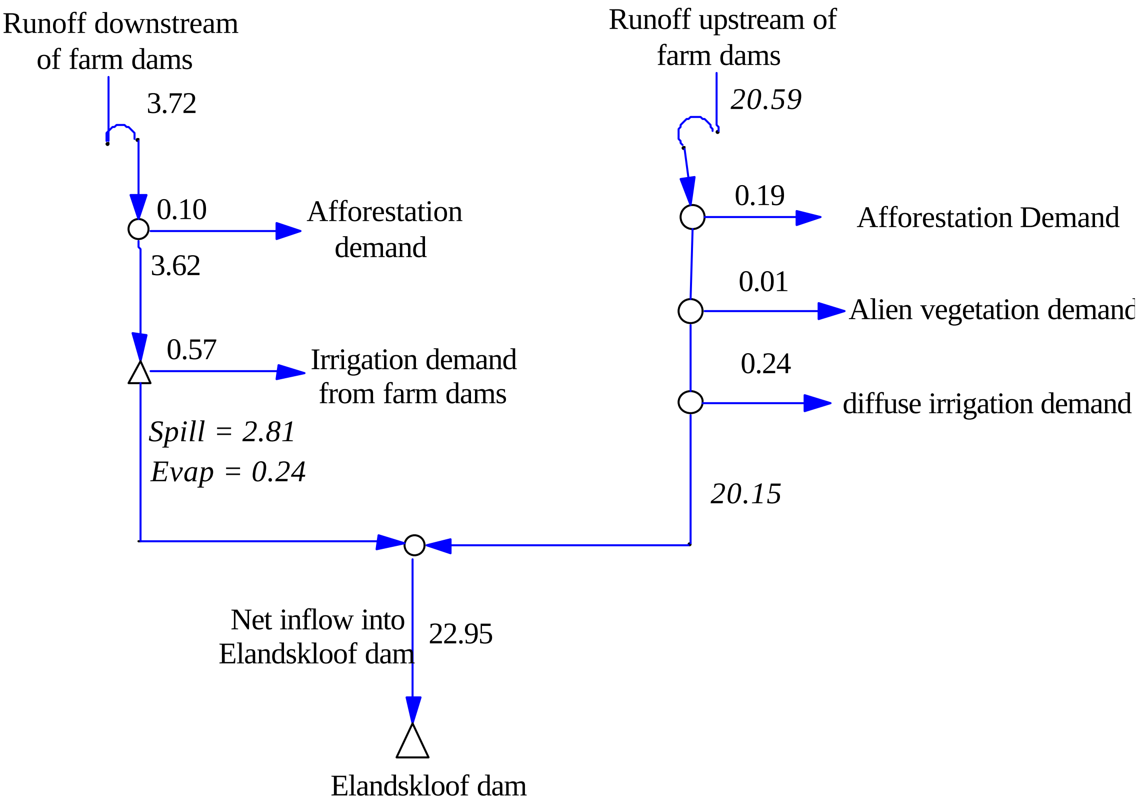


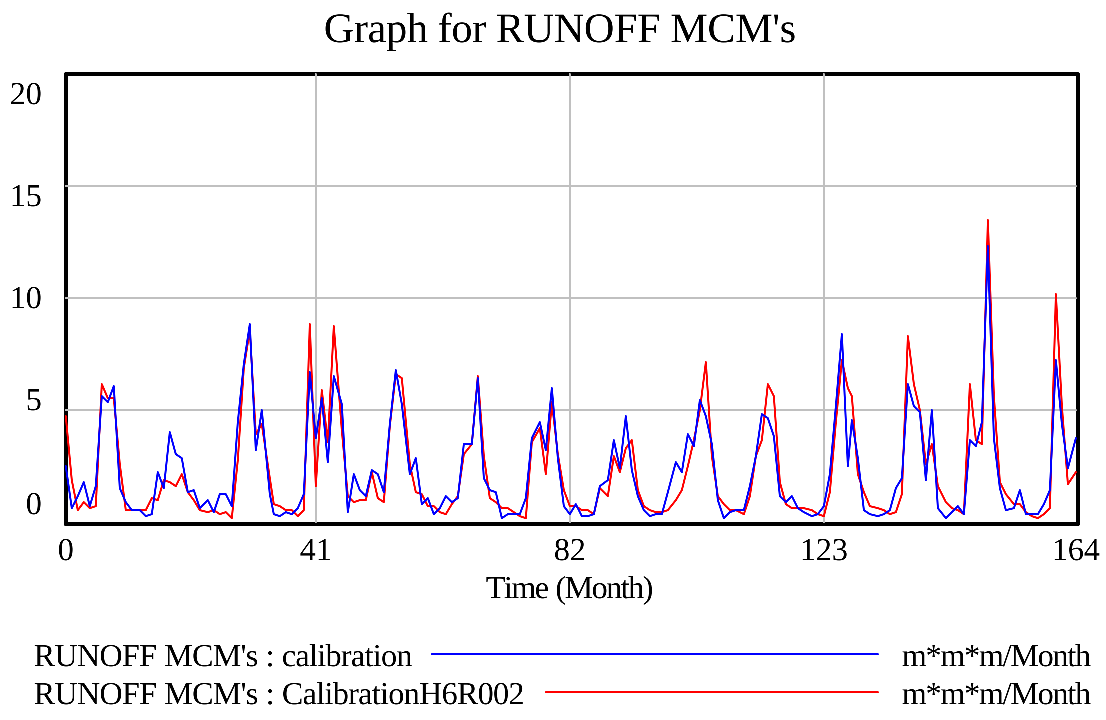
Figure 20. Model configuration sub catchment H6R002.

Notes:

BSE requirements: I have calibrated to naturalized flow, thus the following need to be **accounted for in the BSE model**:

- **met** demands need to be accounted for: forestry (.29 MCM/a), alien vegetation (.01 MCM/a), irrigation demand from farm dams (.57 MCM/a) and irrigation demand from the river (.24 MCM/a)
- **farm dam not modeled—but the met demands to be taken out of downstream flow (part of irrigation demand see above).**

- **Make sure these demands are accounted for in hydrology (i.e. perhaps build small dam in Watbal, as these demands will not nec. be taken care of in the BSE model).**



Calibration:
Figure 21. Calibration test. The mean runoff is matched (2.24 MCM/mo)

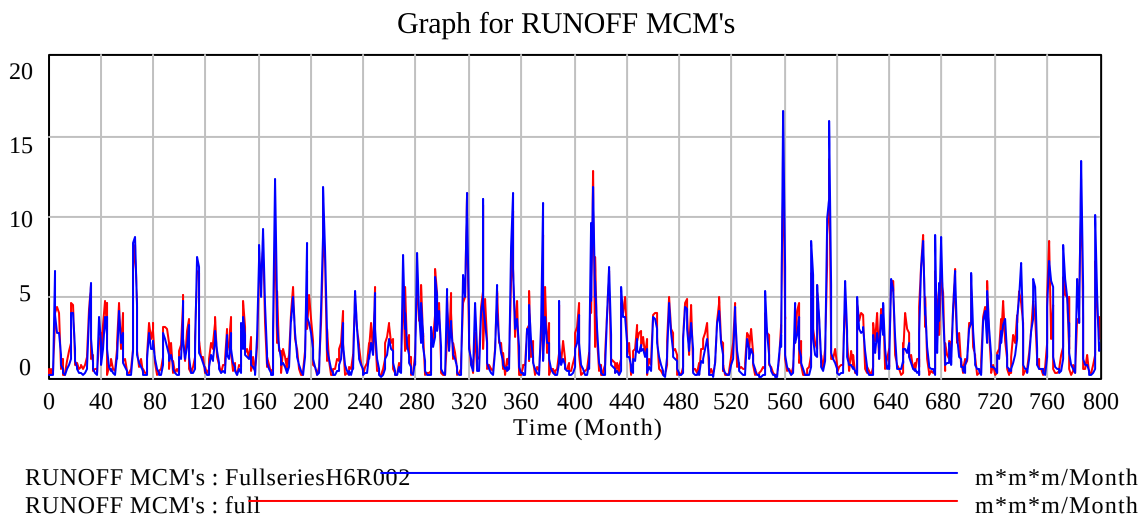


Figure 22. Calibration test. The modeled series is slightly higher than the historical (2 MCM/mo versus 1.95 MCM/mo).

4. Node 10: H6R001 (Riviersonderend)

Sub catchment area	365	km^2
MAP:	955	mm
MAE (S-PAN):	1465	mm
Afforested area	2888	km^2
Irrigation area	43763	km^2
Alien veg	12.15	km^2
FARM DAM capacity	8432	MCM
Incremental Naturalized MAR	157.42	MCM

Table 11. Properties H6R001

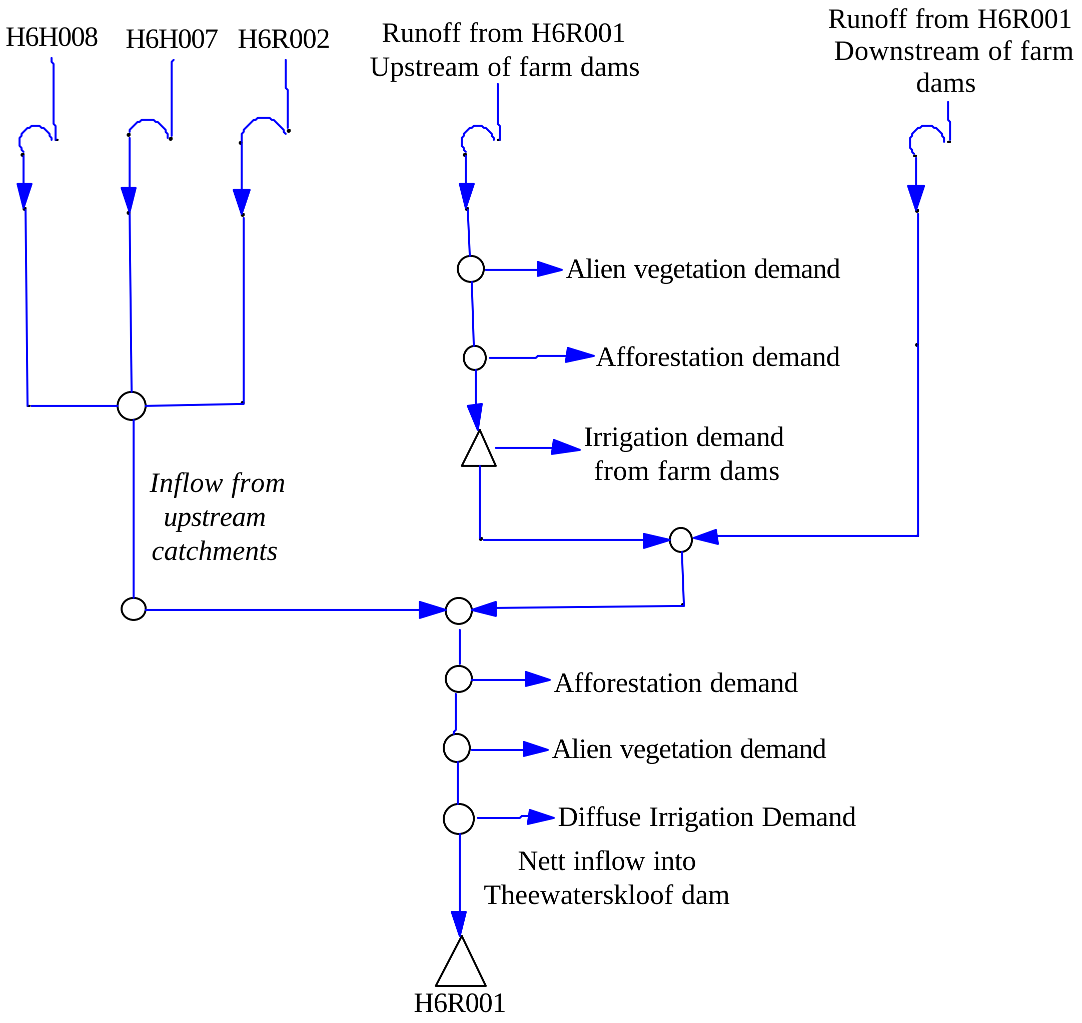


Figure 23. The model configuration of H6R001.

Notes:

<u>BSE requirements</u>: I have calibrated to naturalized flow, thus the following need to be **<u>accounted for in the BSE model</u>**:

- **met** demands need to be accounted for: upstream of farm dams: forestry (.35 MCM/a), alien vegetation (.08 MCM/a), irrigation demand from farm dams (12.16 MCM/a); downstream of farm dams: 6.95 MCM/a.
- **farm dam not modeled—but the met demands to be taken out of downstream flow (part of irrigation demand see above).**

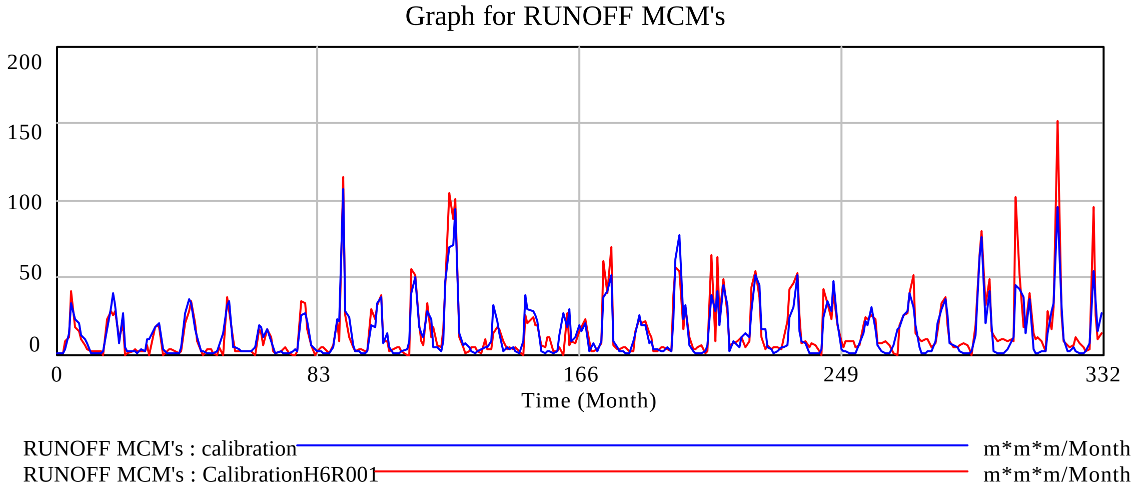


Figure 24. Calibration period for H6R001.

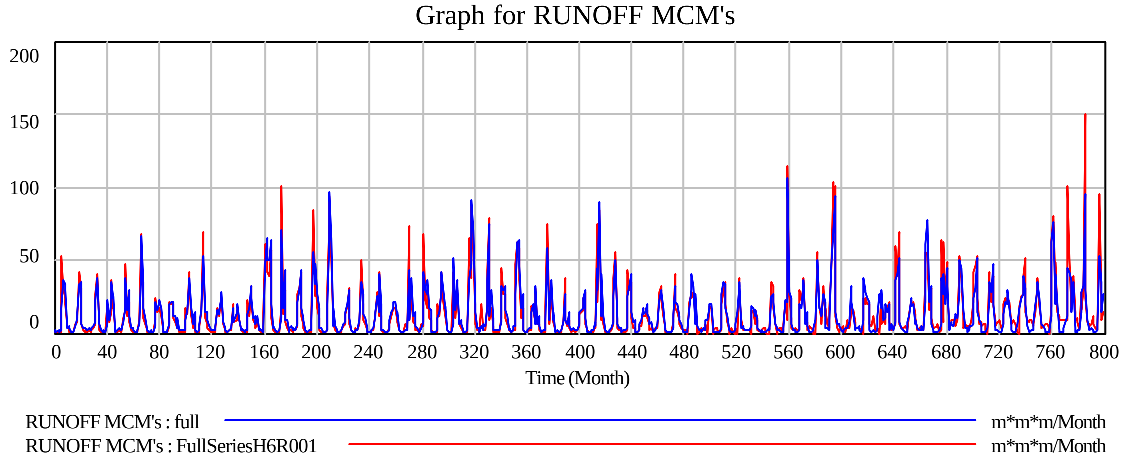


Figure 25. Calibration tested against full series.

Note the calibration period was an exceptionally wet period. When the original calibration was done, the subsequent test of the calibration resulted in too much water. It was decided to recalibrate to a longer, more representative time series.

Section IV. Storage Characteristics.

This section is incomplete

There are three different types of infrastructure represented here:

a. Volume to surface area linear approximations for each dam—(Theewaterskloof, Berg River, and Farm Dams)
b. Properties of hydrologic infrastructure

a. Volume to surface area graphs

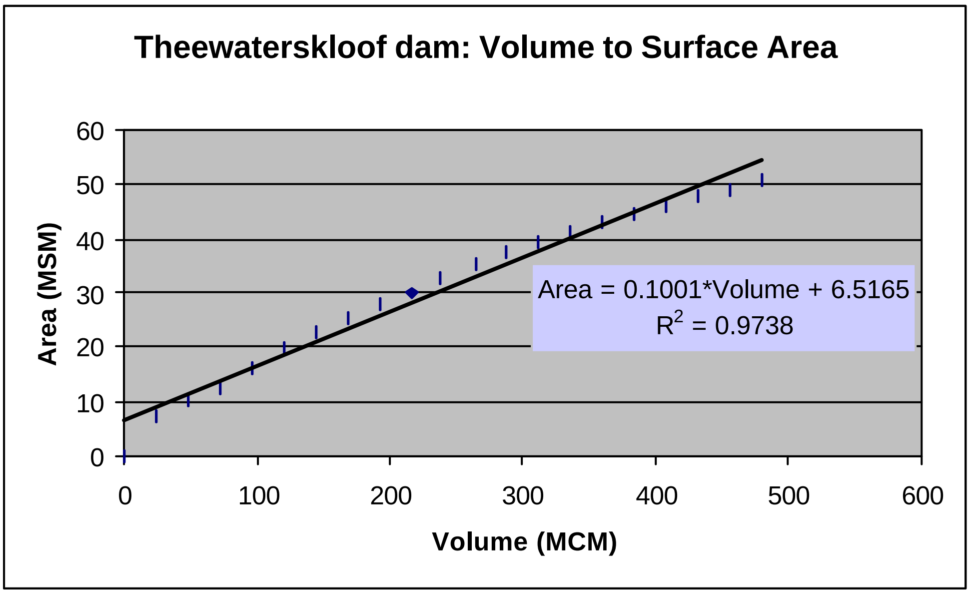


Figure 26. Volume to Surface Area curve for Theewaterskloof dam.

Figure 27. Volume to Surface Area Curve for proposed berg River Dam.

Figure 28-35. Volume to Surface Area curves for Representative Farm Dams

Section V. Data Sources

1. The hydrologic model requires information on:
    a. Precipitation,
    b. Temperature,
    c. Vapour Pressure
    d. Evaporation
    e. Runoff
    f. Met upstream water demands (for naturalization):
        i. Farm Dams,
        ii. Irrigation (met demands do not include return flows)
        iii. Urban demands

A. Precipitation data was obtained from Ninham Shand. This was extended from information at: http://www.dwaf.gov.za/hydrology/cgi-bin/his/cgihis.exe/station

B. Temperature Data was obtained from' Roland Schultze (Stations shown in Map A2)

C. Vapour Pressure, Temperature and Precipitation data was also obtained from the ½ degree by ½ degree dataset; although only vp data was used for the purposes of calibration.

D. Evaporation Data was obtained from the WR90 data set, as well as from ninham Shand. (Note conversion factor from S-pan obtained from WR90 worksheets)

E. Runoff Data was obtained from NS, WCSA (don't have this resource here), and extended by: http://www.dwaf.gov.za/hydrology/cgi-bin/his/cgihis.exe/station

F. Upstream water demands were obtained from NS and WCSA

Appendix 4
(Draft to be submitted as AIACC Working Paper)

Adaptation to Climate Change for Agriculture in The Gambia:

An explorative study on adaptation strategies for millet

D R A F T version 08

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Adaptation to Climate Change for Agriculture in The Gambia: an explorative study on adaptation strategies for millet

[to be submitted as AIACC Working Paper]

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5 Overview

The Gambia climatic conditions can be classified as sub-tropical with distinct dry and rainy seasons. The dry season is from November to May with average temperatures around 21-27 ^{o}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 ^{o}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 1000 mm y^{-1}, but considerable differences exist between years. Average climatic conditions for Banjul are plotted in Figure 3.

6 Variation in precipitation

Considerable year-to-year variation in precipitation occurs in The Gambia. In addition 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 4) 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 three 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}).

From these figures 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.

7 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 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. 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. The CRU grids that cover The Gambia are displayed in Figure 6.

A quick comparison between the observed rainfall and the gridded rainfall shows that averages for the entire country match very well (Figure 7). Plotting the long-term average precipitation patterns reveals that, according to the CRU-dataset, the north-south gradients is more profound than the east-west one. This gradient is also visible in the vegetation patterns as displayed in the Landsat image (Figure 1).

8 *Agriculture*

The Gambia remains predominantly an agrarian economy. The sector contributes up to 20 percent of the country's GDP, generates about 40 percent 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 percent from crops and 5 percent 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 despite a revival in production levels in recent years. 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 percent 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 some success in relation to horticulture, cotton and the introduction of sesame, diversification progress 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 possibilities 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 groundnut milling, cereal processing, dairy production, cotton ginning 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 exists.

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 managed 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.

9 *Drought Index*

10 *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 characterized 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.

11 Defining Drought

12 Rainfall

Situated in the tropical, semi-arid region of Africa, rainfall in The Gambia is highly variable, such that any meaningful assessment involving this parameter, should delve into its long-term behaviour, if pertinent conclusions are to be reached. Daily data 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 (13^{o} 21´ N, 16^{o} 38´ W), Yallal (13^{o} 33´ N, 15^{o} 43´ W), Janjanbureh (13^{o} 32´ N, 14^{o} 46´ W), and Basse (13^{o} 19´ N, 14^{o} 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 finally used to fill the data gap for the period of 1 - 10 August, 1990. 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. [5]

It is worthy of mention that preliminary analysis of the spatial distribution of rainfall in The Gambia, shows the existence of three rainfall zones which could be called the “Eastern”, “Middle” and “Western” thirds of the country. Differences in rainfall in these three broad zonations could be attributed to distance from the ocean and dynamics governing the location of the ITD at ground level during the early part of the rainy season. Thus, the “Western third” generally receives the highest amount of rainfall, followed by the “Eastern third” and the “Middle third”, in decreasing order.

13 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 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.

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 ------).

The main output of this model is the cumulative water satisfaction index (WSI), with runoff/drainage and total water requirements as secondary products.

Since drought is mainly associated with low moisture availability, we decided to confine 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 susceptible to be caused by a shortage of moisture 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*). It is worthy of mention that grain production at national level only meets about 50% of domestic grain requirement (draft ANR Sector Policy Paper, 2001) and thus shows the fragility of the Gambian economy vis-à-vis stressors in the food production chain.

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Three sowing dates were selected for each of the sites and for each season, in order to better simulate sowing conditions in farmers’ fields, from where the yield figures were obtained. Table 1 shows a water balance simulation during the 2002 growing season for early millet (90-100 days cycle), predominant in

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

Yallal and fast becoming the major upland cereal grown in the country. The various simulation dates (June 11-20, June 21-30, and July 1-10) resulted in WSI values of 87%, 87% and 96%, respectively. The WSI for a growing season is thus defined as the mean of the 3 values.

Contrary to expectations, an attempt to correlate yields (obtained from the various annual National Agricultural Sample Surveys, conducted by the Department of Planning) with seasonal WSI 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.

14 Drought characterization

Meanwhile Figure 10 shows a significant correlation between seasonal rainfall and yield. In conformity with expectation, the figure shows that in general, assuming management options and 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 and that higher rainfalls do not necessarily give high yields. From the above, it would appear that both rainfall intensity and temporal distribution are the key determinants of yield in this environment, as could seen in Figure 11, where the 1991 (seasonal rainfall of 544mm, yield of 1027 kg/ha) season was quite dry but gave average yields, and 1997 (seasonal rainfall of 956mm, yield of 620 kg/ha) was quite wet but yields were below average.

A drought in the Gambian agricultural context could therefore be 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 intensity would somehow compensate for any 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.

15 Water-Crop Simulation Model

16 SWAP

The Soil-Water-Atmosphere-Plant (SWAP) module was applied to simulate all the terms of the water balance and to simulate crop growth. SWAP is an integrated physically based simulation model for water, solute and heat transport in the saturated-unsaturated zone in relation to crop growth. 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 on, a continuous development of the program started. 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 already for many different conditions and locations and has been proven to produce reliable and accurate results (SWAP, 2003). A more 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).

The SWAP model have 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).

In the next sections the main processes that are included in the SWAP model will be described. The soil water module and the crop growth module are the two major components relevant to this study.

17 Soil Water Module

The core part of the soil water module (see Figure 14) is the vertical flow of water in the unsaturated-saturated zone, which can be described by the well-known Richards' equation:

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

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 in case of a uniform root distribution as:

$$S(h) = \alpha(h)\frac{T_{pot}}{|z_r|} \tag{2}$$

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.

Crop yields can be computed using a simple crop-growth algorithm based on Doorenbos & Kassam (1979) or by using a detailed crop-growth simulation module that partitions the carbohydrates produced between the different parts of the plant, as a function of the different phenological stages of the plant (Van Diepen et al. 1989).

The partitioning of potential evapotranspiration into potential soil evaporation and crop transpiration is based on the leaf area index. 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 modeled 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) and will be described after a brief theoretical description of crop growth processes.

18 Crop Growth Processes

Potential production of a crop is based on the fixation of solar energy in biomass referred to as photosynthesis, according to the well-know process:

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

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

Important in this process is to make a distinction between C3 and C4 plants. Examples of C3 plants are potato, sugarbeet, 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. Interesting is that only about 1% of the plant species is C4 and are mainly found in the warmer regions. Main reasons is that optimal temperatures for maximum assimilation rates is about 20^oC for C3 plants and 35^oC for C4 plants.

The difference between C3 and C4 plants is the way the carbon fixation takes place. C4 plants are more efficient in this and especially the loss of carbon during the photorespiration process is negligible for C4 plants. C3 plant may lose up to 50 % of their recently-fixed carbon through photorespiration.

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 C3 plants. This maximum is only reached if no water, nutrient or light (PAR) limitations occur.

A detailed description of the impact of climate change on crop growth is provided in section 5.2.

19 Crop Growth Module

A brief overview of the detailed crop growth module as applied here to calculate the maximal obtainable (=potential) yield is given here. Figure 14 shows the main processes and relations included in the detailed crop module referred here to as WOFOST. WOFOST (WOrld FOod STudies) has been developed and applied extensively in a wide range of studies over different locations, both in as a stand-alone as well as integrated in SWAP. The intercepted radiation energy is a function of the incoming radiation and the leaf area index (*LAI*). WOFOST computes at three selected moments of the day incoming photosynthetically active radiation just above the canopy. 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 maintenance, depending on the amount of dry matter in the various living plant organs, the relative maintenance rate per organ and the 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). Than conversion into structural dry matter takes place, and part of the assimilates is 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 *DVS*. Leaf senescence occurs due to water stress, shading (high *LAI*), and also due to life span exceeding.

Some simulated crop growth processes are influenced by temperature, such as the maximum rate of photosynthesis and the maintenance respiration. 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).

20 Climate Change Scenarios

Past climate change studies in The Gambia that have used Global Circulation Model (GCM) results to predict future climate changes demonstrated a considerable variance and an inconsistency in the direction of climate change, depending upon the GCM (US Country Studies, 1993; GOG, 2003). In this study, more recent versions of three GCMs[6] for the A2 and B2 IPCC SRES scenarios (IPCC, 2001) were downscaled to the Gambia; however, similar discrepancies in the resulting climate change were also observed as shown in Table 2.

This chapter is organized into three sections. Section I describes the downscaling process of the three GCM model scenarios to fit the Gambian context. This section begins with a description of the IPCC SRES scenarios, the selection of the three 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 application of the knn model to produce conditioned datasets. Finally, Section III describes the impact of carbon dioxide on crop growth.

21 Local Adjustment

The use of GCM climate data for modeling 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.

22 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 evolution 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.

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[6] Three transient general circulation models (GCMs) are used: Max Planck (MP) ECHAM4 model (Roeckner et al., 200?), The Hadley Center (HC) HadCM? model (Cullen, 200?), and the Geophysical Fluid Dynamics Laboratory (GF) GFDLr30 model (Delworth et al., 2002). Descriptions of the model scenarios can be found in the IPCC Third Assessment Report.

- 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 purposes of this study, two IPCC SRES scenarios were chosen, the so called “draft marker” scenarios: A2 and the B2. In conjunction with these storylines, several GCM were run. We have chosen three GCM models from this group[7], based on the results of previous climate change studies of The Gambia (US country studies and UNFCC communications). Since the magnitude and signal of climate change were highly variable and inconsistent dependent upon the GCM in these previous studies, we decided to select a variety of GCMs which would capture these inconcsistences, and test whether or not these descrepencies remain in later versions of the GCMs.

23 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). Figure XXX indicates the location of the three meteorological stations that were used for this study. 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[8] 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. The CRU grids that cover The Gambia are displayed in Figure XXX.

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 5.1.3. As shown in Figure X the three 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.

24 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 nine downscaled variables (3 climate variables * 3 GCM Scenarios * 2 IPCC SRES scenarios) for three time periods: the reference period (1961 – 1990), the period 2010 – 2039, and the period 2070 - 2099. The downscaling procedure is as follows:

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[7] list gcm models here

[8] 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.

STEP 1. The reference period is set for all variables at 1961 – 1990. The station data is daily, and will need to first be converted 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 1 was used to attain the corrected, or adjusted, climate parameter, thus creating the "adjusted reference period GCM time series":

$$a'_{gcm,M} = \left(\frac{a_{gcm,M} - \overline{a_{gcm,M}}}{s_{gcm,M}} \right) \cdot s_{obs,M} + \overline{a_{obs,M}} \qquad \text{Eq. 1}$$

where
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
ó$_{gcm}$ the standard deviation of the simulated climate parameter
ó$_{obs}$ 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. Compute the precipitation adjustment *ratio*, and the temperature adjustment *difference*. From the unadjusted reference period GCM data and the adjusted reference period GCM data, the monthly downscaling factors can be easily computed, as shown in equations 2 and 3.

$$\text{Ratio}_M = \overline{P_{M,UA}} - \overline{P_{M,A}} \qquad \text{Eq. 2}$$

where

Ratio_M	is the monthly precipitation adjustment ratio for month M
$\overline{P_{M,UA}}$	is the average *unadjusted* gcm time series monthly precipitation for the reference period for month M
$\overline{P_{M,A}}$	is the average adjusted gcm time series monthly precipitation for the reference period for month M

$$\text{Difference}_M = \overline{T_{M,UA}} / \overline{T_{M,A}} \qquad \text{Eq. 3}$$

Where

Difference_M	is the monthly temperature adjustment difference (*either* minimum or maximum) for month M
$\overline{T_{M,UA}}$	is the average *unadjusted* gcm time series for either maximum or minimum monthly precipitation for the reference period for month M
$\overline{T_{M,A}}$	is the average *unadjusted* gcm time series for either maximum or minimum monthly precipitation for the reference period for month M

STEP 4. Downscale the unadjusted 2010 - 2039 and the 2060 - 2099 GCM series using the monthly correction factors computed in Step 3, to produce adjusted GCM series for the corresponding period. To do this, add the monthly difference factor to the unadjusted temperature time series, and multiply the ratio factor by the unadjusted precipitation time series.

STEP 5. 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.

25 Results of the adjustment

The results shown here are only for the Yundum meteorological station, for the IPCC SRES A2 scenario and the HadCM3 model. The average annual rainfall, and resulting percentage change in the future climate scenarios from the adjusted reference time period is shown in Table x. The HadCM3 model did a poor job of reproducing the historical rainfall, as the adjusted GCM time series for the reference period is approximately 33 - 50% higher than its unadjusted counterpart. This may be in part due to the influence of the ocean, as the GCm does a particularly poor job capturing the mean of the Yundum station which lies nearest to the coast. Notice that there is a slight discrepancies between the observed and adjusted time series mean for the reference period, this is due to adjustments made during the downscaling process in order to prevent the occurrence of negative rainfall values in low rainfall months.
The figure shows a dramatic reduction in precipitation in the near future and distant future.

	Reference period (1961-1990)			Near Future (2010 - 2039)		Distant Future (2070 - 2099)	
Station	Observed	Unadjusted GCM	Adjusted GCM	Adjusted GCM	% Change from Reference GCM	Adjusted GCM	% Change from Reference GCM
Yundum	976	525	977	888	-9%	411	-58%
Yallal	752	525	750	676	-10%	298	-60%
Basse	842	525	845	756	-10%	461	-45%

Table x. Average annual rainfall, and percentage change for each climate change scenario from the adjusted reference period for the three representative stations and the A2HadCM3 scenario.

Table x shows the average annual maximum temperature [might be better to show this in a simple plot of monthly averages for the three scenarios!!], and percentage change for each climate change scenario from the adjusted reference period for the three representative stations and the A2HadCM3 scenario. The trend indicates a significant increase in maximum temperatures, especially for the coastal station, Yundum. The reference period GCM time series had to be significantly downscaled in order to fit the observed. The monthly trends can be seen in Figure x, which denote a particular *warming* for the x months…

Table x is similar to the above Table x, but it shows the mean annual minimum temperature series. The minimum temperatures from the GCM reference period were very close to the observed time period. The results indicate a slightly higher warming for the minimum temperatures than for the maximum temperatures for the distant future period. However, for the near term period the warming trend is slightly less for the minimum temperature than it is for the maximum temperature time series. This is due to the… Figure x indicates the monthly distributional changes.

In order to focus a little bit more on the variation in the time series, the results of the downscaling process for the three variables, monthly precipitation, minimum and maximum temperature for the Yundum station are shown through use of box whisker plots. Figure x shows the distribution of the annual precipitation for the observed reference period, the unadjusted reference period, and the adjusted reference period, the adjusted 2010 – 2039, and the adjusted 2070 – 2099.

Several dramatic results can be observed from Figure x. Left of the dotted vertical line, the distribution of the observed and the unadjusted GCM series for the reference period can be seen. Thus, the precipitation must be significantly upscaled in order to fit the observed distribution. As expected the Figure demonstrates that the adjusted GCM distribution for the reference time period is almost identical to the observed time series (in principal it should be identical, but negative precipitation had to be adjusted to zero in the months where the observed average was zero). Right of the dotted vertical line, the impacts of climate change can be seen—the precipitation is much lower and slightly more variable than the observed. Although the variability doesn't significantly change across the three GCM scenarios (over time).

The box-whisker plot for the maximum annual temperature for the observed reference period, the unadjusted reference period, the adjusted reference period, the adjusted 2010 – 2039, and the adjusted 2070 – 2099 are shown in Figure x. The results indicate that the maximum annual temperature had to be dramatically reduced to better fit the reference period of the Yundum maximum temperature data series. This may reflect the location of the Yundum station, which is influenced by the ocean due to its close proximity. To the right of the dotted vertical line, a general increase in temperature is observed for the GCM scenarios. The difference in the means of the GCM reference period and the 2070- 2099 period is approximately 6 degrees, representing a 16% increase.

Similarly, the 5 data series for the minimum average annual temperature are plotted in Figure x. The reference period GCM data was scaled down to fit the observed Yundum data. Notice that the absolute change in minimum temperature is less than the absolute change in maximum temperature from the reference to the period 2070 – 2099. The difference in the means of the GCM reference period and the 2070- 2099 period is approximately 4 degrees, representing a 20% increase.

26 Impact of CO_2 on Crop Growth

Crop production is affected by the air’s CO_2 level. Photosynthetically Active Radiation (PAR) is used by the plant as energy in the photosynthesis process to convert CO_2 into biomass. Important in this process is to make a distinction between C3 and C4 plants. Examples of C3 plants are potato, sugarbeet, 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.

The difference between C3 and C4 plants is the way the carbon fixation takes place. C4 plants are more efficient in this and especially the loss of carbon during the photorespiration process is negligible for C4 plants. C3 plant may lose up to 50 % of their recently-fixed carbon through photorespiration. This difference has suggested that C4 plants will not respond positively to rising levels of atmospheric CO_2. However, it has been shown that atmospheric CO_2 enrichment can, and does, elicit substantial photosynthetic enhancements in C4 species (Wand et al., 1999).

Modeling 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 has 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 kind of experiments (CSCDGH, 2003).

For the SWAP model the impact of elevated CO_2 levels the so-called Light Use Efficiency was adjusted to account for this. Bouman et al. (2001) derived the following equation based one 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 arbitrary we assumed here, based on the CSCDGH dataset, for C4 plants the impact is 50% of the one 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.

27 Impact of Climate Change on Crop Production

28 Reference Situation

29 Yundum

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 three meteorological stations with some additional data from the CRU dataset (solar radiation, relative humidity).

In Table 3 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 droughts is substantial with very low yields for the years 1972, 1977, 1980 and 1983 (Figure 15).

The average precipitation over the 30 years period is 976 mm and is used for crop transpiration, soil evaporation and percolation to the deep 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 (Figure 16). 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 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 realize 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 (CRW) 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 higher values than 100% (see Figure 16 bottom), 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 a low percolation in 1984 as most of the rains that year are 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 and rainfall might be too intensive to be stored in the root zone.

In terms of strategies to use water more productive it is important to realize 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.

30 Impact of Climate Change

31 Near Future (2010-2039)

The major impact of climate change on millet yields will be the projected changes in precipitation. As shown in FIGURE XXX, a reduction in rainfall of XXX 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 40^{o}C, 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 fertilization can have a positive impact on the photosynthesis process, although for C4 plants 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.

As shown in Table 4 the overall impact of these changes on millet is that the average yield over the period 2010-2039 is almost similar as compared to the reference (1961-1990). However, the variation in yields between years has almost doubled as indicated by the Coefficient of Variance 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. Figure 17 shows this increase in variation in yields, where it is clear that years with zero yields and years with high yields will be more profound in the near future.

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

32 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 analyze the extreme as a worst scenario case.

Figure 17 en Table 4 indicate, 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 so-called production potential of millet is going up 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 (Figure 17).

It is obvious that the only adaptation to this extreme reduction in precipitation is shifting to irrigated agriculture. However, the lower rainfall means that also 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.

33 Adaptation Strategies

34 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 than ones for the distant future (2070-2099). For the near future most important is that adaptation will be focused to reducing the expected increase in variation in yield, while for the distant future only the introduction of irrigated agriculture seems to be the only solution to continue with arable farming. Given the extreme reduction in precipitation as projected by the HADCM3 in comparisong 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 explore, but only some potential measures were mentioned focusing on:

1. crop breeding programs
2. soil fertility
3. planting dates
4. irrigation
5. integrated agricultural systems
6. early warning systems
7. 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 fertilizer, and (iii) introduction of irrigation.

35 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 resistance, (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 for the near future (2010-2039) the model was run.

Actual millet yields will increase by about 25% and also a reduction in year-to-year variation will occur (Table 5). However, still years with low yields will occur as precipitation is still too low even for the drought resistance crops. As discussed earlier, projections of rainfall indicates that values can be as low as 310 mm y^{-1} according to the HADCM3 model.

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's 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 loaning schemes.

36 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, XXX). 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 already reasonably high soil water holding capacities so the major benefit from an increased use of fertilizer will be on the crop. In terms of fertilizer, the approach we follow here is not specific in whether this will be by means of chemical or natural fertilizer. The SWAP model is not specific in the amount of fertilizer 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 can be done by the DSSAT model (GOTB, 2003).

The use of fertilizer will increase crop yields and reduces year-to-year variation (Table 5). However, since fertilizer will mainly play a role in terms of the production potential of the crop and only a minor role on the drought resistance, still many years with low yields can be expected (Figure 18).

37 Irrigation

One of the most obvious adaptation strategies is the introduction of irrigation. Especially 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, at the moment is the long-term average rainfall 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 one requires a proper analyses of salt water intrusion, which can be up to 100 km inland.

The use of groundwater for irrigation purposed 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 5 and (Figure 18) show that the full irrigation has an enormous impact on crop yields and variation in yields. Yields will increase by almost 60% 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. On average about 200 mm y^{-1} of irrigation is required.

Given the constraints in the 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 17%.

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 somewhat higher levels..

38 Conclusions, Recommendations

Due to the discrepancies observed in the GCM output, it was decided to include additional climate change scenarios using a non-parametric k-nearest neighbor (knn) resampling methodology (Yates et al., 2003). The method is a bootstrap technique that resamples from the historical data. It finds neighbors from the historical data to the current state and resamples one of the neighbors as the simulated value to the next step. For details on the algorithm refer to Lall and Sharma, 1996; Rajagopolan and Lall, 1999. The model may be used to produce alternative climate data sets conditioned upon hypothetical climate scenarios, in this case, shorter drier growing seasons or more frequent ENSO events.

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Tables

Table 1. Water Balance Simulation for year 2002 at Yallal.

Water Balance at Yallal in 2002 (Crop Cycle of 100 days)

Sowing Date: Dekad II June

Month	Dekad	PN	PA	Normal PET	KCR	WR	PA - WR	RS (100 mm)	S/D	Index
May	3		2.6	58.9						
June	1		0	48.1						
	2		40.1	45.3	0.3	13.6	26.5	26.5		100
	3		15.2	42.4	0.4	17.0	-1.8	24.8		100
July	1		29	37.1	0.5	18.6	10.5	35.2		100
	2		7.4	35.2	0.8	28.2	-20.8	14.4		100
	3		32.1	37.6	1	37.6	-5.5	8.9		100
August	1		15.2	34.7	1	34.7	-19.5	0.0	-10.6	96
	2		13.8	36.3	1	36.3	-22.5	0.0	-22.5	87
	3		123.7	40.7	0.8	32.6	91.1	91.1		87
September	1		52.5	38.0	0.6	22.8	29.7	100.0	20.8	87
	2		63.6	39.2	0.5	19.6	44.0	100.0	44	87

Sowing Date: Dekad III June

Month	Dekad	PN	PA	Normal PET	KCR	WR	PA - WR	RS (100 mm)	S/D	Index
May	3		2.6	58.9						
June	1		0	48.1						
	2		40.1	45.3						
	3		15.2	42.4	0.3	12.7	2.5	2.5		100
July	1		29	37.1	0.4	14.8	14.2	16.6		100
	2		7.4	35.2	0.5	17.6	-10.2	6.4		100
	3		32.1	37.6	0.8	30.1	2.0	8.5		100
August	1		15.2	34.7	1	34.7	-19.5	0.0	-11	96
	2		13.8	36.3	1	36.3	-22.5	0.0	-22.5	87
	3		123.7	40.7	1	40.7	83.0	83.0		87
September	1		52.5	38.0	0.8	30.4	22.1	100.0	5.1	87
	2		63.6	39.2	0.6	23.5	40.1	100.0		87
	3		6.5	44.1	0.5	22.1	-15.6	84.5		87

Sowing Date: Dekad I July

Month	Dekad	PN	PA	Normal PET	KCR	WR	PA - WR	RS (100 mm)	S/D	Index
May	3		2.6	58.9						
June	1		0	48.1						
	2		40.1	45.3						
	3		15.2	42.4						
July	1		29	37.1	0.3	11.1	17.9	17.9		100
	2		7.4	35.2	0.4	14.1	-6.7	11.2		100
	3		32.1	37.6	0.5	18.8	13.3	24.5		100
August	1		15.2	34.7	0.8	27.8	-12.6	11.9		100
	2		13.8	36.3	1	36.3	-22.5	0.0	-10.6	96
	3		123.7	40.7	1	40.7	83.0	83.0		96
September	1		52.5	38.0	1	38.0	14.5	97.5		96
	2		63.6	39.2	0.8	31.4	32.2	100.0	15	96
	3		6.5	44.1	0.6	26.5	-20.0	80.0		96
October	1		47.4	47.6	0.5	23.8	23.6	103.6		96

Table 2. GCM annual average precipitation for 2010 – 2039 and 2070 – 2099 as a percentage of average annual precipitation for the observed reference period, 1961- 1990.

	Reference period (1961-1990)			Near Future (2010 - 2039)		Distant Future (2070 - 2099)	
Station	Observed	Unadjusted GCM	Adjusted GCM	Adjusted GCM	% Change from Reference GCM	Adjusted GCM	% Change from Reference GCM
Yundum	976	525	977	888	-9%	411	-58%
Yallal	752	525	750	676	-10%	298	-60%
Basse	842	525	845	756	-10%	461	-45%

	Reference period (1961-1990)			Near Future (2010 - 2039)		Distant Future (2070 - 2099)	
Station	Observed	Unadjusted GCM	Adjusted GCM	Adjusted GCM	% Change from Reference GCM	Adjusted GCM	% Change from Reference GCM
Yundum	32.0	38.4	32.0	34.9	9%	38.1	19%
Yallal	34.4	38.4	34.4	34.0	-1%	39.4	15%
Basse	37.6	38.4	37.6	38.6	3%	41.8	11%

	Reference period (1961-1990)			Near Future (2010 - 2039)		Distant Future (2070 - 2099)	
Station	Observed	Unadjusted GCM	Adjusted GCM	Adjusted GCM	% Change from Reference GCM	Adjusted GCM	% Change from Reference GCM
Yundum	19.9	20.1	19.9	21.3	7%	24.5	23%
Yallal	20.4	20.1	20.4	21.7	6%	24.8	22%
Basse	20.7	20.1	20.7	22.3	8%	25.5	23%

Table 3. Water balance for the Yundum reference situation. Values are average (mm y^{-1}), Coefficient of Variation (%) and crop yields (kg ha^{-1}) over the period 1961-1990.

Water Balance					
In	*Avg*	*CV*	*Out*	*Avg*	*CV*
Precipitation	976	30	Transpiration	186	25
Storage	-5		Evaporation	341	18
			Percolation	441	57
Crop Yield					
	1081	30			

Table 4. Impact of climate change on precipitation and millet yields for Yundum. Percantages in brackets are changes relative to the reference period 1961-1990.

	1961-1990	2010-2039	2070-2099
Precipitation			
Average (kg ha^{-1})	976	882 (-10%)	409 (-58%)
CV (%)	30	33	58
Yield			
Average (kg ha^{-1})	1081	1069 (-1%)	354 (-67%)
CV (%)	30	50	167

Table 5. Results of the adaptation strategies as explored with the model for the the near future (2010-2039). ***Change*** *indicates the change in yield compared to the no adaptation,* ***CV*** *is the year-to-year Coefficient of Variation in yields.*

	average (kg ha^{-1})	Yield change (%)	CV (%)
No adaptation	1069		50
Crop variety	1327	+24	34
Fertilizer	1480	+38	38
Irrigation	1702	+59	10
Supplemental Irr.	1250	+17	37

Figures

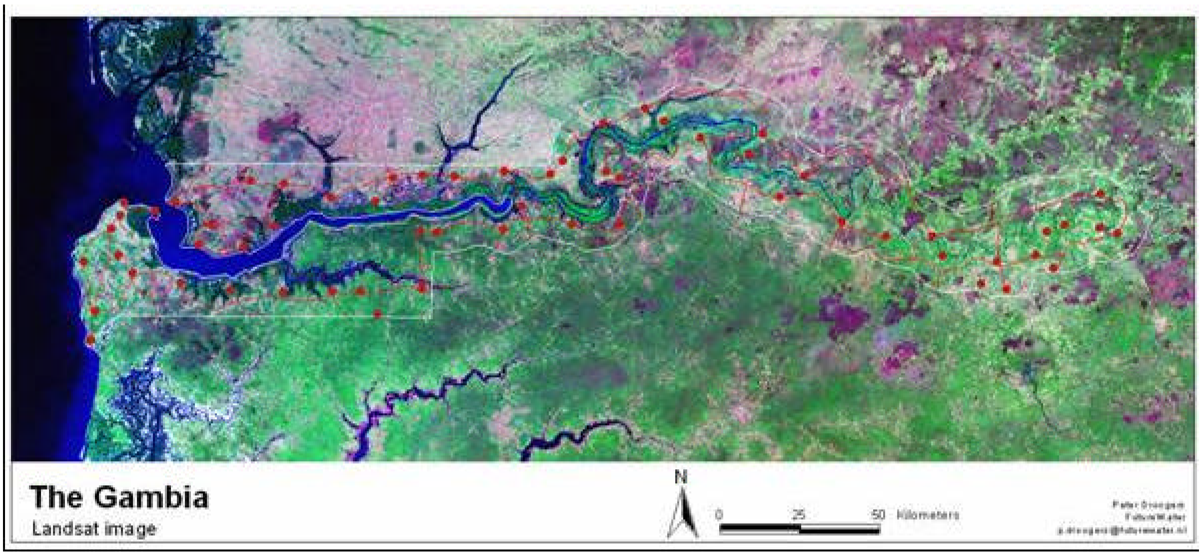

Figure 1. Overview of The Gambia. Landsat composite from 1990.

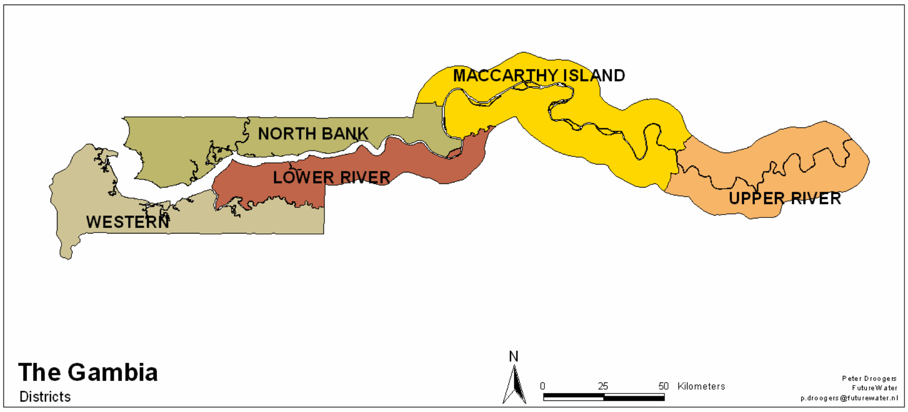

Figure 2. Major regions in Gambia.

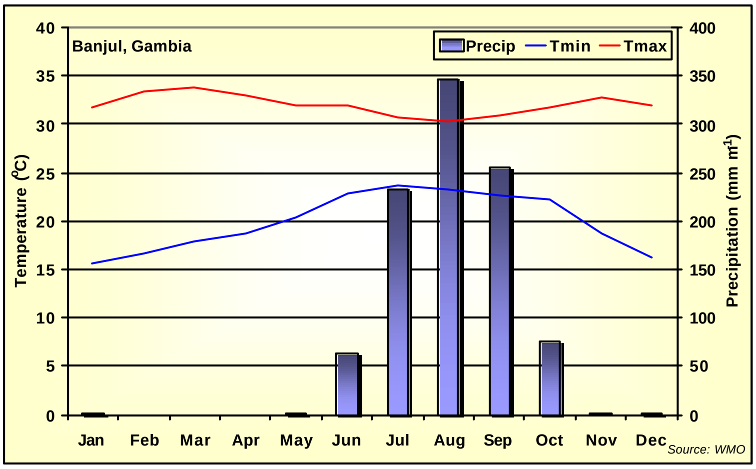

Figure 3. Average climate conditions for Banjul. Source: World Meteorological Organization (WMO).

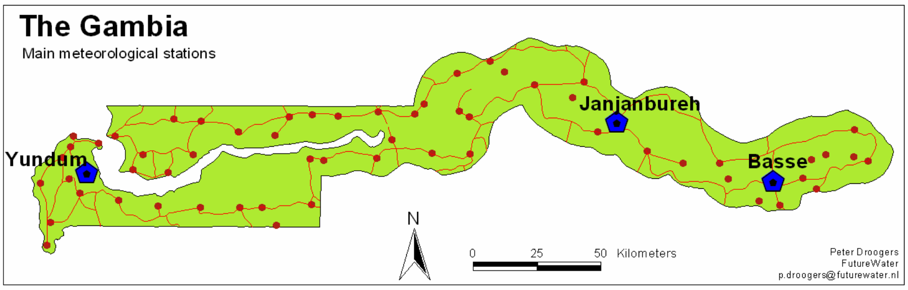

Figure 4. Three main meteorological stations for which long-term precipitation data are available.

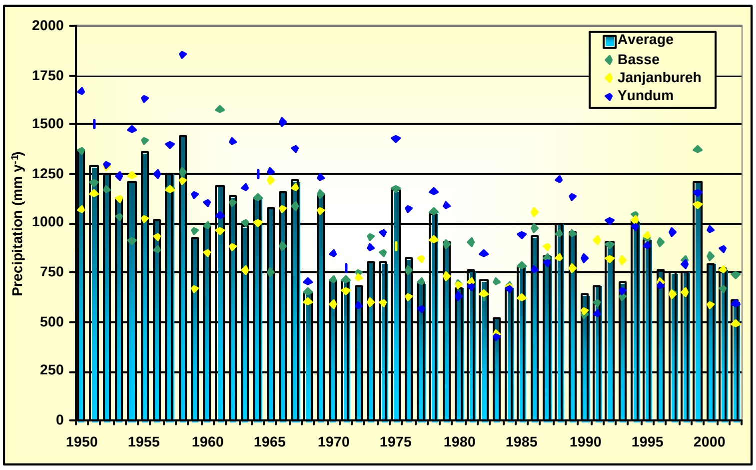

Figure 5. Observed annual precipitation over the last 50 years for the main meteorological stations.

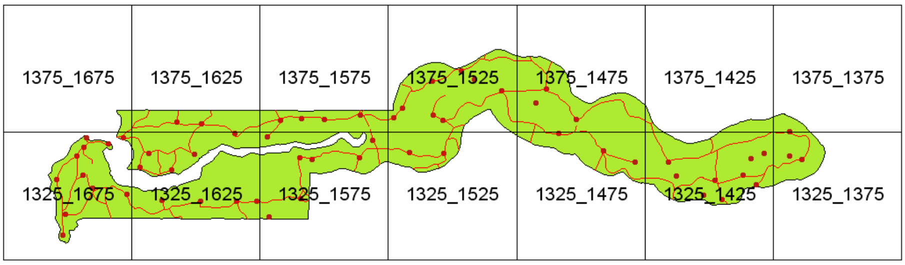

Figure 6. Grids as used in the CRU climate dataset.

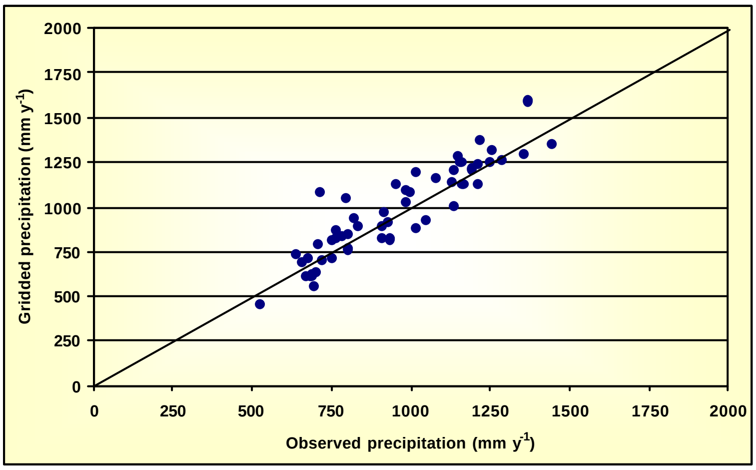

Figure 7. Observed and gridded annual precipitation for the entire country over the perdiod 1960-2000. Observed data is the average for the stations Yundum, Basse and Janjanbureh, gridded data is the average for the 14 CRU-grids covering The Gambia.

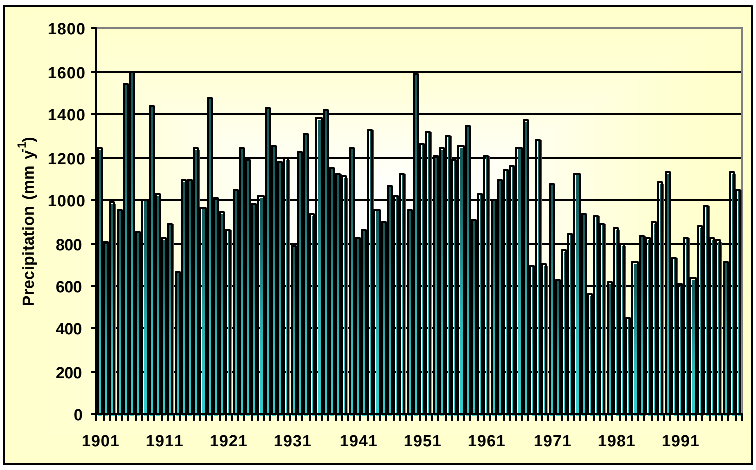

Figure 8. Annual precipitation for the entire country over the period 1901-2000. Data is based on gridded observed precipitation from the CRU dataset.

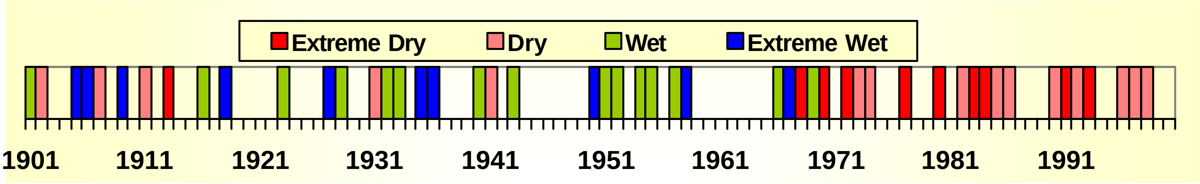

Figure 9. Variation in annual precipitation over the entire country. Extreme dry and wet reflects the 10% driest respectively wettest years, dry and wet reflect the 25% driest and wettest years. Data is based on gridded observed precipitation from the CRU dataset.

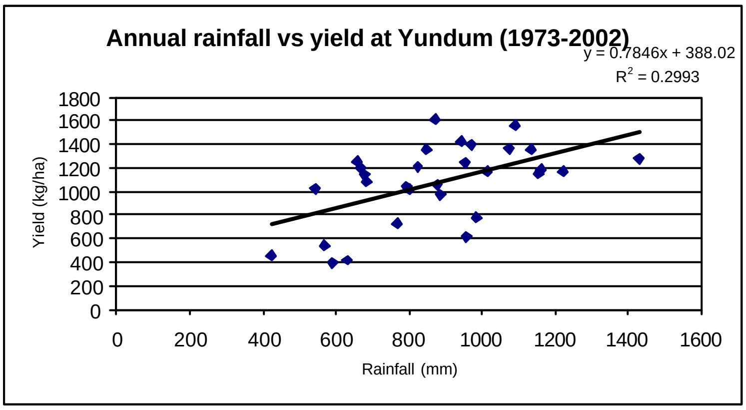

Figure 10. Regression plot of seasonal rainfall and yield at Yundum

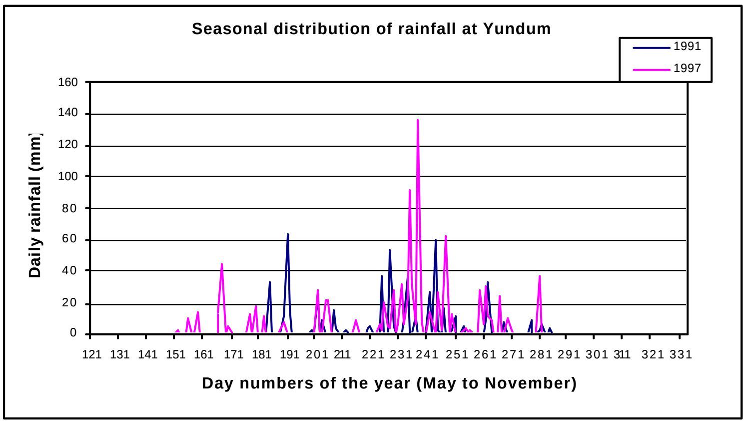

Figure 11. Ten-day distribution of seasonal rainfall in 1991 & 1997.

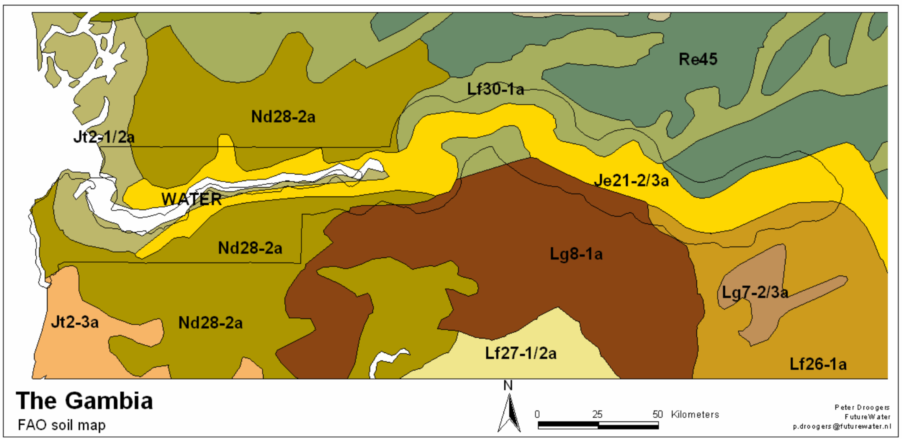

Figure 12. Soil map according to the FAO soil map of the world.

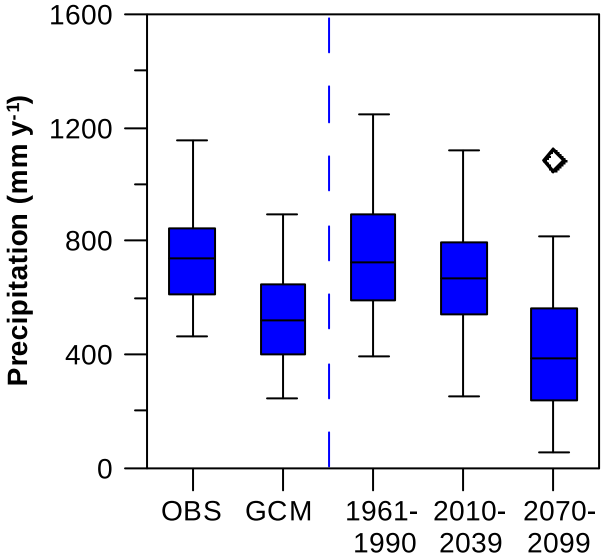

Figure x. Plot of the distributions of the annual precipitation for the 5 time series for Yundum A2HadCM4 model: observed reference period, the unadjusted reference period, and the adjusted reference period, the adjusted 2010 – 2039, and the adjusted 2070 – 2099.

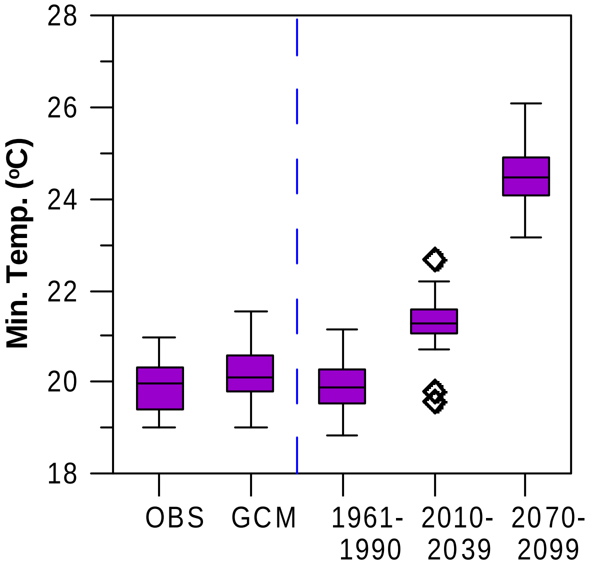

Figure x. Plot of the distributions of the annual minimum temperature for the 5 time series for Yundum A2HadCM4 model: observed reference period, the unadjusted reference period, and the adjusted reference period, the adjusted 2010 – 2039, and the adjusted 2070 – 2099.

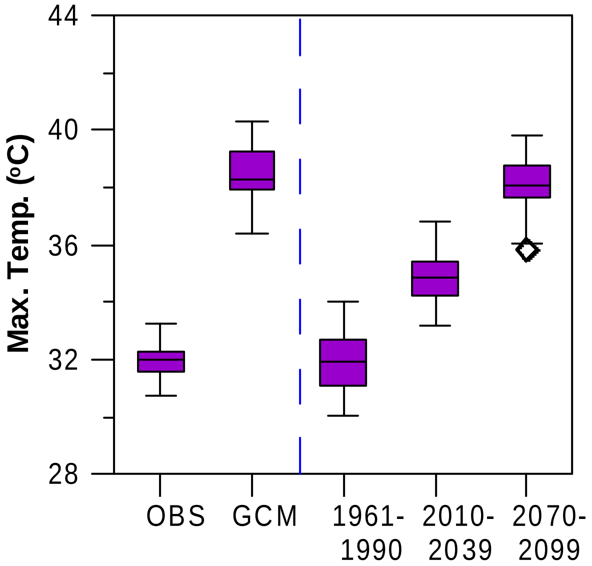

Figure x. Plot of the distributions of the annual maximum temperature for the 5 time series for Yundum A2HadCM4 model: observed reference period, the unadjusted reference period, and the adjusted reference period, the adjusted 2010 – 2039, and the adjusted 2070 – 2099.

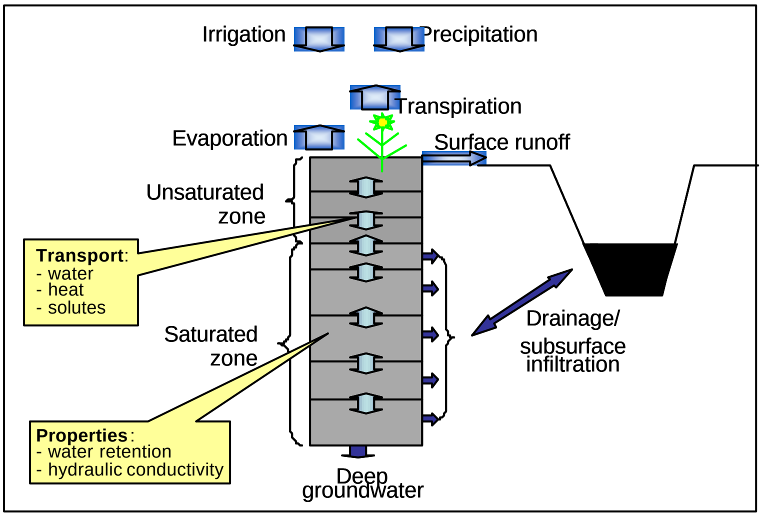

Figure 13. Overview of the main processes included in the soil-water-crop module of SWAP-WOFOST.

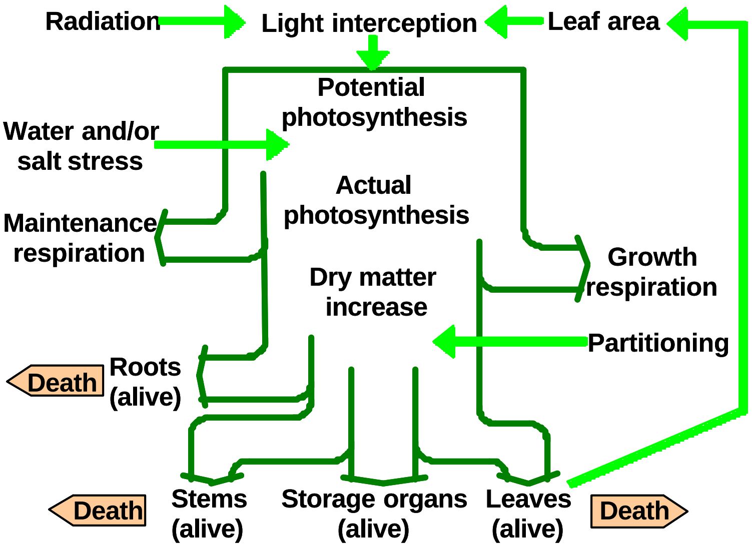

Figure 14. Overview of the main processes included in the detailed crop growth module of SWAP-WOFOST.

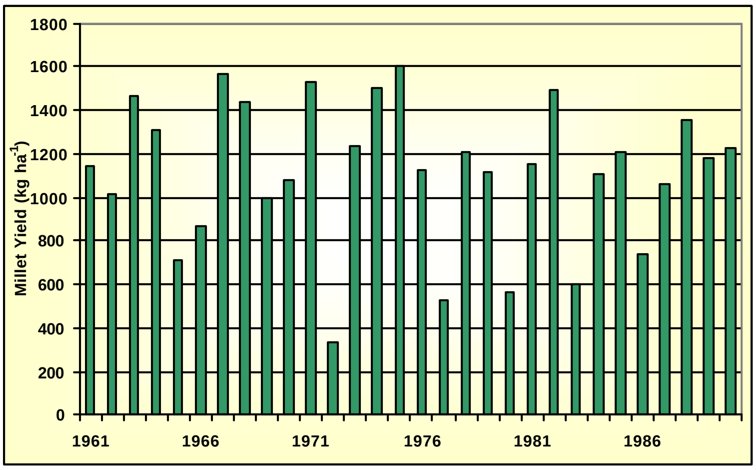

Figure 15. Simulated millet yields for the reference Yundum.

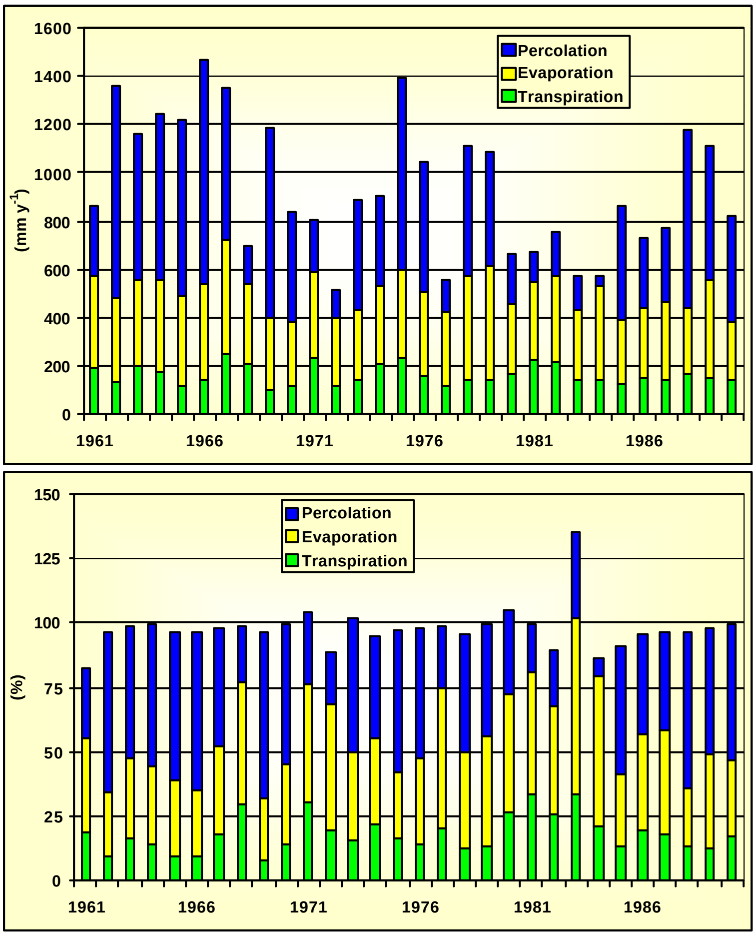

Figure 16. Variation in the annual water balance for the reference Yundum, in total mm y^{-1} (top) and as percentage (bottom).

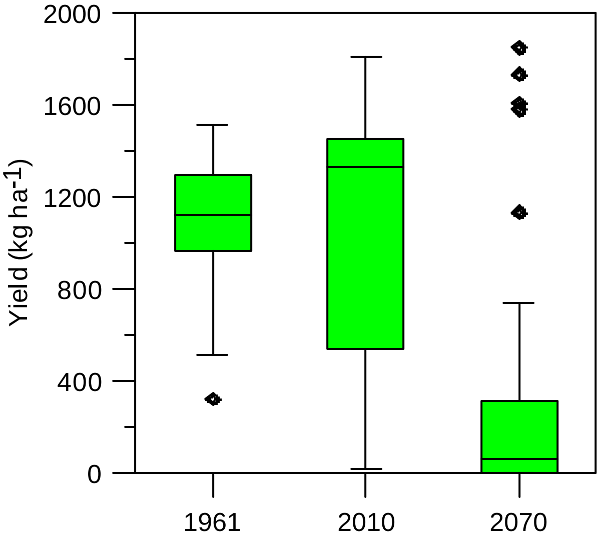

Figure 17. Millet yields for the reference situation (1961-1990), the near future (2010-2039) and the distant future (2070-2099).

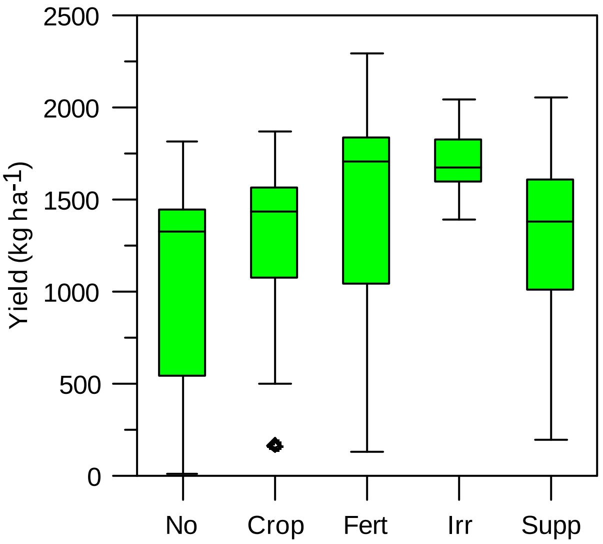

Figure 18. Millet yields for the near future (2010-2039) with and without adaptation strategies. No is no adaptation (impact), Crop is improved crop variety, Fert is enhanced use of fertilizer, Irr is introduction of irrigation, and Supp is application of supplemental irrigation.