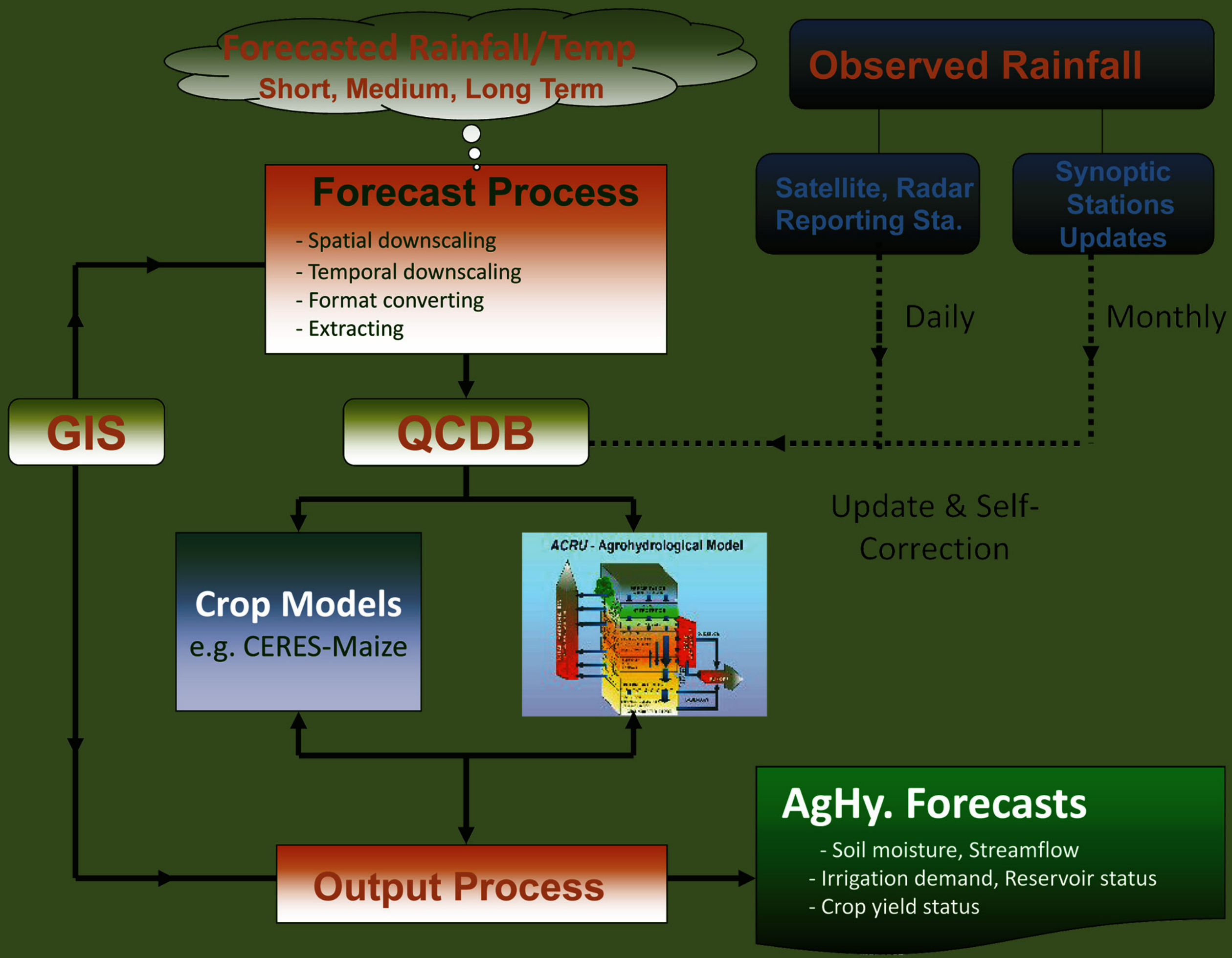
Development and Applications of Rainfall Forecasts for Agriculturally-Related Decision-Making in Selected Catchments of South Africa

TG Lumsden & RE Schulze (Editors)



WATER RESEARCH COMMISSION

TT 538/12

DEVELOPMENT AND APPLICATIONS OF RAINFALL FORECASTS FOR AGRICULTURALLY-RELATED DECISION-MAKING IN SELECTED CATCHMENTS OF SOUTH AFRICA

Report to the
Water Research Commission

by

TG Lumsden and RE Schulze (Eds)
University of KwaZulu-Natal, Pietermaritzburg

Contributors

Schulze, RE (Ch 1,2,3,4,5,6,7,12,13,14)
Lumsden, TG (Ch 1,2,5,6,8,13,14)
Ghile, YB (Ch 2,3,5,6,7)
Zuma-Netshiukhwi, G (Ch 5,6,9,10)
Engelbrecht, CJ (Ch 4,11,12)
Phahlane, O (Ch 5,9,10)
Tadross, MA (Ch 4,9,12)
Engelbrecht, FA (Ch 4,12)
Kunz, RP (Ch 11,12)
Steyn, AS (Ch 4,10)
Crespo, O (Ch 6)
Walker, S (Ch 6)
Gobaniyi, B (Ch 4)
Horan, MJC (Ch 12)
Johnston, P (Ch 9)
Landman, WA (Ch 4)
Landman, S (Ch 4)
Louw, DB (Ch 5)
Marx, E (Ch 4)
Nape, KM (Ch 10)
Pegram, GGS (Ch 4)
Stone, D (Ch 4)
Brown, N (Ch 4)

WRC Report No. TT 538/12

October 2012

Obtainable from

Water Research Commission
Private Bag X03
GEZINA, 0031
South Africa

orders@wrc.org.za or download from www.wrc.org.za

The publication of this report emanates from a project titled *Development and Applications of Rainfall Forecasts for Agriculturally-Related Decision-Making in Selected Catchments of South Africa* (WRC Project No. K5/1646)

Please cite as:

Lumsden, TG and *S*chulze, RE (Eds) 2012. ***Development and Applications of Rainfall Forecasts for Agriculturally-Related Decision-Making in Selected Catchments of South Africa.*** Water Research Commission, Pretoria, RSA, WRC Report 1646/1/12. pp 207.

ISBN 978-1-4312-0333-8
Printed in the Republic of South Africa

EXECUTIVE SUMMARY

BACKGROUND, RATIONALE AND OBJECTIVES

Background to the Project

In April 2005 the Water Research Commission (WRC) held a workshop to define the terms of reference for a solicited research project involving the application of rainfall forecasts to aid decision making in the agricultural sector. In June/July of the same year an official call for proposals for a five year project was made and from the various submissions, each with their own unique strengths, the WRC constituted a consortium comprising of the University of KwaZulu-Natal (UKZN), the University of Cape Town (UCT), the South African Weather Service (SAWS), the University of the Free State (UFS) and the Agricultural Research Council (ARC), with the University of Pretoria (UP) also brought into the project as a sub-contractor to the UFS. Additionally, the Council for Scientific and Industrial Research (CSIR) became involved in the project during 2010, through the provision of short-range and seasonal forecasts to the UP, UFS and UKZN.

Rationale Behind the Project

The rationale of the project, which finds expression through its Terms of Reference (ToR), was the following:

- The South African climate is highly variable over short and longer periods.
- This day-by-day as well as intra- and inter-seasonal variability was likely to be amplified by the global changes in climate, along with changes in other baselines such as those of population or land use.
- Agricultural production and water management are intrinsically linked to climate variability, and many decisions are made based on weather and climate information (“now-casts”, as well as short, medium and longer term forecasts), especially on assumptions regarding weather and climate in the near future.
- Farmers need such information to help them plan for operations such as planting, irrigating and harvesting of their crops.
- Weather and climate forecasting can aid users to make more informed decisions and assist in planning activities.
- Forecasts have the potential to reduce risk in the long term and improve water use efficiency, and are becoming more skillful as research efforts continue.
- However, gaps exist between the products of weather and climate forecasting, both in the links to resulting agrohydrological responses, and in the application of forecasting information to agricultural decision-making.

Overall and More Specific Objective

From the above, the overall objective of this project was to develop and test techniques and models for translating weather and climate forecasts in South Africa into applications for decision support at a range of spatial scales in both rainfed and irrigated agricultural production and water management, in order to reduce risks associated with vagaries of day-to-day to seasonal climate variability.

The development of a series of early warning systems was envisaged which would provide:

- different lead times and
- “translations” (including spatial and temporal downscaling) of weather and climate forecasts to intermediate parameters (such as daily precipitation amounts), and to more explicit agrohydrological outcomes including, for example, soil moisture status, growth potential, crop yield estimates and streamflows (to meet irrigation demands), as well as plant dates and fertilizer levels
- at catchment specific scales for selected critical catchments, which were to be studied in detail.

More specific objectives of the project, identified in the Project Contract, included

- engagement with stakeholders in regard to forecast needs and other issues,

- selection and configuration of the catchments for detailed study,
- updating of weather / climate data,
- acquisition, downscaling, and archiving of weather/climate forecasts,
- translation of weather / climate forecasts into agrohydrological forecasts through use of agrohydrological models,
- evaluation of downscaled weather / climate forecasts and resulting agrohydrological forecasts, including uncertainty, sensitivity and benefit/cost analyses, and
- interpretation of forecast information, with emphasis on dissemination of information in a targeted manner to stakeholders and incorporation of stakeholder feedback.

STRUCTURE OF THE FINAL REPORT

The project's final report consists of 14 chapters with 23 authors from 7 institutions contributing to the various sections of chapters. By chapter the report is structured as follows:

CHAPTER 1 SETTING THE SCENE (*TG Lumsden and RE Schulze*)
CHAPTER 2 FORECASTING AS A STAKEHOLDER STRATEGY FOR VULNERABILITY MODIFICATION IN THE MANAGEMENT OF AGRICULTURAL SYSTEMS (*RE Schulze, TG Lumsden and YB Ghile*)
CHAPTER 3 CHALLENGES AND APPROACHES TO MAXIMISE BENEFITS FROM AGRO-CLIMATIC FORECASTS (*YB Ghile and RE Schulze*)
CHAPTER 4 DEVELOPMENT, DOWNSCALING AND VERIFICATION OF WEATHER AND CLIMATE FORECASTS (*RE Schulze, MA Tadross, AS Steyn, FA Engelbrecht, CJ Engelbrecht, WA Landman, S Landman, N Brown, B Gobaniyi, D Stone, E Marx and GGS Pegram*)
CHAPTER 5 BACKGROUNG INFORMATION ON CASE STUDY CATCHMENTS (*RE Schulze, G Zuma-Netshiukhwi, O Phahlane, DB Louw, TG Lumsden and YB Ghile*)
CHAPTER 6 CASE STUDY APPLICATIONS OF WEATHER AND CLIMATE FORECASTS (*G Zuma-Netshiukhwi, S Walker, O Crespo, TG Lumsden, YB. Ghile and RE Schulze*)
CHAPTER 7 THE INITIAL RESEARCH BASED FRAMEWORK FOR AN AGROHYDROLOGICAL FORECASTING SYSTEM FOR SOUTH AFRICA (*YB Ghile and RE Schulze*)
CHAPTER 8 TOWARDS AN OPERATIONAL AGROHYDROLOGICAL FORECAST FRAMEWORK (*TG Lumsden*)
CHAPTER 9 STAKEHOLDER INTERACTIONS (*G Zuma-Netshiukwi, O Phahlane, MA Tadross and P Johnston*)
CHAPTER 10 BENEFIT ANALYSES OF AGROHYDROLOGICAL FORECASTING (*G Zuma-Netshiukhwi, O Phahlane, KM Nape and AS Steyn*)
CHAPTER 11 UPDATING AND QUALITY CONTROL OF CLIMATE DATABASES FOR APPLICATION IN FORECASTING AND VERIFICATION (*CJ Engelbrecht and RP Kunz*)
CHAPTER 12 ARCHIVING OF INFORMATION AND FORECASTS (*RE Schulze, MJC Horan, RP Kunz, CJ Engelbrecht, FA Engelbrecht and MA Tadross*)
CHAPTER 13 WORKSHOPS, TECHNOLOGY TRANSFER AND CAPACITY BUILDING (*TG Lumsden and RE Schulze*)
CHAPTER 14 GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDA-TIONS (*RE Schulze and TG Lumsden*)

ACHIEVING THE OBJECTIVES

A perusal of the chapter titles above and the chapter, figure and table details provided in the Table of Contents already gives an indication of the degree to which the objectives of the project have been met, some entirely and others possibly requiring follow-up research at a later stage. The project outcomes in regard to the Terms of Reference are summarised in the table below which gives chapter sections from the final report cross-referenced to the Terms of Reference.

Terms of Reference	Description of Terms of Reference / Specific Objectives	Reference to Chapter Sections in Report
1	Motivate for, and select, critical catchments for more detailed applications / stakeholder involvement	Ch 5.1, 5.2, 5.3, 5.4
2	Identify end user groupings and interact with target end users re. their forecasting needs	Ch 2.1, 2.2, 2.3, 2.4, 2.5, 2.6; Ch 3.2
3	Obtain endorsement and support from relevant end user groups	Ch 5.1, 5.2, 5.3, 5.4, 5.5
4	Inventorise / update relevant available data	Ch 11.1, 11.2, 11.3, 11.4; Ch 12.1, 12.2, 12.3
5	Update historical databases for verification	Ch 11.1, 11.2, 11.3, 11.4
6	Archive weather / climate forecasts	Ch 12.3
7	Enhance weather / climate forecasts and downscaling techniques	Ch.1; Ch 4.1, 4.2, 4.3, 4.4, 4.5; Ch 7.3, 7.4,
8	Derive daily weather inputs for different lead times for agrohydrological models	Ch 4.3, 4.4; Ch 7.1, 7.2, 7.3, 7.4; Ch 8.1, 8.2, 8.3
9	Verification of downscaling techniques and resulting forecasts, incl. uncertainty analyses	Ch 3.1; Ch 4.3, 4.4, 4.5 Ch 6.7
10	Interpret / present forecast information for users	Ch 6.1, 6.2, 6.3, 6.4, 6.5, 6.6, 6.7; Ch 9.1, 9.2, 9.3; Ch10.4
11	Link with existing dissemination initiatives	Ch 6.1, 6.2, 6.3, 6.4, 6.5, 6.6; Ch 10.4
12	Undertake benefit / cost analyses of integrated forecast systems	Ch 10.1, 10.2, 10.3, 10.4
13	Publications; capacity building	Ch 13

SUMMARY OF MAIN FINDINGS

CHAPTER 1 SETTING THE SCENE (TG Lumsden and RE Schulze)

Chapter 1 sets the scene of the project in providing information on the rationale, the objectives and scale of operation, as well as placing the project within a broader context of climate related and risk management studies in regard to timing, location, and magnitudes of climate related events in order to enhance operational reliability in the many decisions which need to be made by using either shorter or longer lead times of the forecasts, and where each decision has potential economic benefits.

CHAPTER 2 FORECASTING AS A STAKEHOLDER STRATEGY FOR VULNERABILITY MODIFICATION IN THE MANAGEMENT OF AGRICULTURAL SYSTEMS (RE Schulze, TG Lumsden and YB Ghile)

Chapter 2 addresses forecasting as a stakeholder strategy for vulnerability modification in the management of agricultural systems by first classifying types of forecasting, distinguishing clearly between weather vs. climate forecasts, then evaluating agrohydrological forecasts with respect to types (near real time vs. short and medium term vs. seasonal agrohydrological forecasts) and their potential applications, and thereafter providing a summary of potential forecast applications, of information requirements of farmer stakeholders and how forecasts can be disseminated

The table below summarises the vast array of potential applications, identified in various workshops held under the auspices of this project, of forecasts at different lead times for the agricultural and related water resources sectors.

Lead Time	Agriculture	Water Resources
Near Real Time (re-active decisions)	***Agronomic*** • Planting/ploughing/other land operations • Pest/disease control operations • Haymaking decisions • In-field machinery operations/trafficability • Fruit picking ***Livestock*** • Stock management and movement • Chicken farming: heating, cooling • Game capture • Sheep shearing ***Logistics/Financial*** • Energy management (e.g. irrigation) ***Natural Hazards*** • Fire suppression (SAWS/DWA, timber industry, sugar industry, fire protection agencies, farmer unions, Eskom) • Controlled burning • Pump equipment and machinery removal •	***Disaster Management*** • Evacuation (e.g. pumps, stock) • Evacuation procedures • Safety releases from reservoirs ***Streams and Dams*** • Reservoir inflows ***Irrigation*** • In-field decisions
1-6 Days (pro-active decisions)	***Agronomic*** • Aquaculture • Planting / harvesting decisions (incl. equipment maintenance) ***Livestock*** ***Logistics/Financial*** • Marketing of products (crop, wool etc.) • Energy management • Irrigation – equipment, fertigation, and labour planning ***Natural Hazards*** • Controlled firebreak burning • Frost probability	***Disaster Management*** • Preparation for flood events • Storm surge analysis • Reservoir safety releases ***Streams and Dams*** • Streamflow forecasts • Reservoir inflow forecasts • IFR releases (freshettes) ***Irrigation*** • Irrigation water orders • Irrigation scheduling
7-14 Days	***Agronomic***	***Disaster Management***

	• Land preparation: Timing of • Crop type selection e.g. maize vs. sorghum • Selection of substitute crops • Fertilizer applications • Pest/disease control operations ***Livestock*** • De-stocking	• Water poverty relief planning ***Streams and Dams*** • Streamflows forecasts • Reservoir inflow forecasts • Reservoir management decisions • IFR low flow releases
	Logistics/Financial • Financial planning (contracts) • Futures trading ***Natural Hazards***	***Irrigation*** • Irrigation water allocations • Irrigation scheduling decisions
1 month	***Agronomic*** • Sugarcane haulage: Truck orders • Tillage/ planting decisions • Planning of other infield operations ***Livestock*** ***Logistics/Financial*** • Crop yield estimates • Feedback on previous month's crop estimate • Fertilizer orders • Labour/equipment planning ***Natural Hazards*** Early warning: Rainfall/temperature forecasts	***Disaster Management*** • Water poverty relief planning ***Streams and Dams*** • Streamflow forecasts • Reservoir inflow forecasts • Reservoir management decisions • IFR low flow releases ***Irrigation*** • Irrigation water allocations • Planning of irrigation timing
3 months	***Agronomic*** • Crop type and plant date decisions ***Livestock*** ***Logistics/Financial*** (Strategic decisions) • Planting/ harvesting equipment orders • Fertilizer orders • Transport scheduling • Mill opening/closing decisions • Crop variety selection • Crop yield estimates • Crop storage planning (grain/ sugar) • Conservation structure maintenance ***Natural Hazards***	***Disaster Management*** ***Streams and Dams*** • Streamflows forecasts • Reservoir inflow forecasts • Reservoir management - status review - curtailment planning ***Irrigation***

In various workshops the following points emanated from stakeholders regarding the dissemination of forecasts:

- for forecasts disseminated electronically, the majority of users prefer email as the medium of dissemination, rather than the internet (which may be slow in remote areas),
- for resource poor farmers, the following channels would be suitable for dissemination of forecasts, *viz*. cellphones and radio (very important), extension services, word of mouth, written word, Agri TV, the local chief (through meetings with the community),
- indigenous knowledge is still applied in decision-making by some users,

- forecasts should be made available in local languages,
- interpretation must be included with forecasts,
- care should be taken to avoid “interpretations of interpretations” during the dissemination process (this leads to misinterpretation),
- information should be tailored, in that it is understandable and relevant to the user,
- the education level of users is an important consideration, and it needs to be ensured that forecasts are understood by the user since, an example being the concept of probability which is often not understood by users,
- training of people involved in the forecast dissemination chain is required,
- forecasts should not be prescriptive, but should rather provide users with relevant information to enable them to make their own decisions,
- forecasts need to be "in your face" and repeated a number of times in order to raise the awareness of users, and
- the products of the research should be promoted through carefully selected forums to ensure uptake.

CHAPTER 3 CHALLENGES AND APPROACHES TO MAXIMISE BENEFITS FROM AGRO-CLIMATIC FORECASTS (YB Ghile and RE Schulze)

Chapter 3 on challenges and approaches to maximise benefits from agro-climatic forecasts, elaborates in some respects on information contained in **Chapter 2** and forms the backdrop of several later chapters. It was found that the benefits which might accrue do not only depend on the scientific advances of agro-climatic forecasts, but also on an effective way of dissemination as well as on appropriate education of forecast presenters and decision makers (cf, **Chapter 2**). Apart from forecast quality considerations, the format and speed of dissemination of forecasts, as well as the willingness and ability of decision makers to make a change, are critical elements in the usefulness of forecasts. Nonetheless, the production of skilful and timely forecasts continues to be one of the major issues challenging to meteorologists. Owing to the inherent uncertainties in the weather and model limitations to account for the local rain-bearing features, weather and climate forecasts are not as accurate as desired. The accuracy of such forecasts will be further degraded during the rainfall-soil-plant transformation by agricultural models. The reason for this is that complex and non-linear processes are not always explicitly represented by many of the agrohydrological models used.

A brief review is presented in **Chapter 3** of some of the elements that contribute towards forecast uncertainties and techniques developed to minimise forecast errors, followed by the description of some commonly used verification techniques for assessing forecast quality. The chapter further describes the potential application of forecast updating by the combined use of conceptual physically based models in simulation mode plus stochastic models in the updating mode, in order to eliminate, or minimise, errors resulting from inadequacies in the hydrological model or the incorrect estimation of rainfall forecast by weather prediction models. Finally, the challenges and approaches in communication process and use of agro-climatic forecasts to modify decisions are described briefly.

CHAPTER 4 DEVELOPMENT, DOWNSCALING AND VERIFICATION OF WEATHER AND CLIMATE FORECASTS (RE Schulze, MA Tadross, AS Steyn, FA Engelbrecht, CJ Engelbrecht, WA Landman, S Landman, N Brown, B Gobaniyi, D Stone, E Marx and GGS. Pegram)

The development, downscaling and verification of weather and climate forecasts are covered in **Chapter 4**. The chapter commences with an audit illustrating that there is no lack of climate forecasts available for South Africa. It is important to note that the availability of forecasting products changed rapidly during the course of the project, and may be expected to continue changing over the coming years. Such changes result from losses from the small pool of experienced climate modellers to either emigration or to a high inter-institutional turnover within South Africa, the coming and going of postgraduate and post-doctoral students at tertiary institutions, and continuing advances in supercomputing capabilities in the country (resulting in forecasts of increasingly fine spatial resolution). The consequence of the above to this project was that what was available in the form of forecasts of different lead times at the beginning of the project was not what was available at the end of the project, making the operationalising and tailoring of products to specific sectors a difficult task. This chapter focuses on the forecasting products available at the CSIR and CSAG during the final two years of the project. However, it also refers to some of the forecasting products available when the project commenced in 2006.

Chapter 4 goes on to providing an overview of downscaling techniques before describing the short range weather and seasonal forecasts from the CSIR and the University of Pretoria using the C-CAM forecasting system (including hindcasts, forecast verifications and decoding and dissemination of C-CAM data). This is followed by an outline of the seasonal climate forecasts available from the Climate Systems Analysis Group (CSAG) at UCT (including sections on the GCMs selected, implementing the SOMD statistical downscaling procedure, testing the skill of downscaled forecasts, sensitivity to horizontal resolution, forecast model verification and the development of a seasonal attribution forecast. The chapter concludes with an outline of ongoing developments on seasonal temperature forecasts from the SAWS in collaboration with the UKZN, in which a technique based on conditional merging is extended to condition coarse resolution temperature forecast fields (~ 100 km by 100 km) with detailed (i.e. ~ 1.7 by 1.7 km) mapping of temperature information.

CHAPTER 5 BACKGROUNG INFORMATION ON CASE STUDY CATCHMENTS (RE Schulze, G Zuma-Netshiukhwi, O Phahlane, DB Louw, TG Lumsden and YB Ghile)

With specific developments and applications of forecasts being tested in selected catchments, catchments in different parts of South Africa experiencing different climatic regimes and with different agricultural practices were selected. **Chapter 5** provides some background on the Modder / Riet catchment in the semi-arid parts of the Free State, the Upper Olifants in a temperate zone of Mpumalanga, the Berg / Breede in the winter rainfall region of the Western Cape and the sub-humid Mgeni catchment in KwaZulu-Natal. The descriptions cover physical as well as socio-economic background relevant to the application of forecasts.

CHAPTER 6 CASE STUDY APPLICATIONS OF WEATHER AND CLIMATE FORECASTS (G Zuma-Netshiukhwi, S Walker, O Crespo, TG Lumsden, YB Ghile and RE Schulze)

In **Chapter 6** seven case study applications of weather and climate forecasts are presented. The first is a study on the development of a tailor-made advisory for end users in the Modder / Riet catchment followed by a similar, but more detailed study of a tailor-made advisory for an individual farm, also in the Modder / Riet catchment. The third case study is on scenario development in the Modder / Riet catchment using crop growth models, followed by a study using downscaled forecasts with crop models to identify beneficial management decisions in the Berg catchment. The fifth study considers applications of scientific rainfall forecasts and indigenous knowledge in the Modder / Riet catchment, while the sixth case study is focused on applications of runoff, soil moisture and irrigation demand forecasts in the Berg / Breede catchment. The final study evaluates short and medium range rainfall forecast models in the Mgeni catchment from a hydrological perspective.

It should be noted that this is a “mixed bag’ of case studies. They are

- independent (but edited) contributions,
- some short others longer,
- some completed in the early phases of the project others at a later stage,
- some highly scientific others of a more anecdotal type
- some relating to crop yields others relating to water yield, but
- mostly taken from work undertaken by project members who have either completed or are still working towards higher degrees (MSc, PhD) under the auspices of this project.

CHAPTER 7 THE INITIAL RESEARCH BASED FRAMEWORK FOR AN AGROHYDROLOGICAL FORECASTING SYSTEM FOR SOUTH AFRICA (YB Ghile and RE Schulze)

One of the objectives of this project was to work towards developing a framework for agrohydrological forecasting for South Africa. This was achieved in two phases, the first being in the early stages of the project with emphasis on a *research* based framework for an agrohydrological forecasting system for South Africa (**Chapter 7**) with the second, building upon the first, moving towards an *operational* agrohydrological forecast framework (**Chapter 8**).

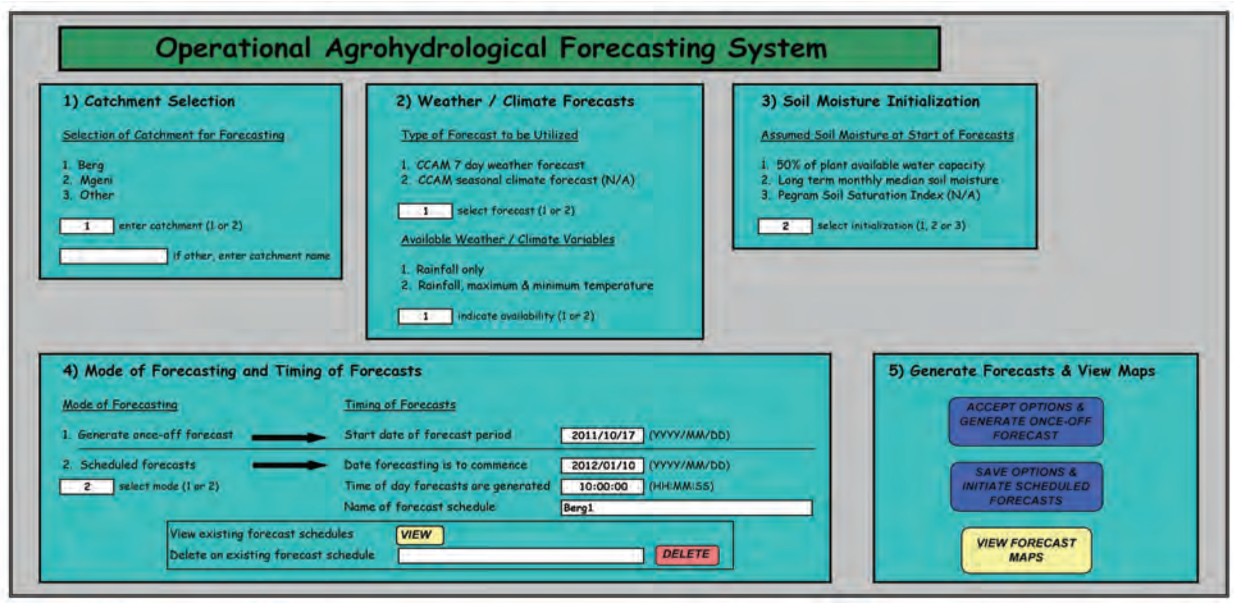
In regard to the research based forecasting framework described in **Chapter 7**, a GIS based framework was developed to serve as an aid to process all the computations required in the translation of the daily to seasonal climate forecasts into daily quantitative values suitable as input in crop or hydrological models. The framework was designed to include generic windows which allow users to process the near real time rainfall fields estimated by remotely sensed tools, as well as forecasts of weather / climate models into suitable scales and formats that are needed by many daily time step agrohydrological models. The key features of this initial framework are that it:

- facilitates the selection of near real time remotely sensed observations, as well as short term, medium term and longer term forecasts supplied by various weather and climate models from different institutions across a range of time scales;
- links to comprehensive GIS functionality that provides tools for spatial disaggregation, data structure and reformatting, as well as for post-processing of data / information through tabulation, mapping and report generation;
- translates categorical seasonal forecasts into a daily time series of values suitable for agrohydrological models through generic algorithms developed within the framework;
- converts ensembles of rainfall forecasts into suitable formats which are understood by GIS;
- downscales grid layers to Quaternary Catchments; and, finally,
- extracts rainfall data to *ACRU* model formatted text input files.

Such an application of near real, plus daily to seasonal rainfall forecasts as a nested input to one or more agrohydrological models, thereby enabling the forecasting of agrohydrological variables across a range of time scales and lead times, is a new concept in southern African context. What is presented in **Chapter 7** nevertheless remains a research tool which, with further development and refinement is considered to have the potential to play an important role in bridging the gaps that exist between outputs of weather and climate models and their practical application in agrohydrological models. The development of the research framework was viewed as a work in progress which was taken a step further from the highly versatile and highly specialised system that it was (but able to run on one computing system only, and only up until 2007 with the GIS software supported at that time), towards a more operational system in **Chapter 8**.

CHAPTER 8 TOWARDS AN OPERATIONAL AGROHYDROLOGICAL FORECAST FRAMEWORK (TG Lumsden)

The development of the more operational agrohydrological forecast framework in **Chapter 8**, of which the user interface is shown diagrammatically below, presents a much more practical approach in taking the user through steps which include generating a forecast for the first time, the various options in generating the forecast such as catchment selection, the weather / climate forecast selection, soil moisture initialisation options, the mode of forecasting and timing of forecasts, the actual forecast generation and viewing of output, steps in the forecast generation process and an overview of the software design. Examples of 7 day agrohydrological forecasts are given in the chapter.



Since the framework at this point in time represents a semi-operational system that requires further future development in a number of areas, some of these are presented, including links to a near real time system, automation of downloading the forecasts, use of near real time satellite derived soil moisture content to initialize the model, "hotstarting" of the agrohydrological model to enable the carry-over of store values from one forecast to the next, as well as the need to identify a partner to generate agrohydrological forecasts on an operational basis beyond the lifetime of the project, and the need for the development of an online portal through which the forecasts can be disseminated.

CHAPTER 9 STAKEHOLDER INTERACTIONS (G Zuma-Netshiukwi, O Phahlane, MA Tadross and P Johnston)

Practical experiences by project team members in regard to stakeholder interactions are discussed in **Chapter 9**. The ARC's experiences in the Modder / Riet catchment are the first focus, including project initiatives and presenting the "bigger picture" of climate forecasts and agricultural disaster risk management in the Free State province. Similarly, the ARC's experiences in the Upper Olifants catchment are evaluated, also from a perspective of tailor-made advisories for end users. A third set of experiences is that of the UCT group when engaging farmers and disseminating forecasts, and in this instance the farmers' problems with probabilistic seasonal forecasts is highlighted.

CHAPTER 10 BENEFIT ANALYSES OF AGROHYDROLOGICAL FORECASTING (G Zuma-Netshiukhwi, O Phahlane, KM Nape and AS Steyn)

Having utilised climate forecasts for the agricultural sector and developed an agrohydrological climate driven forecast system, a series of benefit analyses of such forecasts is presented in **Chapter 10**. From an ARC perspective the first section deals with the question as to which institutions, organisations and companies are involved in forecasting and decision-making in the Modder / Riet and Upper Olifants catchments – and the list is long. Evaluations on qualitative forecast benefits from farmer interactions in both the Modder / Riet and the Upper Olifants catchments follow. The major focus of the chapter is, however, an economic benefit analysis of maize management decisions using seasonal rainfall scenarios in which a verification study of maize yield estimates from the APSIM model is followed first by an analysis of simulated maize yields and more importantly then by a comparative economic benefit analysis of different management decisions. Here costs and benefits of different planting dates, planting densities, weeding frequencies and fertilizer application rates are assessed under various seasonal rainfall conditions. From the benefit : cost analysis, practices are recommended for rainfed maize production in the Modder / Riet catchment for a range of seasonal rainfall forecasts.

CHAPTER 11 UPDATING AND QUALITY CONTROL OF CLIMATE DATABASES FOR APPLICATION IN FORECASTING AND VERIFICATION (CJ Engelbrecht and RP Kunz)

Operational forecasting systems require continually updated daily climate data as input to their applied irrigation, soil moisture and crop yield models, especially of daily rainfall, maximum and minimum temperatures and their derivatives. The unavailability of these in South Africa formed the challenge addressed in **Chapter 11** on updating and quality control of climate databases for application in forecasting and verification. Two major initiatives were undertaken as part of this project. The first was updating and quality control of the ARC climate database, which included with a discussion on quality control procedures employed on the climate station data. The second was an updating and quality control of the SAWS rainfall database by the UKZN, in which processes of elimination of stations with poor quality, the disaggregation of accumulated totals into daily sequences and the infilling procedures for missing daily data were under scrutiny.

The lack of a national facility to update climate data and perform quality control and infilling of missing data was, once again, highlighted by these two case studies. Good quality and complete climate datasets are required in many contexts. The two case studies presented here are not the only initiatives in South Africa by research groups to embark on updating and quality controlling daily climate data. It is important to avoid duplication of effort in managing data quality, since it is a time consuming task that requires specialist skills. A single source of quality controlled and infilled data also promotes consistency in datasets.

A recommendation from this project is, therefore, that sustained and adequate funding (possibly from multiple sources) be made available for one institution in South Africa to be made responsible for the collation (from different sources) and uniform quality control of climate data, and that these data then be made freely available to all *bona fide* researchers. This would save not only the many WRC projects from major duplication of effort in updating climate related databases, but would also ensure that the same datasets be used across the many disciplines in South Africa that utilise climate data.

CHAPTER 12 ARCHIVING OF INFORMATION AND FORECASTS (RE Schulze, MJC Horan, RP Kunz, CJ Engelbrecht, FA Engelbrecht and MA Tadross)

A data and information intensive project such as this one was requires systematic archiving of information and forecasts. In **Chapter 12** the archiving of non-climatic information (e.g. the Quinary Catchments Database, the land cover and land use database as well as the soils database) is outlined, as is the archiving of historical climate information and then the archiving of original and translated forecasts from both the CSIR and the CSAG stables of weather / climate forecasts.

CHAPTER 13 WORKSHOPS, TECHNOLOGY TRANSFER AND CAPACITY BUILDING (TG Lumsden and RE Schulze)

Outreach and capacity building are important components of a project such as this one, and details of these are given in **Chapter 13**. This multi-faceted and multi-institutional project did itself proud in this regard. During the course of the project its team members initiated and / or were involved in 12 specialist workshops, in total 16 presentations on the project were made nationally and internationally by team members at symposia, conferences and workshops and at the time of completing this report five papers on the project had been published in refereed scientific journals, one further paper was in preparation and several more are anticipated. Emanating directly from this project were 3 completed PhDs, 5 Masters degrees and 3 Honours degrees, while 4 PhDs are in various stages of completion.

CHAPTER 14 GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDA-TIONS (RE Schulze and TG Lumsden)

The final chapter of the report, **Chapter 14**, is made up of a general discussion with a summary, conclusions drawn and recommendations for future related research. All of those components are included in this Executive Summary.

RECOMMENDATIONS FOR FUTURE RELATED RESEARCH AND DISSEMINATION OF FORECASTS

This multi-institutional and multiple level project highlighted that for weather and climate forecasts to be successful in agricultural decision making, six basic ingredients are necessary, *viz*.

- the forecasts have to be *accurate* at a local scale,
- the forecasts have to be *timely*,
- the forecasts have to be *understood* by all the various sectors making up the farming community,
- the *economic benefits* of applying forecasts need to be clearly demonstrated (not to forget the long term environmental spin-offs),
- the forecast systems have to be *operational* for the various sectors in agriculture for a range of lead times from days through weeks to a season ahead, and
- the *archiving* of forecasts and other research products is crucial.

On the Accuracy of Forecasts

- In order for climate forecasts to gain more acceptance among farmers (and others), continued basic research is required into minimising forecast uncertainties / forecast errors and enhancing the spatial resolution at which forecasts are presented. Such research goes beyond that which can be achieved only at the country level within South Africa and has to be undertaken by South African researchers in collaboration with international institutions which develop forecasts.
- Forecasts need to go beyond only those of rainfall, which was the focus of this project. Accurate and detailed temperature forecasts, for example, have many applications in agriculture. The developments on medium range temperature forecasts from the SAWS in collaboration with the UKZN, based on a technique of conditional merging of coarse resolution temperature forecast fields (~ 100 km by 100 km) with detailed (i.e. ~ 1.7 by 1.7 km) mapping of temperature information therefore needs to continue, become formalized as a project (as against being a sideline hobby) and needs to be extended to shorter range temperature forecasts as well.

On the Timeliness of Forecasts

- Operational forecasting systems require continually updated daily climate data as input to their applied irrigation, soil moisture and crop yield models, especially of daily rainfall, maximum and minimum temperatures and their derivatives.

- The lack of a national facility to provide up-to-date climate data (i.e. yesterday's data today in order to initialise agrohydrological forecasting systems) and perform adequate quality control and infilling of missing data was highlighted by this project. Good quality and complete climate datasets are required in many contexts. The two case studies presented in **Chapter 11** are not the only initiatives in South Africa by research groups to embark on updating and quality controlling daily climate data. It is important to avoid duplication of effort in managing data quality, since it is a time consuming task that requires specialist skills. A single source of quality controlled and infilled data also promotes consistency in datasets.
- A recommendation from this project is, therefore, that sustained and adequate funding (possibly from multiple sources) be made available for one institution in South Africa to be made responsible for the collation (from different sources) and uniform quality control of climate data, and that these data be up-to-date and then be made freely available to all *bona fide* researchers. This would save not only the many WRC projects from major duplication of effort in updating climate related databases, but would also ensure that the same datasets be used across the many disciplines in South Africa that utilise climate data.

On the Understanding and Interpretation of Forecasts

- Since the benefits from agro-climatic forecasting which might accrue do not depend only on the scientific advances of the forecasts *per se*, further research into effective ways of disseminating and communicating the tailored forecasts, as well as on appropriate education of forecast presenters and decision makers, is required. This is the case not only for subsistence / emerging farmers, but for the commercial agricultural sector as well, as was highlighted in Chapter 9 relating to farmers' problems in understanding the nature of probabilistic seasonal forecasts.

On the Economic Benefits of Forecasting

- An important focus of this project was on economic benefit analyses of management decisions (in this case for dryland maize) using seasonal rainfall scenarios, where costs and benefits of different planting dates, planting densities, weeding frequencies and fertilizer application rates were assessed under various seasonal rainfall conditions. Such benefit analyses need to be undertaken in South Africa for crops other than maize, for regions beyond the Modder / Riet catchment, and for climate forecasts covering a range of lead times from days to weeks to months, and not only for seasonal forecasts. This is a major research undertaking, but with the potential of vast savings to the agricultural sector.

On the Operationalisation of Forecasts

- In this project a research version of a forecasting framework was developed, illustrating the potential in bridging the gaps existing between outputs of climate models and their practical application through agrohydrological models. This research framework was viewed as a work in progress which was then taken a step further from the highly versatile but equally highly specialised system that it was, towards a more operational system in **Chapter 8**.
- The framework at this point in time, however, represents only a semi-operational system that requires considerable further future development in a number of areas, including
  - automation of downloading the forecasts,
  - use of near real time satellite derived soil moisture content to initialise the model,
  - "hotstarting" of the agrohydrological model to enable the carry-over of store values from one forecast to the next,
  - "nesting" of short lead time forecasts (days) within longer lead time forecasts (weeks to months and up to a season ahead) or even decadal projections, and
  - tailoring the forecasts to a range of agricultural operations, regions and crops,

  as well as the need to identify a partner to generate agrohydrological forecasts on an operational basis beyond the lifetime of a research project, and the need for the development of an online portal through which the forecasts can be disseminated.
- Operationalising climate forecasts and tailoring products to specific sectors such as agriculture, and within agriculture to commercial vs. subsistence farmers or irrigators vs. dryland operators or farmers in the summer vs. winter rainfall regions, requires *consistency in forecast products*. This remains a challenge needing to be addressed, as the experience during this project was that the availability of forecasting products changed rapidly during the course of this project, and is expected to continue changing over the coming years. Such changes result partially from advances in forecasting systems and being able to present forecasts at ever finer spatial resolutions.

- However, successfully operationalising such forecasts also implies *consistency in staffing* and *retention of skilled personnel*. This project was set back on numerous occasions by losses from the small pool of experienced climate modellers at the various institutions engaged in developing forecasting tools to either emigration or to a high inter-institutional turnover within South Africa, as well as to the coming and going of postgraduate and post-doctoral students at tertiary institutions who all make a contribution, but their *output* does not always translate into a project's *outcomes*. In some way or other funding agencies (together with other institutions) need to address the issue of skill retention beyond only skill development.

On Archiving of Forecasts and Other Research Products

- At first glance from **Chapter 12** the archiving of research products and weather / climate forecasts appears to have been satisfactorily achieved. However, from this project some of the archiving occurred at universities (with knowledge of certain products frequently vested in an individual), other at parastatals and some in institutions of the State. For the sake of continuity in research and to overcome loss of institutional memory which is currently prevalent in many institutions, thought needs to be given to improving the archiving of not only this project's products, but that of many other WRC projects.

A FINAL PERSPECTIVE

Two final conclusions come to the fore:

- First, this has been a multi-institutional project addressing issues of climate forecasting on multiple levels from high level climate science to stakeholder interactions with subsistence farmers and to qualitative as well as quantitative economic benefit analyses. While multi- and trans-disciplinary research is welcomed and enriching, it is also difficult and often frustrating to manage from the researchers' perspectives. Thought should be given to engaging smaller teams with more focused objectives and outcomes.
- All TORs have been successfully addressed, some in more depth than others, and numerous ideas for further research have been proposed above. In order not to lose research momentum in this field and to gain value for monies invested thus far, the project team believes that one or more follow-up projects should be identified as soon as possible in order to achieve an operational forecast system tailor made for agricultural decision making to the benefit of individual farmers' livelihoods and the country's economy as a whole.

ACKNOWLEDGEMENTS

The project team wishes to acknowledge the WRC for initiating, managing and funding this solicited project, and we thank in particular Dr Andrew Sanewe and Dr Gerhard Backeberg for their guidance, patience and understanding during the course of this project. Grateful thanks go to Mrs Cynthia O'Mahoney for assistance in preparing the final document. The Reference Group of this project, the members of which made many valuable suggestions for which we are thankful, was at various stages made up of the following (with affiliations at the time of serving on the Reference Group):

Dr AJ Sanewe	Water Research Commission (Chairman)
Dr G Backeberg	Water Research Commission
Prof JC Smithers / Prof GPW Jewitt	University of KwaZulu-Natal
Prof CJ de W Rautenbach	University of Pretoria
Prof C Vogel	University of the Witwatersrand
Dr N Lecler / Dr A Singels	South African Sugarcane Research Institute
Mr C Swiegers / Dr B Mwaka	Department of Water Affairs
Ms PJ Dibeke / Ms PT Masuku	Department of Agriculture, Forestry and Fisheries
Mr DJ Pretorius / Mr M Matsepe	Department of Agriculture, Forestry and Fisheries
Ms MJ Gabriel	Department of Agriculture, Forestry and Fisheries
Dr S Mpandeli	Agricultural Research Council
Ms M-J Kgatuke	Centre for High Performance Computing

TABLE OF CONTENTS

		Page
EXECUTIVE SUMMARY		iii
CHAPTER 1	**SETTING THE SCENE (*TG Lumsden and RE Schulze*)**	1
1.1	BACKGROUND TO THE PROJECT	1
1.2	RATIONALE	1
1.3	OBJECTIVES	2
1.3.1	Overall Objective	2
1.3.2	More Specific Objectives	2
1.3.3	Scales of Operation	3
1.4	PLACING THE PROJECT WITHIN A BROADER CONTEXT OF CLIMATE RELATED AND RISK MANAGEMENT STUDIES	3
1.4.1	Climate Related Studies	3
1.4.2	Risk Management	4
1.5	LAYOUT OF THE REPORT IN RELATION TO THE PROJECT'S TERMS OF REFERENCE AND ITS SPECIFIC OBJECTIVES	5
CHAPTER 2	**FORECASTING AS A STAKEHOLDER STRATEGY FOR VULNERABILITY MODIFICATION IN THE MANAGEMENT OF AGRICULTURAL SYSTEMS (*RE Schulze, TG Lumsden and YB Ghile*)**	6
2.1	TYPES OF FORECASTING	6
2.2	WEATHER vs. CLIMATE FORECASTS	7
2.3	AGROHYDROLOGICAL FORECASTS: TYPES AND POTENTIAL APPLICATIONS	7
2.3.1	Near Real Time Agrohydrological Forecasts	7
2.3.2	Short and Medium Term Agrohydrological Forecasts	7
2.3.3	Long Term (Seasonal) Agrohydrological Forecasts	8
2.4	SUMMARISING POTENTIAL FORECAST APPLICATIONS	8
2.5	INFORMATION REQUIREMENTS OF FARMER STAKEHOLDERS	10
2.6	DISSEMINATION OF FORECASTS	11
CHAPTER 3	**CHALLENGES AND APPROACHES TO MAXIMISE BENEFITS FROM AGRO-CLIMATIC FORECASTS (*YB Ghile and RE Schulze*)**	12
3.1	FORECAST QUALITY	12
3.1.1	Sources of Uncertainty in Forecasting	12
3.1.1.1	*Agrohydrological model errors*	13
3.1.1.2	*Data errors*	13
3.1.1.3	*Weather and climate model errors*	13
3.1.2	Improving the Quality of Forecasts	13
3.1.2.1	*Ensemble forecasting systems*	13
3.1.2.2	*Techniques for spatial downscaling*	14
3.1.3	Verification of Forecasts	15
3.1.4	Procedures for Updating Forecasts	20
3.2	COMMUNICATION OF AGRO-CLIMATIC INFORMATION	21
3.3	APPLICATION OF AGRO-CLIMATIC INFORMATION	22
3.4	CONCLUDING REMARKS	22
CHAPTER 4	**DEVELOPMENT, DOWNSCALING AND VERIFICATION OF WEATHER AND CLIMATE FORECASTS (*RE Schulze, MA Tadross, AS Steyn, FA Engelbrecht, CJ Engelbrecht, WA Landman, S Landman, N Brown, B Gobaniyi, D Stone, E Marx and GGS Pegram*)**	24
4.1	THERE IS NO LACK OF CLIMATE FORECASTS FOR SOUTH AFRICA: AN AUDIT OF WHAT IS AVAILABLE	24

		Page
4.2	DOWNSCALING TECHNIQUES: BACKGROUND	25
4.2.1	Overview of Downscaling	25
4.2.2	Statistical Downscaling and the Methodology Adopted by the UCT and UFS Groups, i.e. SOMS and SDSM	25
4.3	SHORT RANGE WEATHER AND SEASONAL FORECASTS FROM THE CSIR AND THE UNIVERSITY OF PRETORIA	30
4.3.1	The C-CAM Forecasting System	30
4.3.2	C-CAM Hindcasts at the Short-Range Time-Scale	30
4.3.3	Forecast Verifications	30
4.3.4	Decoding and Dissemination of C-CAM Data	35
4.4	SEASONAL CLIMATE FORECASTS FROM THE CSAG	36
4.4.1	The GCMs Selected	36
4.4.2	Implementing the SOMD Statistical Downscaling Procedure	37
4.4.3	Testing the Skill of Downscaled Forecasts	37
4.4.4	Testing Predictors for the SOMD Statistical Downscaling Procedure	37
4.4.5	Using Satellite Observations for the SOMD Downscaling Procedure	38
4.4.6	Evaluation of GCM Simulations Using Observed Sea Surface Temperatures (SSTs)	39
4.4.7	CAM3 Sensitivity to Horizontal Resolution	41
4.4.8	CAM3 Forecast Verification	41
4.4.9	Developing a Seasonal Attribution Forecast	43
4.5	MEDIUM RANGE TEMPERATURE FORECASTS FROM THE SAWS AND UKZN	47
CHAPTER 5	**BACKGROUND INFORMATION ON CASE STUDY CATCHMENTS (*RE Schulze, G Zuma-Netshiukhwi, O Phahlane, DB Louw, TG Lumsden and YB Ghile*)**	51
5.1	SELECTION OF CASE STUDY CATCHMENTS	51
5.2	THE MODDER / RIET CATCHMENT	52
5.3	THE UPPER OLIFANTS CATCHMENT	54
5.4	THE BERG / BREEDE CATCHMENT	57
5.4.1	The Berg Catchment	57
5.4.2	The Breede Catchment	59
5.4.3	Demarcation of the Total Study Area	61
5.4.4	The Urban Water Sector	62
5.4.5	Summary	62
5.5	THE MGENI CATCHMENT	63
5.5.1	Location	63
5.5.2	Climate and Hydrology	63
5.5.3	Vegetation and Land Use	64
5.5.4	Water Use	65
5.5.5	Subcatchment Information for Simulations with the *ACRU* Model	66
CHAPTER 6	**CASE STUDY APPLICATIONS OF WEATHER AND CLIMATE FORECASTS (*G Zuma-Netshiukhwi, S Walker, O Crespo, TG Lumsden, YB Ghile and RE Schulze*)**	68
6.1	CASE STUDY 1: DEVELOPMENT OF A TAILOR-MADE ADVISORY FOR END USERS IN THE MODDER / RIET CATCHMENT	69
6.1.1	Study Area	69
6.1.2	Rainfall Variations	69
6.2	CASE STUDY 2: DEVELOPMENT OF A TAILOR-MADE ADVISORY FOR RUSTFONTEIN FARM IN THE MODDER / RIET CATCHMENT	73
6.3	CASE STUDY 3: SCENARIO DEVELOPMENT IN THE MODDER / RIET CATCHMENT USING CROP GROWTH MODELS	76
6.4	CASE STUDY 4: USING DOWNSCALED FORECASTS WITH CROP MODELS TO IDENTIFY BENEFICIAL MANAGEMENT DECISIONS IN THE BERG CATCHMENT	78

TABLE OF CONTENTS (continued)

		Page
6.4.1	Background and Concepts	78
6.4.2	Methods	79
6.4.3	Illustration of the Approach with Rainfed Winter Wheat in the Berg River Catchment	79
6.4.4	Results	80
6.4.4.1	*Simulated optimal outcomes in the criteria space*	80
6.4.4.2	*Efficient variables identified in the decision space*	80
6.4.5	Tentative Conclusions	81
6.5	CASE STUDY 5: APPLICATIONS OF SCIENTIFIC RAINFALL FORECASTS AND INDIGENOUS KNOWLEDGE IN THE MODDER / RIET CATCHMENT	82
6.5.1	Background	82
6.5.2	Farming Systems	82
6.6	CASE STUDY 6: DEVELOPMENT OF SEASONAL RUNOFF, SOIL MOISTURE AND IRRIGATION DEMAND FORECASTS IN THE BERG / BREEDE CATCHMENT	91
6.6.1	Challenges Associated with Applying Relatively Coarse Scale GCM Forecast Output Directly in the *ACRU* Model	91
6.6.2	Seasonal Runoff Forecasts	92
6.6.3	Soil Moisture Forecasts	94
6.6.4	Irrigation Demand Forecasts	95
6.6.5	Conclusions	96
6.7	CASE STUDY 7: EVALUATION OF SHORT AND MEDIUM RANGE RAINFALL FORECAST MODELS IN THE MGENI CATCHMENT FROM A HYDROLOGICAL PERSPECTIVE	97
6.7.1	Introduction	97
6.7.2	Methods of Comparison	98
6.7.3	Results and Discussion	98
6.7.3.1	Evaluation of the C-CAM rainfall forecasts	98
6*.7.3.2*	*Evaluation of the UM rainfall forecasts*	104
6.7.3.3	*Evaluation of the NCEP-MRF rainfall forecasts*	109
6.7.3.4	*Combined use of the C-CAM and UM rainfall forecasts*	112
6.7.4	Conclusions	114
CHAPTER 7	**THE INITIAL RESEARCH BASED FRAMEWORK FOR AN AGROHYDROLOGICAL FORECASTING SYSTEM FOR SOUTH AFRICA (*YB Ghile and RE Schulze*)**	116
7.1	THE NEED FOR A GIS BASED FRAMEWORK	116
7.2	NEAR REAL TIME ESTIMATES OF PRECIPITATION DERIVED FROM SATELLITE, RADAR AND RAINGAUGE DATA	118
7.3	SHORT AND MEDIUM FORECASTS FROM WEATHER PREDICTION MODELS	120
7.3.1	The C-CAM Rainfall Forecasts	120
7.3.2	The UM Rainfall Forecasts	121
7.3.3	The NCEP-MRF Rainfall Forecasts	121
7.3.4	Transferring and Reformatting of Forecasts	122
7.4	CATEGORICAL SEASONAL FORECASTS FROM CLIMATE MODELS	123
7.4.1	Methods of Temporal Downscaling	123
7.4.2	Generating Daily Rainfall Values	124
7.5	THE *ACRU* AGROHYDROLOGICAL MODELLING SYSTEM	126
7.5.1	Reasons for Selecting the *ACRU* Model	126
7.5.2	A Brief Description of the *ACRU* Model	127
7.6	SUMMARY	128

TABLE OF CONTENTS (continued)

		Page
CHAPTER 8	**TOWARDS AN OPERATIONAL AGROHYDROLOGICAL FORECAST FRAMEWORK (*TG Lumsden*)**	129
8.1	INTRODUCTION	129
8.2	DEVELOPMENT OF THE OPERATIONAL AGROHYDROLOGICAL FORECASTING FRAMEWORK	129
8.2.1	General Considerations	129
8.2.2	Generating a Forecast for the First Time	130
8.2.3	Options in Generating a Forecast	131
8.2.3.1	Catchment selection	131
8.2.3.2	Weather / climate forecast selection	131
8.2.3.3	Soil moisture initialisation options	131
8.2.3.4	Mode of forecasting and timing of forecasts	133
8.2.3.5	Forecast generation and viewing of output	133
8.2.4	Steps in the Forecast Generation Process	133
8.2.5	Overview of Software Design	136
8.3	FURTHER DEVELOPMENT NEEDS	136
CHAPTER 9	**STAKEHOLDER INTERACTIONS (*G Zuma-Netshiukwi, O Phahlane, MA Tadross and P Johnston*)**	137
9.1	AGRICULTURAL RESEARCH COUNCIL EXPERIENCES IN THE MODDER / RIET CATCHMENT	137
9.1.1	Project Initiatives and Experiences	137
9.1.2	Seeing the Bigger Picture of Climate Forecasts in the Modder / Riet Catchment: Overall Agricultural Disaster Risk Management in the Free State	138
9.2	AGRICULTURAL RESEARCH COUNCIL EXPERIENCES IN THE UPPER OLIFANTS CATCHMENT	140
9.2.1	Project Initiatives and Experiences	140
9.2.2	Development of a Tailor-Made Advisory for End Users	141
9.3	UNIVERSITY OF CAPE TOWN EXPERIENCES ON ENGAGING FARMERS AND DISSEMINATING FORECASTS	142
9.3.1	Project Initiatives and Experiences	142
9.3.2	Farmers' Problems with Probabilistic Seasonal Forecasts	142
CHAPTER 10	**BENEFIT ANALYSES OF AGROHYDROLOGICAL FORECASTING (*G Zuma-Netshiukhwi, O Phahlane, KM Nape and AS Steyn*)**	147
10.1	WHO PRODUCES AND USES WEATHER AND CLIMATE FORECAST INFORMATION? THE CASE OF INSTITUTIONS, ORGANISATIONS AND COMPANIES INVOLVED IN FORECASTING AND DECISION-MAKING IN THE MODDER / RIET AND UPPER OLIFANTS CATCHMENTS	147
10.2	QUALITATIVE BENEFITS FROM FARMER INTERACTIONS IN THE MODDER / RIET CATCHMENT	149
10.3	QUALITATIVE BENEFITS FROM FARMER INTERACTIONS IN THE UPPER OLIFANTS CATCHMENT	150
10.4	ECONOMIC BENEFIT ANALYSIS OF MAIZE MANAGEMENT DECISIONS USING SEASONAL RAINFALL SCENARIOS	152
10.4.1	Background and Objectives	152
10.4.2	Verification of Yield Estimates from the APSIM Model	154
10.4.3	Analysis of Simulated Maize Yields	158
10.4.4	Comparative Economic Benefit of Different Management Decisions under Various Seasonal Rainfall Conditions	162
10.4.5	Recommended Practices for Rainfed Maize Production under Various Seasonal Rainfall Conditions	170

Page

CHAPTER 11 UPDATING AND QUALITY CONTROL OF CLIMATE DATABASES FOR APPLICATION IN FORECASTING AND VERIFICATION (*CJ Engelbrecht and RP Kunz*) 174

11.1 THE CHALLENGE 174

11.2 UPDATING AND QUALITY CONTROL OF AGRICULTURAL RESEARCH COUNCIL CLIMATE DATABASE 175

11.2.1 Inventory of Stations 175

11.2.2 Quality Control Procedures Employed on the Station Data 176

11.3 UPDATING AND QUALITY CONTROL OF SOUTH AFRICAN WEATHER SERVICE RAINFALL DATABASE BY THE UNIVERSITY OF KWAZULU-NATAL 177

11.3.1 Inventory of Stations 177

11.3.2 Elimination of Poor Quality Stations 177

11.3.3 Disaggregating Accumulated Totals into Daily Sequences 179

11.3.4 Infilling of Missing Daily Data 179

11.4 CONCLUDING THOUGHTS 181

CHAPTER 12 ARCHIVING OF INFORMATION AND FORECASTS (*RE Schulze, MJC Horan, RP Kunz, CJ Engelbrecht, FA Engelbrecht and MA Tadross*) 182

12.1 NON-CLIMATIC INFORMATION 182

12.1.1 Quinary Catchments Database 182

12.1.2 Land Cover and Land Use 183

12.1.3 Soils 183

12.2 HISTORICAL CLIMATE INFORMATION 183

12.3 ARCHIVING OF WEATHER AND CLIMATE FORECASTS 183

12.3.1 From the CSIR Stable 183

12.3.2 From the CSAG Stable 183

CHAPTER 13 WORKSHOPS, TECHNOLOGY TRANSFER AND CAPACITY BUILDING (*TG Lumsden and RE Schulze*) 184

13.1 WORKSHOPS / TEAM MEETINGS 184

13.2 CONFERENCE PRESENTATIONS 185

13.3 SCIENTIFIC PAPERS IN REFEREED JOURNALS 186

13.4 CAPACITY BUILDING 186

CHAPTER 14 SUMMARY, RECOMMENTDATIONS AND CONCLUSIONS (*RE Schulze and TG Lumsden*) 188

14.1 RECAPTURING THE RATIONALE AND OBJECTIVES OF THE PROJECT 188

14.1.1 Rationale Behind the Project 188

14.1.2 Overall and More Specific Objective 188

14.2 ACHIEVING THE OBJECTIVES 189

14.3 SUMMARY OF MAIN FINDINGS 189

14.4 RECOMMENDATIONS FOR FUTURE RELATED RESEARCH AND DISSEMINATION OF FORECASTS 196

14.5 A FINAL PERSPECTIVE 198

REFERENCES 199

LIST OF FIGURES

		Page
Figure 1.3.1	The forecast project framework, with flows of information indicated by arrows	3
Figure 1.4.1	A risk management framework (Schulze, 2004)	4
Figure 3.1.1	Schematic diagram for calculating the Linear Errors in Probability Space (Source: http://www.bom.gov.au)	19
Figure 3.4.1	Determinants of the potential for human populations to benefit from agro-climatic forecasts (after Hansen, 2002)	23
Figure 4.2.1	Steps in statistical downscaling by means of regression methods (Steyn, 2006)	26
Figure 4.2.2	SDSM climate scenario generation (after Wilby and Dawson, 2007)	28
Figure 4.3.1	C-CAM's 0.5 ° (about 60 km) variable resolution grid over tropical and southern Africa. The model resolution decreases to about 400 km in the far-field	31
Figure 4.3.2	C-CAM's quasi-uniform grid of about 2 ° (200 km) resolution in the horizontal	31
Figure 4.3.3	Bias of the C-CAM 60 km resolution forecasts in predicting daily rainfall totals over southern Africa (for the first day of model integration)	32
Figure 4.3.4	Brier skill score (BSS) of the C-CAM forecasts of daily rainfall totals (for the first day of model integration), using persistence as the reference forecast	33
Figure 4.3.5	Kendall's tau correlations calculated between the observed and downscaled C-CAM DJF rainfall simulations over the 27-year test period from 1979 / 80 to 2002 / 03	34
Figure 4.3.6	Area-averaged observed DJF rainfall indices (blue) over four southern African regions as specified in the text, vs. the corresponding downscaled C-CAM hindcast indices (green). The years on the x-axes refer to the December months of the DJF seasons. Kendall's tau correlations and associated ρ-values, and mean squared error skill scores with climatology as a reference forecast (MSESS) are shown	35
Figure 4.4.1	Comparison of the UCT downscaling (SOMD) with the UK developed (SDSM) downscaling over Rabat, Morocco	37
Figure 4.4.2	ROC score, Brier score and RPS assessing the performance of the probabilistic downscaled forecasts averaged for all the years for the SON seasons within the period 1970-2000. Left column top to bottom: Observed SON rainfall, Modelled SON rainfall and RPS score. Middle column top to bottom: ROC scores for above-normal, near-normal and below-normal rainfall. Right column top to bottom: Brier scores for above-normal, near-normal and below-normal rainfall	38
Figure 4.4.3	RPS skill scores for El Niño, La Niña and neutral years respectively for SON season	38
Figure 4.4.4	Statistical downscaling of RFE satellite based observations of rainfall, with the example being for a climate change simulation using the MPI-ECHAM5 model	39
Figure 4.4.5	CAM and HadAM3 position of the anticyclones (a) and sub-tropical jet (b)	40
Figure 4.4.6	The mean number of cut-off lows observed (from NCEP) and simulated (from HadAM3 and CAM3) in each month from 1980 to 2000	40
Figure 4.4.7	The observed (from NCEP) annual variation of the mean number of cut-off lows and the mean number of simulated (from HadAM3 and CAM3) cut-off lows	40
Figure 4.4.8	CAM3 Simulated (1980-1990) mean rainfall (shaded) and surface wind vectors (arrows) over Southern Africa at Low (2 x 2.5, latitude x longitude) and High (1 x 1.25, latitude x longitude) horizontal grid resolutions for June-August (JJA) and December-February (DJF) months. The left and right panels are for Low and high resolutions simulations, respectively, while the upper and lower panels are for JJA and DJF simulations, respectively	41

LIST OF FIGURES (continued)

		Page
Figure 4.4.9	Mean rainfall over southern Africa from CMAP (top panel), CAM3 (middle panel) and mean error (lower panel) for summer (left panel) and winter (right panel)	42
Figure 4.4.10	ROC scores, defined as the area under the ROC curve, for the total rainfall is tested for 26 year forecasts and only significant values are shown	42
Figure 4.4.11	Brier Score (a) and Brier Skill Score (b) from DJF (left panel) and JJA (right panel) rainfall forecast over southern Africa for the total rainfall is tested for 26 year forecasts	43
Figure 4.4.12	Schematic of CSAG seasonal attribution forecast	44
Figure 4.4.13	November 2009 best guess and hindcast forecasts	44
Figure 4.4.14	Chance of exceeding 1 in 10 year hot month threshold	45
Figure 4.4.15	Fraction of chance attributable to GHG emissions	45
Figure 4.4.16	World's first operational attribution forecast suggesting how the odds of having an extremely warm November (1 in 10 year event) have changed due to the emission of greenhouse gases	46
Figure 4.5.1	Major topographic features which influence temperature distribution of South Africa, Lesotho and Swaziland	47
Figure 4.5.2	Average maximum temperature climate for February (Schulze, 2008)	48
Figure 4.5.3	The NCEP maximum temperature forecast (1˚ degree resolution smoothed to 1 arc minute) with forecast lead time of 1 day issued for 15 February 2012 with model analysis date being 14 February	48
Figure 4.5.4	Climate-conditioned NCEP maximum temperature forecast for 15 February 2012 with a forecast lead time of 1 day	49
Figure 4.5.5	Bias-corrected and climate-conditioned NCEP maximum temperature forecast for 15 February 2012 with a forecast lead time of 1 day	49
Figure 4.5.6	Verification of the methodology to condition and to correct NCEP maximum temperature forecasts using detailed historical climate information from Schulze (2008) and 14 day running mean bias-correction. The results present the performance of the forecasts over an area-averaged domain of South Africa for the one year period December 2010 to November 2011 for forecast lead times of one day up to day 14. The legend presents the following: *Atlas* is from the SA Atlas (Schulze 2008); *NCEP* is raw NCEP GEFS ensemble forecast means; *C* represents climate-conditioned forecasts; and *B/C* represents the final bias-corrected forecast	50
Figure 5.2.1	Location of the Modder / Riet study catchment, showing towns and rivers	52
Figure 5.2.2	Isohyets of mean annual rainfall in the Modder / Riet catchment (AGIS, 2006)	52
Figure 5.2.3	Location of climate stations in the Modder / Riet catchment (AGIS, 2006)	52
Figure 5.3.1	Location of the Upper Olifants catchment (ARC-ISCW Gislib, 2004)	54
Figure 5.3.2	Isohyets of mean annual rainfall in the Upper Olifants catchment (AGIS, 2006)	55
Figure 5.3.3	Location of climate stations in the Upper Olifants catchment (AGIS, 2006)	55
Figure 5.4.1	Description of the Berg River basin and inter basin transfers from the Breede (Source: Kleynhans *et al*., 2008)	57
Figure 5.4.2	Estimated irrigated land use in the Berg River basin (Louw *et al*., 2011)	58
Figure 5.4.3	Estimated rainfed land uses in the Berg River Basin (Louw *et al*., 2011)	59
Figure 5.4.4	The Breede catchment (Louw *et al*., 2011)	59
Figure 5.4.5	Aggregated agricultural land uses in the Breede part of the study region (Louw *et al*., 2011)	61
Figure 5.4.6	Demarcation of the total study region (Louw *et al*., 2011)	61
Figure 5.5.1	Overview of the Mgeni and its Quaternary Catchments	63
Figure 5.5.2	Baseline land cover in the Mgeni catchment, represented by Acocks' (1988) Veld Types	64

LIST OF FIGURES (continued)

		Page
Figure 5.5.3	Catchment land cover and land use (Source: DEAT, 2001)	65
Figure 5.5.4	Subcatchment configuration and streamflow cascading pattern of the Mgeni catchment	67
Figure 6.1.1	Long-term annual (July to June) rainfall for Glen Agricultural Research weather station (from ARC-ISCW climate databank)	69
Figure 6.1.2	Long-term mean monthly rainfall trends for Glen weather station	70
Figure 6.1.3	Three month rainfall probability of non-exceedence from October to February	71
Figure 6.1.4	Three month rainfall probability of non-exceedence from January to May	71
Figure 6.2.1	Long-term (July to June) annual rainfall for Rustfontein farm	73
Figure 6.2.2	Rustfontein farm mean monthly rainfall and standard deviation	74
Figure 6.2.3	Highest and the lowest recorded monthly rainfall for Rustfontein farm	75
Figure 6.4.1	Berg River catchment area overlapped with geological soils features as well as available temperature and precipitation stations used to select two study cases where to set up the APSIM Crop Model	78
Figure 6.4.2	Best combinations of highest potential yields (kg/ha) and lowest nitrogen losses (kg/ha) achieved under climates derived from the CNRM GCM for downscaled control (1961-2000) and far future (2081-2100) periods	80
Figure 6.4.3	Decision combinations of weekly sowing dates (with 1 representing 1 April and 10 representing 12 June) and fertilizer amounts (kg/ha) that resulted in the best simulated outcomes (shown in previous figure), with the left graphic depicting results from the control climate period (1961-2000) and the right graphic from the far future (2081-2100)	81
Figure 6.5.1	SAWS 14 day rainfall forecast for receiving > 1 mm during February 2008	86
Figure 6.5.2	SAWS 14 day rainfall forecast for receiving > 5 mm during February 2008	87
Figure 6.5.3	SAWS rainfall probability map for August to December 2008	88
Figure 6.5.4	SAWS 14 day rainfall probabilities for August 2009	88
Figure 6.5.5	SAWS 14 day rainfall probability for October 2009	89
Figure 6.6.1	The process of identifying irrigation region boundaries in the Berg / Breede system using satellite imagery	93
Figure 6.6.2	Irrigation regions identified in the Berg / Breede system	94
Figure 6.6.3	Nodes of interest identified in the Stellenbosch irrigation region	95
Figure 6.7.1	Four day lead time rainfall forecasts from the C-CAM model over QC U20E in the Mgeni catchment for Events A to D on 17 November 2006, 24 December 2006, 30 January 2007 and 04 March 2007	99
Figure 6.7.2	Scores of Hit, Miss, False Alarm and Correct Null defined by the threshold of 50th percentile for 17 November 2006, 24 December 2006, 30 January 2007 and 04 March 2007	100
Figure 6.7.3	CSI, POD and FAR scores of 4 day lead time forecasts from the C-CAM model as a function of threshold percentiles for the rainfall events of 17 November and 21 December 2006	101
Figure 6.7.4	CSI, POD and FAR scores of 4 day lead time forecasts from the C-CAM model as a function of threshold percentiles for the rainfall events of 30 January and 04 March 2007	102
Figure 6.7.5	Time series comparisons of daily streamflows simulated with the ACRU model at the mouth of the Mgeni catchment, derived from the C-CAM rainfall forecasts both with and without updating procedures for the period 01 November 2006 to 31 January 2007	102
Figure 6.7.6	Comparisons of accumulated streamflows simulated with the ACRU model at the mouth of the Mgeni catchment, derived from the C-CAM rainfall forecasts both with and without updating procedures for the period 01 November 2006 to 31 January 2007	103

LIST OF FIGURES (continued)

		Page
Figure 6.7.7	Coefficient of determination, bias, RMSE and MAE of accumulated Quaternary Catchment streamflows simulated with the ACRU model when using the C-CAM 1 day lead time rainfall forecasts both with and without updating, for the period of 01 November 2006 to 31 January 2007	103
Figure 6.7.8	Two day lead time rainfall forecasts from the UM model over QC U20E in the Mgeni catchment for Events A to D on 17 November 2006, 24 December 2006, 30 January 2007 and 04 March 2007	104
Figure 6.7.9	Scores of Hit, Miss, False Alarm and Correct Null defined by the threshold of 50th percentile for November 2006, 24 December 2006, 30 January 2007 and 04 March 2007	105
Figure 6.7.10	CSI, POD and FAR scores of 2 day lead time rainfall forecasts from the UM model as a function of threshold percentiles for the rainfall events on 17 November and 21 December 2006	106
Figure 6.7.11	CSI, POD and FAR scores of 2 day lead time rainfall forecasts from the UM model as a function of threshold percentiles for the rainfall events on 30 January and 04 March 2007	107
Figure 6.7.12	Time series comparisons of daily streamflows simulated with the ACRU model at the mouth of the Mgeni catchment, derived from the UM rainfall forecasts both with and without updating procedures for the period 01 November 2006 to 31 January 2007	108
Figure 6.7.13	Comparisons of accumulated streamflows simulated with the ACRU model at the mouth of the Mgeni catchment, derived from the UM rainfall forecasts both with and without updating procedures for the period 01 November 2006 to 31 January 2007	108
Figure 6.7.14	Coefficient of determination, bias, RMSE and MAE of accumulated Quaternary Catchment streamflows simulated with the ACRU model when using the UM 1 day lead time rainfall forecasts with and without updating for the period 01 November 2006 to 31 January 2007	109
Figure 6.7.15	The 2.5° grid boxes over southern Africa for the NCEP-MRF forecasts, with the Mgeni catchment shown in its relevant grid box	110
Figure 6.7.16	The spread of NCEP ensemble rainfall forecasts for 17 November 2006, 21 December 2006, 30 January 2007 and 04 March 2007. The box-and-whiskers represent the minimum, lower quartile, median, upper quartile and maximum values of the ensemble members. The x signs indicate the ensemble mean value. Diamonds represent the observed values	111
Figure 6.7.17	Time series comparisons in the 30ºS 30ºE grid box of accumulated rainfalls of 5 day forecasts derived from the NCEP-MRF rainfall model for the period 01 November 2006 to 31 January 2007	112
Figure 6.7.18	Scattergram of NCEP simulated 1 day forecasts from the means of 22 ensembles versus observed rainfalls for the period 01 November 2006 to 31 January 2007	112
Figure 6.7.19	Time series comparisons of daily streamflows at the mouth of the Mgeni catchment, derived from the C-CAM, UM and combined rainfall forecasts for the period 01 November 2006 to 31 January 2007	113
Figure 6.7.20	Comparisons of accumulated streamflows at the mouth of the Mgeni catchment, derived from the C-CAM, UM and combined rainfall forecasts for the period 01 November 2006 to 31 January 2007	114
Figure 7.1.1	A schematic flow chart demonstrating the structure of the initial agrohydrological forecasting framework developed in this project	117
Figure 7.1.2	The main window showing options for near real time, short and medium as well as long range forecasting in the GIS based framework for the agrohydrological forecasting system	118
Figure 7.2.1	The *ASCII to Grid* windows for format conversion	119
Figure 7.2.2	The screen for adding a grid layer for extracting daily rainfall values over a selected catchment	119

LIST OF FIGURES (continued)

		Page
Figure 7.2.3	The screen for extracting daily rainfall values to *ACRU* formatted rainfall files	120
Figure 7.3.1	A screen showing the short and medium range forecasting model options	120
Figure 7.3.2	An example of a one week lead time probabilistic forecast from NCEP-MRF ensemble rainfall forecasts at 2.5º resolution over southern Africa (Source: SAWS, 2005)	121
Figure 7.4.1	A window for translating seasonal categorical rainfall forecasts into daily time series values based on the analogue method	125
Figure 7.4.2	A window for extracting daily rainfall values from randomly selected analogue years	126
Figure 7.5.1	The *ACRU* agrohydrological model: Schematic of inputs, modes of operation, simulation options and objectives / components (After Schulze, 1995)	127
Figure 7.5.2	The *ACRU* agrohydrological model: Schematic of its multi-layer soil water budgeting and partitioning and redistribution of soil water (After Schulze, 1995)	128
Figure 8.2.1	User interface of the operational agrohydrological forecasting system which allows for the selection of available options for the generation of forecasts	132
Figure 8.2.2	Seven day forecasts of rainfall, topsoil moisture and subsoil moisture in the Berg Catchment for the period 17-23 October 2011	134
Figure 8.2.3	Seven day forecasts of baseflow, stormflow, runoff and accumulated streamflow in the Berg Catchment for the period 17-23 October 2011	135
Figure 9.3.1	April-May-June 2009 seasonal forecasts produced by SAWS, CSAG showing variations and spatial scale	143
Figure 9.3.2	March-April-May 2010 precipitation forecast from CSAG	144
Figure 9.3.3	March-April-May 2010 forecasts from SAWS for above and below normal precipitation	144
Figure 9.3.4	The seasonal forecast for October to December 2009 which suggested that below normal rainfalls were expected over the larger part of the South African summer rainfall regions as a result of El Niño related drought conditions likely to set in	145
Figure 9.3.5	The actual rainfall for November 2009 (SAWS)	146
Figure 10.3.1	Methods of weather forecasting received by farmers	150
Figure 10.4.1	The Modder River catchment indicating various soil types and land types within the selected quaternary catchments	153
Figure 10.4.2	Comparison of measured and simulated maize yields for PAN 6479 under different plant population densities, with the maize planted during the 1-15 November period, a fertilizer application rate of 100 kg ha^{-1} N and three weedings	156
Figure 10.4.3	Comparison of measured and simulated maize yields for Pioneer 3237 under different plant population densities, with the maize planted during the 1-15 November period, a fertiliser application rate of 100 kg ha^{-1} N and three weedings	156
Figure 10.4.4	Cumulative distribution function of long-term simulated maize yields for PAN 6479 planted during 1-15 November under different weeding frequencies (using a plant population density of 18 000 plants.ha^{-1} and fertilizer application rate of 50 kg N.ha^{-1})	160
Figure 10.4.5	Cumulative distribution function of long-term simulated maize yields for Pioneer 3237 planted during different planting dates (using a plant population density of 12 000 plants.ha^{-1}, fertilizer application rate of 50 kg N.ha^{-1} and weeding twice)	160

LIST OF FIGURES (continued)

Page

Figure 10.4.6 Cumulative distribution function of long-term simulated maize yields for PAN 6479 planted during 1-15 November under various fertilizer application rates (using a plant population density of 15 000 plants.ha^{-1} and weeding twice) 161

Figure 10.4.7 Cumulative distribution function of long-term simulated maize yields for Pioneer 3237 planted during 1-15 November under various weeding frequencies (using a plant population density of 9 000 plants.ha^{-1} and a fertilizer application rate of 35 kg N.ha^{-1}) 162

Figure 10.4.8 Cumulative distribution function of long-term gross margins for PAN 6479 associated with three different plant population densities and two weeding frequencies during NN-NN rainfall conditions (using a fertilizer application rate of 35 kg N.ha^{-1} and planted during 1-15 November) 168

Figure 10.4.9 Cumulative distribution function of long-term gross margins for Pioneer 3237 associated with two different planting dates and three plant population densities during NN-NN rainfall conditions (using a fertilizer application rate of 75 kg N.ha^{-1} and weeding twice) 169

Figure 10.4.10 Flow chart of recommended practices in the Modder River catchment for maize variety PAN 6479 during NN-NN rainfall conditions 172

Figure 10.4.11 Flow chart of recommended practices in the Modder River catchment for maize variety Pioneer 3237 during NN-NN rainfall conditions 173

Figure 11.2.1 Distribution of ARC automatic weather stations as of July 2010, with these stations data being available in DSSAT format 175

Figure 11.2.2 Number of automatic weather stations for which data are available on a monthly basis, for the period January 2000 to July 2010 176

Figure 11.3.1 Distribution of SAWS rainfall stations with quality controlled / infilled data for the period 2000-2007 177

Figure 12.1.1 Delineation of the RSA, Lesotho and Swaziland into 5 838 hydrologically interlinked and cascading Quinary Catchments (Schulze and Horan, 2011) 182

LIST OF TABLES

		Page
Table 1.5.1	Links between the project's Terms of Reference, its more specific objectives and the chapter sections in which they are discussed in this report	5
Table 2.4.1	Potential applications of forecasts at different lead times for the agricultural and water resources sectors	9
Table 3.1.1	Schematic contingency table for categorical forecasts of a binary event, with the number of observations in each category being represented by A, B, C, D and N (Source: Livezey, 2003)	17
Table 5.3.1	Description of municipalities and major towns within the Upper Olifants catchment	54
Table 5.5.1	Subcatchment physiographic information of the Mgeni catchment (After Schulze, 1997)	66
Table 6.1.1	Statistical summary of historical monthly rainfall for Glen station	71
Table 6.5.1	Farmers with and without access to scientific rainfall forecasting from a 2007 survey	83
Table 6.5.2	Indigenous indicators and their use in interpreting rainfall conditions	84
Table 6.5.3	Rainfall probabilities for southern Free State from August to December 2008 (SAWS)	87
Table 6.6.1	Comparative analysis of number of days that daily rainfall thresholds over the JJA season are exceeded for the rainfall station representing catchment G10A, versus the corresponding pixel of the 2009 C-CAM seasonal forecast	91
Table 6.6.2	Categories of runoff considered in the production of a qualitative forecast of runoff for the Berg / Breede catchment for August-September-October 2009	94
Table 8.2.1	Statistics of performance of the ACRU model in selected WMUs of the Upper Breede and Mgeni Catchments (After Warburton *et al*., 2010)	130
Table 9.1.1	Earmarked communities in the Modder / Riet Catchment	137
Table 9.2.1	Earmarked communities in the Upper Olifants Catchment	140
Table 10.1.1	Summary of institutions, services, information sources, clients, dissemination methods, frequencies of information provision and products involved in climate forecasts in the Modder / Riet and Upper Olifants catchments	147
Table 10.3.1	Evaluating the effectiveness of farmers workshops and the usefulness of the weather forecasts to the farmers	151
Table 10.4.1	Details of the selected sites within the QCs	152
Table 10.4.2	Combination of 3-month rainfall scenarios to create analogue seasons for the summer growing season October to December and January to March	153
Table 10.4.3	Number of growing season rainfall scenarios per QC	154
Table 10.4.4	Plausible management practices used to validate APSIM	154
Table 10.4.5	Verification results for APSIM using various management practices for PAN 6479	157
Table 10.4.6	Validation results for APSIM using various management practices for Pioneer 3237	158
Table 10.4.7	Management practices used in the simulation of maize yields	159
Table 10.4.8	Stepwise regression for predictors of maize yield during NN-NN rainfall conditions	159
Table 10.4.9	Field and maintenance costs associated with different tillage practices	162
Table 10.4.10	Seed costs associated with different plant population densities	162
Table 10.4.11	Fertilizer (N) application costs	163
Table 10.4.12	Costs corresponding to various weeding frequency	163
Table 10.4.13	The combinations of management practices that provided higher yields for PAN 6479 during NN-NN rainfall conditions	163
Table 10.4.14	Combinations of management practices that provided higher yields for Pioneer 3237 during NN-NN rainfall conditions	164

LIST OF TABLES (continued)

		Page
Table 10.4.15	Reference table for yield expectance, field costs and economic benefit under various sets of management practices during NN-NN rainfall conditions for PAN 6479	164
Table 10.4.16	Reference table for yield expectance, field costs and economic benefit under various sets of management practices during NN-NN rainfall conditions for Pioneer 3237	166
Table 10.4.17	Summary of best management practices together with the corresponding economic analysis under different seasonal rainfall scenarios for PAN 6479	170
Table 10.4.18	Summary of best management practices together with their corresponding economic analysis under different seasonal rainfall scenarios for Pioneer 3237	170
Table 11.2.1	Inventory of ARC climate data available for the period 2000-2008	175
Table 11.3.1	Analysis of the occurrence of accumulated totals in the SAWS rainfall dataset (2000-2007)	178
Table 11.3.2	Stations eliminated as target stations for infilling of accumulated rainfall totals or missing daily values	178
Table 11.3.3	Breakdown of missing data at 498 stations requiring infilling of missing daily data	179
Table 11.3.4	Breakdown of stations subjected to various infilling techniques / procedures	180

LIST OF ABBREVIATIONS

ACRU	Agricultural Catchments Research Unit
ADM	A conceptual rainfall-runoff model by Franchini (1996)
ADRM	Agricultural Disaster Risk Management
AGCM	Atmospheric General Circulation Model
AMIP	Atmospheric Model Intercomparison Project
AN-AN	Above-normal rainfall in early growing season followed by above-normal rainfall in the later growing season
ANN	Artificial Neural Network
APSIM	Agricultural Production Systems Simulator
AR	Auto Regressive (Model)
ARC	Agricultural Research Council
ARIMA	Auto Regressive Integrated Moving Average
AWS	Automatic Weather Station
BCSD	Bias Corrected Spatial Disaggregation
BN-BN	Below-normal rainfall in early growing season followed by below-normal rainfall in the later growing season
BS	Brier Score
BSS	Brier Skill Score
CAM3	Community Atmospheric Model
CCA	Canonical Correlation Analysis
C-CAM	Conformal-Cubic Atmospheric Model
CCT	City of Cape Town
CDF	Cumulative Probability Density Function
CHPC	Centre for High-Performance Computing
CICS	Canadian Institute for Climate Studies
CMC	Canadian Meteorological Center
CPT	Climate Predictability Tool
CSAG	Climate Systems Analysis Group (at UCT)
CSI	Critical Success Index
CSIR	Council for Scientific and Industrial Research
CSIRO	Commonwealth Scientific and Industrial Research Organsation
CWG	Conditional Weather Generator
DAFF	Department of Agriculture, Forestry and Fisheries
DBF	Data Base File
DEAT	Department of Environmental Affairs and Tourism
DJF	December, January, February
DM	District Municipality
DWA	Department of Water Affairs
ECMWF	European Centre for Medium-Range Weather Forecasts
EFS	Ensemble Forecasting Systems
EOF	Empirical orthogonal function
ET	Ensemble Transform
EWS	Early Warning System
FAR	False Alarm Ratio
FTP	File Transfer Protocol
GCM	General Circulation Model (also: Global Climate Model)
GFS	Global Forecasting System
GHG	Greenhouse gases
GIS	Geographic Information System
HS	Heidke Score
HSS	Heidke Skill Score
IDW	Inverse Distance Weight
IFR	Instream Flow Releases
ISCW	Institute for Soil, Climate and Water (of the ARC)
JJA	June, July, August
JMA	Japanese Meteorological Agency
LAM	Limited Area Model

LEPS	Linear Errors in Probability Space
LFR	Long Range Forecast
LI	Linear Interpolation
LTF	Linear Transfer Function
MAE	Mean Absolute Error
MAM	March, April, May
MAP	Mean Annual Precipitation
MAR	Multivariate Autoregressive
METSYS	Research group within the South African Weather Service
MLR	Multiple Linear Regression
MOS	Model output statistics
MRF	Medium Range Forecast
MSESS	Mean squared error skill score
NAC	National Agrometeorology Committee
NCEP	National Centre for Environmental Prediction
NCEP-MRF	National Center for Environmental Prediction for Medium Range Forecasting
NN-NN	Near-normal rainfall in early growing season followed by near-normal rainfall in the later growing season
NWP	Numerical Weather Prediction
OVK	Oranje Vrystaatse Koöperasie
PC	Primary Catchment
PCM	Parallel Climate Model
POD	Probability of Detection
PP	Perfect Prognosis
PQPF	Probabilistic quantitative precipitation forecast
QC	Quaternary Catchment
QCD	Quaternary Catchments Database
QDA	Quadratic Discriminant Analysis
QnCDB	Quinary Catchments Database
QPF	Quantitative Precipitation Forecast
RCM	Regional Climate Model
RMSE	Root Mean Square Error
RPS	Ranked Probability Score
RPSS	Ranked Probability Score Skill
RSA	Republic of South Africa
RTSS	Revised True Skill Statistic
SADC	Southern African Development Community
SAWS	South African Weather Service
SD	Spatial Disaggregation
SDSM	Statistical Downscaling model
SIMAR	Spatial Interpolation and Mapping of Rainfall
SOM	Self Organising Map
SOMD	Self Organising Map based Downscaling
SON	September, October, November
SST	Sea Surface Temperature
UCT	University of Cape Town
UFS	University of the Free State
UK	United Kingdom
UKZN	University of KwaZulu-Natal
UM	Unified Model
UP	University of Pretoria
USA	United States of America
WCWSS	Western Cape Water Supply System
WMA	Water Management Area
WRC	Water Research Commission

CHAPTER 1

SETTING THE SCENE

TG Lumsden and RE Schulze

Summary

1.1 BACKGROUND TO THE PROJECT
1.2 RATIONALE
1.3 OBJECTIVES
1.4 PLACING THE PROJECT WITHIN A BROADER CONTEXT OF CLIMATE RELATED AND RISK MANAGEMENT STUDIES

* * * * *

1.1 BACKGROUND TO THE PROJECT

In April 2005 the Water Research Commission (WRC) held a workshop to define the terms of reference for a solicited research project involving the application of rainfall forecasts to aid decision making in the agricultural sector. In June / July of the same year an official call for proposals for a five year project was made. Among the submissions to the WRC were two which were made by a consortium comprising of the University of KwaZulu-Natal (UKZN), University of Cape Town (UCT) and the South African Weather Service (SAWS) and another consortium comprising of the University of the Free State (UFS) and the Agricultural Research Council (ARC). During the evaluation process, the submissions of these two consortia were deemed to have their own unique strengths. The WRC thus requested that the institutions involved submit a proposal for a combined, integrated project (having double the original budget), which would retain the strengths of the original proposals. This proposal was submitted and accepted by the WRC, leading to the formation of this multi-institutional project. In addition to the institutions mentioned above, the University of Pretoria (UP) was also brought into the project as a sub-contractor to the UFS in order to provide short-range and seasonal forecasts. Additionally, the Council for Scientific and Industrial Research (CSIR) in South Africa became involved in the project during 2010, through the provision of short-range and seasonal forecasts to the UP, UFS and UKZN.

The methodology that was proposed to achieve the objectives of the project required that an Inception Workshop be held in order to engage relevant stakeholders with respect to:

- establishing requirements and priorities for forecasts in terms of suitable:
  - spatial scales,
  - lead times,
  - quantities and/or indices that can be applied in decision making, as well as
  - confidence levels,
- refining the proposed methodology,
- aiding in selecting priority areas / catchments for more detailed study, and
- obtaining stakeholder endorsement and support for the project.

1.2 RATIONALE

- The South African climate is highly variable over short and longer periods.
- This day-by-day as well as intra- and inter-seasonal variability is likely to be amplified by the global changes in climate, along with changes in other baselines such as those of population or land use.
- Agricultural production and water management are intrinsically linked to climate variability, and many decisions are made based on weather and climate information ("now-casts", as well as short, medium and longer term forecasts), especially on assumptions regarding weather and climate in the near future.
- Farmers need such information to help them plan for operations such as planting, irrigating and harvesting of their crops.

- Weather and climate forecasting can aid users to make more informed decisions and assist in planning activities.
- Forecasts have the potential to reduce risk in the long term and improve water use efficiency, and are becoming more skilful as research efforts continue.
- However, gaps exist between the products of weather and climate forecasting, both in the links to resulting agrohydrological responses, and in the application of forecasting information to agricultural decision-making.
- This WRC funded project aims to develop techniques and models for "translating" forecasts with different lead times from the near real time, to days and up to several months in advance into agrohydrological applications for decision support.

This project is undertaken within the context of the 2001 Strategic Plan for South African Agriculture, which states that one "component of the comprehensive risk management strategy is an early-warning system that includes adequate access to and utilization of timely, accurate, relevant and free information about the weather". Thus, for example, the National Department of Agriculture (now renamed Department of Agriculture, Forestry and Fisheries) has, since the end of 2002, been advising farmers on climate conditions and practices to follow, based on a long-term climate outlook, in order to reduce farmers' susceptibility to adverse weather conditions. Decisions in agriculture, however, are made with varied lead times. This project therefore sets out to develop a nested series of early warning systems which will provide:

- different lead times, for example, from near real time (i.e. "now-casts") to 1 day, 4 days, 1 week, 3 weeks, 1 month and 1 season; and
- "translations" (including spatial and temporal downscaling) of weather and climate forecasts to intermediate parameters (such as daily precipitation amounts and intensities, dry spell duration, or number of raindays), and to more explicit agrohydrological outcomes including, for example, soil moisture status, growth potential, crop yield estimates, streamflows and dam levels to meet irrigation demands, plant dates, fertilizer levels and infield operations.

The focus of the project will be undertaken at two scales, *viz*.

- the national scale, assuming in the main rainfed conditions, and
- catchment specific scales for selected critical catchments, which will be studied in greater detail, especially also with respect to irrigation water supply and demand.

1.3 OBJECTIVES

1.3.1 Overall Objective

The overall objective of this project was to develop and test techniques and models for translating weather (i.e. short term) and climate (i.e. medium to longer term) forecasts in South Africa into applications for decision support at a range of spatial scales in both rainfed (cropping and grazing) and irrigated agricultural production, agricultural water management and the distribution, processing and marketing of agricultural products, in order to reduce risk associated with vagaries of day-to-day to seasonal climate variability.

1.3.2 More Specific Objectives

More specific objectives of the project, identified in the Project Contract, may be grouped by major thrusts, *viz*.

- engaging of stakeholders with regard to forecast needs and other issues,
- selection and configuration of catchments for detailed study,
- updating of weather / climate data,
- acquisition, downscaling, and archiving of weather/climate forecasts,
- translation of weather / climate forecasts into agrohydrological forecasts through use of agrohydrological models,
- evaluation of downscaled weather / climate forecasts and resulting agrohydrological forecasts, including uncertainty, sensitivity and benefit / cost analyses, and

- interpretation of forecast information, with emphasis on dissemination of information in a targeted manner to stakeholders and incorporation of stakeholder feedback.

1.3.3 Scales of Operation

As already mentioned, the project is focused at two scales, *viz.*

- the catchment scale, where for selected critical catchments detailed local land use / irrigation / dam / end user information will be incorporated, and
- the national scale, which has a countrywide focus, but incorporates less detailed local information.

In order to achieve the objectives of the project, an agrohydrological forecasting system will be developed according to the framework outlined in **Figure 1.3.1**, where flows of information in the figure are indicated by arrows.

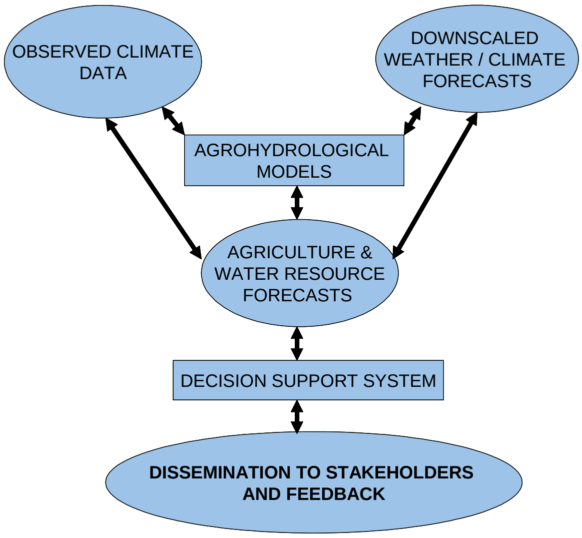


Figure 1.3.1 The forecast project framework, with flows of information indicated by arrows

1.4 PLACING THE PROJECT WITHIN A BROADER CONTEXT OF CLIMATE RELATED AND RISK MANAGEMENT STUDIES

1.4.1 Climate Related Studies

Climate studies consist of those related to the

- *historical state*, at appropriate time scales (from sub-daily to decadal) and space scales (from those affecting the individual household to global), with detail "exploding" as the timeframe changes from (say) annual to monthly, to daily, and with many applied problems in agriculture and water resources having to grapple with availability, length, networks, quality and appropriateness of the data; the
- "*now-state*" of weather in its dynamic forms, monitored remotely by radar and satellite; and the
- *future states*, in which one can distinguish between
  - the *immediate future* of minutes, hours and up to one or several days ahead, at which operational decisions need to be made,
  - the *near future* of one day to one season forecasts by probabilistic, normative or categorical means, with each lead time having specific tactical applications in agriculture and related water resources, and
  - the *distant future* related to greenhouse gas induced climate change and the strategic decisions which have to be made in that regard (Schulze, 2006).

It is in the immediate future and near future categories of future climate states that this project has its niche, but with cognisance constantly having to be taken of historical, now-state and distant future climates.

1.4.2 Risk Management

Agrohydrological forecasts need to provide information on

- timing,
- location, and
- magnitudes

of climate related events in order to enhance operational reliability in the many decisions which need to be made by using either shorter or longer lead times of the forecasts, and where each decision has potential economic benefits.

As such, the application and benefits of "translating" climate forecasts into operational decisions should be viewed within the broader framework of

- risk management and, therefore,
- adaptive water resource management.

Risk management, by definition, provides a formalised framework within which decision makers *and* stakeholders can compare the harm caused by risks (e.g. a flood or drought), with the benefits associated with potentially reducing that risk (Schulze, 2004).

In **Figure 1.4.1**, applications of forecasts fall into the right-hand branch of *Risk Mitigation and Control*. While the *primary hazard* event (e.g. the flood or drought *per se*) cannot generally be modified, *secondary hazards* can be, by actions such as structural protection against the damages by floods/droughts (e.g. storing water or releasing some of it before the flood arrives). It is, however, in the *vulnerability modification* sub-branch through non-structural *preparedness* and *early warning systems* that this project is seen to be contributing towards risk management and, by implication, adaptive water resource management.

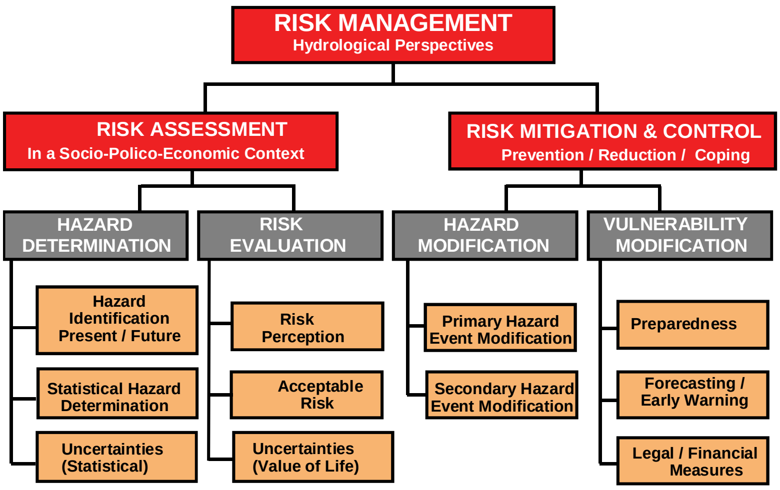


Figure 1.4.1 A risk management framework (Schulze, 2004)

It was also considered important to understand the needs of the end user so that the forecast information that is disseminated is appropriate to the user.

An appeal was made to have warnings issued with forecasts, where appropriate. This would ensure that a critical situation is highlighted in a forecast bulletin and not hidden within other details of less importance.

1.5 LAYOUT OF THE REPORT IN RELATION TO THE PROJECT'S TERMS OF REFERENCE AND ITS SPECIFIC OBJECTIVES

These specific objectives outlined in **Section 1.3** were identified in the original Terms of Reference (ToR) of this project and the links between ToRs, the specific project objectives and the major sections making up the chapters of this report are summarised in **Table 1.5.1**.

Table 1.5.1 Links between the project's Terms of Reference, its more specific objectives and the chapter sections in which they are discussed in this report

Terms of Reference	Description of Terms of Reference / Specific Objectives	Reference to Chapter Sections in Report
1	Motivate for, and select, critical catchments for more detailed applications / stakeholder involvement	Ch 5.1, 5.2, 5.3, 5.4
2	Identify end user groupings and interact with target end users re. their forecasting needs	Ch 2.1, 2.2, 2.3, 2.4, 2.5, 2.6; Ch 3.2
3	Obtain endorsement and support from relevant end user groups	Ch 5.1, 5.2, 5.3
4	Inventorise / update relevant available data	Ch 11.1, 11.2, 11.3, 11.4; Ch 12.1, 12.2, 12.3
5	Update historical databases for verification	Ch 11.1, 11.2, 11.3, 11.4
6	Archive weather / climate forecasts	Ch 12.3
7	Enhance weather / climate forecasts and downscaling techniques	C3.1; Ch 4.1, 4.2, 4.3, 4.4, 4.5; Ch 7.3, 7.4,
8	Derive daily weather inputs for different lead times for agrohydrological models	Ch 4.3, 4.4; Ch 7.1, 7.2, 7.3, 7.4; Ch 8.1, 8.2, 8.3
9	Verification of downscaling techniques and resulting forecasts, incl. uncertainty analyses	Ch 3.1; Ch 4.4; Ch 6.7
10	Interpret / present forecast information for users	Ch 6.1, 6.2, 6.3, 6.4, 6.5, 6.6; Ch 9.1, 9.2, 9.3; Ch 10.4,
11	Link with existing dissemination initiatives	Ch 6.1, 6.2, 6.3, 6.4, 6.5, 6.6; Ch 10.4,
12	Undertake benefit / cost analyses of integrated forecast systems	Ch 10.1, 10.2, 10.3, 10.4, 10.5
13	Publications; capacity building	Ch 14

CHAPTER 2

FORECASTING AS A STAKEHOLDER STRATEGY FOR VULNERABILITY MODIFICATION IN THE MANAGEMENT OF AGRICULTURAL SYSTEMS

RE Schulze, TG Lumsden and YB Ghile

Summary

2.1 TYPES OF FORECASTING
2.2 WEATHER vs. CLIMATE FORECASTS
2.3 AGROHYDROLOGICAL FORECASTS: TYPES AND POTENTIAL APPLICATIONS
2.4 SUMMARISING POTENTIAL FORECAST APPLICATIONS
2.5 INFORMATION REQUIREMENTS OF FARMER STAKEHOLDERS
2.6 DISSEMINATION OF FORECASTS

* * * * *

Vulnerability is not a consequence only of the year-to-year variability of climate *per se*, but also of its unpredictability. Many critical agricultural and related water resource decisions that interact with climatic conditions must be made in advance, based on available climate information and assumptions (Hansen, 2002). The emerging ability to provide timely and skilful short, medium and longer term agrohydrological forecasts has the potential to reduce risk in the long term and to provide valuable support to meet the competing demands for increasingly scarce fresh agricultural and related water resources. The incorporation of forecasting within the framework of risk management has, therefore, been acknowledged to play a vital role in modifying decisions, to either prepare for expected adverse conditions or to take advantage of expected favourable conditions (Hammer *et al.,* 2001; Hansen, 2002). Connecting climate forecasts with applications such as the management of agricultural and water resources decisions is, however, not straightforward, and remains an area in which much needs are yet to be learned. While there has been a growing literature on potential applications of climate forecasts to mitigate risks in agricultural and water resources systems, there has been relatively little research done on the issue of applying climate forecasts in decisions to modify the vulnerability of humans and properties to the adverse impacts of climate variability. In this chapter, current forecast types and techniques are briefly reviewed.

2.1 TYPES OF FORECASTING

Although a considerable literature distinguishes between the terms forecasts, outlooks and predictions (e.g. Maidment, 1993), in practice there are no naming conventions (Hartmann *et al.,* 1999).

- *Forecasting* is generally considered as being the estimation of conditions at a specific future time, or during a specific time interval, while
- *prediction* is the estimation of future conditions, without reference to a specific time.

For very long lead times, however, the distinction between forecasting and predictions is blurred, as forecasting accuracy decreases with increases in lead times (Lettenmaier and Wood, 1993). Forecasting techniques exist along a continuum of sophistication, ranging from simple implicit subjective processes (e.g. “feeling” that tomorrow’s condition will be much like today’s condition), to complex objective techniques which require many types of data, representations of the physical processes, and teams of scientific experts (Hartmann *et al.,* 1999). The broad range of forecasting encompasses various products (e.g. weather forecasts, crop forecasts, fire hazard forecasts, hydrological forecasts, aviation forecasts), with time scales ranging from minutes to seasons, and hence lead times from minutes to over a year. Therefore, the wide variety of forecast products and techniques can be categorised, according to several different perspectives (Hartmann *et al.,* 1999) which are discussed below.

2.2 WEATHER vs. CLIMATE FORECASTS

Although this chapter concentrates on agrohydrological forecasts, the distinction between weather, climate and agrohydrological forecasts is first highlighted in order to obtain a better understanding on issues of applying the various forecasting techniques and products.

According to commonly used definitions, weather forecasts track the movement and evolution of specific air masses and cover periods approaching two weeks, while climate forecasts are usually considered as extended weather outlooks and cover periods of one month and longer, i.e. climate forecasts describe the predictability of weather statistics, and not day-to-day variations in weather (Hartmann *et al.,* 1999; Kabat and Bates, 2002). Because the climate system is so complex, it is almost impossible to take all the factors that determine the future seasonal climate into account. Therefore, climate forecasts are generally provided in terms of the probability that the rainfall or temperature will be either below normal, near normal or above normal (Kabat and Bates, 2002).

2.3 AGROHYDROLOGICAL FORECASTS: TYPES AND POTENTIAL APPLICATIONS

Weather and climate forecasts are critical inputs to agrohydrological forecasts. Agrohydrological forecasts are predictable on scales equivalent to both weather and climate forecasts owing to integrative behaviour of hydrological processes (Hartmann *et al.,* 1999). Although any classification of forecasts is subject to some overlap, four types of agrohydrological forecasting may be distinguished, depending on the lead times. These four types of forecasts and the potential usefulness of such forecasts are briefly presented on the sub-sections which follow.

2.3.1 Near Real Time Agrohydrological Forecasts

The temporal coverage of near real time agrohydrological forecasts varies from hourly to daily, with lead times from minutes up to several days in advance (Lettenmaier and Wood, 1993). These forecasts are most often used for flood warning purposes and for real time water resources and agricultural operations. Real time agrohydrological information is very important in areas of fast response because, as people place more pressure on the vulnerable areas (e.g. floodplains) for habitation or agriculture (or other businesses), so there is a greater potential for loss of life and damage to property by catastrophic events such as flash floods (Pegram and Sinclair, 2002). The information received from automatic weather stations, together with information obtained from satellite and radar images, is integrated into models to produce near real time agrohydrological forecasts.

Since structural measures are often insufficient to reduce risks associated with extreme events at the required local level, an important role is played by non-structural measures (Toth *et al.,* 1999). Some of the potential applications of near real time agrohydrological forecasts in agriculture and water resources include:

- dissemination of warning messages regarding the extent of extreme events, such as floods (Hossain, 2003),
- evacuation of people and mobile assets (e.g. pump equipment and machinery) from threatened high risk areas (Hossain, 2003; Schulze, 2005),
- providing information on the status of inflows into dams, such as timing of peak flows (Schulze, 2005),
- reservoir safety releases (Schulze, 2005),
- mobilisation of resources and planning relief and rehabilitation measures (Hossain, 2003), and
- precautionary measures to divert floods either into, or away from, agricultural areas, depending on the soil moisture status of the area.

2.3.2 Short and Medium Term Agrohydrological Forecasts

Short term agrohydrological forecasts are taken to be those with a temporal coverage from one day up to about three days, while medium agrohydrological forecasts cover time scales usually up to two weeks. The lead times of short and medium term agrohydrological forecasts vary from a day up to several days or a few weeks. Such forecasts are useful to making adjustments to agricultural planning and water management, for example, by allowing a farming community to react on time, especially at planting and harvesting times (Webster and Grossman, 2003).

Some of the potential applications of short and medium term agrohydrological forecasts in agriculturally related operations are (Schulze, 2005):

- tillage, planting, transplanting and harvesting decisions,
- fertilizer and pest control application decisions,
- taking precautionary measures to protect assets, livestock and agricultural infrastructures, such as forage silos, embankments, roads, etc. (Hossain, 2003),
- firebreak burning operations,
- labour and equipment planning,
- crop yield estimates
- reservoir regulation decisions (e.g. formulation of reservoir release strategies),
- reservoir safety releases and
- irrigation scheduling.

2.3.3 Long Term (Seasonal) Agrohydrological Forecasts

Long term agrohydrological forecasts are those with longer lead times and time scales, usually up to several months ahead. At present, little forecast skill is possible for agrohydrological variables when forecast lead times extend beyond three months (Lettenmaier and Wood, 1993; SAWS, 2005). Reliable long term agrohydrological forecasts can improve the decisions in the management of agricultural systems by reducing risks associated with inter-seasonal and inter-annual climate variability. Long term agrohydrological forecasts can assist farmers, agribusiness managers and governments in many ways to best manage their properties, strategies and short and long term policies. The potential applications in agriculturally related activities include (Klopper, 1999; Hossain, 2003; Schulze, 2005):

- crop variety selection (e.g. introduction of fast growing varieties),
- planting and harvesting decisions (delayed or earlier),
- conservative use of fertilizers, insecticides and pesticides,
- maintenance of conservation structures,
- fertilizer, planting and harvesting equipment orders,
- reducing stock (e.g. selling cattle before the drought season started),
- labour and equipment planning,
- transport and storage scheduling,
- crop yield estimates,
- planning national food import, storage and distribution programmes,
- adjustment of risk profiles,
- development of drought and flood response policies
- reservoir management, such as status reviews and / or curtailment planning (Chiew *et al.,* 2003; Schulze, 2005),
- allocation of irrigation water and planning of irrigation timing, depending on forecasts such as soil moisture and streamflow (Lettenmaier and Wood, 1993; Schulze, 2005), and
- evaluation and implementation of mitigation measures, such as water conservation during droughts (Lettenmaier and Wood, 1993).

2.4 SUMMARISING POTENTIAL FORECAST APPLICATIONS

A tabulated summary of the above potential forecast applications was also developed at the Inception Workshop for a range of more specific lead times. This table was based on the input of both stakeholders and team members (**Table 2.4.1**). The applications were subsequently grouped according to logical headings for both the agricultural and water resources sectors.

Some key applications will need to be identified in **Table 2.4.1** so that relevant, tailored forecasts can be developed accordingly. It will not be possible to develop tailored forecasts for all applications in the Table owing to time and resource constraints.

Table 2.4.1 Potential applications of forecasts at different lead times for the agricultural and water resources sectors

Lead Time	Agriculture	Water Resources
Near Real Time (re-active decisions)	***Agronomic*** • Planting/ploughing/other land operations • Pest/disease control operations • Haymaking decisions • In-field machinery operations/trafficability • Fruit picking ***Livestock*** • Stock management and movement • Chicken farming: heating, cooling • Game capture • Sheep shearing ***Logistics/Financial*** • Energy management (e.g. irrigation) ***Natural Hazards*** • Fire suppression (SAWS/DWA, timber industry, sugar industry, fire protection agencies, farmer unions, Eskom) • Controlled burning • Pump equipment and machinery removal •	***Disaster Management*** • Evacuation (e.g. pumps, stock) • Evacuation procedures • Safety releases from reservoirs ***Streams and Dams*** • Reservoir inflows ***Irrigation*** • In-field decisions
1-6 Days (pro-active decisions)	***Agronomic*** • Aquaculture • Planting / harvesting decisions (incl. equipment maintenance) ***Livestock*** ***Logistics/Financial*** • Marketing of products (crop, wool, etc.) • Energy management • Irrigation – equipment, fertigation, and labour planning ***Natural Hazards*** • Controlled firebreak burning • Frost probability	***Disaster Management*** • Preparation for flood events • Storm surge analysis • Reservoir safety releases ***Streams and Dams*** • Streamflow forecasts • Reservoir inflow forecasts • IFR releases (freshettes) ***Irrigation*** • Irrigation water orders • Irrigation scheduling
7-14 Days	***Agronomic*** • Land preparation: Timing of • Crop type selection e.g. maize vs sorghum • Selection of substitute crops • Fertilizer applications • Pest/disease control operations ***Livestock*** • De-stocking	***Disaster Management*** • Water poverty relief planning ***Streams and Dams*** • Streamflows forecasts • Reservoir inflow forecasts • Reservoir management decisions • IFR low flow releases

Table 2.4.1 continued

	Logistics/Financial • Financial planning (contracts) • Futures trading ***Natural Hazards***	***Irrigation*** • Irrigation water allocations • Irrigation scheduling decisions
1 month	***Agronomic*** • Sugarcane haulage: Truck orders • Tillage/ planting decisions • Planning of other infield operations ***Livestock*** ***Logistics/Financial*** • Crop yield estimates • Feedback on previous month's crop estimate • Fertilizer orders • Labour/equipment planning ***Natural Hazards*** Early warning: Rainfall/temperature forecasts	***Disaster Management*** • Water poverty relief planning ***Streams and Dams*** • Streamflow forecasts • Reservoir inflow forecasts • Reservoir management decisions • IFR low flow releases ***Irrigation*** • Irrigation water allocations • Planning of irrigation timing
3 months	***Agronomic*** • Crop type and plant date decisions ***Livestock*** ***Logistics/Financial*** (Strategic decisions) • Planting/ harvesting equipment orders • Fertilizer orders • Transport scheduling • Mill opening/closing decisions • Crop variety selection • Crop yield estimates • Crop storage planning (grain/ sugar) • Conservation structure maintenance ***Natural Hazards***	***Disaster Management*** ***Streams and Dams*** • Streamflows forecasts • Reservoir inflow forecasts • Reservoir management - status review - curtailment planning ***Irrigation***

2.5 INFORMATION REQUIREMENTS OF FARMER STAKEHOLDERS

In the course of the project farmer stakeholders from both the commercial and emerging sectors gave the following feedback at workshops on variables to be forecast for their decision making:

- farmers are interested in the onset of the rainy season, distribution within the season and cessation of the rainfall season
- most farmers are interested in the seasonal (3 month) forecasts and would use this for deciding when to plant
- farmers would prefer receiving advice on planting decisions based on general yield forecast information rather than the yield forecasts themselves, as actual yields are very specific to a farmers' field / farm
- some emerging farmers work with their extension officers to select cultivars, while others will just plant want they have available

- temperature forecasts could be useful for managing tomato crops, animals (e.g. pigs, angora goats), pesticide applications and time of harvesting of crops
- if temperature forecasts were not available, they could be produced by perturbing average temperatures based on the prevailing rainfall conditions (i.e. develop rainfall-temperature correlations)
- commercial farmers are also interested in short term forecasts for making decisions about pesticide and fertilizer applications
- crop yield forecasts (t/ha) could be used by insurance companies, the Crop Estimates Committee, fertilizer companies, etc.

2.6 DISSEMINATION OF FORECASTS

In various workshops the following points emanated from stakeholders regarding the dissemination of forecasts:

- for forecasts disseminated electronically, the majority of users prefer email as the medium of dissemination, rather than the internet (which may be slow in remote areas),
- for resource poor farmers, the following channels would be suitable for dissemination of forecasts:
    - cellphones and radio (very important),
    - extension services,
    - word of mouth,
    - written word,
    - Agri TV,
    - the local chief (through meetings with the community),
- indigenous knowledge is still applied in decision-making by some users,
- forecasts should be made available in local languages,
- interpretation must be included with forecasts,
- care should be taken to avoid “interpretations of interpretations” during the dissemination process (this leads to misinterpretation),
- information should be tailored, in that it is understandable and relevant to the user,
- the education level of users is an important consideration, and it needs to be ensured that forecasts are understood by the user since, for example, the concept of probability is often not understood by users,
- training of people involved in the forecast dissemination chain is required,
- forecasts should not be prescriptive, but should rather provide users with relevant information to enable them to make their own decisions,
- forecasts need to be "in your face" and repeated a number of times to raise the awareness of users, and
- the products of the research should be promoted through carefully selected forums to ensure uptake.

Regarding the format of the forecast information that is presented to users, it should be emphasised that the forecasts should be probabilistic in nature to convey to the end user that a range of outcomes is possible.

CHAPTER 3

CHALLENGES AND APPROACHES TO MAXIMISE BENEFITS FROM AGRO-CLIMATIC FORECASTS

YB Ghile and RE Schulze

Summary

3.1 FORECAST QUALITY
3.2 COMMUNICATION OF AGRO-CLIMATIC INFORMATION
3.3 APPLICATION OF AGRO-CLIMATIC INFORMATION
3.4 CONCLUDING REMARKS

* * * * *

In **Chapter 2** a brief description was provided on the role that forecasting could play in modifying decisions to either reduce expected adverse conditions or to take advantage of favourable conditions. However, the availability of agro-climatic forecasts *per se* is not sufficient to ensure that decision makers will mitigate the potential negative consequences of climate variability or, alternatively, capitalise on potentially beneficial events (Podestá *et al.,* 2002). Benefits only arise when the use of agro-climatic forecasts results in decisions that improve management of climate related risks in water resources and agricultural operations. According to many researchers (e.g. Pielke, 2000; Hansen, 2002; Podestá *et al.,* 2002), sustained and effective application of agro-climatic forecasts requires three components to occur simultaneously, *viz.*

- the generation of skilful and timely climatic forecasts (i.e. forecast quality),
- the effective communication of that information, and
- the application of that climate information to modify decisions or policies (i.e. forecast value).

In practice however, the application of these components is not straightforward, let alone applying them simultaneously. Thus, it is important to explore the prerequisites, approaches and impediments associated with each of these components as a means of maximising the benefits from agro-climatic forecasts.

3.1 FORECAST QUALITY

Climatic forecasts should, in the first instance, be statistically valid (Ritchie *et al.,* 2004) and the information should be both

- prognostic (what is likely to happen?) and
- diagnostic (what has happened in the recent past, or what is happening now?).

The reason for the latter is that diagnostic information can provide a relevant context within which to interpret a climate forecast (Podestá *et al.,* 2002). Sources of uncertainty and methods to evaluate forecast quality are therefore described briefly, as forecast quality is a central issue for anyone wishing to use agro-climatic forecasts.

3.1.1 Sources of Uncertainty in Forecasting

Improved understanding of ocean-atmosphere interactions, more powerful remote sensing tools and the advances in simulation of complex non-linear systems with powerful computers has facilitated the generation of climate forecasts with increasingly more accuracy. However, there are some unavoidable errors in the generation of weather, climate and, as a result, agricultural forecasts. These errors arise from three sources (Lettenmaier and Wood, 1993), *viz.*

- errors from the process representations in the agrohydrological models used,
- data errors, and
- forecast errors from the weather and climate models used.

3.1.1.1 Agrohydrological model errors

Errors in agrohydrological models often arise from an incorrect conceptualisation of the rainfall-runoff processes by the agrohydrological model (Lettenmaier and Wood, 1993). As has been highlighted in **Chapter 3**, agrohydrological models are limited by their representation of the local spatial heterogeneities and non-stationarities of rainfall-soil water-runoff processes. Errors arising out of inadequate model conceptualisation are ideally improved by research on relevant processes and incorporating the findings in improved algorithms (UKCIP, 2003; Schulze, 2008). Alternatively, as an interim solution when adequate agrohydrological observations are available, good simulations of agrohydrological outputs may be obtained by changing values of some internal variables or parameters (UKCIP, 2003; Collischonn *et al.,* 2005).

3.1.1.2 Data errors

With climatic data it is often difficult to assess the "truth" of observed data because of several factors. Sources of errors in the observations include random and biased errors as well as sampling errors. Errors in model inputs such as precipitation as a result of sparseness of the raingauge network, observer errors, raingauge splash errors and extrapolation errors will be amplified, for example, through the agrohydrological forecasts (Lettenmaier and Wood, 1993; UKCIP, 2003).

3.1.1.3 Weather and climate model errors

Advances in computing and improved understanding of the atmosphere-ocean system, have enabled Numerical Weather Prediction (NWP) and General Circulation Models (GCMs) to respectively predict the weather in the near and more distant future. These models use equations of fluid motion, which are initialised with present conditions to predict the movement and evolution of disturbances such as frontal systems and tropical cyclones that cause rainfall (Ganguly and Bras, 2001). Despite the progress made in these models, weather forecasts have, as yet, obtained only limited success, i.e. their skill drops off with lead time and varies from one location to another. The reason for this is their limited representation of meso-scale atmospheric processes, terrain, land and sea distribution (Mecklenburg *et al.,* 2000; Schmidli *et al.,* 2006).

Moreover, no matter how good atmospheric models may become, the forecasts will always fail up to a point because the atmosphere is a chaotic dynamical system, and any error in the initial condition will lead to increasing errors in the forecast, eventually leading to a greater or smaller loss of predictability after a certain period of time (Toth *et al.,* 1997). The rate of the error growth depends on factors such as the circulation regime, season and geographic domain (Toth *et al.,* 1997). Thus, rainfall forecasts are still limited by the resolution of the simulated atmospheric dynamics and the sensitivity of sub-grid scale parameterisations of the rainfall forming processes (Lettenmaier and Wood, 1993; Toth *et al.,* 1997; Pappenberger *et al.,* 2005).

3.1.2 Improving the Quality of Forecasts

As was mentioned above, uncertainty is inherent in the forecasting process. However, minimising these uncertainties to acceptable levels promotes the value of the forecast. A technique termed "ensemble forecasting" has been developed by many weather forecasting centres around the world in order to assess the forecast uncertainty due to errors in the initial conditions of the atmosphere. In order to address the problems related with spatial resolution, several statistical and dynamical models have also been developed. These techniques are described in more detail in the sub-sections which follow.

3.1.2.1 Ensemble forecasting systems

Ensemble forecasting is a technique developed to assess the flow-dependent predictability of the atmosphere by running a NWP model several times, with slightly perturbed initial conditions which lie within the estimated cloud of uncertainty that surrounds the control analysis (Toth *et al.,* 1998). In non-linear dynamical systems this approach offers the best possible forecast with the maximum information content. In a statistical sense, averaging the ensemble members provides a more reliable forecast than simply using any one of the single forecasts, including that started from the control analysis (Toth *et al.,* 1997). Ensemble forecasting has become a common practice to assess the flow-dependent predictability of the atmosphere, and to create quantitative probabilistic forecasts at many NWP centres around the world, e.g. at the National Center for Environmental Prediction (NCEP) in the USA, the European Centre for Medium-Range Weather Forecasts (ECMWF), the Canadian Meteorological Centre (CMC), the Japan Meteorological Agency (JMA) and the SAWS (Toth *et al.,* 1997; Toth *et al.,* 2005). However, questions relating to the generation of adequate sampling of initial perturbations, and to estimating the analysis error in a probabilistic sense, remain major research issues for an ensemble forecasting system (Wei *et al*., 2005).

According to Toth *et al.* (1997) and Wei *et al*. (2005) initial perturbation techniques are broadly classified into either as first or second generation techniques. The first generation initial perturbation techniques are commonly used at different centres for initial perturbations. These methods, reviewed in more detail in Ghile (2007), include

- *Singular vectors*, which identify the direction of fastest forecast error growth for a 2 day period at the beginning of the forecast (Toth *et al.,* 1997; Wei *et al*., 2005);
- *Breeding*, a technique which captures the fastest growing errors that are most likely to be responsible for the error in the control forecast; and
- *Perturbed Observations*:, which generate initial conditions by assimilating randomly perturbed observations using different models in a number of separate analysis cycles (Wei *et al*., 2005),

while second generation initial perturbations include the *Ensemble Transform Kalman Filter*, *Ensemble Transform* (ET), *ET with breeding* and *singular vectors with Hessian norm* (Wei *et al*., 2005), with a common feature being that the initial perturbations are more consistent with the data assimilation systems when compared with the first generation initial perturbation techniques.

3.1.2.2 Techniques for spatial downscaling

Knowledge of precipitation fields at fine resolution is a vital ingredient for climate forecasting. In the absence of full deterministic modelling of small-scale rainfall, it is common practice to use a spatial downscaling procedure (Rebora *et al.,* 2005). Many techniques have been developed for the spatial downscaling of rainfall. According to Schmidli *et al.* (2006) and Wood *et al.* (2004), the spatial downscaling methods that have been most widely used are categorised broadly into either

- statistical (e.g. Canonical Correlation Analysis, CCA; Multiple Linear Regression, MLR; Multivariate Autoregressive Model, MAR; Conditional Weather Generator, CWG; or Climate analogue), or
- dynamical (e.g. CHRM, HadRM3, HIRHAM).

Statistical downscaling methods use the observed relationships between large-scale circulation and the local climates to set up statistical models that attempt to translate anomalies of the large-scale flow into anomalies of some local climate variable (Zorita and von Storch, 1999; Schmidli *et al.,* 2006). Statistical downscaling methods are commonly used because of their relative simplicity and lower costs when compared with dynamical methods (Zorita and von Storch, 1999; Wood *et al.,* 2004). The climate analogue method is considered to be the simplest of the downscaling schemes and it compares the large-scale atmospheric circulation simulated by a GCM to historical observations. The most similar analogue is selected and simultaneously observed local weather data are then associated to the simulated large-scale pattern. A major problem associated with the climate analogue method is the need for accurate and long observations (Zorita and von Storch, 1999).

Dynamical models use the so-called Limited Area Models (LAMs) to account the regional and local characteristics such as topography, which influence rainfall patterns. These LAMs are atmospheric or oceanic models of limited geographical area with finer horizontal resolutions than GCMs, but which use the large-scale fields simulated by the GCMs as boundary conditions and the local variables to provide weather forecasts at a regional scale (Zorita and von Storch, 1999; Wood *et al.,* 2004; Rebora *et al.,* 2005; Schmidli *et al.,* 2006). The LAMs are capable of simulating the regional climate conditions such as orographically induced precipitation. However, some systematic errors still exist in these models due to errors in sub-grid parameterisations, which are taken over from the parent GCMs (Zorita and von Storch, 1999).

Several researchers (e.g. Zorita and von Storch, 1999; Wood *et al.,* 2004; Rebora *et al.,* 2005; Schmidli *et al.,* 2006) have evaluated the differences between various statistical and dynamical downscaling methods, based on their implications for hydrological forecasts. For example, Wood *et al.* (2004) compared three statistical downscaling methods, *viz.* Linear Interpolation (LI), Spatial Disaggregation (SD) and Bias Corrected Spatial Disaggregation (BCSD), by using climate simulations produced by the Parallel Climate Model (PCM). Each method was applied to both PCM output directly and to dynamically downscaled PCM output with a Regional Climate Model (RCM). They concluded that dynamical downscaling does not lead to large improvements in hydrological simulations relative to the direct use of PCM output when BCSD was used. With LI of PCM and RCM outputs, the hydrological simulations were found to be poor, while applying SD improved sub-grid spatial variability and displayed better hydrological simulations (Wood *et al.,* 2004).

It should be noted that a rainfall field generated by any spatial downscaling method is one possible realisation of the small scale field and should not be considered as providing the “true” rainfall distribution (Rebora *et al.,* 2005).

3.1.3 Verification of Forecasts

The quality of agro-climatic forecasts is highly dependent on geographic location, season and lead times. Routine forecast quality control is usually performed by model developers and / or the forecast providers themselves. However, the quality of a forecast does not necessarily address its practical usefulness for a decision maker. The quality of agro-climatic forecasts produced by various models needs to be assessed from users’ perspectives before the products would have any relevance to them. Hence, forecast performance assessments should include measures that express relevant properties of forecasts that help users to judge the usefulness of forecasts for their specific purposes (Hartmann *et al.,* 2002; Mailier *et al.,* 2006). Although research in forecast verification is continually growing, the nature of forecast products, the wide range of customer requirements and the different nature of delivery systems have complicated the development of standard measurements that would be useful to all the people making decisions (Mailier *et al.,* 2006). According to Jolliffe and Stephenson (2003), the three important reasons to verify the quality of forecasts are to:

- improve forecast quality by identifying the problems associated with the forecasts,
- compare the quality of different forecast systems in order to know to what extent one forecast system gives better results than another, and to
- monitor forecast quality in order to find out how accurate the forecasts are when compared to actual observations and to assess the degree of improvement over time.

Mailier *et al.* (2006) propose the following points as being good practice in quality assessments:

- the assessment procedures should be clearly and full described, including descriptions / definitions of all technical terms used,
- forecast formats should be suitable to objective quality assessment, with qualitative terms avoided wherever feasible,
- the assessment methodology should, in principle, be repeatable by a user,
- the assessment methodology should be carefully chosen to produce information that is meaningful to the user,
- uncertainty about the forecasts should be presented in a simple format that the user can easily understand,
- users should be aware of the statistical properties and possible deficiencies of the methods used in the assessment,
- assessments should include the different facets of forecast performance, and
- the choice of the sample used for the assessment should be justified, in order to provide stable and representative estimates.

An assessment of forecast quality depends on the type of forecast, i.e. whether it is deterministic (non-probabilistic), qualitative (e.g. scattered showers) or probabilistic (e.g. categorical, continuous). Qualitative forecasts are difficult to verify as different users will likely interpret them differently. Hence there is always a subjective interpretation, whether or not a forecast is a good one. Qualitative forecasts can only be verified in circumstances where a technical definition underlies a descriptive forecast (Mailier *et al.,* 2006). Most forecast techniques have some strengths, but all have some weaknesses (Jolliffe and Stephenson, 2003). This implies that more than one score (measure) is often needed for better decision making. The evaluation should consider all aspects of correspondence between forecasts and observations. In this regard, Murphy (1993) describes the following relevant terms

- *bias:* the correspondence between the average forecast and the average observation,
- *association:* the strength of the linear relationship between the forecasts and the observations,
- *accuracy:* the degree of correspondence between forecasts and observations,
- *skill:* the accuracy of forecasts compared to other forecasts produced using a standard strategy,
- *consistency*: the degree of correspondence between the forecaster's judgement and the forecast
- *reliability:* the correctness of forecast uncertainty,
- *resolution:* the extent to which outcomes differ from given forecasts,
- *discrimination:* the extent to which forecast depart from given observations,
- *sharpness:* the extent to which forecast depart from climatology, and
- *uncertainty*: variability of observations regardless of the forecast.

These are major attributes that contribute to the evaluation of forecast quality. A short definition of commonly used verification scores that can be used to assess the skill of continuous and categorical forecasts is given in this section.

In regard to continuous verification scores, *bias*, *relative bias*, *correlation coefficient, Root Mean Square Error* (RMSE) and *Mean Absolute Error* (*MAE*) are commonly used and they provide statistics on how much the forecast values differ from the observations. Most continuous verification scores are sensitive to large errors (Lettenmaier and Wood, 1993; Nurmi, 2003).

Bias measures systematic error in the forecast. It measures the degree to which the forecast is consistently above or below the observed value (Lettenmaier and Wood, 1993; Nurmi, 2003). It is expressed as

$$\text{bias} = \frac{1}{N}\sum_{i=1}^{N} O_i - \frac{1}{N}\sum_{i=1}^{N} F_i \qquad 3.1$$

where

F_i	=	forecast value of day i or pixel i,
O_i	=	observed value of day i or pixel i, and
N	=	total number of days or pixels.

The *correlation coefficient* measures the degree of linear association between the forecast and the observed values. However, it is important to bear in mind that the *correlation coefficient* evaluates forecast accuracy in terms of random error only (Lettenmaier and Wood, 1993). Thus, forecast errors could be large, even with a near-perfect correlation, if appreciable bias is present (Lettenmaier and Wood, 1993; Mason, 2000). The *correlation coefficient* is expressed as

$$r = \frac{\sum_{i=1}^{N}(F_i - \bar{F})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^{N}(F_i - \bar{F})^2}\sqrt{\sum_{i=1}^{N}(O_i - \bar{O})^2}} \qquad 3.2$$

where

r	=	correlation coefficient
F_i	=	forecast value of day i or pixel i,
$\bar{F}$	=	average forecast value of all days or pixels,
O_i	=	observed value of day i or pixel i,
$\bar{O}$	=	average observed value of all days or pixels, and
N	=	total number of days or pixels.

The *RMSE* measures the average error magnitude while *MAE* measures the average squared error magnitude and both methods measure systematic and random errors (Lettenmaier and Wood, 1993; Mason, 2000; Nurmi, 2003). They are expressed as

$$RMSE = \frac{1}{N}\sum_{i=1}^{N}(F_i - O_i)^2 \qquad 3.3$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}| F_i - O_i | \qquad 3.4$$

where

F_i	=	forecast value of day i or pixel i,
O_i	=	observed value of day i or pixel i, and
N	=	total number of days or pixels.

The pixel-by-pixel scoring criteria, *viz.* the Critical Success Index (CSI), the Probability of Detection (POD) and the False Alarm Ratio (FAR) are also commonly used to assess the overall degree of positional accuracy over a selected area (Wilks, 1995). These statistics are calculated as follows:

$$CSI = \frac{H}{H + M + FA} \qquad 3.5$$

$$POD = \frac{M}{H + M} \qquad 3.6$$

$$FAR = \frac{FA}{H + FA} \qquad 3.7$$

where

CSI	=	the Critical Success Index,
POD	=	the Probability of Detection, i.e. the Hit Rate,
FAR	=	the False Alarm Ratio,
H	=	number of pixels for which both the estimated and observed values exceed a specified threshold,
M	=	number of pixels for which only the observed values exceed a specified threshold, and
FA	=	number of pixels where only the estimated values exceed a specified threshold.

A variety of categorical verification scores are used operationally to verify agro-climatic forecasts. There are many textbooks, research papers and technical papers providing detailed information of these scores (e.g. Wilks, 1995; Potts *et al.,* 1996; Zhang and Casey, 1999; Joliffe and Stephenson, 2003; Livezey, 2003; Nurmi, 2003; Mailier *et al.,* 2006). What follows below, however, focuses on the discussion of the five more commonly used scoring methods, *viz.* the

- Heidke Score (HS),
- Revised True Skill Statistics (RTSS),
- Linear Errors in Probability Space (LEPS),
- Brier Score (BS), and
- Ranked Probability Skill (RPS).

Categorical forecasts are usually assessed by reducing them to a series of binary (i.e. yes and no) forecasts (Livezey, 2003). Often a 2 x 2 contingency table is constructed to transform categorical probabilistic forecasts into binary events based on decision probability thresholds (**Table 3.1.1**).

Table 3.1.1 Schematic contingency table for categorical forecasts of a binary event, with the number of observations in each category being represented by A, B, C, D and N (Source: Livezey, 2003)

Forecast	Observed		Total
	Yes	No	
Yes	A	B	A+B
No	C	D	C+D
Total	A + C	B + D	A +B +C + D = N

Given a set of forecasts, it is possible to calculate the number of times that the forecast was correct. The HS (**Equation 3.8**) is a simple measure of forecast accuracy for binary (i.e. yes or no) forecasts. It is simply the sum of points scored, divided by the total number of forecasts (Mason, 2000).

$$HS = \frac{A + D}{N} \times 100 \qquad 3.8$$

where

HS	=	the Heidke Score,
A	=	number of hits,
D	=	number of correct rejections, and
N	=	total number of observations.

The problem with the HS is that a high score is achievable both if the forecasted event is rare or extremely common (Mason, 2000). The HS is often compared with some reference forecasts such as climatology, persistence or random chance to form a single index called Heidke Skill Score, HSS (Mason, 2000; Banitz, 2001), which is expressed as

$$HSS = \frac{A - E}{N - E} \times 100 \qquad 3.9$$

where

HSS	=	the Heidke Skill Score,
A	=	number of hits,
E	=	number of forecasts expected to be correct, based on a reference such as climatology, persistence or random chance, and
N	=	total number of observations.

The RTSS is another technique similar to the HSS. However, the RTSS score (**Equation 3.10**) measures the fraction of correct forecasts after eliminating those forecasts which would be correct due purely to random chance. It gives the best estimates on an "unequal" trial basis as it gives equal emphasis to the ability to forecast events and non-events (Zhang and Casey, 1999). The RTSS is given as

$$TSS = \frac{N_{CM} - N_{CCM}}{N - N_{CCO}} \qquad 3.10$$

where A, B, C, D, and N are the components in the **Table 3.1.1** and

RTSS	=	the True Skill Statistics,
N	=	total number of observations,
N_{CM}	=	number of correct forecasts from the forecast model, i.e. (A+D),
N_{CCM}	=	number of correct forecasts that could be achieved by chance, i.e. (A+C)* P_{yes} + (B+D)* P_{no},
N_{CCO}	=	number of observed events that can be correctly forecasted by chance, i.e. (A+B)* P_{yes} + (C+D)* P_{no}.
P_{yes}	=	climatological probabilities, i.e. (A+B) / N, and
P_{no}	=	climatological probabilities, i.e. (C+D) / N,

It is important to bear in mind that the HS and RTSS scores do not penalise the errors in terms of their severity between each categories.

The LEPS scoring matrices are calculated from the distance between the forecasts and observations in continuous cumulative probability space (**Figure 3.1.1**). It rewards good forecasts, and penalises two-category misses much more than one-category misses (Zhang and Casey, 1999; Klopper and Landman, 2003; Livezey, 2003).

LEPS is then computed by the following equation (**Equation 3.11**):

$$LEPS = \frac{1}{N}\sum_{i=1}^{N}| CDF_o(F_i) - CDF_o(O_i)| \quad 3.11$$

where

LEPS	=	the Linear Error in Probability Space,
CDF_o	=	cumulative probability density function of observations, obtained from an appropriate climatology,
F_i	=	forecast value of category i,
O_i	=	observed value of category i.

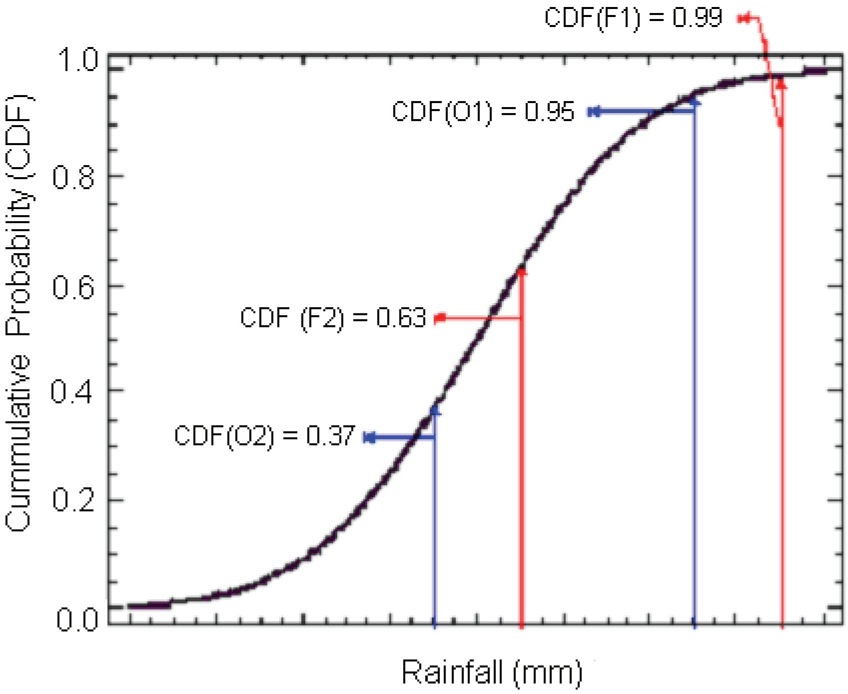


Figure 3.1.1 Schematic diagram for calculating the Linear Errors in Probability Space (Source: http://www.bom.gov.au)

Potts *et al.* (1996) derived an improved version of the LEPS score that does not discourage forecasting extreme values if they are warranted. It is given by:

$$LEPS = 3(1 - | CDF_o(F_i) - CDF_o(O_i)| + CDF_o^2(F_i) - CDF_o(F_i) + CDF_o^2(O_i) - CDF_o(O_i)) - 1 \quad 3.12$$

In the LEPS matrix, a score of +100 % will indicate perfect hits and a 0 score indicates a result as good as the climatology, while a score of -100 % shows no hits. LEPS has been developed for continuous variables as well (Livezey, 2003).

The BS and RPS provide combined measures of reliability and sharpness. The RPS is similar to the BS, but is used for more than two categories (Mason, 2000). The BS and RPS measure the sum of squared differences in cumulative probability space for two categories and multi-category probabilistic forecasts respectively. They penalise forecasts more severely if the weight of the forecasts are not closer to the actual observed distribution (Zhang and Casey, 1999; Nurmi, 2003). RPS is given by

$$RPS = \frac{1}{M-1}\sum_{m=1}^{M}[(\sum_{i=1}^{m}F_i) - (\sum_{i=1}^{m}O_i)]^2 \quad 3.13$$

where

M	=	number of categories,
F_i	=	the forecasted probability in forecast category i, and
O_i	=	an indicator (0 = no, 1 = yes) for observation in category i.

The BS and RPS can also be expressed as skill scores indicating the fractional improvement relative to a reference forecast (Mason, 2000). Hence,

$$RPSS = \frac{RPS_{forecast} - RPS_{reference}}{0 - RPS_{reference}} = 1 - \frac{RPS_{forecast}}{RPS_{reference}} \qquad 3.14$$

where

RPSS	=	the Ranked Probability Score Skill (fraction),
$RPS_{forecast}$	=	the probabilistic forecasted RPS (fraction), and
$RPS_{reference}$	=	the RPS expected from the reference forecast (fraction).

The RPSS ranges from -∞ to 1, with a score less than or equal to 0 indicating no skill when compared to the reference forecast, and a score of 1 indicating a perfect forecast. The RPSS is, however, highly unstable when applied to small data sets (Mason, 2000).

The above categorical verification techniques measure the skill, sharpness and reliability of forecasts relative to the quality of some other forecasts produced by standard procedures. Reliability addresses the questions as to whether repeated application of forecast procedures will produce similar results. It measures the forecaster's level of confidence to produce reliable forecasts (Scott and Collopy, 1992; Mason, 2000; Schneider and Garbrecht, 2003). According to Mason (2000), perfect reliability occurs if:

- forecasts are statistically consistent with the observations, but it does not necessarily mean that the forecasts are accurate, and
- the forecaster's confidence is appropriate.

Climatology, random, persistence and median values are simple forecast strategies used for a reference strategy (Mason, 2000; Hallowes, 2002). The forecast skill is usually defined as the percentage improvement in accuracy over the reference forecast (Zhang and Casey, 1999; Mason, 2000). Care should be taken to select appropriate reference forecasts so that the computed skill reflects the true usefulness of the forecast (Mailier *et al.,* 2006).

Not all categorical verification techniques account for possible near-misses across category boundaries, and they do not account for the accuracy of the forecasts within a category (Mason, 2000). In addition, part of the information from categorical forecasts will be lost during the transformation to binary forms (Zhang and Casey, 1999).

3.1.4 Procedures for Updating Forecasts

Most agrohydrological models use mathematical equations to describe the various components of spatially and temporally varying agrohydrological processes. In most conceptual and parameter optimising agrohydrological models, the forecast errors may result from inadequacies in the model structure, incorrect conceptualisation of the model parameter and errors in the data, as well as errors induced by the lack of knowledge of the future rainfall (Toth *et al.,* 1999; Xiong *et al.,* 2004). When any agrohydrological model is intended for use in a real time forecasting system, it will be associated with explicit or implicit updating procedures whereby, at the time of making the forecast, errors already observed in recent forecasts will be used to modify the forecast (Xiong *et al.,* 2004).

Univariate linear statistical models such as the *AutoRegressive* (AR), the *AutoRegressive Integrated Moving Average* (ARIMA), the *Linear Transfer Function* (LTF) or, alternatively, *Artificial Neural Networks* (ANN), which is a non-linear statistical model, are commonly used in the updating mode to post-process the forecasts made by the conceptual or physically based hydrological model. Descriptions of these models are widely available in research papers (e.g. Toth *et al.,* 1999; Madsen and Jacobsen, 2001; Xiong *et al.,* 2004; Goswami *et al.,* 2005). These statistical models are not alternatives to deterministic or conceptual models, rather they are used to predict simulation errors induced by unsatisfactory model paramaterisation, or errors cascaded from rainfall forecasts. Various types of updating schemes may be implemented that may compensate for the deficiencies of the hydrological models. According to Anctil *et al.* (2003) and Goswami *et al.* (2005), four types of updating procedures exist. They are described below.

Updating of Input Variables: Additional input information from the most recently measured variables can be used in the updating procedure. Thus, the forecasting system can be corrected as and when daily observed rainfall, temperature and runoff data become available, in order to account for any spatio-temporal errors that may have occurred in previous forecasts.

Updating of State Variables: Day-to-day catchment state variables deviate from the so-called average conditions simulated with a conceptual agrohydrological model (Anctil *et al.,* 2003). The state variables need to be calibrated or updated continuously to render the potential of agrohydrological forecasting more useful to decisions in agricultural operations. Schulze *et al.* (1998) identified the following state variables that need day-to-day updates in the *ACRU* model (Schulze, 1995 and updates):

- baseflow store and baseflow releases,
- stormflow store and stormflow releases,
- soil moisture in the topsoil and subsoil,
- dam levels, abstractions, water transfers and return flows, and
- irrigation abstractions and return flows.

Updating of Model Parameters: This is the least favoured updating scheme because it is not sound practice to modify model parameters at each time step. Moreover, this is an iterative process, quite time consuming and computationally demanding, especially when the model includes a large number of parameters (Toth *et al.,* 1999; Anctil *et al.,* 2003; Goswami *et al.*, 2005).

Updating of Output Variables: This updating scheme is commonly used. Toth *et al.* (1999), for example, applied six different stochastic models, aimed at updating the discharge forecasts produced by a conceptual rainfall-runoff model called ADM (Franchini, 1996). They found that all the six updating models were more efficient than the ADM model. Similar results have also been reported by Xiong *et al.* (2004) after three updating schemes using ANN discharge forecasting had been applied on ten catchments in various countries. The statistical models attempt to predict the simulation series error produced by the conceptual or deterministic hydrological models. The updated forecast is then the sum of the simulated plus the predicted error values (Toth *et al.,* 1999; Anctil *et al.,* 2003; Xiong *et al.,* 2004).

The selection of the updating scheme depends on what is considered by the modeller to be the main cause of any discrepancy between observed and forecasted values (Anctil *et al.,* 2003). In this study, updating with daily observed rainfall values was used for simulating one day streamflow forecasts with the *ACRU* model (Schulze, 1995), in order to correct for any errors that may have occurred by the lack of knowledge in the forecast of the previous day.

3.2 COMMUNICATION OF AGRO-CLIMATIC INFORMATION

The communication process is the second component of an effective agro-climatic system and it includes preparation of weather forecasts for public and private interests, as well as educating end users about forecast issues (e.g. contents, formats, limitations and dissemination). Communication using participatory approaches and collaborative learning is an important step in promoting use of agro-climatic forecasts (Podestá *et al.,* 2002). Communication should flow in both directions, i.e. from scientists to practitioners or decision makers and vice versa, in order to create opportunities for mutual learning. Information received at one step may produce a demand for other information. Feedback is important as an indicator of users' reactions that allow scientists to improve forecasts for specific purposes, and stakeholders to learn about capabilities and limitations of agro-climatic forecasts (Hobbs, 1980; Klopper, 1999; Podestá *et al.,* 2002).

The wide range of users and increasing demand for agro-climatic forecasts implies a similarly broad range of requirements and expectations of the forecasts. Requirements may vary in terms of the desired weather format and spatio-temporal scales (Hobbs, 1980).

The nature and speed of forecast dissemination are major issues that may influence the usefulness of forecasts. Advances in technology have facilitated the transmission of forecasts in a real time mode. Newspapers, radio, television, cellphone and the internet are important devices for the forecast dissemination to users. However, misinterpretation of the forecast by users and the media is a major problem (Hobbs, 1980). A survey conducted by Klopper (1999) indicates that some users do not fully understand the definition of the agro-climatic forecast terms. Moreover, some believed the newspapers to be more desirable while others preferred to listen to radio or television broadcasts. The media may also be more interested in the style and attractiveness of the forecasts than the accuracy. These types of confusion indicate that the news media and end users should be educated on how the forecasts should be interpreted. Technical advices on how to respond to agro-climatic forecasts should ideally come from trusted sources such as agricultural extension agents or technical consultants, and not directly from forecast provider institutions. The reason for this is that end users (e.g. farmers) may evaluate the credibility of forecasts based on its source. Usually they act positively when the information comes from sources that they already know and trust (Hobbs, 1980; Hansen, 2002).

The communication process is a challenging issue and is often impeded by financial, technical and cultural barriers (Glantz, 1996; Podestá *et al.,* 2002). Many societies have had long traditions of using a variety of different indicators to predict the weather conditions. However, more efforts must be made to ensure closer articulation with end users. Such interaction will provide better insights of their needs and expectations. It would also promote trust building communication between forecasters and end users (Podestá *et al.,* 2002).

3.3 APPLICATION OF AGRO-CLIMATIC INFORMATION

Agro-climatic forecasts must ideally contribute to a change in decisions, which leads to desirable outcomes, regardless of how accurate and well communicated the forecast is (Hammer *et al.,* 2001; Hansen, 2002; Podestá *et al.,* 2002; Ritchie *et al.,* 2004). If a forecast system is validated, but fails to generate changed decisions, the information will have only academic value. However, if the forecast system has a positive value of information, but has not been statistically validated, then the system is not useful, as the value may be the result of chance (Ritchie *et al.,* 2004).

Decision makers should be able to examine the value of forecasts for a specific purpose, and evaluate its economic return in terms of cost-loss ratio analysis. In fact, it is not easy for a decision maker to make a rational decision that minimises the expected losses and maximises the expected benefits under uncertain forecasts. According to Podestá *et al.* (2002), changes in decision making processes depend on the following conditions:

- the quality of agro-climatic forecasts, with appropriate lead time and geographic and temporal resolution,
- the feasibility of alternative actions that can be taken in response to a agro-climatic forecast,
- the ability of decision makers to evaluate the outcomes of those alternative actions, and
- the willingness of decision makers to change their decisions in an already complicated decision-making environment.

A decision support system is another key element that can facilitate the use of agro-climatic forecasts. Decision support tools allow the exploration of multi-dimensional decision space that would help decision makers to evaluate the consequences of alternative management in respond to forecasts (Podestá *et al.,* 2002). Recognising the importance of the three components, Hansen (2002) proposed a framework that represents the opportunity to benefit from agro-climatic forecasts. The opportunity to benefit falls within the intersection of human vulnerability, agro-climatic forecasting and decision capacity, as shown in **Figure 3.4.1**.

3.4 CONCLUDING REMARKS

This chapter commenced by outlining the approaches required to maximise benefits from the use of agro-climatic forecasts. It was found that the benefits which might accrue do not only depend on the scientific advances of agro-climatic forecasts, but also on an effective way of dissemination as well as on appropriate education of forecast presenters and decision makers. Apart from forecast quality considerations, the format and speed of dissemination of forecasts, as well as the willingness and ability of decision makers to make a change, are critical elements in the usefulness of forecasts. Nonetheless, the production of skilful and timely forecasts continues to be one of the major issues challenging to meteorologists. Owing to the inherent uncertainties in the weather and model

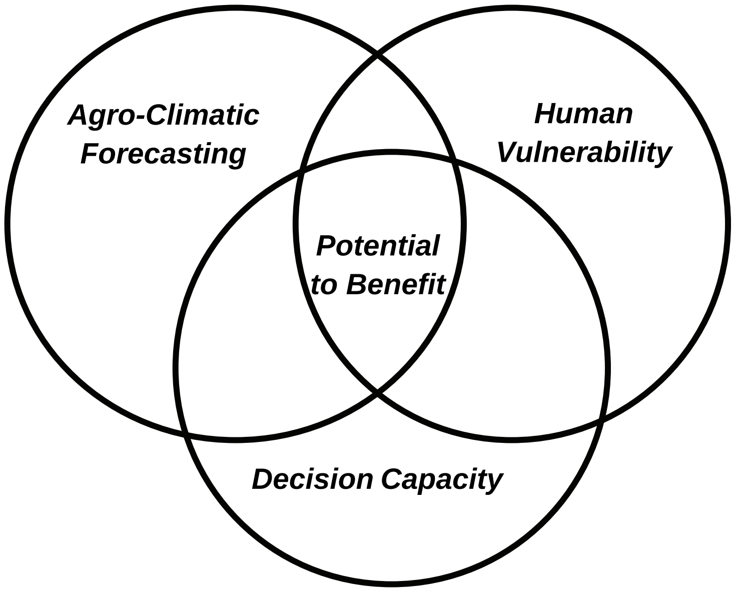


Figure 3.4.1 Determinants of the potential for human populations to benefit from agro-climatic forecasts (after Hansen, 2002)

limitations to account for the local rain-bearing features, weather and climate forecasts are not as accurate as desired. The accuracy of such forecasts will further be degraded during the rainfall-soil-plant transformation by agricultural models. The reason for this is that the complex and non-linear processes are not explicitly represented by most agrohydrological models.

A brief review was presented of some of the elements that contribute towards forecast uncertainties and techniques developed to minimise forecast errors, followed by the description of some commonly used verification techniques for assessing forecast quality. The chapter further described the potential application of forecast updating by the combined use of conceptual physically based models in simulation mode plus stochastic models in the updating mode, in order to eliminate, or minimise, errors resulting from inadequacies in the hydrological model or the incorrect estimation of rainfall forecast by weather prediction models. Finally, the challenges and approaches in communication process and use of agro-climatic forecasts to modify decisions were described briefly.

CHAPTER 4

DEVELOPMENT, DOWNSCALING AND VERIFICATION OF WEATHER AND CLIMATE FORECASTS

RE Schulze, MA Tadross, AS Steyn, FA Engelbrecht, CJ Engelbrecht, WA Landman, S Landman, N Brown, B Gobaniyi, D Stone, E Marx and GGS Pegram

Summary

4.1 THERE IS NO LACK OF CLIMATE FORECASTS FOR SOUTH AFRICA: AN AUDIT OF WHAT IS AVAILABLE
4.2 DOWNSCALING TECHNIQUES: BACKGROUND
4.3 SHORT RANGE WEATHER AND SEASONAL FORECASTS FROM THE CSIR AND THE UNIVERITY OF PRETORIA
4.4 SEASONAL CLIMATE FORECASTS FROM THE CSAG
4.5 MEDIUM RANGE TEMPERATURE FORECASTS FROM THE SAWS AND UKZN

* * * * *

4.1 THERE IS NO LACK OF CLIMATE FORECASTS FOR SOUTH AFRICA: AN AUDIT OF WHAT IS AVAILABLE (RE Schulze)

At any point in time in recent years there has not been a lack of weather and seasonal forecasts for the entire South Africa, and the larger southern African region. The listing below is from an audit by members of this project for 2011:

- Council for Scientific and Industrial Research (all forecasts generated using the C-CAM model)
  - C-CAM 7-day forecast, updated every day at 60 km resolution over Africa
  - C-CAM 7-day forecast, updated every day at 15 km resolution over southern Africa
  - C-CAM seasonal ensemble forecast (3 to 6 months ahead), updated every month at 200 km resolution
- South African Weather Service
  - 14-day medium range (NCEP) forecast, updated every day, using 22 member ensembles at 2.5° resolution and 60 members at 1° resolution,
  - UM 2-day forecast with data assimilation, updated every day at 12 km resolution over southern Africa,
  - UM 2-day forecast without data assimilation, updated every day at 12 km resolution over southern Africa
  - UM 2-day forecast without data assimilation, updated every day at 15 km resolution over southern Africa
  - ECHAM seasonal ensemble forecast (5 months ahead), updated every month at a resolution of 2.8°.
- University of Cape Town
  - HadAM3 seasonal ensemble forecast (3 to 6 months ahead), updated every month at a resolution of 2.5° x 3.75°.
  - HADAM3P seasonal ensemble forecast (3 to 6 months ahead), updated every month at a resolution of 2.5° x 3.75°.

It may be noted that the availability of forecasting products have changed rapidly during the course of the project, and may be expected to continue changing over the coming years. Such changes result from losses from the small pool of experienced climate modellers to either emigration or to a high inter-institutional turnover within South Africa, the coming and going of postgraduate and post-doctoral students at tertiary institutions, and constant advances in supercomputing capabilities in the country (resulting in forecasts of increasing spatial resolution). The consequence to this project was that what was available in the form of forecasts of different lead times at the beginning of the project was not what was available at the end of the project, making the operationalising and tailoring of products to specific sectors a difficult task. This chapter focuses on the forecasting products currently available at the CSIR and CSAG during the final year of the project. However, it also refers to some of the forecasting products available when the project commenced in 2006.

4.2 DOWNSCALING TECHNIQUES: BACKGROUND (MA Tadross, AS Steyn and FA Engelbrecht)

4.2.1 Overview of Downscaling

On modern supercomputers, GCMs may typically be integrated at spatial resolutions ranging from 100 to 200 km in the horizontal, when being used for seasonal forecasting or the projection of future climate change. The majority of the current operational seasonal forecasting systems in South Africa rely on GCM simulations ranging in resolution from about 100 to about 300 km in the horizontal. At these resolutions, GCMs are not capable of describing the topography and land-surface characteristics of the southern African region in detail. Additionally, many small-scale atmospheric phenomena such as thunderstorms cannot be resolved explicitly at the spatial resolutions of GCMs. Such phenomena need to be parameterised (treated statistically) within the GCM simulations.

The spatial resolution of GCMs is too coarse for the simulations to find application in regional studies of the impact of climate variability and climate change on water management and agriculture. Dynamic or statistical downscaling may be used in order to obtain much more detailed simulations over an area of interest, using the GCM simulations as forcing. Dynamic downscaling refers to the process where a numerical regional climate model (either a limited-area model or a variable-resolution global model) is applied over an area of interest at high spatial resolution, whilst being forced with the output of a GCM. At grid resolutions of typically 50 km or finer, regional climate models are capable of resolving the regional topography at much higher resolution than the forcing GCM, and can also much better resolve certain weather systems, such as meso-scale convective complexes and tropical lows and cyclones. However, dynamic downscaling is complicated by similar problems to those of GCM simulations, namely systematic biases and errors due to inadequate parameterisations and scale. The alternative of statistical downscaling involves the process where empirical relationships are established between the synoptic-scale circulation features (that can be resolved by the GCM) and the associated observations of a climate parameter (typically rainfall or temperature) at a much higher resolution. By assuming that these relationships remain stationary in time, the GCM simulations of changes in synoptic-scale circulation patterns can be translated to changes in the associated climate parameters.

4.2.2 Statistical Downscaling and the Methodology Adopted by the UCT and UFS Groups, i.e. SOMS and SDSM

A number of statistical downscaling techniques, that could potentially be applied in combination with dynamical downscaling, were identified in a survey of available methods. These include:

- empirical methods,
- regression methods,
- weather pattern-based approaches, and
- stochastic weather generators.

Some details on these respective methods are outlined below:

Empirical methods

With these methods the local variable in question (e.g. surface air temperature or precipitation) can be predicted from values of the corresponding variable simulated at nearby GCM grid-points, with empirical adjustments to allow for systematic simulation errors and unresolved sub-grid scale effects (Murphy, 1998).

It should be noted that this technique does not comply with the general recommendations as laid out, for example, by the Canadian Institute for Climate Studies, CICS (2006). This does not, however, imply that this technique cannot be used in conjunction with another downscaling method such as high resolution modelling as part of a more sophisticated hybrid approach.

Regression methods

These approaches generally involve establishing linear or non-linear relationships between sub-grid scale parameters and coarser resolution (grid scale) predictor variables (Wilby and Wigley, 1997). In more sophisticated techniques such as 'expanded downscaling' (Burger, 1996), the model mean and short-term variability are estimated by linking the covariance of the global circulation with the covariance between local weather variables in a bi-linear way. Since the internal weights of an artificial neural network (ANN) model imitate non-linear regression coefficients, is seems reasonable to group ANN approaches under regression methods (Hewitson and Crane, 1996).

Figure 4.2.1 illustrates the application of regression methods in statistical downscaling. The core of the process is the 'transfer function' which relates the large scale predictor variables provided by the GCM to the local scale observed predictand variables.

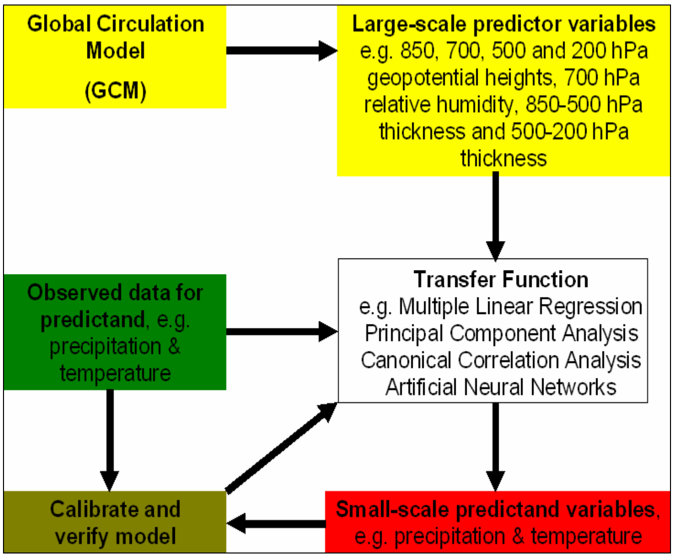


Figure 4.2.1 Steps in statistical downscaling by means of regression methods (Steyn, 2006)

According to Wilby *et al*. (2002), cited in CICS (2006), the identified large scale climate (predictor) variables should be:

- physically and conceptually sensible with respect to the site variable (the dependent variable or predictand),
- strongly and consistently correlated with the predictand,
- readily available from archives of observed data and GCM output, and
- accurately modelled by GCMs.

In most spatial downscaling studies, the predictor data used are first normalised with respect to the period mean and standard deviation, rather than the actual data themselves being used (CICS, 2006). Having derived a regression equation or trained an ANN to relate the observed local and regional climates, the equations may then be 'forced' using regional scale climate data obtained from a GCM operating in either a 'control' or 'perturbed' state (Wilby and Wigley, 1997).

An alternative approach, relating to the empirical method, involves regressing the same parameter from a regional to local scale, or across several scales (e.g. Carbone and Bramante, 1995, cited in Wilby and Wigley, 1997).

Weather pattern-based approaches

These approaches typically involve statistically relating observed station or area-averaged meteorological data to a given weather classification scheme, which may be either objectively or subjectively derived (Wilby and Wigley, 1997). The circulation-to-environment approach, as put forward by Yarnal (1993), finds the investigator assessing specific environmental variables relative to synoptic classes. The investigator designs a fairly general synoptic classification to relate to a region. The classification typically represent the entire period for which data are available and is independent of the environmental response. Synoptic classifications can either employ ‘synoptic types’ which classify similar weather properties (e.g. distinct combinations of weather elements) or ‘map-pattern classifications’ which classify the relationships among objects (e.g. pressure patterns). Yarnal (1993) identified the following synoptic classification methods:

- manual synoptic types,
- correlation-based map patterns,
- Eigenvector-based synoptic types,
- Eigenvector-based map patterns,
- Eigenvector-based regionalisations,
- compositing,
- circulation indices, and
- specification.

Having selected a classification scheme it is then necessary to condition the local surface variables, such as precipitation, on the corresponding (daily) weather patterns (Wilby and Wigley, 1997). This is accomplished by deriving conditional probability distributions for observed data. The precipitation series may be further disaggregated by month or season, or by the dominant precipitation mechanism (Wilby *et al*., 1995, cited in Wilby and Wigley, 1997). The ‘forcing’ weather pattern series are typically generated using Monte Carlo techniques or from the pressure fields of GCMs (Wilby and Wigley, 1997).

The methodology utilised for this project by the UFS group is outlined below:

The methodology used by the UFS group followed the procedure outlined by Lines and Barrow (2002), Wilby *et al*. (2002) and Lines *et al*. (2005). The study made use of the Statistical Downscaling Model (SDSM) developed by Wilby *et al*. (2002), who also used SDSM to develop single-site ensemble scenarios of daily rainfall under current and future regional climate forcing for Toronto, Canada. Lines *et al*. (2005) used SDSM to downscale the expected climate change impacts with respect to daily mean, maximum and minimum temperature as well as precipitation for 14 sites across Atlantic Canada. In a more recent study Wilby *et al*. (2006) also used SDSM to downscale daily temperature, precipitation and potential evaporation for the River Kennet in the UK.

Within the nomenclature of downscaling techniques SDSM is best described as a hybrid of the stochastic weather generator and regression-based methods (Wilby *et al*., 2002). The SDSM software reduces the task of statistically downscaling daily rainfall into the following discrete steps (Wilby *et al*., 2002):

- quality control and data transformation;
- screening of predictor variables;
- model calibration;
- weather generation (using observed predictors);
- generation of climate change scenarios (using climate model predictors); and
- statistical analysis.

Figure 4.2.2 provides a diagrammatical depiction of the SDSM scenario generation process.

A perfect prognosis (PP) approach was followed, where the forecast or simulated predictor variables are taken at face value – assuming them to be perfect. In model calibration, observed predictors (in the form of NCEP reanalysis data) were used to describe the observed predictand (in the form of daily rainfall data for selected Quaternary Catchments in the Upper Olifants River catchment). In implementation, the GCM simulation of the predictors was substituted into the regression equation to downscale daily rainfall projections under the A2 and B2 emission scenarios at five selected Quaternary Catchments (QCs) within the Upper Olifants River catchment. The downscaling was performed for the summer months of December, January and February (DJF).

The set of generic predictors which was identified across all five QCs included surface airflow strength, vorticity, divergence and specific humidity, 850 hPa wind direction and relative humidity as well as 500 hPa relative humidity and meridional wind velocity. Generally, all the predictors exhibited a reasonably low explanatory power. The considerable variation in the resultant correlations between the large-scale predictors and the observed daily precipitation at the selected QCs may very well have stemmed from the convective nature of the rainfall patterns, being irregularly distributed in space and time. Generally, the downscaling model results were not very encouraging as the model failed to produce satisfactory results for four of the five QCs.

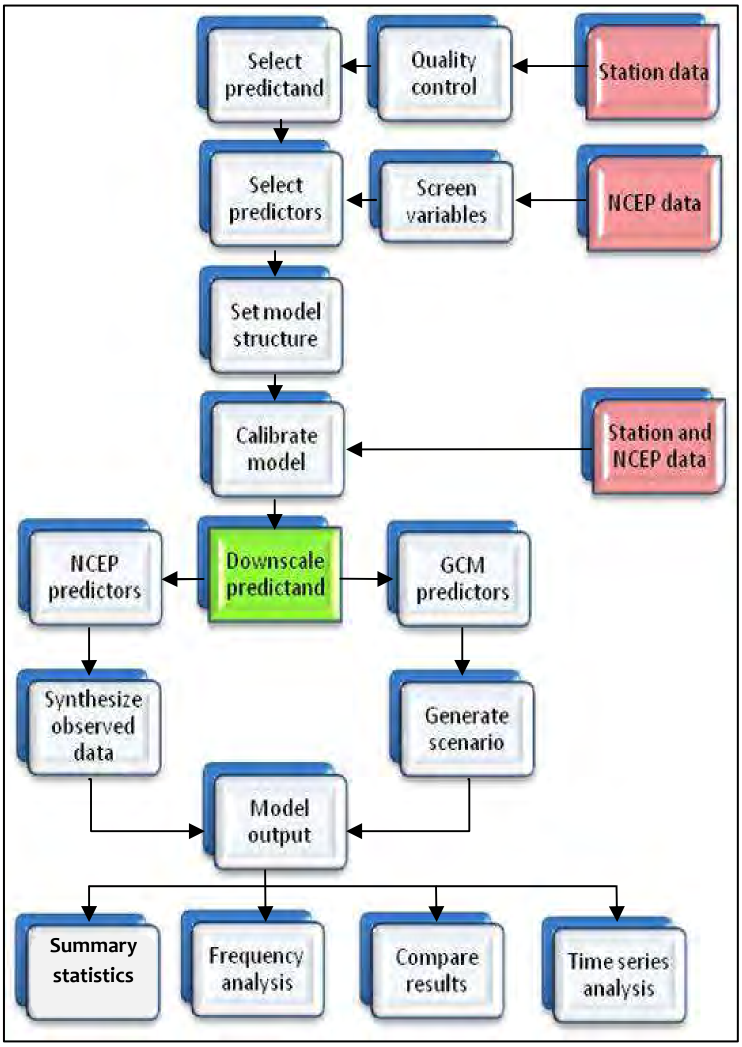


Figure 4.2.2 SDSM climate scenario generation (After Wilby and Dawson, 2007)

The methodology utilised for this project by the CSAG group at UCT is outlined below:

In utilising statistical methods to approximate the regional scale response to the large scale forcing, various methods were developed, including the SOMD (Self Organising Map based Downscaling) developed at the University of Cape Town. Details of the method can be found in Hewitson and Crane (2006). The method recognises that the regional response is both stochastic as well as a function of the large scale synoptics. As such it generates a statistical distribution of observed responses to past large scale observed daily synoptic states. These distributions are then sampled based on the GCM generated daily synoptic states in order to produce a time series of GCM downscaled daily values for the observed variables on which it is trained (typically temperature and rainfall). An advantage of this method is that the relatively poorly resolved grid scale GCM precipitation and surface temperature are not used by the downscaling, but the relatively better simulated large scale circulation (pressure, wind and humidity) fields are used. The procedure is as follows:

- For each day of the observations, classify the daily synoptic state using a SOM of 10 m u and v winds, 700 hPa u and v winds, 500-850 hPa lapse rate, 2 m surface temperature, relative humidity and specific humidity taken from the NCEP reanalysis;
- Create a cumulative distribution function (CDF) of the observed variable for each synoptic type;
- Map the GCM daily synoptic states to the SOM using the same variables as above;
- Randomly sample from the CDF of each synoptic state to which the GCM states map.

This then allows a stochastic sampling of the local observed variable, conditioned on the large-scale synoptic state.

4.3 SHORT RANGE WEATHER AND SEASONAL FORECASTS FROM THE CSIR AND THE UNIVERSITY OF PRETORIA (FA Engelbrecht, WA Landman, S Landman and CJ Engelbrecht)

4.3.1 The C-CAM Forecasting System

The Conformal-Cubic Atmospheric Model (C-CAM) was used to produce routine short-range and seasonal forecasts during the course of the project. Forecasts were originally obtained from the University of Pretoria, whilst a new C-CAM forecasting established at the CSIR supported the project during the 2010-2012 period.

C-CAM is a variable-resolution global atmospheric model. It may be applied either at quasi-uniform resolution, or in stretched-grid mode to provide high resolution over an area of interest. Detail on the geometrical aspects and dynamical features of C-CAM can be found in McGregor and Dix (2001) and McGregor (2005a; 2005b). C-CAM has been used extensively over southern Africa, for the purpose of regional climate modelling and the projection of future climate change (Engelbrecht, 2005; Engelbrecht *et al*., 2009; Engelbrecht *et al*., 2011; Engelbrecht *et al*., 2012) and also for seasonal forecasting (Landman *et al*., 2009; Landman *et al*., 2010) and short-range weather forecasting (Potgieter, 2006; Engelbrecht *et al*., 2011; Landman *et al*., 2012a). The operational C-CAM short-range forecasting system at CSIR applied in this project is described by Landman *et al*. (2010), with the skill of the forecasts described by Engelbrecht *et al*. (2011), Landman (2012) and Landman *et al*. (2012a).

In order to obtain the C-CAM short-range weather forecasts, the model code is integrated on multi-processor computers of the CSIR Natural Resources and the Environment (NRE). Two different forecast products are issued once daily:

- A 7-day forecast over Africa, of horizontal resolution about 60 km. Output fields are available at six-hourly intervals on a 0.5° resolution grid (**Figure 4.3.1**).
- A 7-day forecast over southern Africa, of horizontal resolution about 15 km. Output fields are available at six-hourly intervals on a 0.15° resolution grid.

The 0Z analysis field of the Global Forecasting System (GFS) is used to initialize the short-range forecasts. The 7-day 15 km forecast is forced by the 60 km resolution forecast, using a new spectral nudging technique described by Thatcher and McGregor (2009) and Thatcher and McGregor (2010).

At the beginning of a month, an ensemble of C-CAM seasonal forecasts is also obtained. These forecasts are initialized using a lagged-average forecasting approach, using the GFS analysis fields for model initialisation. For the seasonal forecasts, C-CAM is integrated at a quasi-uniform resolution of about 200 km. These forecasts are forced at their lower boundary by persisted SST anomalies. Output is available at daily time intervals on a 2° resolution grid (**Figure 4.3.2**).

4.3.2 C-CAM Hindcasts at the Short-Range Time-Scale

Using the supercomputers of the Centre for High-Performance Computing (CHPC) in South Africa, the CSIR has completed a full set of C-CAM hindcasts for the period October 2006 to December 2010, at a resolution of 0.5°. The hindcasts mirror exactly the model set-up applied in the operational forecasting system. Since January 2011 the system has run operationally. Hindcasts for the same period, at a resolution of 0.15°, were also constructed, with these higher resolution hindcasts having been completed for the summer half-years of 2006-7, 2007-8 and 2009-10. This very extensive set of hindcasts is highly suitable for the purpose of model verification.

4.3.3 Forecast Verifications

Short-range weather forecasts

One component of the project was to obtain extensive verification results describing the accuracy and skill of the C-CAM short-range forecasting system over South Africa.

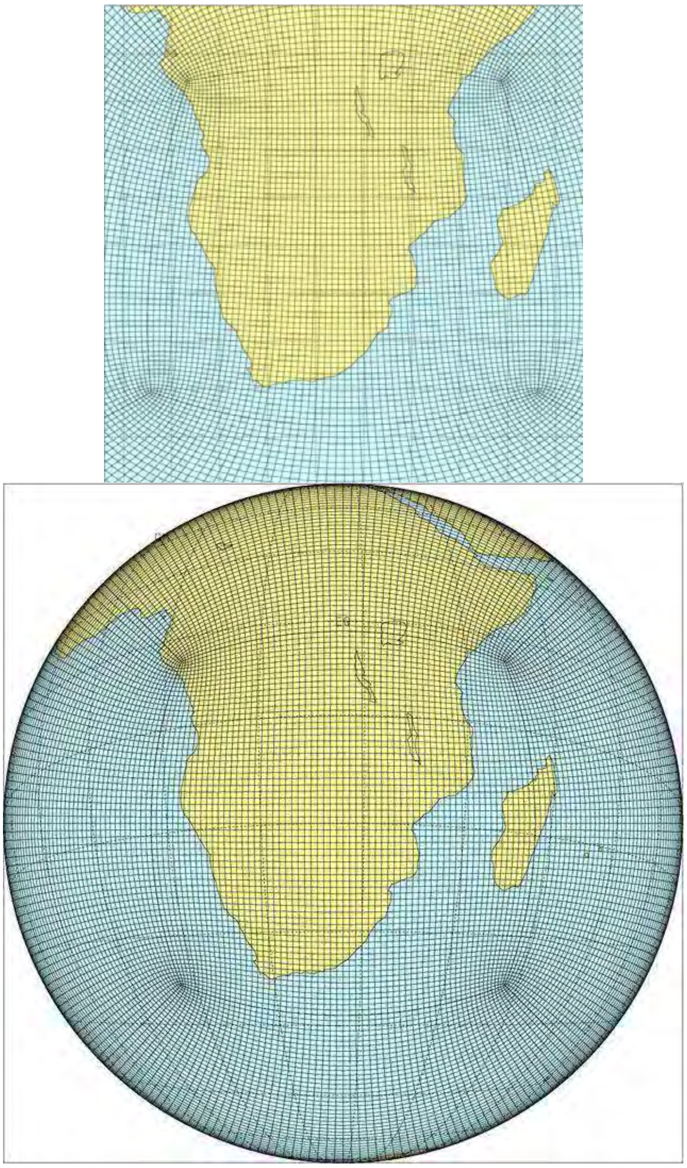


Figure 4.3.1 C-CAM's 0.5° (about 60 km) variable resolution grid over tropical and southern Africa. The model resolution decreases to about 400 km in the far-field

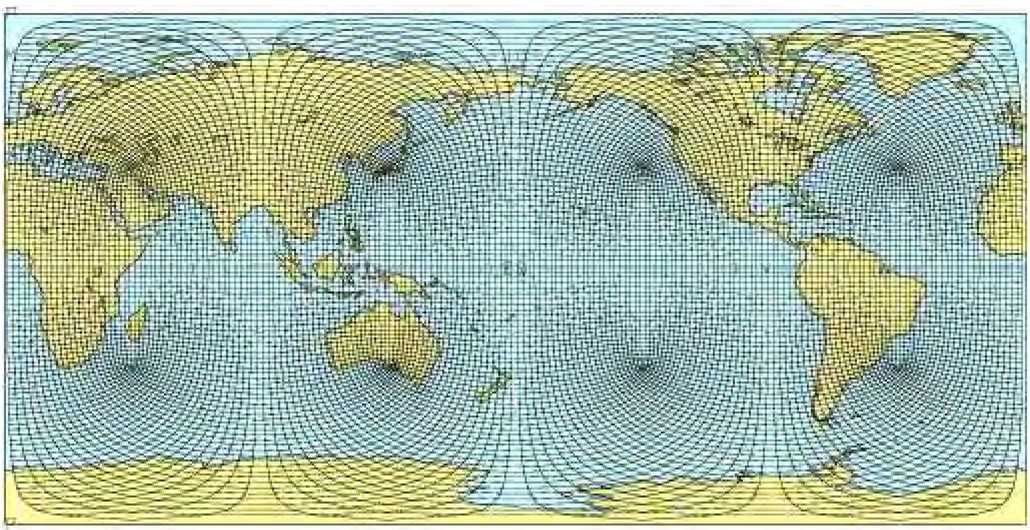


Figure 4.3.2 C-CAM's quasi-uniform grid of about 2° (200 km) resolution in the horizontal

Here we report on the use of the large set of hindcasts performed to verify C-CAM's skill in short-range weather forecasting over southern Africa. In particular, the hindcasts that were performed for the summer seasons (December to February) of 2006 / 7, 2007 / 8 and 2008 / 9 at 0.5° resolution are here verified against observations.

Verification of the C-CAM forecasts is based on daily rainfall data for the periods under consideration, as recorded by weather stations of SAWS and the Agricultural Research Council (ARC). Gridded daily rainfall data were constructed from the weather stations at a resolution of 0.25° (Landman, 2012). The forecasts were interpolated to the same grid in order to facilitate the model verification. The bias of the forecasts in representing daily summer (December to February, DJF) rainfall totals over South Africa (for the first day of model integration) is displayed in **Figure 4.3.3**. The model has a general wet bias in predicting summer rainfall (0.58 mm/d on average and as large as 2 mm/d over parts of the eastern Free State). The Brier skill score (BSS) of the forecasts in predicting 24 h summer rainfall totals (first day of model integration) is displayed in **Figure 4.3.4** for various rainfall thresholds. Persistence was used as the reference forecast in calculation of the BSS. The forecasts are in general not skilful in predicting the occurrence or non-occurrence of rainfall above the threshold of 1 mm – as a result of the model predicting a frequency of such events which is too high (see Landman *et al*., 2012). The forecast of rainfall events above the 10 mm/d threshold is skilful over most of the country, the exceptions being regions along the eastern escarpment and the lowveld of eastern South Africa. The model forecasts of rainfall exceeding the threshold of more than 25 mm of rain occurring over a 0.25° x 0.25° area within a 24-hour period have skill over persistence for most of the country.

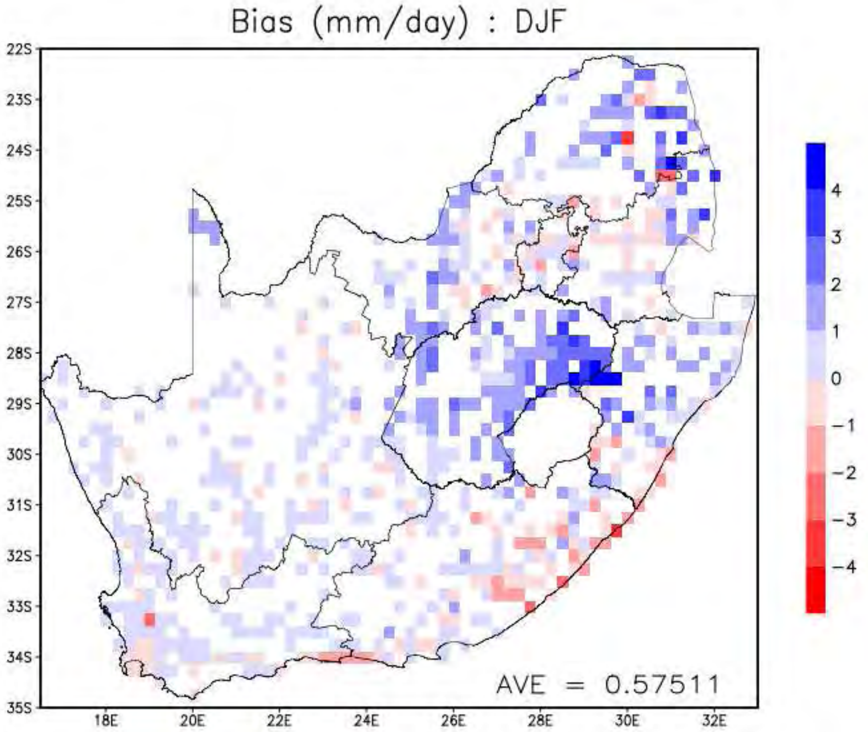


Figure 4.3.3 Bias of the C-CAM 60 km resolution forecasts in predicting daily rainfall totals over southern Africa (for the first day of model integration)

More in-depth descriptions of the forecast accuracy and skill, for both the 60 km and 15 km resolution forecasts, are provided by Landman (2012). In this study, it is shown that the short-range forecasts of C-CAM and the Unified Model (used for operational weather forecasting at SAWS) have similar skill over the southern African region, and that there is potential for the development of a multi-model short-range weather-forecasting system in South Africa.

Seasonal Forecasts

The ability of the C-CAM simulation set to describe the observed seasonal-to-interannual rainfall variability over southern Africa during the peak of the austral summer period, i.e. December to

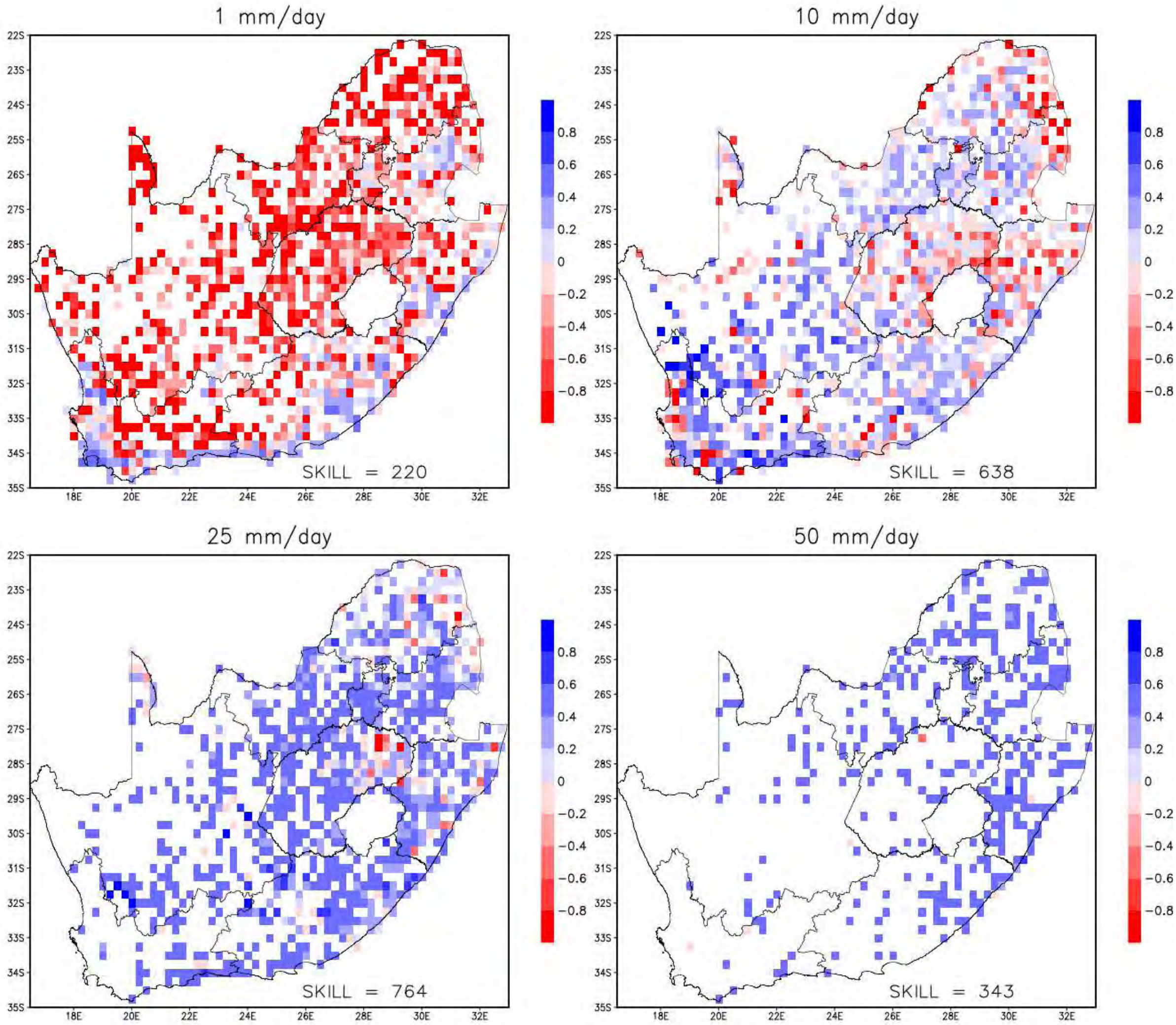


Figure 4.3.4 Brier skill score (BSS) of the C-CAM forecasts of daily rainfall totals (for the first day of model integration), using persistence as the reference forecast

February (DJF) is assessed here. Verification is performed for the 24 DJF seasons, from 1979 / 80 to 2002 / 03. The basis for this verification is a set of Atmospheric Model Intercomparison Project (AMIP) simulations, performed at the University of Pretoria for the period 1979 to 2003. In these simulations, the C-CAM atmosphere responded to forcing of sea-surface temperatures, as recorded over the period under consideration. The model was integrated on the same quasi-uniform grid that is applied for operational seasonal forecasting. AMIP simulations may be regarded as providing an upper boundary of the seasonal forecasting skill of a modeling system.

The approximately 200 km horizontal resolution of C-CAM used here is too coarse to represent local sub-grid features, possibly contributing to the raw model simulations overestimating seasonal rainfall totals. However, it has been demonstrated that such biases over southern Africa can be minimized through statistical post-processing of the model data (e.g. Landman and Goddard, 2002). Model output statistics (MOS) equations are developed here because they can compensate for systematic deficiencies in the AGCM directly in the regression equations (Wilks, 2006). Since it has been found that the 850 hPa geopotential height field is a good predictor in a MOS system, this C-CAM output variable is used to produce rainfall simulations at approximately 50 km horizontal resolution. The MOS equations are developed by using the canonical correlation analysis (CCA) option of the Climate Predictability Tool (CPT) of the IRI (http://iri.columbia.edu). C-CAM's 850 hPa geopotential field used in the MOS is restricted to a domain that covers an area between the equator and 45°S, and 15°W to 60°E. Empirical orthogonal function (EOF) analysis is performed on both the predictor (C-CAM's 850 hPa geopotential height fields) and predictand sets (CRU-TS 3.1 0.5° x 0.5° resolution DJF seasonal rainfall totals – the option of the CPT is used that transforms the rainfall data into an approximate normal distribution) prior to CCA, and the number of EOF and CCA modes to be retained in the CPT's CCA procedure is determined using cross-validation skill sensitivity tests. The EOF analysis is performed on correlation matrices of the predictor and predictand sets.

In order to minimize the chance of obtaining biased results, cross-validation is performed on the ensemble mean, therefore estimating C-CAM's ability to produce interannual deterministic output for mid-summer rainfall over southern Africa. A large 5-year-out window is used, meaning that two years are omitted on either side of the predicted year. The verification measures presented for testing the simulation output of C-CAM are the Kendall rank correlation coefficient commonly referred to as the Kendall's tau, and the mean squared error skill score (MSESS; Wilks, 2006). For the latter verification measure, climatology is used as the reference forecast. Kendall's tau is considered a robust (to deviation from linearity) and resistant (to outlying data) alternative to Pearson or 'ordinary' correlation, and also measures discrimination (are the forecasts discernibly different given different outcomes?).

A spatial description of C-CAM's skill in simulating summer rainfall over southern Africa, over the 24-year test period provided by the AMIP simulations, is provided by Kendall's tau correlations between observed and simulated DJF rainfall (**Figure 4.3.5**). For local significance, Kendall's tau values larger than 0.34 are significant at the 99% level, values larger than 0.25 are significant at 95%, and values larger than 0.19 are significant at the 90% level. The area of largest correlation is found over the northeastern parts of South Africa, including the far northeastern South African area adjacent to Zimbabwe. This latter high-skill area over South Africa has also been identified by other physical models which have been verified in a true operational forecast setting (Landman *et al*., 2012a) as an area of high mid-summer rainfall forecast skill, supporting the results that are being presented here for C-CAM.

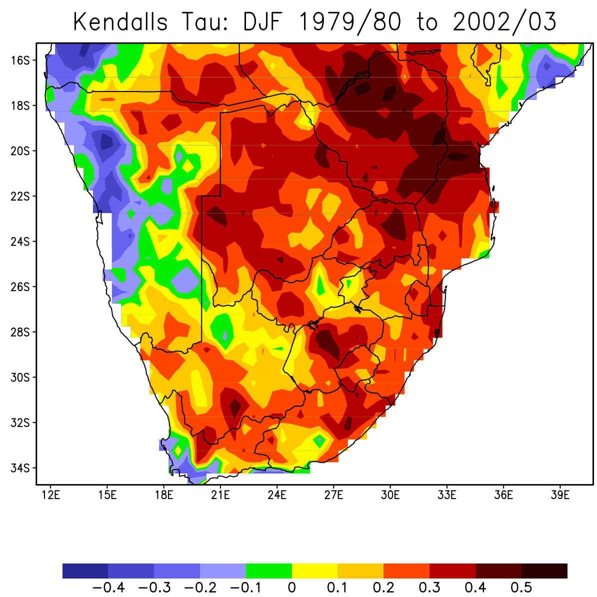


Figure 4.3.5 Kendall's tau correlations calculated between the observed and downscaled C-CAM DJF rainfall simulations over the 27-year test period from 1979 / 80 to 2002 / 03

A temporal description of C-CAM's skill in simulating the interannual variations in mid-summer rainfall over southern Africa is provided next. **Figure 4.3.6** shows simulated vs. observed rainfall indices for a number or regions, which are defined as follows: 'Zimbabwe' covers the region 15.25°S to 22.75°S and 24.75°E to 32.75°E; 'Botswana' covers 16.75°S to 25.75°S and 19.75°E to 28.75°E; 'Eastern South Africa' stretches from 22.75°S to 33.75°S and 24.75°E to 32.75°E; and 'Western South Africa' ranges from 25.75°S to 33.75°S and 19.75°E to 24.75°E. For each of these regions, the simulated and observed rainfall over the specified gridded areas is area-averaged and then normalized in order to produce a set of rainfall indices. All the Kendall's tau values are significant at least at the 95% level of confidence ($\rho < 0.05$), and the MSESS values for all regions, excluding 'Western South Africa' which receives most of its annual rainfall during autumn, indicating that C-CAM outscores the use of the observed climatology as an indication of the rainfall for each year. The best result is obtained for 'Zimbabwe' where the model simulations explain 45% of the rainfall variance ($R^2 = 0.45$).

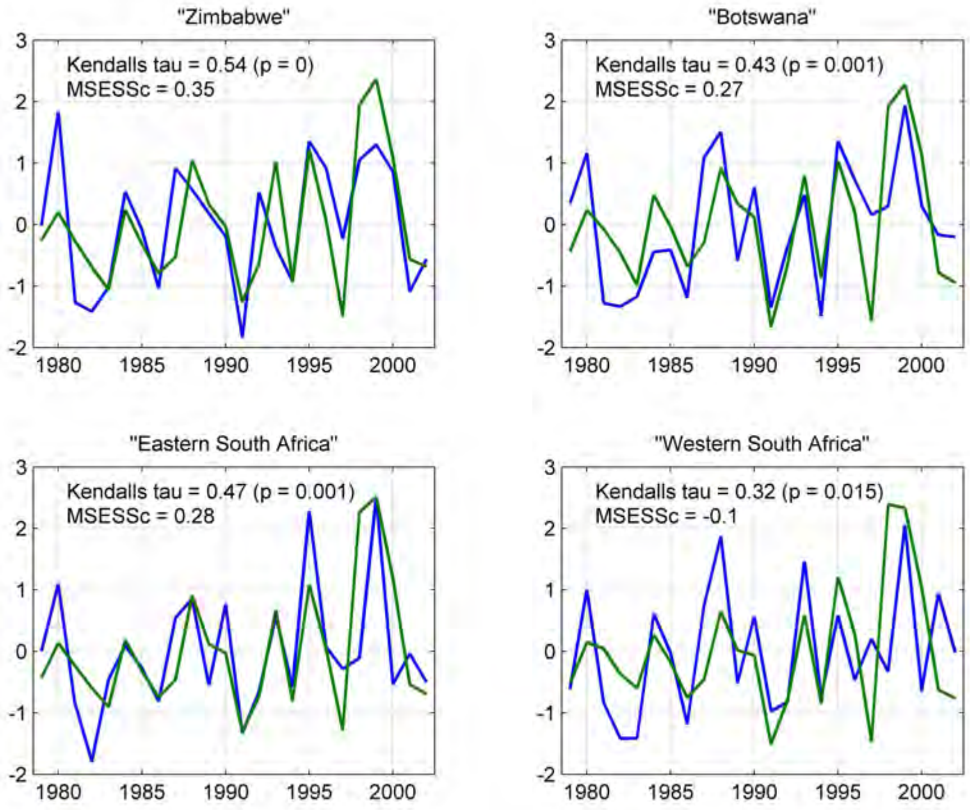


Figure 4.3.6 Area-averaged observed DJF rainfall indices (blue) over four southern African regions as specified in the text, vs. the corresponding downscaled C-CAM hindcast indices (green). The years on the x-axes refer to the December months of the DJF seasons. Kendall's tau correlations and associated ρ-values, and mean squared error skill scores with climatology as a reference forecast (MSESS) are shown

4.3.4 Decoding and Dissemination of C-CAM Data

All the C-CAM forecast products were made available on request to participants in the project. Routines were developed to convert the NetCDF format of the C-CAM data to ASCII format, as required by most end users. A range of C-CAM forecast products may also be viewed on the SA Risk and Vulnerability Atlas website at http://rava.qsens.net/themes/climate_template/ where it can be used operationally by various groups. Alternatively, all the model data (for the various scales and for a wide range of variables) can be retrieved from the ftp site at ftp://ftp.csir.co.za.

4.4 SEASONAL CLIMATE FORECASTS FROM THE CSAG (MA Tadross, N Brown, B Gobaniyi, D Stone)

4.4.1 The GCMs Selected

Seasonal forecasts at UCT were investigated using four GCMs which, along with their configuration characteristics, are:

- CAM3 Community Atmospheric Model (NCAR, USA); currently 2° x 2.5° (in the future 1° x 1°, 26 vertical levels)
- HadAM3 (Met Office, UK); 2.5° x 3.75°, 19 vertical levels;
- HadAM3P (Met Office, UK); 1.25° x 1.875°, 19 vertical levels; and
- CAM-EULAG (Iowa State University, USA); in the future 1° x 1°, 26 vertical levels.

All four models are run globally though CAM3 and CAM-EULAG are currently only run for research purposes, with HadAM3 and HadAM3P used for operational seasonal forecasts. The motivation behind utilising many GCMs for the seasonal forecasts has not been to pick the best GCM, but to know the best way of combining the model outputs for making multi-model ensemble forecasts, as well as looking for ways to improve the performances of the GCMs over Africa

Different SST boundary forcing methods were also investigated for seasonal forecasts, including:

- Statistical SST Forecasts (from the CSIR);
- Using persisted SST Anomalies;
- Slab Ocean Model;
- Coupled-Ocean Model.

It is assumed that using persisted SSTs provides the simplest approach and therefore the lower boundary on predictability. For the purposes of making operational seasonal forecasts the persisted and statistically forecast SSTs are currently used.

All four models have been installed both on the computational cluster at CSAG and at the Centre for High-Performance Computing (CHPC), with the operational models run on the CSAG cluster. Several areas of work using these models were undertaken to improve their implementation and validate their forecasts:

- Monthly production of the seasonal forecast using HadAM3P. The method uses persisted SSTs to run a 10-member ensemble for 6 months into the future, the results of which are fed into the seasonal forecasts produced by the LRF group at SAWS. A 10 member ensemble using observed SSTs (AMIP type run for the 1960-2005 period) was produced on the local cluster. Owing to the increase in resolution (and appropriate change in the timestep) resulting in an 8 fold increase in computation compared to the older version of the model, these runs took approximately 45 days. Hindcast forecasts using persisted SSTs were generated for 4 seasons (SON, DJF, MAM, JJA) for the same 1960-2005 period, but these were lost when a disk system failed at CHPC;
- A 27-year (1980-2006) baseline simulation with CAM3 was completed on the CHPC machines at low (2° x 2.5°) and high (0.9° x 1.25°) horizontal grid resolutions. For each resolution we produced 10 member ensembles;
- Development of skill and validation procedures. Climate forecasts on the UCT system before converting forecasts to a common format which are used by UKZN in their agrohydrological models (e.g. *ACRU*);
- Further development of methods for treating multi-model large ensembles to identify signal versus noise, and to develop probabilistic projections. This is the subject of several student theses;
- Statistical downscaling methods were further refined. Development was focused on maintaining the spatio-temporal coherence of downscaled estimates of precipitation and temperature, which is particularly important for modelling of downstream hydrological impacts, as well as using satellite observations as a basis for downscaling regions wider further afield than South Africa.

4.4.2 Implementing the SOMD Statistical Downscaling Procedure

Scripts were developed to implement the SOMD statistical downscaling procedure (developed at the University of Cape Town) as a post processing procedure of the seasonal forecasts made using HadAM3P. A comparison of the statistical downscaling with another well-established method in global use has been performed over North Africa; an example of the comparison is given in **Figure 4.4.1**.

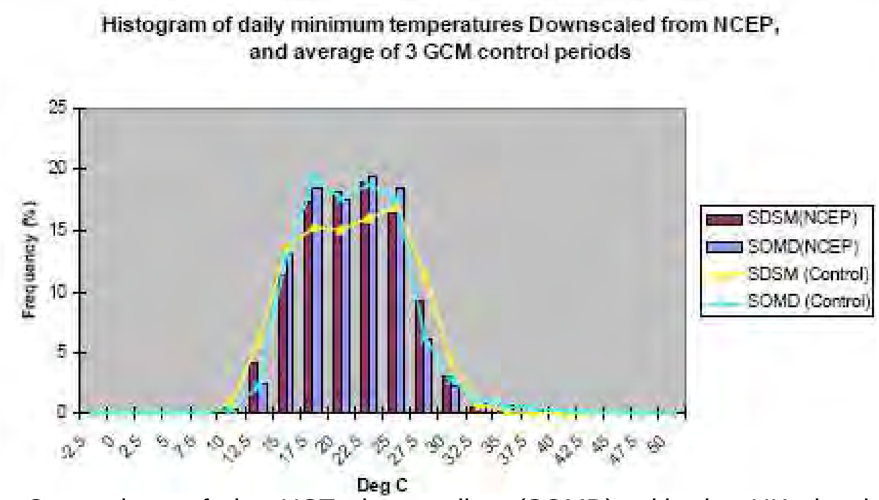


Figure 4.4.1 Comparison of the UCT downscaling (SOMD) with the UK developed (SDSM) downscaling over Rabat, Morocco

4.4.3 Testing the Skill of Downscaled Forecasts

The skill of the new downscaled forecast system was evaluated using data that was extracted before the loss of the disk storage system. ROC, Brier and RPSS skill scores were calculated at SAWS using the downscaled HadAM3P data. These skill scores were evaluated for El-Niño, La Niña and neutral years, to test the different skill levels of the downscaled forecasts depending on the large-scale forcing**. Figure 4.4.2** illustrates examples of the results for the SON season for all years and for the Brier (right), ROC (centre) and RPSS (left) skill scores. This suggests that the downscaled forecasts have skill in some areas (notably the far north east of the country) during this season.

Figure 4.4.3 shows the differences between El Nino, La Niña and neutral years. During El Niño there is skill in the south, northwestern parts and in the northern parts of SA (also during neutral years), with no skill in the Eastern Cape and Gauteng regions. During La Niña years there is also some evidence of skill in the Western Cape.

Tests have proceeded with the implementation of the statistical downscaling – these have revealed that the projected changes in rainfall using climate change models are particularly sensitive to the inclusion of specific humidity as a predictor. This happens because the predictor variables (used to define the synoptic weather types in the SOM procedure) are partially auto-correlated which can place more emphasis on changes in particular variables, more than other variables. Given this sensitivity and that changes in specific humidity are potentially less important for simulating change in the current climate (and that the training data comes from an older version of the reanalysis), the statistical downscaling of the seasonal forecasts do not use specific humidity as a predictor (relative humidity is still used to provide information on moisture content of the atmosphere)

4.4.4 Testing Predictors for the SOMD Statistical Downscaling Procedure

Tests were undertaken with the implementation of the statistical downscaling. These revealed that the projected changes in rainfall using climate change models are particularly sensitive to the inclusion of specific humidity as a predictor. This happens because the predictor variables (used to define the synoptic weather types in the SOM procedure) are partially auto-correlated which can place more emphasis on changes in particular variables, more than other variables. Given this sensitivity and that changes in specific humidity are potentially less important for simulating change in the current climate (and that the training data comes from an older version of the reanalysis), the statistical downscaling of the seasonal forecasts do not use specific humidity as a predictor (relative humidity is still used to provide information on moisture content of the atmosphere).

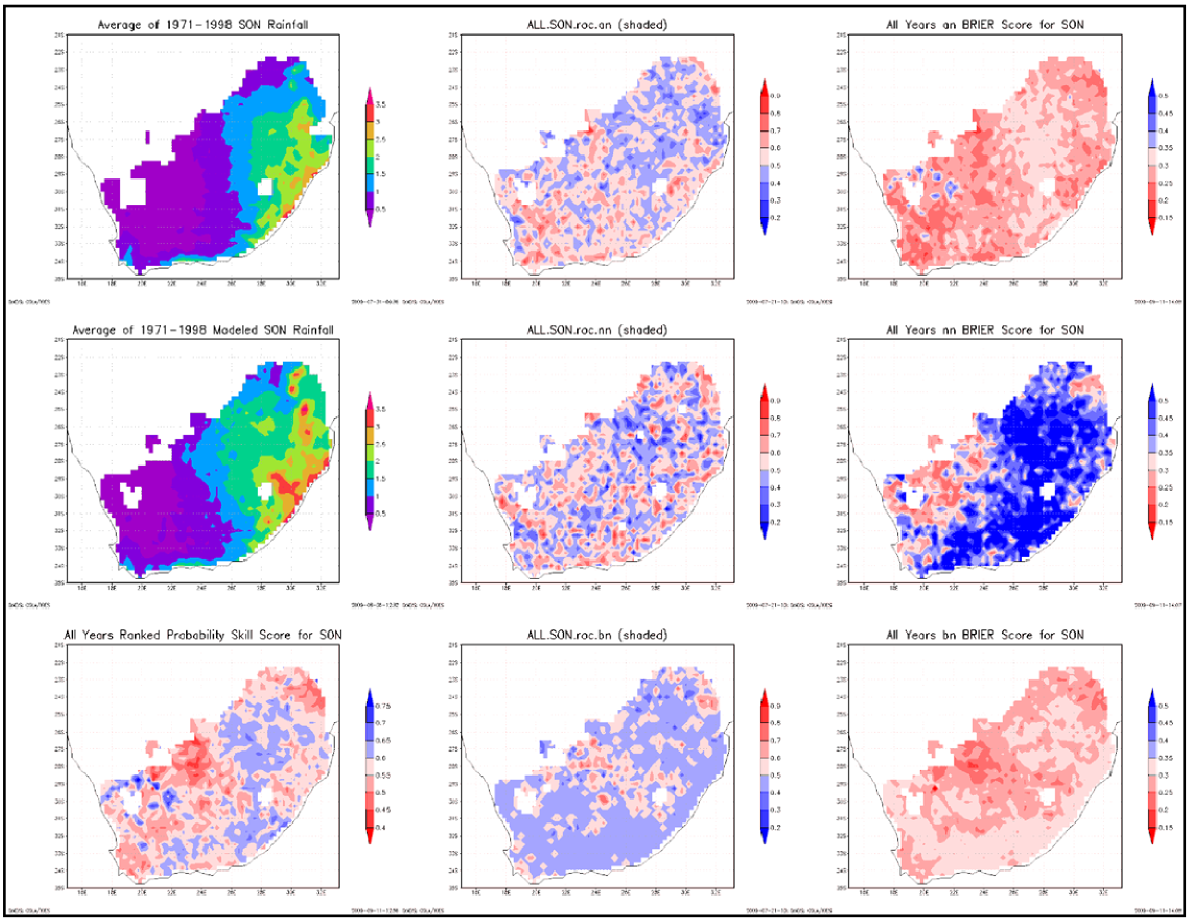


Figure 4.4.2 ROC score, Brier score and RPS assessing the performance of the probabilistic downscaled forecasts averaged for all the years for the SON seasons within the period 1970-2000. Left column top to bottom: Observed SON rainfall, Modelled SON rainfall and RPS score. Middle column top to bottom: ROC scores for above-normal, near-normal and below-normal rainfall. Right column top to bottom: Brier scores for above-normal, near-normal and below-normal rainfall

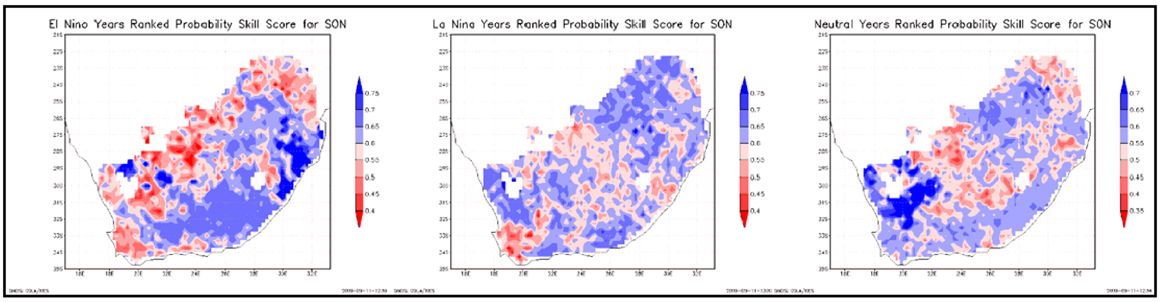


Figure 4.4.3 RPS skill scores for El Niño, La Niña and neutral years respectively for SON season

4.4.5 Using Satellite Observations for the SOMD Downscaling Procedure

Satellite observations were used to downscale rainfall on 0.1 degree grids for the whole of SADC (cf. example in **Figure 4.4.4**), which enables the forecasts to be downscaled and used beyond South Africa's borders. It was necessary to un-bias the satellite observations using station data, which was achieved in collaboration with scientists from the Okavango Research Institute. As these data have been used by FEWS for running WRSI crop models, it can potentially be used to downscale seasonal forecasts for use by humanitarian monitoring groups working within SADC.

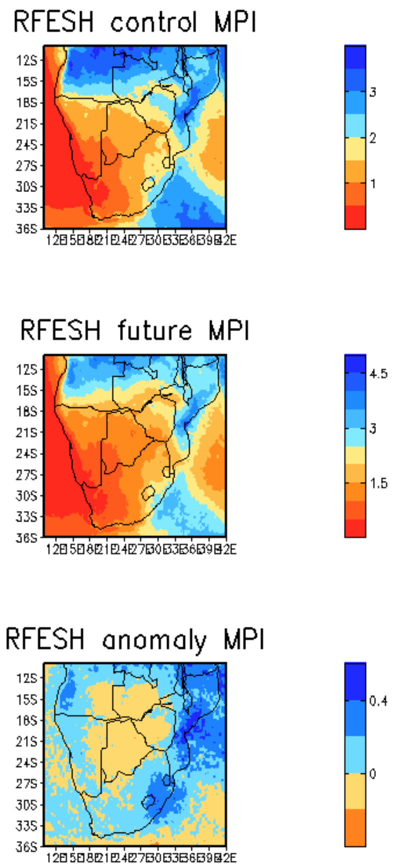
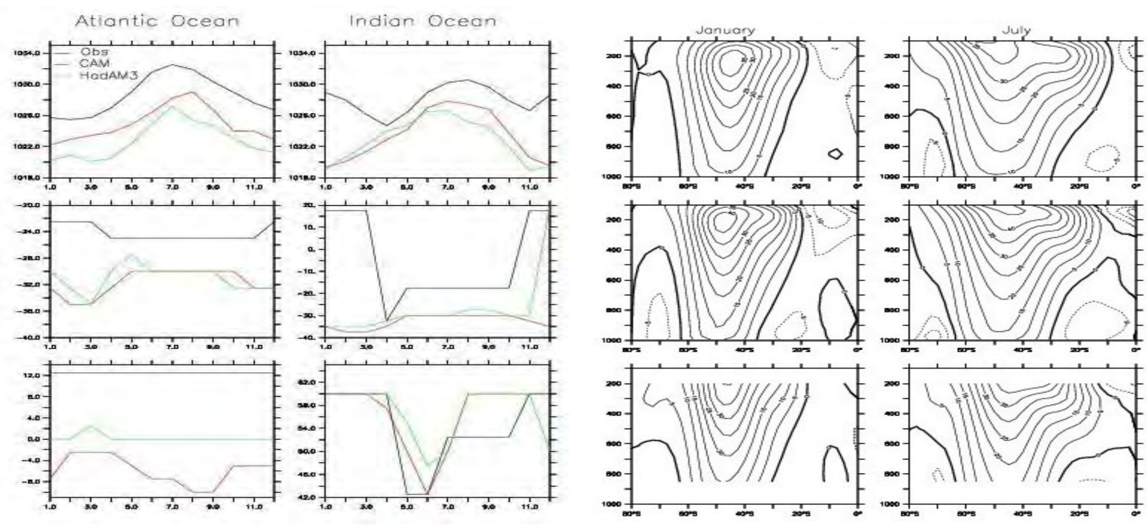


Figure 4.4.4 Statistical downscaling of RFE satellite based observations of rainfall, with the example being for a climate change simulation using the MPI-ECHAM5 model

4.4.6 Evaluation of GCM Simulations Using Observed Sea Surface Temperatures (SSTs)

Analysis of the HadAM3 and CAM3 AMIP runs allows a categorization of how well each model simulates the annual and seasonal cycles as well as inter-annual variability. **Figure 4.4.5** shows how the two models simulate the position of the anticyclones and sub tropical jet in relation to the observations;

Additionally the capability of CAM3 and HadAM3 in simulating the occurrence of cut-off low pressures over Southern Africa was evaluated. **Figure 4.4.6** compares the monthly variation of number of cut-low from the two models with the observed (NCEP reanalysis). A high mean number is observed at the onset and secession of winter season. Both models under estimate the number cut-off lows throughout the period, except in May and in June, where HadAM3 over estimates their frequency. **Figure 4.4.7** shows the observed annual variation of the cut-off lows. Although, both models generally under estimate the number of cut-off lows, HadAM3 simulation gives better estimates.



(a) (b)

Figure 4.4.5 CAM and HadAM3 position of the anticyclones (a) and sub-tropical jet (b)

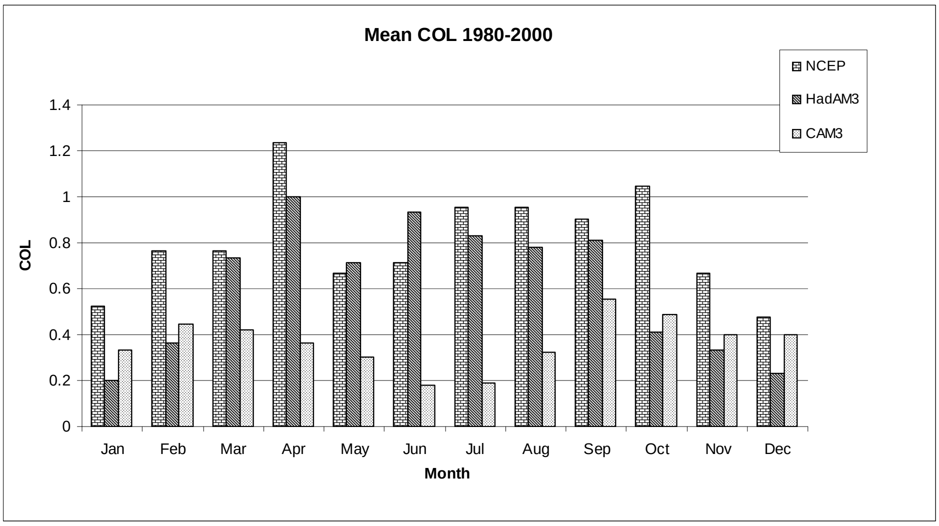


Figure 4.4.6 The mean number of cut-off lows observed (from NCEP) and simulated (from HadAM3 and CAM3) in each month from 1980 to 2000

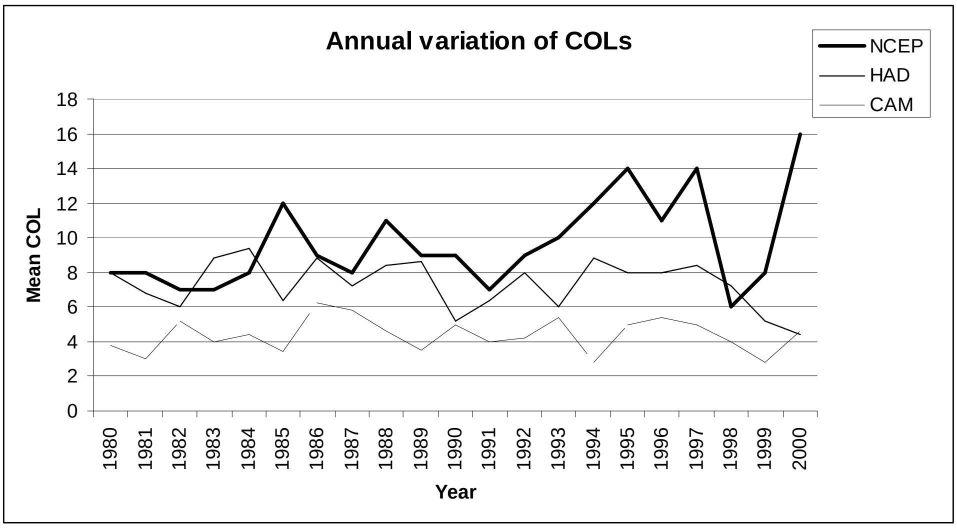


Figure 4.4.7 The observed (from NCEP) annual variation of the mean number of cut-off lows and the mean number of simulated (from HadAM3 and CAM3) cut-off lows

4.4.7 CAM3 Sensitivity to Horizontal Resolution

Initial experiments with CAM3 were undertaken to determine the sensitivity of the model to horizontal resolution and a preliminary analysis (**Figure 4.4.8**) shows that CAM3 is only moderately sensitive to these changes. In terms of surface wind changes appear to be mostly associated with wind speed and less so with wind direction. Even so these changes in convergence can result in slight changes in rainfall (**Figure 4.4.8**).

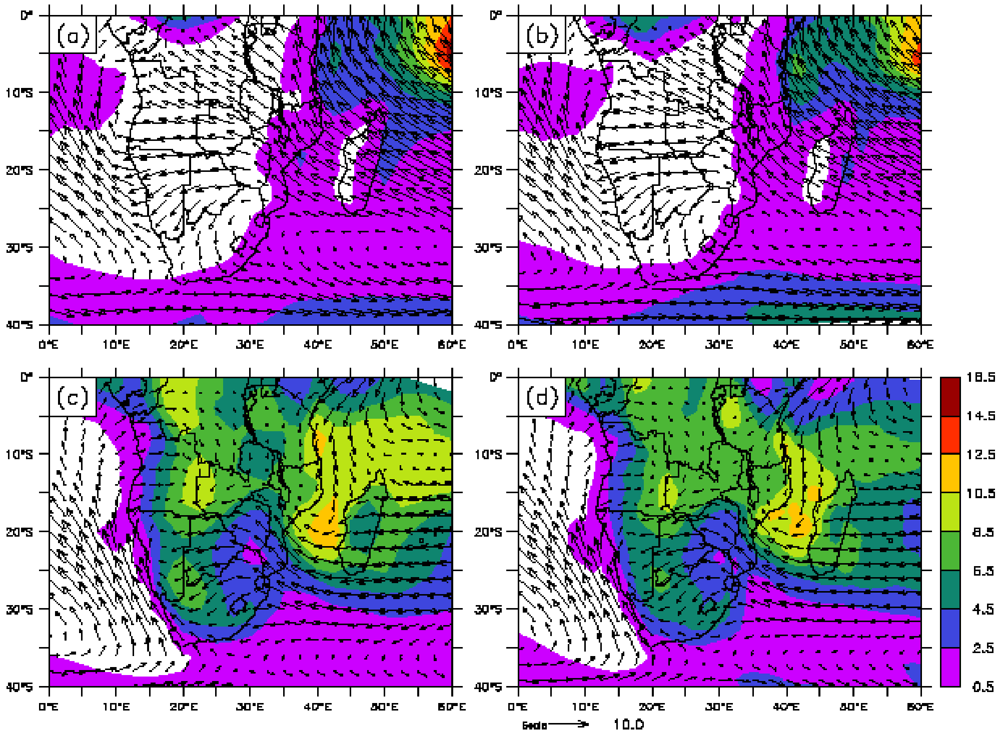


Figure 4.4.8 CAM3 Simulated (1980-1990) mean rainfall (shaded) and surface wind vectors (arrows) over Southern Africa at Low (2 x 2.5, latitude x longitude) and High (1 x 1.25, latitude x longitude) horizontal grid resolutions for June-August (JJA) and December-February (DJF) months. The left and right panels are for Low and High resolutions simulations, respectively, while the upper and lower panels are for JJA and DJF simulations, respectively

4.4.8 CAM3 Forecast Verification

This is part of the preliminary results from a study that investigates and compares the skills of the seasonal forecasts produced from CAM3 over Southern Africa and discusses the forecast skill of the model for seasonal rainfall over Southern Africa. The focus of this study is a statistical analysis of the performance of CAM3 in predicting probabilities of rainfall events during summer and winter over southern Africa

The correlation between the ensemble mean rainfall and CMAP observed rainfall is 0.68 for DJF and 0.52 for JJA for the 26 year (1980-2005 / 2006) period. **Figure 4.4.9** explains the 26 years mean forecasts and their mean errors for the seasonal mean from DJF and JJA. Mean rainfall is relatively high over southern Africa during summer (DJF) and relatively low in winter (JJA). The rainfall generally increases towards the equator in both seasons; low rainfall is observed over south west of the region in DJF. Maximum rainfall is observed in the middle east of the region. CAM3 simulated a very different pattern of the mean rainfall for DJF. However, it simulates the rainfall in the middle east region as observed but fails to simulate the low rainfall over western Cape rains. CAM3 shows errors ranging from 1-5 for DJF at most part of the region. During JJA, the model reproduces rainfall well except that it shows more rainfall at the northwest of the study region and could not capture the western Cape rains during that season. For JJA, the model shows some errors at the northwest of southern Africa.

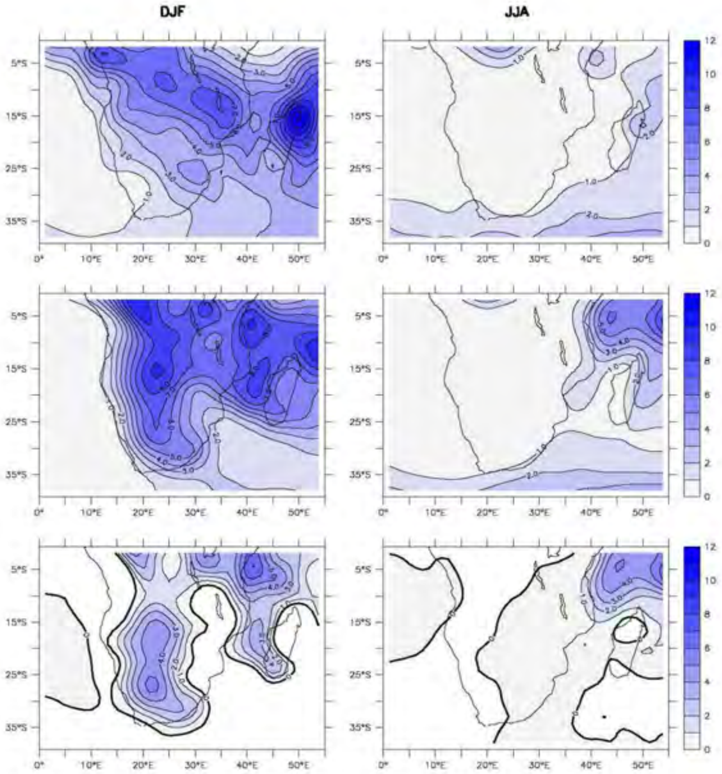


Figure 4.4.9 Mean rainfall over southern Africa from CMAP (top panel), CAM3 (middle panel) and mean error (lower panel) for summer (left panel) and winter (right panel)

In **Figure 4.4.10** areas that are significant are plotted. The DJF forecast is showing some skill at the northeast (over Congo, Angola and Rwanda) and at southwest (over Zambia, Zimbabwe and some part of South Africa). The JJA forecast is skillful in most part of the southern continent

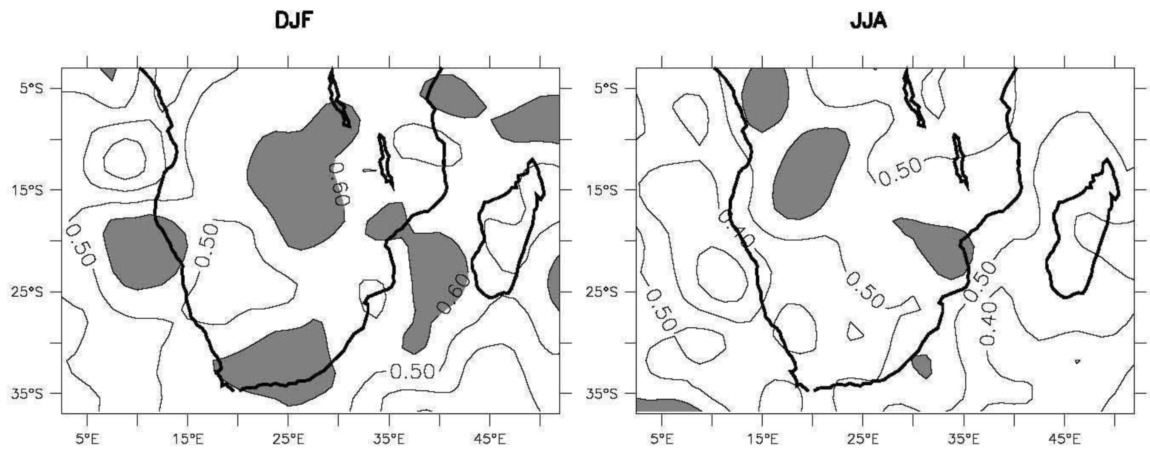


Figure 4.4.10 ROC scores, defined as the area under the ROC curve, for the total rainfall is tested for 26 year forecasts and only significant values are shown

A brier score of 0.2 to 0.3 is shown over most part of Southern Africa in both seasons (**Figure 4.4.11a**). The score is the mean squared error of the probability forecasts for rainfall. The DJF has between 0.3 to 0.4 errors near the equator and also over Cape Town. The forecast shows some skills at the shaded areas (skill is set from 0 to 0.3). These show good skills from the forecast.

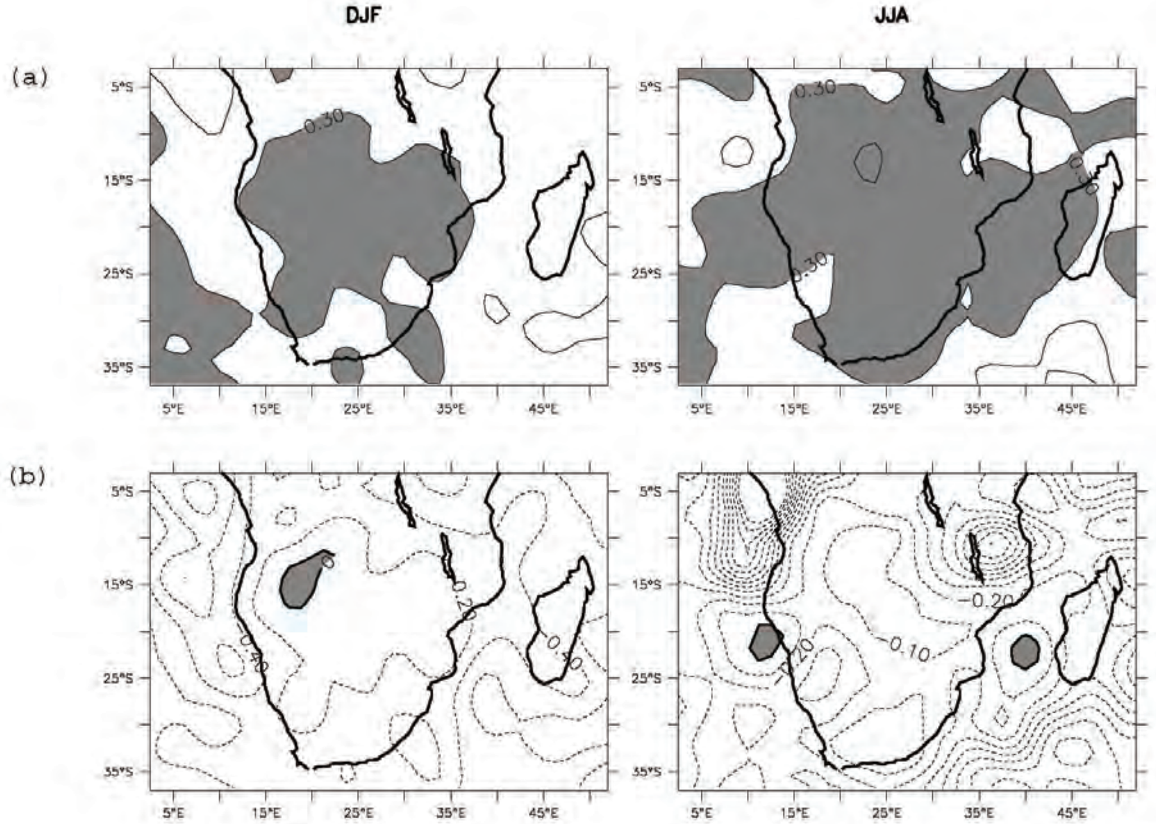


Figure 4.4.11 Brier Score (a) and Brier Skill Score (b) from DJF (left panel) and JJA (right panel) rainfall forecast over southern Africa for the total rainfall is tested for 26 year forecasts

However, taking the climatological forecast into consideration as the reference forecast, the improvement of the probabilistic forecast relative to that is measured in the BSS. The BSS is shown in **Figure 4.4.11b**, where most part of the region show no or negative skill for whether or not it rained with a probability above the mean threshold. It means the forecast has the same skill as climatology. Zero to positive scores (shaded parts) representing some skills is shown only small parts of the region in both seasons.

The model forecast shows a lot of bias estimates from the observed frequencies associated with the different forecast probability values. Various measures used show that the forecast is not able to discriminate in advance between situations under which the events occur with lower or higher climatological frequency values. The forecast has low resolution and only some skills over Southern Africa in both seasons.

4.4.9 Developing a Seasonal Attribution Forecast

"Was this weather event caused by our emissions of greenhouse gases?" As everyone becomes increasingly aware and concerned about climate change this question keeps being asked by taxpayers and those trying to implement strategies to adapt to climate change. Unfortunately, the climate change research community has focused more on the past and future rather than the present, and thus the popular and urgent attribution questions have remained unanswered. Adaptation activities have had to make do with products designed for informing mitigation activities. To cover this need, we have produced the world's first real-time product to examine whether and how human greenhouse gas emissions have contributed to our seasonal weather. This service is produced in parallel with the standard forecast (**Figure 4.4.12**). A second counterfactual forecast is also performed with natural greenhouse gas concentrations and correspondingly reduced ocean temperatures (representing the world without the influence of human emissions of greenhouse gases), and the two forecasts are compared.

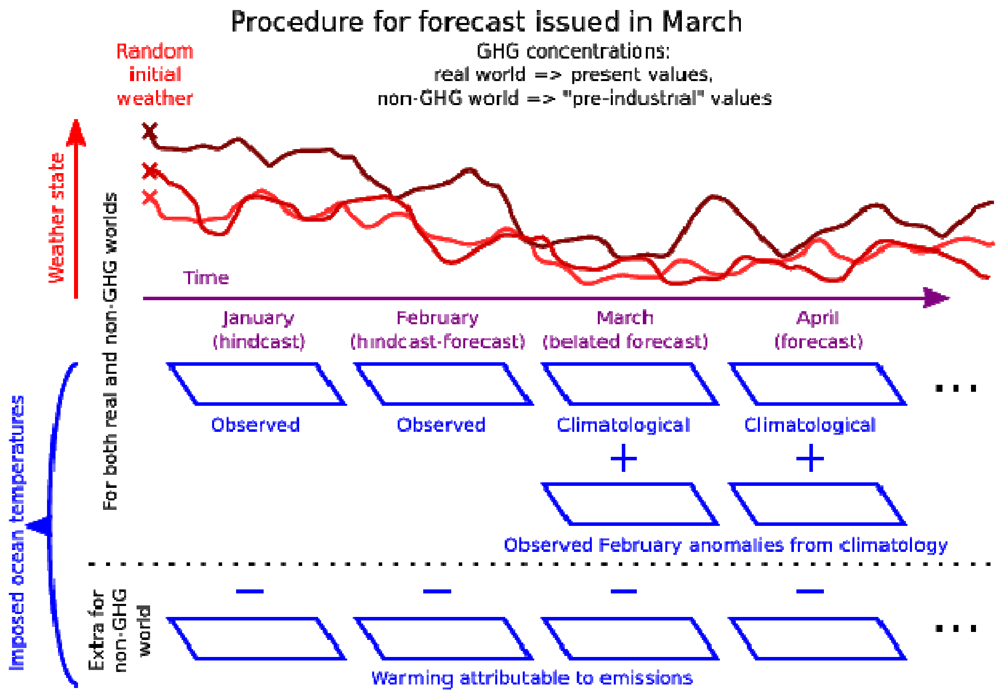


Figure 4.4.12 Schematic of CSAG seasonal attribution forecast

Figure 4.4.13 shows the "best guess" forecasts and hindcasts for November 2009 temperature averaged over the SADC region using two models, with the real forecasts in red and the counterfactual non-greenhouse gas forecasts in blue; values from observational datasets are denoted with the black “x” in the middle. **Figure 4.4.14** shows the forecast and hindcast chance of an unusually hot November 2009 over SADC (with 10% being the climatological expected value). **Figure 4.4.15** shows a map generated by one of the models of the forecast attributable risk of a usually dry November 2009-January 2010 season; anthropogenic emissions have apparently increased the odds of such an event substantially over much of the continent.

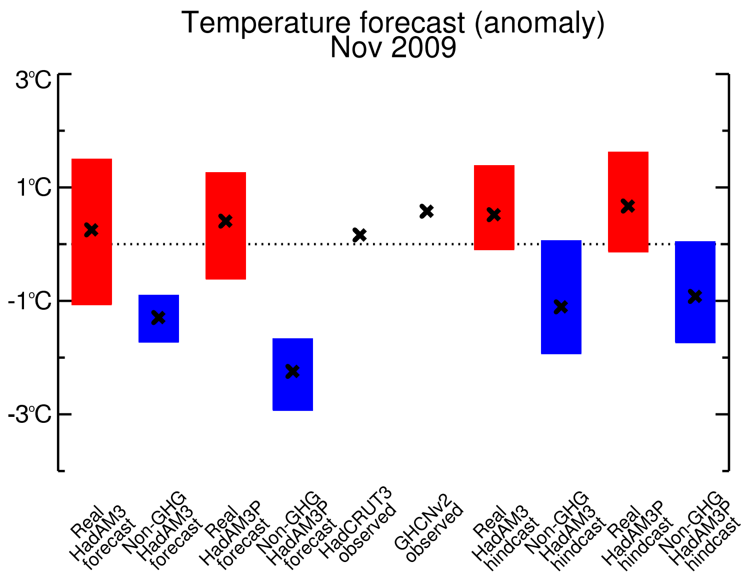


Figure 4.4.13 November 2009 best guess and hindcast forecasts

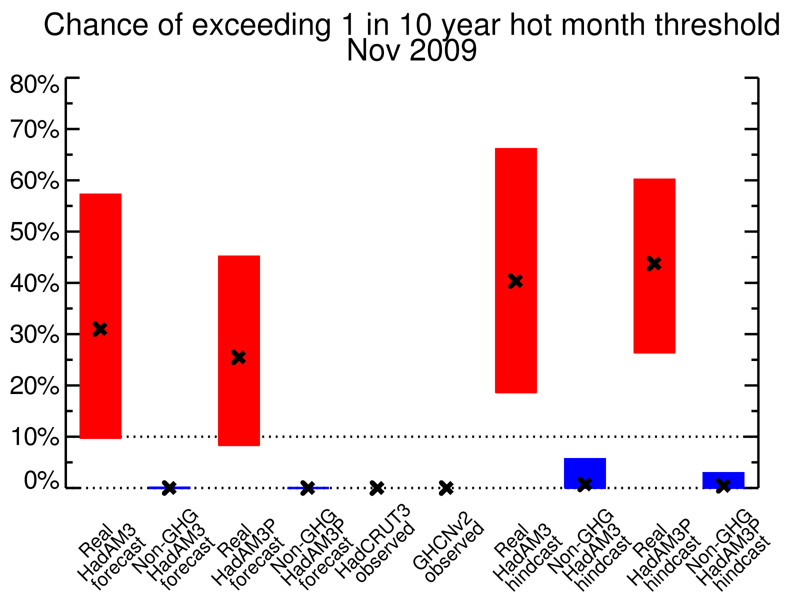


Figure 4.4.14 Chance of exceeding 1 in 10 year hot month threshold

The attribution forecast system has been officially launched (see http://www.gfcsa.net/csag.html or http://www.csag.uct.ac.za/~daithi) and a paper has been submitted to the Journal of Applied Meteorology and Climatology. This is the World's first operational attribution forecast and has been sanctioned by the UK Met. Office and the University of Oxford. An example of the first forecast for November 2010, issued in October 2010 is given in **Figure 4.4.16**.

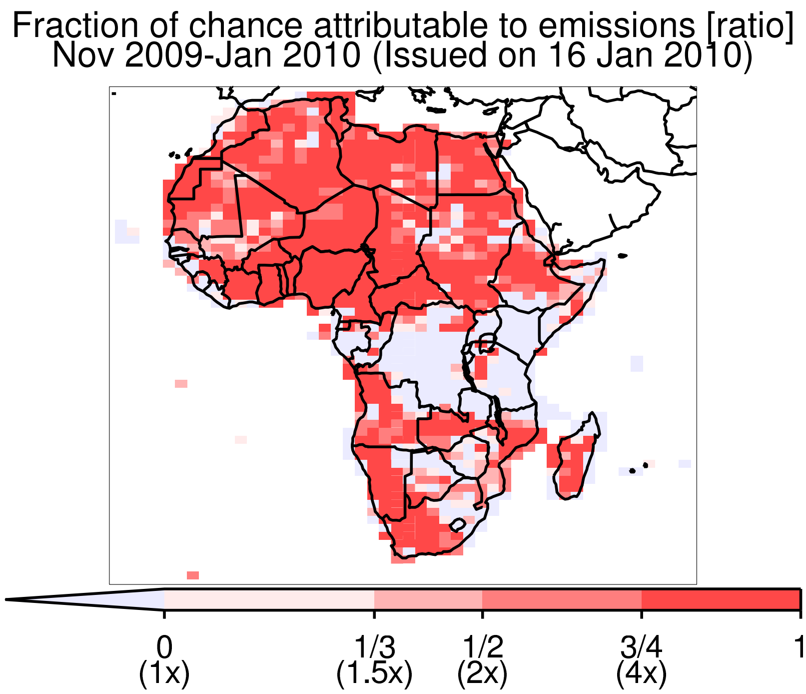


Figure 4.4.15 Fraction of chance attributable to GHG emissions

There are several plans for additional runs using larger ensembles to test the functionality of the attribution forecasts using a range of models and in collaboration with international partners in the UK and USA.

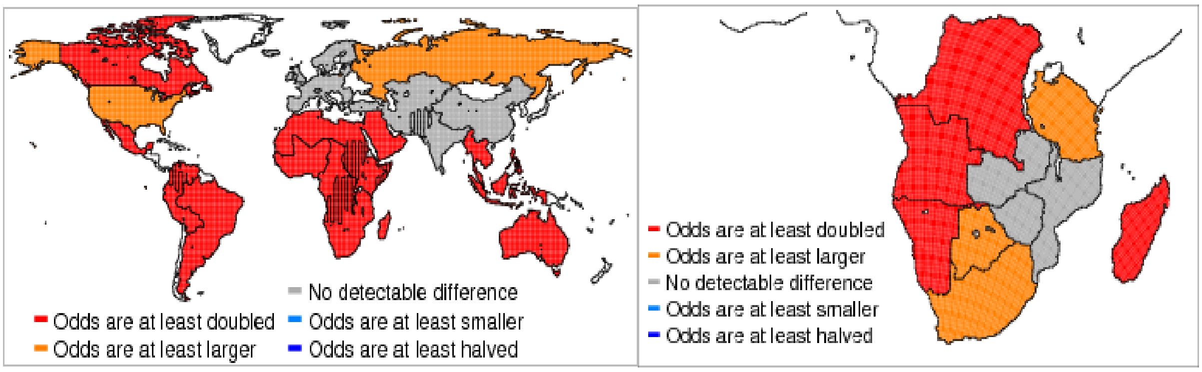


Figure 4.4.16 World's first operational attribution forecast suggesting how the odds of having an extremely warm November (1 in 10 year event) have changed due to the emission of greenhouse gases

4.5 MEDIUM RANGE TEMPERATURE FORECASTS FROM THE SAWS AND UKZN (E Marx, GGS Pegram and RE Schulze)

Temperature forecasts are traditionally of considerable interest to users and the need for improved site specific forecasts are increasing. Many smaller Weather Services do not have the resources to run ensemble prediction systems that cover all the forecast time-ranges. Therefore, regional downscaling techniques are an efficient way for these services to add value to the forecast fields obtained from external sources. Global centres such as the National Centre for Environmental Prediction (NCEP) in the USA makes valuable global, medium range forecasts products available to users and national meteorological services such as SAWS.

The climate of South Africa is determined by its location at the southern point of Africa, the surrounding oceans, its latitudinal extent and its topography. A major part of South Africa is situated on a plateau at altitudes between 1 000 m and 1 500 m. This plateau reaches its highest elevation in the mountains of Lesotho with an elevation exceeding 3 000 m. Especially on the eastern side, the plateau is terminated by an escarpment characterised by deep valleys that flow onto a narrow coastal plain. Over the southern parts of the country ranges of west-east orientated mountain ranges and valleys are the result of pre-historic geological folding of sedimentary rocks. These features are depicted in the topography map for South Africa and the Kingdoms of Lesotho and Swaziland as shown in **Figure 4.5.1**.

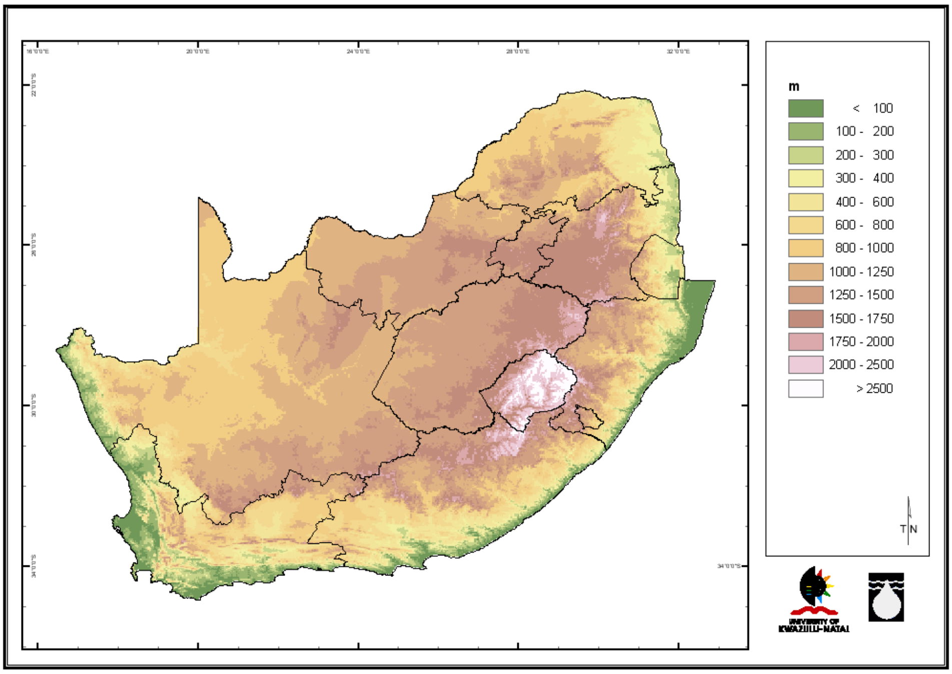


Figure 4.5.1 Major topographic features which influence temperature distribution of South Africa, Lesotho and Swaziland

In this Chapter a technique based on conditional merging, as originally developed for radar rainfall estimates by Sinclair and Pegram (2005), is extended to condition coarse resolution model fields with detailed climate information.

Elaborating on the above, the UKZN team is assisting SAWS in the development of a methodology to downscale medium range temperature forecasts using the detailed historical climate information produced in a WRC project by Schulze and Maharaj (2004) and presented in the "South African Atlas of Climatology and Agrohydrology" (Schulze, 2008). In the development of the methodology SAWS utilised the approach of Pegram *et al*. (2005) who combined radar and raingauge rainfall estimates using conditional merging. The methodology reported here combines the 1 degree resolution (~ 100 km by 100 km) NCEP medium range temperature forecasts with the 1 arc minute of a degree resolution (i.e. ~ 1.7 by 1.7 km) monthly temperature grids produced by Schulze and Maharaj (2004) to produce 1 arc minute resolution maximum and minimum temperature forecasts.

The monthly temperature grids in Schulze (2008) were originally created by generating 50 year daily temperature time series for the 429 700 grid points (1 arc minute resolution) making up the RSA, Lesotho and Swaziland using 970+ temperature control stations and derived monthly and regional lapse rates for both maximum and minimum temperatures. The map for February for maximum temperature is shown in **Figure 4.5.2**.

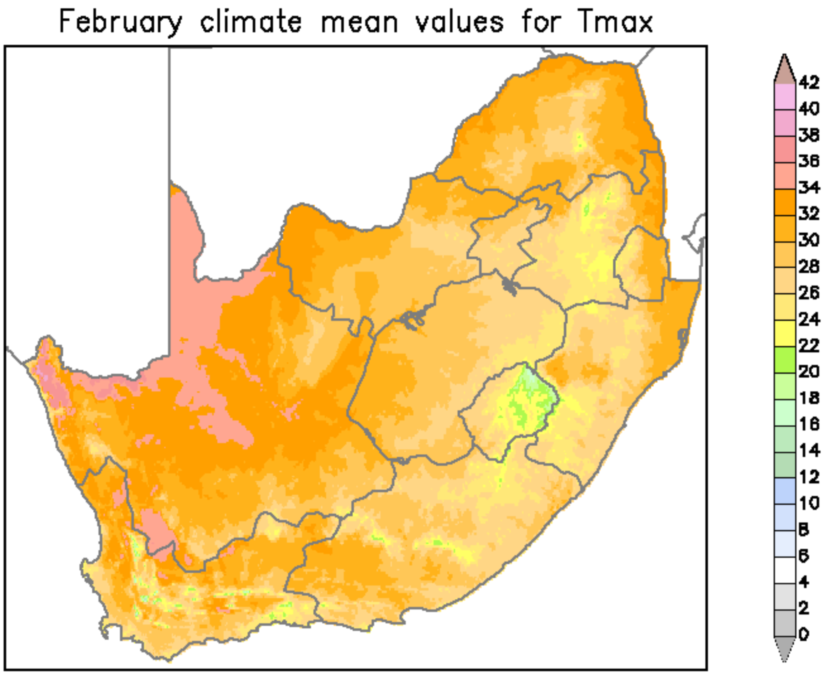


Figure 4.5.2 Average maximum temperature climate for February (Schulze, 2008)

The Atlas grids were re-sampled to the resolution of the NCEP grid, after which “difference” grids were generated where these were the difference between the re-sampled grids and the original grids. The difference grids are then added to the NCEP temperature forecast grids (**Figure 4.5.3**) to obtain the conditioned forecast grids. The climate-conditioned forecasts for 15 February 2012 is shown in **Figure 4.5.4**.

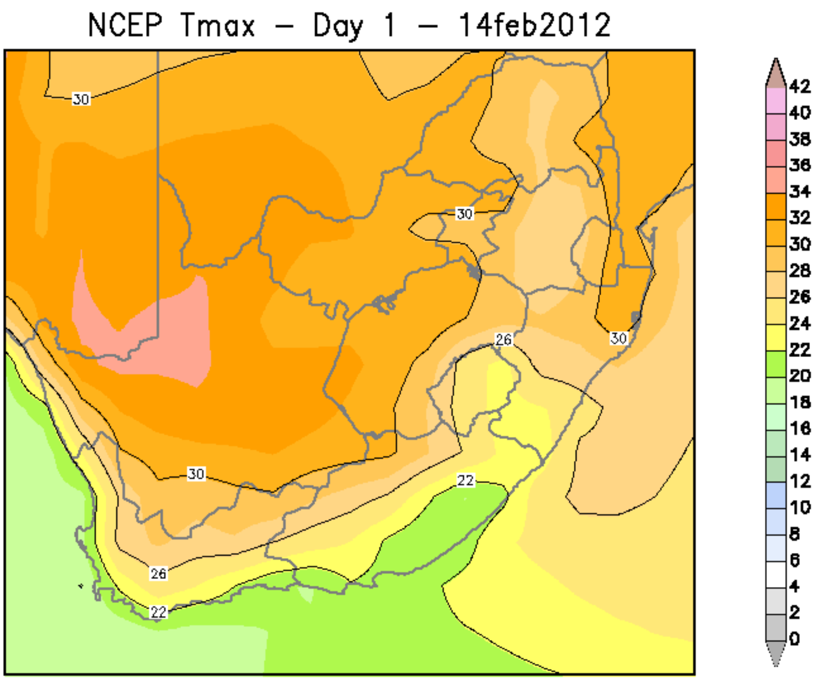


Figure 4.5.3 The NCEP maximum temperature forecast (1˚ degree resolution smoothed to 1 arc minute) with forecast lead time of 1 day issued for 15 February 2012 with model analysis date being 14 February

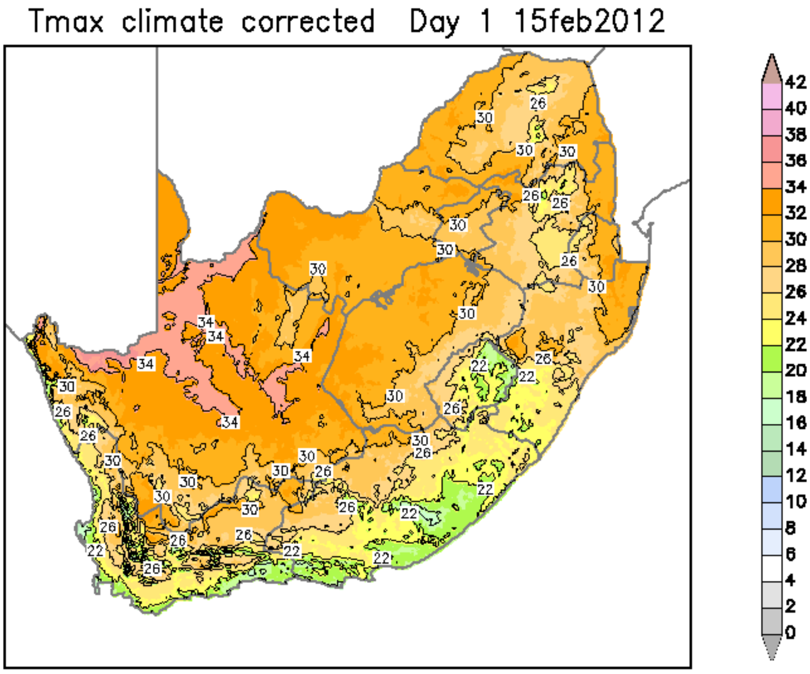


Figure 4.5.4 Climate-conditioned NCEP maximum temperature forecast for 15 February 2012 with a forecast lead time of 1 day

The next step in the conditioning process is to apply the daily bias-correction method to correct the temperature forecasts using past 14 days temperature actual. The 14 day bias means are calculated at approximately 160 synoptic station across the country and interpolated to a bias mean grid field using the inverse bilinear interpolation technique developed by Pegram (in preparation for publication at time of completion of this Report). The essence of this interpolation technique is to preserve the original bias value at a station after the values were interpolated to a grid field. The climate-conditioned temperature forecasts are then corrected by removing the bias using the bias grid field. The bias-corrected and climate-conditioned temperature forecast is shown in **Figure 4.5.5**.

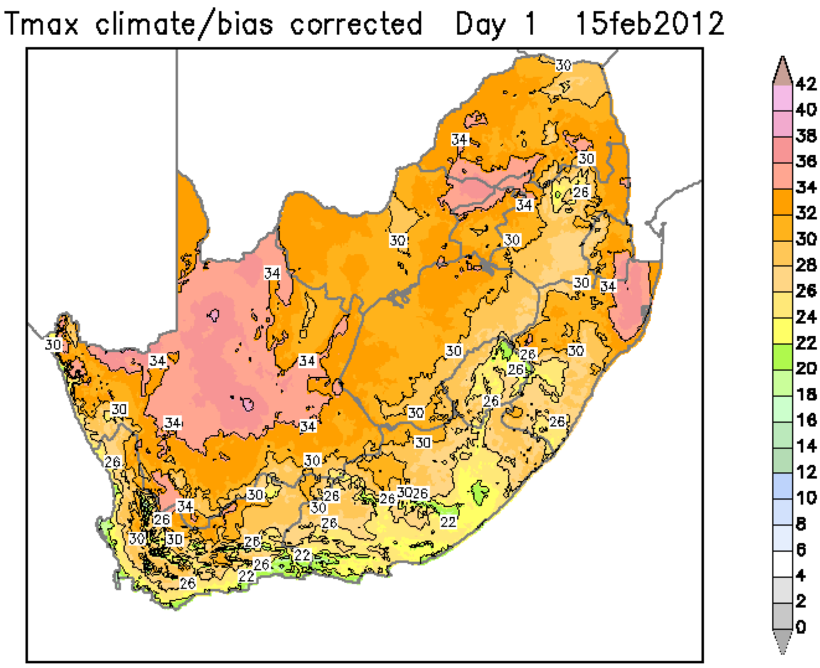


Figure 4.5.5 Bias-corrected and climate-conditioned NCEP maximum temperature forecast for 15 February 2012 with a forecast lead time of 1 day

This conditioning and correcting technique is applied on NCEP minimum and maximum temperature forecasts for forecast lead time of 1 day up to day 14.

A verification of the technique was undertaken by determining the percentage of correct forecasts within 2° C for maximum temperature. **Figure 4.5.6** was created by looking at the area-average over South Africa for the one year period from December 2010 to November 2011. Results show that the conditioned and corrected forecasts were generally closer to observed temperatures than the original coarse-scale forecasts.

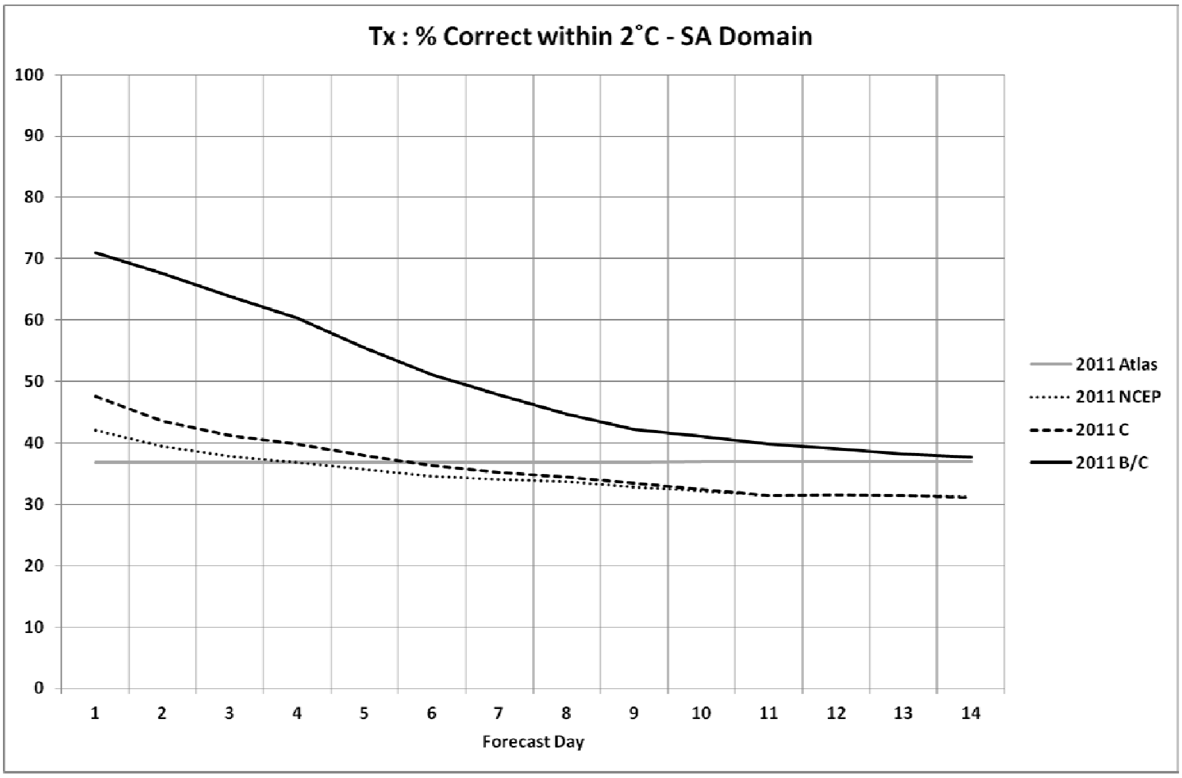


Figure 4.5.6 Verification of the methodology to condition and to correct NCEP maximum temperature forecasts using detailed historical climate information from Schulze (2008) and 14 day running mean bias-correction. The results present the performance of the forecasts over an area-averaged domain of South Africa for the one year period December 2010 to November 2011 for forecast lead times of one day up to day 14. The legend presents the following: *Atlas* is from the SA Atlas (Schulze 2008); *NCEP* is raw NCEP GEFS ensemble forecast means; *C* represents climate-conditioned forecasts; and *B/C* represents the final bias-corrected forecast

The methodology could potentially be applied to forecasts generated by other models (e.g. WRF, Unified Model) for different time scales, thus producing seamless forecasts at a common resolution. Another potential benefit of the methodology is that temperature forecasts can easily be referenced to historical climate values, enabling alerts to be generated when certain thresholds are exceeded.

CHAPTER 5

BACKGROUND INFORMATION ON CASE STUDY CATCHMENTS

RE Schulze, G Zuma-Netshiukhwi, O Phahlane, DB Louw, TG Lumsden and YB Ghile

Summary

5.1 SELECTION OF CASE STUDY CATCHMENTS
5.2 THE MODDER / RIET CATCHMENT
5.3 THE UPPER OLIFANTS CATCHMENT
5.4 THE BERG / BREEDE CATCHMENT
5.5 THE MGENI CATCHMENT

* * * * *

5.1 SELECTION OF CASE STUDY CATCHMENTS

Catchments were selected for the assessment of the impact of weather / climate information into agricultural decision-making. These catchments are Modder / Riet located in the Free State province, the Upper Olifants catchment located in Mpumalanga province, the Berg / Breede catchments in the Western Cape Province and the Mgeni catchment in KwaZulu-Natal. These catchments differ greatly in terms of soil types, vegetation composition, crop suitability, climatic conditions and farming systems, and were used for different purposes within this research.

5.2 THE MODDER / RIET CATCHMENT (G Zuma-Netshiukhwi)

The Modder / Riet catchment, stretching from the Free State towns of Brandfort, Bloemfontein and Dewetsdorp in the east to Douglas in the Northern Cape province (**Figure 5.2.1**), is located in a semi-arid summer rainfall region that is climatically marginally suitable for dryland crop production. The 500 mm annual rainfall isohyet, which lies to the west of Bloemfontein, thus passes through this catchment (**Figure 5.2.2**). For many agronomic crops, an annual rainfall of 500 mm is generally considered to be the threshold for viable rainfed agriculture. The natural rainfall variability therefore has a considerable impact on the success of agricultural production in this region, which implies that early indications for an above or below normal rainfall season before planting commences can have considerable impacts on eventual yields. Both commercial and resource-poor farming activities are to be found in this area, which creates the opportunity for evaluating the impact of the various lead-time forecasts and advisories within these farming communities. The University of the Free State (UFS) had, at the commencement of the project, already established links with the emerging farmers in the Sannaspos area to the east of Bloemfontein, while the Agricultural Research Council (ARC) at that stage was planning to work closely with both commercial and resource-poor farmers in the Koffiefontein area. There are a number of climate stations in this area (**Figure 5.2.3**) and the data from both the ARC and the South African Weather Service (SAWS) station databases are available. Verification of rainfall forecasts may also be aided by the fact that this catchment falls under the coverage of the Bloemfontein and De Aar weather radars.

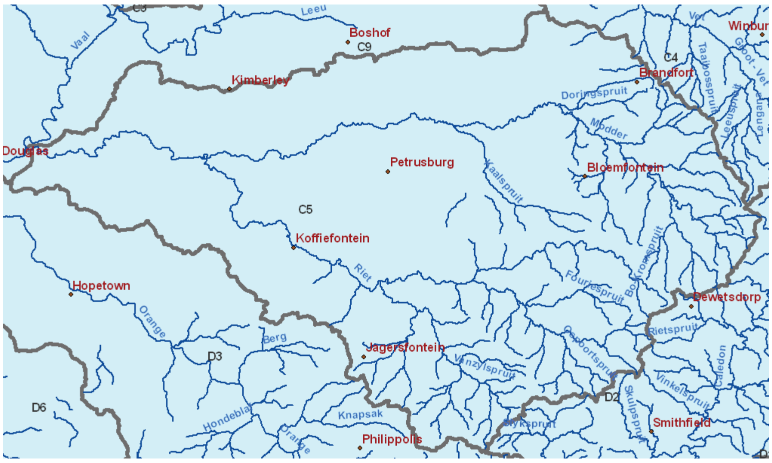


Figure 5.2.1 Location of the Modder / Riet study catchment, showing towns and rivers

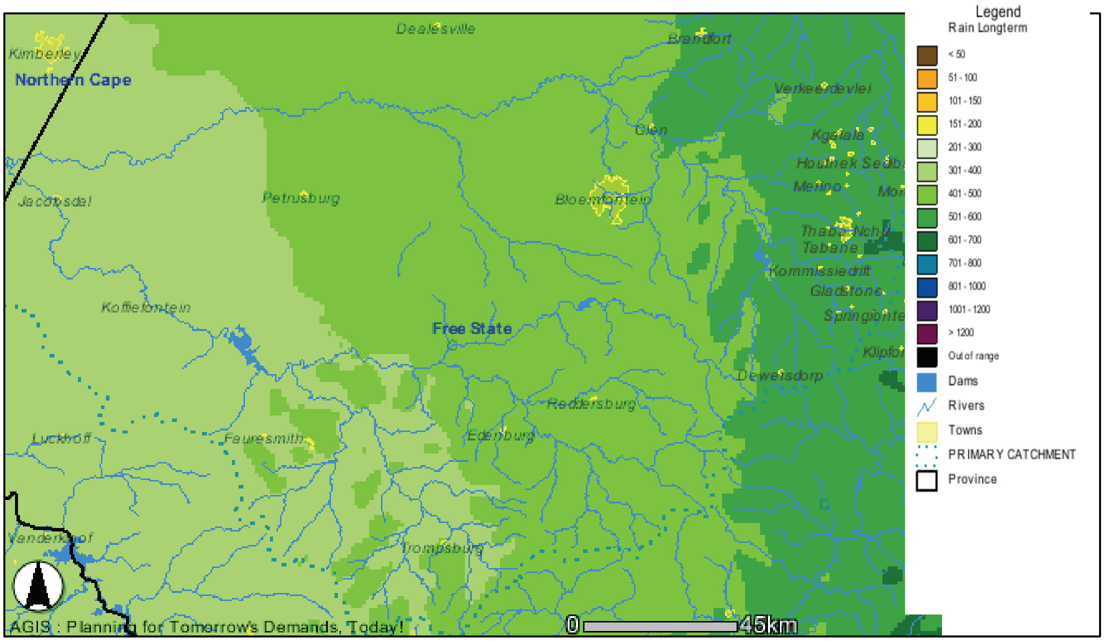


Figure 5.2.2 Isohyets of mean annual rainfall in the Modder / Riet catchment (AGIS, 2006)

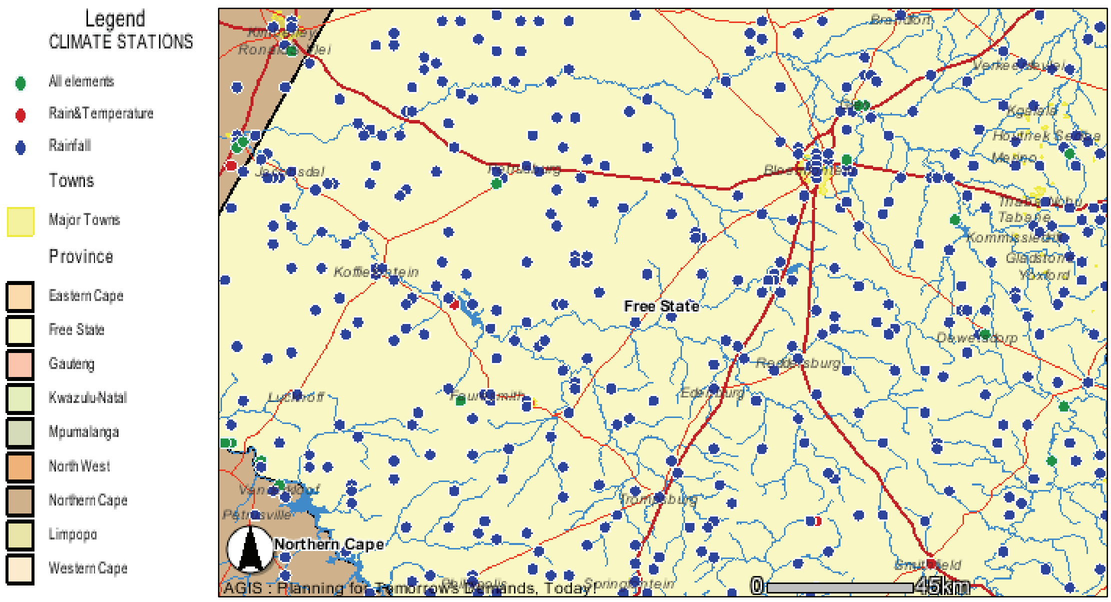


Figure 5.2.3 Location of climate stations in the Modder / Riet catchment (AGIS, 2006)

The following stakeholders were identified by the project team in the Modder / Riet catchment:

- Free State Department of Agriculture
- Free State Department of Water Affairs and Forestry
- Municipalities:
  - Mangaung
  - Letsemeng
- Water User Associations:
  - Kalkfontein
  - Orange-Riet
- Farmers:
  - Commercial farmers
  - Emerging farmers
  - Irrigation farmers
  - Dryland farmers
- NAFU (National African Farmers' Union)
- OVK (Oranje Vrystaatse Koöperasie).

5.3 THE UPPER OLIFANTS CATCHMENT (O Phahlane)

The Upper Olifants catchment is located in the west of Mpumalanga province between latitudes 25°-26°S and 31°-33°E (**Figure 5.3.1**). Encompassing about 25% of Mpumalanga, and with favourable conditions for agricultural activities, the Upper Olifants area falls within the Olifants Water Management Area (WMA). The major rivers in the Olifants water management area include the Olifants, Elands, Wilge and Steelpoort Rivers. The Olifants River in the upper Olifants catchment has two main tributaries, *viz*. the Wilger River and the Groot Olifants River. The main features of this area are coal mining, power generation, agriculture, industrial development and large residential areas.

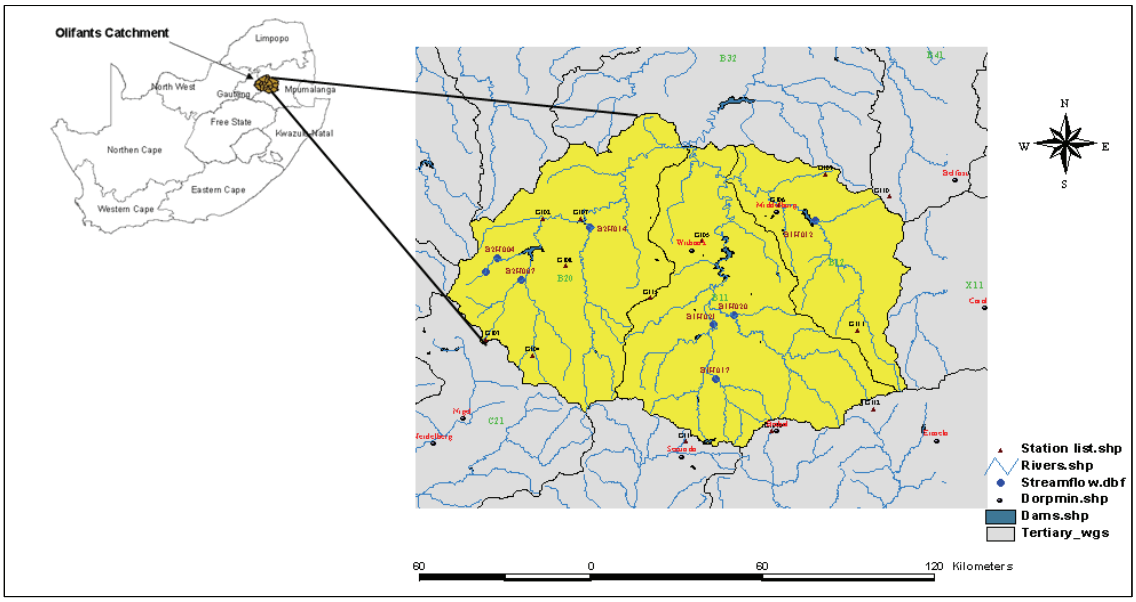


Figure 5.3.1 Location of the Upper Olifants catchment (ARC-ISCW Gislib, 2004)

The catchment falls within three district municipalities (DMs), *viz*. the Nkangala DM, the Greater Sekhukhune DM and the Motsweding DM. The district municipalities are made up of local municipalities, and these are listed on **Table 5.3.1**. The Groot Olifants sub-catchment falls within Nkangala DM and the Wilger sub-catchment falls within the Motsweding DM.

Table 5.3.1 Description of municipalities and major towns within the Upper Olifants catchment

District Municipalities	**Nkangala**			**Motsweding**
Local Municipalities	Highland	Steve Tshwete	Emalahleni	Kangweni
Major Town	Stoffberg	Middelburg	Witbank	Bronkhortspruit
	Belfast	Hendrina		

Source : http://www.demarcation.org.za/municprofileonline

The catchment falls mainly within the Grassland Biome, with the Escarpment and the Lowveld forming a transitional zone between this grassland area and the Savanna Biome (Low and Rebelo, 1996). The Groot Olifants sub-catchment habitat has shales and sandstones of the Vryheid and Volksrust Formations (Karoo Sequence) predominating the underlying rock types, giving rise to deep, red to yellow sandy soils. The Wilger sub-catchment's soils are formed from shales, while soils on ridges and plains are of quartzitic origin. Plinthic catena soil forms are rare. A very large area of the upper Olifants interior is occupied by Plantic catena which, in its perfect form, is represented by Hutton, Bansvlei, Avalon and Longlands soil forms. Glenrosa or Mispah soil forms are found in the southwestern parts of Witbank in the Groot Olifants sub-catchment. These soil forms derive from pedologically young landscapes that are neither predominantly rock not predominantly alluvial or aeolian and in which the dominant soil forming processes have been rock weathering, with the formation of orthic topsoil horizon and clay illuviation giving rise typically to lithocutanic horizons.

From an agricultural perspective, this catchment is positioned in a sub-humid to sub-tropical summer rainfall region (**Figure 5.3.2**) in which both commercial as well as resource-poor farming activities take place. Groblersdal is an important irrigation area which yields a wide variety of products such as citrus fruit, cotton, tobacco, wheat and vegetables. Carolina-Bethal-Ermelo is a sheep production area with potatoes, sunflower seeds, maize and peanuts also being produced in this region. The presence of both dryland and irrigation farmers creates the opportunity for the evaluation of the usefulness of

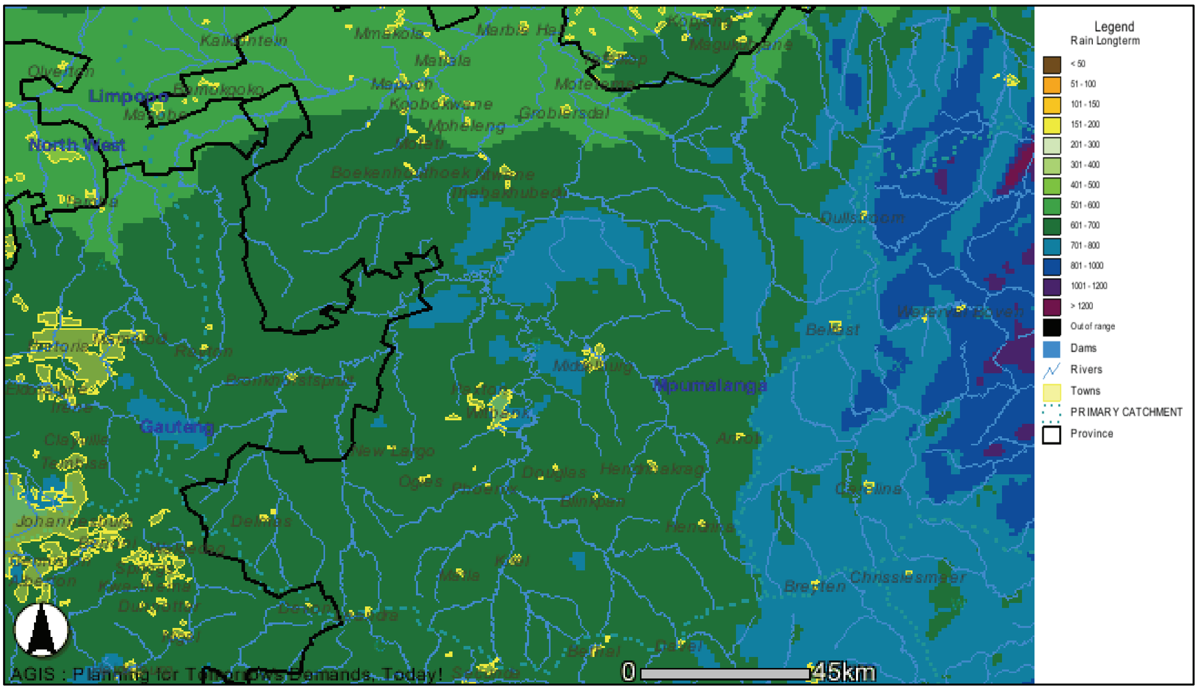


Figure 5.3.2 Isohyets of mean annual rainfall in the Upper Olifants catchment (AGIS, 2006)

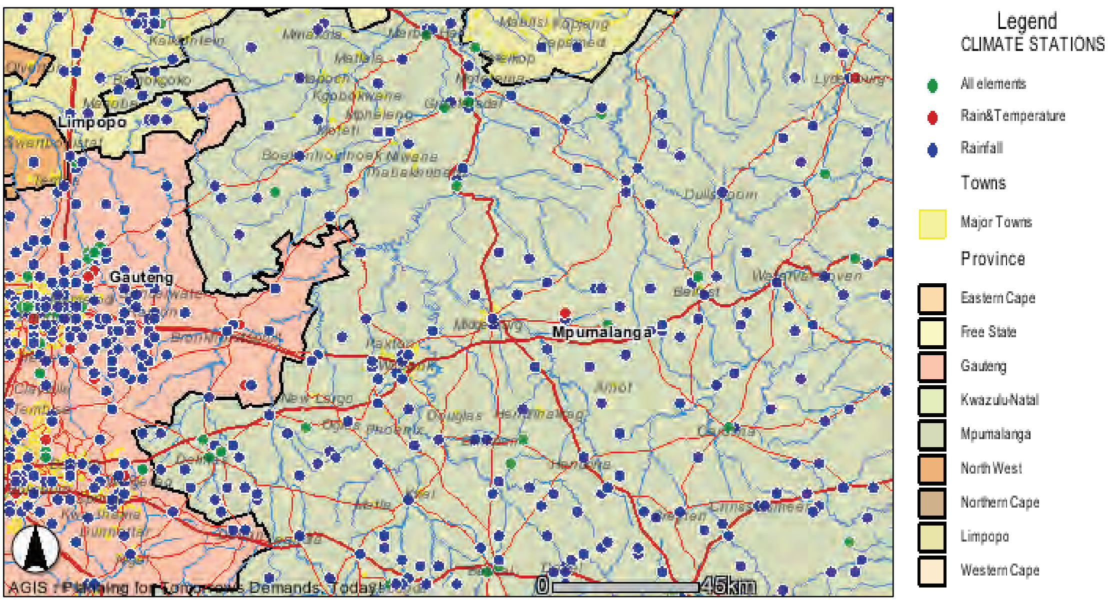


Figure 5.3.3 Location of climate stations in the Upper Olifants catchment (AGIS, 2006)

rainfall forecast applications. At the commencement of the project the ARC was already involved with some communities in this area, and these relationships were strengthened by working together for mutual benefit.

There are a number of climate stations in this area (**Figure 5.3.3**) and the data from both the ARC and SAWS station databases are available. Verification of rainfall forecasts was also aided by the fact that this catchment falls under the coverage of the Irene, Ermelo and Polokwane radars.

The following stakeholders in the Olifants catchment were identified by the project team as being relevant to this research:

- Mpumalanga Department of Agriculture
- Mpumalanga Department of Water Affairs and Forestry (Nelspruit and Groblersdal)
- Bloem Water
- Municipalities:
    - Witbank
    - Groblersdal
- Irrigation Boards:
    - Loskop
    - Selens River
    - Gousberg (Bronkhorstspruit)
- Farmers:
    - Commercial farmers
    - Emerging farmers
    - Irrigation farmers
    - Dryland farmers
- NTK (Noord Transvaalse Koöperasie)

5.4 THE BERG / BREEDE CATCHMENT (DB Louw and TG Lumsden)

The Western Cape Water Supply System (WCWSS) serves the City of Cape Town (CCT), surrounding urban centres and irrigators. It consists of infrastructure components owned and operated by both the CCT and the Department of Water Affairs (DWA). Essentially within the Berg catchment, the system connects to the Breede catchment through inter basin transfers and the following two sections provide a summary of the Berg River basin and parts of the Breede River basin.

5.4.1 The Berg Catchment

The upper region of the Berg catchment is surrounded by mountain ranges up to 1 500 m to the south, east and west. The river basin is fairly narrow (10-15 km) between the sources in the Groot Drakenstein and Wellington, while northwards of Wellington the Limietberg continues to bound the valley to the west. In the east, the basin levels out and the river valley widens to approximately 25 km. **Figure 5.4.1** shows the extent of the Berg catchment.

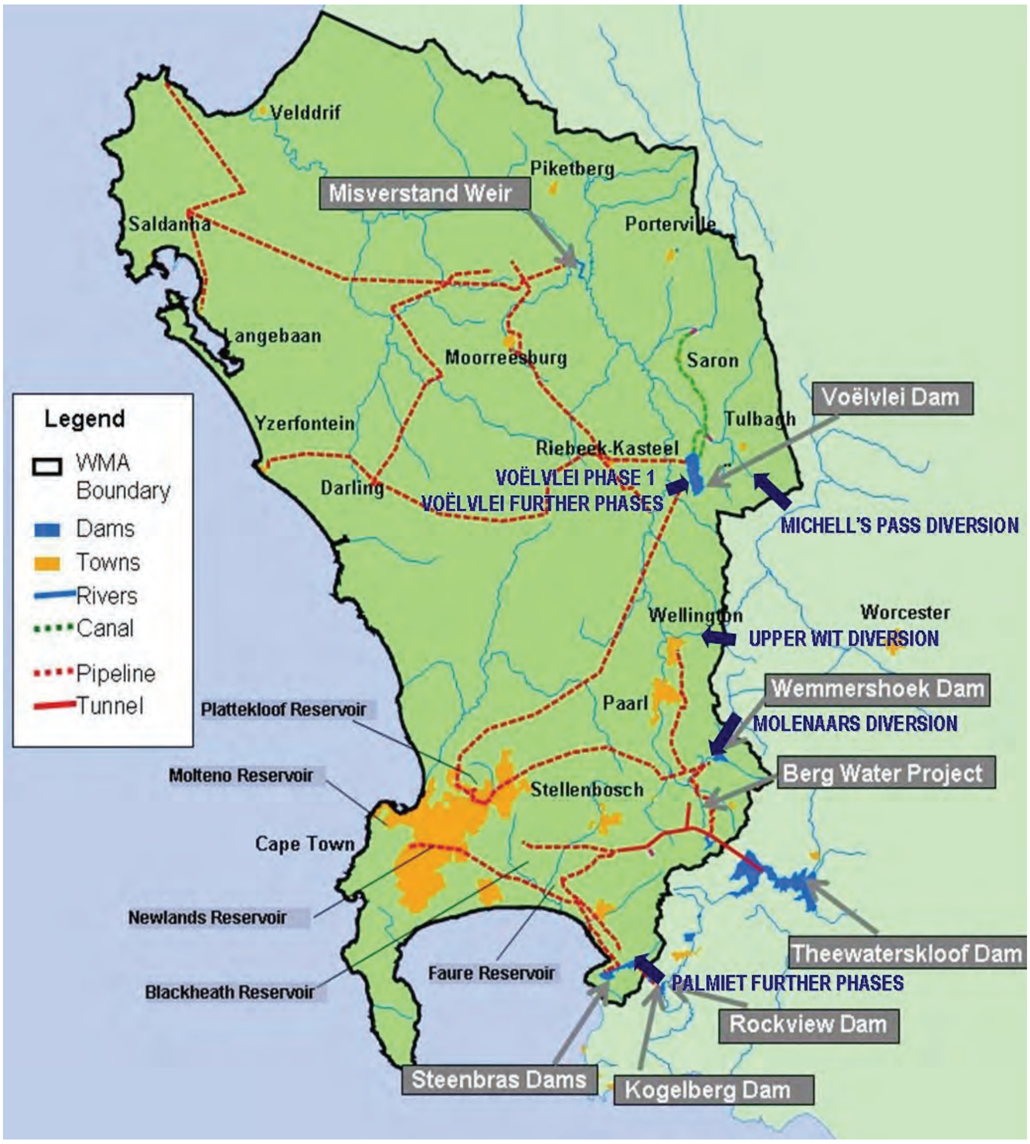


Figure 5.4.1 Description of the Berg River basin and inter basin transfers from the Breede (Source: Kleynhans *et al*., 2008)

The climate which prevails in the Berg catchment is classified as a humid zone and it experiences winter rainfall and high summer evaporative demand. Precipitation is from cold fronts approaching the area from the northwest. As a result of the topographical influence of the mountains, considerable spatial variability is experienced in the mean annual precipitation (MAP). In the high lying areas of the Groot Drakenstein, the MAP is around 2 600 mm, while further northwards, where the topography levels out, the MAP drops to below 500 mm (Schulze, 2008).

The area is characterised by a significant seasonal variation in monthly evaporation, which is typically 40 to 50 mm in winter, and 230 to 250 mm in the summer months. The mean annual evaporation throughout the basin shows less spatial variability than the mean annual precipitation. The high rainfall / low evaporation during winter and low rainfall / high evaporation during summer is an important climatic feature of this region (Schulze, 2008).

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

The Berg River is an important water supply source to the agricultural as well as the urban sectors. The Berg River basin is an interesting case study because of its complex nature, the fact that it supplies amongst others water to the Cape Metropolis and also because of its strategic importance for high valued summer crops in the winter rainfall region of the Western Cape.

In the Lower Berg River areas, towards the north, land utilisation changes from viticulture to dryland wheat farming. Apart from crops and forestry, indigenous "fynbos" vegetation is found in most areas. This growth varies from dense concentrations in gulleys to sparse coverings on rocky mountain slopes.

It may be seen from **Figure 5.4.2** that approximately 27% of the irrigated land is used for white wine production, 26% for red wine and 16% for table grape production. The remainder of the area (about 31%) is utilised for the production of citrus, olives, stone fruit, other fruits and vegetables and small areas are under wheat, proteas and oats.

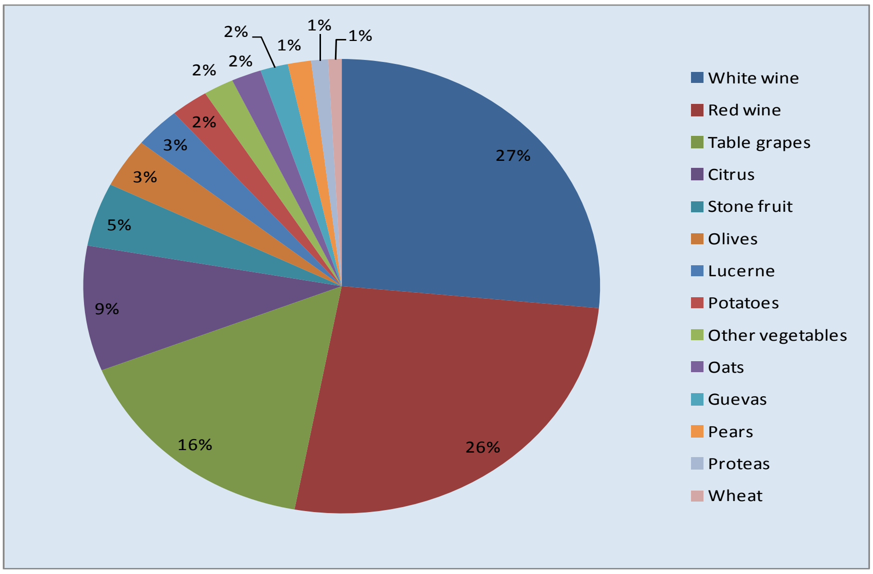


Figure 5.4.2 Estimated irrigated land use in the Berg River basin (Louw *et al*., 2011)

In the Berg catchment below Wellington the agriculture is typically rainfed. The majority of rainfed crops are wheat (38%), viticulture for white wines (21%) and lucerne (12%), with several other crops of less significance (**Figure 5.4.3)**.

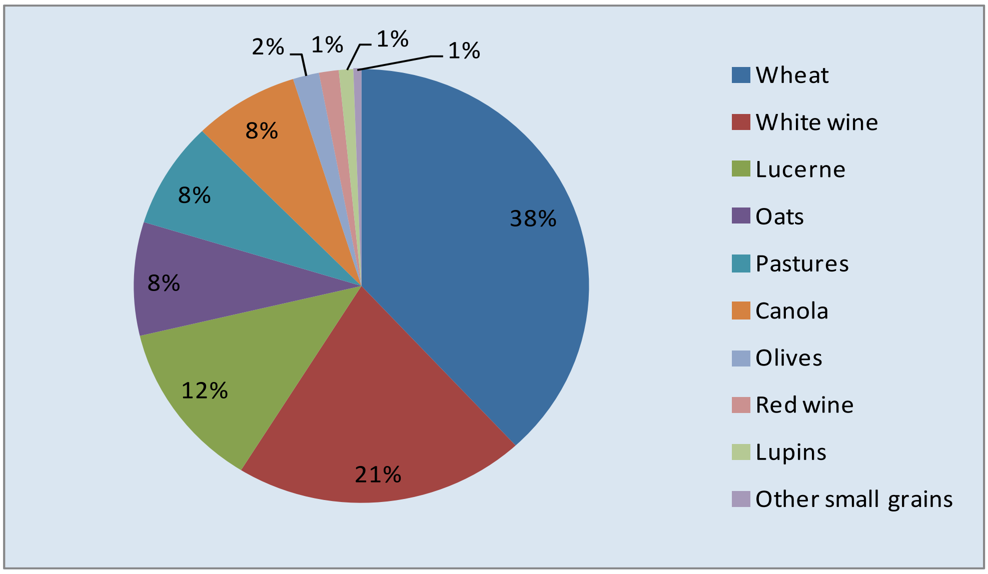


Figure 5.4.3 Estimated rainfed land uses in the Berg River Basin (Louw *et al*., 2011)

5.4.2 The Breede Catchment

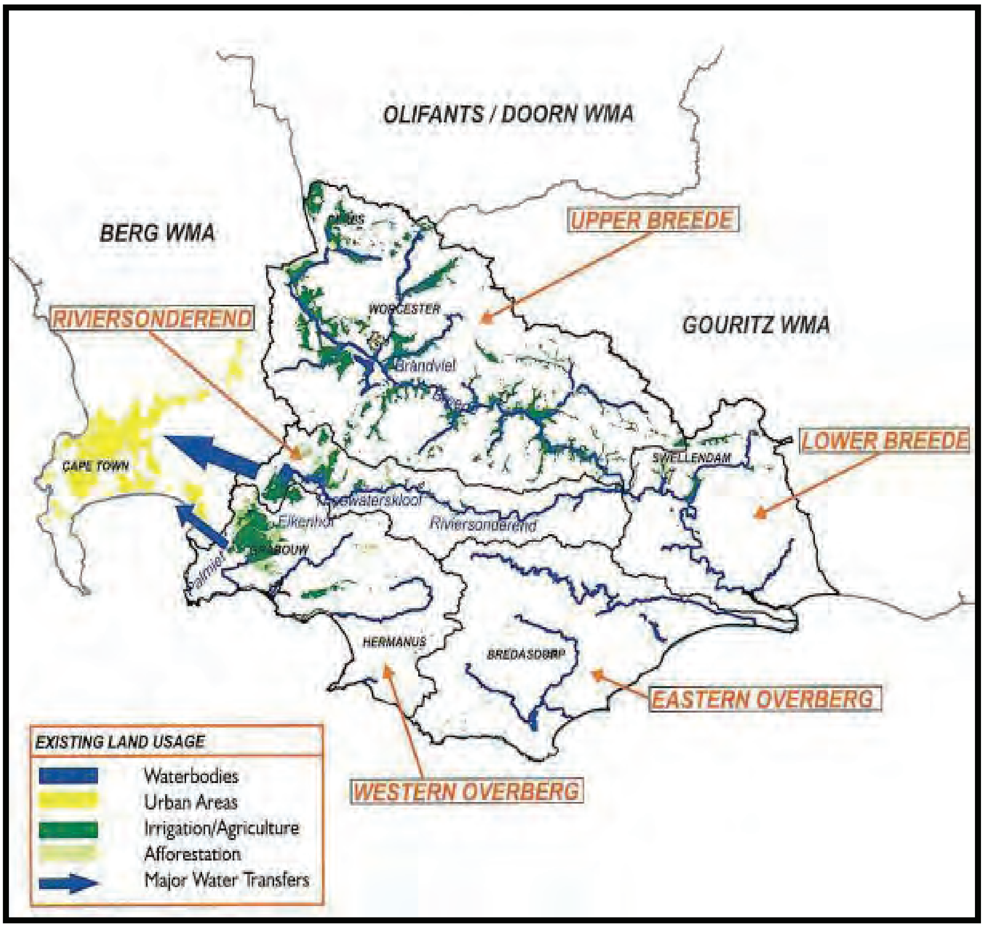


Figure 5.4.4 The Breede catchment (Louw *et al*., 2011)

The Breede is the largest river in the Western Cape Province with a total catchment area of 12 600 km^2 (**Figure 5.4.4**) and comprising 7 drainage basins (DWAF, 2007). The river lies east of Cape Town, and extends from Cape Infanta up into the Hex River Mountains. Originating in the Ceres

Valley, it drains in a southeasterly direction meeting the Indian Ocean at Witsand / Cape Infanta (Sebastian Bay) and flows through a key agricultural region in the Western Cape (DWAF, 2007).

Being a winter rainfall region, ~ 80% of precipitation falls within the months of April to September, brought by mid-latitude cyclones which are dominant over the region in these months. As is the case with many mountainous areas, there is a considerable spatial variation in rainfall. In the western mountain areas rainfall can be as high as 2 300 mm/a, whereas in the middle reaches rainfall decreases to as low as 400 mm/a (DWAF, 2007). There is intensive irrigation in the Breede and Riviersonderend River valleys (i.e. the Breede component of the Water Management Area) as well as in the extreme west of the Western Overberg, notably in the Palmiet River catchment.

Operation of the Breede River is such that water is collected during the winter period in large storage dams, such as Brandvlei and Theewaterskloof, for subsequent dispersal during summer. A unique feature in the operation of the Theewaterskloof Dam is the transfer of water into the dam from the Berg River Water Management Area for seasonal storage, as the Berg River does not have sufficient storage capacity of its own in the form of dams and reservoirs. During the dry season, the water is then transferred back into the Berg River together with a large quantity of additional water from the Breede River in order to meet the demands for water from the Berg River (DWAF, 2007).

A major inter-basin transfer takes place between the Breede and Berg WMAs via the Riviersonderend-Berg-Eerste River Government Water Scheme (Theewaterskloof Dam), which also supplies water for irrigators in the Riviersonderend sub-area and to the Overberg Water Board schemes in the Overberg. Of the total scheme yield of 234 million m^3/a, an average annual net transfer of 161 million m^3/a takes place into the Berg WMA, within which the largest beneficiary in the Berg WMA is the City of Cape Town (CCT). Irrigators in the Berg and Eerste River catchments also have an allocation out of this scheme. Four other small transfer schemes totalling approximately 12 million m^3/a also transfer water out of the Breede River.

An inter-basin transfer also takes place out of the Palmiet River (Overberg West) into the Upper Steenbras Dam (Berg WMA), via the Palmiet Pumped Storage Scheme. The average annual volume transferred is 22.5 million m^3/a and this is utilised by the CCT. The Overberg Water Board operates the Ruensveld West and Ruensveld East Schemes, which abstract water from the Riviersonderend River. The water is treated and distributed to rural users and used also for stock watering. Collectively, the transfers from the two Ruensveld Schemes total ~ 4 million m^3/a.

Steynskloof Dam (Worcester) and De Bos Dam near Hermanus are the only dams of significant size that are owned by local authorities and for which the primary purpose is urban water supply. The remaining larger dams supply water primarily for irrigation. Farm dams collectively provide about 83 million m^3 of storage.

It was mentioned above that only those sub-catchments within the Breede River basin where there is a link (inter-basin transfer) to the Berg River WMA were included in the study region for the purpose of this study. These include:

- The Villiersdorp / Grabouw region,
- The Riviersonderend, and
- The Palmiet River.

The agricultural land use in these regions (aggregated to the total) is estimated in **Figure 5.4.5**. The major crops are apples (44%), lucerne (13%) and pears (10%). The remainder of the area (33%) is used for a large variety of other crops including citrus, viticulture, olives, stone fruit and vegetables.

However, it is important to note that there are significant differences between the Riviersonderend area and the other two areas (Villiersdorp / Grabouw and the Palmiet River). In these two areas, apples and pears as well as stone fruit are the most significant crops.

There is only significant rainfed production is the Riviersonderend region where the farm structure is comparable to that of the Berg River basin below Wellington. Most farms consist of a combination of irrigation and rainfed agriculture. The majority of the rainfed crops are small grains (wheat, oats and barley).

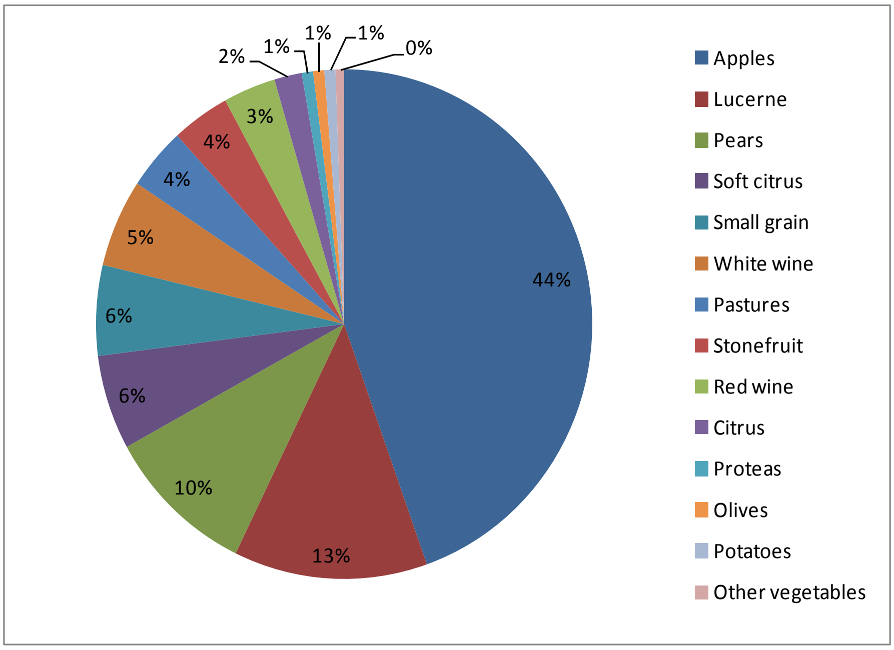


Figure 5.4.5 Aggregated agricultural land uses in the Breede part of the study region (Louw *et al.*, 2011)

5.4.3 Demarcation of the Total Study Area

Figure 5.4.6 shows the total study area. The area includes about 56 000 ha of irrigation land and 28 000 ha of rainfed agriculture.

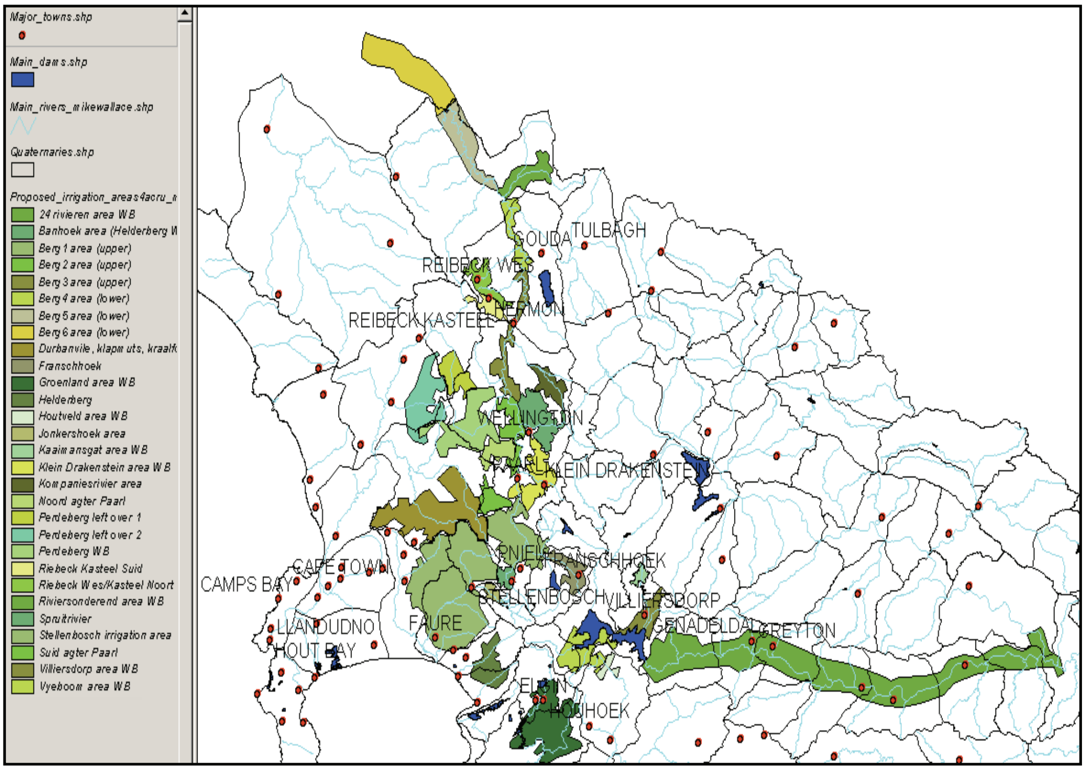


Figure 5.4.6 Demarcation of the total study region (Louw *et al.*, 2011)

5.4.4 The Urban Water Sector

The Western Cape Water Supply System (WCWSS) is a complex water supply system in the Western Cape region comprising an inter-linked system of six dams, pipelines, tunnels and distribution networks. Some elements of the system are owned and operated by the Department of Water Affairs and some by the City of Cape Town. The principal dams, all located in the Cape Fold Mountains to the east of Cape Town, are:

- Theewaterskloof Dam,
- Wemmershoek Dam,
- Steenbras Dams (Upper and Lower),
- Voëlvlei Dam, and
- Berg River Dam.

In 2009, 63% of the water in the system was being used for domestic and industrial purposes in the city of Cape Town, 5% in smaller towns and 32% in agriculture.

The largest component of the WCWSS is the Riviersonderend Government Water Scheme, which is a large inter-basin water transfer scheme that regulates the flow of the Sonderend River flowing southwards towards the Indian Ocean, the Berg River flowing northwards towards the Atlantic Ocean and Eerste River which flows into False Bay. Its centerpiece is the Theewaterskloof Dam on the Sonderend River, the largest dam in the system with a storage capacity of 480 million m^3. It is linked to the Berg River via a tunnel system through the Franschhoek Mountains. During winter, when water requirements are lower, this tunnel system conveys surplus flows from the Berg River Dam and the tributaries of the Berg River to the Theewaterskloof Dam, where the water is stored. In summer, when water requirements are high, water can be released back via the tunnel system into the catchments of the Berg and Eerste River.

Other storage dams of the WCWSS are the Voëlvlei Dam (159 million cubic meters), the Wemmershoek Dam (59 million m^3) in the Berg River basin, the Upper and Lower Steenbras Dams on the Steenbras River as well as the Palmiet Pumped Storage Scheme dams on the Palmiet River, from which water can be transferred to the Steenbras dams.

In 2009 storage capacity in the system was increased by 17% from 768 to 898 million m^3 through the completion of the Berg River Dam.

5.4.5 Summary

The description of the Berg and Breede River catchments highlights the complexity of the water management issues in these regions. The description of the water supply and requirements of the irrigation regions provide a background of the dimensions of the study region to be modelled. These dimensions can be summarised as follows:

- During the winter (the rainy season) there is ample water, but in the summer (dry season) there is severe pressure on the resource due to both a high irrigation and urban demand.
- Few dam sites (and other water supply augmentations) remain for which additional storage capacity can be developed without very high cost (financial and environmental).
- During the summer months the evaporation losses are very high due to high temperatures.
- High-value export crops are being produced in both the Berg and Breede River water catchments. This renders these regions as strategic pillars of the economy of the Western Cape Province because of its multiplier effects. Approximately 65% of all secondary industries in the province are dependent on agriculture.
- Although water demand strategies have been implemented to curb the growth in urban water use, these strategies can only alleviate the problem; they cannot solve it.
- There is mounting pressure to reallocate water from agricultural use to urban use.

5.5 THE MGENI CATCHMENT (YB Ghile and RE Schulze)

For a comprehensive verification exercise, catchments representing a wide range of climates with complete hydrological and climatic data are ideally needed for continuous assessment of the reliability of these models. In this study the Mgeni catchment was selected to serve as a point of departure in the verification phase, largely because of the availability and completeness of rainfall data from a relatively dense network of raingauges.

5.5.1 Location

The Mgeni catchment is home to ~ 7 million people in the Durban-Pietermaritzburg metropolitan area and produces approximately 20% of South Africa's gross national product from only 0.35% of the country's area. It is one of the South Africa's tertiary level catchments which have been delineated by the Department of Water Affairs (DWA). The catchment is located from 29º 13′-29º 46′ S and 29º 46′-30º 54′ E (**Figure 5.5.1**). The catchment, with an area of 4 469 km^2, ranges in altitude from zero to 2 103 m (Schulze *et al.,* 2004).

5.5.2 Climate and Hydrology

Rainfall is strongly seasonal and varies from 680 mm near the coast to 1 200 mm in the more rugged western parts of the Mgeni catchment, with 80% of the inland rainfall occurring largely as convective storms in the summer months (October-March), while along the coast lower intensity general rains in summer make up 65-70% of annual total (Schulze *et al.,* 2004). The catchment mean annual precipitation is 902 mm (Schulze *et al.,* 2004). Maximum daily temperatures are experienced in summer from December to February and minimum daily temperatures in winter in June and July (Schulze, 1997). Mean daily midwinter (July) maximum temperature increases from 12 °C in the inland to 24 °C on the coast on average, while means of daily maxima in midsummer (January) increase from 25 °C in the inland to 28 °C along the coast (Schulze, 1997). The catchment's mean annual temperature ranges form 16 to 18 °C (DWAF, 2001). Snow occurs occasionally in winter at the higher altitudes of above 1 200 m near the Drakensberg, while the risk of hail also increases with proximity to the mountains (Rural Development Services, 2002).

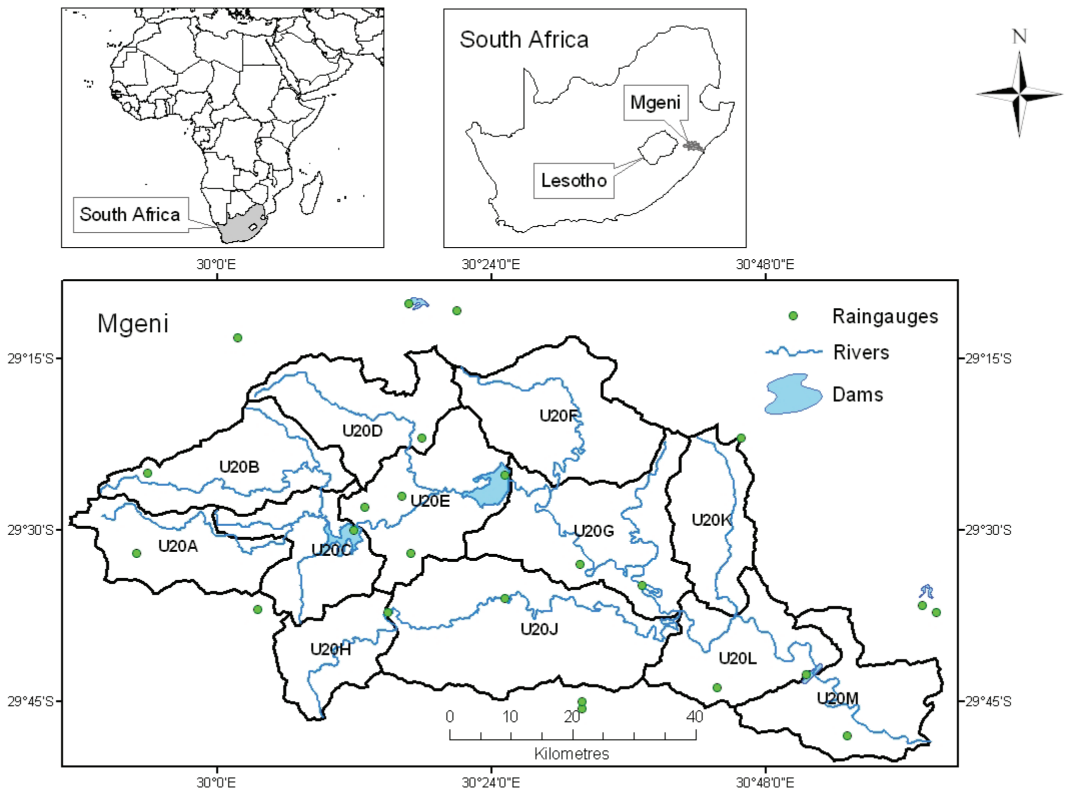


Figure 5.5.1 Overview of the Mgeni and its Quaternary Catchments

The Mgeni catchment is characterised by high spatial and temporal variability of rainfalls and streamflows and is subjected to periodic droughts and heavy flooding (Kienzle *et al*., 1997; Schulze, 1997; Schulze and Perks, 2000). Research conducted by Schulze (1997) has indicated that the inter-annual coefficient of variation (CV %) over the Mgeni catchment ranges between 25 and 30%, while that of the annual runoff is between 50 and 100%. The conversion ratio of mean annual rainfall to mean catchment runoff is 18%. Climatically the Mgeni catchment is classified as a sub-humid zone (e.g. Van Zyl, 2003). However, considering the strong rainfall seasonality, low rainfall to runoff conversion and high ratio of annual evaporative demand, parts of the Mgeni catchment may be regarded as hydrologically semi-arid (Schulze, 1997).

5.5.3 Vegetation and Land Use

In this study the classification used to represent natural land cover conditions for the Mgeni catchment was that of Acocks' (1988) Veld Types (**Figure 5.5.2**)

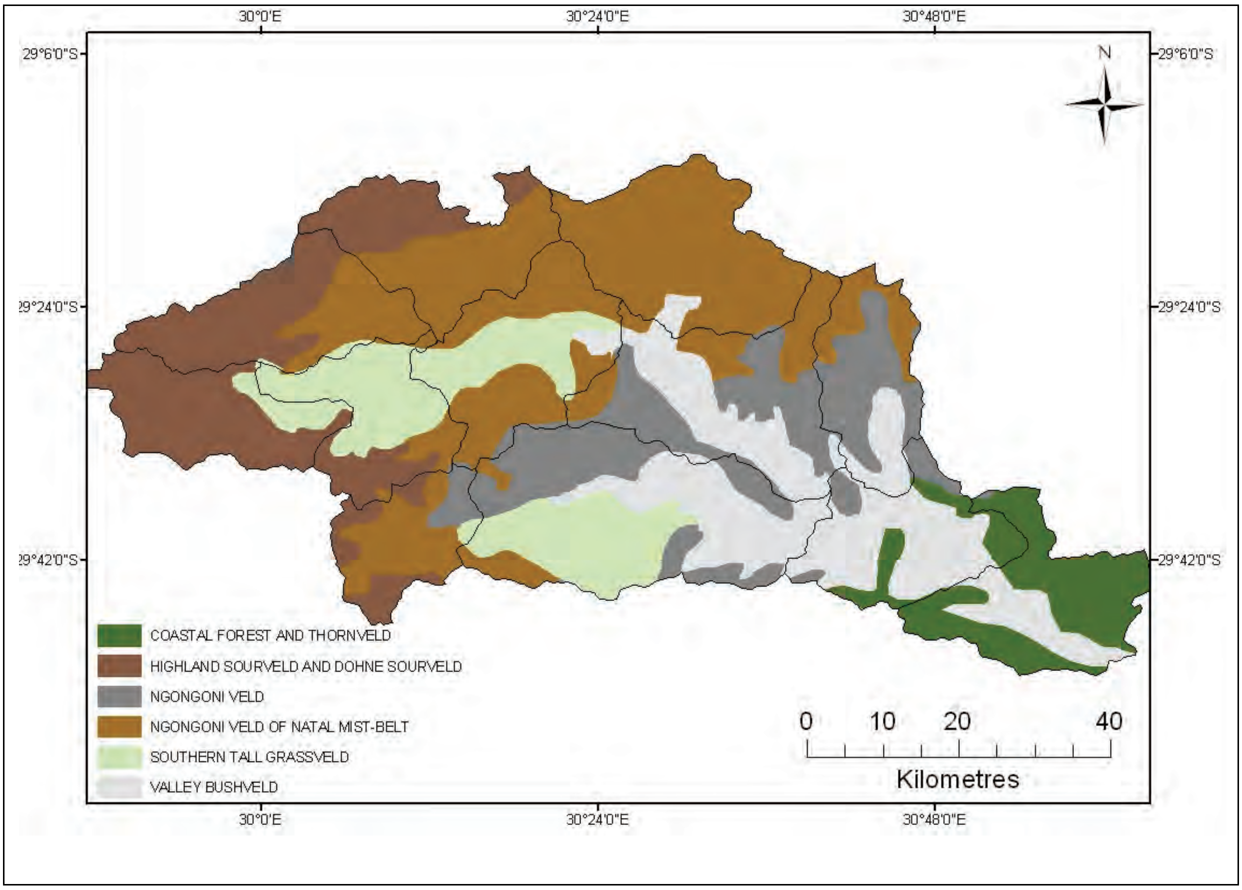


Figure 5.5.2 Baseline land cover in the Mgeni catchment, represented by Acocks' (1988) Veld Types

However, natural land cover has been altered significantly by humans and, as shown in **Figure 5.5.3**, approximately 37% of the Mgeni catchment is under agriculture, consisting mainly of commercial production forestry, sugarcane plantations and subsistence farming, with some temporary commercial dryland and irrigated agriculture. About 3% of the catchment consists of degraded bushland and shrubland, while 52% remains under natural vegetations and is comprised of grassland, bushland, and natural forest. Roughly 8% of the catchment land cover is urban, mostly residential, industrial, and commercial development associated with the cities of Durban at the coast and Pietermaritzburg inland (DEAT, 2001).

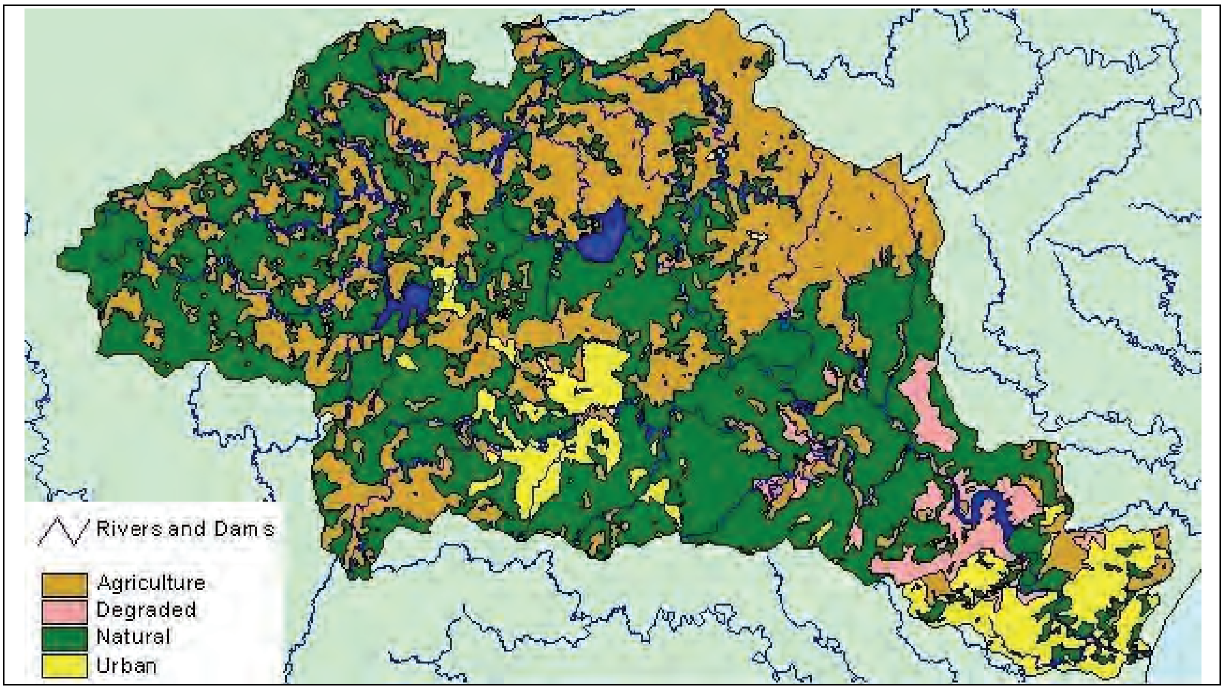


Figure 5.5.3 Catchment land cover and land use (Source: DEAT, 2001)

5.5.4 Water Use

A number of large storage dams have been constructed along the length of the Mgeni River (cf. **Figure 5.5.1**) from which water is abstracted and supplied to demand centres via various supply routes (Schäfer and Van Rooyen, 1993; Kienzle *et al.,* 1997; Kjeldsen and Rosbjerg, 2001). The Mgeni River is approximately 232 km in length (DEAT, 2001). The water resources of the Mgeni river basin are utilised for the supply of water to the Durban and Pietermaritzburg metropolitan complex, which is the third largest industrial and urban consumer base in southern Africa after Johannesburg and Cape Town.

Since the mid 1980s, Umgeni Water, the authorised water board responsible for the management and bulk water supply of water, has supplied a mean volume of 20 million m^3 annually to consumers living within and adjacent to the Mgeni catchment area (Schulze *et al.,* 2004). Irrigation and afforestation are also the major water users in the Mgeni catchment. In addition to the surface water resources there are also groundwater resources which supply a considerable number of boreholes in the catchment.

Rapid rural, urban and industrial development within the Mgeni catchment, together with a predicted growth in the population to between 9 and 12 million by 2025, will increase water demand to be in excess of the available water resources (Kjeldsen and Rosbjerg, 2001). On the other hand, water quality of the streams, rivers and dams within the Mgeni river catchment has also been at risk. This is due mainly to the occurrence of irrigated and urban return flows, intensified agricultural practices and the unorganised growth of large informal settlements. Transport of suspended solids, pathogens and phosphorus during frequent convective thunderstorms is also common, leading to a severe deterioration of the water quality of the Mgeni river system (Kienzle *et al.,* 1997). Mean annual sediment yield within the Mgeni catchment ranges from 500-700 tonnes/km^2 (DWAF, 2001).

Considering the above water related problems, the DWA and Umgeni Water have carried out a number of feasibility studies to assess how water could be transferred from other catchments to the Mgeni system. Several alternatives have been attempted, including transfers of water from Mkomazi River. However, to date only the transfer of water from the Mearns diversion weir in the Mooi River to a tributary of the Mgeni has proved to be economically viable (Fair, 1999; DWAF, 2004).

5.5.5 Subcatchment Information for Simulations with the *ACRU* Model

ACRU is a multi-layer soil budgeting model in which the streamflow generation process is based on the premise that, after satisfying the initial abstractions (through interception, depression storage and infiltration before runoff commences), the streamflow produced is a function of the magnitude of rainfall and the soil water deficit from a critical response depth of the soil (Schulze, 1995; Smithers and Schulze, 1995). Hence, detailed information on soils, land use and climate are required by *ACRU* to realistically simulate the soil water deficit antecedent to rainfall events on a daily basis. This information is given in Ghile (2007) and is not repeated here. However, in order to integrate the spatial variability of rainfall, soils and land cover in the Mgeni catchment, the *ACRU* model had to be configured in "distributed" mode with information / data from the Quaternary Catchments Database (QCD) being extracted at the level of Quaternary catchments (QCs). Although each QC is assumed to represent a relatively homogenous hydrological response unit, more than one soil type or land cover may still exist within it. In such cases, area-weighted values were assigned according to their respective areas within a QC.

Physiographic information for each of the 12 QCs that make up the Mgeni catchment is shown in **Table 5.5.1**. Rainfall and temperatures in the Mgeni area tend to be closely related to altitude, with higher parts receiving higher amount of rainfalls and lower values of temperature. In addition to altitude, aspect has a major bearing on rainfall. The reason for this is that moist air enters the area from the southeast, and as a result the southeasterly slopes tend to be wetter than the northwesterly ones (Rural Development Services, 2002).

Table 5.5.1 Subcatchment physiographic information of the Mgeni catchment (After Schulze, 1997)

Quaternary Catchment	Latitude (Degree. Minutes)	Longitude (Degree. Minutes)	Altitude (m)	Area (km^2)	MAP (mm)
U20A	29º 32′	29º 57′	1595.1	295.0	1007
U20B	29º 24′	30º 03′	1420.2	355.0	989
U20C	29º 35′	30º 08′	1204.9	280.6	931
U20D	29º 21′	30º 13′	1318.7	340.4	1040
U20E	29º 29′	30º 19′	945.7	392.4	974
U20F	29º 19′	30º 28′	908.3	437.8	981
U20G	29º 31′	30º 34′	778.3	497.3	895
U20H	29º 41′	30º 08′	1270.0	221.0	942
U20J	29º 40′	30º 29′	761.1	683.0	840
U20K	29º 20′	30º 43′	778.7	272.9	952
U20L	29º 40′	30º 46′	437.4	331.0	808
U20M	29º 45′	30º 52′	262.6	362.7	923

The *ACRU* model was configured to simulate accumulated streamflows from subcatchments cascading downstream at the exit of each QC. **Figure 5.5.4** shows the subcatchment configuration and flow cascading pattern of the Mgeni catchment. The shaded boxes are those QCs with major dams and with water flowing in from upstream.

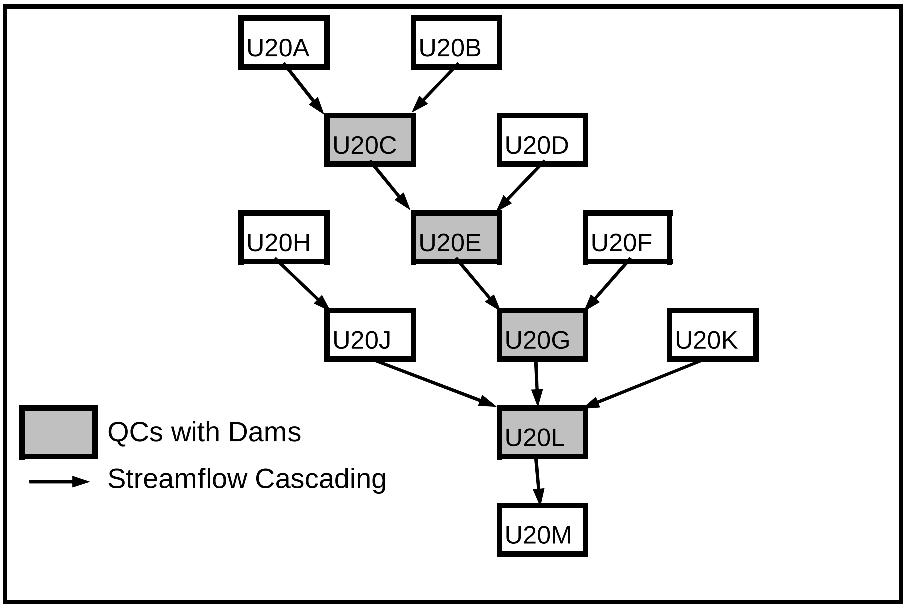


Figure 5.5.4 Subcatchment configuration and streamflow cascading pattern of the Mgeni catchment

CHAPTER 6

CASE STUDY APPLICATIONS OF WEATHER AND CLIMATE FORECASTS

G Zuma-Netshiukhwi, S Walker, O Crespo, TG Lumsden, YB Ghile and RE Schulze

Summary

6.1 CASE STUDY 1: DEVELOPMENT OF A TAILOR-MADE ADVISORY FOR END USERS IN THE MODDER / RIET CATCHMENT
6.2 CASE STUDY 2: DEVELOPMENT OF A TAILOR-MADE ADVISORY FOR RUSTFONTEIN FARM IN THE MODDER / RIET CATCHMENT
6.3 CASE STUDY 3: SCENARIO DEVELOPMENT IN THE MODDER / RIET CATCHMENT USING CROP GROWTH MODELS
6.4 CASE STUDY 4: USING DOWNSCALED FORECASTS WITH CROP MODELS TO IDENTIFY BENEFICIAL MANAGEMENT DECISIONS IN THE BERG CATCHMENT
6.5 CASE STUDY 5 APPLICATIONS OF SCIENTIFIC RAINFALL FORECASTS AND INDIGENOUS KNOWLEDGE IN THE MODDER / RIET CATCHMENT
6.6 CASE STUDY 6: DEVELOPMENT OF SEASONAL RUNOFF, SOIL MOISTURE AND IRRIGATION DEMAND FORECASTS IN THE BERG / BREEDE CATCHMENT
6.7 CASE STUDY 7: EVALUATION OF SHORT AND MEDIUM RANGE RAINFALL FORECAST MODELS IN THE MGENI CATCHMENT FROM A HYDROLOGICAL PERSPECTIVE

In this Chapter a number of case studies by members of the project team are presented. It should be noted that this is a “mixed bag’ of case studies. They are

- independent contributions with the authors responsible for their respective sections,
- some short others longer,
- some completed in the early phases of the project others at a later stage,
- some highly scientific others of a more anecdotal type
- some relating to crop yields others relating to water yield and
- some taken from higher degrees (MSc, PhD) completed under the auspices of this project while others were taken from annual reports.

6.1 CASE STUDY 1: DEVELOPMENT OF A TAILOR-MADE ADVISORY FOR END USERS IN THE MODDER / RIET CATCHMENT (G Zuma-Netshiukhwi)

6.1.1 Study Area

This case study was conducted in the Modder / Riet catchment, described in **Chapter 5**, and covers the central-western parts of the Free State province. This catchment covers the Motheo and Lejweleputswa districts. Farmers who participated and benefited from this project were identified in or near the following towns: Sannaspos, Brandfort, Soutpan and Koffiefontein. Operational study groups were identified in Sannaspos and Koffiefontein, and re-established in Brandfort and Soutpan for a preliminary survey, investigation and impact assessment. Farmers who participated were commercial and resource poor farmers conducting either rainfed or irrigation farming, or both.

6.1.2 Rainfall Variations

The annual rainfall pattern as presented in **Figure 6.1.1** was calculated using Julian days from July to the following June, using total monthly values to generate total annual rainfall for each of 57 years. The standard set by the World Meteorological Organisation (WMO) to analyse long term data is 30 years. Based on the set standards this study, however, analysed 57 years of rainfall data to quantify and present graphically the mean annual rainfall. The average annual rainfall for the Glen weather station was calculated to be 468 mm.

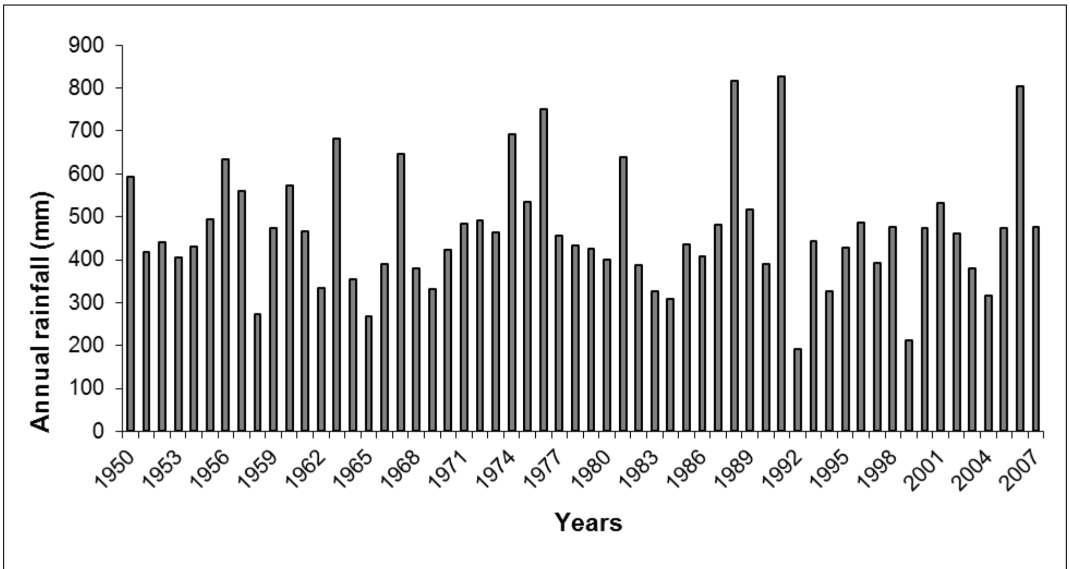


Figure 6.1.1 Long-term annual (July to June) rainfall for Glen Agricultural Research weather station (from ARC-ISCW climate databank)

The analyses showed that 56% years received below mean and 44% above mean annual rainfall. In 22% of years less than 400 mm was recorded and 7% received below 300 mm annual rainfall. The 7% years that recorded below 300 mm annual rainfall were the driest years with rainfall amounts that ranged between 190 mm and 274 mm for annual rainfall. These occurred in 1958, 1965, 1992 and 1999. The wettest years for this weather station recorded annual rainfalls ranging from 634 mm to 828 mm, and these occurred in 1956, 1963, 1967, 1974, 1976, 1981, 1988, 1991 and 2006. A mere, 15% of the 57 years had annual rainfall above 630 mm. The mean annual rainfall variation shows that rainfall is not consistently close to the mean value, but that it differs year to year within a wide range as a result of rainfall variability.

The importance of analysing such data is to understand the rainfall trends and patterns over the long term, so that the data can be used in future rainfall forecasts and to set boundaries for better planning for farming practices. Mean annual rainfall trends can assist the farmer not to expect consistently similar amounts of rainfall from year to year. It shows that annual rainfall fluctuates and extremes can occur (in 1992 / 3 only about 190 mm and 1988 / 89, in 1990 / 91 and in 2006 over 800 mm were received). Under these conditions the farmers must be prepared with adaptation strategies to minimise or avoid crop failure. Mean monthly rainfall is analysed below to identify summer planting months for the southwestern Free State.

Long term monthly mean rainfall patterns are shown in **Figure 6.1.2**. High (> 40 mm per month) monthly rainfalls are received from October to March which is during the summer and the planting season, with rainfall amount increasing from 45 mm in October to 73 mm in January. The amount of rainfall received from April to September decreases from 42 mm in April to between 6 mm and 8 mm from June to August and only 24 mm in September.

The long term annual rainfall and long term monthly rainfall provided good grounds to understand rainfall patterns for the southwestern Free State. This kind of information in **Figure 6.1.1** and **Figure 6.1.2** could be used by the farmers as an indication of when to plant and which agricultural strategies to consider, as well as to select suitable crop types and cultivars. The planting season is highly associated with the rainfall season for rainfed crops by the farming community. Interpretation and applications of seasonal forecasts are not always easy for farmers who have no access to scientific information such as weather / climate forecast bulletins.

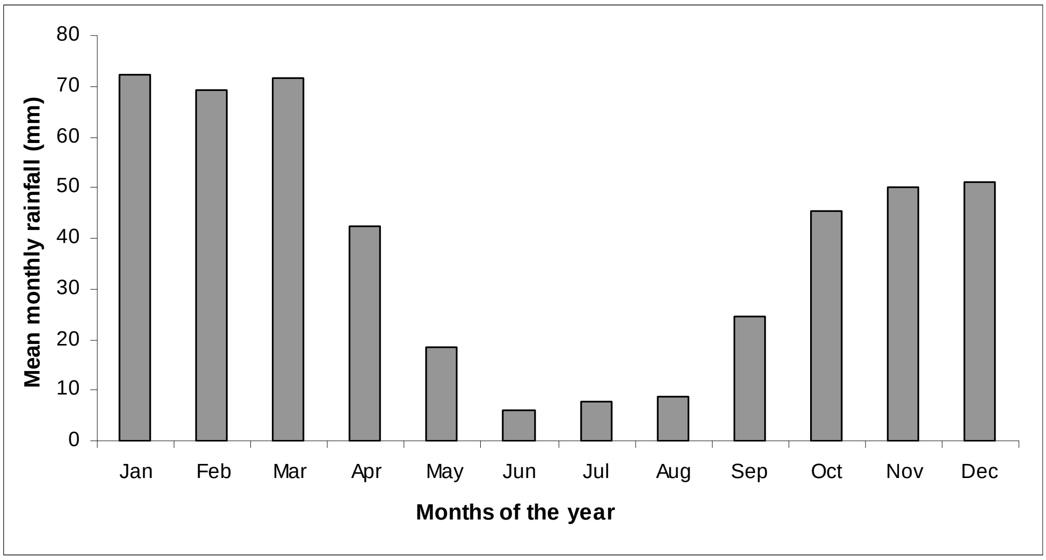


Figure 6.1.2 Long-term mean monthly rainfall trends for Glen weather station

A mean monthly rainfall greater than 20 mm was used as a criterion to identify summer planting months, and for this reason the season starts in September and ends in April. Therefore, May to August are omitted as their mean monthly rainfall is less than 20 mm. Rainfalls received in April occur during the rest period and can be stored in the soil for winter planting preparations. The summer season is the plant growing period with most crops (e.g. maize, vegetables) being produced during this season and only some in the winter season. The total mean (**Table 6.1.1**) from September to March adds up to 384 mm, from October to April to 426 mm and November to May 374 mm. These seasonal mean values can assist the farmer in crop selection as certain crops need a certain minimum amounts of water for their growing season. The standard deviation (**Table 6.1.1**) shows the variability of rainfall received across the months. The standard deviation for the summer planting season is higher (e.g. 31 mm for December and 55 mm for January) compared to winter months (e.g. 8 mm for June to 37 mm for September). The highest recorded values occurred from September to March, with April being the first month of winter season for this area. The above information is sufficient to identify the summer planting period, and with this information the farmers are able to plan accordingly in regard to crop type and cultivar selection.

Table 6.1.1 Statistical summary of historical monthly rainfall for Glen station

Months	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Mean	72	69	72	42	18	6	8	9	25	45	50	51
Standard Deviation	55	47	44	35	21	8	14	14	37	39	36	31
Median	64	65	66	38	12	3	0	3	8	36	48	52
Highest Recorded	204	238	196	186	79	34	63	65	165	182	178	142
Lowest Recorded	0	7	0	0	0	0	0	0	0	0	0	6

Weather / climate information can be the pillar to guide a farmer on when to perform certain agricultural activities and, as a result, to improve decision making. Understanding rainfall information is most critical for crop production in order to plant during the rainy season when the climatic conditions are conducive for growth. **Figure 6.1.3** and **Figure 6.1.4** graphically represent the probability of non-exceedence for three monthly rainfall periods (October to December, November to January, December to February) and show the probability of rainfall with the boundaries of the near-normal (0.33 to 0.66).

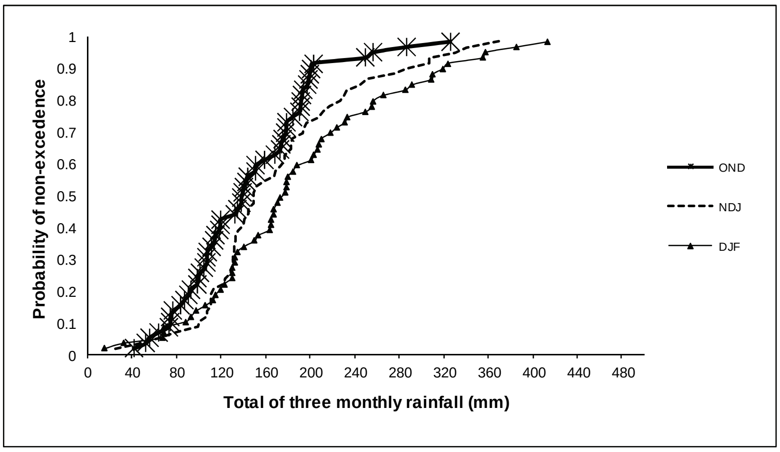


Figure 6.1.3 Three month rainfall probability of non-exceedence from October to February

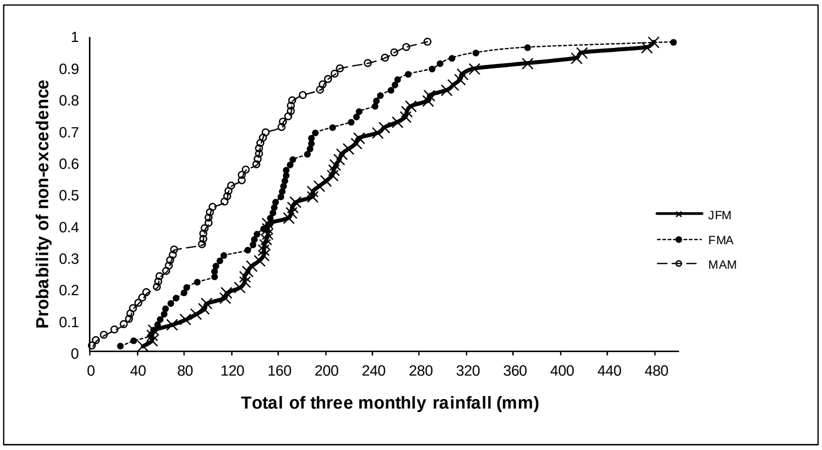


Figure 6.1.4 Three month rainfall probability of non-exceedence from January to May

Four categories of probability are illustrated from **Figure 6.1.3** and **6.1.4**. For example, a 0.16 probability would indicate a rainfall season that is well below normal (less than 0.33), near normal would range from 0.33 to 0.66 and 0.90 would indicate an extreme wet season. These probabilities of non-exceedence are good indications that more rainfall is received in certain periods than in others.

This information can guide the farmer to select the best season according to his / her crop's plant water requirements. However, farmers in the southwestern Free State start planting from as early as September to meet market demand and to maintain status as reliable suppliers for vegetables and other crops. These values for three month periods are useful when looking at the seasonal forecasts, but they do not show the dry spells within a season, and therefore other analyses need to be undertaken with daily precipitation values to assess the length of the dry spells and the probability of recurrence.

It became very crucial for the study to investigate the probability of dry spells to be able to develop advisories that indicate the months within the season that are more prone to prolonged dry spells than others and that can cause damages to crop development through water stress.

6.2 CASE STUDY 2: DEVELOPMENT OF A TAILOR-MADE ADVISORY FOR RUSTFONTEIN FARM IN THE MODDER / RIET CATCHMENT (G Zuma-Netshiukhwi and S Walker)

Rustfontein farm is located in the southwestern part of the Free State within the Modder / Riet catchment and is owned by Mr Scott, a commercial farmer. The Scott group runs a variety of agricultural enterprises in crop production and animal husbandry. Six raingauges were installed on this farm to record rainfall and daily rainfall data collection started in 1954 and continues to the present.

During on-farm visits an informal interview was held with Mr Scott and his farm workers. They regard rainfall as an important climate parameter and the deciding factor before on-farm practices are considered. The Scott group is committed to keeping records on a daily basis whether rainfall is received or not. The Scott group produces maize, lucerne, wheat and vegetables. The farm is mainly sustained by production of small stock (sheep, goats, pigs and poultry) and large stock (Brahman, Hereford and Nguni cattle). Rustfontein farm's owner and his labourers are well experienced in the various agricultural activities that need to be undertaken each season. **Figure 6.2.1** shows the long-term annual rainfall for Rustfontein farm.

This exercise was undertaken to ultimately develop advisories which are specific for the Scott group in order to improve on-farm decision making and farming practices. The long-term mean annual rainfall for Rustfontein farm is 566 mm. The driest years received rainfall below 350 mm in 1963 and 1979. The wettest years were 1955, 1975, 1980, 1986, 1987, 1995 and 2001 and they received above 750 mm of rainfall (**Figure 6.2.1**).

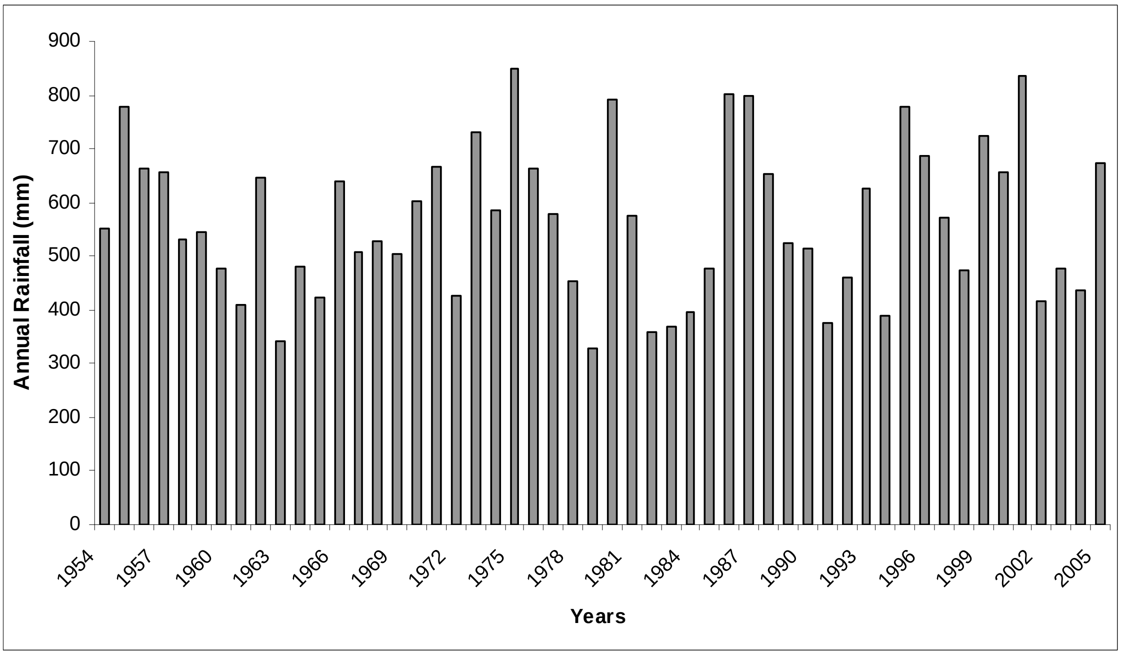


Figure 6.2.1 Long-term (July to June) annual rainfall for Rustfontein farm

Based on the annual rainfall information analysed, the Scott group was advised to consider using this information for tactical and operational planning and for making decisions on when to expect good rains and when to expect poor rains. This information can be used to identify crops that are well suited to the area and with the use of dry spell probabilities the farmers could decide on which agricultural activities to undertake. The seasonal rainfall forecast also guides the selection of planting dates, suitable crop types and cultivars. The rainfall pattern was explained indicating that rainfall amounts vary from year to year (**Figure 6.2.1**). The lowest annual rainfall received over 50 years with the amount of 327 mm in 1979 and the highest was in 1975 with rainfall amount of 848 mm of rainfall (**Figure 6.2.1**).

Thus, this information can be used to calculate the probability of obtaining good amounts of rainfall in a three month period and to identify and select months with probabilities of higher and lower rains.

The long-term rainfall data could be further analysed for seasonal forecasts to determine whether the season would be above-normal, normal or below-normal. For example, for above-normal rainfall conditions the Scott group was advised to increase the maize plant population from 15 000 to 30 000 plants / ha, to make a short season cultivar choice and to plant late in December for the 2009 / 2010 season. The group was also advised to plant and add few more ha for lucerne and increase the plant population.

The 14 day forecast was checked for the probability of dry spells as the days for cutting Lucerne approached. Lucerne was cut when the dry days were more than 10 days, as it has to be cut and dried in the field for 7 days before making bales for livestock during winter. Therefore, it is important to continuously check the 7 to 14 day weather forecast to minimise the risk of damaging the livestock and destroying lucerne. If lucerne is cut, allow adequate drying out period before baling bales.

To further understand the rainfall patterns for the Rustfontein farm, monthly mean rainfall and standard deviations were calculated (**Figure 6.2.2**). The variability of mean monthly rainfall is also shown to indicate the months which receive different amounts of rainfall. The planting season on Scott's farm starts in October as the mean monthly rainfall greater than 40 mm from October onwards. Planting and land cultivation is advisable during that period when the top soil's moisture content is adequate. October receives a mean rainfall above 50 mm and so the farmer needs to look at probabilities and the chance of planting when rains exceeding 25 mm in 5 days are expected. The highest mean rainfall is reached in January in the mid-summer season. As the season continues, by March the mean rainfall declines to 78 mm. In April only 53 mm of rainfall is received on average. May falls outside of the summer season as less than 20 mm rainfall is received on average. The Scott farm has irrigation facilities on its premises. Therefore, planting of different crops and varieties can occur as early as September, but they were advised the check on the average last frost date from the frost chart. Lucerne is sown from mid-September to early October as it is harvested January-February and is stored as bales for livestock feed through the winter month.

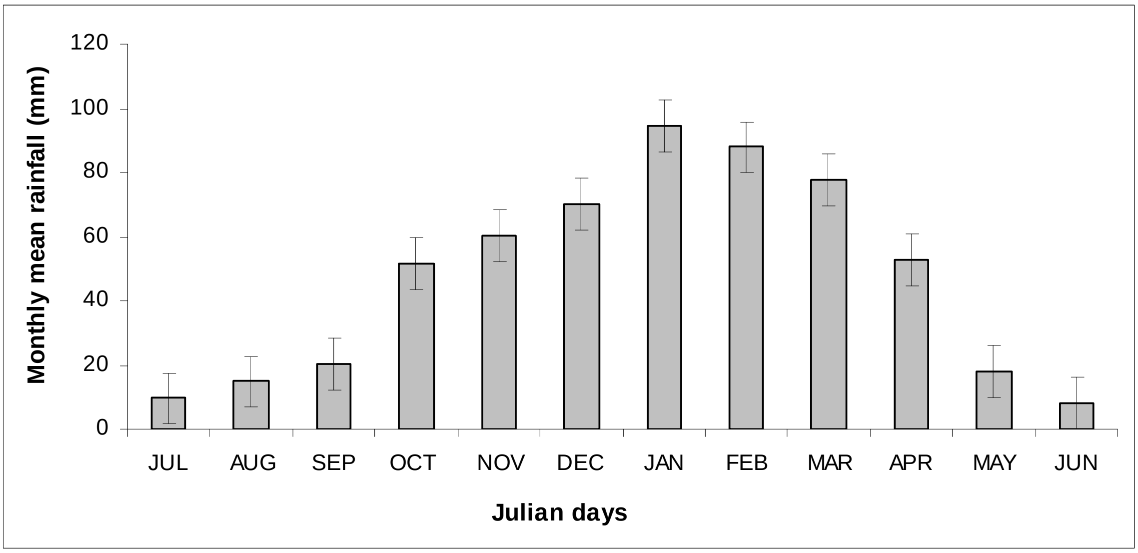


Figure 6.2.2 Rustfontein farm mean monthly rainfall and standard deviation

Provided irrigation is available on Scott's farm maize can be planted as early as 1 November. Maize on this farm is produced to make silage to feed small and large livestock. With information presented in **Figure 6.2.2** serial planting can be planned in advance to ensure that maize is produced to make enough silage to sustain the livestock through the winter season. Fresh and dry grain maize is produced for consumption and for milling to feed small livestock. The use of dry spell probabilities could be beneficially used by the farmer as it provides support in decision making.

Another example, *viz*. the cutting of fresh stalk maize, should be done on dry days and when cut it is compacted to remove the air and covered with plastic sale to prevent air or water entry. Milling of grain should be done on dry days to prevent exposure of water as the maize meal might become spoiled should it absorb water. Dry spell probability is very useful for on-farm and off-farm activities. These decisions were brainstormed with the Scott group during the field visit in October 2008, as part of an action learning cycle during planning and reflection.

As presented in **Figure 6.2.1** for annual rainfall and **Figure 6.2.2** for monthly rainfall, this information is analysed to understand rainfall patterns and to identify seasonal boundaries. Some years receive high rainfall and some years receive lower rainfall, as do individual seasons and months. For example, **Figure 6.2.3** shows the highest and the lowest monthly rainfall received on Scott's farm. The highest and the lowest monthly rainfall received were both in February with an amount of 343 mm in 1987 and 5 mm in 1967, and at the Glen experimental farm 238 mm occurred February 1988 and the lowest value was no rainfall in January of 1969. Given this information it is very important for the farmer to keep records of rainfall by installing raingauges at 1.2 m height on the farm in different places and calculating the average after rainfall events.

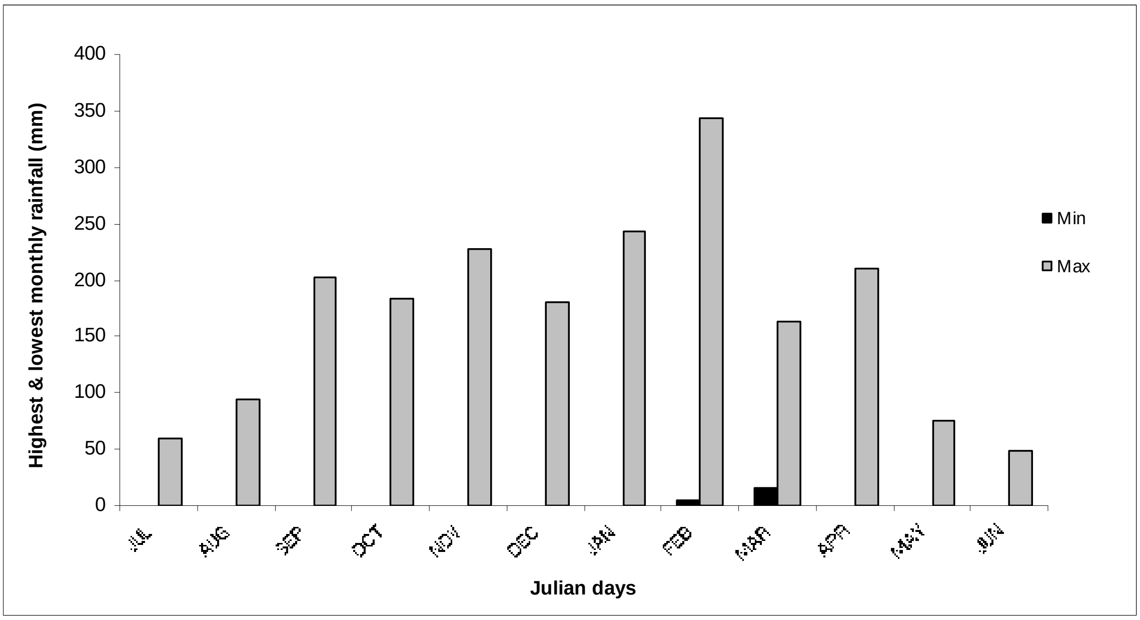


Figure 6.2.3 Highest and lowest recorded monthly rainfall for Rustfontein farm

Daily rainfall readings were analysed to predict probabilities of receiving different periods of dry spells. Dry spell probabilities can be used to guide the farmers to prepare and make good and scientifically supported decisions in advance for irrigation and other agricultural activities. If the number of days or period to receive dry spells is known, farmers could utilise this information on the following questions: when to irrigate? and how much to irrigate? Decreases in available soil water to the plant results in crop water stress. Water stressed crops wilt and may result into reduced crop yields or even complete crop failure in extreme cases. If the crops are water stressed during reproductive stages that means for that season there would be low to little yield. For example, a neighbouring farmer to Mr Scott's in the season of 2009 / 2010 planted maize in late November 2009 and harvested 0-1 ton/ha whereas Mr Scott harvested 2-3 ton/ha as he planted late December 2009. A practical which had been arranged for a tractor maintenance course to be held in Sannaspos was cancelled on a set date due to rainfall, because the organisers had not checked the short-term forecast. After this incident farmers appreciated the availability of forecast products. Therefore, historical rainfall information together with the weather / climate forecast is important to guide the farmer on farm management strategies prior planting to crop storage.

6.3 CASE STUDY 3: SCENARIO DEVELOPMENT IN THE MODDER / RIET CATCHMENT USING CROP GROWTH MODELS (G Zuma-Netshiukhwi and S Walker)

A series of scenarios based on different agricultural practices was developed using crop growth models for farmers from different backgrounds and farming experiences. The study was conducted in the Modder / Riet catchment in the southwestern Free State by personnel who were involved and ran different crop models. The outputs from the different crop models used, e.g. Eco-Crop 2, DSSAT, APSIM and AquaCrop, are incorporated with the weather / climate outlook or seasonal forecasts to generate and analyse scenarios for crop production management practices. Scenarios were developed based on baseline requirement, seasonal conditions, land, budget considerations, economic status, implements available and expertise. The results indicate that different seasonal conditions could generate a range of final crop yields at different probabilities. Thereafter, optimal practices can be selected for implementation. The crop production scenarios were developed in a manner to minimise risks for profitable yield production in order to improve the livelihoods of farmers.

Decision makers in crop production use scenarios to assess and answer the following questions: What to plant? When to plant? Which cultivar to use? How to plant? Where to plant what? What seasonal conditions to expect? In short, scenarios are used to assess what decisions to make under prescribed seasonal conditions in order to utilise rainfall effectively and efficiently. Under normal to above-normal seasonal conditions, scenarios would be that the farmers could consider early or late planting, short or medium or long cultivar choice, effective fertilizer application, etc. Under below-normal seasonal conditions the best scenarios would range from late planting, short cultivar selection, drought tolerant crops, minimising fertilizer application, etc. For example, the DST framework is focused on making improved decisions for strategic seasonal planning to benefit from available rainfall and for ultimately, better socio-economic status for farmers. The DST framework would serve as a support tool for researches and extension officers to develop tailor made advisories for farmers.

Component factors are important to identify during consultation with experts for scenario development as these influence crop production. The climatic conditions, crop suitability, planting window, selection of suitable cultivars and understanding of the seasonal forecasts were identified to be the driving forces by researches for sound decision making. The relevant stakeholders for the provision of suitable information such as the weather / climate producers, agronomic advisers, agrometeorologists, extension officers and others remain part of the team needed to resolve problems faced by farmers. However, the survey conducted during the diagnostic phase showed that 88% of farmers in the southwestern Free State rely on indigenous knowledge for planning. The authors are of the opinion that introducing scientifically developed and tested information to farmers could improve farming decisions and eventually the farmers' livelihoods.

The generation of scenarios was based on the seasonal conditions for improved crop production. The reference scenarios for this study are that resource poor farmers use indigenous knowledge to decide on when to perform agricultural activities in the southwestern Free State. Provision of scientific information to farmers can serve as an intervention to minimise risks and influence them to obtain better production. The baseline in this type of a study was the conditions and level of yield production before the farmers were introduced to scientific information as a support for improved decision making. For example, if the seasonal forecasts reflect good chances of receiving above-normal rainfall, the scenarios would be for farmers to increase planting population accordingly, to try and plant few days before the onset of rainfall, and to select a medium to long season cultivar, etc. The scenarios in this type of a study are constructed based on the climatic conditions and the farmer's resources, i.e. what a farmer can afford. Scenarios constructed are based on the combination of predictive inputs, such as the seasonal conditions, the farmer's capacity and experience, crop suitability and farm capability.

The management practices considered are well planned relating to the budget, expertise, implements, labour and land available that season. Therefore, strategies considered and implemented by the commercial farmers differ from the ones performed by the resource poor farmer due to differences in affordability and experience in farming. The performance at the end of season indicates the ability of the farmer to make sound decisions. The selection of alternatives for improved decision making by the farmer could be supported by the local intermediaries for making suitable adjustment for any types of seasonal conditions.

Therefore, valuable and proficient on-farm decision making needs a continuous re-evaluation of scenarios or options that were chosen and implemented for the past seasons. This process leads to learning and reflecting from past mistakes and short falls. For example, planting Swiss chard seedlings during cold months is not advisable as the seedlings are very sensitive to low temperatures. This was a lesson learnt by Mr Cangiso who then produces enough seedlings in summer and as winter sets in the plants are well established in the fields. By introducing the action research cycle (i.e. act-plan-observe-reflect) together with the DST, decision makers are able to make better choices. These two progressive processes allow the farmer to reiterate decisions made and create room to express feedback. Under conditions where the assisted decisions taken yielded good crop production, the decision makers develop confidence in the scientific information and would then always search for it prior engaging to agricultural operational activities. However, should farmers be dissatisfied with the final crop production, different options need to be considered to improve production as well as inviting other expertise or specialists from the other fields of agriculture for interdisciplinary decision making to minimise risks related to crop failure.

6.4 CASE STUDY 4: USING DOWNSCALED FORECASTS WITH CROP MODELS TO IDENTIFY BENEFICIAL MANAGEMENT DECISIONS IN THE BERG CATCHMENT (O Crespo)

6.4.1 Background and Concepts

The UCT group combined crop model simulations with optimisation algorithms in order to

- simulate agricultural impacts under future climate predictions, and
- look for beneficial adaptation options in response to a changing climate.

Agricultural management is currently performed as best as it can be with farmers adapting their decision making processes as best they can given predictions of the future climate. In order to provide guidance tools for helping these decisions, we investigated proposing options that will mitigate the adverse effects of predicted weather in the future. The best management options are computed by optimisation of different management strategies using the APSIM crop model.

According to different soils characteristics and available climate data, the APSIM crop model was set up in the winter wheat area of the Berg Catchment with the help of the Western Cape Department of Agriculture. Rainfed winter wheat was modelled adjacent to Philadelphia (33°40'S, 18°34'E; western arrow on **Figure 6.5.1**) on a sandy soil. It was necessary to develop routines written in R for estimating reference evapotranspiration (ET0) from downscaled estimates of temperature as the full set of variables for calculating Penman Monteith evapotranspiration are not provided by the downscaled climate forecasts.

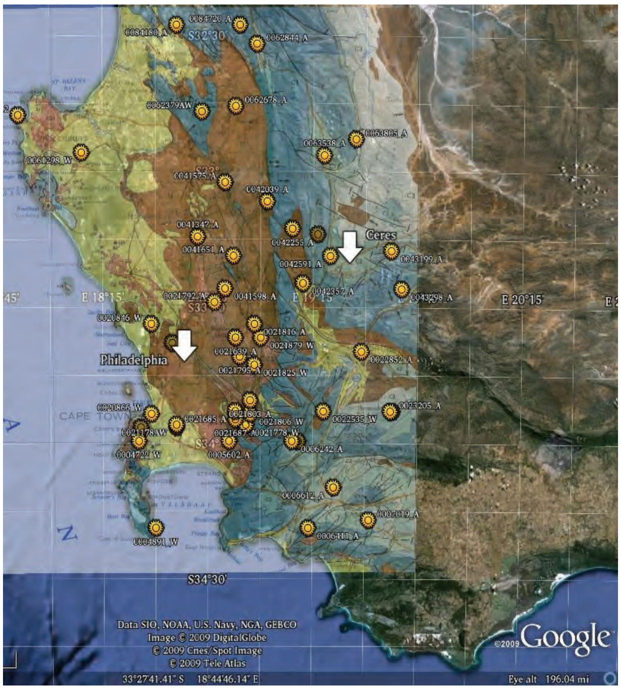


Figure 6.4.1 Berg River catchment area overlapped with geological soils features as well as available temperature and precipitation stations used to select two study cases where to set up the APSIM Crop Model

The multi-objective optimisation procedure is implemented using the APSIM crop model, where:

- Thousands of simulations with different parameter options, representing different management options, are simulated for an ensemble of forecast climates;
- The efficacy of each management option (sowing date, fertilizer application etc.) is evaluated against a set of objectives e.g. maximise yield, reduce nitrogen loss to the soil;
- A set of criteria spaces are developed (cf. **Figure 6.4.2**) which describe the range of criteria under different management options and climates;
- This leads to a set of identified optimal decisions (cf. **Figure 6.4.3**).

Agricultural systems are complex systems in which decisions can have multiple, and sometimes competing, outcomes when considering multiple perspectives. Defining a single optimal decision thus depends on the decision maker determining a single set of preferences. Trying to gain an advantage from the multiplicity of preferences and interests available, a multi-objective optimisation approach allows one to present various alternatives that translate the different and sometimes conflicting preferences (e.g. higher yields, less water). The final decision will, however, have to be made by the decision maker, with indicators available on, for example, expected amplitudes and variability of simulated outcomes.

The aim of the optimisation process is to look for *efficient* decision variables (e.g. sowing dates, irrigation amounts and scheduling, fertilizer amounts and frequencies of application) regarding multiple objectives (e.g. maximising crop yields and/or minimising nitrogen losses and/or minimising water use). A decision is defined within a decision space and is considered to be efficient on condition that its evaluation, defined in the criteria space, is optimal. A candidate is optimal from a multi-criteria point of view as long as its evaluation along every criterion is at least as good as that of any other candidate, and at least better than one of the criteria.

6.4.2 Methods

The optimisation approach used here has been inspired largely by the P2m algorithm used in Crespo *et al*. (2010) for the exploration of optimal irrigation strategies. The new optimisation algorithm is called X-pos. It is produced under a General Public Licence (GPL) and the raw code is freely available under the R-forge project on the web page http://r-forge.r-project.org/projects/xpos-r/.

The attraction of this optimisation approach under changing climate conditions lies in its multi-criteria evaluation technique. It deals with decision making under uncertainty in a way that allows maintaining information about weather variability. Though the meteorological data used here are not uncertain, crop decisions are made without knowledge of the weather which is about to occur. Because of this, the decision making is said to be done under uncertainty. The X-pos algorithm sorts decision areas as being efficient by comparing the multi-criteria optimality of ensembles (i.e. of groups). These groups include the outcomes simulated from a single decision subject to possible multiple weather occurrences. The number of simulated weather occurrences is potentially unlimited, yet only a few are necessary to represent the overall uncertainty as a result of the evaluation replications. The approach then allows one to present the sensitivity of different outcomes to weather variability, which is valuable information for decision making.

The X-pos optimisation algorithm consists of a hierarchical decomposition procedure as follows:

- *Initialisation*:
  The entire decision space is considered as the first decision region to be investigated.
- *Starting the iteration*:
  The one region selected for further investigation is broken down into two parts that are sampled and evaluated by simulation. As long as the broken parts embed more than one discernible (user defined) decision area, they are added to the list of regions pending further investigation. A multi-criteria evaluation is performed by comparing outcome groups of the pending regions. Only the one that is most likely including multi-objective optimum is selected and investigated further.
- *Stopping the iteration*:
  The breaking, evaluating and selecting routines are repeated until either the pending region list is empty, or time or run numbers limits have been reached.

6.4.3 Illustration of the Approach with Rainfed Winter Wheat in the Berg River Catchment

The APSIM crop model was set up to simulate rainfed winter wheat yields with a N and P fertilization at sowing and an additional N fertilization 30 days after sowing. The crop is usually sown as soon as possible in May, and the total amount of N applied is about 150 kg per hectare. The following values illustrate a case where the combination of the most efficient sowing date plus N fertilization amount was evaluated. The sowing date simulated was one of 10 weekly sowing alternatives ranging from 10 April (indexed 1) until 12 June (indexed 10). The N fertilization total amounts explored ranged from 0 to 400 kg, with 2/3 applied at sowing and the remainder 30 days after sowing.

Two criteria were used to guide the optimisation approach, *viz*. the simulated wheat yield and the N losses, with the former to be maximized and the latter to be minimised. The optimisation approach was run for a control climate period (1961-2000) in order to make comparisons with results from projected future climate periods. In this report results from only the control and far future (2081-2100) are shown, based on the daily climate statistically downscaled from a single GCM, *viz*. CNRM.

6.4.4 Results

6.4.4.1 Simulated optimal outcomes in the criteria space

In interpreting results in **Figure 6.4.2** below the following should be noted: first, that the yield axis goes from highest yields on the left to the lower yields on the right, with this so because the approach actually minimises all objectives and with those to be maximised being negated, and secondly, that all the boxes plotted have been identified as optimal and the ones highlighted in red being those that specifically reached the highest yields, and in green those that specifically maintain the lowest N losses.

The simulations do indeed confirm that those two (chosen purposefully for the exercise) are conflicting objectives (**Figure 6.4.2**). Now a decision maker can assess the expected outcomes regarding both objectives depending on his/her own set of preferences. The simulation also allows the identification of optimal compromises, with this often being highly beneficial because what may otherwise be regarded as a secondary objective produces for only very little loss when compared to the main objective. Furthermore, the boxes in **Figure 6.4.2** are the rectangular boundaries of the multiple outcomes of a single decision combination simulated under multiple daily climate occurrences of a future climate. Thus the width and height of such boxes (while not showing it explicitly) are directly related to the variability of the outcomes given the future climate variability.

As such, the pieces of information presented on such a graphic are useful indicators of conflicting outcomes and their robustness in a changing climate. They are thus tools to help decision makers to make own final choices.

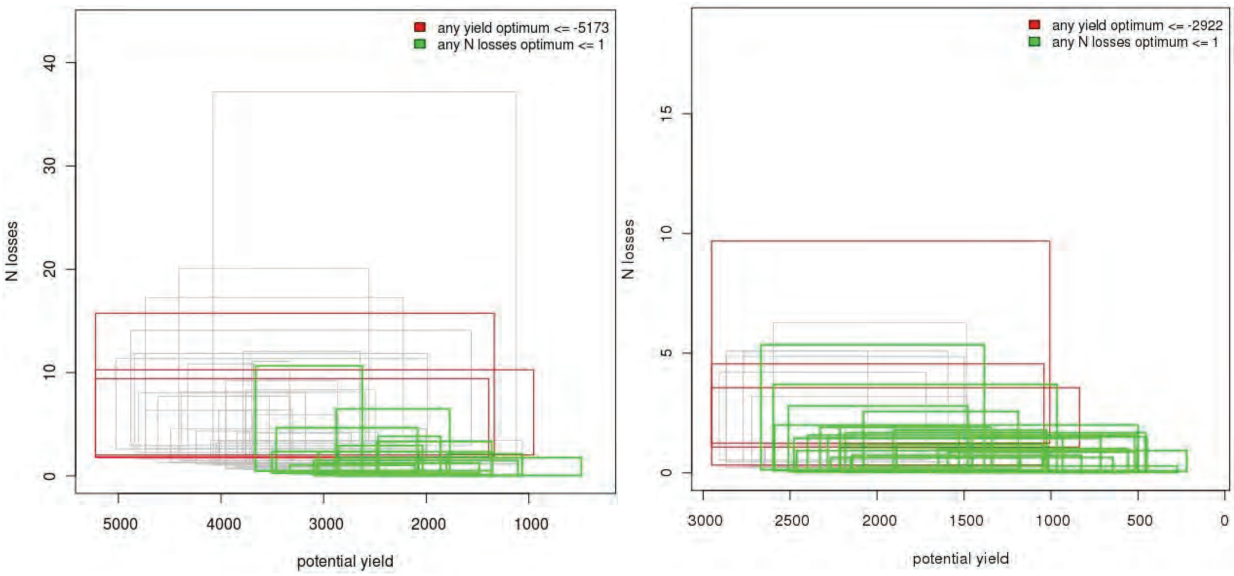


Figure 6.4.2 Best combinations of highest potential yields (kg/ha) and lowest nitrogen losses (kg/ha) achieved under climates derived from the CNRM GCM for downscaled control (1961-2000) and far future (2081-2100) periods

6.4.4.2 Efficient variables identified in the decision space

In **Figure 6.4.3** it is shown that the space has been fully explored. Only the *efficient* combinations of decisions have been coloured, in this case in red if they reach the highest yield, in green if they achieved the lower N losses and in grey for the optimal compromises.

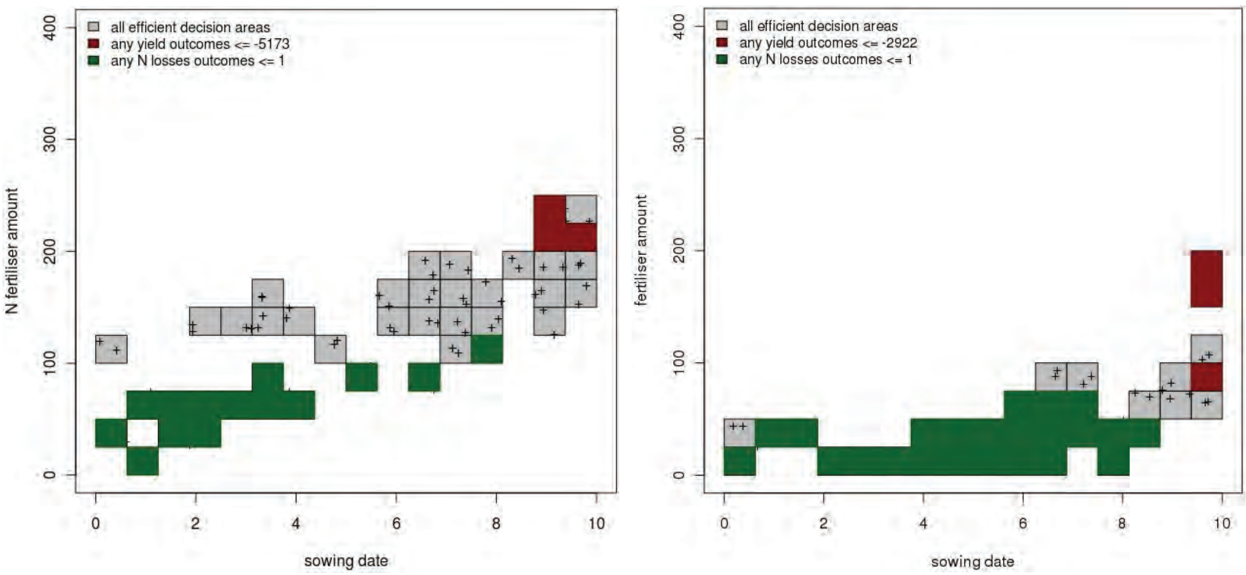


Figure 6.4.3 Decision combinations of weekly sowing dates (with 1 representing 1 April and 10 representing 12 June) and fertilizer amounts (kg/ha) that resulted in the best simulated outcomes (shown in previous figure), with the left graphic depicting results from the control climate period (1961-2000) and the right graphic from the far future (2081-2100)

The efficient decisions show a linear relationship between sowing dates and fertilizer amounts for the control period from 1961-2000. The earlier you sow, the less you need N fertilization in order to reach an optimal combination. It also shows that early sowing and low N amounts would lead to minimisation of N losses, while later sowing and high N fertilization would lead to the highest yields. It is interesting to note that to date, the common combination of sowing as early as possible in May in the berg catchment (on average in the second week of May, i.e. index 6 on the graph) and applying 150 kg of N is one of the identified optima and, more specifically, a wise compromise in between these two conflicting objectives.

Under far future climate scenarios this linear relationship is forced later in time. According to the simulations, fertilization would have no impact for a sowing prior to 14 May, but only after that date. Then only a larger amount of N increases the simulated yields. Under these conditions the currently applied wise compromise would not be optimal any longer, and this single illustration result would suggest a delay in the sowing date under far future climate conditions.

6.4.5 Tentative Conclusions

The results emphasise the conflict that lies in the investigation of efficient alternatives. Indeed, cropping systems are usually promoted either for larger productivity, or for climate change adaptation and soil pollution control. The results shown in this section illustrated that focusing on a single one of those aspects would disproportionately and detrimentally impact on the other. Here is an approach in which criteria are optimised from both sides, and the approach thus explores multi-objective optima in which sensible compromises are selected before making a final decision.

This approach requires large computing resources to handle multi-criteria comparisons, a large decision space and a large criteria space. It does, however, provide the final decision maker with compromises otherwise excluded, as well as a potential quantification of benefits vs. costs of the different options. The inclusion of variable and changing daily climate input also allows a representation of the sensitivity of the outcomes to both inter-annual variability and climate change.

6.5 CASE STUDY 5: APPLICATIONS OF SCIENTIFIC RAINFALL FORECASTS AND INDIGENOUS KNOWLEDGE IN THE MODDER / RIET CATCHMENT (G Zuma-Netshiukhwi and S Walker)

6.5.1 Background

The study was conducted in the Modder / Riet catchment covering the central-west of the Free State and part of the Northern Cape (cf. **Chapter 5**). This catchment covers the Motheo and Lejweleputswa districts. Farmers who participated and benefited from this project were identified in or near the following towns: Sannaspos, Brandfort, Soutpan and Koffiefontein. Operational study groups were identified in Sannaspos and Koffiefontein, and re-established in Brandfort and Soutpan for preliminary survey, investigation and impact assessment. Farmers who participated were commercial and resource poor farmers conducting either or both rainfed and irrigation farming.

6.5.2 Farming Systems

Motheo involves a large area of commonage farming with sheep and cattle. The predominant crops planted in this area are vegetables, maize, sunflower and sorghum. Lejweleputswa is also dominated by livestock, vegetables, maize and sunflower production under dryland farming and irrigation (www.fsagric.fs.gov.za).

During study groups and / or on-farm visits, participatory tools to engage with the farmers were successfully utilised to interact with the farmers. The effective tools for participatory interaction during weather forecast discussions were identified to be monthly meetings held regularly. Participatory tools and techniques were used to collect research data. These included individual interviews, key informants, focus group discussion and buzz questions. At meetings held with the farmers the buzz questions were asked to probe for more information. The farmers showed a willingness to learn, participate and have access to weather / climate information.

The participants age group ranged from 23 and 87 years. Some farms in the study are owned by a group of beneficiaries that benefited from Land Redistribution for Agricultural Development (LRAD), others were individually owned, family owned, government owned (leased farms) or operated by original farm owners. Each farm is headed by the elders in a group or family to guide and signal which agricultural activities are suitable for the season. At meetings, farmers and stakeholders from different sectors were invited to come and inform the farmers on their role to the community, e.g. fire fighters, bank representatives, food processors, animal producers, agricultural unions and successful commercial farmers. The discussions were very stimulating and inspiring and for the fact that 70% of participants were elders. Participant attendance during the study increased as they realised that they could receive useful weather and climate knowledge produced from scientific methods and discuss their indigenous knowledge and experiences.

The scientific weather / climate information is available to commercial farmers, but resource poor farmers had no access to scientific forecasts. However, the commercial farmers also used traditional indicators to forecast rainfall, although they depend mostly on scientifically proven information. From the survey that took place during the diagnostic phase, it became known that agrometeorological information was not popular, as shown by 88% of farmers. The commercial farmers use scientific information available from different sources through internet, their farming experience and traditional indicators, but most resource poor farmers need thorough training to the use of scientific information to make improved on-farm decisions for improved crop production and yields so as to sustain food security. During the survey farmers listed different types of agricultural enterprises operational on their farms, financial constraints to run farms, lack of implements to prepare the land, and other constraints.

In the Modder / Riet catchment farmers are involved in crop and livestock production. The results from a survey investigating the exposure farmers have to weather / climate information showed that 88% (**Table 6.5.1**) of farmers that responded to questionnaires had no exposure to weather / climate forecast, and that they developed decisions for farming guided by indigenous indicators to predict rainfall. Therefore, this study explored how the farmers use traditional indicators for short-term and long-term planning for the rainy season. The main crops that are planted in the area are maize, sunflower, lucerne, wheat and vegetables produced under rainfed conditions. However, farmers are faced with, and have to adapt to, climate variability and the most common and threatening weather and climate hazards were identified as floods, drought, strong dry winds, black frost and hailstorms. The lack of skill to select suitable planting dates for the coming sowing season and interpreting the forecasts could have adverse impacts, resulting in food insecurity, sometimes starvation, malnutrition and hunger. For example, floods could result to overflowing of dams and river banks, causing damage to field crops by causing waterlogging and plant damage. Early frost could destroy flowers on fruit trees, early planted vegetable seedlings and reduce crop quality. Strong winds could result in losses of livestock and result in soil erosion.

Table 6.5.1 Farmers with and without access to scientific rainfall forecasting from a 2007 survey

Number of Participants	Those who have Access to Scientific Forecasts	Those who Use Indigenous Knowledge
394	11%	88.8%

Weather and climate forecasts are one risk management tool that plays a role in agricultural decision making. All agricultural enterprises are productive according to the given climatic conditions of a particular environment. This project encouraged the farmers to make use of indigenous knowledge, farm experience and scientific weather forecast available from the South African Weather Service (SAWS) and other institutions that produce weather forecasts, so as to produce balanced and scientifically grounded decisions. This information could be used to support farmers to help them understand when, where, what and how to select a suitable agricultural enterprise, tillage method, cropping system and the proper time to engage in certain agricultural activities.

After identifying different difficulties confronted by the farmers to be successful in agricultural business, the introduction of different types of weather / climate information to the farmers and agrometeorological advisories became the priority. Having understood that there was no support service to provide climate related information to most farmers, it became the researchers' tasks to set topics with the farmers that were discussed relating to scientific information for improved decision making and management practices.

Indigenous rainfall indicators (**Table 6.5.2**) were identified during the survey so as to make weather / climate information useful to the farmers in addition to the traditional indicators they understood. Looking back to the long-term rainfall data, for example, the impacts of the floods that occurred over parts of South Africa in the 1975, 1987, 1988, 1995 and 2001 seasons and the droughts that occurred in the 1963, 1979, 1983, 1997, 1998 and 2002 seasons, could have been reduced with forecasts of such harsh events, and farmers would have been able to make adjustments according to the forecasted events. For example, during drought seasons the farmers could have used drought tolerant crops or early maturing plants and other intervention strategies as necessary. Integration of scientific and indigenous information could be useful to augment and improve on-farm decision making strategies, especially considering that farmers operate on different perceptions. Therefore, verification of traditional rainfall and seasonal forecast becomes a point of interest to try to investigate how traditional indicators are influenced by climate parameters since they are used as traditional rainfall or seasonal predictors in the southwestern Free State.

The scientific forecasts are difficult to interpret and incorporate into decision making by both commercial and resource poor farmers. Such weather information as broadcast on a daily basis on radio and television stations is not sufficient to guide a farmer for long-term planning, but only sufficient to make decisions for tactical (i.e. the season ahead) planning. Therefore, traditional indicators are used by resource poor farmers as indicators of planting season and activities to be taken. In regions or districts dominated by commercial farmers, who have access to all types of scientific information, the use of indigenous knowledge is valueless, is disappearing and considered a myth.

A total of 394 commercial and resource poor farmers responded to the request to filling in a questionnaire, so as to get their perspective regarding the use of indigenous knowledge to predict climate conditions. The total of 80% of participants acknowledge the existence of environmental indicators used to predict climate irregularities such as drought, floods, frost days, thunderstorms, etc. The farmers and officials in the Department of Agriculture, Forest and Fisheries for the selected region became the key informants on the traditional indicators, and its interpretation that is communicated informally through individual contacts and community gatherings.

These traditional indicators are based on a variety of aspects such as the month of the year, soil wetness after rainfall, appearance of plants, animal behavior and appearance of birds and insects, moon phases, star constellation, clouds, wind and temperature. The appearance of plants and cloud types are the factors that appeared to be most favoured by farmers. For example, the sprouting of a variety of plants including aloes (*Aloe ferox*), peach trees (*Prunus persia*), apricot trees (*Prunus armeniaca*) and the shedding of leaves of the fig tree (*Ficus carica*) indicate the beginning of the planting season (**Table 6.5.2**).

Table 6.5.2 Indigenous indicators and their use in interpreting rainfall conditions

Indicator	Weather Related Indicator	Time of Occurrence	Activity to Do or Action to Take
Appearance of plant	• Blossoming of fruit trees above normal like peach (*Prunus persica*), apricot (*Prunus armeniaca*), budding of *acacia spp*., and other ornamental trees in the farm surrounding and development of young leaves, grass emerging, sprouting of *Aloe ferox* in the mountains is the indication of good rains • Flowering of wild lilies in the veld indicates summer ha arrived • Dropping of fruits before maturity indicates very dry season or drought season ahead • Dropping of leaves of fig tree (*Ficus carica)* indicates summer • Immature fruits drying on trees and/or dropping from the trees is an indication of drought	September September September/October September September/October	Spring season, prepare for sowing in November Farmers should consider drought tolerant crops and short cultivar varieties
Months of the year	• July to forecast for first rains that moisten the soil, • August rains	July August	After rains the land can be ripped The soil is ready to be turned over to minimise weeds
Clouds	• Dark clouds indicates rainfall • Dark clouds are an indication of heavy rainfalls to occur within few hours • Dark clouds proceeding strong winds indicates thunderstorms in few hours • Rainbow colours: red dominating means more rains to come, if blue colour dominates and clear sky appears it means that rain has passed.	September-March Throughout the seas	Sowing/rainfall season Always be prepared to minimise damages that might occur due to heavy rains and arrange for roof water harvesting to be stored for use as irrigation is needed
Cloud types	• Stratus cloud is a sign for cold days	June, July	Prepare for extreme cold conditions
Soil structure and its dryness	• Soil well moistened tested by hand • Soil not well moistened	October-December October-December	Introduce seeds or seedlings under wet watered soils Wait for rainfall onset
Appearance of various insects	• Appearance of red ants and rapidly increasing size of anthills which are moist is used to predict good rains • Occurrence of army worms is an indication of drought	November/December Mid-April, July and early August	Prepare for sowing season Prepare for drought season
Birds	• First appearance of sparrows • Flock of swallows proceeding dark clouds	October-March	Rainy season is at hand farmers should prepare for planting and to minimise risk and disaster that might result from above normal rains

	• Migration and immigration of birds good sign of rainfall	October-March	Planting time for vegetables and cash crops suitable for the area, farmer should follow moon phases as control to the days with and without rainfall
Moon phases	• Moon crescent facing upwards indicates upholding water and when facing downwards is releasing rainfall in next three days • Moon surrounded by the moisture (halo profusion) means good rains • First rains should occur before the appearance of the new moon and full moon covered by the clouds indicates good rains	 September/November October/November	
Star constellation	• Star pattern and the movement of stars from west to east at night under clear skies, indicates indicate onset of rainfall in 3 days and patterns also used to predict cessation of rainfall	August-November	Prepare the land and buy inputs to plant as it is the rainy season, select suitable days, cultivar and crops to plant
Animal behavior of domestic animals	• Grunting of pigs indicates low humidity and increase in temperature • Well-fed calves jumping around happily in the veld and on their way home from grazing in the mountains and unwilling to graze the following morning indicates good rains on the way • Increased libido in goats and sheep with frequent mating is a sign for good rains	October to March Throughout the season August, September, October	Prepare for agricultural activities
Appearance of reptiles	• Certain snakes moving down the mountain sign of good rains • Frequent appearance of tortoises wandering around indicates should get good rains	August, September September- November	Prepare for growing season with good rains
Wind swirls	High frequency in occurrence of wind swirls is the sign for good rains	October-November	Farmers should prepare and plant since good rains are predicted
Wind direction	Early in the morning direction from W-E signal good rains	November-March	Prepare and plan ahead for rains to come
Mist covering hills and mountains	This is a signal for good rains to come	Throughout the season	Ensure that when rain comes the crops are already planted and developing
Atmospheric temperature	High temperature at night is a sign for good rains and a long crop growing season, low temperatures at night is an indication for late onset of rains and late planting season	September-November	Farmers plan on when to plant and crop types of a season to expect
Water sources	Drying up of wells, springs, river and wetlands rapidly is an indication of good rains	Spring	Farmers could prepare for a good rainy season and plan their activities in advance.

For example, vegetable farmers in the Lejweleputswa district said that sprouting of aloe plants and blooming of peach trees indicate the beginning of the rainy season and farmers should prepare land to plant immediately after rain water has infiltrated into the soil. Farmers in the Motheo district (Sannaspos) observe the behavior of livestock, and if calves are playing around in the veld, this is interpreted as the rains coming in 2-3 days (Mr Mahlanga, July 2007). In the Jakobsdal and Koffiefontein areas observations of the movement of snakes and tortoises are interpreted as the coming of a good rainfall season (Mr Mokhele, January, 2009), as turned out to be the case during season 2008 / 2009 (**Figure 6.5.1**).

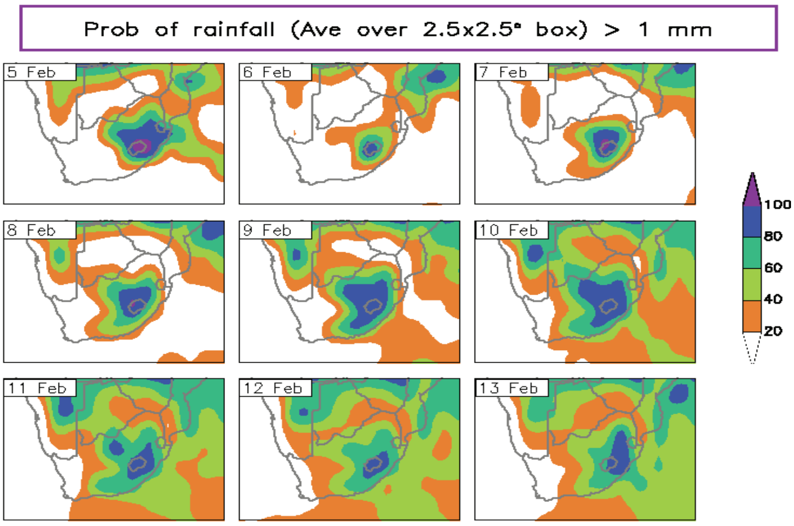


Figure 6.5.1 SAWS 14 day rainfall forecast for receiving > 1 mm during February 2008

Higher than usual blossoming of peach trees, apricot trees (Mr Martins, August 2008, Soutpan) and other trees in the southwestern Free State as occurred in September 2008 and 2009 was used by farmers to predict a good rainfall season, and it came to pass. It turned out that both the 2008 / 2009 and 2009 / 2010 seasons received good rains in this area. For the season 2008 / 2009, Mr Cilliers from Phillipolis noticed that the snakes and tortoises were busy in the veld and predicted that good rains were to come. When rains started falling he celebrated and cut off his beard after 27 years. The SAWS 14 day forecast showed a 60-80% probability of rainfall. Of the farmers surveyed, those who had been farming for more than 40 years in the southwestern Free State recalled the floods of 1987 / 1988 and 1995 and confirmed those to be La Niña years, while the droughts that occurred in 1983, 1997 / 8 and 2002 were recorded as El Niño years. Regrettably, when farmers were requested to share the indicators that appeared prior to these events, no forewarnings were recollected by the farmers interviewed, and they could only tell of events that had. Therefore, traditional indicators for rainfall and seasonal rainfall seem to provide predictions of only short lead times. The lack of these signs at times when expected is a weakness and can be seen as unreliable, and moreover there were no signs named that indicated when to expect a poor rainy season.

The indigenous knowledge and scientific products on rainfall forecasting differ, they operation at different scales and use different forecasting methods. However, for meteorological indicators such as wind patterns, temperature, clouds, etc. these are interpreted the same, for example, westerly winds in southern Africa bring moisture from the Atlantic Ocean and this condenses to produce precipitation. Farmers for decades have used biological, meteorological and astronomical indicators to forecast rainfall and scientific forecasters use meteorological indicators such as wind, sea surface temperature, clouds, etc. The scientific forecast is generated on a large geographic scale, i.e. on a 200 km grid, the lightning is observed over 5 km, and forecasts are provided at lead times of 6 hours, 7 days, 14 days, one month, a season and up to six months ahead. Indigenous knowledge, on the other hand, provides forecasts for only rainfall and for a very short time ahead, and this results in unreliability as it does not assist farmers to arrange for timing and distribution to make proper farming decisions. A scientific forecast provides a good indication of the probability of receiving a specified amount of rainfall, for example, the 14 day forecast presents the probability of receiving > 20 mm; > 5 mm (**Figure 6.5.2**) and > 1 mm (**Figure 6.5.1**) of rainfall.

Given below is the traditional rainfall forecast provided by Mr Danie Cilliers, alerting the farmers of good rains to come. He advised commercial, backyard gardeners and resource poor farmers to go back to the fields and plant vegetables, grain crops at high population densities since high rainfalls were expected. His forecast stated the following:

> *"Springbok are lambing well, snakes and tortoises are active and there was a full moon, which means lots of rain for Philippolis and the rest of southern Free State".* Farmers Weekly, 13 February 2008.

The 14 day rainfall forecast during 2008 February indicated the probability that ranged from 60-80% of rainfall greater than 1 mm (**Figure 6.5.1**) and 40-60% of receiving rainfall greater than 5 mm (**Figure 6.5.2**) for different days. Therefore, this is an indication that these two methods could complement each other. The difference between the two is that the scientific method is quantitative and provides forecast for a given lead time and at different scales whereas traditional methods are qualitative and only provide forecasts by observing environmental indicators.

The seasonal forecast issued in July 2008 indicated that above-normal rainfall was predicted for August, September, October, November and December. At the monthly meetings with the farmers the forecast was communicated two months in advance in a probabilistic manner, along with the advisory for the specified season. The advisory recommended two planting dates, *viz*. 15 November 2008 for farmers who irrigated and the last week of December 2008 for farmers producing rainfed crops.

The following probabilistic occurrences are presented in **Table 6.5.3** and **Figure 6.5.3**. The scientific forecast specified the chances of receiving rainfall on a three month basis. Higher probabilities, at 45%, of receiving rainfall were for the months October-November-December, the period which also shows the lowest chances of receiving below-normal rainfall at 22%.

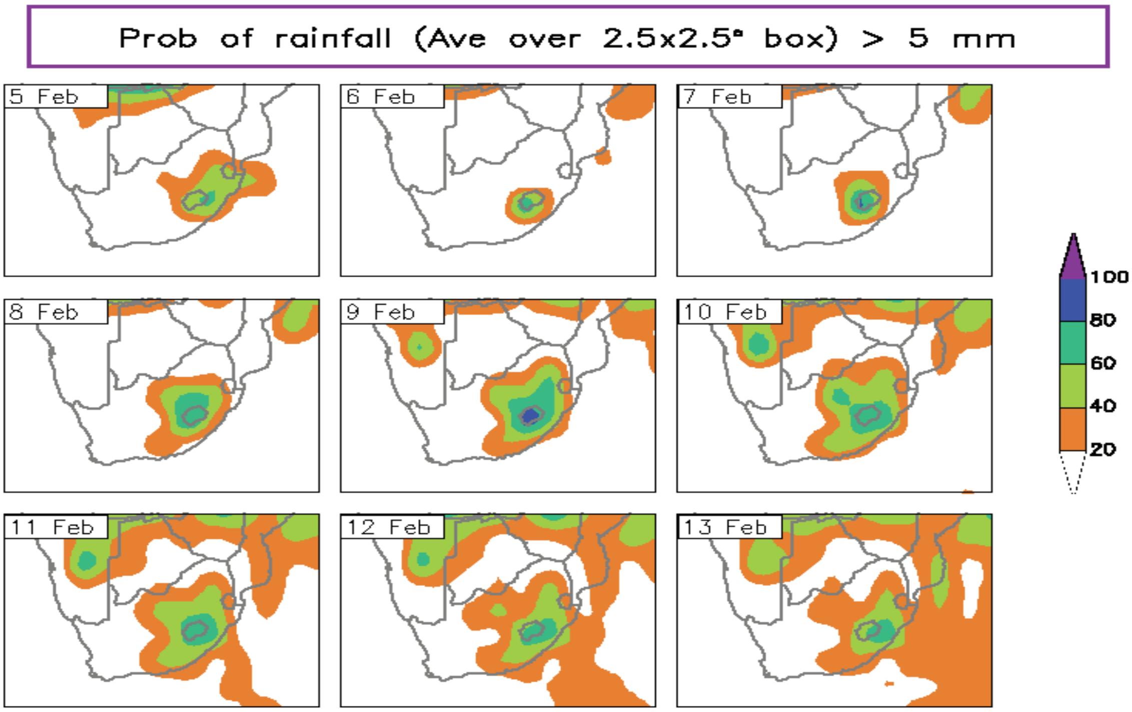


Figure 6.5.2 SAWS 14 day rainfall forecast for receiving > 5 mm during February 2008

Table 6.5.3 Rainfall probabilities for southern Free State from August to December 2008 (SAWS)

Probabilities	ASO (%)	SON (%)	OND (%)
Above-normal	40	40	45
Normal	27	27	33
Below-normal	33	33	22

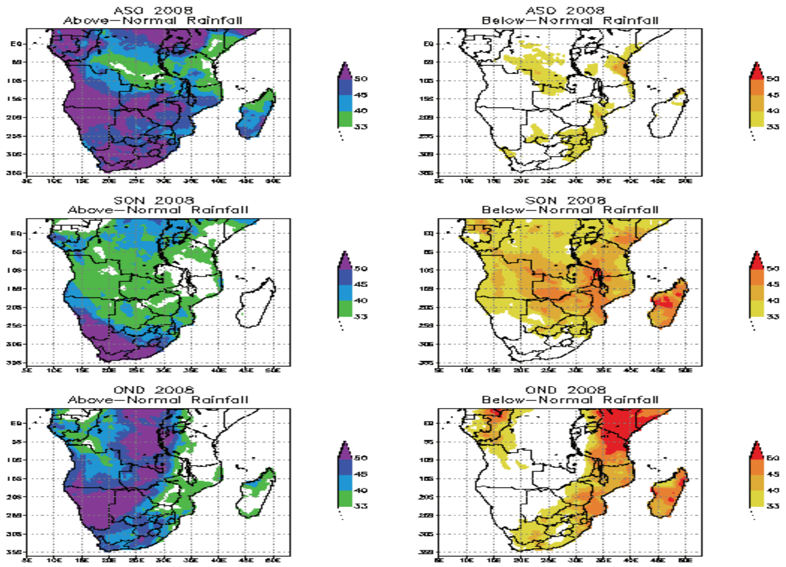


Figure 6.5.3 SAWS **r**ainfall probability map for August to December 2008

The other advantage of considering scientific forecasts over indigenous forecasts is that they provide a range of rainfall in a probabilistic manner for a specified lead time. Therefore, this information should guide the farmers to make tactical and operational decisions on agricultural activities such as land preparation or tillage, planting, weeding, fertilizer applications, insecticide applications, frost preventative measures, harvesting and crop storage. It can guide the farmer's decision throughout the planting season until harvest. On the other hand, weather / climate forecasting using indigenous knowledge only allows the farmers to make decisions in terms of possible rainfall onset using localised indicators such as the moon phases, wind direction and intensity during the planting season.

During 2008 / 2009, farmers argued about the reliability of the forecast and decided to wait and see what would happen, while using the indigenous knowledge such as observing the clouds, types of insects, wind patterns, etc. When in the first week of January the farmers observed a swarm of swallows flying around, they confirmed that it was the month to receive rainfall. They also observed the westerlies and witnessed that rainfall was to come in few days. In January to February 2010 after this exercise, farmers noted that they had received over 200 mm of rainfall. Another example is presented in **Figure 6.5.2**, whereby the farmer predicted cold conditions and lower chances of rainfall by just observing the cloud types. This observation and experience is a good indication that there is a possibility to bridge the two different knowledge systems. Some indigenous indicators thus possibly hold the same interpretive skill as scientific variables used for rainfall and temperature forecasts.

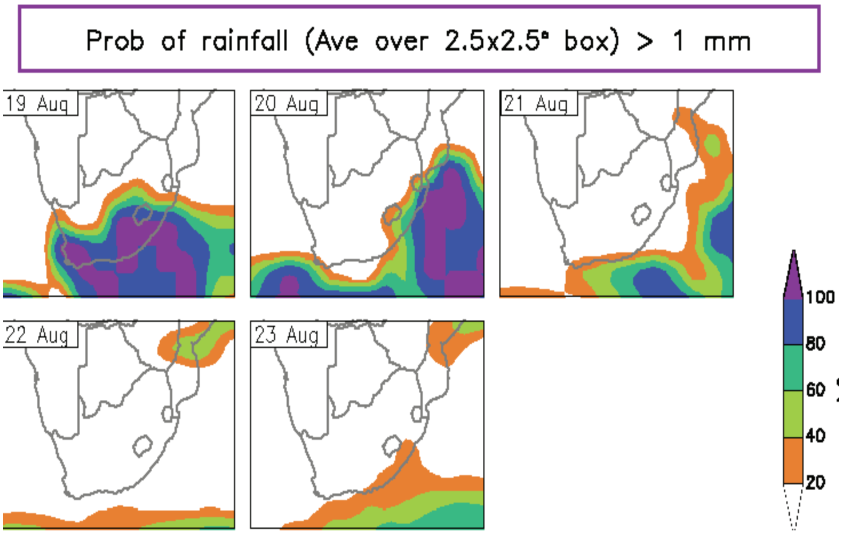


Figure 6.5.4 SAWS 14 day rainfall probabilities for August 2009

Mr Mpinga's rainfall forecast at an informal interview held November 2008 mentioned that the rainfall was expected to fall on the 3rd day of each month during the rainy season. The wind direction early in the morning at about 03:00, from west to east is a good indicator of rainfall. If the rainfall does not fall that means it should be expected on the 15th day of the same month. He said that, at about 05:00 the westerlies become light and disappear. Therefore, Mr Mpinga can tell if the rain is to come or not, and when it is expected to rain. His concern with his knowledge is that he cannot predict the approximate amount of rainfall to expect and when exactly to be expected.

The traditional forecasters for October 2009 were put to test (**Figure 6.5.5**). They were requested to predict rainfall and mention which the day or week that it should be expected. They were requested to communicate the indicators to the researcher before the rain came by using the Short Message System (SMS). The participating farmers followed the instructions and the outcomes were that, all participants predicted rainfall for the second week of October 2009. Comparing that to the 14 day forecast a probability of 80-100% from the 10-12 October 2009 was shown. During that period above 15 to 25 mm of rainfall was measured over three days. The indicators that were mentioned by farmers were busy reptiles in the veld, westerly winds at night, accumulation of dark clouds, flocks of swallows flying around and the smell of rain. It was also interesting to know that farmers claim that they can smell the coming of rains a day to a week before the rain occurs. As much as scientific rainfall forecasters perceive the indigenous rainfall indicators to be a myth (Landman, 2008, personal communication at the University of the Free State), the indigenous forecasters believe that it is only the Creator who is aware of the coming of rains or not, and not the scientists. The senior author's observation as the project progressed, was that farmers became more interested to learn about the weather / climate products and its usability for agricultural applications. For example, some farmers called the researchers to be updated on the seasonal conditions, and a few farmers made initiatives to have access to e-mail in order to receive weather bulletins for planning before the season started. The Ladybrand group sent their chairperson to request the frost chart for them in order to identify days free of frost as they intended to produce tomatoes.

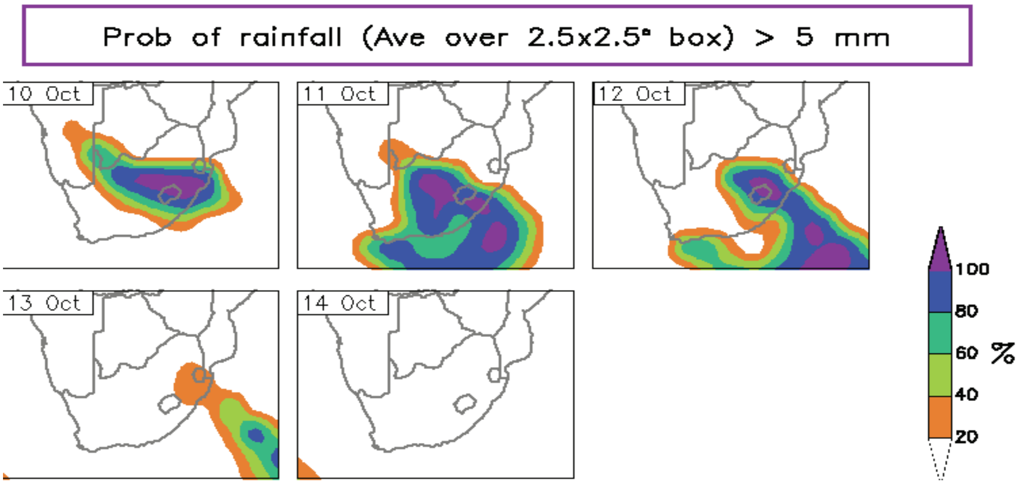


Figure 6.5.5 SAWS 14 day rainfall probability for October 2009

During the discussion groups with the farmers, they were requested to identify disadvantages of traditional forecasting which were mentioned as follows:

- it is not constant, but it can work well when combined with scientific forecasts,
- it is culturally based and interpreted differently for different areas,
- it does not provide future predictions,
- it cannot predict mid-season dry spells probabilities,
- it does not indicate a rainfall distribution per se, but only prepares for the onset, and
- it is not trusted by the scientific forecast producers as they perceive it as based on superstition.

The disadvantages with regard to the scientific forecast, the farmers mentioned that:

- it is not easily available and they were not sure where to obtain it,

- it is difficult to make decisions based on probabilistic information, and
- it is not point specific as it only covers the big towns, not villages or farm scale locations.

The best outcome from this study was that a system for the farmers to learn and share their information and experience was set up. Through the process of interacting with the farmers, farmers learnt and steadily adapted the use and the application of the weather / climate information and other agrometeorological information for agricultural decision making.

6.6 CASE STUDY 6: DEVELOPMENT OF SEASONAL RUNOFF, SOIL MOISTURE AND IRRIGATION DEMAND FORECASTS IN THE BERG / BREEDE CATCHMENT (TG Lumsden)

This case study details the application of seasonal rainfall forecasts to produce initial forecasts of runoff, soil moisture and irrigation water demand in the Berg / Breede Catchment system (described in **Chapter 5**). The study was exploratory in nature in that it was undertaken to help identify issues that would need to be addressed with regard to the future operationalisation of agrohydrological forecasting. These initial agrohydrological forecasts were developed at the scale of Quaternary Catchments. The challenges associated with applying relatively coarse (spatial) scale daily GCM forecast output directly in the *ACRU* model are discussed before describing the agrohydrological forecasts produced.

6.6.1 Challenges Associated with Applying Relatively Coarse Scale GCM Forecast Output Directly in the *ACRU* Model

The *ACRU* agrohydrological model (Schulze, 1995 and updates) was selected to develop agrohydrological forecasts for reasons given in **Section 7.5**. Before generating agrohydrological forecasts, the implications of applying relatively coarse scale GCM forecast output directly in a simulation model such as *ACRU* were investigated. The GCM forecasts considered were the C-CAM seasonal climate forecasts generated at the University of Pretoria. The C-CAM forecasts were supplied as a 12 member ensemble of daily rainfall, maximum temperature and minimum temperature for a three month period at a spatial resolution of 1° x 1° in latitude and longitude. Examination of the daily rainfall values in the forecasts revealed that there was a mismatch in temporal variability between the gridded forecast values and the typical values one would find in a dataset from a rainfall station where rainfall is measured at a point. Since gridded rainfall values represent the areal average of rainfall over a 1° x 1° resolution pixel, there are typically a higher number of raindays, combined with lower rainfall amounts per day, than would be observed in a point station dataset. This is illustrated in an analysis of the number of days where rainfall is equal to or above certain thresholds. This analysis was performed on the observed data for the station selected by Schulze *et al*. (2010) to represent rainfall in Quaternary Catchment G10A in the upper Berg River Catchment. The number of days that rainfall is above 0, 1, 5, 10, 20 and 40 mm as well as the number of days rainfall is equal to 0 mm was determined for a wet (1962), dry (1978) and medium (1996) June-July-August (JJA) season and is tabulated in **Table 6.6.1**. The analysis for the relevant pixel in the gridded rainfall forecast dataset for a recent season (JJA 2009) was also tabulated in **Table 6.6.1**. A randomly selected member of the forecast ensemble was chosen for this purpose. This member was later found to be a wetter than average member.

Perusal of **Table 6.6.1** reveals that the higher (5, 10, 20, 40 mm) thresholds of observed (point scale) rainfall are not too well represented by the C-CAM forecast (which represents area averages), and is indicative of the mismatch in temporal variability between the gridded forecasts and the observed station values. This is the case regardless of whether one compares the 2009 C-CAM forecast with a wet, dry or average year in the observed station record.

Table 6.6.1 Comparative analysis of number of days that daily rainfall thresholds over the JJA season are exceeded for the rainfall station representing catchment G10A, versus the corresponding pixel of the 2009 C-CAM seasonal forecast

Threshold	Number of Days a Rainfall Threshold is Exceeded			
	Observed Station Rainfall			C-CAM Forecast
	Wet Season	Ave Season	Dry Season	2009 Season
Days = 0 mm	53	51	64	39
Days > 0 mm	39	41	28	53
Days > 1 mm	39	39	26	23
Days > 5 mm	33	26	15	5
Days > 10 mm	25	21	12	1
Days > 20 mm	19	19	8	0
Days > 40 mm	14	13	7	0

A possible solution to this problem is to develop probabilistic categorical rainfall forecasts based on the C-CAM forecast data and then to use analogue observed data (from relevant stations) to represent the categorical forecasts at point locations. For example, if the categorical rainfall forecast was for above normal conditions, years in the observed record where rainfall was above normal would be selected for use in agrohydrological forecasting. Thus the rainfall files used in agrohydrological modelling would be derived from observed station data and would have a temporal variability that is typical of the point location concerned. The approach of using probabilistic categorical rainfall forecasts (sourced from SAWS), together with analogue observed data, was used successfully in the generation of the runoff, soil moisture and irrigation demand forecasts described in the following sections.

6.6.2 Seasonal Runoff Forecasts

A seasonal runoff forecast was generated for the Berg / Breede catchment system using the research based framework for agrohydrological forecasting that is reported in **Chapter 7**. The forecast was for the August-September-October (ASO) period of 2009, and was generated at Quaternary Catchment resolution. Model inputs (e.g. soils, land cover) were derived from the Quaternary Catchments Database with land cover being assumed to be natural vegetation (Acocks, 1988).

The rainfall forecast used in the generation of the runoff forecast was the ASO 2009 seasonal forecast issued operationally by the SAWS. This was a multi-model forecast, and included C-CAM as one of the component climate models. This forecast was a probabilistic categorical forecast. For reasons discussed in **Section 6.6.1**, this type of forecast when downscaled with analogue observed data overcomes the mismatch in temporal variability between observed data and coarse scale GCM data (highlighted in **Table 6.61**). The format in which this forecast was obtained and applied took the form of probabilities of below, near and above normal rainfall (averaged over the four component climate models used by SAWS) on a 0.5 degree resolution grid for the country.

When running the framework for agrohydrological forecasting it selects 20 analogue seasons from the 50 year historical record available, with the numbers of below, near and above normal seasons (for ASO) being in proportion to the rainfall forecast probabilities. The 20 seasons of data were then input to the *ACRU* model (according to the 'Historical Sequence Method' described by Ghile (2007) to generate the ensemble runoff forecast. Since up-to-date quality controlled and infilled observed rainfall data were not available for the lead-up period to the forecast season, data from two "average" historical years were used for the lead-up period. Thus the *ACRU* model was initialised for the forecast simulations assuming average wetness conditions.

Each member of the ensemble of daily runoff sequences was summed to give a seasonal total of runoff. These members' seasonal totals were then categorised as being either below, near or above normal in terms of the long term (50 year) simulated runoff record (determined in a separate exercise). This then allowed for the probability of below, near and above normal seasonal runoff to be calculated. The probabilities of below (P_{BN}), near (P_{NN}) and above (P_{AN}) normal seasonal runoff are presented in **Figure 6.6.1**.

There are no obvious patterns in the runoff forecasts. There are possibly more catchments that have a higher probability than chance (33%) for near normal runoff than there are for below and above normal runoff.

In an effort to summarise the information in **Figure 6.6.1** in a more qualitative form for decision-making, a map was produced which shades the catchments according to the category of runoff having the highest forecast probability (**Figure 6.6.2**). Intermediate runoff categories were introduced for this purpose, namely, below to near normal, near to below normal, near to above normal and above to near normal. The definitions of the qualitative runoff categories assumed are given in **Table 6.6.2**.

Referring to **Figure 6.6.2**, there are again no obvious patterns in the seasonal runoff forecast for ASO 2009. This may be attributable to the *ACRU* model being initialised for the forecast simulations assuming "average" wetness conditions, as opposed to actual conditions. The lack of obvious patterns would be likely to change if strong El Niño or La Niña conditions were to develop.

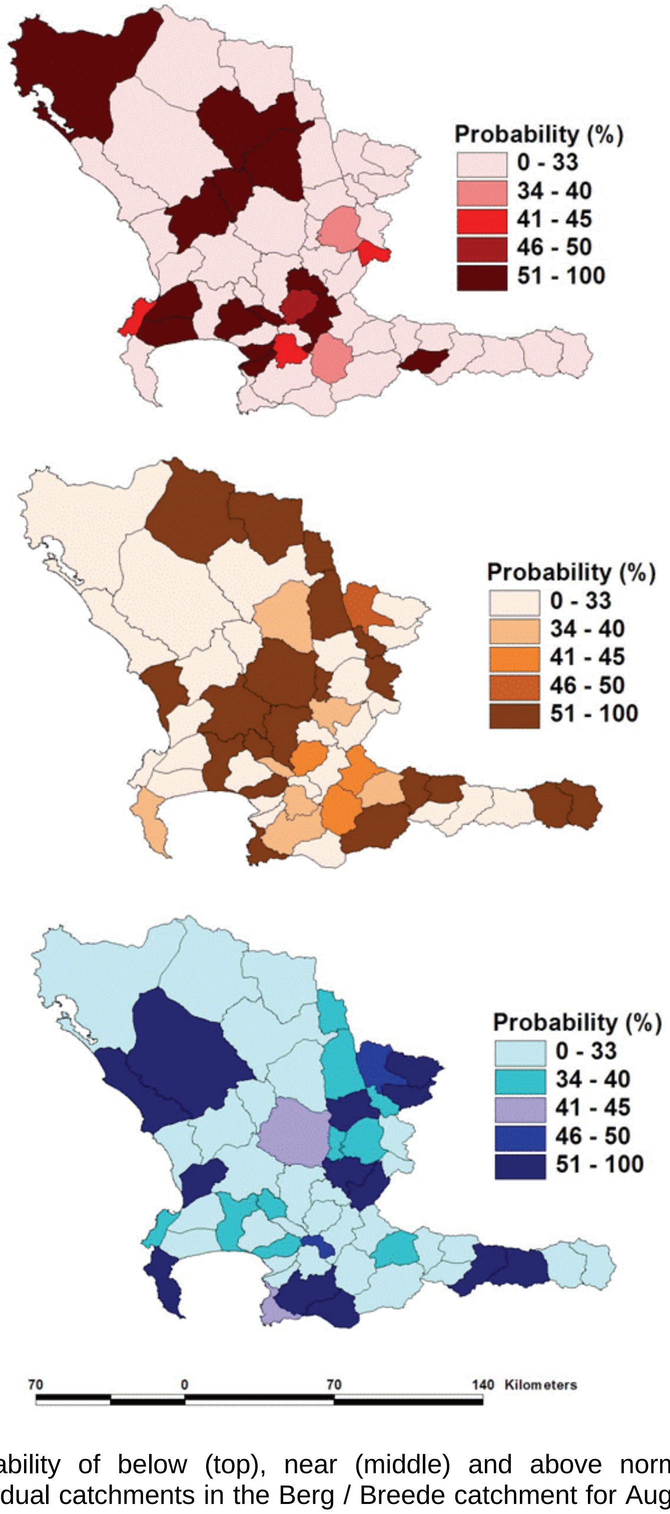


Figure 6.6.1 Probability of below (top), near (middle) and above normal (bottom) runoff for individual catchments in the Berg / Breede catchment for August-September-October 2009

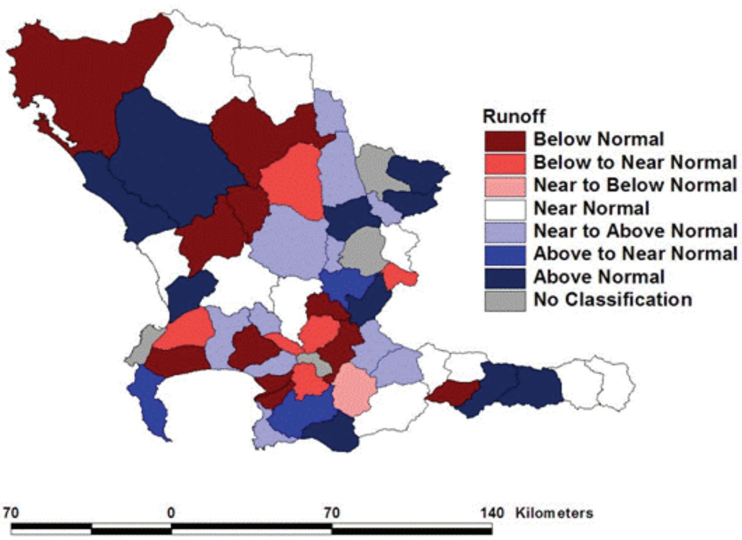


Figure 6.6.2 Qualitative forecast of runoff for individual catchments in the Berg / Breede catchment for August-September-October 2009

Table 6.6.2 Categories of runoff considered in the production of a qualitative forecast of runoff for the Berg / Breede catchment for August-September-October 2009

Qualitative Runoff Categories	Definition (Refers to Original Tercile Categories)
Below normal*	P_{BN} runoff is at least 40% higher than next most probable category of runoff
Below to near normal	P_{BN} runoff > P_{NN} runoff > P_{AN} runoff
Near to below normal	P_{NN} runoff > P_{BN} runoff > P_{AN} runoff
Near normal*	P_{NN} runoff is at least 40% higher than next most probable category of runoff
Near to above normal	P_{NN} runoff > P_{AN} runoff > P_{BN} runoff
Above to near normal	P_{AN} runoff > P_{NN} runoff > P_{BN} runoff
Above normal*	Probability of above normal runoff is at least 40% higher than next most probable category of runoff
No classification	P_{AN} runoff > P_{NN} runoff and P_{BN} runoff > P_{NN} runoff OR Probabilities of two categories of runoff are equal and probability of third category is not at least 40% higher than the equal categories

* take precedence over intermediate category definitions

6.6.3 Soil Moisture Forecasts

The generation of agrohydrological forecasts was expanded to include soil moisture forecasts. Soil moisture is an important variable to consider in assessing, for example,

- plant growth
- stormflow generation
- in-field trafficability of farm machinery and soil compaction.

A seasonal forecast of soil moisture in the topsoil (i.e. the so-called 'A' horizon) was generated for the August-September-October (ASO) season of 2009. The research based framework for agrohydrological forecasting (**Chapter 7**) was utilised to generate the forecast. Within this framework, the *ACRU* model was applied, with model inputs (e.g. soils) being derived from the Quaternary Catchments Database (Schulze *et al*., 2005). Land cover was assumed to be natural vegetation throughout the Berg / Breede system. The SAWS seasonal rainfall forecast for ASO 2009 was used in generating the soil moisture forecast. Since up-to-date quality controlled and infilled observed rainfall data were not available for the lead-up period to the forecast season, rainfall data from two "average" historical years were used for the lead-up period. Thus the *ACRU* model was initialised for the forecast simulations assuming average wetness conditions.

Each member of the ensemble of daily soil moisture sequences produced was averaged to give a seasonal average of soil moisture. These members' seasonal averages were then categorised as being either below, near or above normal in terms of the long term (50 year) simulated soil moisture record. This then allowed for the probability of below, near and above normal seasonal soil moisture to be calculated. The probabilities of below (P_{BN}) and above (P_{AN}) normal seasonal soil moisture are presented in **Figure 6.6.3**.

Figure 6.6.3 shows that probabilities of below normal soil moisture are generally higher than those for above normal conditions. Different methods of presenting the probabilistic forecast information need to be explored in consultation with end users.

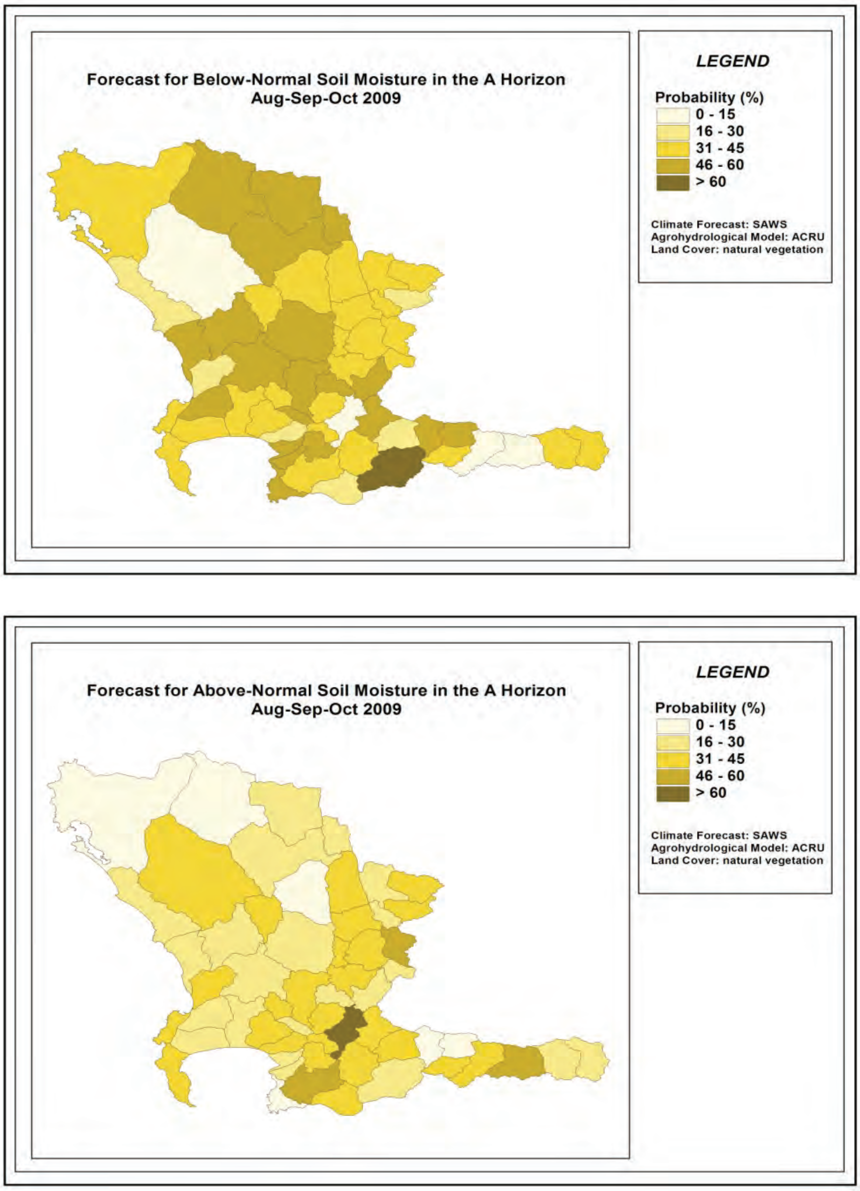


Figure 6.6.3 Probability of below (top map) and above normal (bottom map) soil moisture in the topsoil (A) horizon for the Berg / Breede System for August-September-October 2009

6.6.4 Irrigation Demand Forecasts

The potential to generate an irrigation demand forecast was evaluated. Forecasts in the study area could be generated for a single soil with its characteristics or for multiple likely soils each with their respective characteristics. The crop considered in these forecasts was grapes given their widespread distribution and economic importance in the Berg / Breede catchment. Drip irrigation was assumed in forecasts since this is widely practised. Thus interception of irrigated water was considered to be zero and spray evaporation losses were minimal. Irrigation on demand (e.g. at 50% depletion of plant available water) up to the soil's drained upper limit was assumed, as good management is practised in the region. An irrigation demand forecast was generated for ASO 2009, but is not shown here since the demand at this time of year is negligible owing to its being the beginning of the growing season. It also coincides with the end of the rainy season when soil moisture levels are high. Although the irrigation demands were negligible (and are not presented here), the work reported nevertheless demonstrates that irrigation demand forecasts can be produced.

6.6.5 Conclusions

The generation of the various agrohydrological forecasts presented in this case study in the Berg / Breede catchment has highlighted a number of issues that need to be addressed with regard to the future operationalisation of these forecasts. These issues include the following:

- The research based agrohydrological forecasting tool (cf. **Chapter 7**) does not automatically create analogue climate files for all catchments (currently it creates analogue climate files for one catchment at a time based on manual input from the user).
- The creation of analogue climate files does not account for leap years (currently done manually)
- A facility is needed to automate the process of running *ACRU* using the 20 analogue climate files created for a catchment.
- Actual observed climate data should be used in the lead up to generating a runoff forecast (instead of assuming "average" conditions). This depends on the availability of up-to-date, quality controlled / infilled (where necessary) observed climate data. There is also a need to incorporate a facility in the agrohydrological forecasting tool to automatically add these observed data to the analogue climate files before running *ACRU*.
- A facility is also needed to automatically process the daily output sequences simulated by *ACRU* to determine the seasonal totals/averages (depending on the variable concerned) and then to categorise them into below, near or above seasonal values.

6.7 CASE STUDY 7: EVALUATION OF SHORT AND MEDIUM RANGE RAINFALL FORECAST MODELS IN THE MGENI CATCHMENT FROM A HYDROLOGICAL PERSPECTIVE (YB Ghile and RE Schulze)

6.7.1 Introduction

Most agrohydrological models employed for short and medium range forecasting depend on quantitative precipitation forecast (QPF) inputs, which are issued as either deterministic or probabilistic forecasts or as ensembles of probabilistic forecasts, over a pre-determined lead time (Goswami and O'Connor, 2006). The basis of current short (i.e. 1-3 day) and medium (i.e. 4-15 day) range forecasting practice is Numerical Weather Prediction (NWP), a science that has been developed rapidly over the past few decades (Anstee, 2004). NWP models can be categorised into global, regional or mesoscale, based on the extent of their spatial cover. Global models have global extent, while regional models cover only a fraction of the globe such as a continental land surface and surrounding oceans. Mesoscale models cover a relatively smaller area, ranging up a few hundreds of square kilometres. Since the spatial resolution of NWP models is constrained by the computational time and memory capacity of the computers used to run them, global models have the coarsest resolution of the three categories whereas mesoscale models have, relatively, the finest resolution (Anstee, 2004).

Generally improvements of the NWP models with respect to spatial and temporal resolution, as well as to more detailed representations of the atmospheric processes, have led to a significant improvement of weather forecasts (Golding, 2000; Habets *et al.,* 2004). In spite of these improvements, the skill of the NWP models has not yet reached an acceptable level of confidence, especially for longer lead time forecasts (Habets *et al.,* 2004; Roads, 2004; Bocchiola and Rosso, 2006; Federico *et al.,* 2006). The reasons for this are that rainfall is hugely variable both in space and time, and that great uncertainties affect the performances of the NWP models (Bocchiola and Rosso, 2006). In NWP models, the physical processes, which are at sub-grid scale, are represented in parameterised form. Thus, NWP models cannot account for local environmental attributes that influence the production of rainfall (Maini *et al.,* 2004). Another key problem in NWP modelling is the instability of the atmosphere, as well as the sensitivity of the rainfall forecasts to small changes in initial conditions of the atmosphere (Ahrens and Juan, 2007).

According to Habets *et al.* (2004) the application of NWP precipitation forecasts into hydrological models to predict streamflows or peak flows is limited by three types of error:

- localisation of the events,
- timing of the events, and
- precipitation intensity.

However, NWP precipitation forecasts are often associated with other tools in order to correct some of the errors prior to their application with hydrological and/or crop yield models. Commonly used techniques that may improve upon these global-scale models are regional climate modelling and statistical post-processing methods (Hay and Clark, 2003; Habets *et al.,* 2004; Maini *et al.,* 2004). Such methods can account for the local topographic and other environmental variables that control precipitation (Maini *et al.,* 2004). The introduction of Ensemble Forecasting Systems (EFS) to account for the probability distribution of atmospheric states arising from uncertainties in the initial state has also enabled some NWP models (e.g. NCEP) to display better results than using only a single deterministic forecast that is initiated by the best known, but nevertheless uncertain, atmospheric state (Golding, 2000; Hay and Clark, 2003; Ahrens and Juan, 2007).

In South Africa, several institutions such as the SAWS, the University of Pretoria, the University of Cape Town and the Council for Scientific and Industrial Research (CSIR) have been actively involved in research relating to quantitative precipitation forecasting in order to make short (1-3 day) and medium (4-15 day) rainfall forecasts operationally feasible for application into daily time-step hydrological and / or crop yield models. Incorporating such forecasts within the research based framework for an agrohydrological forecasting system has been a major task of this study (cf. **Chapter 7**). At the present time, experimental forecasts issued by the SAWS from the National Centre for Environmental Prediction for Medium Range Forecasting (NCEP-MRF) model and the Unified Model (UM), as well as forecasts provided by the University of Pretoria and the CSIR from the

Conformal-Cubic Atmospheric Model (C-CAM), are incorporated within the framework for short and medium range agrohydrological applications. However, since these models have not been extensively tested in southern Africa, there is a strong need for objective assessments both in regard to rainfall characteristics and hydrological results in order to evaluate the skill and confidence of these models.

This chapter therefore aims at evaluating the archived rainfall forecasts from the C-CAM, UM and NCEP-MRF models on the Mgeni catchment. Methods of comparison and forecasting procedures are described in **Section 6.7.2**, while the results obtained from each model are briefly discussed in **Section 6.7.3**. Conclusions are presented in **Section 6.7.4**.

6.7.2 Methods of Comparison

The C-CAM and UM models have only recently (i.e. 2006) been adopted for southern Africa and the archived rainfall hindcasts from these two models are therefore only available for the period from May 2006 to date. The four highest daily observed rainfall events which occurred on 17 November 2006, 21 December 2006, 30 January 2007 and 04 March 2007 were selected for a pixel-by-pixel comparison over Quaternary Catchment U20E within the Mgeni catchment. Each 1' x 1' pixel value within U20E in the forecast lead time of the C-CAM and UM models was compared against the corresponding pixel value in the reference rainfall image and the Critical Success Index, CSI, the Probability of Detection, POD and the False Alarm Ratio, FAR (Wilks, 1995) were then used to assess the overall degree of their positional accuracy.

Observed and forecasted pixel rainfall values within each Quaternary Catchment (QC) of the Mgeni catchment were averaged to be used as input into the *ACRU* model for subsequent streamflow analysis. The semi-distributed catchment mode of the *ACRU* model was run with historical observed daily rainfall from year 2000 up to the time of the forecast start in order to create representative antecedent conditions and to initialise stores (e.g. soil moisture status in the top- and subsoil, the baseflow store and releases). Two scenarios were then used for the simulation of accumulated streamflows from subcatchments cascading downstream at the exit of each QC for the period from 01 November 2006 to 31 January 2007. For the first scenario, the *ACRU* model was run with rainfall forecasts obtained from both the C-CAM and UM models from the time of the forecast start up to the end of the forecast period, while for the second scenario the *ACRU* model was initiated at each day of the forecast period with observed rainfall of the previous day (i.e. up to the “this morning” state) before a hydrological forecast was made for the next day with rainfall forecasts obtained from the NWP models. In other words, the bias due to the incorrect initial state of the catchment was corrected and only the error in the rainfall forecast generates some differences with the reference run.

Daily rainfall values measured by raingauges distributed across the Mgeni catchment for the selected evaluation period were interpolated using the Natural Neighbour method to serve as the “ground truth” for the verification. The “observed streamflows” were the simulated streamflows with the *ACRU* model using the so-called ground truth rainfalls. The coefficient of determination (r^2), bias, Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) were then computed in order to assess the skill of the C-CAM and UM models with and without updating schemes. Owing to the scale gap, the NCEP-MRF forecasts at grid box of 2.5° cannot be applied directly with the *ACRU* model. These forecasts were therefore verified only against observed rainfalls.

6.7.3 Results and Discussion

The four selected rainfall events*, viz.* on 17 November 2006, 21 December 2006, 30 January 2007 and 04 March 2007 have been named Event A, Event B, Event C and Event D, respectively, for the sake of comparison in this chapter. Since each model runs for different lead times and at different spatial scales, individual comparisons against observations were first presented in **Sub-sections 6.7.3.1, 6.7.3.2** and **6.7.3.3** in order to assess to the extent to which the lead time of each model is skilful, while in **Sub-section 6.7.3.4** the comparison between the combined output of the C-CAM and UM models and the observational reference are discussed.

6.7.3.1 Evaluation of the C-CAM rainfall forecasts

C-CAM is a variable-resolution, hydrostatic model developed by the CSIRO in Australia for the purposes of regional climate modeling and numerical weather prediction (cf. McGregor, 2005a). The model is formulated on a quasi-uniform grid, derived by projecting the panels of a cube towards the surface of the earth. The two dimensional projection of the squares onto the sphere forms the horizontal grid pattern used for the atmospheric model (e.g. McGregor, 2005a; McGregor, 2005b). An innovation that makes the C-CAM model more powerful is the ability to stretch the conformal-cubic grid over any selected region by a method termed the “Schmidt transformation” (McGregor, 2005a; McGregor, 2005b). The C-CAM model has been adapted not only for short and seasonal term forecasting, but also for future climate change projections over southern Africa. Engelbrecht (2005) and Engelbrecht et al. 2009) has, for example, applied the model for climate change simulations over southern and tropical Africa for the period 2070-2100.

By November 2007 the archived hindcasts were available only for the 15 km spatial resolution rainfall forecasts of 4 days’ lead time (Engelbrecht, 2007). The evaluation of these forecasts is presented here.

A visual comparison of the 4 day lead time rainfall forecast over QC U20E is presented in **Figure 6.7.1** for the four selected events. The distributions of Hits (H), Misses (M), False Alarms (FA) and Correct Nulls (CN) within the threshold of 50th percentile are given in **Figure 6.7.2**. For Event A the 1 and 2 day lead time forecasts displayed similar distribution with 7.8% FA and 92% CN, while 92% of

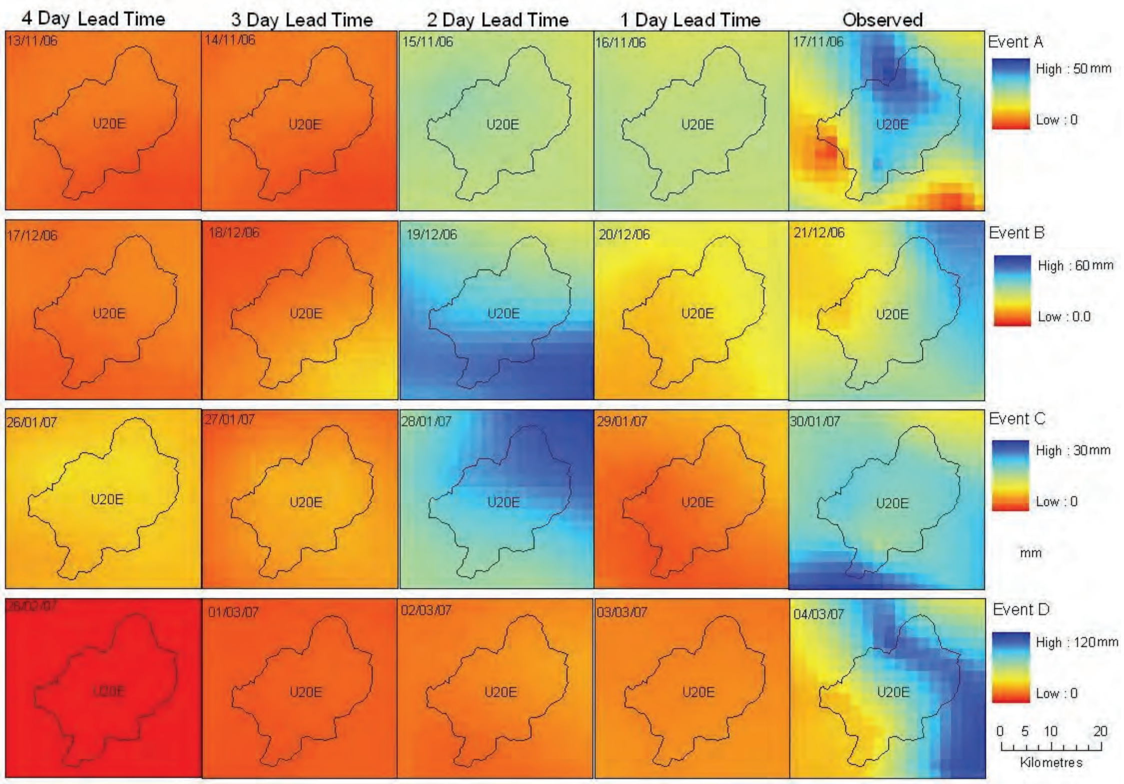


Figure 6.7.1 Four day lead time rainfall forecasts from the C-CAM model over QC U20E in the Mgeni catchment for Events A to D on 17 November 2006, 24 December 2006, 30 January 2007 and 04 March 2007

the pixel rainfall values were missed in the 3 and 4 day lead time forecasts. For Event B the 1, 3 and 4 day lead time forecasts missed majority of the pixels with large rainfall values. On the contrary, the 2 day lead time forecast for Event B tended to over-estimate, even though majority of the rainfall pixels are scattered in the CN range. Similar to Event B, the 1, 3 and 4 day lead time forecasts for Event C are clustered with the range of H and M ranges, while most of rainfall pixels for the 2 day lead time forecast fell within the ranges of FA and CN. For Event D the C-CAM model captured the pixels with low rainfall values, but most of the pixels with large rainfall values are missed (**Figure 6.7.2**). The pixel-by-pixel comparisons of the CSI, POD and FAR (**Equations 3.5**, **3.6**, **3.7** in **Chapter 3**) as a function of threshold rainfall percentiles for these four events are presented in **Figures 6.7.3** and **6.7.4**. For Event A the 1 and 2 day lead time forecasts displayed similar results with CSI and POD scores up to the 70th percentile, while the skill for the 3 and 4 day lead time forecasts was only up to the 20th percentile. No FAR was scored for Event A except for the 1 and 2 day lead time forecasts at the 60th and 70th threshold percentiles.

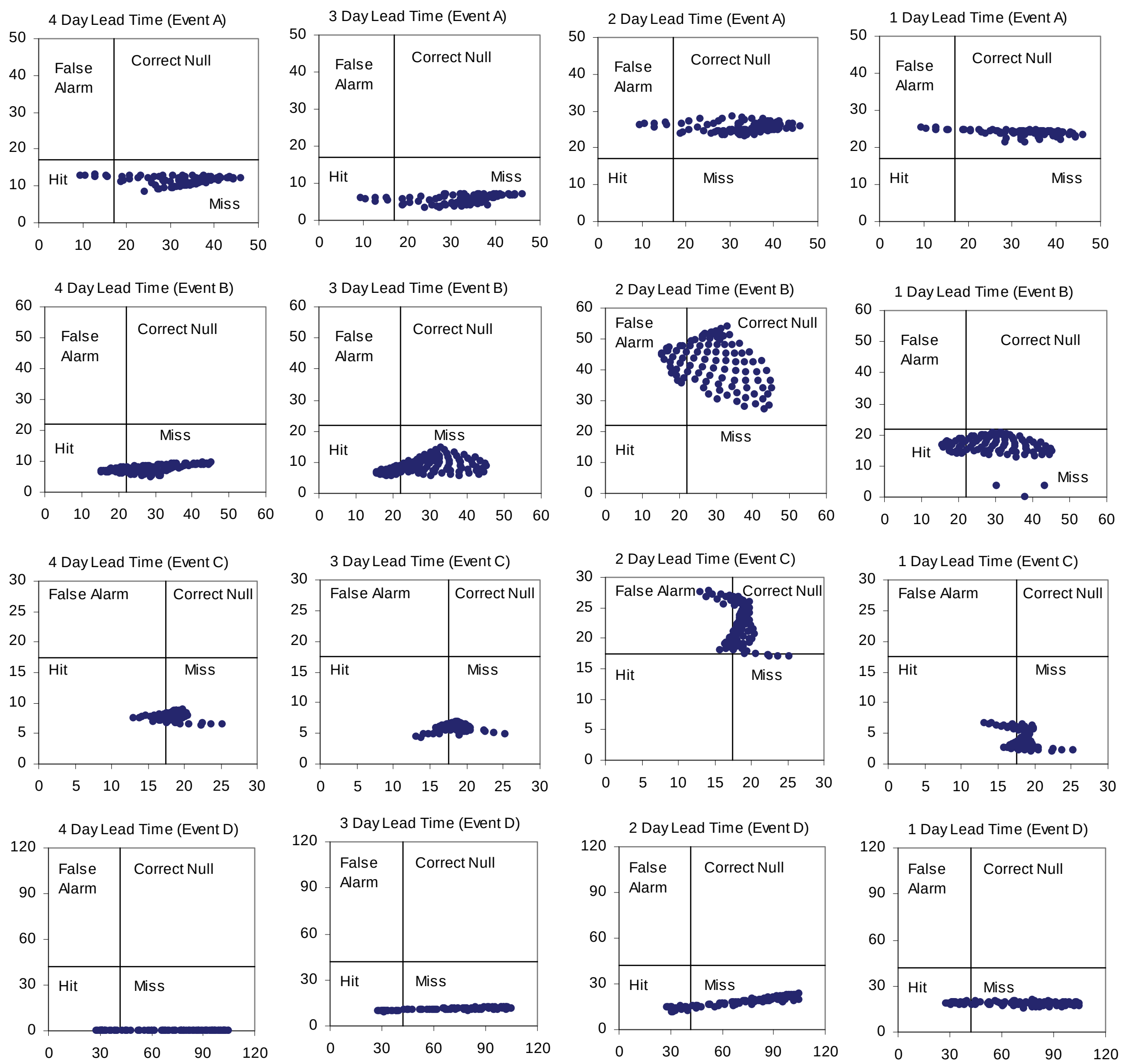


Figure 6.7.2 Scores of Hit, Miss, False Alarm and Correct Null defined by the threshold of 50th percentile for 17 November 2006, 24 December 2006, 30 January 2007 and 04 March 2007

Surprisingly, for Events B and C the 2 day lead time forecasts edged out the 1 day forecast, with CSI and POD scores up to the 70th and 80th percentiles, respectively. However, most pixel rainfalls in the 2 day lead time forecasts for these two events were significantly above their corresponding pixel rainfalls from observations, resulting in high FAR scores in most of the higher threshold percentiles (**Figures 6.7.3 and 6.7.4**). On the day of Event D more than 100 mm of rainfall was recorded by five raingauges located around QC U20E. However, the C-CAM model has failed to capture the higher pixel rainfalls even on the 1 day lead time forecast. Most pixel rainfalls in the forecasts were significantly below their corresponding pixel rainfalls in the observations (**Figure 6.7.4**).

The 1 day lead time forecast displayed relatively more skilful forecasts than the longer range forecasts and was used as input into the ACRU model for streamflow simulations both with and without updating scenarios for the period of 01 November 2006 to 31 January 2007. Plots of daily and accumulated daily streamflows cascaded from all QCs to the mouth of the Mgeni catchment for the two scenarios are presented in **Figures 6.7.5** and **6.7.6** respectively.

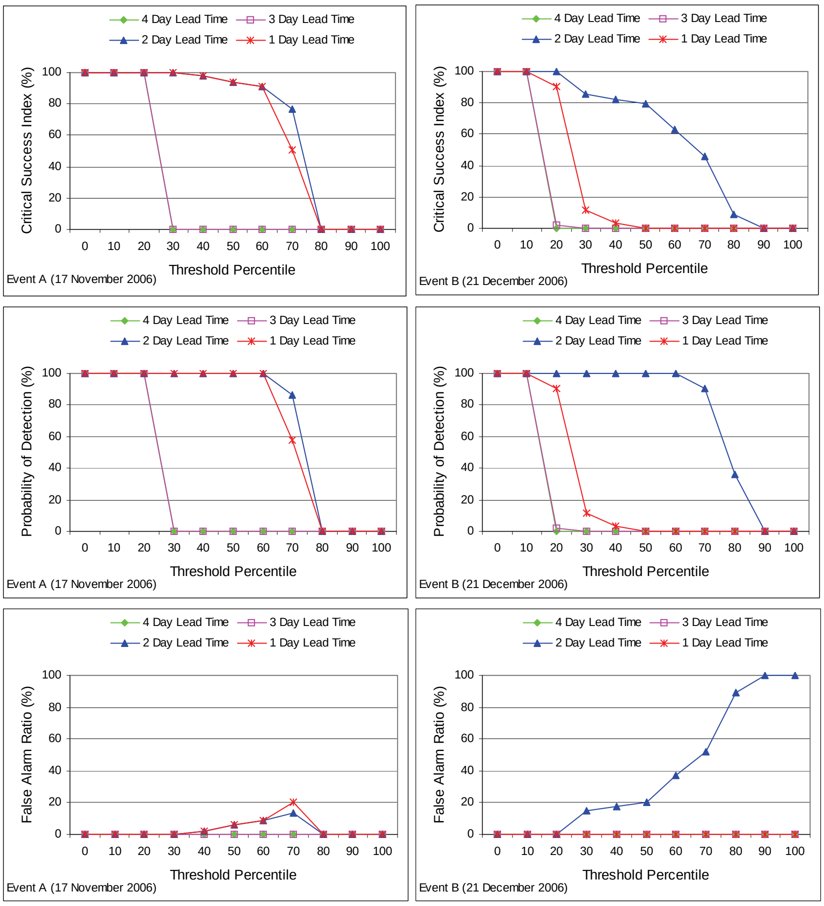


Figure 6.7.3 CSI, POD and FAR scores of 4 day lead time forecasts from the C-CAM model as a function of threshold percentiles for the rainfall events of 17 November and 21 December 2006

The streamflow forecasts when using the C-CAM rainfall forecasts without the updating scenario displayed significant under-estimation. The explanation for this under-estimation obviously lies in the fact that the ACRU model was initiated with uncorrected rainfalls on each successive day throughout the study period. The error cascade in the rainfall forecasts of each day had a significant influence on the ACRU streamflow simulation state variables such as the fraction of water that become a streamflow from the topsoil, subsoil and intermediate/groundwater stores on a given day, and consequently on the streamflow forecasts. However, the C-CAM based streamflow forecasts were seen to improve considerably when the ACRU model was initiated with observed rainfalls at the start of each day in the forecast period. As may be seen in **Figures 6.7.5** and 6**.7.6**, the daily time series and accumulated daily streamflows simulated with the updating scenario appeared much closer to the reference streamflows, with the total streamflow ratio was improving from 0.56 to 0.90.

Statistical comparisons with respect to the coefficient of determination (r^2), bias, the Root Mean Square Error (RMSE) and the Mean Absolute Error (MAE) are presented in **Figure 6.7.7**, so as to highlight the significance of the improvements made by the updating procedure. As was expected, the r^2 values are relatively higher for the updated forecasts, ranging from 0.23 to 0.72 for the various QCs that make up the Mgeni catchment, thereby indicating a better agreement than the uncorrected scenario for which the r^2 range was only between 0.01 and 0.37. The updating procedure has also reduced the bias, RMSE and MAE values to minimum levels (**Figure 6.7.7**), suggesting that the daily correction of the *ACRU* streamflow state variables based on observed rainfall has a significant influence in reducing both the systematic and random errors in the accumulated streamflow forecasts.

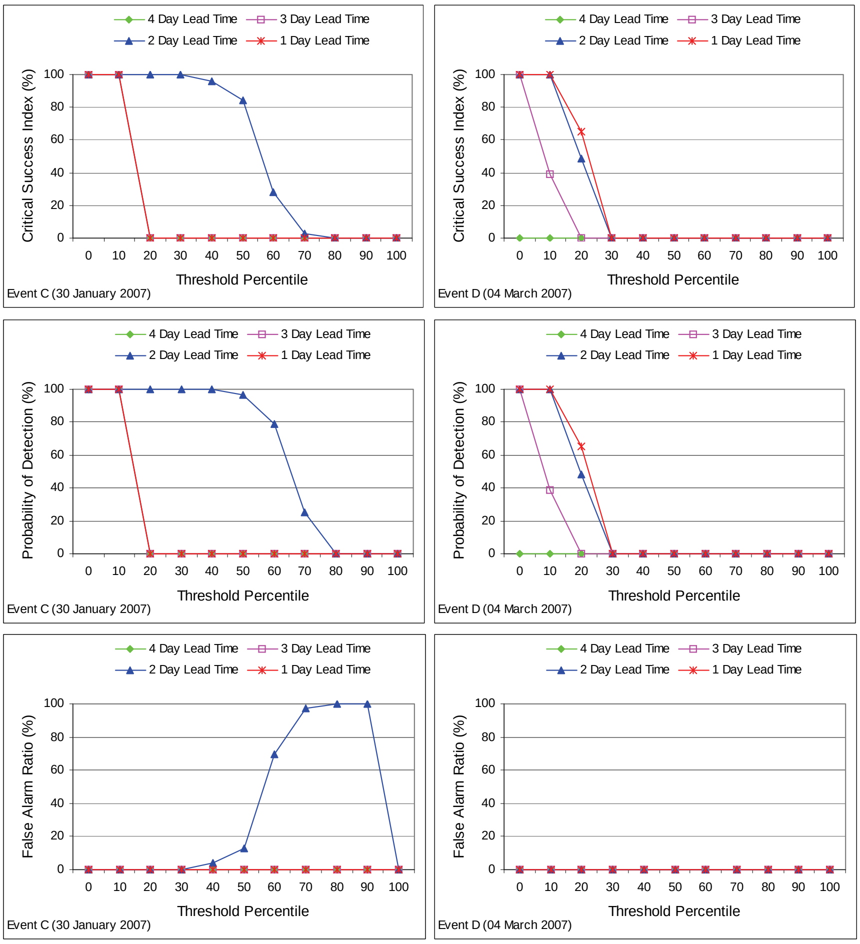


Figure 6.7.4 CSI, POD and FAR scores of 4 day lead time forecasts from the C-CAM model as a function of threshold percentiles for the rainfall events of 30 January and 04 March 2007

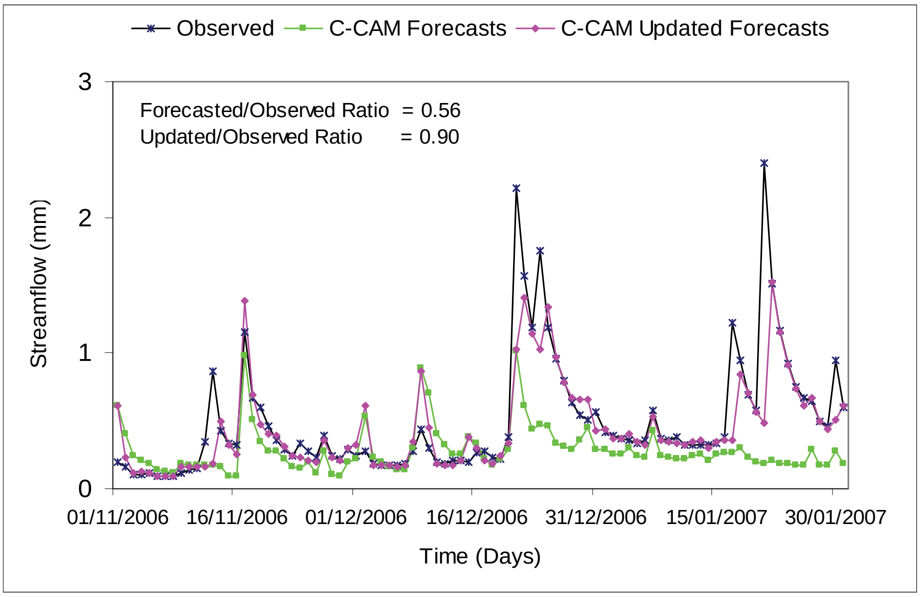


Figure 6.7.5 Time series comparisons of daily streamflows simulated with the ACRU model at the mouth of the Mgeni catchment, derived from the C-CAM rainfall forecasts both with and without updating procedures for the period 01 November 2006 to 31 January 2007

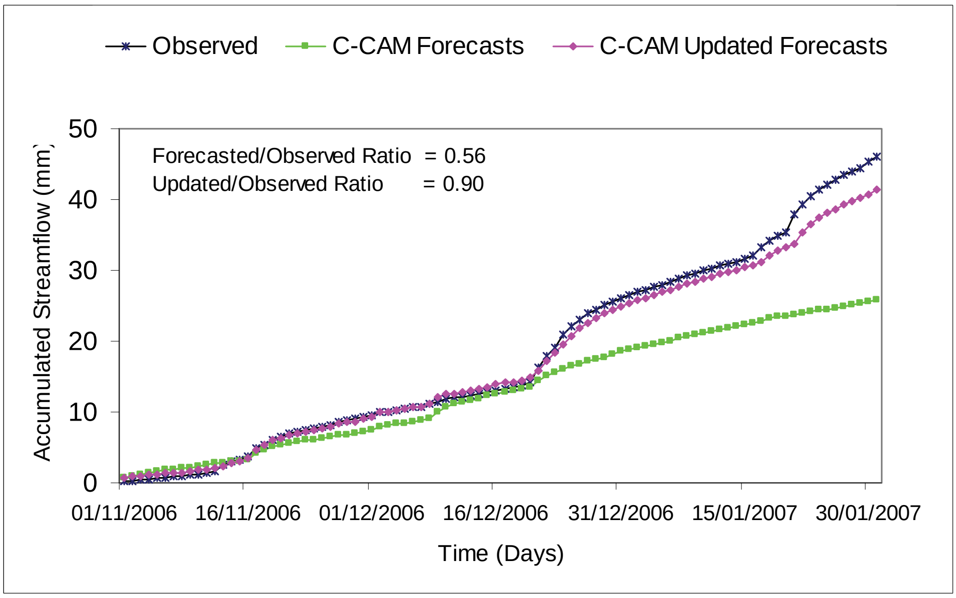


Figure 6.7.6 Comparisons of accumulated streamflows simulated with the ACRU model at the mouth of the Mgeni catchment, derived from the C-CAM rainfall forecasts both with and without updating procedures for the period 01 November 2006 to 31 January 2007

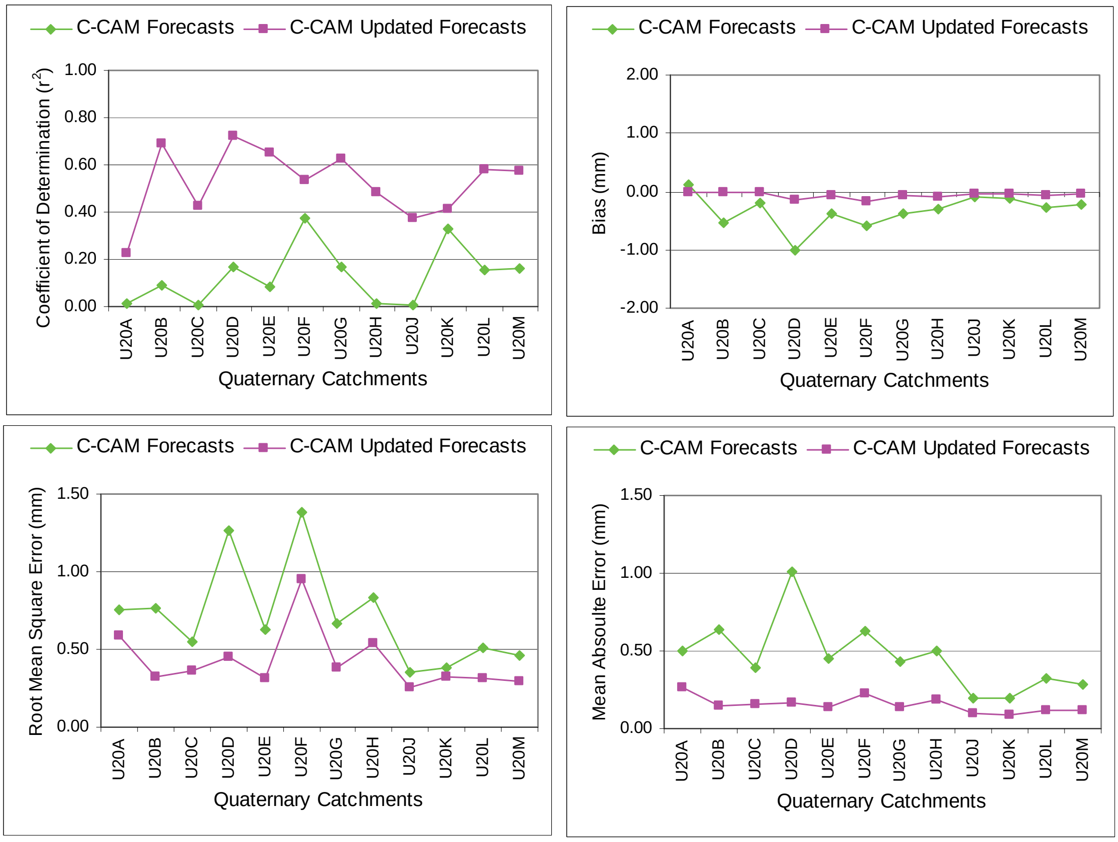


Figure 6.7.7 Coefficient of determination, bias, RMSE and MAE of accumulated Quaternary Catchment streamflows simulated with the ACRU model when using the C-CAM 1 day lead time rainfall forecasts both with and without updating, for the period of 01 November 2006 to 31 January 2007

In conclusion, the C-CAM model has suffered from both under-estimation and over-estimation in the analysis of the four individual daily rainfall events, indicating the variability of the model's performance from storm to storm. Overall, the observed rainfalls over the entire study period were under-estimated by the model. Consequently, the streamflow forecasts were consistently below their corresponding observed flows. However, the under-estimation was seen to improve significantly when a daily correction with observed rainfalls was made to initiate the *ACRU* model with the correct "now-state" of the catchment. An error of 34% in the total streamflow forecasts of the first scenario was attributed to an incorrect initialisation of the *ACRU* model used for each forecast run.

6.7.3.2 Evaluation of the UM rainfall forecasts

The Unified Model (UM) is made up of atmospheric, oceanic, wave and sea-ice numerical submodels and can cover either all, or part, of the Earth's surface area with multiple atmospheric layers. The various submodel components have been designed to run individually or in a merged mode for a specific modelling application (UK Met Office, 2007). Operationally, the UK Meteorological Office runs a number of configurations of its UM model, ranging from the global model, with a spatial resolution of 100 km, down to a high resolution of 4 km local model. The choice of horizontal and vertical resolution may be varied by a user (UK Met Office, 2007). Since 2006 the SAWS has been actively working on the implementation of this new Unified Model as a new NWP system for southern Africa. The 12 km resolution rainfall forecasts of 2 days' lead time was available in 2007 and could be used for short term agrohydrological applications. The evaluation of these forecasts in the Mgeni catchment is demonstrated below. In **Figure 6.7.8** the 1 and 2 day lead time rainfall forecasts over QC U20E are shown for events A, B, C and D, along with the reference observation, while in **Figure 6.7.9** their Hits (H), Misses (M), False Alarms (FA) and Correct Nulls (CN) scores are plotted within the boundary of the 50th threshold percentile.

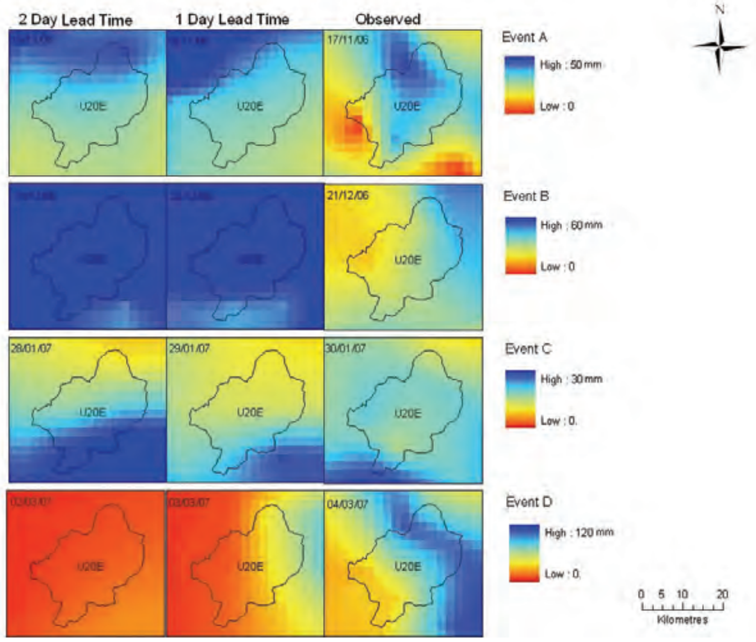


Figure 6.7.8 Two day lead time rainfall forecasts from the UM model over QC U20E in the Mgeni catchment for Events A to D on 17 November 2006, 24 December 2006, 30 January 2007 and 04 March 2007

For Events A and B the 1 and 2 day lead time forecasts are positively biased with high scores of FA. However, for Event C the 1 day lead time forecast are clustered along the boundaries of the four categories, while the 2 day lead time forecast is more stretched to the FA side. For Event D the UM model failed to capture most of the pixels with high rainfall values, even though the model skill is better in the 1 day lead time forecast than the 2 day ahead forecast. The CSI, POD and FAR scores for the 1 and 2 day lead time UM forecasts as a function of threshold percentiles are illustrated in **Figures 6.7.10** and **6.7.11**.

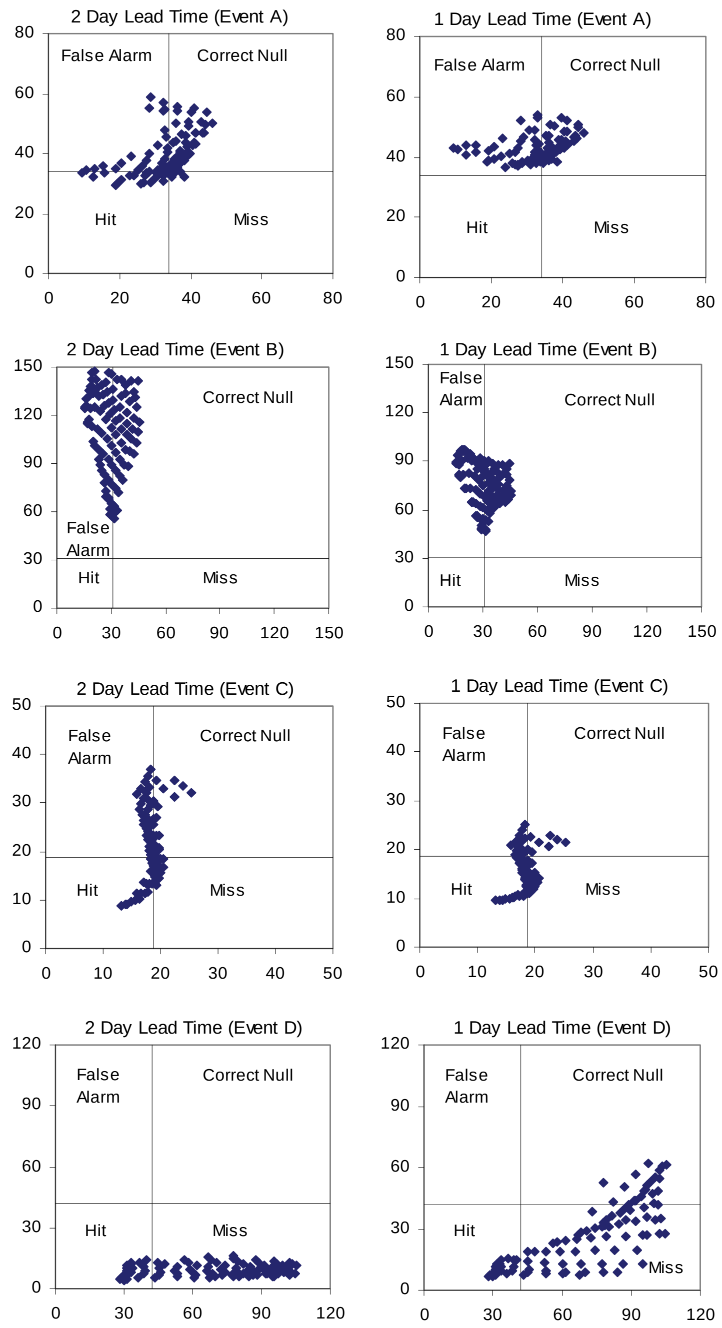


Figure 6.7.9 Scores of Hit, Miss, False Alarm and Correct Null defined by the threshold of 50th percentile for November 2006, 24 December 2006, 30 January 2007 and 04 March 2007

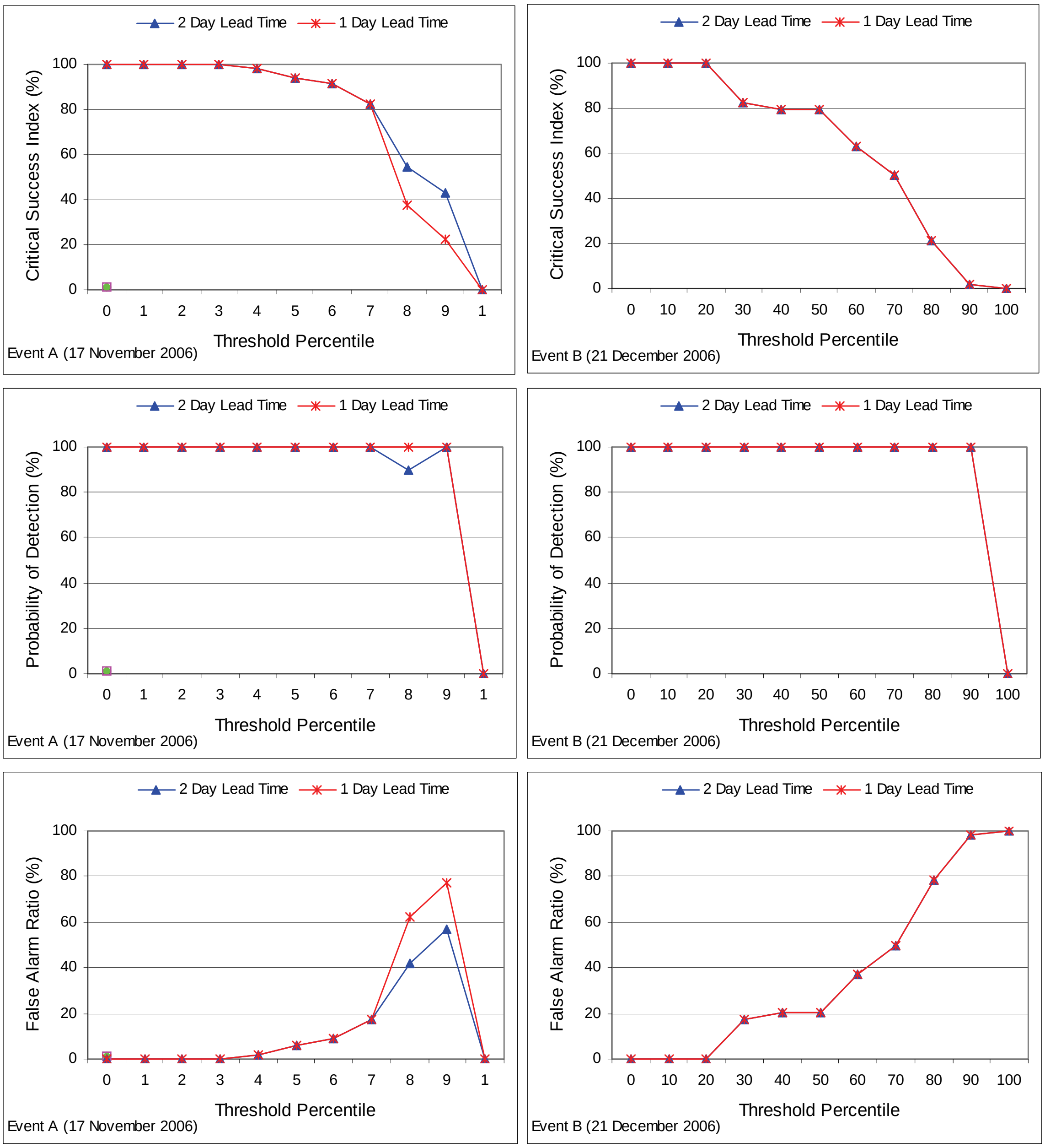


Figure 6.7.10 CSI, POD and FAR scores of 2 day lead time rainfall forecasts from the UM model as a function of threshold percentiles for the rainfall events on 17 November and 21 December 2006

For Events A and B the 1 and 2 day lead time forecasts showed the same pattern over the entire range of threshold percentiles. The probability to detect a rainfall event up to the 90th percentile was 100% for both events. The CSI score dropped quickly with the increasing rainfall rate, ranging from 80% at the 70th percentile for Event A to 23% and 43% at the 90th percentile for the 1 and 2 day lead time forecasts, respectively, while for Event B the CSI ranged from 80% at the 50th percentile to 0% at the 90th percentile for both lead times. The probability of FAR for Event A for the 1 and 2 day lead time forecasts was seen to increase respectively from 5% at the 50th percentile to 77% and to 56% at the 90th percentile. For Event B, the FAR score for both lead times increased, starting from 18% at the 30th percentile to 100% at the highest threshold percentile (**Figure 6.7.8**).

For events C and D the CSI and POD scores dropped quickly with the threshold percentiles rate. The 2 day lead time forecast displayed a better statistical performance than the 1 day lead time forecast for Event C, but with higher FAR values for high rainfall thresholds. A significant under-estimation of the rainfall pixels was observed over the entire area (i.e. U20E) on the day of Event D. The 2 day lead time forecast displayed no skill scores over the entire domain except at the lowest threshold percentile (0%), while the skill of 1 day lead time forecast was extended up to the 50th percentile (**Figure 6.7.9**)

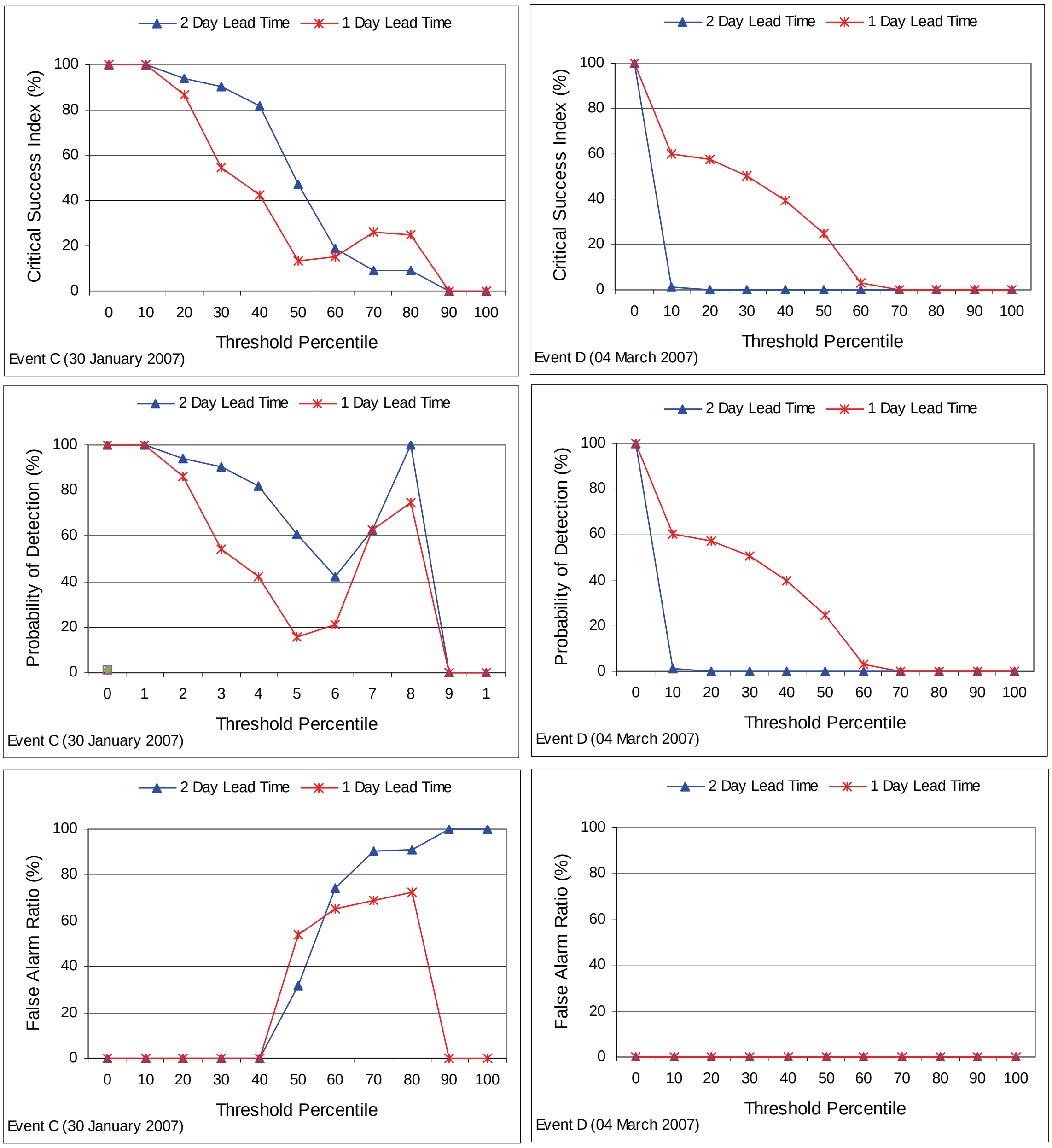


Figure 6.7.11 CSI, POD and FAR scores of 2 day lead time rainfall forecasts from the UM model as a function of threshold percentiles for the rainfall events on 30 January and 04 March 2007

The UM model slightly over-estimated the rainfall for the majority of rainfall pixels in Events A, B and C and the results obtained from the 1 and 2 day lead time forecasts were generally very similar for these three events. The model's performance for Event D was poor, even though the skill increased slightly with decreasing lead time.

As was the case in **Sub-section 6.7.3.1**, the evaluation was extended by transforming the 1 day ahead UM rainfall forecasts into streamflow forecasts with the *ACRU* model, both with and without updating scenarios for the evaluation period of 01 November 2006 to 31 January 2007. Plots of daily time series and accumulated daily streamflows cascaded from all QCs to the mouth of the Mgeni catchment are presented in **Figures 6.7.10** and **6.7.11**, respectively. In **Figure 6.7.14** plots of r^2, bias, RMSE and MAE are shown for each of the QCs that make up the Mgeni catchment. In general, the r^2 values with and without updating are very close to one another, ranging between 0.0 and 0.44. However, the improvement made by the updating scenario is highly noticeable in term of improvements to the bias, RMSE and MAE values.

It is evident from the plots in **Figures 6.7.10**, **6.7.11**, **6.7.12** and **6.7.13** that throughout the study period the UM model consistently over-estimated values compared to those of the observed. The streamflow ratio 3.91 was decreased to 1.59 when the updating scenario was used. Nevertheless, the updated forecasts are still positively biased by 59% according to the reference observed run, which is significant.

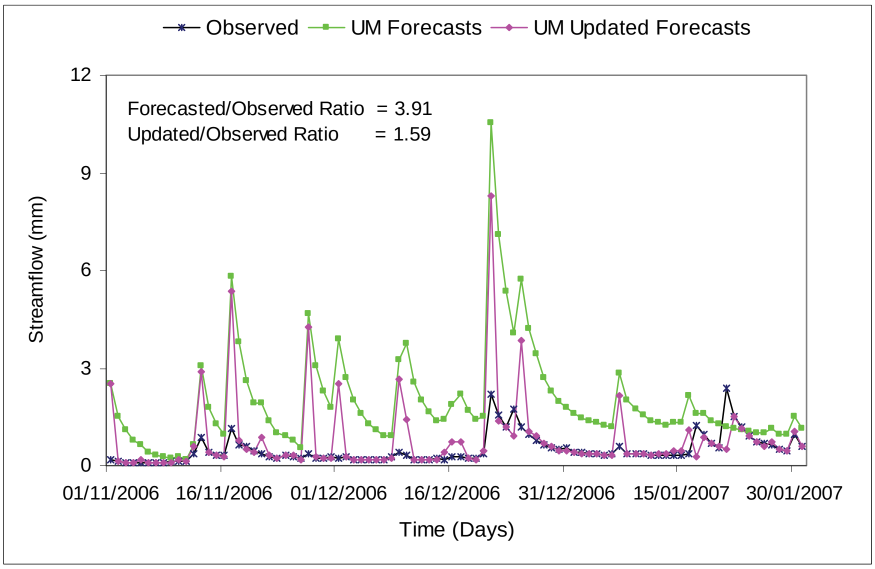


Figure 6.7.12 Time series comparisons of daily streamflows simulated with the ACRU model at the mouth of the Mgeni catchment, derived from the UM rainfall forecasts both with and without updating procedures for the period 01 November 2006 to 31 January 2007

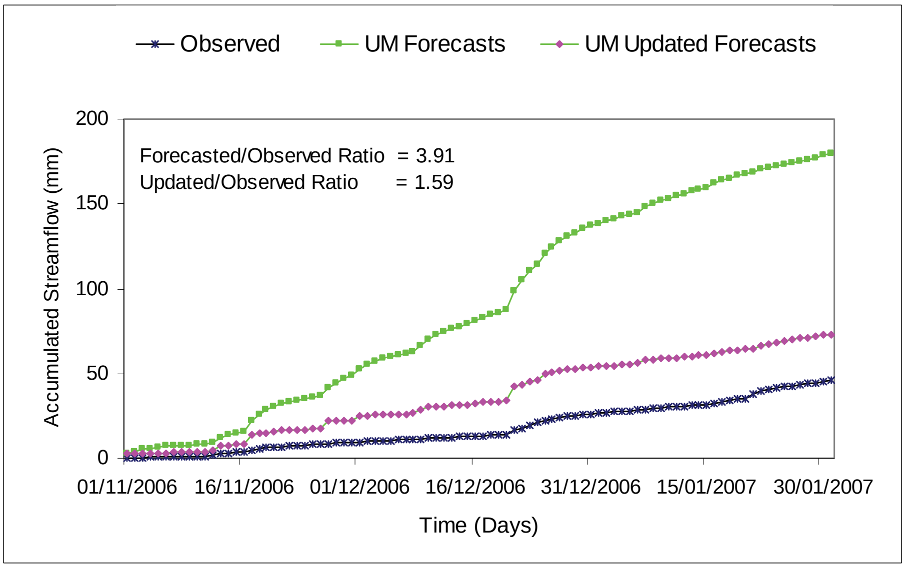


Figure 6.7.13 Comparisons of accumulated streamflows simulated with the *ACRU* model at the mouth of the Mgeni catchment, derived from the UM rainfall forecasts both with and without updating procedures for the period 01 November 2006 to 31 January 2007

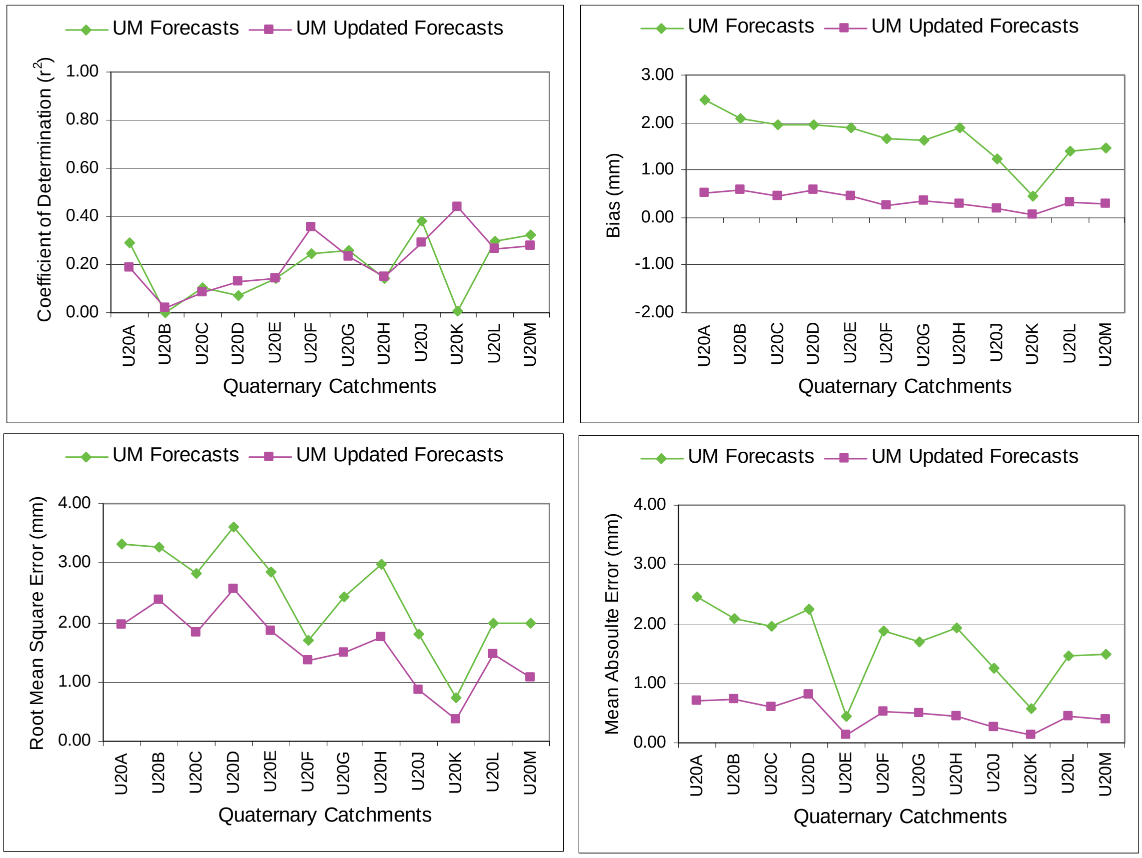


Figure 6.7.14 Coefficient of determination, bias, RMSE and MAE of accumulated Quaternary Catchment streamflows simulated with the ACRU model when using the UM 1 day lead time rainfall forecasts with and without updating for the period 01 November 2006 to 31 January 2007

6.7.3.3 Evaluation of the NCEP – MRF rainfall forecasts

A number of ensemble based forecast products are being produced at the National Center for Environmental Prediction (NCEP) and distributed to a wide range of users both nationally in the USA and internationally (Toth *et al.,* 1997). The output of the Medium Range Forecast model (NCEP-MRF) has been used operationally for medium range forecasts in South Africa since 2003. Unlike the C-CAM and UM models, the NCEP-MRF model uses the so-called Ensemble Forecasting System (EFS) to estimate the probability distribution of the "true state of the atmosphere" around the control analysis. The motivation for use of the EFS is that probabilistic forecasts initiated from slightly different initial states and model parameters provide better results than a single deterministic forecast initiated by the best known state (Ahrens and Jaun, 2007). The 2007 NCEP ensemble forecasts are generated every day, one with 22 members at a grid spacing of 2.5° x 2.5° and another with 60 members at a grid spacing of 1° x 1°, both running for up to a14 day lead time. The latter product has recently been applied in South Africa by the SAWS and the historical archive of forecasts available for this study are the 2.5° grid spaced values. The evaluation of these coarse scaled forecasts at the Mgeni catchment is presented below.

Owing to the coarse resolution of the data (2.5°), the Mgeni catchment is entirely contained within one grid box (**Figure 6.7.15**). The verification is undertaken against raingauge data by computing the average rainfall of all rainfall stations which fall inside the grid box. With a grid space of 2.5°, only a crude representation of observed precipitation distribution could be achieved, especially in southern Africa where large scale rain bearing frontal systems are enhanced by local topography (Tennant *et al.,* 2006). Tennant *et al.* (2006) have attempted to verify the 2.5° grid spaced forecasts against SAWS station data by averaging the rainfall values of the stations within a grid box. Approximately 30 to 200 rainfall stations fall into each 2.5° grid box, with the lower station density found in the more arid western interior of South Africa. They found that the NCEP-MRF model over-estimates rainfall amounts by up to 300% over the summer rainfall areas of South Africa. This significant bias becomes greater for higher rainfall amounts. In contrast to the summer rainfall areas, rainfall is under-estimated in the winter rainfall areas of South Africa.

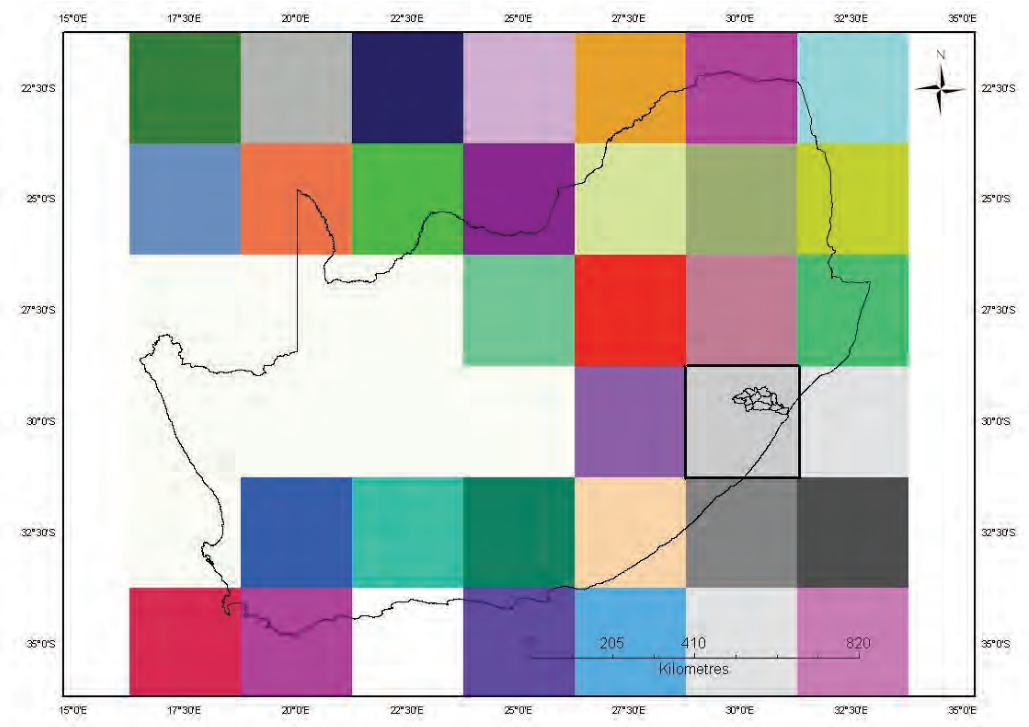


Figure 6.7.15 The 2.5° grid boxes over southern Africa for the NCEP-MRF forecasts, with the Mgeni catchment shown in its relevant grid box

Nevertheless, the model performance has been continuously improving through upgraded model physics, resolution and data assimilation, and these effects are automatically manifest in the 2.5° grid spaced outputs (Tennant *et al.,* 2006). With further improvement and refinement, these forecasts have the potential to play an increasingly important role for large scale catchments in the short and medium range of an agrohydrological forecasting system. The present study is aimed at examining if the coarse resolution (2.5°) is sufficient to resolve weather systems responsible for the summer rainfall over the Mgeni catchment. For operational use, however, these large scale forecasts should be downscaled to a finer resolution based on the use of a statistical or dynamical rainfall downscaling model, which is beyond the scope of this study.

The evaluation commenced with the investigation of ensemble members for the four selected rainfall events in order to assess the extent to which they could explain the uncertainty associated with a particular forecast. In **Figure 6.7.16** the inter-quartile range of 24-hour accumulated precipitation amount is shown, plotted from 22 ensemble members for Events A, B and C, but from only 11 members for Event D. The spread of the ensemble describes the breadth of the range of forecasts made by the EFS. For a good ensemble forecast the “observed value lies somewhere within the range of the forecasts given by the ensemble members” (Ebert, 2001). In the case of Event A, the observation is significantly less than the driest ensemble member, even though the spread of the ensembles is large in ranging from 33.0-91.8 mm. This large spread suggests a lack of confidence in the forecast for that particular day. The spread for Event B is also large (6.4-67.0 mm), but the observation was captured within the lower inter-quartile range. In the cases of Events C and D the spread was relatively small. The observed value for Event C lies within the lower inter-quartile range of the ensemble values, whereas in the case of Event D the observation is higher than the wettest ensemble member. The model’s under-forecast for Event D is possibly due to the absence of 11 ensemble members of the 22.

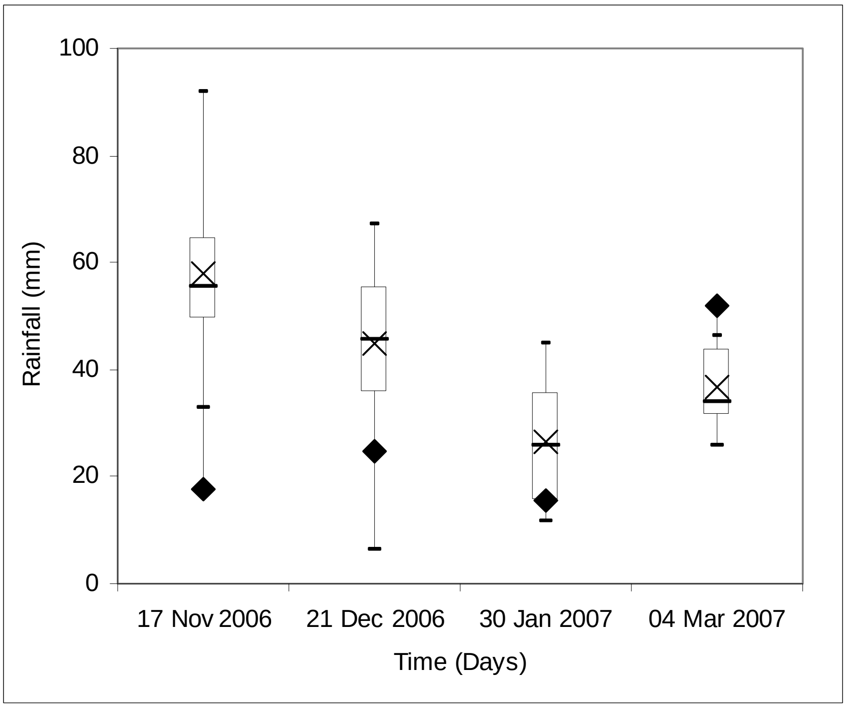


Figure 6.7.16 The spread of NCEP ensemble rainfall forecasts for 17 November 2006, 21 December 2006, 30 January 2007 and 04 March 2007. The box-and-whiskers represent the minimum, lower quartile, median, upper quartile and maximum values of the ensemble members. The x signs indicate the ensemble mean value. Diamonds represent the observed values

The most important benefit that the ensemble forecasts can offer is that they can be used to provide Probabilistic Quantitative Precipitation Forecasts (PQPFs), as is done in many centres (e.g. NCEP, SAWS). It has been shown by many researchers (e.g. Toth and Kalnay, 1997; Ebert, 2001; Zhu *et al.,* 2002) that NCEP ensemble forecasts based on probabilistic values have the potential to provide a more meaningful indication not only for the temporal distribution, but also of possible spatial distributions of rainfall in the short and medium range forecasts. PQPFs are computed by counting how many of the ensemble members exceed a daily accumulated rainfall, or any given threshold, and then dividing that number by the total number (in this case 22) of ensemble forecasts (Toth *et al.,* 1997). In future the same procedure can also be followed to generate probabilistic ensembles of streamflow forecasts by ingesting each of the ensemble rainfall forecasts into a hydrological model, provided that the spatial scale of these forecasts are comparable to those for which the hydrological model is applied.

In this study it is hypothesised that the most likely spatial representation of the rain field is given by the ensemble mean. In order to assess the extent to which the lead times of the NCEP forecasts are skilful, the ensemble means for each of 5 day lead time forecasts at the 30°S 30°E grid box for the period of 01 November 2006 to 31 January 2007 were compared against average rainfall values of all stations that fall into the box (**Figure 6.7.17**). It was found that the 1-5 day forecasts show very similar patterns throughout the study period, although the quality of the forecasts increases with decreasing lead time, as expected. Nonetheless, the NCEP-MRF model showed a tendency to over-forecast throughout the study period.

A plot of 1 day forecasts, which are relatively more skilful than the 2 to 5 day ones, versus observed rainfalls reveals a positively biased performance of the NCEP model (**Figure 6.7.18**). The association is quite strong for less extreme events of < 20 mm per day, while there is more scatter with higher rainfalls. Taking the space scale limitation into account, however, the model's performance is considered satisfactory. These results reflect that the NCEP-MRF model is capable of identifying a rainfall event, but with a tendency to over-estimate the amount.

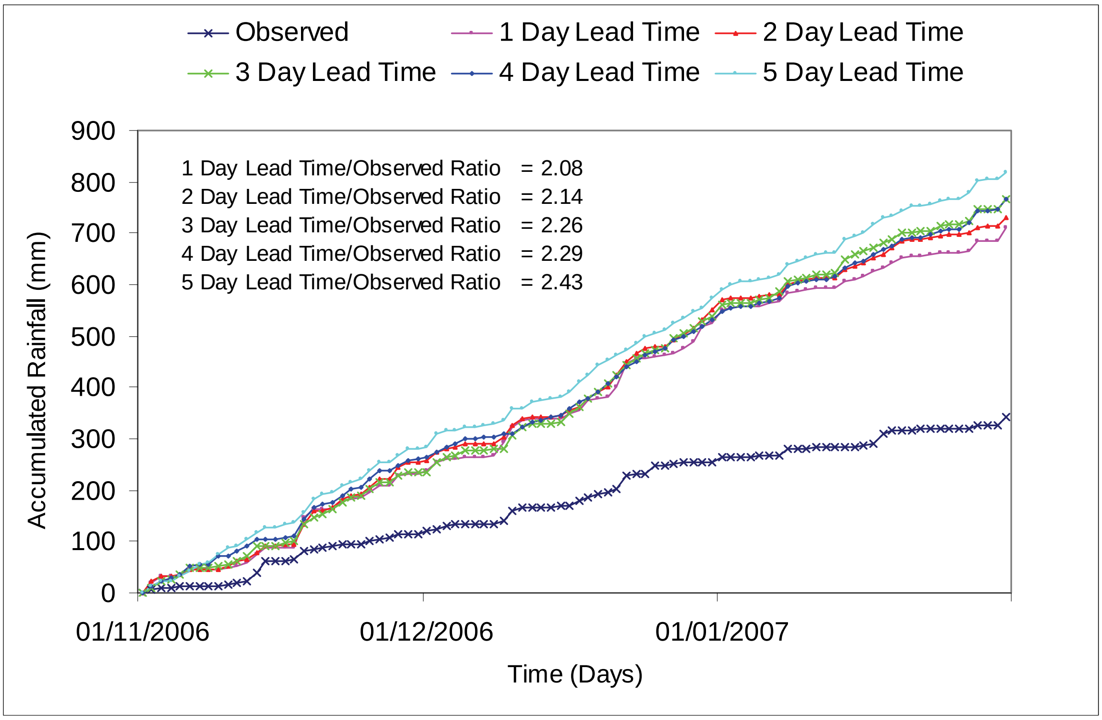


Figure 6.7.17 Time series comparisons in the 30ºS 30ºE grid box of accumulated rainfalls of 5 day forecasts derived from the NCEP-MRF rainfall model for the period 01 November 2006 to 31 January 2007

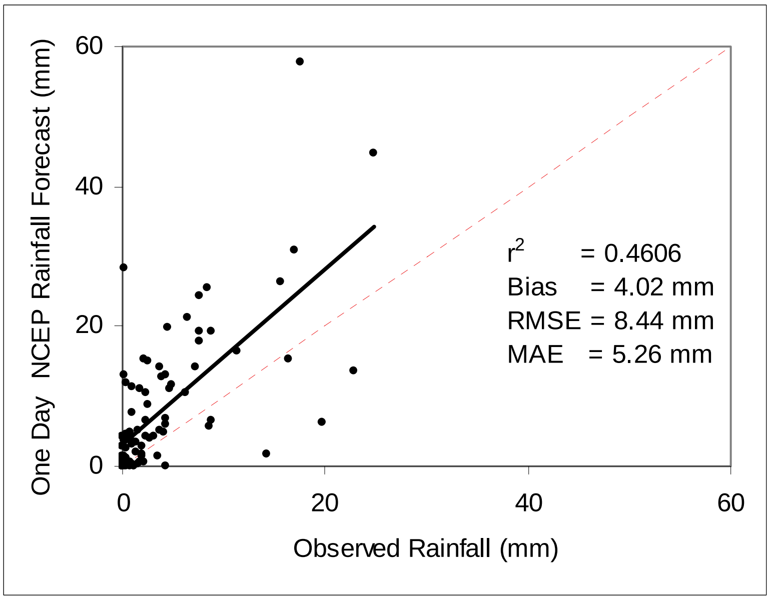


Figure 6.7.18 Scattergram of NCEP simulated 1 day forecasts from the means of 22 ensembles versus observed rainfalls for the period 01 November 2006 to 31 January 2007

6.7.3.4 Combined use of the C-CAM and UM rainfall forecasts

All NWP models predicting weather at shorter ranges, or its various statistics at a longer time ranges, are based upon the same laws of physics (Toth *et al.,* 2006). However, the quality of the forecasts is often constrained by the model formation through the variation of assumptions and approximations as to how the physical processes are parameterised in the models, as well as by their the levels of vertical and horizontal resolutions, forecast methodologies and data assimilation methods (Ebert, 2001; Anstee, 2004). As a result, no two models will display the same forecasts in exactly the same manner. Generally, different models will tend to "cluster" around the perfect forecast, with some a little too wet while others are a little too dry (Ebert, 2001). In this instance, the C-CAM and UM models responded differently for the same season and the same area. Although they displayed similar patterns to the reference run, the C-CAM model showed a tendency to under-forecast whereas the UM model tended to over-forecast throughout the study period. This is particularly noticeable on the occasions of heavy rains (**Figure 6.7.19**).

The daily QPFs of the two models for the period of 01 November 2006 to 31 January 2007 were combined by "weighted averaging" in order to evaluate the extent to which their combined prediction could improve the accuracy of the forecasts. No particular model was favoured and the success of the "weighted averaging" to produce a better combined QPF is dependent on the performance of the models relative to each other on a given day. It was found that the combined forecast was influenced more by the outputs of the UM model than the outputs of the C-CAM model. As a result, the combined output was superior in relation to the UM than the C-CAM forecasts, both in terms of individual daily and accumulated flows (**Figures 6.7.19** and 6**.7.20**). The under-estimation in the total streamflow forecasts of the C-CAM forecasts was reduced from 34% to 10%, while the over-estimation in the UM Model was decreased from 291% to 89%.

The advantage of using multiple models to determine rainfall is the ability to estimate the probability of receiving rain (Ebert, 2001). For example, if the C-CAM and UM models both predict that at least 10 mm would fall at a particular location, then the probability of receiving at least 10 mm will be 2 / 2, or 100%. If there is disagreement the chance will be 1/2, or 50%. Likewise, the probability of streamflow exceeding a given threshold can also be calculated and mapped at catchment or national scale. The greater the number of NWP forecasts the greater the skill will be of the probabilistic forecasts. Decision makers can then have more confidence in such probabilistic forecasts than any of the individual deterministic estimates.

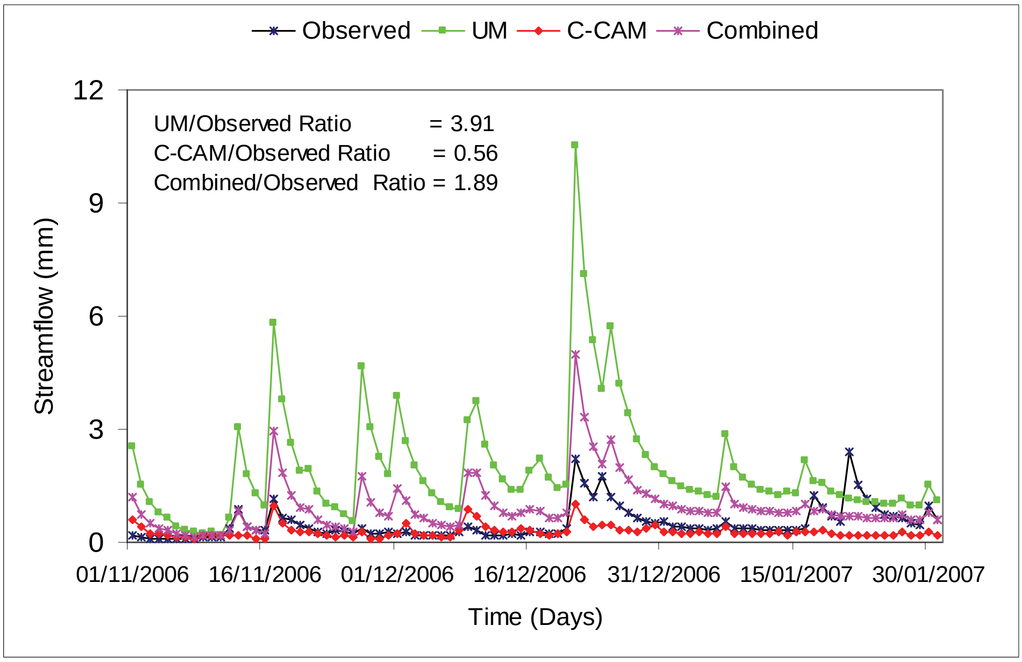


Figure 6.7.19 Time series comparisons of daily streamflows at the mouth of the Mgeni catchment, derived from the C-CAM, UM and combined rainfall forecasts for the period 01 November 2006 to 31 January 2007

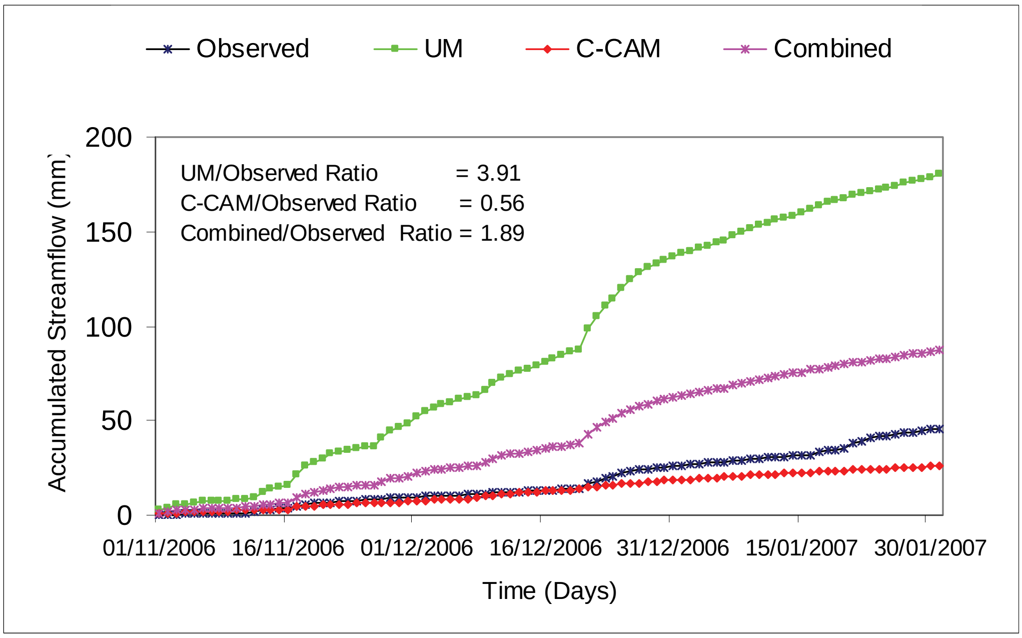


Figure 6.7.20 Comparisons of accumulated streamflows at the mouth of the Mgeni catchment, derived from the C-CAM, UM and combined rainfall forecasts for the period 01 November 2006 to 31 January 2007

6.7.4 Conclusions

In this chapter three experimental NWP models were evaluated from a hydrological perspective, *viz.* the C-CAM, UM and NCEP-MRF. The results obtained from each model are encouraging. However, the quality of the results varied between the three models, between the modes of simulation (i.e. with and without updating) and between the selected events. Each model was evaluated separately for four selected days with relatively high amounts of rainfall, as well as for a continuous period of 92 days.

For the four selected events, the C-CAM model scored some skill with the 1 and 2 day lead time rainfall forecasts, whereas for the 3 and 4 day forecasts the skill was low and unreliable. Except for Event D (04 March 2007), there was no significant difference between the 1 and 2 day lead time UM rainfall forecasts. The 2 day forecast was slightly superior to the 1 day forecast for Event C (30 January 2007), but for Event D the 2 day forecast showed no skill. Results obtained for the continuous period showed that streamflow forecasts based on the C-CAM model suffered from consistent under-estimation, while conversely the UM based streamflow forecasts suffered from consistent over-estimation. Since the degree of over-estimation by the UM model was more significant than the degree of under-estimation of the C-CAM model, their combined output was positively biased. However, considerable improvement was achieved in their individual streamflow forecasts when the state variables of the catchment were updated at the start of each day with observed rainfalls up to the previous day.

The NCEP-MRF rainfall forecasts were verified only against observed rainfalls owing to spatial scale differences. It was shown that these forecasts over-predicted those of the observed values for both the selected single events (except for Event D) and over the continuous period of time, although the quality of the forecasts increased slightly with decreasing lead time. The ensemble approach was effective for Events B (21 December 2006) and C (30 January 2007), but failed to capture Events A (17 November 2006) and D (04 March 2007). Despite the limitations of the coarse spatial scale, the correlation between the 1 day forecast and the reference was fair.

In conclusion, when taking into account the discrepancies between the forecast period (02:00 to 02:00) and observed period (08:00 to 08:00), scale issues and uncertainties in the reference run, the performances of the three models seem to be reasonable. The occurrences of the rainfall were signaled correctly over most of the study period, especially by the C-CAM and UM models, but with a tendency to respectively under- and over-estimate the correct amount.

The results obtained from this research reveal that there is still room for improvements in each of these models, especially in making the models' spatial scales more compatible with requirements of hydrological models for application in small and medium sized catchments and in improving the rainfall forecast skill, especially for longer lead times.

CHAPTER 7

THE INITIAL RESEARCH BASED FRAMEWORK FOR AN AGROHYDROLOGICAL FORECASTING SYSTEM FOR SOUTH AFRICA

YB Ghile and RE Schulze

Summary

7.1 THE NEED FOR A GIS BASED FRAMEWORK
7.2 NEAR REAL TIME ESTIMATES OF PRECIPITATION DERIVED FROM SATELLITE, RADAR AND RAINGAUGE DATA
7.3 SHORT AND MEDIUM FORECASTS FROM WEATHER PREDICTION MODELS
7.4 CATEGORICAL SEASONAL FORECASTS FROM CLIMATE MODELS
7.5 THE *ACRU* AGROHYDROLOGICAL MODELLING SYSTEM
7.6 SUMMARY

* * * * *

An effective, operational agrohydrological forecasting system should provide the right information, at the right time, to address the needs of decision makers and operational users in agricultural and water resources management. This project evolved over a period of time and the main aim of this specific Chapter is to illustrate the development of an initial research based framework that facilitates the application of near real, plus daily, multi-day to seasonal rainfall forecasts as a nested set of inputs to agrohydrological and / or crop yield models, thereby enabling the forecasting of agrohydrological variables across a range of time scales and lead times in southern Africa, defined here as the RSA plus Lesotho and Swaziland. This aim was achieved by integrating different sources of forecast information available in the period 2006 to 2008 from radar, satellite, and weather / climate models. Generic methodologies were developed for temporal downscaling of probabilistic categorical seasonal forecasts to a daily time series of values suitable for application in agrohydrological models. Many of the concepts and structures of this initial framework were tested in Case Study 7 of **Chapter 6** and are carried forward into **Chapter 8** which follows, and in which first steps are taken at operationalising the forecast system.

7.1 THE NEED FOR A GIS BASED FRAMEWORK

The effective and efficient management of agricultural operations and related water resources relies on skilful and timely forecasts of agrohydrological variables such as soil moisture, crop yields, streamflows, irrigation water requirements or reservoir levels. In turn, a key factor for accurate agrohydrological forecasts are accurate and prompt weather / climate forecasts on, for example, rainfall and temperature, as input to the agrohydrological model being used. Weather and climate forecasts for southern Africa (e.g. from SAWS or CSAG or the CSIR) have been shown to posses certain levels of skill when they are compared against observations (e.g. Klopper and Landman, 2003; Engelbrecht *et al*., 2011). The challenge, however, still lies in the improvement of the spatial and temporal resolution of the weather and climate forecasts, and the "translation" of these forecasts into suitable scales and forms that are required by agrohydrological models. These challenges must be addressed if crop yield or agrohydrological models are to contribute to the task of transformation of weather / climate forecasts into more tangible attributes mentioned above.

This calls for the development of generic methodologies to link the outputs of weather and climate models with agrohydrological models. Owing to the complexity and iterative calculations of the translation process from climate to agrohydrological forecasts, manual calculations and data extractions are out of question. A Geographic Information System (GIS) based framework therefore becomes a very important platform for gathering, filtering, translating and generating information that can be used directly with agrohydrological models for an effective agrohydrological forecasting system. Within this framework, GIS organises spatial information, provides techniques for pre-processing data (including spatial disaggregation), provides data structure and format conversion and displays post-processed information through reformatting, tabulation, mapping and report generation. A schematic flow chart demonstrating the structure of the initial GIS based framework for the agrohydrological forecasting system developed in this project is provided by **Figure 7.1.1**.

During the early phases of this project from 2006-2008 a number of different institutions were involved in producing weather and climate forecasts that could potentially benefit end users. At that time forecasts issued by the South African Weather Service (SAWS) and the University of Pretoria (UP) were adopted for the generation of agrohydrological forecasts within this framework. Following that period certain forecast products ceased to be used and others became available, also from different institutions (e.g. the new suite of forecast products from the CSIR), as different forecasters use different weather and climate models that may perform better than others under particular conditions and / or for specific locations. However, with so many providers and different formats, there is real potential for confusion among users as to which forecasts to use, especially when the forecasts are not similar. Weather and climate forecasts encompass a broad range of variables (e.g. rainfall, temperature, solar radiation, frost), but rainfall was the key variable of interest in this initial framework as it is the main determinant of both agricultural and related hydrological responses in southern Africa. At a later stage beyond 2008 the development of this initial framework was therefore expected to continue in order to incorporate other weather variables and forecast products issued by other institutions.

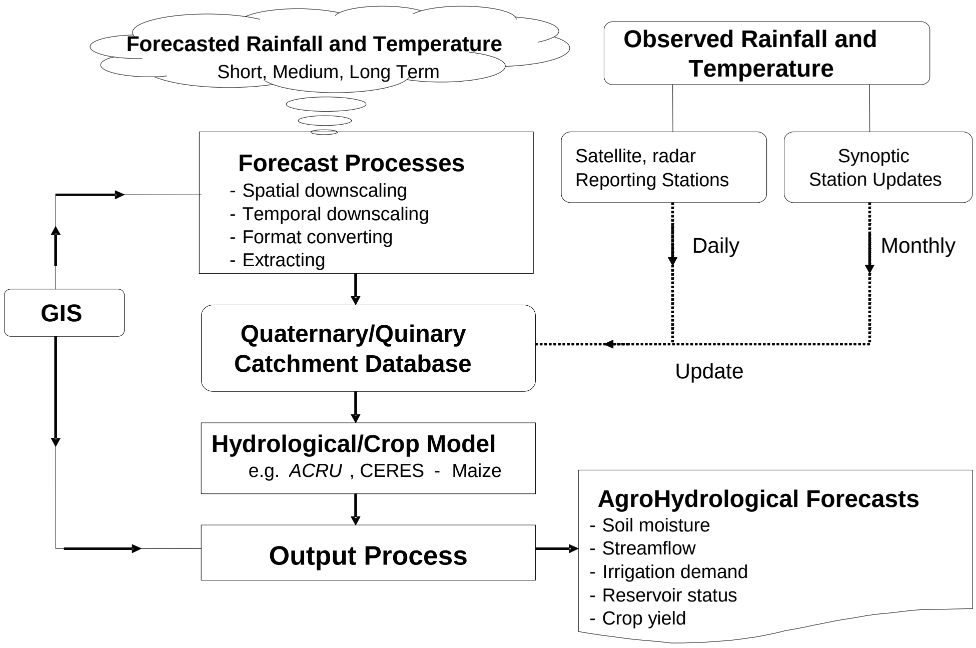


Figure 7.1.1 A schematic flow chart demonstrating the structure of the initial agrohydrological forecasting framework developed in this project

Based on the framework shown in **Figure 7.1.1**, a GIS based computer program was developed using the Visual Basic programming language that links to GIS and processes all the calculations required to translate the multi-day, monthly and / or to seasonal climate forecasts into daily quantitative values suitable for application with daily time step crop yield or hydrological models. The program runs on the Windows operating system. Once the program is initiated, the user has options to select the forecast types in the main window (**Figure 7.1.2**). In its initial 2008 state the program was designed to operate at the spatial scale of the 1946 Quaternary Catchments (QCs) into which South Africa has been delineated by the Department of Water Affairs (DWA) for operational decision making. The program has three major components, *viz.*

- near real time observations derived from radar, satellite and daily reporting weather stations,
- short (up to 44 days) and medium term (up to 14 days) forecasts from various Numerical Weather Prediction (NWP) models, and
- monthly and seasonal (up to 3 months) forecasts from climate models.

These components are described in more detail in the sections which follow. A brief explanation is made on how to use the GIS based program. However, it has not been written in the conventional style of a software user manual. In a later section, the *ACRU* agrohydrological modelling system (Schulze, 1995a and updates), which was selected in this research to generate agrohydrological forecasts, is also described briefly.

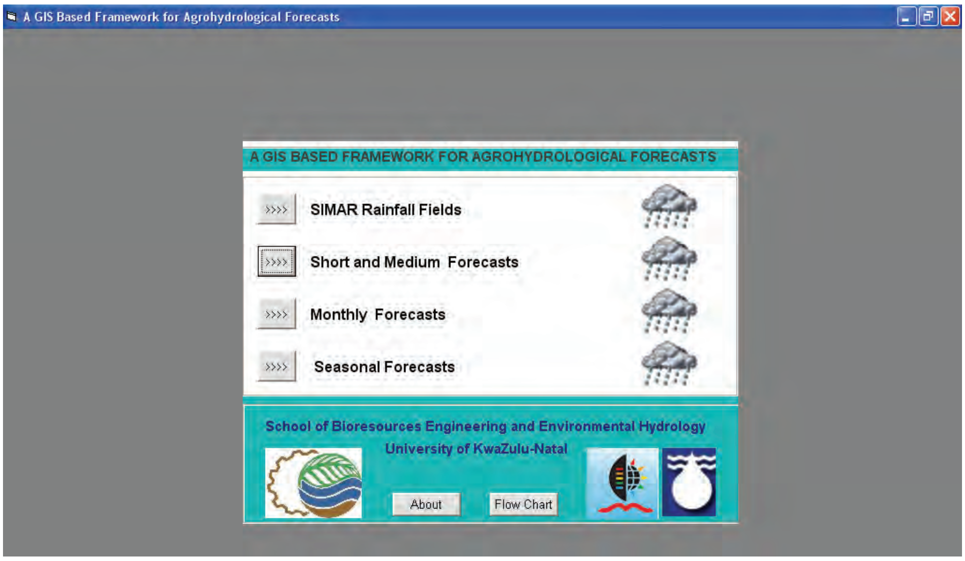


Figure 7.1.2 The main window showing options for near real time, short and medium as well as long range forecasting in the GIS based framework for the agrohydrological forecasting system

7.2 NEAR REAL TIME ESTIMATES OF PRECIPITATION DERIVED FROM SATELLITE, RADAR AND RAINGAUGE DATA

Near real time weather information is, of necessity, required for nowcasting, especially in areas of fast agrohydrological responses, and also to simulate the "now state" of various hydrological state variables such as soil moisture contents, streamflows, reservoir levels. Approaches for nowcasting are based mainly on rainfall estimated by conventional ground stations, radars, satellites and NWP models. These data and information sources have their respective strengths and weaknesses. The use of conventional ground stations has become less efficient to meet the existing and anticipated management requirements in agricultural and water resources management because their distribution is sparse and data are frequently not available in mountainous areas where runoff is often generated, nor in other remote areas (Deyzel *et al.,* 2004; Kroese, 2004). For the above reasons, the use of near real time remotely sensed observations from radar reflectivity measurements and satellite images has, therefore, been acknowledged to play a key role in agrohydrological applications, assisting in more timely decision making operations, especially for flash flood related disaster management. In the 2006-2008 period, however, the outputs from satellite and radar images, although providing useful information on precipitation patterns, did not seem able to provide accurate rainfall values at the temporal and spatial resolution required by many agrohydrological models (Toth *et al.,* 2000). This is mainly so because of the problems related to ground clutter and false accumulation of rain fields when totals of rainfall are required. The raingauge networks then play a vital role in investigations regarding the elimination of ground clutter and also in verifications of radar and satellite derived rainfall on the ground (Deyzel *et al.,* 2004; Kroese, 2004).

By taking into consideration the merits and limitations of these data sources, the METSYS group of the SAWS and the School of Civil Engineering of University of KwaZulu-Natal, in collaboration with the Department of Water Affairs and the national electricity utility ESKOM developed a rainfall monitoring system termed SIMAR, for **S**patial **I**nterpolation and **MA**pping of **R**ainfall. The system integrates raingauge, radar and satellite derived data in the production of daily rainfall maps of 24 hour accumulated rainfall at a resolution of one arc minute, i.e. approximately 1.7 km x 1.7 km over the southern Africa region. These maps were, at the time of developing the initial framework, accessible on the Internet.

The SIMAR project aims at producing one rainfall field that is acceptable by all water users (Deyzel *et al.,* 2004; Pegram, 2004). The generation of the merged radar / satellite / gauge rainfall field is a three step process, starting with the merging of the radar and raingauge fields followed by the merging of satellite and raingauge fields. Thereafter the two resultant merged fields are combined (Pegram, 2004). In order to convert these maps into a suitable format and to downscale them to a particular location of interest (e.g. Quaternary Catchments) and use them as input into agrohydrological models, the following steps are required:

1. *Downloading rainfall maps*
   The accumulated rainfall for 24 hours, derived from daily reporting stations, radar and satellite across southern Africa arrives at the METSYS office in Bethlehem in the Free State by 09:00 daily. Daily rainfall maps from the radar, gauge and satellite information, together with the merged fields, are then completed by 11:30 and the results are posted on the METSYS website (Pegram, 2004). At this stage, however, these maps are considered to be demonstration versions which cannot be accessed in GIS. The accessible rainfall maps, which are given in ASCII format, can be downloaded from the SAWS ftp server on a daily basis.
2. *Converting formats*
   From the main window (**Figure 7.1.2**), clicking on the *SIMAR Rainfall Fields* option button initiates the *ASCII to Grid* window (**Figure 7.2.1**) to allow an ASCII format conversion to a grid format. This can be done by browsing the location into which the ASCII file is saved, and by specifying the output name and output directory. The grid layer will then be saved on the specified directory.

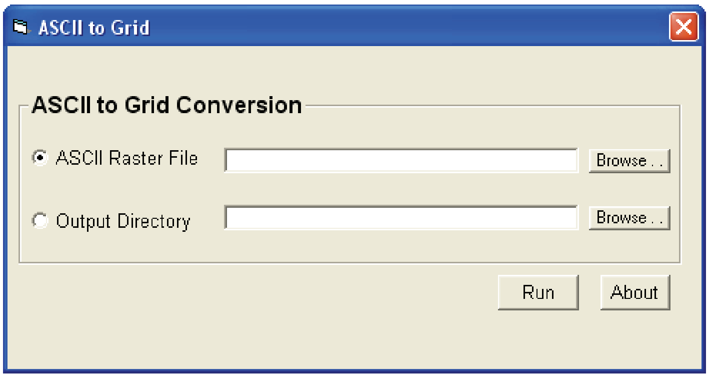


Figure 7.2.1 The *ASCII to Grid* windows for format conversion

3. *Running ArcMap*
   Once the format conversion has been completed, the *Forecasting tool* developed in the *ArcMap* shell automatically pops up. Clicking on the *SIMAR* button initiates the SIMAR window (**Figure 7.2.2**). The converted grid layer and shape file are added by browsing its path.

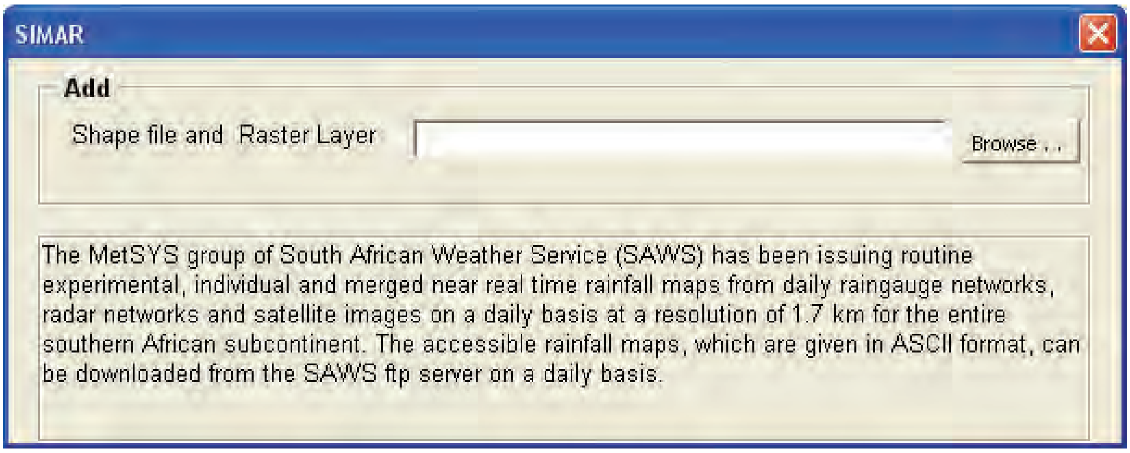


Figure 7.2.2 The screen for adding a grid layer for extracting daily rainfall values over a selected catchment

4. *Calculating catchment mean value and Joining of the Data*
The joining of the data can be done by averaging the points falling within each subcatchment of the chosen shape layer. Then the output is displayed automatically in "excel" format in the working directory.
5. *Converting to ACRU format*
By inputting the forecast date as "yyyy/mm/dd" format in **Figure 7.2.3**, rainfall values representing each location will be extracted from the layer to respective *ACRU* model formatted input text files.

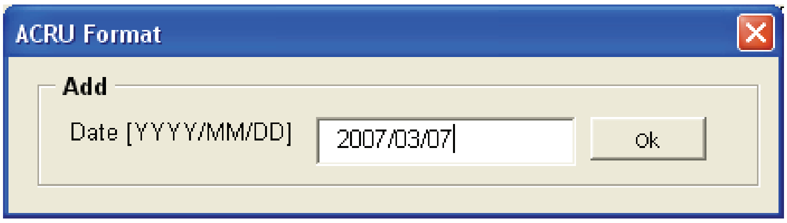


Figure 7.2.3 The screen for extracting daily rainfall values to *ACRU* formatted rainfall files

7.3 SHORT AND MEDIUM FORECASTS FROM WEATHER PREDICTION MODELS

The SAWS in 2006 was employing the Unified Model (UM) for short range weather forecasts (up to 2 days) and the National Center for Environmental Prediction for Medium Range Forecasting (NCEP-MRF) model for medium and extended range forecasts (up to 14 days) across the southern Africa. The rainfall forecasts from these two models and the forecasts issued at that time by the University of Pretoria (UP) using the Conformal-Cubic Atmospheric Model (C-CAM) were incorporated in the initial framework for short and medium range agrohydrological forecasting systems (**Figure 7.3.1**). The resolution, uncertainty and challenges associated with these models, as well as the procedures constructed to convert these forecasts into a suitable form, are described in detail in the sub-sections which follow.

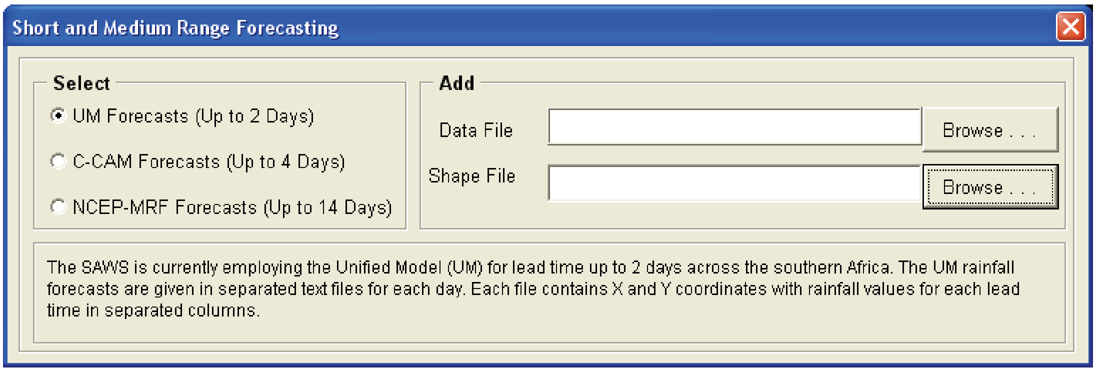


Figure 7.3.1 A screen showing the short and medium range forecasting model options

7.3.1 The C-CAM Rainfall Forecasts

The Conformal-Cubic Atmospheric Model (C-CAM) is a variable-resolution global circulation model developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Marine and Atmospheric Research in Melbourne, Australia (McGregor, 2005a; 2005b). A key feature of C-CAM is its ability to be applied in stretch mode in order to focus the model resolution over any particular area of interest (Engelbrecht, 2005; McGregor, 2005a; 2005b), as is discussed in **Chapter 4**. In order to obtain the short-range weather forecasts used in the initial GIS framework, the model was first applied at a relatively coarse resolution of about 60 km over tropical and southern Africa. Far-field nudging was then used in 4-day regional forecasts with a 15 km resolution (cf. **Chapter 4**). Although simulations are performed at a time step of five minutes, results are aggregated and issued on a daily basis. The 15 km resolution rainfall forecasts of four days' lead time were incorporated in this initial framework for application in the short term agrohydrological forecast system.

7.3.2 The UM Rainfall Forecasts

The UM is a non-hydrostatic weather forecasting model which had been developed in the UK Meteorological Office by the end of 1980s, but was introduced into operational service in 1992 (UK Met Office, 2007). The formulation of the model supports global and regional domains and is applicable to a wide range of temporal and spatial scales that allow it to be used for both numerical weather prediction and climate modelling as well as a variety of related research activities (Kershaw, 2006). The UM is designed to run either in atmosphere or ocean mode separately, or in a coupled mode. In each mode a run consists of an optional period of data assimilation followed by a prediction phase. Forecasts of a few days ahead are required for numerical weather prediction, while for climate modelling the prediction phase may be for tens, hundreds or even thousands of years (UK Met Office, 2007). The SAWS adopted the model for the southern Africa region in 2006 and at that time the UM model was run four times per day, providing model forecast guidance at a 12 km resolution for up to 2 days ahead (Van Hemert, 2007).

7.3.3 The NCEP-MRF Rainfall Forecasts

At the NCEP the ensemble forecasting approach has been applied operationally for the short range forecasts by applying the ETA and Regional Spectral Models, and for the medium and extended range by using the Medium Range Forecast Model (MRF). Different ensemble based products have been generated and these are distributed via File Transfer Protocol (FTP) to a wide range of users both nationally and internationally (Toth *et al.,* 1997).

Since 2003 the NCEP-MRF forecasts at a grid spacing of 2.5° resolution with 22 ensemble members has been used operationally in South Africa for medium range forecasts up to 14 days ahead (Tennant *et al.,* 2006). At the point in time that this initial framework was developed, however, the SAWS was also downloading a 1° x 1° grid spaced NCEP-MRF forecasts with 60 ensemble members every day, in addition to these 2.5° scaled forecasts (Tennant, 2007). One of the most challenging aspects of incorporating the NCEP-MRF rainfall forecasts into the initial framework for the agrohydrological forecasting system was that of condensing the vast amounts of model output and information into an operationally relevant and useful form. In 2007 the SAWS was using the 2.5° grid spaced forecasts to produce one or two week lead time probabilistic rainfall forecasts by calculating the forecast probability that 24 hour precipitation amounts were exceeding certain threshold values (usually 5 mm and 20 mm) over 2.5° by 2.5° grid boxes (**Figure 7.3.2**). For each day, 345 sets (i.e. 15 days and 23 ensembles) of unique forecasts were generated at each of the 2.5° by 2.5° grid boxes, with each ensemble representing an average probabilistic quantitative precipitation forecast (PQPF) for that 2.5° grid box.

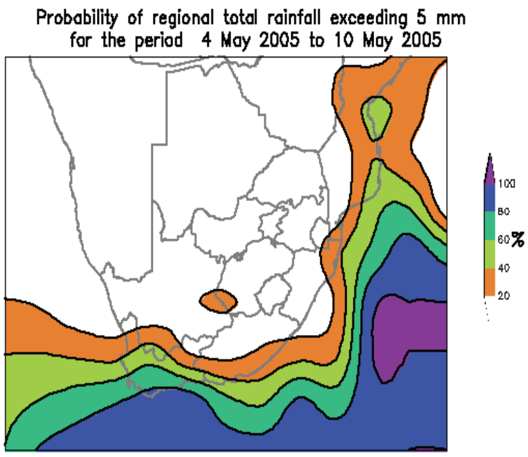


Figure 7.3.2 An example of a one week lead time probabilistic forecast from NCEP-MRF ensemble rainfall forecasts at 2.5° resolution over southern Africa (Source: SAWS, 2005)

At each grid box the number of ensemble members having a 24-hour precipitation amounts greater than the threshold limit are counted and the forecast probability is expressed as follows (Tennant, 2005):

$$F_P = \frac{M}{23} \times 100 \qquad 7.1$$

where

F_P = forecast probability (%), and
M = number of ensembles greater than a given threshold limit.

In order to take full advantage of the ensemble system, similar procedures should also be followed in the simulation of agrohydrological forecasts. However, most agrohydrological models run at a much finer spatial resolution than 2.5° or 1° and each ensemble member should be represented as geospatial (i.e. raster) data to be downscaled to the relevant catchment scale. By considering the computation time and file space required in the downscaling process, use of 23 or 60 ensemble forecasts becomes extremely cumbersome and difficult to comprehend. Hence, a single mean value of the ensemble members for each 2.5° or 1° grid box for a forecast lead time of 1 day up to 14 days was used in the simulation of agrohydrological forecasts in this initial framework. Many studies (e.g. Toth *et al.,* 1997; Ebert, 2001) have shown that averaging the ensemble members allows not only the reduction of data sets and computational requirement, but also provides a more accurate forecast than any of the single ensemble forecasts.

7.3.4 Transferring and Reformatting of Forecasts

In May 2007 members of this WRC forecasting project (K5/1646) decided that all weather and climate forecasts would be fed to the University of Cape Town (UCT) in ASCII text format and the coarse spaced forecasts would be interpolated via cubic spline to a Quaternary (i.e. ~0.25°) or Quinary (i.e. ~0.1°) catchment scale. Forecasts would then be imported in ASCII format from the UCT for the application of agrohydrological forecasts.

The C-CAM, UM and NCEP-MRF rainfall forecasts were provided in ASCII format in separated text files for each day. Each file contains X and Y coordinates with rainfall values for each lead time in separated columns. A program was developed within this initial framework to convert these ASCII text file to a Data Base File (DBF) format in order to access it in GIS. The following steps were required to convert the C-CAM, UM and NCEP-MRF rainfall forecasts into suitable formats and to downscale them over a particular location of interest (a QC in this study) and use them as input in agrohydrological models:

1. *Downloading rainfall forecasts*
   Rainfall forecasts should be imported or downloaded from the UCT ftp server on a daily basis.
2. *Selecting the model option*
   From the main window of observation and forecast options in **Figure 7.1.2**, clicking on the *Short and Medium Forecasts* option initiates the *Short and Medium Range Forecasting* window which is nested in the *ArcMap* shell (**Figure 7.3.1**).
3. *Browsing the location of a file and converting to a DBF file*
   After selecting one of the models in **Figure 7.3.1**, the location into which the data and shape files can be browsed by clicking on the *Browse* buttons. The text file will then be converted to a DBF file and the coarse spaced forecasts would be interpolated via Inverse Distance Weight (IDW) to a Quaternary (i.e. ~0.25°) or Quinary (i.e. ~0.1°) catchment scale.

From **Section 7.2**, steps 3 and 4 should be then followed to calculate catchment mean rainfall values, to join data to selected layer and, finally, to extract the rainfall forecasts to *ACRU* model formatted text input files.

Owing to their coarse spatial resolution, the NCEP-MRF rainfall forecasts are generally recommended for large scale agrohydrological forecasts. For small scale applications, dynamically downscaled rainfall forecasts from the C-CAM and UM models should be used. The high spatial and temporal resolution of the C-CAM and UM forecasts allows the identification of features such as topography, land-sea distribution and land uses that influences the development of rainfall patterns over a particular region. Hence, the rainfall forecasts obtained from those models were expected to be more skilful than the forecasts made by NCEP-MRF model. However, since different GCM models exhibit different skill levels, the confidence that may be placed in downscaled rainfall forecasts is dependent foremost on the validity of the parent GCM model used to generate the large-scale fields. It must be noted that at the time that this initial framework was being developed in 2007, there was ongoing research at the University of the Free State (UFS) and University of Pretoria (UP) to combine dynamical downscaling with one or more statistical downscaling models. It was envisaged that at a later stage these models could possibly be incorporated in this framework.

7.4 CATEGORICAL SEASONAL FORECASTS FROM CLIMATE MODELS

In southern Africa, seasonal (3-6 months) hydro-climatic forecasts are frequently required by different sectors of society as the region is severely affected by droughts and floods. Among the various sectors, agriculture and water resources obviously can benefit considerably from such long term forecasts.

A wide range of statistical and dynamical models have been developed by a number of institutions to issue seasonal forecasts for southern Africa. Until the recent past, the statistical models were most dominantly used in seasonal forecasts for southern Africa. Major improvements have been made in recent years in understanding southern Africa's seasonal climate by shifting from using only the empirical-statistical methods to more sophisticated forecast schemes involving the use of dynamical models (Landman and Goddard, 2005). In addition, the feasibility of producing probabilistic seasonal rainfall forecast skill for five equi-probable categories was in progress (Landman *et al.,* 2005). Global Climate Models (GCMs) as forecast tools over southern Africa are currently available. GCMs are, however, unable to represent local sub-grid processes and tend to over-estimate rainfall over southern Africa. Moreover, the sub-gird representation of rainfall at mid-latitudes is highly complicated and may not be explicitly estimated by a GCM (Reason *et al.,* 2006). Recalibrated GCM output to regional levels was developed to overcome such systematic biases and this has the potential to outscore simple statistical models (Landman *et al.,* 2001; Bartman *et al.,* 2003). At the time that this initial framework was being developed. the SAWS was compiling seasonal rainfall outlooks by combining output from Canonical Correlation Analysis (CCA), Quadratic Discriminant Analysis (QDA) and Atmospheric General Circulation Models (AGCMs). Results had shown that a combination of these different models consistently deliver a more skilful forecast than any individual model on its own (Klopper and Landman, 2003). Regional Climate Models (RCMs) have been used operationally in southern Africa since 2006 and they have the potential to simulate the seasonal rainfall variability and can subsequently be used to provide operational seasonal rainfall forecasts in the future (Reason *et al.,* 2006).

Seasonal forecasts of climate variables such as rainfall and temperature are often expressed as probabilities of occurrence within the above, near and below normal categories (Zhang and Casey, 1999). This approach has been adopted because of the inherent variability of the atmosphere and a lack of understanding of all the various components of the climate system (SAWS, 2005). A probability is assigned to each category, indicating the chance of a particular category to occur during the target season. The subsequent forecast probabilities indicate the direction of the forecast as well as the degree of confidence in the forecast. The higher the confidence in the forecast, the higher the assigned probability will be for that specific category. When there is no confidence in the forecast, climatological probabilities (33.3%) are assigned to each of the three categories (SAWS, 2005).

The SAWS has been producing seasonal forecasts in three equi-probable categories of below normal, near normal and above normal rainfalls for monthly and three consecutive months. These forecasts were available routinely on the SAWS website. However, production of seasonal climate forecasts in itself is not enough for operational hydrological and agricultural decision making. Often in operational agrohydrological services, there is a need to estimate the consequences of seasonal climate forecasts with respect to agrohydrological variables that are closer to the actual problems faced by society such as soil moisture contents and crop yield estimates or streamflow amounts or reservoir levels,. Hence, generic methodologies were developed in this initial framework for temporal downscaling of categorical seasonal forecasts into a daily time series of values suitable for agrohydrological models.

7.4.1 Methods of Temporal Downscaling

Basically, weather generators and analogue methods are the most widely used methods for generating time series data that can be used as input to agrohydrological models. A stochastic *weather generator* employs stochastic methods to generate synthetic sequences of weather (Clark *et al.,* 2004). Stochastic weather generators have been used widely for simulating climate variables (e.g. precipitation, temperature, solar radiation) in climate change studies, but relatively little research had been done in relation to seasonal prediction (Feddersen and Andersen, 2005). The Markov Chain model is a widely used statistical technique to generate the sequence of rainy and dry (no rain) days. It is based on the assumption that the state of any particular day is conditioned by the states of the previous day, or sequence of days. A distribution (e.g. Gamma) is fitted to the observed rainfall amounts for the target site. For the rainy days, rainfall values are sampled from the fitted distribution. Another set of weather generator methods generates weather by re-sampling data from historical records several times (e.g. Clark *et al*., 2004).

The second, relatively simple, approach is the *analogue* method which considers the assumption that a current synoptic situation will likely develop in the similar way as similar past synoptic situations have (WMO, 1992). Indices of climatic information, such as the ENSO status, SST or SOI and daily mean sea level pressure can be used to select analogue years from past records which had a similar status to that of the current situation, provided that these indices are well established for the target region. For example, indices of ENSO and SOI have been used in Ethiopia (e.g. Bekele, 1992) and Australia (e.g. Piechota *et al.,* 1998; Chiew *et al.,* 2003; Ritchie *et al.,* 2004) for similar purposes. The analogue approach has been used previously by several researchers in South Africa (e.g. Schulze *et al.*, 1998; Lumsden, 2000; Hallowes, 2002; Bezuidenhout, 2005) by first ranking the historical rainfall records in ascending order. The ranked rainfall totals are then grouped into three categories of seasonal rainfalls, *viz.* below normal, near normal and above normal. One approach is to select the median year in each category as the analogue year and daily rainfall values representing the selected forecast season are then extracted from the selected median years.

The temporal downscaling method developed in this initial framework uses both the analogue and weather generator approaches. The analogue method used in this framework is also based on ranking of historical rainfall records, but analogue years are selected randomly, conditioned by the probability assigned to each category. Each category is weighted, based on the level of the confidence in the forecast. The higher the assigned probability, the higher the number of analogue years that will be sampled from that particular category.

7.4.2 Generating Daily Rainfall Values

To generate the daily rainfall values representing the selected forecast season from each of the selected analogue years, two methods, *viz.* the *Historical Sequence Method* and the *Ensemble Re-ordering Based Method* (also termed the "Schaake shuffle") have been adopted in this study.

The *Historical Sequence Method* is based on the assumption that "daily rainfall values within the forecast season develop in similar sequences developed in the selected analogue years representing each category" (Schulze *et al.*, 1998). This approach provides one possible realisation of the past climate which is likely to occur in the future and attempts to preserve the historical temporal persistence of the past weather conditions that occurred in the selected analogue years.

Synthetic sequences of rainfall that are statistically consistent (in terms of the mean, variance, skew, long term persistency) with the observed characteristics of the historical data can provide alternative realisations that are equally likely to occur in the future and which can then be used to quantify uncertainty associated with climate variability. The synthetic sequences method randomly generates unique replicates (sequences), i.e. sequences of rain that have not observed. However, the approach should preserve the statistical moments of the historical time series from which they are populated (Clark *et al*., 2004; Chiew *et al.,* 2005).

The "Ensemble Re-ordering" approach was applied by Clark *et al*. (2004) and uses random chance as the determining factor for an observation to be included in the sample that represent the forecast day. In this respect, the ensembles used to populate the sequences are randomly selected from a mix of different dates of all historical years, or from a subset of preferentially selected years. For each forecast day, the ensemble members are re-ordered so as to preserve the spatio-temporal variability in the historical records.

An algorithm was coded within the initial framework that enables the processing of all the steps required for conditioning the random selection of analogue years on the probability assigned to each category (**Figure 7.4.1**). Moreover, the program was designed to automatically extract daily data sets that represent estimates of future conditions for the targeted forecast season based on the *Historical Sequence* and *Ensemble Re-ordering Based Methods* (**Figure 7.4.2**). The following steps are contained in the algorithm and are applicable to both the monthly and seasonal (3 months) categorical climate forecasts:

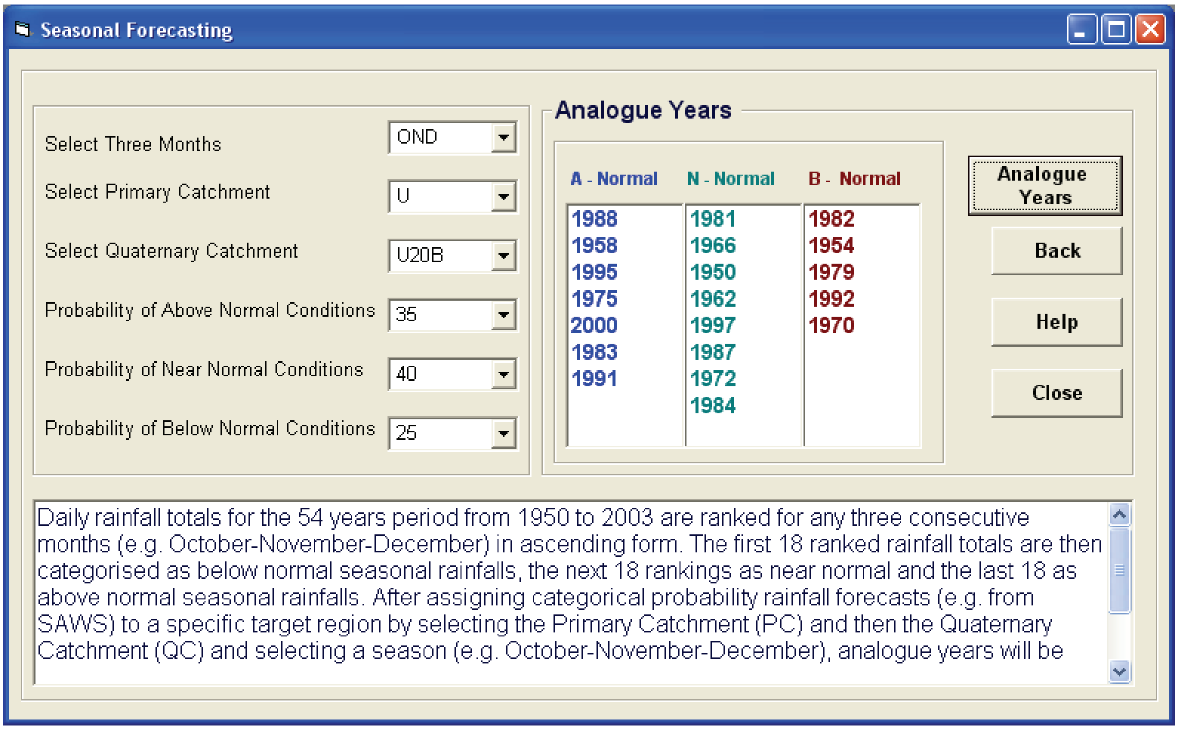


Figure 7.4.1 A window for translating seasonal categorical rainfall forecasts into daily time series values based on the analogue method

1. *Ranking of daily rainfall totals*
   Quality checked daily rainfall totals for the 54 years period from 1950 to 2003 were ranked for monthly and any three consecutive months (e.g. October-November-December) in ascending (lowest to highest) order. The first 18 ranked rainfall totals were then categorised as representing "below normal" seasonal rainfalls, the next 18 rankings as "near normal" and the highest 18 as "above normal" seasonal rainfalls.
2. *Assigning inputs and selecting analogue years*
   First, a season (e.g. October-November-December), the Primary Catchment (PC) and a Quaternary Catchment (QC) within the PC, as well as categorical probability rainfall forecasts obtained from various institutions (e.g. from SAWS) were selected from their respective drop down menus (**Figure 7.4.1**). Thereafter analogue years were randomly sampled, based on the probability assigned to each category. Since probabilities of categorical climate forecasts are usually given in multiples of 5 percentiles, the analogue years that represent each category were obtained by dividing the probability forecast by 5. In each run, therefore, 20 analogue years in total were selected to represent the probability assigned to the three categories (**Figure 7.4.1**). For example, for each of the three categories, if the probabilities of above, near and below normal rainfall are 35%, 40% and 25%, the respective number of analogue years would be 7, 8 and 5.
3. *Extracting daily rainfall values from selected analogue years*
   Daily rainfall values representing the selected forecast season could then be extracted based on either the *Historical Sequence Method* or the *Ensemble Re-ordering Based Method* (**Figure 7.4.2**).

If the *Historical Sequence Method* was selected, 20 independent daily rainfall files from each of the analogue years would be generated. Each file had daily data sets extracted from the same dates in the historical records of the analogue years, and these files were then automatically used as the daily rainfall files for agrohydrological models.

If the *Ensemble Re-ordering Based Method* was chosen (**Figure 7.4.2**), the daily rainfall values from each of the selected analogue years for the target season were collected in a temporal array. The program then randomly re-sampled ten ensemble members for each forecast day of a given season from a mix of dates in the temporal array. Another random selection of dates from all historical years (1950-2003) of the same season was then used to re-order the temporal correlation structure of the ensembles selected from the preferentially selected analogue years. The random selection of dates from the historical records was only used for the first forecast day, and was persisted with for the subsequent forecast lead times. The re-ordered ensemble members could then be used as inputs into agrohydrological models. Unlike many other weather generator models, the temporal persistence is not preserved intrinsically, but is constructed as a post-processing step (Clark *et al.*, 2004).

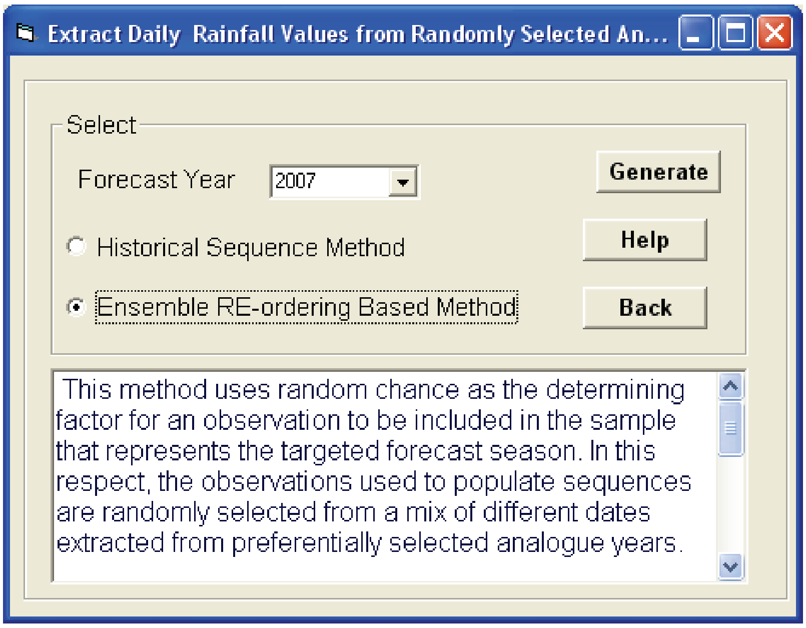


Figure 7.4.2 A window for extracting daily rainfall values from randomly selected analogue years

The main objective of developing this initial framework for southern Africa is to facilitate the translation of state-of-the-art weather and climate forecasts into suitable quantitative values which can be input into the daily time step crop and agrohydrological models. Once the translation process is completed, the subsequent step is the generation of agrohydrologically related forecasts (e.g. soil moisture, crop yields, irrigation requirements, streamflows, reservoir levels,). For this purpose, the *ACRU* agrohydrological modelling system (Schulze, 1995a and updates) is employed in this specific study to generate agrohydrological forecasts. At a later stage it is envisaged that other daily models such as CERES-Maize or APSIM could be imbedded within the framework. A brief overview of the *ACRU* model follows below.

7.5 THE *ACRU* AGROHYDROLOGICAL MODELLING SYSTEM

7.5.1 Reasons for Selecting the *ACRU* Model

ACRU is a daily time step, multi-purpose and multi-level conceptual-physical agrohydrological simulation model. It was selected for this study because it has been widely verified under highly varying hydrological regimes on gauged catchments in southern Africa (cf. reviews by Schulze, 1995; Schulze and Smithers, 2004) and elsewhere (e.g. Dunsmore *et al.,* 1986; Ghile, 2004). It can simulate not only daily streamflows, but also daily soil moisture for a top- and subsoil horizon, irrigation water requirements, crop yields for selected crops (e.g. maize, wheat, sugarcane) and perform reservoir yield analyses. Furthermore, for southern Africa, *ACRU* is linked to extensive databases containing quality controlled daily rainfall, minimum and maximum temperatures for the period of 1950 to 2000 as well as to baseline land cover and soil information for each of the 1 946 hydrologically interlinked Quaternary Catchments (QCs) and the 5 838 Quinary Catchments that make up southern Africa (Schulze, 2006; Schulze and Horan, 2010).

The linking of the *ACRU* model to the databases is known as the Quaternary Catchments Database (QCD), which was used in this initial framework, or the Quinary Catchments Database (QnCDB), which may be used in subsequent enhancements. A detailed description of the *ACRU* model in terms of inputs, simulation options and outputs is provided by Schulze (1995) and Smithers and Schulze (1995; 2004). In the section which follows, only a brief overview of the concepts imbedded in the *ACRU* model is presented.

7.5.2 A Brief Description of the *ACRU* Model

As a conceptual-physical soil water budget model, *ACRU* (Schulze, 1995 and updates) integrates various water budgeting and runoff producing components of the terrestrial hydrological system, as well as operational aspects of water resource management, all with risk analysis (Schulze, 1995; Schulze and Smithers, 2004). The model was designed as a daily time-step, two layer soil water budgeting model which has been structured to be sensitive to land use changes on soil moisture, evaporative rates and runoff regimes. The model has been considerably updated from original versions to its present status (Schulze and Smithers, 2004) in order to simulate those components and processes of the hydrological cycle which are affected by the soil water budget, such as stormflow, baseflow, irrigation demand, sediment yield or crop yield, and to output any of those components on a daily basis (where relevant), or as monthly and annual totals of the daily values.

A summary of the concepts of the *ACRU* model with respect to inputs, operational modes, simulation options and objectives is given in **Figure 7.5.1**. **Figure 7.5.2** represents a schematic of the multi-layer soil water budgeting by partitioning and redistribution of soil water, as conceptualised in the *ACRU* model.

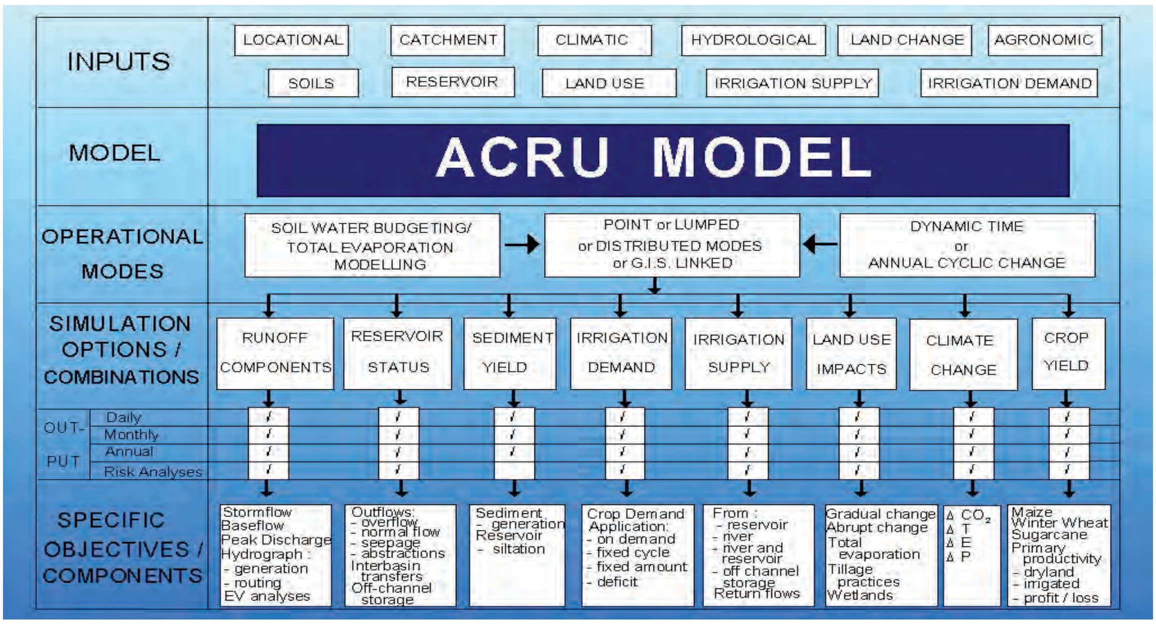


Figure 7.5.1 The *ACRU* agrohydrological model: Schematic of inputs, modes of operation, simulation options and objectives / components (After Schulze, 1995)

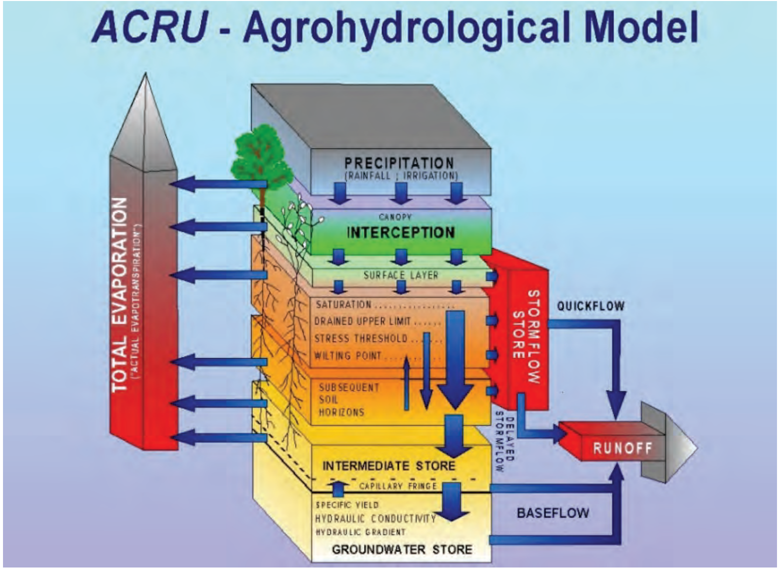


Figure 7.5.2 The *ACRU* agrohydrological model: Schematic of its multi-layer soil water budgeting and partitioning and redistribution of soil water (After Schulze, 1995)

7.6 SUMMARY

The development of effective procedures for the application of weather and climate forecasts into forecasts of various agrohydrological variables (e.g. streamflows, soil moisture, crop yields, irrigation demand) plays a prominent role in operational decision-making in the agriculture and water sectors. For this purpose, a GIS based initial framework was developed to serve as an aid to process all the computations required in the translation of the daily to seasonal climate forecasts into daily quantitative values suitable as input in hydrological or crop models. The framework was, and is being further, designed to include generic windows which allow users to process the near real time rainfall fields estimated by remotely sensed tools, as well as forecasts of weather / climate models into suitable scales and formats that are needed by many daily time step agrohydrological models. The key features of this initial framework are that it:

- facilitates the selection of near real time remotely sensed observations, as well as short term, medium term and longer term forecasts supplied by various weather and climate models from different institutions across a range of time scales;
- links to comprehensive GIS functionality that provides tools for spatial disaggregation, data structure and reformatting, as well as for post-processing of data/information through tabulation, mapping and report generation;
- translates categorical seasonal forecasts into a daily time series of values suitable for agrohydrological models through generic algorithms developed within the framework;
- converts ensembles of rainfall forecasts into suitable formats which are understood by GIS;
- downscales grid layers to Quaternary Catchments; and, finally,
- extracts rainfall data to *ACRU* formatted text input files.

The application of near real, plus daily to seasonal rainfall forecasts as a nested input to one or more agrohydrological models, thereby enabling the forecasting of agrohydrological variables across a range of time scales and lead times, is a new concept in southern African context. With further development and refinement, this initial framework has the potential to play an important role in bridging the gaps that exist between outputs of weather and climate models and their practical application in agrohydrological models. The development of the framework is an ongoing process and is expected to continue beyond the initial stage, in order to incorporate other weather variables and forecast products issued by other institutions.

The outputs from this initial framework in which multiple forecasts are downscaled spatially to Quaternary Catchments and temporally to daily values needs to be evaluated either agriculturally or hydrologically. In this report a hydrological evaluation in a tested catchment, *viz*. the Mgeni (cf. **Chapter 5**), was opted for.

CHAPTER 8

TOWARDS AN OPERATIONAL AGROHYDROLOGICAL FORECAST FRAMEWORK

TG Lumsden

Summary

8.1 INTRODUCTION
8.2 DEVELOPMENT OF THE OPERATIONAL AGROHYDROLOGICAL FORECASTING FRAMEWORK
8.3 FURTHER DEVELOPMENT NEEDS

8.1 INTRODUCTION

For the research conducted in this project to find maximum application in the South African hydrological and agricultural sectors, it is important that the forecasting systems that have been developed be rendered operational. This objective was largely achieved for the weather and climate forecasts. To fully benefit from these weather / climate forecasts, it is desirable that they be translated into operational agrohydrological forecasts. This chapter describes work that was conducted towards developing operational agrohydrological forecasts in the project.

The research based framework for agrohydrological forecasting described in **Chapter 7** proved to be a valuable tool in the development and evaluation of agrohydrological forecasts in the project (cf. **Sections 6.6** and **6.7**). The tool was developed in the initial stages of the project and utilised weather and climate forecasts available at that point in time. These weather / climate forecasts have, however, evolved over time, with new ones available and others no longer available. Furthermore, the GIS software upon which the research framework depended also evolved, rendering the framework no longer functional in its original form. This necessitated the development of a new framework for operational application. This framework utilised aspects of the initial GIS framework, but focused more on the operational context rather than on, for example, sophisticated downscaling procedures.

8.2 DEVELOPMENT OF THE OPERATIONAL AGROHYDROLOGICAL FORECASTING FRAMEWORK

8.2.1 General Considerations

The development of the operational forecasting framework focused on two catchments considered in the project, i.e. the Berg and Mgeni catchments. However, the framework was designed in a manner that allows for other catchments to be added.

The operational framework was designed to utilise the *ACRU* model to perform agrohydrological simulations. However, the design could be modified to utilise other simulation models.

An operational forecasting system requires a near real time feed of quality controlled observed climate data in order to capture conditions in the catchment prior to issuing a forecast (cf. **Section 6.6.5**). Since a near real time feed of data was not available for application in this project (for reasons discussed in **Chapter 11**), provision was made to initialise key stores in the *ACRU* model with specified conditions prior to the generation of forecasts. These stores included the soil water stores (A and B horizon) and the baseflow store (cf. **Section 8.2.3.3**).

In order to maintain flexibility in the operational framework, allowances were made for other types of simulation options. These include the ability to incorporate different forecast ranges, levels of data availability and modes of forecasting. Further details of these are given in **Section 8.2.3**.

8.2.2 Generating a Forecast for the First Time

A requirement of the operational forecasting framework is that an initial input (menu) file of the *ACRU* model (including information on soils, land cover, historical climate etc.) be available for the catchment or catchments concerned before operational forecasting can commence. This includes needing to link the weather / climate forecasts to the catchments and representing this in the *ACRU* menu (i.e. the selection of appropriate pixels or forecast stations from the weather / climate forecasts and the calculation of rainfall and temperature adjustment factors to adjust the forecasts to better represent conditions in the catchments). Input menu files have been prepared for the Berg and Mgeni catchments assuming baseline vegetation cover and no water resources infrastructure (dams, transfer schemes, etc.) or abstractions. If desired, the menu files could be revised to reflect actual vegetation and the resulting runoff forecasts generated by the system could then be fed into existing configurations of yield models incorporating infrastructure and abstractions, enabling analysis of the balance between water supply and demand. The weather / climate forecasts were linked to the catchments in a similar manner to that described in Lumsden *et al*. (2010).

A further requirement before commencing forecasting is to verify that the *ACRU* model is able to adequately represent agrohydrological responses in the catchment of interest under known historical climate conditions before attempting to forecast future climatic conditions. For the Upper Breede and Mgeni catchments, verifications of historical streamflow simulations have been performed by Warburton *et al*. (2010). The climate and topography of the Upper Breede catchment is similar to the upper and middle regions of the Berg catchment. Adequate model performance in the Upper Breede is thus likely to imply adequate performance in the Berg catchment (since these are neighbouring catchments). The adequacy of simulations was assessed by the following criteria: a percentage difference between the sum of simulated daily flows ($\sum Q_s$) and sum of observed daily flows ($\sum Q_o$) of less than 15% of $\sum Q_o$, a percentage difference between the standard deviation of simulated daily flows (σ_s) and standard deviation of observed daily flows (σ_o) of less than 15% of σ_o, and a coefficient of determination (R^2) value in excess of 0.7 for daily simulated flows. These criteria were taken from Smithers and Schulze (2004). In addition, the goodness-of-fit was further assessed by considering whether the Nash-Sutcliffe efficiency index (Nash and Sutcliffe, 1970), E_f, was similar in magnitude to R^2. The values of these statistics for the Water Management Units (WMUs) evaluated in these catchments are given in **Table 8.2.1**. The verification period for the Upper Breede WMUs was 1987 – 1999 while for the Mgeni WMUs it was 1987 – 1998.

Table 8.2.1 Statistics of performance of the *ACRU* model in selected WMUs of the Upper Breede and Mgeni Catchments (After Warburton *et al*., 2010)

Statistic	**Upper Breede Catchment WMUs**		**Mgeni Catchment WMUs**			
	Koekedou	Upper Breë	Mpendle	Lions River	Karkloof	Henley
Mean of observed daily flows (mm/day)	1.021	0.376	0.796	0.582	0.803	0.629
Mean of simulated daily flows (mm/day)	1.091	0.372	0.733	0.524	0.698	0.605
% difference in means of daily flows	-6.83	-1.21	7.91	9.95	13.05	3.86
Standard deviation of observed daily flows (mm)	5.323	0.812	1.823	1.734	1.228	1.246
Standard deviation of simulated dailyflows (mm)	5.639	0.768	2.011	1.947	1.305	1.541
% difference in standard deviations of daily flows	-5.94	5.39	-10.34	-12.31	-6.26	-23.67
Coefficient of determination: R^2	0.864	0.712	0.836	0.882	0.713	0.785
Nash-Sutcliffe efficiency index: E_f	0.785	0.516	0.802	0.847	0.655	0.654

The statistics in **Table 8.2.1**, along with other analyses conducted, led Warburton *et al*. (2010) to conclude that the simulations for the Koekedou and Upper Breë WMUs in the Upper Breede catchment were, respectively, highly acceptable and acceptable, and that the catchment's streamflows could be simulated with reasonable confidence. The statistics of performance of the WMUs in the Mgeni catchment, together with other analyses, revealed that the simulations were highly acceptable in the Mpendle WMU and acceptable in the Lions River and Karkloof WMUs. The simulations in the Henley WMU were acceptable for all criteria except the percentage difference in standard deviations of simulated and observed daily flows. The difficulty in simulating variability of flows was attributed to the large portions of informal residential areas in the WMU. These areas are unstructured and diverse in nature making it difficult to represent the land uses and compacted areas present. Overall Warburton *et al*. (2010) concluded that the relatively diverse Mgeni catchment could be simulated with reasonable confidence. It should be noted that for both the Upper Breede and Mgeni verification studies, inputs to the *ACRU* model were derived from national land use and soils information, together with default input values from the *ACRU* User Manual where no better information was available. No fieldwork was carried out to determine values of input variables. The study by Warburton *et al*. (2010) adds to the available literature confirming that the model's process representation is a relatively accurate reflection of reality at a daily time step and over a range of climatic regions. From the results of that study it was concluded that the *ACRU* model is appropriate as a tool to assess hydrological responses of catchments to land use and climate changes.

8.2.3 Options in Generating a Forecast

The options available in generating a forecast using the operational agrohydrological forecasting framework are discussed in the order that they appear in the user interface (**Figure 8.2.1**).

8.2.3.1 Catchment selection

The user indicates the catchment for which a forecast is to be generated. The Berg and Mgeni catchments are available as choices, as are 'Other' for which catchments can be user specified.

8.2.3.2 Weather / climate forecast selection

The user indicates the weather / climate forecasts that will be utilised in generating agrohydrological forecasts. It was not possible within the timeframe of this project to address all the issues identified in **Section 6.6.5** with regard to the operationalisation of seasonal agrohydrological forecasts. Hence the only weather / climate forecasts available for generating agrohydrological forecasts in the present operational framework are the 7 day C-CAM forecasts produced by the CSIR. Since these forecasts are available at a fine spatial (± 15 km) and temporal (daily) resolution, and are deterministic in nature, most of the operational challenges identified in **Section 6.6.5** are not of concern for these forecasts. The option shown in the user interface to generate seasonal forecasts is not currently active (**Figure 8.2.1**).

The user is also required to indicate the availability of climate variables associated with the selected weather / climate forecasts. In the initial development of the operational framework only rainfall forecasts were available at the 7 day range, however, later on maximum and minimum temperature forecasts also became available at this forecast range. The availability of temperature forecasts has implications for the estimation of, for example, reference potential evaporation. In the absence of temperature forecasts, potential evaporation is estimated from monthly mean temperature (using a monthly version of the Hargreaves and Samani, 1985 equation), giving rise to evaporation estimates that are not sensitive to day-to-day variations in temperature. If daily maximum and minimum temperature forecasts are available, then a daily version of the equation (sensitive to day-to-day variations) is used, thus giving a more realistic simulation. This becomes critical in more temperature sensitive forecasts, for example, of irrigation demand and soil moisture.

8.2.3.3 Soil moisture initialisation options

Options to initialise soil moisture stores include commencing simulations with soil moisture pre-set at 50% of plant available water capacity or, alternatively, at the level of long term monthly median values of soil moisture. In the case of the Berg and Mgeni catchments monthly median values are available to the user and were derived from Schulze *et al*. (2011).

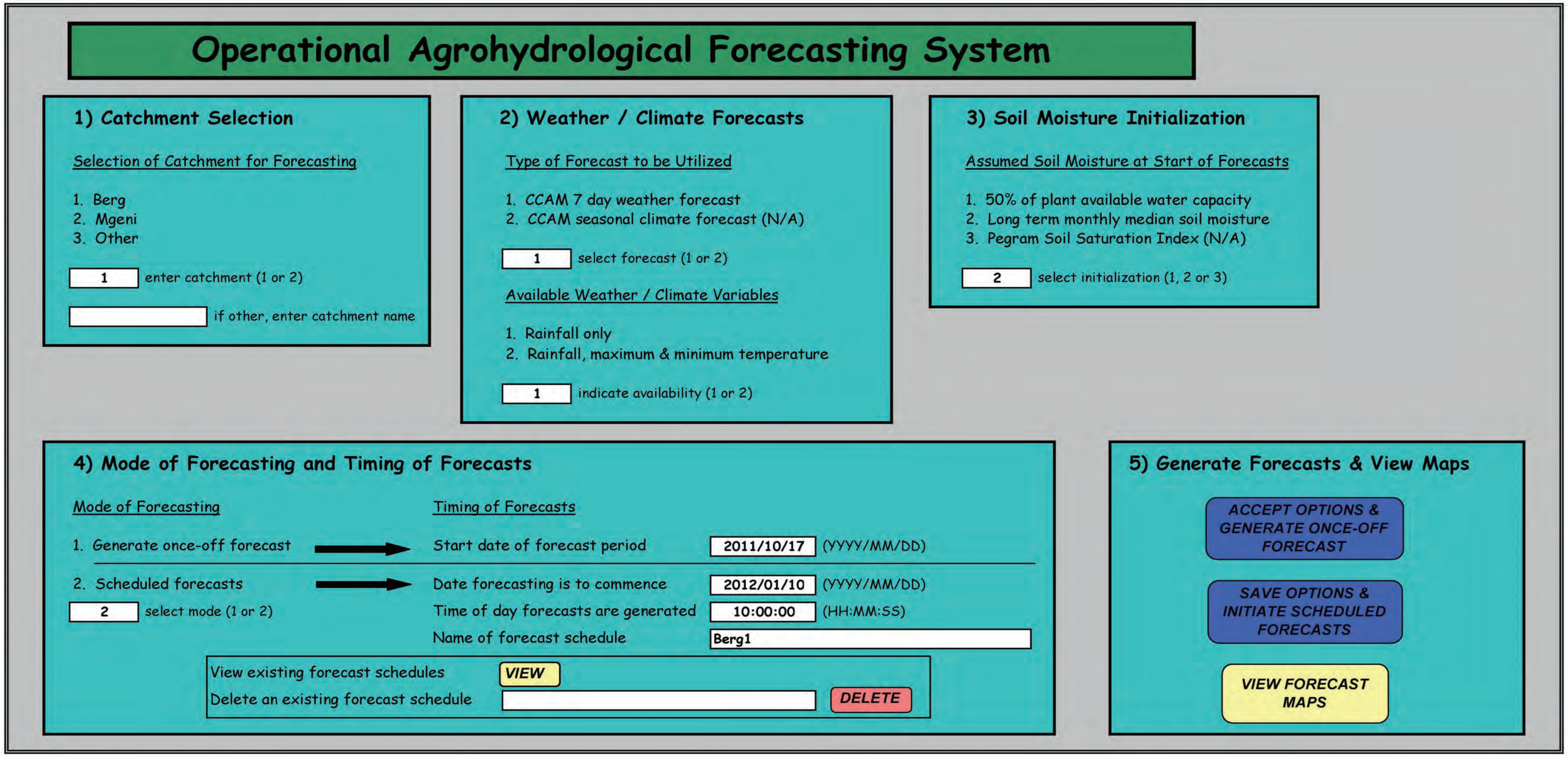


Figure 8.2.1 User interface of the operational agrohydrological forecasting system which allows for the selection of available options for the generation of forecasts

Initialisation of the baseflow store is discussed here as it is a similar process to initialisation of the soil moisture stores. Only one method is available, namely, initialisation according to long term monthly median values (derived from Schulze *et al*., 2011). As only one method is available, this is currently implemented automatically (without notification in the user interface) since, if the baseflow store is not initialised, the model code would set the store to be zero at the commencement of a simulation, leading to very low baseflow simulations for short simulation periods (as in a 7 day forecast).

8.2.3.4 Mode of forecasting and timing of forecasts

Two modes of forecasting are available to the user, *viz*. generating a once-off forecast and scheduled (ongoing) forecasts. If a once-off forecast is generated, the start date of the forecast period must be specified. If scheduled forecasts are to be generated, the date on which forecasting is to commence must be specified, along with the time of day that the forecasts should be generated. Since only 7 day forecasts can be generated at present, it is assumed that all forecasts are generated on a daily basis, i.e. at the same frequency with which the 7 day C-CAM weather forecasts become available. Scheduled forecasting allows for different forecast schedules to be saved, and for these to be viewed and deleted, as required.

8.2.3.5 Forecast generation and viewing of output

Two buttons are provided to generate forecasts, one for once-off forecasts and the other for scheduled forecasts. The options selected for once-off forecasts are saved temporarily, and are overwritten the next time a forecast is generated. For scheduled forecasts, the schedules (with their associated options), can be saved under different names.

A button is also provided to initiate the post-processing of *ACRU* output, and the mapping of forecast results. Forecasts maps of streamflow, catchment soil moisture and irrigation demand can be generated. For irrigation demand forecasts in the Berg and Mgeni catchments, the following assumptions were made in the simulations:

- The majority of roots are within the top 0.3 m of the soil profile
- The soil texture is a sandy clay loam soil with plant available water capacity of 0.1 $m.m^{-1}$
- The crop has a water use coefficient of 0.8 throughout the year
- Demand irrigation is initiated when soil water content drops to 0.5 of plant available water capacity, with unlimited water for irrigation assumed to be available.

The post-processing of *ACRU* output, which involves summing or averaging (depending on the variable concerned) of daily output over the period of the forecast, represents a fulfilment (in the context of a 7 day forecast) of the recommendation made in **Section 6.6.5** regarding issues to be addressed for the operationalisation of forecasts.

8.2.4 Steps in the Forecast Generation Process

Once the forecast options have been selected through the forecast system interface (cf. **Section 8.2.3**), the following steps are followed in the generation of forecasts:

- Downloading of weather / climate forecasts (this is currently a manual process owing to institutional security restrictions on FTP transfers)
- Creation of *ACRU* climate files for catchments from gridded / station climate forecasts
- Modification of *ACRU* menus to reflect date of current forecast, availability of climate forecast variables and initialisation of stores (baseflow, soil water)
- *ACRU* simulation runs
- Post-processing of *ACRU* output
- Mapping of forecasts.

An example of the forecast maps produced by the operational framework is presented in **Figure 8.2.2** and **Figure 8.2.3** for the 7 day period from 17-23 October 2012. **Figure 8.2.2** shows forecasts of rainfall, topsoil (A horizon) and subsoil (B horizon) soil moisture, while **Figure 8.2.3** shows forecasts of the components of sub-catchment runoff (i.e. baseflow and stormflow), the runoff from individual catchments and streamflow (which is the accumulated flow from all upstream catchments).

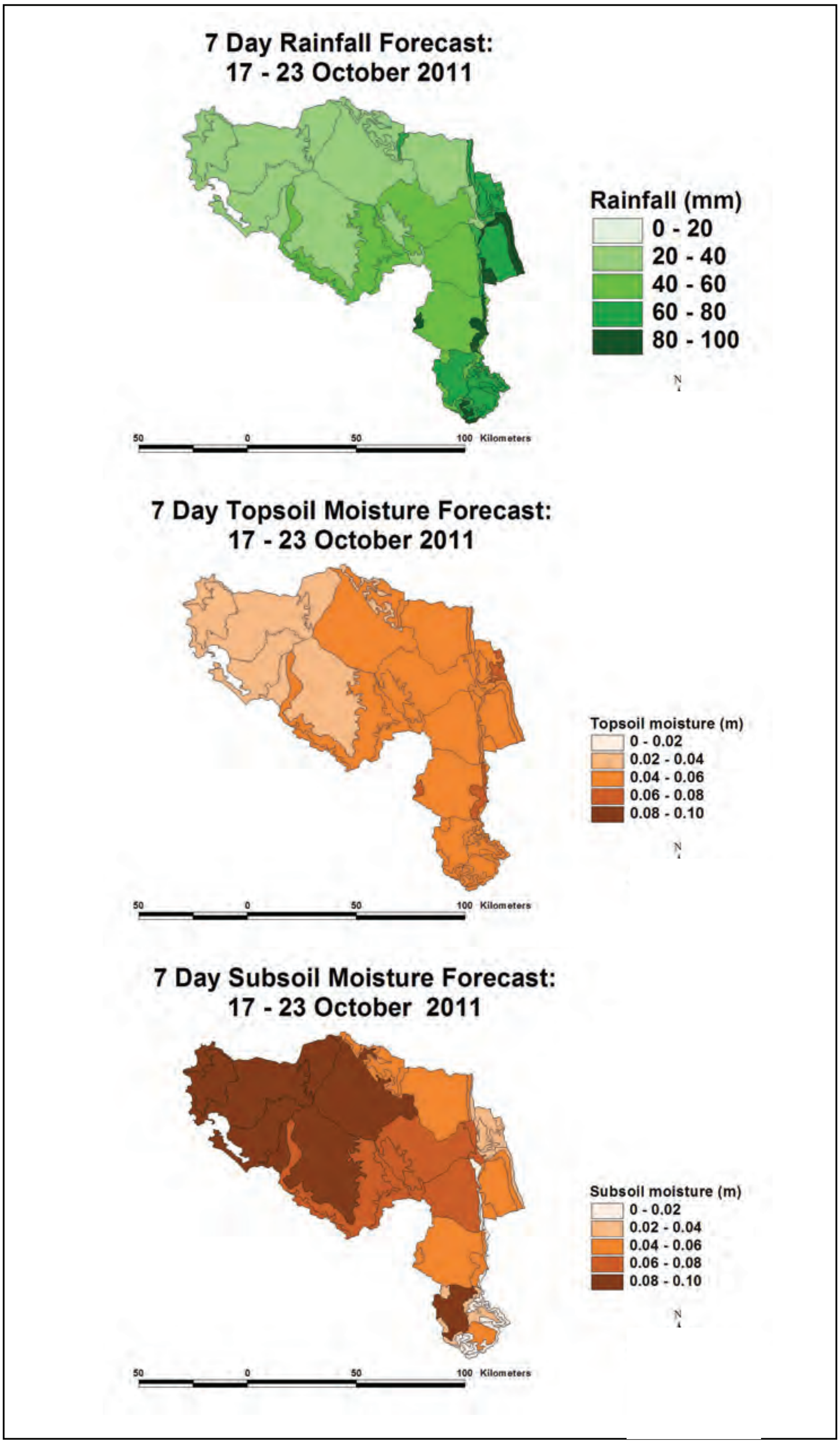


Figure 8.2.2 7 day forecasts of rainfall, topsoil moisture and subsoil moisture in the Berg catchment for the period 17-23 October 2011

The rainfall forecast (**Figure 8.2.2**) indicates more rain in the south and west of the Berg catchment, which coincides with the mountainous regions in the catchment. Topsoil moisture follows a similar pattern, however, for subsoil moisture there are large areas in the northwest that are forecast to be

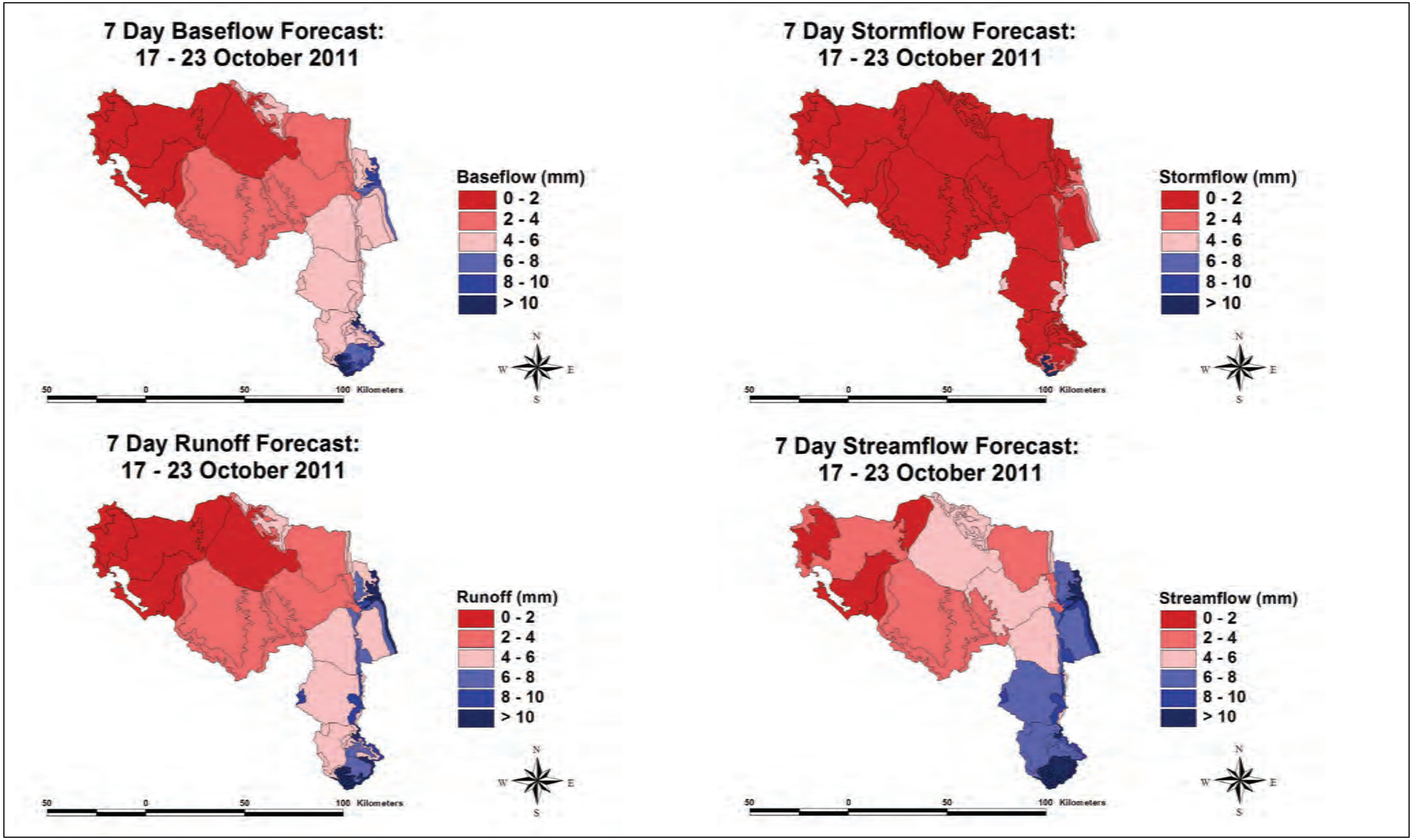


Figure 8.2.3 7 day forecasts of baseflow, stormflow, runoff and accumulated streamflow in the Berg catchment for the period 17-23 October 2011

relatively moist. This may be indicative of lower vegetative water use from this horizon in this region. When comparing baseflow, stormflow and runoff in **Figure 8.2.3** it becomes clear that most individual catchment runoff is derived from baseflow for the forecast period. When comparing the runoff and streamflow forecast maps, the effect of accumulating runoff across contributing catchments (to determine streamflow) is evident, with higher flows being forecast for the catchments through which the main stem of the Berg River flows. This would be even more evident if flows were to be expressed in volumes, as opposed to the depths which are currently shown.

Although the maps in **Figures 8.2.2** and **8.2.3** express the values of the different forecast variables in absolute terms (i.e. in mm), for decision making purposes it may be more useful to express results in relative terms, for example, as percentages of the long term mean over the forecast period.

Although irrigation demand forecasts can be generated an example is not shown here since these forecasts are highly sensitive to the level of soil moisture at the commencement of the forecast period. These soil moisture conditions can only be adequately represented through 'hotstarting' of the *ACRU* model, where soil water content from the previous forecast is carried over to the new forecast period. This issue is discussed further in **Section 8.3** which addresses future development needs.

8.2.5 Overview of Software Design

The structure of the operational forecasting system consists firstly of a simple spreadsheet interface for the selection of forecasting options. The buttons on the interface then launch macros which call a series of batch files and Fortran programmes to prepare *ACRU* climate files and modify the *ACRU* input menu according to the forecast options selected. The forecasting system applies the *ACRU*2000 version of *ACRU* since this version allows for the simulation of short time series (e.g. 7 days) without needing full calendar years of climate data. Furthermore, *ACRU*2000 allows for the initialisation of the baseflow store, which is an important advantage since without initialisation the baseflow store is empty at the commencement of a simulation leading to very low baseflow simulations. The forecast scheduling is carried out using a task scheduling application which executes the steps in the forecast generation process (from the creation of climate files onwards) at the specified times. The post-processing of *ACRU* output is done via a separate spreadsheet interface (as a linked process). The mapping of the forecasts is performed using a GIS application.

8.3 FURTHER DEVELOPMENT NEEDS

The framework reported in this chapter represents a semi-operational system that requires further development in a number of areas:

- The framework needs to be linked to a near real time system to acquire observed climate data and perform quality control and infilling of missing data. Such a system would require significant resources and would best be served by a national data facility.
- A system is required to automate the downloading of weather / climate forecasts on a daily basis (institutional security restrictions currently prevent this).
- In the absence of near real time quality controlled climate data, the initialisation of soil water stores could be significantly improved by the incorporation of near real time satellite driven estimates of soil moisture status, such as those developed by Sinclair and Pegram (2010).
- 'Hotstarting' in the *ACRU* model should be implemented to enable the carry-over of store values from one forecast to the next. This is particularly relevant to stores that cannot be initialised using other sources of current information and where representative store values can only be obtained over time when continuity in simulations can be maintained across successive forecast periods (e.g. the baseflow store). For irrigation demand forecasts to be meaningful it is vital that there is a carry-over of the level of soil moisture from one forecast to the next as the timing of irrigation applications is very dependent on the current soil moisture. Within a 7 day forecast period there is insufficient time for the irrigated soil moisture balance to reach equilibrium from an initial default soil moisture level (currently set at 50% of plant available water).
- The above and other research issues would best be addressed in a follow-up research project.
- A partner should be identified to continue generating agrohydrological forecasts on an operational basis beyond the lifetime of the project, and an online portal developed through which the forecasts can be disseminated.

CHAPTER 9

STAKEHOLDER INTERACTIONS

G Zuma-Netshiukwi, O Phahlane, MA Tadross and P Johnston

Summary

9.1 AGRICULTURAL RESEARCH COUNCIL EXPERIENCES IN THE MODDER / RIET CATCHMENT
9.2 AGRICULTUTAL RESEARCH COUNCIL EXPERIENCES IN THE UPPER OLIFANTS CATCHMENT
9.3 UNIVERSITY OF CAPE TOWN EXPERIENCES ON ENGAGING FARMERS AND DISSEMINATING FORECASTS

9.1 AGRICULTURAL RESEARCH COUNCIL EXPERIENCES IN THE MODDER / RIET CATCHMENT (G Zuma-Netshiukwi)

9.1.1 Project Initiatives and Experiences

The target groups for the study were commercial and resource poor farmers, as well as a water association board. Appropriate farmers were identified. Agricultural crops that are produced include maize, sunflower, wheat, potatoes, spinach, beetroot, carrot and other vegetables. Rainfed and irrigation crop production is practised at small to large scales. Livestock farmers keep cattle, pigs, poultry and sheep. Several farmers own fruit trees such as fig, apricot and peach. A number of different vegetables are grown in this area.

The ARC established links with nine areas within the Catchment. These areas were Jacobsdal, Koffiefontein, Sannaspos, Fauresmith, Dewetsdorp, Trompsburg, Brandfort, Soutpan and Reddersburg. The project was introduced and explained to the farmers involved. The response from the participants was positive and very encouraging, as most of them found this information very valuable. Formal workshops were arranged in each area in collaboration with the local extension officer (EO) to determine the requirements of the farmers with respect to weather forecasts. The farmers were grouped according to their typology to determine the climate parameters, lead times and dissemination methods / format preferred by each group. Bloem Water, Naledi Municipality and the Department of Education were added to the list of stakeholders within this catchment.

In the Modder / Riet catchment three District Municipalities were earmarked for the project, *viz*. Xhariep, Motheo and Lejweleputswa. Xhariep is the largest of all provincial District Municipalities in the Free State. There are 17 towns in the region that are divided into three local municipalities, *viz*. Kopanong, Letsemeng and Mohokare. Within this district Kopanong and Letsemeng municipality towns were selected. Listed in **Table 9.1.1** are the towns selected for the study.

Table 9.1.1 Earmarked communities in the Modder / Riet Catchment

Motheo District		**Xhariep District**		**Lejweleputswa District**
Mangaung Municipality	**Naledi Municipality**	**Letsemeng Municipality**	**Kopanong Municipality**	**Masilonyana Municipality**
Sannaspos	Dewetsdorp	Jacobsdal	Edenburg	Brandfort
		Petrusburg	Fauresmith	Glen
		Koffiefontein	Jagersfontein	Soutpan
			Reddersburg	
			Trompsburg	

In the workshops held with end users, participatory approaches and methods were used to emphasise local knowledge and enable local people to make their own appraisal, analysis, and action among stakeholders. PAR methods (e.g. semi-structured interviews), key informants, direct observations and focus groups were used to gather information from the participants. The participants were also requested to draw a natural resource map to obtain a better understanding of their farms and backyard gardens. The main purpose was to get their perspective on weather forecasts. Most resource poor farmers have no access to seasonal forecasts, and they therefore rely on traditional methods. Although commercial farmers and Water Board Associations receive information from other sources, they did show interest in participating in the project.

Agricultural enterprises identified by the participants include many types of crops and livestock. Participants in each area were requested to identify enterprises with specific forecast requirements. It was established that lead times from 1 week to 3 months were needed to prepare for the coming season. Parameters required are rainfall, temperature and wind. Soutpan residents involved in salt mining requested an hourly to a daily forecast of rainfall, temperature, humidity, wind speed and wind direction. Once a month, a combined forecast with graphs and interpretation is desired.

It was interesting at an early stage to already note in discussions the preferred methods of forecast dissemination, *viz*.

- television programmes (e.g. Ulimo),
- cell phone,
- local radio stations,
- local newspapers,
- extension officers,
- internet (for those who have access), and / or
- agricultural community committees.

Extension officers were also requested to disseminate the information to the farmers through the council and or the chairperson of the agricultural committees.

9.1.2 Seeing the Bigger Picture of Climate Forecasts in the Modder / Riet Catchment: Overall Agricultural Disaster Risk Management in the Free State

The Free State Directorate of Agricultural Disaster Risk Management (FS-ADRM) receives advisories from the National ADRM within the Department of Agriculture Forestry and Fisheries (DAFF) (Motsepe, 2008, personal communication; Wessels, 2009, personal communication). The ADRM unit was established and given the mandate from the presidency for planning and strategically managing risks so as to minimise the effects of natural hazards and agricultural disasters. As articulated in the Disaster Management Act (Act 57 of 2002), the ADRM unit (www.fsagric.fs.gov.za) has to provide for the following:

- an integrated and co-ordinated disaster management policy that focuses on preventing or reducing the risk of disaster, mitigating the severity of disasters, emergency preparedness, rapid and effective response to disasters and post-disaster recovery,
- the establishment of national, provincial and municipal disaster management centres,
- disaster management volunteers, and
- matters related to the above.

Therefore, the DAFF through ADRM introduced an Early Warning System (EWS) for natural hazards to provide and improve awareness of disaster and risk management. The EWS has to issue accurate and timely information from weather / climate and agrometeorological sources so as to provide a warning to individuals at risk with the intention of minimising the severity of disaster. However, for the EWS to be effective according to Act 57 of 2002, it should provide prior risk knowledge, monitoring and warning services, dissemination and communication as well as response capability.

DAFF developed and established the National Agrometeorology Committee (NAC) to plan and put into operation EWS in support of Act 57 of 2002. The NAC is comprised of relevant directorates within DAFF, relevant universities, the Agricultural Research Council, the CSIR, the South African Weather Service and Disaster Centres within local municipalities.

Currently the ADRM unit in the Free State is in its initial phase of development as the Director and the Deputy Director were only appointed in April 2010. The NAC meets on a quarterly basis to review the seasonal forecasts and how to assist the farmers in terms of planning for agricultural activities using the forecasts. This advisory committee meets to make agricultural on-farm decisions and to assist and advise farmers on which response actions to take. The advisories developed in this meeting should be of good quality and user friendly prior to dispatch to extension officers and farmers. The NAC advisory is available from the *agis* website: www.agis.agric.za. The NAC advisory is dispatched from DAFF-ADRM national office to the provincial ADRM. The provincial ADRM transforms these advisories so as to be locally understood, thereafter delivers them to the extension Directorate to be disseminated to the end-users or farmers (National Agromateorological Committee, held September 2010). According to Wessels (2009, personal communication) the ADRM unit in the Free State provides a monthly report on agricultural conditions. This report also includes climatic conditions with emphasis on previous month rainfall conditions, temperature, the Normalised Difference Vegetation Index (NDVI), water supply, veld and livestock conditions. The Provincial DAFF-ADRM and Mangaung Local Municipality (MLM) operate as different entities, but with one mandate of fulfilling Act 57 of 2002. Therefore, there should be close links between these two units. The Provincial Disaster Management Advisory Forum (PDMAF) meets on a quarterly basis and constitutes departments from the Free State province, municipalities as well as community member representatives (Losabe, 2008, personal communication). The MLM Disaster Centre receives warnings from SAWS and disseminates these to the community. The frequent natural disasters in the Free State are winds, floods, dust-storms, heat waves, hail, veld fires and snow (Losabe, 2008, personal communication).

The University of the Free State's (UFS) Department of Soil, Crop and Climate Sciences within the Faculty of Natural and Agriculture Sciences provides graduate, post-graduate and short courses on agrometeorology. The courses entail on-farm practical information for decision making, e.g. analysis of seasonal forecast, calculation of reference evapotranspiration, irrigation scheduling, fire danger index and pest / diseases outbreak. The UFS Disaster Management Training and Education Centre for Africa (DiMTEC), provides training and post graduate education and consultation for disaster risk management. DiMTEC's responsibility is to assist the government in drawing up disaster related policies, develop an advisory issued every two months and post-natural risk assessment.

The Agricultural Research Council – Institute for Soil, Climate and Water (ARC-ISCW) and the South African Weather Service (SAWS) monitor a network of weather stations nationwide. The ARC-ISCW produces disease reports, crop yield estimates, pest outbreaks, seasonal outlooks and agrometeorological zoning, Umlindi and maintains a historical climate data. Umlindi provides information on fire warning, drought monitoring, NDVI, SPI, etc. The ARC-Institute for pasture and Animal Production (API) provides information on veld and rangeland management (Fouche, 2010, personal communication). The ARC-API provides information only to commercial farmers through e-mail, telephone and information days. For example, the advisories generated only when problems are identified, as the farmers call with a concern or where farmers are experiencing poor animal performance. Dr. Herman Fouche evaluates the condition of the veld and ultimately comes with a recommendation that farmers may or may not comply with the stipulated veld management system.

In conclusion it should be emphasised that commercial farmers in the southwestern Free State have been exposed to the agrometeorological advisories for decades, which has resulted in their success in producing good quality crops (Fouche, 2010, personal communication). The resource poor farmers who for decades have relied on traditional forecasting methods have had less success.

9.2 AGRICULTUTAL RESEARCH COUNCIL EXPERIENCES IN THE UPPER OLIFANTS CATCHMENT (O Phahlane)

9.2.1 Project Initiatives and Experiences

The Upper Olifants catchment covers the Nkangala District which encompasses the Emalahleni, Greater Groblersdal, Middelburg and Msukaligwa Municipalities. In this area seven towns were identified to represent the end-users (**Table 9.2.1**).

Table 9.2.1 Earmarked communities in the Upper Olifants Catchment

Nkangala District			
Emalahleni Municipality	**Greater Groblersdal Municipality**	**Middelburg Municipality**	**Msukaligwa Municipality**
Witbank	Loskop	Middelburg	Standerton
Belfast	Groblersdal	Hendrina	Bethal Ermelo

The Agricultural Research Council communicated with the Extension Directors and the Extension Officers to access the community. Extension Officers (from the Department of Agriculture, DoA) played a major role in the arrangements for introducing the project and for planning the workshops. Workshops were held in each municipality. It was established during the workshops that resource poor farmers relied mostly on traditional forecasting methods, however, they were willing to incorporate scientific information to improve production. Commercial farmers and Water Board Associations received seasonal forecasts, but wanted to receive point specific information in order to make better-informed decisions

Middelburg participants preferred to receive the forecast information through the following channels: Ulimo, SMS, Great Middelburg-FM, Kwekwezi FM and the Middelburg Observer. However, 100% of the resource poor farmers preferred Kwekwezi FM and Middelburg Observer since it uses local languages. The farmers proposed that the DoA office in Middelburg should have a big screen that would update the local farmers on seasonal forecasts and other agricultural issues of importance for the season
.
In the Upper Olifants catchment farmers require a short term (1-7 days) and a seasonal forecast (1-3 months), with lead times of a week to a month. Farmers require advance notice of seasonal rainfall and of mid-season dry spells, of the onset of rains, rainfall distribution and cessation of the rainy season. Onset of frost and the last frost date are also considered necessary. Advanced warning on approaching hail, heavy rains, etc. was also requested.

Monthly workshops were held in Upper Olifants catchment for selected target groups. The workshops continued to familiarise the farmers with short term and seasonal forecasts. The forecasts were presented, explained and discussed with the farmers in order to identify suitable agricultural activities and to come up with mitigation intervention for different commodities to minimise agricultural risk per chosen agricultural enterprise. Participatory tools such as focus groups, interviews, buzz questions, power point presentations and pamphlets were used to interact with the participants in these workshops.

The farmers were also encouraged to follow the forecast throughout the season for improved decision making. Mutual benefit was achieved through the monthly meetings and the application of participatory tools. The interaction with the farmers served as a good example of operational awareness on agrometeorological information. It remains a challenge to identify dissemination methods other than these monthly forums with the farmers whereby agrometeorological advisories can be provided to the farmers even beyond the project life span.

In both catchments the resource poor farmers had no access to seasonal forecasts while commercial farmers did access the seasonal forecast from the internet. The technical language used in seasonal forecast bulletins was not well understood by the farmers. Most farmers regarded the seasonal forecasts to be unreliable to some extent. The information given was not always point specific. Use of probabilities was the most ambiguous factor.

During these workshops several traditional seasonal forecast methods were discussed. For example, a face down crescent moon means that the rain would be pouring in three days' time, or a certain star appearing in the 9th month of the year is used as the symbol for the starting of the planting season. When the aloes sprout it indicates that crop planting time is near. When termites make their heaps higher than usual it means that heavy rainfall is on its way. The farmers also look at the cloud patterns and they believe that condensed dark clouds produce rain. At sunset when the horizon is red it indicates that rainfall is on the way. They also noticed that certain behaviour of calves and other livestock forewarned of impeding rain. Accordingly, the farmers decided which operations to undertake regarding agricultural activities.

9.2.2 Development of a Tailor-Made Advisory for End Users

The subsistence farmers in the Upper Olifants obtain seasonal weather forecast (1-3 months) mainly from the extension officers from the Department of Agriculture and the short term weather forecast (1-7 days) from television. There are no specific organisations amongst subsistence farmers which provide weather forecast or tasked to disseminate the weather forecast. However, subsistence farmers would prefer to receive weather forecast from the following sources, Ulimo (local newspaper), SMS, and local radio stations like Great Middelburg-FM and Kwekwezi FM.

The commercial farmers in the upper Olifants catchment obtain their seasonal and short term weather forecast from the internet, the irrigation board, cooperatives and farmers' forums. The long term weather forecast is disseminated to the farmers through farmers' forums and the internet. The short term forecast is obtained from the internet. Commercial farmers require advanced notice of seasonal forecast and short term weather forecast.

9.3 UNIVERSITY OF CAPE TOWN EXPERIENCES ON ENGAGING FARMERS AND DISSEMINATING FORECASTS (MA Tadross and P Johnston)

9.3.1 Project Initiatives and Experiences

The UCT team engaged with water users and resource managers as part of this and another WRC project (K5/1566). Exchanges between project team member Peter Johnston and the maize and wheat farmers were held on a continual basis with the existing UCT forecasts presented to these farmers on a monthly basis and assisting them on its interpretation. The forecasts are disseminated via http://www.gfcsa.net, but indications are that there is limited uptake due to credibility, accuracy and usability.

Though communication is limited with the Free State, the engagement in the Western Cape expanded to include fruit, wheat and grape farmers. Johnston has also appeared in several news articles and programmes including the Cape Times, Landbou Weekblad, SABC after 8 Debate and Agri TV. He emphasises the continued role and value of SCFs in the light of more attention given to climate change forecasts.

Interpretation of forecasts is being hindered by the following factors:

- Visual non-agreement of SAWS and CSAG forecasts vis-à-vis the 3-monthly forecasts (cf. **Figure 9.3.1**);
- Lack of monthly forecasts from SAWS (i.e. for single month periods and not only 3-month periods);
- Spatial resolution issues which give the impression that the forecast has skill at the local scale for which the forecasts show different predictions (cf. **Figure 9.3.1**).

As part of another project in the Berg river catchment Dr Peter Johnston, Dr Mark Tadross and Prof Roland Schulze undertook a 3 day roadshow in 2008 talking to both grain and fruit farmers about the implications of climate change for their industry, as well as highlighting the modelling and information being generated via this project. Workshops were held in Robertson, Worcester, Ceres, Grabouw, Piketberg and Paarl.

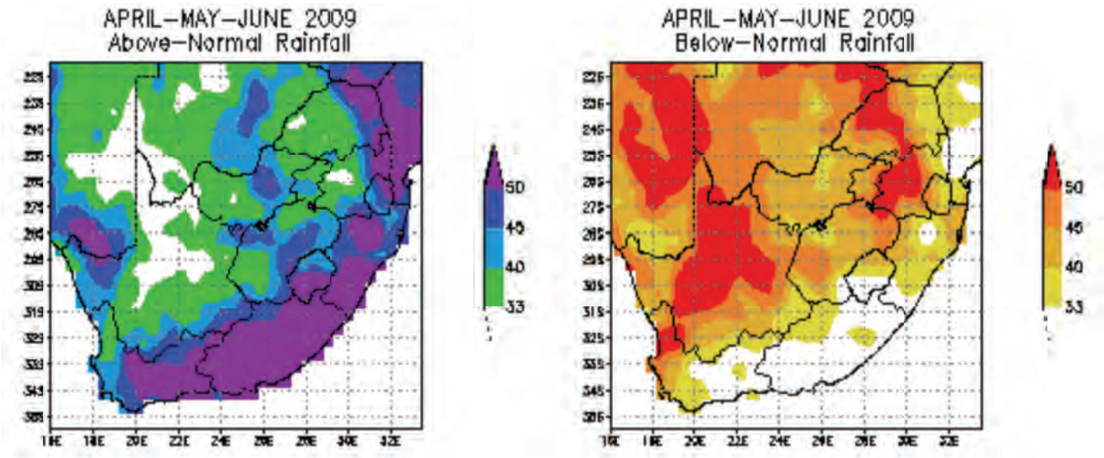
9.3.2 Farmers' Problems with Probabilistic Seasonal Forecasts

Probability is used in forecasts based on specific conditions for which a forecast may have skill and expresses this in terms of uncertainty for specific areas for a specific time period. Such probability forecasts can never be completely wrong because they assume inherent uncertainty. Forecasts that turn out to be inaccurate are invariably misinterpreted to be *wrong*, when the observed outcome was simply *less likely*. Users claim that it is valid to criticise a high probability forecast when it is inaccurate, as uncertainty that must have existed in the forecast, whether in the model or the forecaster's mind, should have been made explicit to users.

Forecasters may be expected to have a responsibility to reveal the anticipated skill level as well as the uncertainty that exists within a forecast so that users can be sufficiently aware of the risks associated with acting on the specific information.

It is intuitively possible that forecasts, especially when trained by specific signals, are more likely to be able to predict conditions outside the 'normal' range. Whereas this gives hope that extreme seasonal conditions will be accurately predicted, the large variation during 'normal' years can be exacerbated by poor forecasts especially if a dry period persists for a number of years. This would be a very typical situation for parts of Southern Africa. An agricultural drought (insufficient soil moisture to sustain crop growth), may be in existence before a meteorological drought (implying a current lack of rainfall) is recognised. Thus the prospect of agricultural drought may be overlooked by a forecast that predicts normal rainfall for a season following a dry one. For this reason forecasts need to be interpreted in terms of local conditions.

SAWS



CSAG

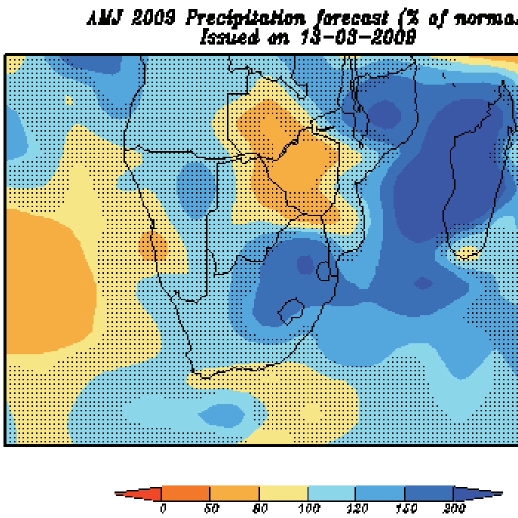


Figure 9.3.1 April-May-June 2009 seasonal forecasts produced by SAWS, CSAG showing variations and spatial scale

The following two forecasts (**Figures 9.3.2** and **9.3.3**) are currently freely available to South African users and previous examples have been used to determine from groups of farmers the answer to the question “do you use them?”. The answer has almost always been “well, can we trust them?”. If it were a simple case of replying that “they have been right x times out of y for area A, for this season” then users would quickly accept, access and use these forecasts. However as can be seen from the two forecasts for the same period, no such information is provided and conclusions can be inferred from the one that are not as obvious from the other. The first (**Figure 9.3.2**) indicates the likely variation of rainfall from the normal. (Note: On the forecast map, shading has been introduced to differentiate two levels of confidence. The clear area shows where the mean of the ensemble forecasts differs from the model climatology [average climate] at the 90% significance level, according to a students’ T-test. It indicates where the model is more 'confident' that the forecast is different to climatology.). In this case the stippled area covers most of South Africa and thus the forecast is merely suggestive, with very little confidence. This forecast period is important for the Western Cape wheat farmers, and as such indicates a possibility of normal to above-normal rainfall.

In the second forecast (**Figure 9.3.3**) from SAWS, below, a different approach is used. The first map shows the probability of above- normal rainfall, showing the SW Cape as 33-45% chance of above-normal rainfall. However the map on the right shows the probability for below-normal and here the same region is indicated to have a 33-45% chance again! Clearly though the resolution on not meant to be interpreted on even a regional farming scale, but nowhere is this stated.

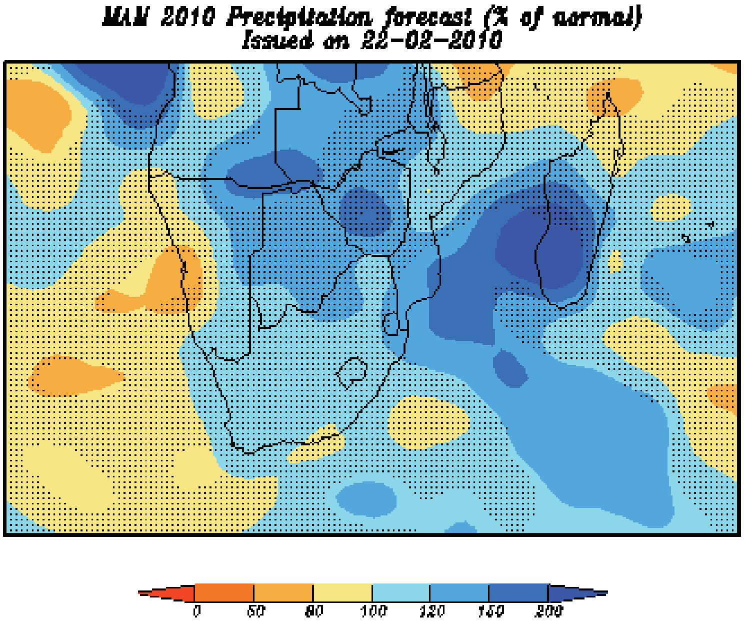


Figure 9.3.2 March-April-May 2010 precipitation forecast from CSAG

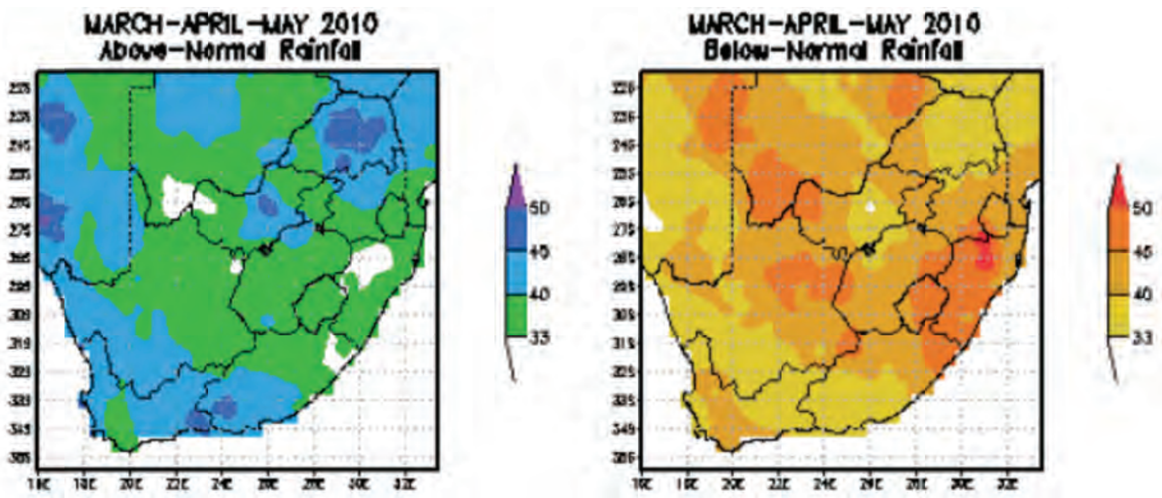


Figure 9.3.3 March-April-May 2010 forecasts from SAWS for above and below normal precipitation

Increased forecast accuracy and resolution would obviously improve forecast utility for users. However, by increasing the resolution it seems that quality must be sacrificed. The specific nature of a forecast may enable it to predict some aspects of the future precipitation or temperature with more accuracy and these would be most useful. With this in mind it is important to focus on the specific needs of the users and to focus research efforts towards increasing skill and utility in these areas.

The nature of probabilistic forecasts makes them open to misinterpretation. An example of this arises when a high probability for above-normal rainfall for a 3-month period is predicted. If a drier first month follows such a prediction in a specific region, the farmer, who to a large extent relies upon a total amount of rainfall, wants to know whether to expect that the following month would be all the wetter in his region to counter the dry period?

Not only has this lead to confusion among farmers, but also frustration among forecasters, who feel their predictions are being misinterpreted (or *over*-interpreted). This emphasises the need for tailored forecasts that will meet specific user requirements, in terms of actionable and mitigating responses. It also highlights the need for forecasters to be aware that their products may be presented as having more meaning (and thus influence) than was initially intended.

At present in Southern Africa and as shown above, only a fairly narrow group of potential users receive forecasts, and a smaller group actually makes use of them. Agriculture, being heavily dependent on rainfall, comprises the main group of users. Efforts have been made in recent years to strengthen forecast utility to agriculture by targeting provincial and local scales of activity through workshops as well as extension officer training in interpretation of seasonal climate forecasts. Users in commercial agriculture have traditionally had greater access to seasonal climate forecasts than users in developing agriculture, as they can potentially approach forecast producers directly (within South Africa, and internationally) through a variety of available channels, including television, the internet and private consultants. They also possess the greatest ability and resources to effect adaptation to climate stress.

Forecasts may be available with a range of accuracy and levels of reliability – but are they of any use to a particular user, how can their value be estimated, and how can they best be used? Various tools are available to help address such issues in seasonal forecasting. Such work needs to not only focus on the match between the 'science' of forecast production but also to examine the wider societal context in which forecasts are embedded (e.g. local knowledge systems, the role of traditional knowledge), what causes problems to uptake (e.g. access to information, access to credit) and how these constraints can be overcome.

Where agencies have utilised forecasts to issue advisories it has been shown that a variety of options must be given to reflect the uncertainties inherent in forecasts. For example, in 2009/10 the strong El Niño conditions which were forecasted (**Figure 9.3.4**) suggested that a drier than normal season was likely over the larger part of the South African summer rainfall regions. Advisories carried the warning with suggestions of reducing plantings and fertiliser purchases. As it happened the rainfall in many regions was, in fact, normal and even above normal (**Figure 9.3.5**).

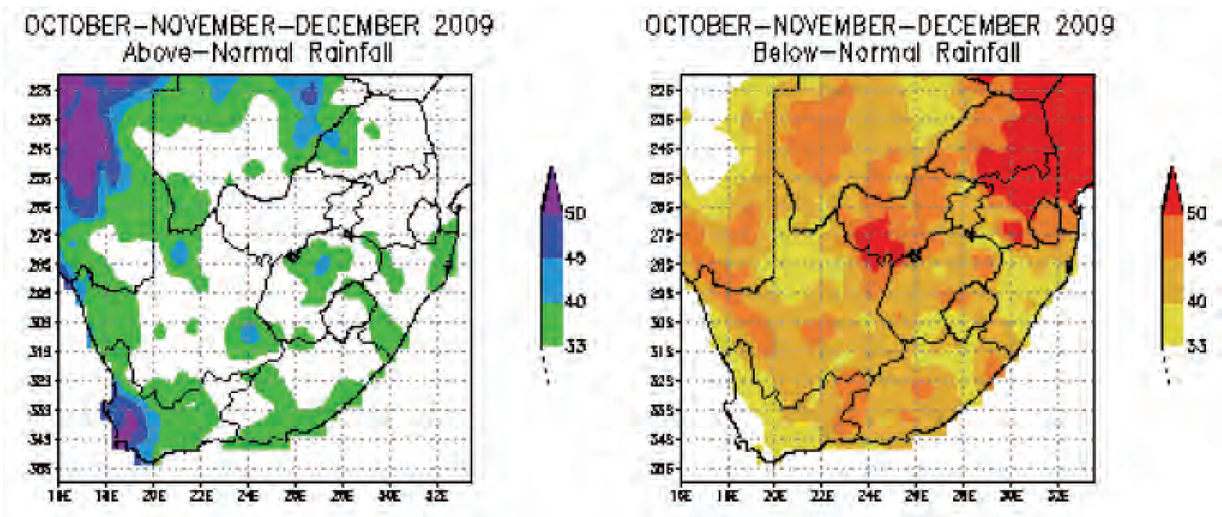


Figure 9.3.4 The seasonal forecast for October to December 2009 which suggested that below normal rainfalls were expected over the larger part of the South African summer rainfall regions as a result of El Niño related drought conditions likely to set in

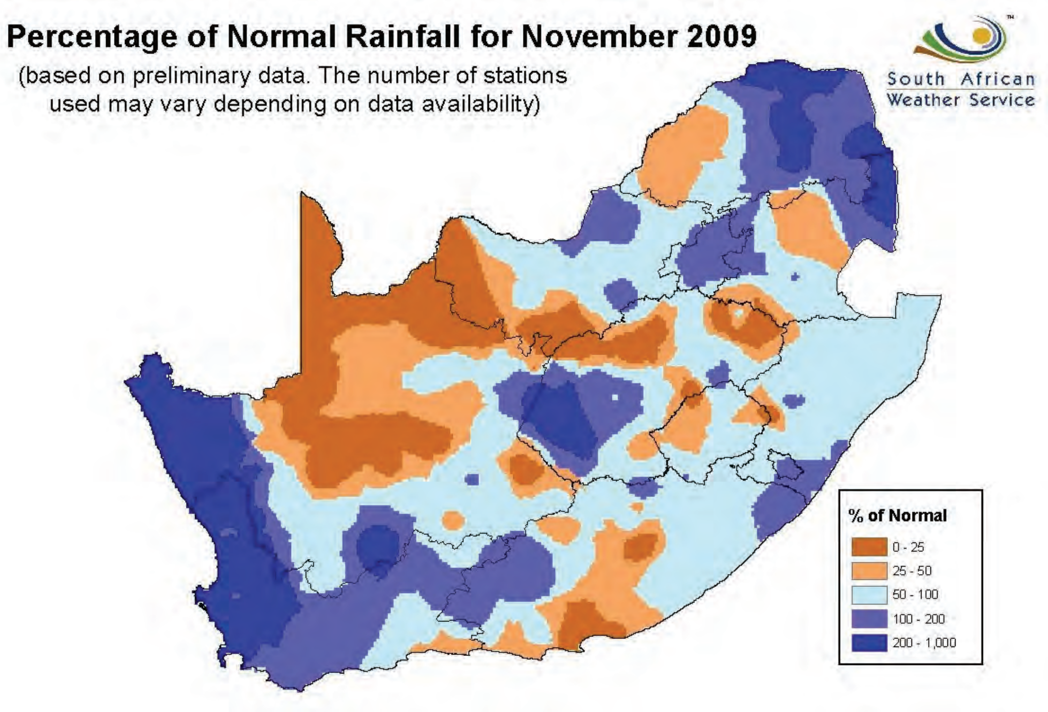


Figure 9.3.5 The actual rainfall for November 2009 (SAWS)

CHAPTER 10

BENEFIT ANALYSES OF AGROHYDROLOGICAL FORECASTING

G Zuma-Netshiukhwi, O Phahlane, KM Nape and AS Steyn

Summary

10.1 WHO PRODUCES AND USES WEATHER AND CLIMATE FORECAST INFORMATION? THE CASE OF INSTITUTIONS, ORGANIZATIONS AND COMPANIES INVOLVED IN FORECASTING AND DECISION-MAKING IN THE MODDER / RIET AND UPPER OLIFANTS CATCHMENTS
10.2 QUALITATIVE BENEFITS FROM FARMER INTERACTIONS IN THE MODDER / RIET CATCHMENT
10.3 QUALITATIVE BENEFITS FROM FARMER INTERACTIONS IN THE UPPER OLIFANTS CATCHMENT
10.4 ECONOMIC BENEFIT ANALYSIS OF MAIZE MANAGEMENT DECISIONS USING SEASONAL RAINFALL SCENARIOS

10.1 WHO PRODUCES AND USES WEATHER AND CLIMATE FORECAST INFORMATION? THE CASE OF INSTITUTIONS, ORGANISATIONS AND COMPANIES INVOLVED IN FORECASTING AND DECISION-MAKING IN THE MODDER / RIET AND UPPER OLIFANTS CATCHMENTS (G Zuma-Netshiukhwi)

The summary table below **(Table 10.1.1**), compiled from experiences in this project in the Modder / Riet and Upper Olifants catchments, illustrates that a large number of institutions provide services and information on weather and climate forecasts to a wide range of clients / target groups using many different methods of dissemination across a range of frequencies. The table shows clearly the importance attached to forecasts and implicitly points to the benefits of these forecasts.

Table 10.1.1 Summary of institutions, services, information sources, clients, dissemination methods, frequencies of information provision and products involved in climate forecasts in the Modder / Riet and Upper Olifants catchments

Institutions	Services/ Information	Source	Clients/ Target groups	Method of Dissemination	Frequency	Products
SAWS	• Climate/weather forecast • Seasonal forecasting • Early warnings	• AWS countrywide • EUMET & NCEP Satellites	• Research Council • Institution • Public • Government & NGO	• Internet • SABC • Telephone • PDMC (committee) • Bulletins • Reports • Warnings • SMS	• Now-cast • Daily • Monthly • Quarterly	• Nowcasting & Daily weather • Short & Long-term forecasting • Long range forecasting • Early warning
OVK	• Extension services • Market outlook • Seasonal forecasting interpretation	• SAWS	• Commercial Farmers	• Radio • Telephone • E-mails • Internet • Information days • Newsletters	• Quarterly • Whenever information available	• Farmer approach system • Farming methods
SENWES	• Technical advise • Soil moisture estimation • Silo operations • Marketing commodities	• Farmers • SAWS • UFS	• Commercial farmers • Researchers • UFS	• Internet • Consultancy • Newsletters	• Daily • Weekly • Monthly	• Soil maps • Agronomic services • Livestock & Pasture services
DIMTEC (UFS)	• Drought, fire & floods assessment • Research & training • Policy implementation	• SAWS • UCT	• Public • Research institutions • Government	• Training • PDMC • SABC • Newsletter	• Two months • Monthly	• Cost & benefit analysis • Impact analysis • Mitigation strategies

PDMC (Local gov. in housing)	• Documentation • Co-ordination of data • Strategic planning	• SAWS • Govt. Dept. • UFS	• Public • Departments • PDMC (committee)	• SMS • SABC • E-mail • Reports	• Whenever information available • Monthly meeting	• Reports • Emergency aid • Awareness campaigns
ARS/Santam	• Seasonal forecasting • Crop estimates • Climate outlook • Early warning • Insurance for crops and livestock	• SAWS • EUMET & NCEP Satellites • ARC • Farmers	• Research institutions • ORPA • KLK • Farmers • Brokers	• Consultancy • SABC • Websites • Information day • Volkblad news paper	• Daily • Twice weekly • Monthly • Quarterly	• Rainfall maps • Veld conditions map • Seasonal outlook
Kennedy Irrigation	• Soil moisture monitoring • Irrigation scheduling • Training • Installation of AWS	• ARC • AWS on farm • SAWS	• Commercial farmers • UFS	• SMS • Agents • Websites	• Daily	• Soil moisture content • Irrigation guidelines
Free State DoA	• Risk & disaster management • Early warnings • Extension services	• SAWS • NDA • ARC • NAC	• Farmers • UFS • NGO • Private sector	• SMS • E-mails • PDMC (committee) • Radio • Newsletter	• Daily • Monthly • Quarterly	• Farm maps • Agriculture conditions maps • Seasonal outlook
NDA	• Early warning unit • Seasonal outlook • Value adding on climate data • Policy formulation & implementation	• SAWS • UCT • ARC • PDoA • NAC	• PDoA • Farmers • NGO • Private sectors	• Bulletins • Advisories • Fax • E-mails • Website • SABC • Extension Officers	• Monthly • Quarterly	• Agricultural maps • Agronomic & livestock management methods
ARC-VPI	• Early warning • Veld & pasture information • Agricultural decision making	• ARC-ISCW • SAWS • Cooperative s • Farmers	• DoA • Research institutes • Farmers • ARS • Banks (Agric. Section)	• Bulletins • Advisories • Website • E-mails • Information days	• Daily • Monthly	• Grazing capacity, rainfall & NDVI maps
ARC-ISCW	• Networking of AWS • Monitoring of climate data • Value adding & interpretation of climate data • Outbreak warnings • Research & technology transfer • Early warnings	• AWS • SAWS • Satellites	• Farmers • Research institutes • Insurance companies • Private sectors • Government departments • NGO	• Reports • Umlindi • E-mails • Website • SABC • Information days • Telephones • NAC meetings	• Daily • Monthly • Quarterly • On request	• vegetation conditions, • maps of monthly and percentage of long-term mean rainfall nationwide • long-term climate surfaces, • climate monitoring, • crop suitability and climate classification

What follow below are three case studies from this project on the benefits of agrohydrological forecasts, two of a qualitative nature and the third more quantitative.

10.2 QUALITATIVE BENEFITS FROM FARMER INTERACTIONS IN THE MODDER / RIET CATCHMENT (G Zuma-Netshiukhwi)

The commercial farmers, resource poor farmers and back-yard gardeners in the Modder / Riet catchment are expected to adopt and take advantage of the use of weather / climate information, as the crop growth and development is highly influenced by climatic conditions. The farmers' experiences during the progress of the project were documented as evidence that consideration of weather / climate information guides to improve decision making for better crop production. The farmers have developed and established good rapport, networks and partnerships with the major stakeholders in weather / climate production and advisory services. Farmers should be expected to have improved in their level of understanding of weather / climate information and its application to agricultural management activities. Farmers should be able to use seasonal forecasts for the selection of suitable planting dates, crop variety, cultivars, etc. As agriculture is a business, farmers are expected meet the market demand by supplying continuously and to generate income through selling their produce in order to have an acceptable life style. That is why weather / climate information is considered, among other factors, a pillar for improved decision making.

The consideration of seasonal climate forecasts prior to planting and post harvesting plays an important role for making necessary adjustments for current conditions. The use of crop growth simulation model output (calibrated for local conditions) leads the way to development of a series of scenarios, as this allows the decision maker to choose optimal conditions. The inclusion of community participation in the research process provided grounds to diffuse scientific information for improved decision making.

Decision tree analysis was necessary to develop and explore scenarios together with end-users under given predictive inputs and seasonal conditions. Decision trees were also essential for the development of scenarios that can fit to the decision support tool framework. Seasonal rainfall forecasts played a significant role in agricultural activities. Rainfall analysis for a specified region helped the Sannaspos farmers, for example, to understand the crop types that are suitable for a region. Therefore farmers were encouraged use the weather / climate information from the producers to make good choices for agricultural activities to undertake.

10.3 QUALITATIVE BENEFITS FROM FARMER INTERACTIONS IN THE UPPER OLIFANTS CATCHMENT (O Phahlane)

The agricultural sector makes a major contribution to the economy in most countries, especially in the developing world, and South Africa is no exception. Berggren (1978) mentions that in many parts of the world knowledge of detailed climatological conditions is of paramount importance in making the best possible use of land available for agriculture.

Extreme meteorological events such as droughts and floods, with their potential to increase agricultural production risk, can cause significant economic losses. Accurate forecasts of agrometeorological events together with timely availability of information and services could facilitate strategic and tactical decisions in increasing and sustainable agricultural production (Weiss *et al*., 2000).

In an attempt to counter the increasing weather information demand, quarterly farmers' workshops were held in three selected towns in Mpumalanga province, *viz*. Belfast, Middelburg and Emalahleni (previously known as Witbank). The workshops were held from 2007 to 2009, during which time farmers were taught about weather forecasts, with practical examples of farmers' decision making also demonstrated. A total of 38 farmers from the three towns participated in the quarterly farmers' workshops. In June 2009 an evaluation of the impact of the workshops was conducted through a questionnaire completed by the participating farmers. The results indicated that the farmers benefited from the workshops, with most indicating that the agrometeorological information received had a positive impact on their production during the 2008 / 2009 season.

The results showed that the farmers' levels of understanding of terms commonly used in seasonal forecasting such as above-normal, near-normal, below-normal and probability were well understood by well over 60% of those interviewed.

Figure 10.3.1 illustrates that the farmers receive weather forecasts from more than one source. More than 80% and 20% of the agrometeorological information is received, respectively, through TV and radio. Less than 10% receive their information from newspapers and meteorological bulletins.

Table 10.3.1 displays the farmer's responses to the questions on the effectiveness of the workshops conducted. The farmers also indicated the usefulness of the forecast information discussed during the workshops. Many farmers indicated that they believed the forecasts, mainly because the previous forecast was discussed before the new forecast was presented.

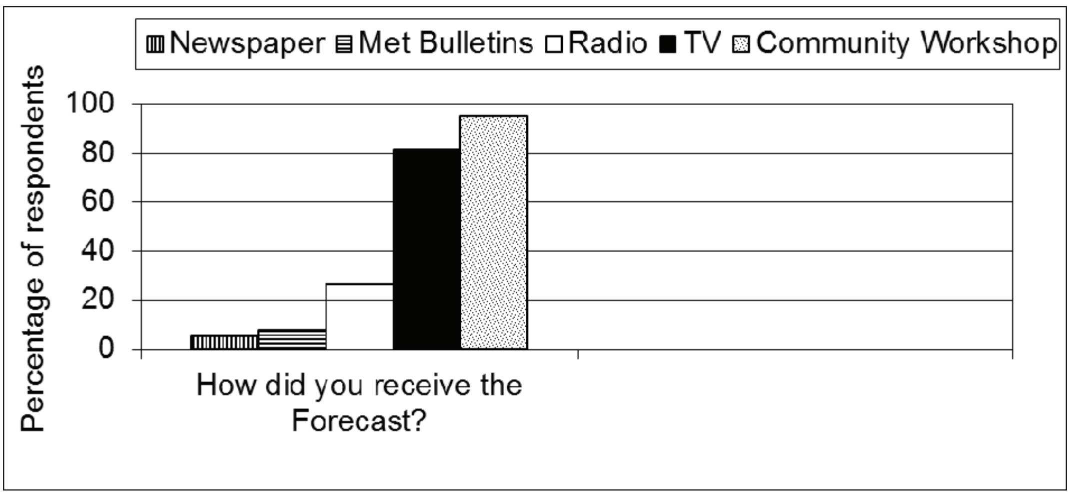


Figure 10.3.1 Methods of weather forecasting received by farmers

Table 10.3.1 Evaluating the effectiveness of farmers workshops and the usefulness of the weather forecasts to the farmers

Question	Yes	No	Other
Did you believe the forecast?	34	4	0
Was the forecast information from ARC-ISCW well explained?	33	5	0
From a source other than ARC-ISCW was the information relevant for decision making?	9	27	2
If the forecast was incorrect twice out of 5 times would you still want to receive it?	24	14	0
Did the forecast you receive have any direct impact on your production during the previous season?	29	4	5

Table 10.3.1 also outlines the importance of the workshop, as only 9 out of 38 farmers indicated that they received agrometeorological information which was relevant to their decision making purposes. Twenty-nine farmers indicated that the information they received had a direct impact on their production during the 2008 / 2009 season.

Agrometeorological information understanding and awareness of services dissemination should be improved to increase the value and importance of these services. The increased and continued improvements in agrometeorological information and services are necessary to make this type of information more accessible and useful to the rural communities.

10.4 ECONOMIC BENEFIT ANALYSIS OF MAIZE MANAGEMENT DECISIONS USING SEASONAL RAINFALL SCENARIOS (KM Nape and AS Steyn)

10.4.1 Background and Objectives

In order to meet the food requirements of an ever-growing population, agricultural production needs to increase. This is especially true for maize (*Zea mays L.*) production in South Africa as it is the staple food for a large portion of the rural indigenous population (Walker and Schulze, 2006). Agricultural production at subsistence level is threatened by climate variability on a seasonal scale. Seasonal climate forecasts are being used increasingly to benefit decision making in the more climate-sensitive sectors of the economy (White, 2000). Hansen and Indeje (2004) identified two problems that farmers are facing when using seasonal climate forecasts to improve management practices. First, the climate forecasts should be translated into crop production. Secondly, the economic outcomes of the management practices should be incorporated under climate forecasts. Seasonal forecasts have to deal with a need that is real and perceived by farmers, *viz*. that the benefits of the forecasts on their decision are compatible with their goals (Hansen, 2002). Unfortunately, small-scale farmers within the Modder River catchment do not know how to incorporate seasonal rainfall information into their management practices.

In regions that are prone to high seasonal climatic variability, crop growth models such as APSIM can be used to assist farmers in making decisions regarding the suitability of different management strategies (Keating and Meinke, 1998). Combining seasonal climate forecasts and model simulations to evaluate management practices could maximise the profitability of farm operations by reducing climatic risk considerably (Hammer *et al.,* 2001). This means that climate forecasts should be translated into crop production, while alternative management practices would be associated with different economic outcomes. In this study the opportunity arose to aid the small-scale farmers by optimising rainfed maize production, with the objective being to produce an advisory for small-scale rainfed maize farmers in the Modder River Catchment. The aim of this advisory was to relay which set of management practices farmers should use under various seasonal rainfall conditions. In addition, the advisory also provided information regarding the potential profit/loss associated with these management practices. Site selection was limited to those Quaternary Catchments (QCs) in which rainfed maize production is practised. From all of the QCs in the Modder Catchment that qualified, the decision was made to choose five QCs that provide a fair spatial representation and fall within different Land Types, i.e. soils soil mapping units. The five selected QCs were C52B, C52C, C52G, C52H and C52J (**Figure 10.4.1**). Details of the selected QCs and their associated soil types are summarised in **Table 10.4.1**.

Table 10.4.1 Details of the selected sites within the QCs

QC	Land Type	Site	Latitude (°)	Longitude (°)	Altitude (m)	Dominant Soil Form	Dominant Soil Series
C52B	Dc17	Near Thaba N'chu	29° 29' 00" S	26° 79' 00" E	1 500	Swartland	Swartland (Sw31)
C52C	Dc17	Thaba N'chu	29° 05' 37" S	26° 54' 33" E	1 500	Arcadia	Gelykvlakte (Ar20)
C52G	Ea39	Glen	28° 57' 00" S	26° 20' 00" E	1 425	Swartland	Swartland (Sw31)
C52H	Ca22	Bainsvlei	29° 08' 12" S	26° 07' 20" E	1 425	Bainsvlei	Bainsvlei (Bv36)
C52J	Ca22	Leeukop	29° 08' 12" S	26° 17' 28" E	1 425	Valsrivier	Lindley (Va41)

Historical rainfall data (1950-1999) were obtained from the Quaternary Catchment (QC) Database developed by the University of KwaZulu-Natal (Schulze *et al.,* 2005). The data from the selected QCs were used to calculate the seasonal rainfall totals for October to December (OND) and January to March (JFM). These two 3-month periods comprise the summer growing season for maize. Sequential 3-month rainfall totals were subsequently grouped into one of the analogue seasons (OND followed by JFM) as detailed in **Table 10.4.2**. Since QC C52G was reserved for model validation, the number of analogue seasons within the other 4 QCs were tallied and presented in **Table 10.4.3**. It immediately became apparent that sensible statistical analyses of simulated maize yields could not be performed on a single QC's results as some analogue seasons occurred only a small number of times within certain QCs (e.g. 3 AN-NN seasons in C52J). After careful consideration the decision was taken to combine analogue seasons across the four QCs presented in **Table 10.4.3** in order to increase the sample population size (total number of analogue seasons within the 49-year period). For example, by combining analogue seasons across QCs it was possible to increase the number of AN-AN years from the initial 4 to 5 per QC to a total of 19.

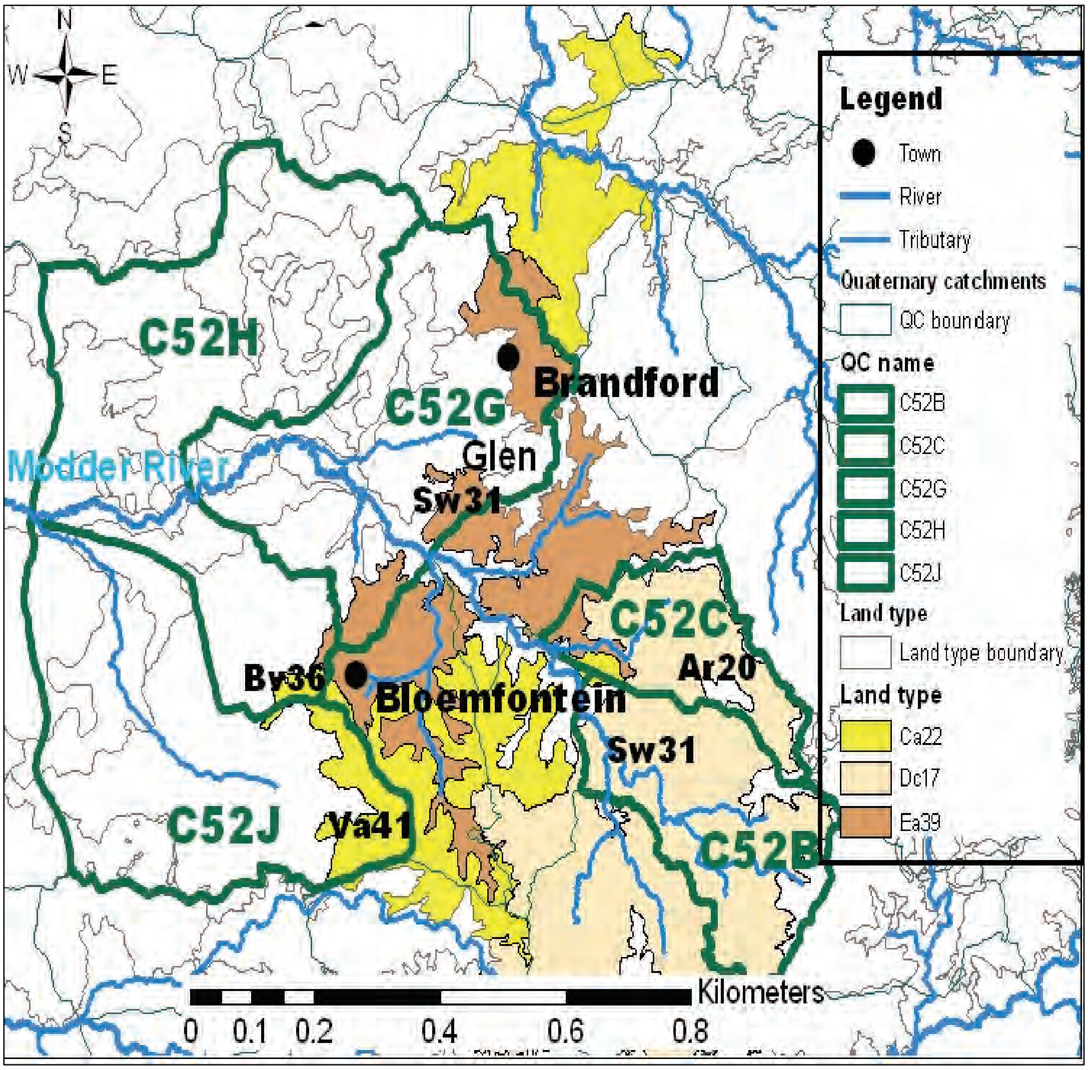


Figure 10.4.1 The Modder River catchment indicating various soil types and land types within the selected quaternary catchments

Table 10.4.2 Combination of 3-month rainfall scenarios to create analogue seasons for the summer growing season October to December and January to March

Rainfall Scenario	OND Rainfall Conditions		JFM Rainfall Conditions
AN-AN	Above-normal		Above-normal
AN-NN	Above-normal		Near-normal
AN-BN	Above-normal		Below-normal
NN-AN	Near-normal	**followed by**	Above-normal
NN-NN	Near-normal		Near-normal
NN-BN	Near-normal		Below-normal
BN-AN	Below-normal		Above-normal
BN-NN	Below-normal		Near-normal
BN-BN	Below-normal		Below-normal

Table 10.4.3 Number of growing season rainfall scenarios per QC

Rainfall Scenario	Quaternary Catchment				Total
	C52B	C52C	C52H	C52J	
AN-AN	4	5	5	5	19
AN-NN	9	5	4	3	21
AN-BN	5	7	7	8	27
NN-AN	7	5	4	5	21
NN-NN	4	8	6	10	28
NN-BN	4	4	5	3	16
BN-AN	5	5	8	6	24
BN-NN	6	6	6	5	23
BN-BN	5	4	4	4	17
Total	49	49	49	49	196

10.4.2 Verification of Yield Estimates from the APSIM Model

Obtaining observed maize yield data and their associated management practice proved to be a major stumbling block. Initially it was hoped to obtain such data from Glen College of Agriculture outside Bloemfontein. Unfortunately, such data was never forthcoming. Actual maize yield data ($kg.ha^{-1}$) for the 1980/81 to 2004/2005 seasons was provided by Department of Agriculture, Forestry and Fisheries (DAFF) for the Bloemfontein region. Unfortunately, agricultural practices used to produce these yields were not available. This dataset was used to validate the simulated maize yields. The decision was made to produce several ensembles of the simulated maize yields using a fairly wide range of plausible management practices based on information obtained from Mr. Dries Kruger, an agronomist at SENWES cooperative in Bloemfontein (**Table 10.4.4**). After careful evaluation it was decided to use the climatological data from the weather station at Glen College of Agriculture (indicated in **Figure 10.4.1**). The soils data used to create the soil module in APSIM was the Swartland series of the Swartland form (Sw31) found in Land Type Ea39 (**Table 10.4.1**).

Table 10.4.4 Plausible management practices used to validate APSIM

Management Practices	Treatments
Planting date	1-15 November; 16-30 November; 1-15 December; 16-30 December
Fertilizer application rate (kg ha^{-1} N)	35; 50; 75; 100
Plant population density (plants ha^{-1})	12 000; 14 000; 16 000; 18 000
Weeding frequency (times per growing season)	1; 2; 3

Within APSIM's maize module, there was only one medium growth period cultivar which is actually planted in the Free State province. This cultivar, PAN 6479, reaches maturity after 109-119 days (Pannar, 2006). According to Mr. John Hargreaves, an APSIM expert at CSIRO, the Australian maize cultivar Pioneer 3237 contained within APSIM exhibits similar characteristics to those planted in rainfed production in South Africa. Pioneer 3237 is a medium growth period cultivar that reaches maturity after 116 -119 days (O' Gara, 2007). Subsequently, two medium growth period maize cultivars were used to verify yield estimates from APSIM, these being PAN 6479 and Pioneer 3237.

Five days were allowed for seedbed preparation by means of disking. For each planting period (**Table 10.4.4**), sowing of maize took place within APSIM when 20 mm of rainfall had accumulated within a 5-day period and the plant available water content was 30 mm or more. If these two criteria were not met, sowing proceeded on the last day of the window period. The model initialisation for sowing depth and row spacing was 70 mm and 1.5 m, respectively. Fertilizer was applied at sowing using LAN (28) as a source of N. Within APSIM, weeds were simulated as an intercrop. Dicotyledonous (dicot) weed varieties were assumed to grow under a plant population density of 5 plants m^{-2}. For each planting period (**Table 10.4.4**), sowing of weed took place within APSIM when 10 mm of rainfall had accumulated over a 5 day period and the available soil water content was 5 mm or more. These conditions had to be satisfied after each weeding control event. Weed control was undertaken 22 days after weed emergence using mechanical procedures.

The model was subsequently applied under rainfed conditions to simulate maize yields for PAN 6479 and Pioneer 3237 from the 1980/81 up to the 2004/2005 growing seasons. The simulated maize yields were analysed and compared to the measured maize yields to verify APSIM yield output over the study area. The statistical methods described by Willmott (1981; 1982), Willmott *et al.* (1985), Wilks (1995), Mendenhall and Sincich (2003), Rinaldi *et al.* (2003), Willmott and Matsuura (2005), Willmott *et al.* (2009) and Willmott *et al.* (2011) were used to in the verification of maize yields from APSIM. The following indices were used to evaluate model performance:

- Coefficient of determination (R^2);
- Mean Error (ME);
- Root Mean Square Error (RMSE);
- Systematic and unsystematic Root Mean Square Error (RMSEs and RMSEu);
- Index of agreement (d); and
- Modelling efficiency.

The analysis of simulated and measured maize yields under different planting dates indicated that the R^2 decreased as the planting date shifted to later in the season with combinations of other management practices for PAN 6479. The R^2 between measured and simulated maize yields under different management practices ranged from 0.66 to 0.07. Simulated maize yields during1-15 November and 16-30 November were highly correlated with the measured maize yields for PAN 6479. The linear relationships between simulated and measured maize yields revealed a higher R^2 for high plant population densities during 1-15 November and 16-30 November, while the worst linear relationship was observed for low plant population densities. A reasonable linear relationship was found to exist between simulated and measured maize yields for the early planting date (1-15 November), a weeding frequency of three times, and maximum fertilizer application rate (average R^2 = 0.64) at two plant population densities (R^2 = 0.66 for 18 000 plants.ha^{-1} and R^2 = 0.63 for 16 000 plants.ha^{-1}). A poor correlation (R^2 = 0.16) existed between the recommended plant population density (14 000 plants.ha^{-1}), a low fertiliser application rate (35 kg N.ha^{-1}) and weeding once. It was found that planting during 16-30 November, the strongest correlation (R^2 = 0.49) was obtained with a plant population density of 18 000 plants ha^{-1}, a fertiliser application rate of 75 kg N.ha^{-1} and weeding frequency of three times. For the same planting date (16-30 November) a poor correlation (R^2 = 0.07) was found between measured and simulated maize yields for a low fertiliser application rate (35 kg N.ha^{-1}) and plant population density (14 000 plants.ha^{-1}). Marginally better relationships between measured and simulated maize yields involved high fertilizer application rates (100 or 75 kg N.ha^{-1}), high weeding frequencies (three times) and high plant population densities (18 000 or 16 000 plants. ha^{-1}).

The linear relationship between simulated and measured maize yields for Pioneer 3237 indicated that the R^2 also decreased as the planting date shifted to later in the season under different combinations of management practices. The coefficients of determination between measured and simulated maize yields under different management practices ranged from R^2 = 0.42 to R^2 = 0.04. This indicated that the correlation between measured and simulated maize yields were lower than 0.5. A slightly better correlation between measured and simulated maize yields (R^2 = 0.42) involved planting 1-15 November using a high fertilizer application rate (75 kg N.ha^{-1}) and weeding frequency (three times) in combination with high plant population densities (18 000 or 16 000 plants.ha^{-1}). A poor relationship (R^2 = 0.04) was observed between measured and simulated maize yields when using a planting date between 16-30 November, fertilizer application rate of 50 kg N.ha^{-1}, a single weeding and plant population density of 12 000 plants.ha^{-1}.

Figures 10.4.2 and **10.4.3** are timeline comparisons of measured and simulated maize yields under different population densities and fertilizer application rates given a planting date of 1-15 November for PAN 6479 and Pioneer 3237, respectively. Comparison between **Figures 10.4.2** and **10.4.3** showed that the model simulated the maize yields for PAN 6479 better than for Pioneer 3237. The simulated maize yields for PAN 6479 followed the same trend as those of the measured maize yields except for the 1987/88, 1989/90, 1997/98 and 2002/2003 seasons. The variation in simulated and measured maize yields for Pioneer 3237 was larger than for PAN 6479. **Figures 10.4.2** and **10.4.3** indicate that during the 1990/91 season, the simulated maize yield for PAN 6479 and Pioneer 3237 were 1 963 and 5 220 kg ha^{-1}, respectively, while the measured maize yield was 1 850 kg ha^{-1}. From these it is clear that the model tends to over-simulate the yield. Exceptions occurred for Pioneer 3237 during the 1984/85, 1987/88 and 1992/93 seasons when the model tended to under-simulate the yield.

The model also managed to simulate low yields for PAN 6479 during extreme climatic events such as drought seasons. An example of this was the 1982/83 drought associated with a strong El Niño event. **Figures 10.4.2** and **10.4.3** also indicate that measured yield during this event was 270 kg ha^{-1}, while for PAN 6479 yields were between 552 and 829 kg ha^{-1} and for Pioneer 3237 yields were between 978 and 1 082 kg ha^{-1}. The lowest difference between the measured and simulated maize yields was 282 and 708 kg ha^{-1}, while the greatest difference was 549 and 812 kg ha^{-1} for PAN 6479 and Pioneer 3237, respectively. The management practices for the simulated yields mentioned above involved different plant population densities with a fertilizer application rate of 100 kg ha^{-1} N and weeding frequency of three times for both cultivars.

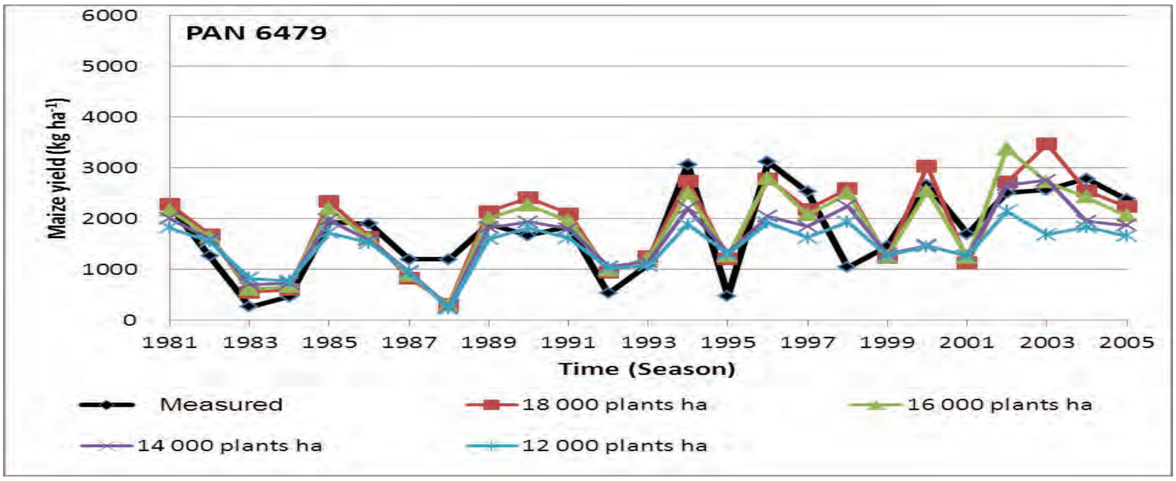


Figure 10.4.2 Comparison of measured and simulated maize yields for PAN 6479 under different plant population densities, with the maize planted during the 1-15 November period, a fertilizer application rate of 100 kg ha^{-1} N and three weedings

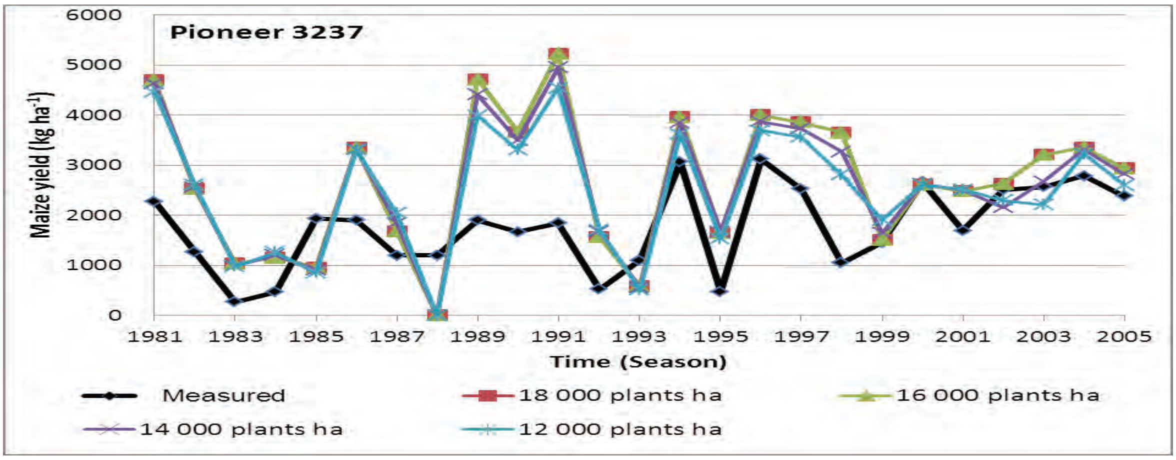


Figure 10.4.3 Comparison of measured and simulated maize yields for Pioneer 3237 under different plant population densities, with the maize planted during the 1-15 November period, a fertiliser application rate of 100 kg ha^{-1} N and three weedings

Another example of an extreme climatic event is the 1988 flood which was associated with a strong La Niña event. Simulated maize yields were between 228 and 318 kg ha^{-1} for PAN 6479 while total crop failure occurred for Pioneer 3237. During this flooding event, the measured maize yield was 1 200 kg ha^{-1}. In this case the model under-simulated the maize yields by more than 800 kg ha^{-1} for PAN 6479 and 1 200 kg ha^{-1} for Pioneer 3237 under different management practices. The reason for the higher difference between measured and simulated maize yields during this event could be ascribed to the fact that measured yields were averaged for the region while actual yields may have been much lower in some flooded areas. The influences of a series of recurring droughts in the 1990s (also associated with the El Niño phenomenon) are also evident in **Figures 10.4.2** and **10.4.3**.

Tables 10.4.5 and **10.4.6** summarise the verification results obtained under different management practices for PAN 6479 and Pioneer 3237, respectively. These results indicate that in general the model simulated the maize yields better for PAN 6479 than for Pioneer 3237 under similar management practices. The poor model performance will need to be addressed (using data from carefully constructed field trials to calibrate the model) before the results presented in the following sections can be used in practice to advise small-scale farmers.

Table 10.4.5 Verification results for APSIM using various management practices for PAN 6479

Management Practices	R^2	ME	RMSE	D-index	$\frac{RMSEs}{RMSE}$	$\frac{RMSEu}{RMSE}$	Modelling Efficiency
Planted during 1-15 November; 18 000 plants.ha^{-1}; 100 kg N.ha^{-1}; Weeding thrice	0.66	126	577	0.89	0.48	0.88	0.59
Planted during 1-15 November; 16 000 plants.ha^{-1}; 100 kg N.ha^{-1}; Weeding thrice	0.63	56	516	0.89	0.43	0.90	0.61
Planted during 1-15 November; 18 000 plants.ha^{-1}; 75 kg N.ha^{-1}; Weeding thrice	0.62	139	547	0.88	0.42	0.91	0.56
Planted during 1-15 November; 18 000 plants.ha^{-1}; 100 kg N.ha^{-1}; Weeding twice	0.62	14	545	0.89	0.29	0.96	0.56
Planted during 1-15 November; 18 000 plants.ha^{-1}; 75 kg N.ha^{-1}; Weeding twice	0.61	19	538	0.88	0.39	0.92	0.57
Planted during 1-15 November; 12 000 plants.ha^{-1}; 35 kg N.ha^{-1}; Weeding once	0.17	-755	1080	0.54	0.90	0.44	-0.72
Planted during 16-30 November; 18 000 plants ha^{-1}; 75 kg ha^{-1} N; Weeding thrice	0.47	174	764	0.82	0.40	0.91	0.30
Planted during 16-30 November; 18 000 plants ha^{-1}; 100 kg ha^{-1} N; Weeding thrice	0.49	122	678	0.82	0.38	0.92	0.32
Planted during 16-30 November; 16 000 plants ha^{-1}; 75 kg ha^{-1} N; Weeding thrice	0.41	26	667	0.79	0.54	0.84	0.34
Planted during 16-30 November; 12 000 plants ha^{-1}; 35 kg ha^{-1} N; Weeding once	0.08	-595	1049	0.50	0.85	0.52	-0.62
Planted during 1-15 December; 18 000 plants ha^{-1}; 100 kg ha^{-1} N; Weeding thrice	0.37	-169	806	0.77	0.38	0.93	0.04
Planted during 1-15 December; 18 000 plants ha^{-1}; 75 kg ha^{-1} N; Weeding thrice	0.34	-159	828	0.76	0.38	0.92	-0.01
Planted during 1-15 December; 12 000 plants ha^{-1}; 50 kg ha^{-1} N; Weeding once	0.14	-761	1131	0.56	0.84	0.54	-0.89
Planted during 16-30 December; 18 000 plants ha^{-1}; 100 kg ha^{-1} N; Weeding thrice	0.24	-407	1000	0.68	0.59	0.80	-0.38
Planted during 16-30 December; 18 000 plants ha^{-1}; 100 kg ha^{-1} N; Weeding twice	0.24	-462	1016	0.67	0.64	0.77	-0.41
Planted during 16-30 December; 12 000 plants ha^{-1}; 50 kg ha^{-1} N; Weeding once	0.08	-851	1238	0.51	0.86	0.52	-1.26

Table 10.4.6 Validation results for APSIM using various management practices for Pioneer 3237

Management Practices	R^2	ME	RMSE	D-index	$\frac{RMSE_s}{RMSE}$	$\frac{RMSE_u}{RMSE}$	Modelling efficiency
Planted during 1-15 November; 18 000 plants ha^{-1}; 75 kg ha^{-1} N; Weeding thrice	0.42	999	1270	0.61	0.46	0.89	-2.04
Planted during 1-15 November; 18 000 plants ha^{-1}; 100 kg ha^{-1} N; Weeding thrice	0.37	973	1497	0.59	0.65	0.76	-2.32
Planted during 1-15 November; 16 000 plants ha^{-1}; 75 kg ha^{-1} N; Weeding thrice	0.41	960	1381	0.62	0.70	0.72	-1.81
Planted during 1-15 November; 16 000 plants ha^{-1}; 100 kg ha^{-1} N; Weeding thrice	0.37	926	1428	0.60	0.65	0.76	-2.01
Planted during 1-15 November; 12 000 plants ha^{-1}; 35 kg ha^{-1} N; Weeding once	0.07	-565	1141	0.52	0.73	0.68	-0.92
Planted during 16-30 November; 18 000 plants ha^{-1}; 75 kg ha^{-1} N; Weeding thrice	0.35	552	1117	0.68	0.50	0.86	-0.84
Planted during 16-30 November; 18 000 plants ha^{-1}; 100 kg ha^{-1} N; Weeding thrice	0.34	548	1160	0.67	0.48	0.88	-0.98
Planted during 16-30 November; 16 000 plants ha^{-1}; 75 kg ha^{-1} N; Weeding thrice	0.34	522	1097	0.68	0.49	0.87	-0.78
Planted during 16-30 November; 12 000 plants ha^{-1}; 100 kg ha^{-1} N; Weeding once	0.05	-544	1176	0.48	0.74	0.68	-1.04
Planted during 1-15 December; 18 000 plants ha^{-1}; 100 kg ha^{-1} N; Weeding thrice	0.28	-176	984	0.70	0.31	0.95	-0.43
Planted during 1-15 December; 18 000 plants ha^{-1}; 50 kg ha^{-1} N; Weeding thrice	0.28	-333	947	0.70	0.48	0.88	-0.32
Planted during 1-15 December; 12 000 plants ha^{-1}; 50 kg ha^{-1} N; Weeding once	0.07	-959	1334	0.51	0.87	0.50	-1.62
Planted during 16-30 December; 18 000 plants ha^{-1}; 50 kg ha^{-1} N; Weeding thrice	0.23	-817	1181	0.60	0.78	0.63	-1.06
Planted during 16-30 December; 16000 plants ha^{-1}; 50 kg ha^{-1} N; Weeding twice	0.21	-843	1197	0.58	0.80	0.60	-1.11
Planted during 16-30 December; 12 000 plants ha^{-1}; 75 kg ha^{-1} N; Weeding once	0.06	-1171	1483	0.37	0.91	0.42	-1.29

10.4.3 Analysis of Simulated Maize Yields

The same maize cultivars (PAN 6479 and Pioneer 3237) used in the verification of the APSIM model were used to simulate maize yields for the entire 49-year period spanning 1950/51 to 1998/99. The cultivars used to simulate maize yields did not perform well during verification. The decision to continue using them stemmed from the fact that the actual yield data were obtained under different cultivars, soil types and management practices, where cultivars similar to PAN 6479 and Pioneer 3237 could be included. Yet, it was crucial to examine how the cultivars performed under historical climatic conditions and how alternative management practices in response to seasonal rainfall conditions could benefit small-scale farmers. The different management practices used to simulate maize and weed are summarised in **Table 10.4.7**. Similar specifications, in terms of seedbed preparation, sowing criteria and fertilizer application rates were used as in the verification setup.

Table 10.4.7 Management practices used in the simulation of maize yields

Management Practices	Treatments
Planting date	1-15 November; 16-30 November; 1-15 December; 16-30 December; 1-15 January
Fertilizer application rate (kg ha^{-1} N)	0; 35; 50; 75; 100
Plant population density (plants ha^{-1})	9 000; 12 000; 15 000; 18 000; 21 000
Weeding frequency (times per growing season)	0; 1; 2; 3

Maize growth was simulated on a daily time-step as the crop responded to climate, soil and nitrogen within the four QCs not used in the verification study of the model. Simulated maize yields were allocated to analogue growing season rainfall scenarios (**Table 10.4.2**). Previous studies (Hammer *et al.*, 2001; Moeller *et al*., 2008) employed a similar method of clustering simulated yields according to analogue seasons. The use of analogue seasons made it possible to determine the optimal management practices under each seasonal rainfall scenario.

For each growing season's rainfall scenario, the simulated maize yields under different management decisions were subjected to analysis using the stepwise linear regression method. This method was used to screen yield predictors (management practices) in order to determine which ones dominate the variation of simulated maize yields. Statistical Analytical Simulation (SAS) was used to accomplish this. The stepwise linear regression method selected those yield predictors that adhered to a partial R^2 value greater than 0.0001 at a significance level of 0.15. Only those yield predictors selected by the stepwise regression method were ranked in order of descending partial R^2 values. Cumulative distribution functions (CDFs) were used to plot maize yields under different sets of yield predictors for various growing season rainfall scenarios. These probability graphs were used to read off the maize yields corresponding to probabilities of 25, 50 and 75%. This was used to identify the highest yielding set of management practices under each growing season rainfall scenario. Owing to the various analogue seasons a huge amount of data was generated. It was decided to only present the results of near-normal followed by near-normal (NN-NN) rainfall conditions here.

NN-NN rainfall conditions are characterised by average amounts of rainfall throughout the cropping season. In the 196 years of combined rainfall data there were 28 NN-NN seasons, this contributing the highest rainfall scenarios experienced in the Modder River catchment. The most significant yield predictors during NN-NN rainfall conditions, as determined by stepwise regression are shown in **Table 10.4.8**.

Table 10.4.8 Stepwise regression for predictors of maize yield during NN-NN rainfall conditions

Cultivar	Predictor Rank	Management Practice	Partial R^2
PAN 6479	1	Weeding Frequency	0.0917
	2	Fertilizer Application Rate	0.0698
	3	Planting Date	0.0579
	4	Plant Population Density	0.0146
Pioneer 3237	1	Planting Date	0.1796
	2	Weeding Frequency	0.0647
	3	Fertilizer Application Rate	0.0632
	4	Plant Population Density	0.0025

Dominating predictors for PAN 6479 and Pioneer 3237 were weeding frequency and planting dates, respectively. The contributions of weeding frequencies and different planting dates to the variation of maize yields in terms of partial R^2 were 0.0917 and 0.1796 for PAN 6479 and Pioneer 3237, respectively (**Table 10.4.8**). Weeding frequency plays an important role in reducing the presence of weeds, since weeds affect the quality and yields of the maize by competing for resources. Since any combination with the other management practices will indicate the significance of choosing different weeding frequencies and planting dates, a random selection among the CDFs was made to illustrate this fact. The CDFs in **Figures 10.4.4** and **10.4.5** illustrate the variation of maize yields under different weeding frequencies and planting dates for PAN 6479 and Pioneer 3237, respectively.

Weeding twice during the growth season would produce the highest yields for PAN 6479 during NN-NN rainfall conditions (**Figure 10.4.4**). At a 50% probability of non-exceedence level a yield of 542 $kg.ha^{-1}$ was obtained without weeding, while a yield of 2 124 $kg.ha^{-1}$ was obtained when weeding twice. Farmers could thus lose approximately 1 572 kg.ha^{-1} with no weeding as opposed to weeding twice.

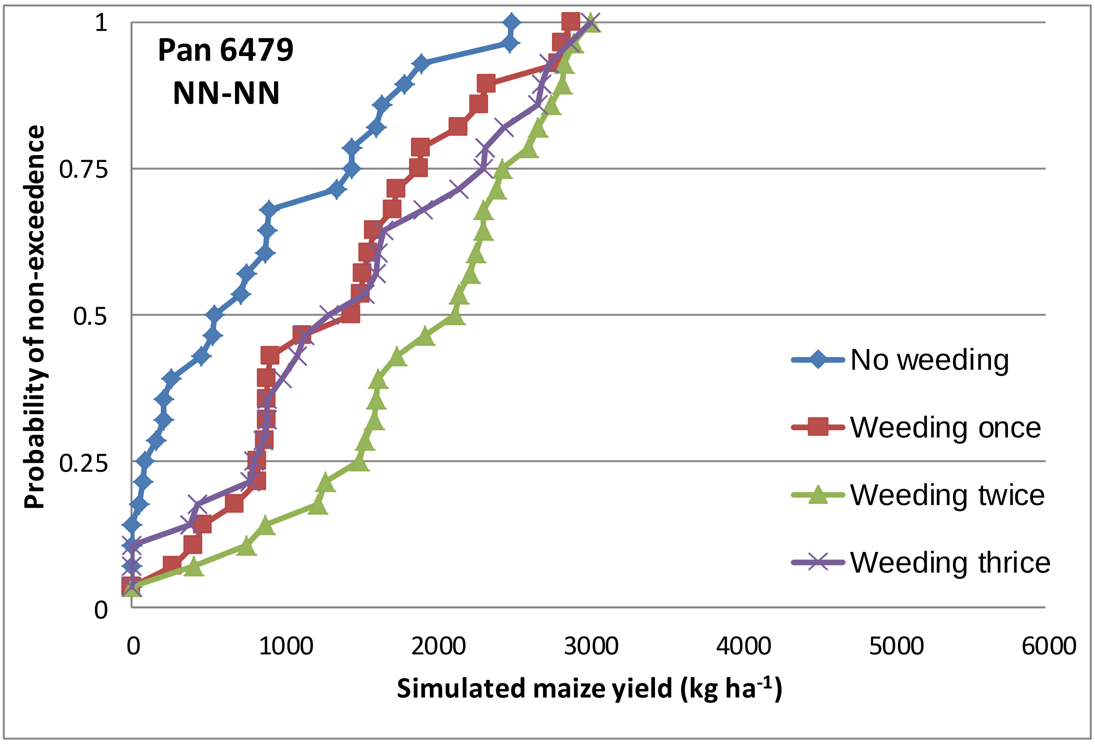


Figure 10.4.4 Cumulative distribution function of long-term simulated maize yields for PAN 6479 planted during 1-15 November under different weeding frequencies (using a plant population density of 18 000 plants.ha^{-1} and fertilizer application rate of 50 kg N.ha^{-1})

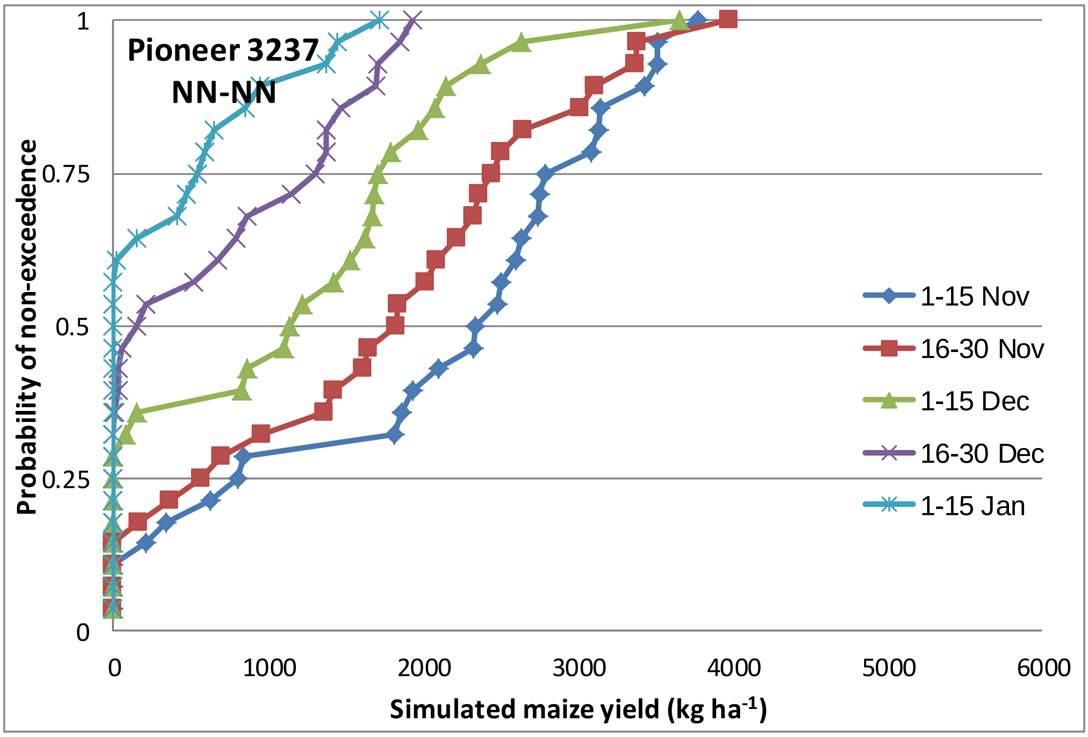


Figure 10.4.5 Cumulative distribution function of long-term simulated maize yields for Pioneer 3237 planted during different planting dates (using a plant population density of 12 000 plants.ha^{-1}, fertilizer application rate of 50 kg N.ha^{-1} and weeding twice)

During these seasonal rainfall conditions maize yields decreased as the planting date shifted to later into the growing season for Pioneer 3237 (**Figure 10.4.5**). At the 50% probability of non-exceedence maize planted during 1-15 November, 16-30 November, 1-15 December, 16-30 December and 1-15 January yielded 2 334, 1 822, 1 137, 150 and 0 kg ha^{-1}, respectively. The yield difference between planting during 1-15 November and 16-30 December was 2 184 kg ha^{-1}. Planting Pioneer 3237 after 15 December would result in crop failure.

The second ranked predictors found to influence maize yield were fertilizer application rate for PAN 6479, where the partial R^2 was 0.0698 , while for Pioneer 3237 the second yield predictor was weeding frequency with a partial R^2 of 0.0667 (**Table 10.4.8**). The CDFs in **Figure 10.4.6** illustrate the variation of maize yields under different fertilizer application rates for PAN 6479 (under optimum weeding frequency), while **Figure 10.4.7** shows the same for weeding frequencies for Pioneer 3237 (under optimum planting dates).

The maize yield obtained without applying fertilizer was 520 kg ha^{-1} while a yield of 2 224 kg.ha^{-1} corresponded to an application of 50 kg N.ha^{-1} fertilizer at the 50% probability of non-exceedence (**Figure 10.4.6**). Farmers could obtain an additional 430 kg.ha^{-1} when applying 50 kg N.ha^{-1} compared to 100 kg N. ha^{-1} at the 75% probability level. This indicates that fertilizer application rates above 50 kg N.ha^{-1} could lead to decreased in maize yields during NN-NN rainfall conditions. For Pioneer 3237 (**Figure 10.4.7**), there was a 50% probability that the yield would not exceed 375 kg.ha^{-1} without weeding and 1 834 kg.ha^{-1} when weeding thrice. The yield difference between weeding three and two times was 95 kg.ha^{-1}, while the yield difference between weeding twice and not weeding was 1 364 kg.ha^{-1}.

The third and fourth ranked predictors for PAN 6479 were planting date and plant population density, respectively. For Pioneer 3237 it was the fertilizer application rate and plant population density (**Table 10.4.7**). Variance of the combination of planting dates and plant population densities with maize yields was 7.3% for PAN 6479, while for Pioneer 3237 the variance was 6.6%. For PAN 6479, these planting dates (1-15 November, 16-30 November and 1-15 November) and plant population densities (12 000 and 15 000 plants.ha^{-1}) contributed highly to maize yields for PAN 6479 (not shown). For Pioneer 3237, the fertilizer application rates were 35 and 50 kg ha^{-1} N and plant population densities of 9 000, 12 000 and 18 000 plants.ha^{-1} performed best (not shown).

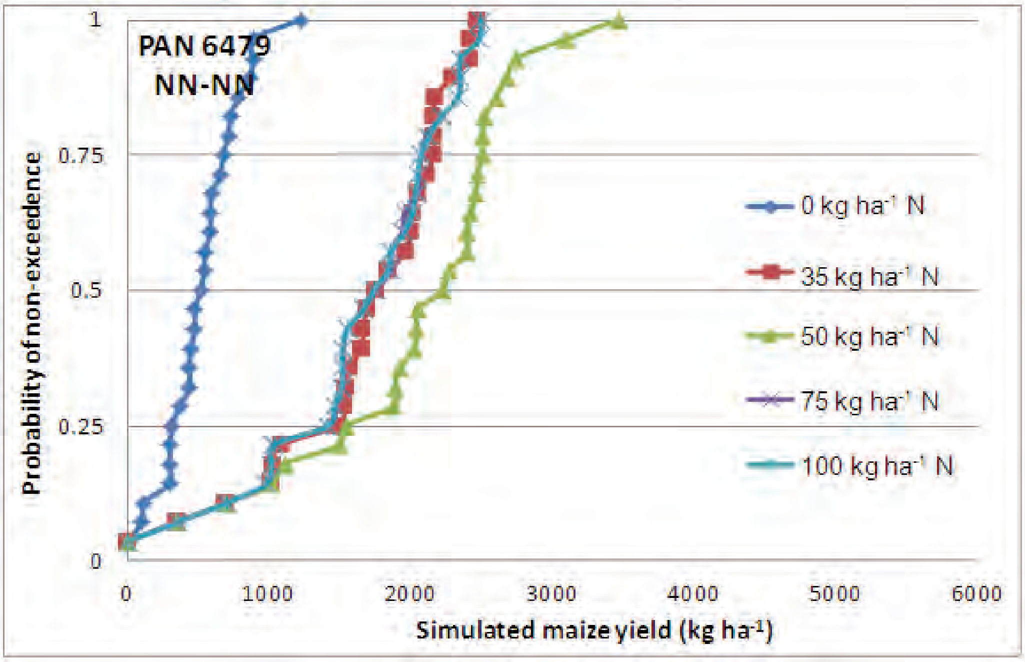


Figure 10.4.6 Cumulative distribution function of long-term simulated maize yields for PAN 6479 planted during 1-15 November under various fertilizer application rates (using a plant population density of 15 000 plants.ha^{-1} and weeding twice)

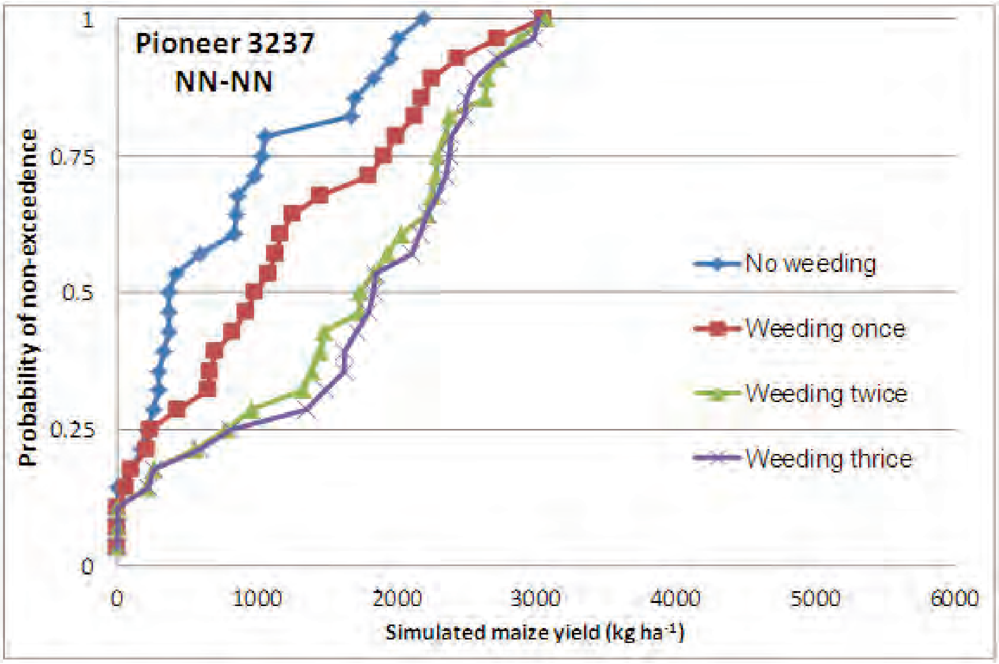


Figure 10.4.7 Cumulative distribution function of long-term simulated maize yields for Pioneer 3237 planted during 1-15 November under various weeding frequencies (using a plant population density of 9 000 plants.ha^{-1} and a fertilizer application rate of 35 kg N.ha^{-1})

10.4.4 Comparative Economic Benefit of Different Management Decisions under Various Seasonal Rainfall Conditions

The costs of tillage practices such as ploughing, ripping, disking and planting (**Table 10.4.9**) were obtained from an agronomist at SENWES cooperative in Bloemfontein. These costs were estimated based on a tractor's average diesel consumption per hectare (R7.90 per litre taken on 11 January 2011, Bloemfontein). Maintenance costs associated with each activity are also included.

Table 10.4.9 Field and maintenance costs associated with different tillage practices

Tillage Practice	Field Cost (R.ha^{-1})	Maintenance Cost (R.ha^{-1})	Total Cost (R.ha^{-1})
Ploughing	18.32 ℓ.ha^{-1} X R7.90 .ℓ$^{-1}$ = R144.73	R68.10	R212.83
Ripping	18.00 ℓ.ha^{-1} X R7.90 .ℓ$^{-1}$ = R142.20	R61.22	R203.42
Disking	6.49 ℓ.ha^{-1} X R7.90 .ℓ$^{-1}$ = R51.27	R41.40	R 92.67
Planting	6.10 ℓ.ha^{-1} X R7.90 .ℓ$^{-1}$ = R48.19	R95.30	R143.49

The total field and maintenance cost for ploughing, ripping, disking and planting was R652.41 .ha^{-1}. Other important expenses that vary according to different combinations of management practices are seed, fertilizer and weeding costs. The seed price was R991.00 per 60 000 seeds for Pannar and R1 950.00 per 80 000 seeds for Pioneer. The prices provided in **Table 10.4.10** were calculated according to the plant population densities that were used in the maize yield simulations (**Table 10.4.7**).

Table 10.4.10 Seed costs associated with different plant population densities

Number of Seeds (ha^{-1})	Seed Cost	
	Pannar (R ha^{-1})	Pioneer (R ha^{-1})
9 000	R148.65	R219.38
12 000	R198.20	R292.50
15 000	R247.75	R365.63
18 000	R297.30	R438.75
21 000	R347.85	R511.88

Limestone Ammonium Nitrate (LAN 28) was used as a nitrogen source at a cost of R210.10 per 50 kg. This implied a cost of R4.20 .kg^{-1}. **Table 10.4.11** indicates the fertilizer application costs based on the various N applications that were used in the maize yield simulations (**Table 10.4.7**).

Table 10.4.11 Fertilizer (N) application costs

Fertilization (kg N.ha^{-1})	LAN (28) (kg.ha^{-1})	Cost (R.kg^{-1}.ha^{-1})
35	125.0	R 525.00
50	178.6	R 750.12
75	267.9	R1 125.18
100	357.1	R1 499.82

The cost of weeding was calculated by multiplying the diesel consumption per hectare for mechanical weeding with the diesel price (R7.90 per litre at the time of analyses) and adding the maintenance cost. The weeding frequency was included in the calculation, as shown in **Table 10.4.12**. The total operational field cost was calculated by adding the first and second field costs.

Table 10.4.12 Costs corresponding to various weeding frequency

Weeding Frequency	Weeding Cost (R ha^{-1})	Maintenance Cost (R ha^{-1})	Total Costs (R ha^{-1})
1	1.9 ℓ.ha^{-1} X R7.90.ℓ$^{-1}$ = R15.01	R9.10	R24.11
2	3.8 ℓ.ha^{-1} X R7.90.ℓ$^{-1}$ = R30.02	R18.20	R48.22
3	5.7 ℓ.ha^{-1} X R7.90.ℓ$^{-1}$ = R45.03	R27.30	R72.33

For Pioneer 3237 and PAN 6479, the various sets of management practices exhibiting the highest yield potential were subjected to an economic analysis. The simulated maize yields were converted to net income values by multiplying them with the SAFEX maize price (R1 321.00 on at the time of analyses on 11 January 2011). The net income values (R.ha^{-1}) obtained in this manner for different sets of management practices were again allocated to analogue growing season rainfall scenarios (defined in **Table 10.4.2**) before they were subjected to further economic analysis.

Following the method described by Moeller *et al*. (2008), gross margins were calculated by subtracting the field costs from the net income values for each set of management practices. These gross margins were used to assess the economic benefit or loss of maize production for PAN 6479 and Pioneer 3237 under each analogue growing season. CDFs were used to plot gross margins under different sets of management practices. These probability graphs were used to determine the optimal set of management practices under each growing season rainfall scenario. Probability levels of 25, 50 and 75% were used to assess the financial risk and potential financial benefits. Owing to the various analogue seasons a huge amount of data was generated. Only the results of near-normal followed by near-normal (NN-NN) rainfall conditions are presented here. The combinations of yield predictors that were subjected to the economic analyses are provided in **Table 10.4.13** for PAN 6479 and in **Table 10.4.14** for Pioneer 3237. The economic benefits associated with each set of management practices are shown in **Table 10.4.15** for PAN 6479 and in **Table 10.4.16** for Pioneer 3237, respectively.

Table 10.4.13 The combinations of management practices that provided higher yields for PAN 6479 during NN-NN rainfall conditions

Management Practices			
Planting Date	**Plant Population Density (plants.ha^{-1})**	**Fertilizer Application Rate (kg N.ha^{-1})**	**Weeding Frequency**
1-15 November	9 000	35	1;2
1-15 November	12 000	35	1;2
1-15 November	12 000	50	3
1-15 November	15 000	35	1;2
1-15 November	15 000	50	1;2
1-15 November	18 000	35	1;2
1-15 November	18 000	50	2
1-15 November	21 000	35	1;2
16-30 November	9 000	35	1;2
16-30 November	12 000	35	1;2
16-30 November	12 000	50	3

16-30 November	15 000	35	1;2
16-30 November	15 000	50	2;3
16-30 November	18 000	35	1;2
16-30 November	18 000	50	2
16-30 November	21 000	35	1;2
16-30 November	21 000	50	2
1-15 December	9 000	35	1;2
1-15 December	12 000	35	1;2
1-15 December	12 000	50	3
1-15 December	15 000	35	1;2
1-15 December	15 000	50	3
1-15 December	18 000	35	1;2
1-15 December	21 000	35	1;2
1-15 December	21 000	50	2;3

Table 10.4.14 Combinations of management practices that provided higher yields for Pioneer 3237 during NN-NN rainfall conditions

Management Practices			
Planting Date	**Plant Population Density (plants.ha^{-1})**	**Fertilizer Application Rate (kg N.ha^{-1})**	**Weeding Frequency**
1-15 November	9 000	35	1;2
1-15 November	12 000	35;50	2
1-15 November	15 000	35;50;75	2
1-15 November	18 000	35;50;75	2
1-15 November	21 000	35	1;2
1-15 November	21 000	50;75	2
16-30 November	9 000	35	1;2
16-30 November	12 000	50;70	2
16-30 November	18 000	75;100	2
16-30 November	21 000	35	1
16-30 November	21 000	75	2

Table 10.4.15 Reference table for yield expectance, field costs and economic benefit under various sets of management practices during NN-NN rainfall conditions for PAN 6479

Management Practices (For PAN 6479 cultivar)	**Probability Levels**	**Yield Expectance (kg.ha^{-1})**	**Field Costs (Rand.ha^{-1})**	**Economic Benefit (Rand.ha^{-1})**
Planted on 1-15 November; 9 000 plants ha^{-1}; 35 kg ha^{-1} N; one weeding	75	1151	1350	170
	50	972	1350	-66
	25	617	1350	-535
Planted on 1-15 November; 9 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding twice	75	1438	1374	525
	50	1344	1374	402
	25	1150	1374	145
Planted on 1-15 November; 9 000 plants ha^{-1}; 50 kg ha^{-1} N; one weeding	75	1145	1575	-62
	50	1011	1575	-240
	25	617	1575	-761
Planted on 1-15 November; 9 000 plants ha^{-1}; 50 kg ha^{-1} N; weeding twice	75	1339	1599	170
	50	1136	1599	-99
	25	465	1599	-985
Planted on 1-15 November; 12 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding once	75	1462	1400	532
	50	1012	1400	-62
	25	667	1400	-519
Planted on 1-15 November; 12 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding twice	75	1833	1424	998
	50	1673	1424	786
	25	1154	1424	101
Planted on 1-15 November; 12 000 plants ha^{-1}; 50 kg ha^{-1} N; one weeding	75	1457	1625	299
	50	1087	1625	-189
	25	665	1625	-747
Planted on 1-15 November; 12 000 plants ha^{-1}; 50 kg ha^{-1} N; weeding twice	75	1835	1649	775
	50	1584	1649	443
	25	1113	1649	-179
Planted on 1-15 November; 12 000 plants ha^{-1}; 50 kg ha^{-1} N; weeding thrice	75	1948	1673	900
	50	1693	1673	563
	25	1449	1673	240
Planted on 1-15 November; 15 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding once	75	1529	1449	571
	50	1029	1449	-90
	25	710	1449	-511
Planted on 1-15 November; 15 000 plants ha^{-1}; 35 kg ha^{-1}	75	2159	1473	1378
	50	1757	1473	848

N; weeding twice	25	1483	1473	486
Planted on 1-15 November;	75	1612	1674	455
15 000 plants ha^{-1}; 50 kg ha^{-1}	**50**	1348	1674	106
N; weeding once	25	904	1674	-480
Planted on 1-15 November;	75	2506	1698	1612
15 000 plants ha^{-1}; 50 kg ha^{-1}	**50**	2224	1698	1240
N; weeding twice	25	1547	1698	345
Planted on 1-15 November;	75	1757	1499	822
18 000 plants ha^{-1}; 35 kg ha^{-1}	**50**	1259	1499	164
N; weeding once	25	859	1499	-364
Planted on 1-15 November;	75	2219	1523	1408
18 000 plants ha^{-1}; 35 kg ha^{-1}	**50**	1779	1523	828
N; weeding twice	25	1520	1523	484
Planted on 1-15 November;	75	2428	1748	1459
18 000 plants ha^{-1}; 50 kg ha^{-1}	**50**	2124	1748	1057
N; weeding twice	25	1485	1748	214
Planted on 1-15 November;	75	1929	1548	1000
21 000 plants ha^{-1}; 35 kg ha^{-1}	**50**	1307	1548	178
N; weeding once	25	833	1548	-448
Planted on 1-15 November;	75	2338	1572	1515
21 000 plants ha^{-1}; 35 kg ha^{-1}	**50**	2072	1572	1165
N; weeding twice	25	1381	1572	252
Planted on 16-30 November;	75	1222	1350	264
9 000 plants ha^{-1}; 35 kg ha^{-1}	**50**	797	1350	-298
N; weeding once	25	458	1350	746
Planted on 16-30 November;	75	1453	1374	545
9 000 plants ha^{-1}; 35 kg ha^{-1}	**50**	1391	1374	463
N; weeding twice	25	1212	1374	227
Planted on 16-30 November;	75	1441	1400	503
12 000 plants ha^{-1}; 35 kg ha^{-1}	**50**	1006	1400	-71
N; weeding once	25	496	1400	-744
Planted on 16-30 November;	75	1805	1424	961
12 000 plants ha^{-1}; 35 kg ha^{-1}	**50**	1691	1424	809
N; weeding twice	25	1349	1424	358
Planted on 16-30 November;	75	1909	1673	849
12 000 plants ha^{-1}; 50 kg ha^{-1}	**50**	1769	1673	663
N; weeding thrice	25	1597	1673	437
Planted on 16-30 November;	75	1553	1449	602
15 000 plants ha^{-1}; 35 kg ha^{-1}	**50**	1091	1449	-9
N; weeding once	25	521	1449	-762
Planted on 16-30 November;	75	1968	1473	1126
15 000 plants ha^{-1}; 35 kg ha^{-1}	**50**	1761	1473	852
N; weeding twice	25	1422	1473	405
Planted on 16-30 November;	75	2139	1473	1353
15 000 plants ha^{-1}; 50 kg ha^{-1}	**50**	1894	1473	1029
N; weeding twice	25	1433	1473	420
Planted on 16-30 November;	75	2209	1723	1195
15 000 plants ha^{-1}; 50 kg ha^{-1}	**50**	1950	1723	854
N; weeding thrice	25	1511	1723	273
Planted on 16-30 November;	75	1616	1499	635
18 000 plants ha^{-1}; 35 kg ha^{-1}	**50**	1156	1499	28
N; weeding once	25	539	1499	-787
Planted on 16-30 November;	75	2043	1523	1175
18 000 plants ha^{-1}; 35 kg ha^{-1}	**50**	1839	1523	906
N; weeding twice	25	1492	1523	447
Planted on 16-30 November;	75	2316	1748	1312
18 000 plants ha^{-1}; 50 kg ha^{-1}	**50**	2033	1748	938
N; weeding twice	25	1409	1748	113
Planted on 16-30 November;	75	1671	1548	659
21 000 plants ha^{-1}; 35 kg ha^{-1}	**50**	1171	1548	-2
N; weeding once	25	611	1548	-741
Planted on 16-30 November;	75	2116	1572	1223
21 000 plants ha^{-1}; 35 kg ha^{-1}	**50**	1803	1572	810
N; weeding twice	25	1464	1572	361
Planted on 16-30 November;	75	2415	1798	1393
21 000 plants ha^{-1}; 50 kg ha^{-1}	**50**	2103	1798	981
N; weeding twice	25	1331	1798	-39
Planted on 1-15 December;	75	1434	1350	544
9 000 plants ha^{-1}; 35 kg ha^{-1}	**50**	797	1350	-298
N; weeding once	25	175	1350	-1118
Planted on 1-15 December;	75	1477	1374	577

9 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding twice	**50**	1393	1374	466
	25	174	1374	-1144
Planted on 1-15 December; 12 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding once	75	1610	1400	727
	50	817	1400	-320
	25	228	1400	-1099
Planted on 1-15 December; 12 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding twice	75	1761	1424	902
	50	1629	1424	728
	25	227	1424	-1124
Planted on 1-15 December; 12 000 plants ha^{-1}; 50 kg ha^{-1} N; weeding thrice	75	1909	1673	849
	50	1772	1673	668
	25	229	1673	-1371
Planted on 1-15 December; 15 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding once	75	1751	1449	864
	50	761	1449	-444
	25	278	1449	-1082
Planted on 1-15 December; 15 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding twice	75	1862	1473	986
	50	1735	1473	819
	25	278	1473	-1107
Planted on 1-15 December; 15 000 plants ha^{-1}; 50 kg ha^{-1} N; weeding twice	75	1862	1473	986
	50	1735	1473	819
	25	278	1473	-1107
Planted on 1-15 December; 15 000 plants ha^{-1}; 50 kg ha^{-1} N; weeding thrice	75	2291	1723	1304
	50	1752	1723	592
	25	279	1723	-1354
Planted on 1-15 December; 18 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding once	75	1797	1499	874
	50	710	1499	-561
	25	316	1499	-1082
Planted on 1-15 December; 18 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding twice	75	1897	1523	983
	50	1644	1523	649
	25	314	1523	-1108
Planted on 16-30 November; 18 000 plants ha^{-1}; 50 kg ha^{-1} N; weeding twice	75	2231	1748	1199
	50	1753	1748	568
	25	328	1748	-1315
Planted on 1-15 December; 21 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding once	75	1736	1548	745
	50	685	1548	-643
	25	333	1548	-1109
Planted on 1-15 December; 21 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding twice	75	1947	1572	1000
	50	1704	1572	679
	25	334	1572	-1131
Planted on 1-15 December; 21 000 plants ha^{-1}; 50 kg ha^{-1} N; weeding twice	75	2379	1798	1345
	50	2025	1798	877
	25	374	1798	-1304
Planted on 1-15 December; 21 000 plants ha^{-1}; 50 kg ha^{-1} N; weeding thrice	75	2437	1822	1398
	50	2149	1822	1017
	25	373	1822	-1329

Table 10.4.16 Reference table for yield expectance, field costs and economic benefit under various sets of management practices during NN-NN rainfall conditions for Pioneer 3237

Management Practices (For Pioneer 3237 cultivar)	**Probability Levels**	**Yield Expectance ($kg.ha^{-1}$)**	**Field Costs ($Rand.ha^{-1}$)**	**Economic Benefit ($Rand.ha^{-1}$)**
Planted on 1-15 November; 9 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding once	75	1912	1421	1105
	50	988	1421	-115
	25	235	1421	-1111
Planted on 1-15 November; 9 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding twice	75	2292	1445	1582
	50	1739	1445	852
	25	773	1445	-424
Planted on 1-15 November; 9 000 plants ha^{-1}; 50 kg ha^{-1} N; weeding twice	75	2523	1670	1662
	50	694	1670	-753
	25	380	1670	-1169
Planted on 1-15 November; 9 000 plants ha^{-1}; 75 kg ha^{-1} N; weeding twice	75	2826	2045	1688
	50	2176	2045	829
	25	610	2045	-1239
Planted on 1-15 November; 12 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding twice	75	2369	1518	1612
	50	1823	1518	890
	25	903	1518	-325
Planted on 1-15 November; 12 000 plants ha^{-1}; 50 kg ha^{-1} N; weeding twice	75	2796	1743	1950
	50	2334	1743	1339
	25	800	1743	-687
Planted on 1-15 November; 12 000 plants ha^{-1}; 75 kg ha^{-1} N; weeding twice	75	3086	2118	1959
	50	2477	2118	1154
	25	686	2118	-1212

Planted on 1-15 November; 15 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding twice	75	2376	1591	1548
	50	1893	1591	910
	25	1005	1591	-264
Planted on 1-15 November; 15 000 plants ha^{-1}; 50 kg ha^{-1} N; weeding twice	75	2777	1816	1853
	50	2067	1816	914
	25	907	1816	-618
Planted on 1-15 November; 15 000 plants ha^{-1}; 75 kg ha^{-1} N; weeding twice	75	3072	2191	1866
	50	2532	2191	1154
	25	748	2191	-1203
Planted on 1-15 November; 18 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding twice	75	2384	1664	1485
	50	1591	1664	437
	25	335	1664	-1221
Planted on 1-15 November; 18 000 plants ha^{-1}; 50 kg ha^{-1} N; weeding twice	75	2857	1889	1884
	50	2140	1889	937
	25	975	1889	-602
Planted on 1-15 November; 18 000 plants ha^{-1}; 75 kg ha^{-1} N; weeding twice	75	3035	2265	1745
	50	2582	2265	1147
	25	758	2265	-1264
Planted on 1-15 November; 21 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding once	75	2303	1713	1329
	50	1100	1713	-260
	25	119	1713	-1556
Planted on 1-15 November; 21 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding twice	75	2403	1738	1437
	50	1909	1738	784
	25	1133	1738	-241
Planted on 1-15 November; 21 000 plants ha^{-1}; 50 kg ha^{-1} N; weeding twice	75	2941	1963	1922
	50	2475	1963	1306
	25	1028	1963	-604
Planted on 1-15 November; 21 000 plants ha^{-1}; 75 kg ha^{-1} N; weeding twice	75	3820	2338	2708
	50	2662	2338	1179
	25	727	2338	-1378
Planted on 16-30 November; 9 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding twice	75	1951	1445	1132
	50	1378	1445	375
	25	569	1445	-693
Planted on 16-30 November; 9 000 plants ha^{-1}; 50 kg ha^{-1} N; weeding twice	75	1741	1670	630
	50	627	1670	-841
	25	295	1670	-1280
Planted on 16-30 November; 9 000 plants ha^{-1}; 75 kg ha^{-1} N; weeding twice	75	2532	2045	1299
	50	1744	2045	258
	25	473	2045	-1420
Planted on 16-30 November; 12 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding twice	75	1983	1518	1102
	50	1466	1518	418
	25	668	1518	-636
Planted on 16-30 November; 12 000 plants ha^{-1}; 50 kg ha^{-1} N; weeding twice	75	2446	1743	1488
	50	1822	1743	663
	25	562	1743	-1001
Planted on 16-30 November; 15 000 plants ha^{-1}; 75 kg ha^{-1} N; weeding twice	75	3341	2191	2222
	50	2251	2191	782
	25	573	2191	-1435
Planted on 16-30 November; 18 000 plants ha^{-1}; 50 kg ha^{-1} N; weeding twice	75	2613	1889	1562
	50	1916	1889	642
	25	842	1889	-777
Planted on 16-30 November; 18 000 plants ha^{-1}; 75 kg ha^{-1} N; weeding twice	75	3341	2265	2149
	50	2251	2265	709
	25	573	2265	-1508
Planted on 16-30 November; 18 000 plants ha^{-1}; 100 kg ha^{-1} N; weeding once	75	3222	2639	1617
	50	2299	2639	398
	25	533	2639	-1935
Planted on 16-30 November; 21 000 plants ha^{-1}; 35 kg ha^{-1} N; weeding once	75	2303	1713	1329
	50	1100	1713	-260
	25	119	1713	-1556
Planted on 16-30 November; 21 000 plants ha^{-1}; 75 kg ha^{-1} N; weeding twice	75	3419	2338	2179
	50	2383	2338	810
	25	519	2338	-1652

The significance tests for the contributions of predictors to maize yields under NN-NN rainfall conditions presented in **Table 10.4.8** showed that weeding frequency was the most significant management practice for PAN 6479, while plant population density was the least significant. For Pioneer 3237, the most significant management practice was the planting date, while plant population density was the least significant (**Table 10.4.8**). From the data presented in **Table 10.4.15** it is evident that the optimum fertilizer application rate was 35 kg N.ha^{-1}, while the best planting date was 1-15

November for PAN 6479. For Pioneer 3237, the optimum fertilizer application rate was 75 kg N.ha^{-1}, while the optimum weeding frequency was twice (**Table 10.4.16**).

Economic analysis of the different sets of management practices under optimum planting date and fertilizer application rates revealed a close relationship between the weeding frequency and plant population density for PAN 6479. For Pioneer 3237 a close relationship existed between the different planting dates and fertilizer application rates under optimum weeding frequency and plant population density. For PAN 6479 the weeding frequencies that contributed most to maize yields were one and two times, while the plant population densities of 9 000, 12 000 and 15 000 plants.ha^{-1} produce profitable maize yield. For Pioneer 3237, the planting dates that dominated the contribution to maize yield were 1-15 November and 16-30 November, while plant population densities of 9 000, 15 000 and 21 000 plants.ha^{-1} resulted in highest yields. The CDFs in **Figure 10.4.8** illustrate the economic benefit associated with two different weeding frequencies and three plant population densities for PAN 6479. **Figure 10.4.9** illustrates the CDFs of the economic benefit associated with two different planting dates and three fertilizer application rates for Pioneer 3237.

At the 50% probability of non-exceedence the gross margins for using weeding frequencies of once and twice at a plant population density of 15 000 plants.ha^{-1} were R704.ha^{-1} and R1 683.ha^{-1}, respectively for PAN 6479 (**Figure 10.4.8**). Their respective field costs were -R62.ha^{-1} and R786.ha^{-1}. A difference in profit between weeding twice and once was R848.ha^{-1} and the field costs difference was R24.ha^{-1}. During these NN-NN seasonal rainfall conditions not weeding or weeding only once will incur financial losses. The profit could also be increased by optimising the plant population density. There was a 75% probability that the gross margin will not exceed R755.ha^{-1}, R1 280.ha^{-1} and R2 006.ha^{-1} when weeding twice at plant population densities of 9 000, 12 000 and 15 000 plants.ha^{-1}, respectively. The respective field costs were R1 374.ha^{-1}, R1 424.ha^{-1} and R1 473.ha^{-1}. The difference in profit between 12 000 and 15 000 plants ha^{-1} was R726.ha^{-1}, while spending only an additional R42.ha^{-1} on field costs.

The most profitable management practices, given an optimum fertilizer application rate and weeding frequency, involved early planting dates for Pioneer 3237. At the 50% probability of non-exceedence the gross margins for maize planted during 1-15 November and 16-30 November at a plant population density of 9 000 plants.ha^{-1} were R829.ha^{-1} and R258.ha^{-1}, respectively (**Figure 10.4.9**). The farmer could gain an additional profit of R571.ha^{-1} when opting to plant during 1-15 November as opposed to 16-30 November. The gross margins for 15 000 plants.ha^{-1} planted during 1-15 November

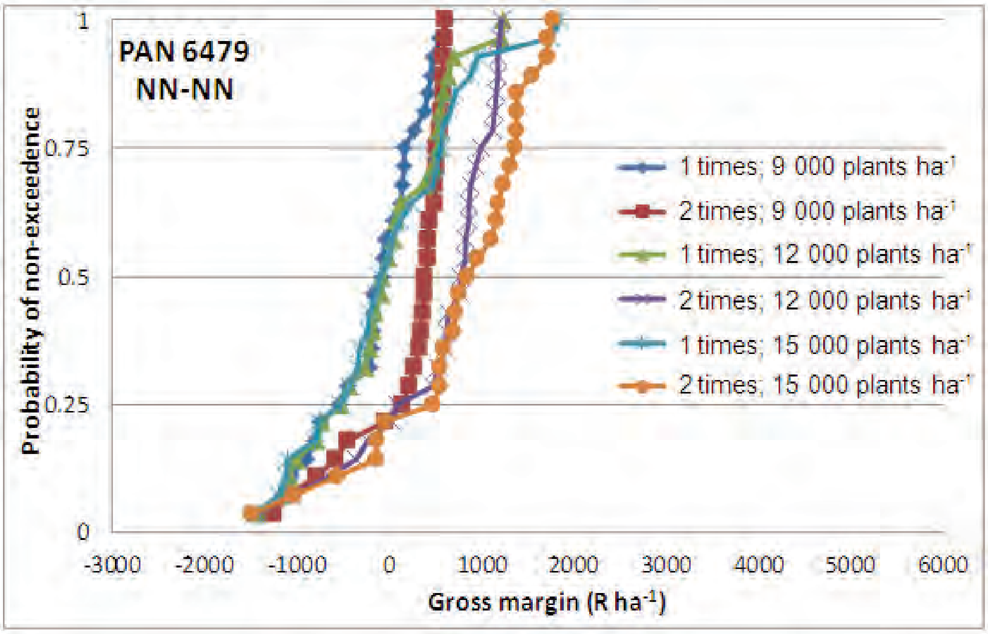


Figure 10.4.8 Cumulative distribution function of long-term gross margins for PAN 6479 associated with three different plant population densities and two weeding frequencies during NN-NN rainfall conditions (using a fertilizer application rate of 35 kg N.ha^{-1} and planted during 1-15 November)

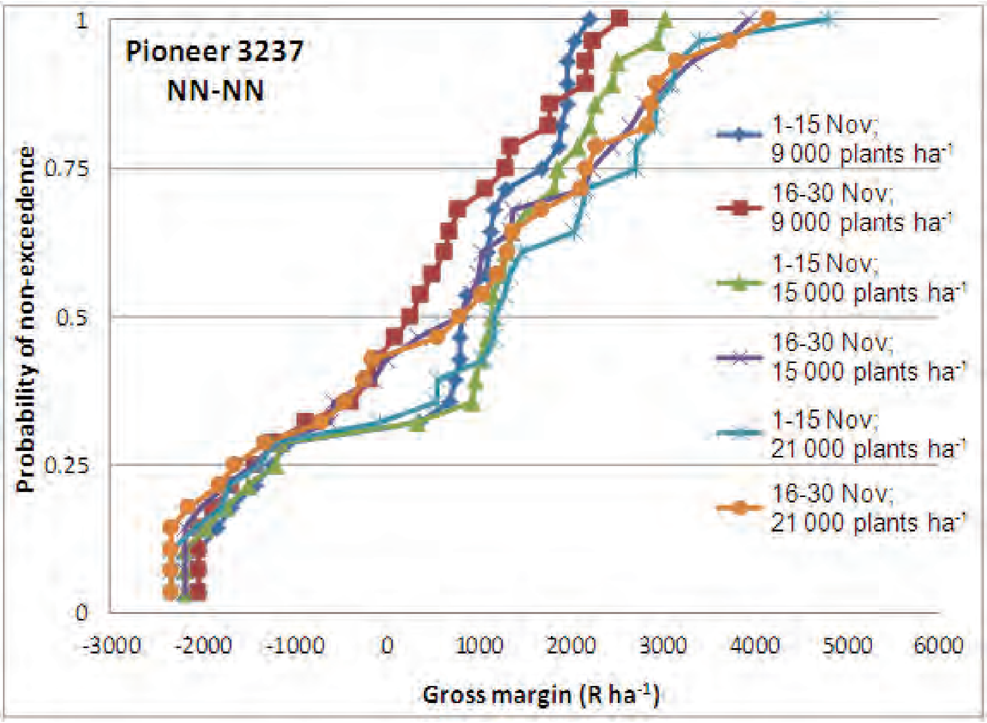


Figure 10.4.9 Cumulative distribution function of long-term gross margins for Pioneer 3237 associated with two different planting dates and three plant population densities during NN-NN rainfall conditions (using a fertilizer application rate of 75 kg N.ha^{-1} and weeding twice)

and 16-30 December were R1 154.ha^{-1} and R782.ha^{-1}, respectively. There was a 75% probability that the gross margin would not exceed R1 688.ha^{-1}, R1 866.ha^{-1} and R2 708.ha^{-1} at plant population densities of 9 000, 15 000 and 21 000 plants.ha^{-1}, respectively.

The results of the economic analysis revealed that the highest yielding set of management practices was not necessarily always the most profitable option. **Tables 10.4.17** and **10.4.18** summarise the best set of management practices for different seasonal rainfall scenarios for PAN 6479 and Pioneer 3237, respectively with, in addition to near-normal rainfall conditions, AN represents above-normal and BN below-normal rainfall conditions. The breakdown of economic analysis is also provided with the expected yield and economic benefit corresponding to 50% probability level. Once again it became clear that planting early (November) is most profitable under all seasonal rainfall scenarios. It was evident that a high plant population density resulted in higher profit when AN rainfall conditions occurred during the second half of the growing season. On the other hand, lower plant population densities proved optimal when the second half of the rainfall season was BN. Interestingly, applying 75 kg N.ha^{-1} never formed part of the management practices summarised in **Table 10.4.17** for PAN 6479. Only during AN-AN and NN-AN seasons was the optimum fertilizer application rate found to be 50 kg N.ha^{-1}, otherwise 35 kg N.ha^{-1} sufficed. Generally speaking, for Pioneer 3237 higher fertiliser application rates (50 to 75 kg N.ha^{-1}) were required. However, during any BN and NN combination the optimum fertilizer application rate was 35 kg N.ha^{-1} (**Table 10.4.18**). The optimum weeding frequency was twice for PAN 6479, but twice or thrice for Pioneer 3237.

For BN-NN and BN-BN rainfall conditions, the management practices which farmers should avoid at all costs for both cultivars were to plant late, i.e. during 1-15 January, using 21 000 plants ha^{-1}, applying 100 kg N.ha^{-1} of fertilizer and not to weed at all. During BN-BN conditions farmers would spend R2 449.ha^{-1} and risk making a loss of R2 488.ha^{-1} at the 75% probability level for PAN 6479. For Pioneer 3237 farmers would spend R2 664.ha^{-1} and risk losing everything as a result of crop failure.

Table 10.4.17 Summary of best management practices together with the corresponding economic analysis under different seasonal rainfall scenarios for PAN 6479

Rainfall Scenario	Management Practices				Economic Analysis		
	Planting Date	Plant Population Density (plants.ha^{-1})	Fertilizer Application Rate (kg N.ha^{-1})	Weeding Frequency	Field Cost (R.ha^{-1})	Expected Yield (50%) (kg.ha^{-1})	Economic Benefit (50%) (R.ha^{-1})
AN-AN	16-30 Nov	21 000	50	2	1 798	2 854	1 972
AN-NN	16-30 Nov	21 000	35	2	1 572	1 814	823
AN-BN	16-30 Nov	15 000	35	2	1 473	1 660	719
NN-AN	16-30 Nov	21 000	50	2	1 798	2 940	2 086
NN-NN	1-15 Nov	15 000	35	2	1 473	1 757	848
NN-BN	16-30 Nov	12 000	35	2	1 424	1 410	439
BN-AN	1-15 Nov	21 000	35	2	1 573	2 205	1 344
BN-NN	1-15 Nov	15 000	35	2	1 474	1 794	897
BN-BN	1-15 Nov	12 000	35	2	1 424	1 128	66

Table 10.4.18 Summary of best management practices together with their corresponding economic analysis under different seasonal rainfall scenarios for Pioneer 3237

Rainfall Scenario	Management Practices				Economic Analysis		
	Planting Date	Plant Population Density (plants.ha^{-1})	Fertilizer Application Rate (kg N.ha^{-1})	Weeding Frequency	Field Cost (R.ha^{-1})	Expected Yield (50%) (kg.ha^{-1})	Economic Benefit (50%) (kg.ha^{-1})
AN-AN	1-15 Nov	18 000	75	2	2 338	4 232	3 253
AN-NN	1-15 Nov	12 000	75	3	2 142	3 686	2 726
AN-BN	1-15 Nov	9 000	50	3	1 694	2 352	1 412
NN-AN	1-15 Nov	18 000	75	3	2 289	3 824	2 763
NN-NN	1-15 Nov	21 000	75	2	2 338	2 662	1 179
NN-BN	1-15 Nov	9 000	35	3	1 469	1 888	1 025
BN-AN	1-15 Nov	18 000	75	3	2 289	3 226	1 973
BN-NN	1-15 Nov	12 000	35	3	1 542	1 454	378
BN-BN	1-15 Nov	9 000	35	2	1 445	1 841	987

10.4.5 Recommended Practices for Rainfed Maize Production under Various Seasonal Rainfall Conditions

Maize producers continually search for agronomic practices that will help them to increase yields and / or reduce input costs. Developing advisories for rainfed maize production, based on different growing season rainfall scenarios, is a major step in addressing this need. After careful consideration it was decided that the advisories would be in the form of flow charts that could later easily be replicated by a software program.

The first part of the advisory flow charts involved describing the growing season rainfall scenario. The idea was that farmers could either use:

- a 6-month seasonal forecast at the beginning of the growing season; or
- a 3-month seasonal forecast at a later stage in the growing season after assessing the rainfall for the first few months.

The second part of the advisory flow chart provided information regarding management practices. These were ranked according to their significance for maize yield prediction. In each case the best, second best and worst set of management practices were emphasised. The best option provided the highest gross margin (i.e. highest profit), while the next best option under each yield predictor was also provided in order to aid farmers should the best option not be viable. The worst option was associated with the lowest gross margin (i.e. least profit or biggest loss). An economic analysis for the best and worst options of management practices were provided in the last part of the advisory flow chart. The economic analysis comprised of field costs, maize yield expectancy and the economic benefits (gross margins) under probability levels of 25, 50 and 75%. Owing to the various analogue seasons a huge amount of data was generated. It was again decided to only present the results of near-normal followed by near-normal (NN-NN) rainfall conditions here.

The optimal yield predictors identified in **Table 10.4.8** were used as recommended management practices for PAN 6479 and Pioneer 3237 during NN-NN rainfall conditions. These practices are now summarised by the flow charts in **Figure 10.4.10** and **Figure 10.4.11** for PAN 6479 and Pioneer 3237, respectively.

During these rainfall conditions the best set of management practices for PAN 6479 involved weeding twice, applying 35 kg N.ha^{-1}, planting during 1-15 November and using a plant population density of 15 000 plants. ha^{-1}. As a result farmers, at the time that this analysis was undertaken, would spend R 1 473.ha^{-1} on field costs, while obtaining a yield of 2 159 kg.ha^{-1} and making a profit of R1 378.ha^{-1} at the 75% probability level. The next best set of management practices involved weeding once with the optimum values for fertilizer application rate, planting date and plant population density. The worst management practice involved no weeding control, applying 100 kg N.ha^{-1}, planting late during 1-15 January at a plant population density of 21 000 plants.ha^{-1}. Farmers would spend R2 499.ha^{-1} on field costs owing to the high plant population density and fertilizer application rate, and then risk making a loss of R1 698.ha^{-1} at the same probability level.

During NN-NN rainfall conditions the best set of management practices for Pioneer 3237 involved planting during 1-15 November, weeding twice, applying 75 kg N.ha^{-1} and using a plant population density of 21 000 plants.ha^{-1} (**Figure 10.4.9**). The worst set of management practices involved planting during 1-15 January, without weeding and applying fertilizer and using 9 000 plants.ha^{-1}. The economic analysis revealed that at a 75% probability, farmers have the chance of making a profit of R2 708.ha^{-1} under the best management practices. Farmers would then obtain a profit of R2 708.ha^{-1} and spend R2 338.ha^{-1} on field costs. When using the worst set of management practices, farmers would make a loss of R872.ha^{-1} at the 50% probability level. Planting date was the most important yield contributor, which implied that the next best set of management practices under an alternative date involved planting during the 16-30 November period.

The management practices provided in the type of advisories developed in this study for various seasonal rainfall scenarios could assist small-scale maize farmers to increase their yields and maximise the associated profit under rainfed conditions. The use of a cropping systems model to add value to the seasonal rainfall forecast (as provided by SAWS and the CSIR) is deemed appropriate as it best captures the complex interactions between climate and management practices to affect yield outcomes. Unfortunately, site-specific calibration of APSIM is required against observed sets of climate, soil and yield data for which the associated management practices are known, before these advisories can be used by extension officers to advise small-scale farmers within the Modder River catchment. Since a relationship has already been established, a golden opportunity now exists to let suitable intermediary institutions (such as the ARC) use these advisory flow charts in training workshops for the agricultural extension officers within the Modder River catchment.

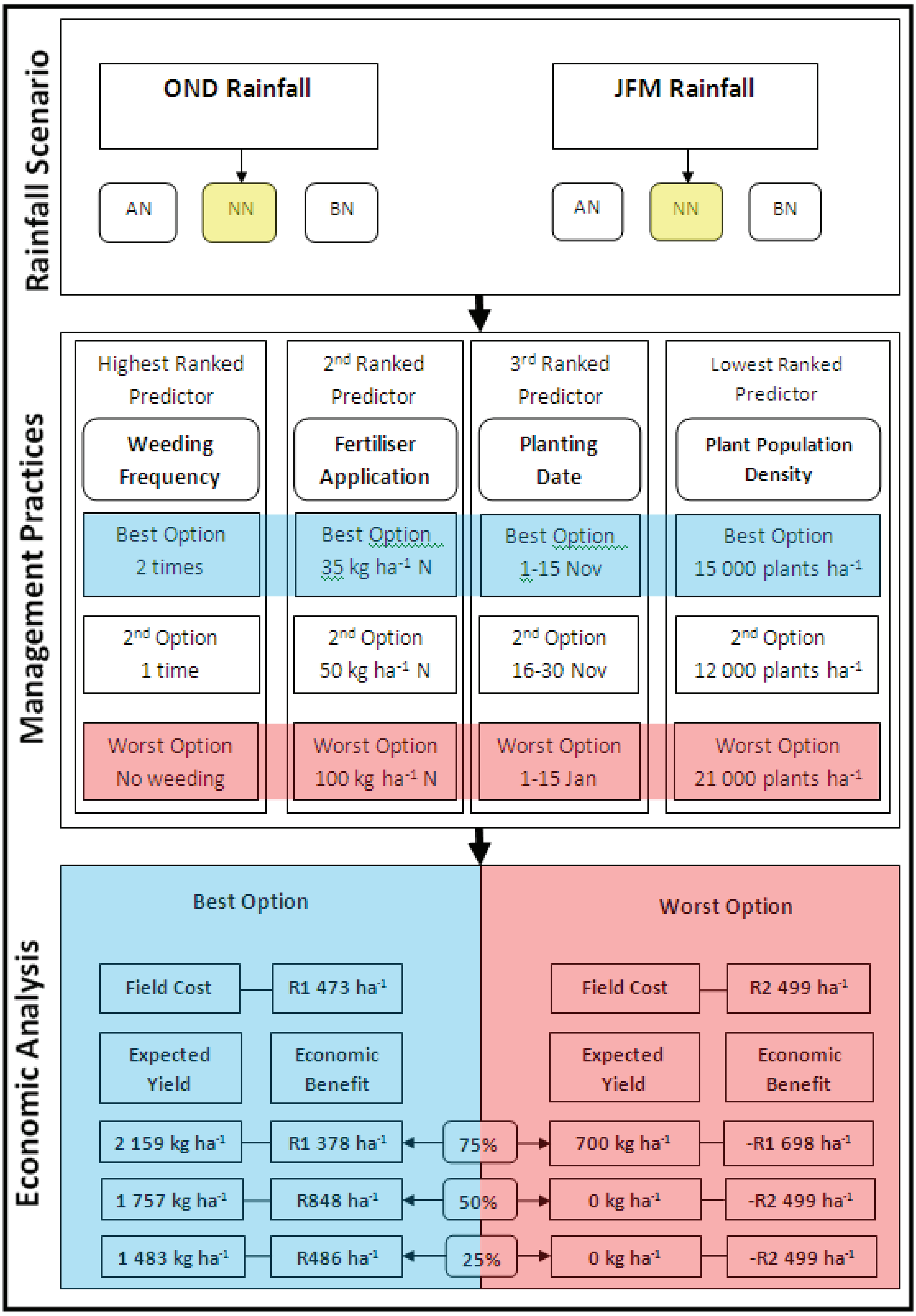


Figure 10.4.10 Flow chart of recommended practices in the Modder River catchment for maize variety PAN 6479 during NN-NN rainfall conditions

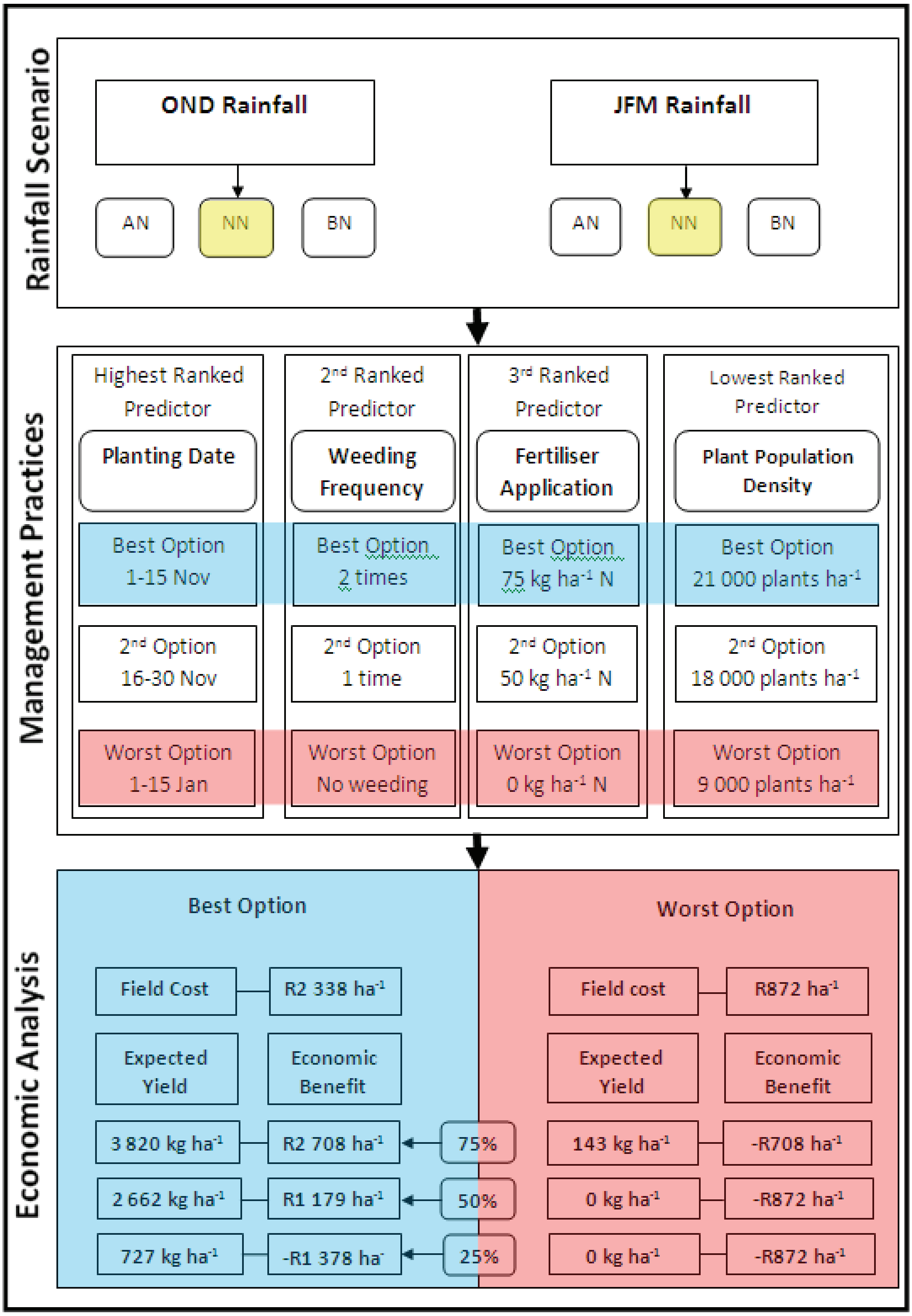


Figure 10.4.11 Flow chart of recommended practices in the Modder River catchment for maize variety Pioneer 3237 during NN-NN rainfall conditions

CHAPTER 11

UPDATING AND QUALITY CONTROL OF CLIMATE DATABASES FOR APPLICATION IN FORECASTING AND VERIFICATION

CJ Engelbrecht and RP Kunz

Summary

11.1 THE CHALLENGE
11.2 UPDATING AND QUALITY CONTROL OF AGRICULTURAL RESEARCH COUNCIL CLIMATE DATABASE
11.3 UPDATING AND QUALITY CONTROL OF SOUTH AFRICAN WEATHER SERVICE RAINFALL DATABASE BY THE UNIVERSITY OF KWAZULU-NATAL
11.4 CONCLUDING THOUGHTS

11.1 THE CHALLENGE

Operational forecasting systems (and other agrohydrological applications) require continually updated daily climate data as input to their applied irrigation, soil moisture and crop yield models, especially of daily rainfall, maximum and minimum temperatures, but also of derivatives of temperature (e.g. relative humidity, potential evaporation, solar radiation). Since the updates are not readily available in South Africa, one component of this project was to update and quality control climate variables for use in this (and other) projects. To have such updates in near real time (i.e. for the day before) in order to initialise applied forecast models for the day from which forecasts were being made, proved to be beyond the scope of this project, as became evident from a series of specialist technical workshops in the course of the project (cf. **Chapter 14**). Two major initiatives were, however, undertaken, and the results of those are reported below.

11.2 UPDATING AND QUALITY CONTROL OF AGRICULTURAL RESEARCH COUNCIL CLIMATE DATABASE (CJ Engelbrecht)

Following a meeting in June 2009 to discuss the updating of climate databases for use in the project, it was decided that an effort in the ARC would first be focused on updating and performing quality control on the ARC data for the historical period (2000-2008). Once this was completed the focus was to shift to updating and cleaning data for more recent seasons (post 2008).

11.2.1 Inventory of Stations

An inventory of the ARC climate data available for 2000-2008 is given in **Table 11.2.1**. These data are from stations across the country.

Table 11.2.1 Inventory of ARC climate data available for the period 2000-2008

Climate Variable	Number of Stations	Earliest Date*	Latest Date*	Minimum Record Length (years)	Average Record Length (years)	Maximum Record Length (years)
Rainfall						
- Hourly (from AWS)	521	Jan 2000	Dec 2008	0.0	4.3	8.8
- Daily (manual stations)	2886	Jan 2000	Oct 2008	0.1	3.4	8.8
Temperature (daily max. & min.)	2248	Jan 2000	Dec 2008	0.1	2.4	8.4

*The earliest and latest dates are not necessarily applicable to a single station but are derived from the entire dataset

For the period January 2000 to July 2010, 497 automatic weather stations (AWSs) were potentially available, depending on their subjection to a number of basic quality control procedures which are described in the following section. It must be noted that the time span covered by each station is not necessarily continuous during this period. For crop yield modeling with the DSSAT suite of models, these data were also available in that model format.

The distribution of stations during this period can be seen in **Figure 11.2.1**, while the number of stations available on a monthly basis during this period can be seen in **Figure 11.2.2**.

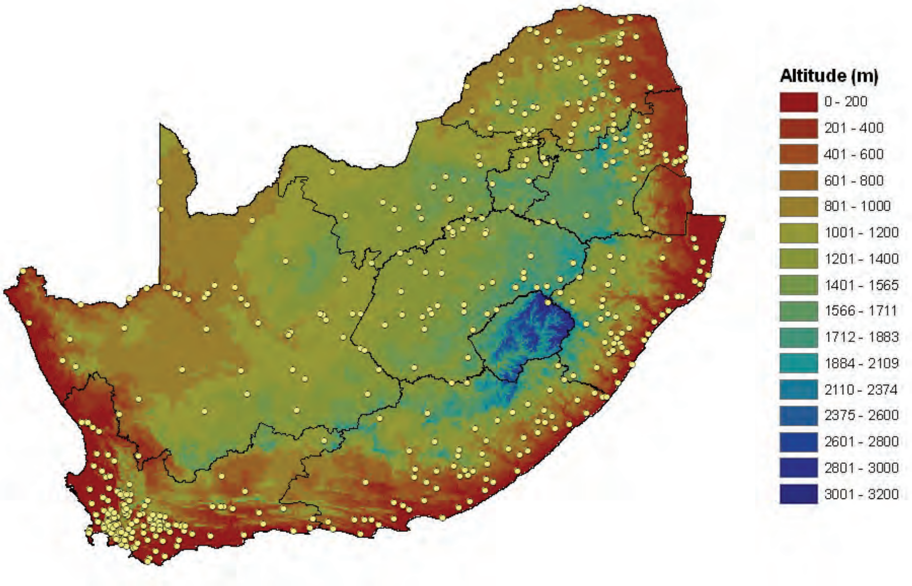


Figure 11.2.1 Distribution of ARC automatic weather stations as of July 2010, with these stations data being available in DSSAT format

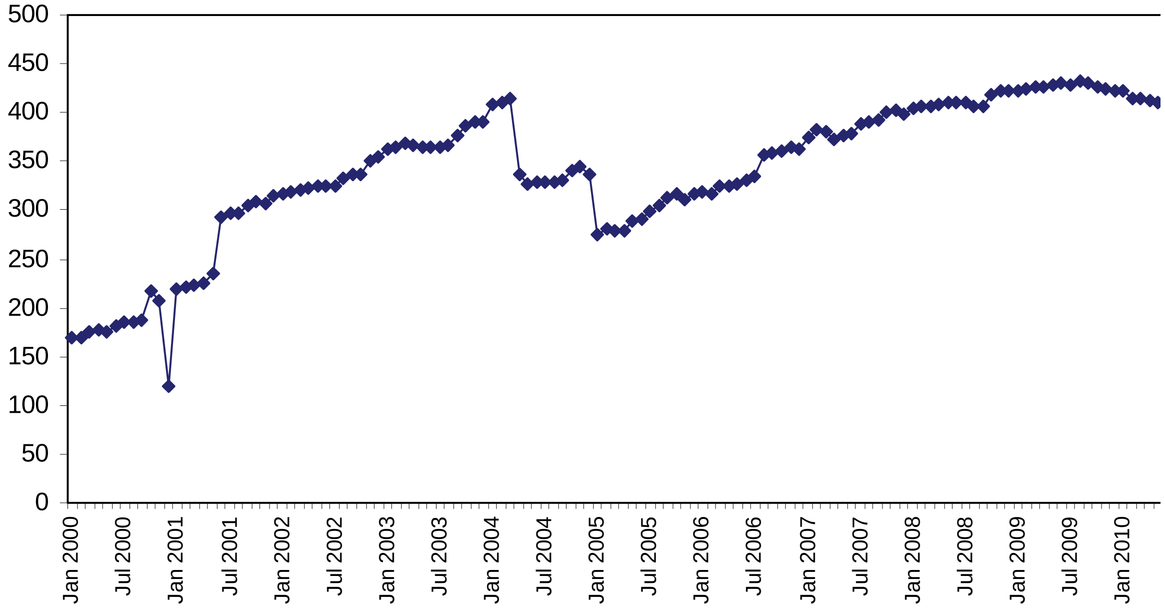


Figure 11.2.2 Number of automatic weather stations for which data are available on a monthly basis, for the period January 2000 to July 2010

11.2.2 Quality Control Procedures Employed on the Station Data

Four procedures that identify potentially poor quality data were employed. These tests were:

- *Missing data check*
  Missing data for all the elements are replaced by the identifier – 999.0
- *Extreme value check*
  Values that fall outside the following ranges for the respective elements are replaced by the identifier – 998.0:
  Maximum temperature: – 16 to 50°C
  Minimum temperature: – 16 to 35°C
  Rainfall: 0 to 597 mm
  Solar radiation: 0 to 30 $MJ.m^2$
- *Internal consistency check*
  Three consecutive values that are identical, for any of the four elements above, are replaced by the identifier – 997.0
- *Station location check*
  Check for correct geographical coordinates and for altitude. Additionally, three independent station location checks are employed. Each station is identified by a unique station identifier. When different stations have the same location and (a) the same data entries, or (b) different data entries, both these stations entries are replaced by the value – 996.0 and – 995.0 respectively. In the case that different stations with different locations possess the same data entries, both those stations entries are replaced by the value–- 994.0.

11.3 UPDATING AND QUALITY CONTROL OF SOUTH AFRICAN WEATHER SERVICE RAINFALL DATABASE BY THE UNIVERSITY OF KWAZULU-NATAL (RP Kunz)

In work done for the forestry industry, the rainfall data for 730 SAWS rainfall stations was subjected to quality control and infilling procedures for the 2000-2007 period. The data were purchased by the forestry industry, who then contracted the UKZN team to perform quality control and infilling of the data. Recent negotiations have allowed for the quality controlled and infilled data to be made available for use in this project. Details regarding the stations concerned and the quality controlling / infilling of the data are reported in detail below.

11.3.1 Inventory of Stations

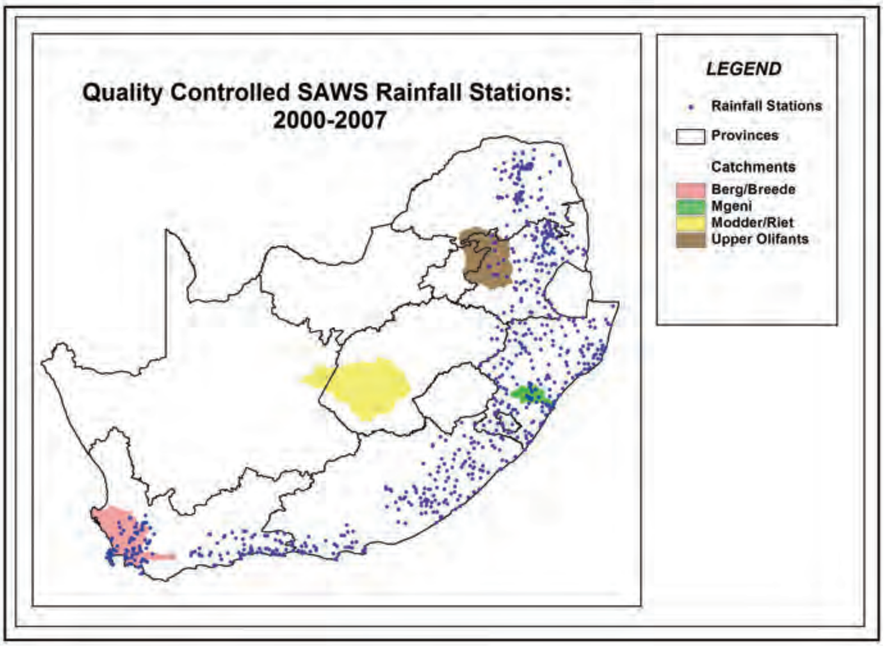


Figure 11.3.1 Distribution of SAWS rainfall stations with quality controlled / infilled data for the period 2000-2007

The 730 SAWS rainfall stations are located in the higher rainfall regions of the country. Stations can be found in three of the selected catchments that form the focus of this project, *viz*. the Berg / Breede, Mgeni and Upper Olifants catchments. No stations are located in the Modder / Riet catchment. The distribution of the stations and the location of the selected catchments are shown in **Figure 11.3.1**.

Data were obtained for two periods, 2000-2004 and 2004-2007. A 4 month overlap period allowed for joining of the data into a continuous 2000-2007 sequence. Every effort was made to infill all missing data. The outcome of a data infilling exercise was dependent on the number of stations available for infilling. Unfortunately, the stations used in this work were limited to stations from the SAWS observation network and did not include stations from the ARC or industry

The quality control and infilling process involved the following steps:

- Elimination of poor quality stations
- Disaggregating accumulated totals into daily sequences
- Infilling of missing daily data

11.3.2 Elimination of Poor Quality Stations

An analysis of data quality was initially conducted to assess if all stations obtained could be used as target stations in the data infilling process. This analysis was focused on the occurrence of accumulated data totals (where the total over several days is recorded rather than individual daily amounts) and missing data. The analysis of the occurrence of accumulated totals is given in **Table 11.3.1**.

Table 11.3.1 Analysis of the occurrence of accumulated totals in the SAWS rainfall dataset (2000-2007)

Sequence Length	Quality Control Codes	Number of Occurrences	Percentage of Total	Accumulated Percentage
2	A,C	61 825	93.17	93.17
3	A,A,C	3 017	4.55	97.72
4	A,A,A,C	598	0.90	98.62
5	A,A,A,A,C	251	0.38	99.00
6	A,A,A,A,A,C	100	0.15	99.15
7	A,A,A,A,A,A,C	86	0.13	99.28
8	A,A,A,A,A,A,A,C	59	0.09	99.37
9	A,A,A,A,A,A,A,A,C	38	0.06	99.42
10	A,A,A,A,A,A,A,A,A,C	33	0.05	99.47
11	A,A,A,A,A,A,A,A,A,A,C	29	0.04	99.52

Under the ‘Quality control code’ column of **Table 11.3.1**, the symbol ‘A’ represents a daily value that is unavailable. The symbol ‘C’ at the end of the quality control code represents the accumulated total of the sequence of unavailable daily values. The frequency of accumulated sequences greatly reduces as the length of the sequences increases. For example, 93.17% of the accumulated totals represent a two day sequence, while only 4.55% represent a three day sequence. In general, accumulated totals are a result of public holidays, weekends or the observer being ill or on holiday.

If a station has too many data missing, it becomes unfeasible to infill those missing data. A total of 15 stations were eliminated as target stations for infilling of data, either because of too many accumulated totals or too many missing daily values. The details of these stations and the statistics of their accumulated totals and / or missing values are given in **Table 11.3.2**. While a station may be eliminated as a target station for data infilling, it could still be used for infilling the data of other stations, i.e. it could be used as a control station.

Table 11.3.2 Stations eliminated as target stations for infilling of accumulated rainfall totals or missing daily values

SAWS ID	Start Date	End Date	% Reliable	% Accumulated Totals	% Missing	% Full Record
0005736_2	2000/01/01	2007/12/31	2.9	97.1	0.0	100.0
0006031_2	2000/01/01	2007/12/31	0.0	94.0	6.0	100.0
0020689_2	2000/01/01	2002/12/31	7.7	92.3	0.0	37.5
0020748_X	2000/01/01	2002/12/31	11.9	88.1	0.0	37.5
0020805_3	2001/05/01	2007/12/31	12.9	0.0	87.1	83.4
0021809_7	2000/01/01	2007/12/31	28.2	71.6	0.2	100.0
0022029_2	2000/01/01	2007/12/31	0.0	76.8	23.1	100.0
0022030_3	2000/01/01	2007/12/31	0.0	92.5	7.5	100.0
0027713_3	2000/01/01	2007/12/31	0.2	99.8	0.0	100.0
0028055_5	2000/01/01	2007/12/31	1.2	98.7	0.0	100.0
0028083_3	2000/01/01	2007/12/31	0.2	99.8	0.0	100.0
0042250_2	2000/01/01	2007/12/31	2.1	96.9	1.0	100.0
0241054_8	2000/01/01	2005/12/31	36.9	14.7	48.4	75.0
0338822_9	2000/01/01	2003/09/30	49.5	1.6	48.9	46.9
0443523_9	2000/01/01	2003/01/31	43.4	0.0	56.6	38.6

11.3.3 Disaggregating Accumulated Totals into Daily Sequences

The process of disaggregating accumulated rainfall totals into daily sequences firstly involved identifying 8 control stations for each target station. The identification of control stations was done by ranking surrounding stations based on their distance and altitude relative to the target station (stations that were closer and at a more similar altitude ranked higher). Distance was given a stronger weighting than altitude. The station with the highest ranking was then selected to disaggregate the accumulated totals of the target station into daily sequences. This was done by considering the proportion of each day's rainfall to the accumulated total at the control station and assuming these same proportions at the target station. If the selected control station had data missing for a period of interest, then data from the next highest ranking control station would be used. Once a target station had its accumulated totals disaggregated, it could then be used as a control station for another target station. The process was therefore iterative. In certain cases, disaggregating of accumulated totals was not possible owing to all the control stations having zero rainfall or missing data for a period if interest. This typically happened as a result of phasing errors where, for example, rainfall falling in the early hours of the morning would be recorded against the previous day's date at a manually recording station (read at 08:00), while automatic stations would record it on the same day's date (read hourly or sub-hourly). In these cases the relevant stations' records (target and control) would be subjected to more sophisticated infilling methods described below where such phasing errors are corrected.

11.3.4 Infilling of Missing Daily Data

When first obtaining the SAWS rainfall data, 81 stations had a complete record. After disaggregating accumulated totals, a further 154 stations had complete records. This left 498 stations that required infilling of missing daily values. **Table 11.3.3** gives a breakdown of the missing data for these 498 stations:

Table 11.3.3 Breakdown of missing data at 498 stations requiring infilling of missing daily data

Days of Missing Data	Number of Stations
1	23
2	12
3-31	53
32-120	257
> 120	153

The primary technique used to infill missing daily data is known as the Expectation Maximization Algorithm, or EMA (Dempster *et al*., 1977; Makhuvha *et al*., 1997a, 1997b; Smithers and Schulze, 2000). The technique involves replacing missing data with an initial estimate and then performing a multiple regression between the target station and a selected control station. The regression relationship is then re-estimated recursively (for different rainfall estimates) until the best fit is found. The technique is sophisticated and superior to other techniques, but is computationally complex and time consuming. In summary, the specific steps that are followed are:

- Calculate monthly rainfall totals for each year of record;
- Perform an initial selection of control stations by identifying all stations within a 200 km radius;
- Refine the initial selection of control stations by also considering differences in MAP and altitude;
- Check phasing of target and control station records and make necessary adjustments (shift records one day later and one day earlier and assess if correlation improves);
- Check if outliers exist in the control station records;
- Select a final control station by considering the outcome of the above steps and a cluster analysis;
- Perform a multiple regression between the target station and the selected control station. The regression relationship is then re-estimated recursively (for different rainfall estimates) until the best fit is found;
- Re-run EMA technique so that infilled target stations can also be utilized as control stations for other target stations (improves control station selection).

Other infilling techniques that were used included the Median Ratio Method (MRM) and (in limited cases) simple rules of thumb (e.g. if less than 15 days are missing and they are in the dry season, replace with 0 mm). The Median Ratio Method adjusts the daily data of the target station in proportion to the ratio of the median monthly rainfall totals of the target and control stations.

Range checks were then performed to ensure that daily values fall within realistic bounds.

In conclusion, 495 of 498 stations were infilled (3 stations were omitted as too few control stations were available). Combined with stations that had complete records from the beginning (81) and after disaggregating accumulated totals (154), this yielded a total of 730 stations (cf. **Figure 11.3.1**). A breakdown of the number of stations subjected to various techniques / procedures is given in **Table 11.3.4**. Also given in **Table 11.3.4** is the number of stations which still contained missing data after all possible techniques / procedures had been applied (infilling not possible).

Table 11.3.4 Breakdown of stations subjected to various infilling techniques / procedures

No. of Stations	Disaggregation of Accumulated Totals	Infilling with EMA / MRM	Replacing with Zero	Data Still Missing
81				
154	Yes			
221		Yes		
138	Yes	Yes		
63		Yes		Yes
29		Yes	Yes	Yes
15	Yes	Yes		Yes
13		Yes	Yes	
8	Yes	Yes		Yes
5	Yes	Yes	Yes	
3	Yes	Yes	Yes	Yes
730				

It was noted in the work that meta data for the stations has changed compared to previous periods. These include changes in:

- Station ID's and names
- Geographic coordinates
- Altitude
- Ownership

This can have important implications for infilling techniques such as the EMA which utilises this information in its procedures. It also has implications for joining the new data (post 2000) to earlier records (pre-2000) since no reliable list of old and new station ID / names is available to match the records. Matching of records (old and new) must therefore be done by comparing meta data such as geographic coordinates and altitude.

The importance of maximising the number of stations available for data infilling procedures is re-emphasised.

11.4 CONCLUDING THOUGHTS

The lack of a national facility to update climate data and perform quality control and infilling of missing data was, once again, highlighted by these two case studies. Good quality and complete climate datasets are required in many contexts. The two case studies presented here are not the only initiatives in South Africa by research groups to embark on updating and quality controlling daily climate data. It is important to avoid duplication of effort in managing data quality, since it is a time consuming task that requires specialist skills. A single source of quality controlled and infilled data also promotes consistency in datasets.

It is a recommendation from this project, therefore, that sustained and adequate funding (possibly from multiple sources) be made available for one institution in South Africa to be made responsible for the collation (from different sources) and uniform quality control of climate data, and that these data then be made freely available to all *bona fide* researchers. This would save not only the many WRC projects from major duplication of effort in updating climate related databases, but would also ensure that the same datasets be used across the many disciplines in South Africa that utilise climate data.

****

This discussion on data updating and quality control leads to the following chapter in which the focus is on archiving of information and data required for a forecasting system / framework.

CHAPTER 12

ARCHIVING OF INFORMATION AND FORECASTS

RE Schulze, FA Engelbrecht, MA Tadross, TG Lumsden, MJC Horan, CJ Engelbrecht and RP Kunz

Summary

12.1 NON-CLIMATIC INFORMATION
12.2 HISTORICAL CLIMATE INFORMATION
12.3 ARCHIVING OF ORIGINAL AND TRANSLATED FORECASTS

12.1 NON-CLIMATIC INFORMATION (RE Schulze, MJC Horan, RP Kunz)

12.1.1 Quinary Catchments Database

For any forecast system to be tailored to specific users within the agricultural and hydrological sectors, and for such forecasts to be used in local decision making, those forecasts ideally need to made at suitably fine spatial resolutions rather than at coarse spatial resolutions. For agrohydrological purposes in South Africa a suitably fine resolution is the altitudinally derived Quinary Catchment.

The sub-delineation of Quaternary into Quinary Catchments, which was undertaken partially through funding from this project, has resulted in 5 838 hydrologically interlinked and cascading Quinaries (**Figure 12.1.1**) covering the RSA, Lesotho and Swaziland. These have been demonstrated to be physiographically considerably more homogeneous than the Quaternaries and on a national and smaller scale are considered to be relatively homogeneous agricultural and hydrological response zones (Schulze and Horan, 2010). Linked to each Quinary is a 50 year dataset of daily rainfall (based on research by Lynch, 2004), maximum and minimum temperatures (Schulze and Maharaj, 2004), solar radiation (Schulze and Chapman, 2008a), maximum and minimum relative humidity (Schulze and Chapman, 2008b) and reference potential evaporation by the Penman-Monteith technique (Penman, 1948; Monteith, 1981; Schulze *et al*., 2008), plus soils (Schulze and Horan, 2008) and land cover attributes (Schulze, 2004) applicable to agrohydrological modelling. This system makes up the Quinary Catchments Database, which has been described in detail in Schulze *et al*. (2011)

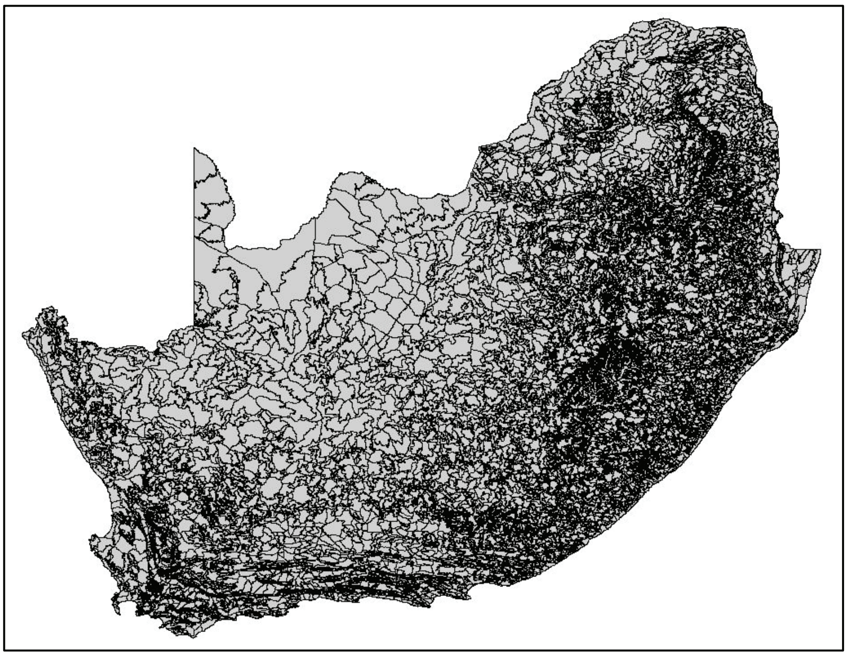


Figure 12.1.1 Delineation of the RSA, Lesotho and Swaziland into 5 838 hydrologically interlinked and cascading Quinary Catchments (Schulze and Horan, 2010)

The Quinary Catchments Database is archived in the School of Agricultural, Earth and Environmental Science at the University of KwaZulu-Natal and is available on request (horan@ukzn.ac.za).

12.1.2 Land Cover and Land Use

Attributes for baseline land cover, represented by the Acocks' (1988) Veld Types are available for the RSA, Lesotho and Swaziland (cf. Schulze, 2004). For actual land use, the National Land Cover 2000 (NLC, 2000) dataset was acquired in digital format from the developers (a CSIR / ARC consortium) and was encoded in order to be "translated" into attributes required for application in agrohydrological modeling and forecasting. These attributes can be applied at both catchment and national scale studies. In a visit by the UKZN team to the Komati Catchment in November 2006 good correspondence was found between the NLC (2000) data set and the land uses present in the Catchment. The land uses shown on the 1 : 50 000 topographic map sheets were also found, in many instances, to correlate well with that present in the catchment.

Digital versions of the Acocks' Veld Types and the NLC (2000), as well as the encoded attributes are archived at the School of Agricultural, Earth and Environmental Science on the Pietermaritzburg campus of the University of KwaZulu-Natal (horan@ukzn.ac.za).

12.1.3 Soils

Existing soil information in the form of the national Land Type database was used in this study. In certain areas of South Africa, *viz*. the former Transkei and Ciskei, this soil information had not previously been available to the project team. This information was acquired from the by the UKZN team and has also been translated into hydrological attributes (Schulze and Horan, 2008). With the Quaternary Catchments having been sub-delineated into more homogeneous agrohydrological response zones for modelling purposes, soil attributes for agricultural and hydrological modeling were assigned to each of the finer scale Quinary catchments. Digital versions of the soils attributes for modelling purposes at Quinary Catchments resolution are archived at the School of Agricultural, Earth and Environmental Sciences on the Pietermaritzburg campus of the University of KwaZulu-Natal (horan@ukzn.ac.za).

12.2 HISTORICAL CLIMATE INFORMATION (MJC Horan, RP Kunz, CJ Engelbrecht)

Historical climate information from 1950-1999 per Quinary Catchment is archived at at the School of Agricultural, Earth and Environmental Sciences on the Pietermaritzburg campus of the University of KwaZulu-Natal (horan@ukzn.ac.za), as is the updated and quality controlled SAWS data referred to in **Chapter 11.3**. The updated and quality controlled ARC daily (and sub-daily) climate data referred to in **Chapter 11.2** is archived at the ARC.

12.3 ARCHIVING OF WEATHER AND CLIMATE FORECASTS (FA Engelbrecht, MA Tadross)

12.3.1 From the CSIR Stable

As alluded to already in **Chapter 4**, all the C-CAM forecast products, as well as those produced by the multi-model ensemble seasonal forecasting system, are available on request to participants in the project. Routines were developed to convert the NetCDF format of the C-CAM data to ASCII format, as required by most end users. A range of C-CAM forecast products may also be viewed on the SA Risk and Vulnerability Atlas website at http://rava.qsens.net/themes/climate_template/ where it can be used operationally by various groups. Alternatively, all the model data (for the various scales and for a wide range of parameters) can be retrieved from the ftp site at ftp://ftp.csir.co.za.

12.3.2 From the CSAG Stable

FTP access has been set up to the UCT system to allow for a central facility for archiving and dissemination of forecast data. Talks with SAWS have also highlighted that the new generation of SAWS forecasts use objective combination techniques. In order for UCT to continue to contribute to the SAWS forecasts the raw data is made available for the SAWS MOS-MEPS procedure via the FTP site. It was decided to use the same FTP central repository for both general dissemination and dissemination to SAWS.

CHAPTER 13

WORKSHOPS, TECHNOLOGY TRANSFER AND CAPACITY BUILDING

TG Lumsden and RE Schulze

Summary

13.1 WORKSHOPS / TEAM MEETINGS
13.2 CONFERENCE PRESENTATIONS
13.3 SCIENTIFIC PAPERS IN REFEREED JOURNALS
13.4 CAPACITY BUILDING

13.1 WORKSHOPS / TEAM MEETINGS

During the course of the project team members initiated and / or were involved in 12 specialist workshops, as indicated below.

2006/09 Mr S. Steyn of the UFS team visited the UP team to facilitate the decoding of output data from the CCAM climate model to various formats required for use by other teams in the project.

2006/11 Dr. J.L. McGregor of CSIRO Atmospheric Research, and main developer of CCAM, visited UP. During this visit, he advised and assisted Dr. Engelbrecht regarding the implementation of the CCAM seasonal forecasting system at UP.

2006/10 Mrs G. Zuma-Netshiukhwi of the ARC and Dr P. Johnson of UCT met in Bloemfontein to discuss the questions that will be posed to end-users in the Modder / Riet and Upper-Olifants Catchments during the second round of community stakeholder workshops to be held in those catchments.

2007/05 Specialist Technical Meeting on the Incorporation of UKZN Forecast Information into ARC Forecast Bulletins for Farmers held at the University of KwaZulu-Natal)

2008/05 Dr F.A. Engelbrecht (UP) met with Dr S. Mason of the International Research Institute (IRI) during a visit of the latter to the South African Weather Service (SAWS). During the visit the research of Mr S. Steyn (UFS) on the statistical downscaling of low resolution short-range weather forecasts was discussed. Dr S. Mason kindly provided not only advice on the research methodology, but also a version of the Climate Predictability Tool capable of running on Linux Platforms. Dr S. Mason additionally provided FORTRAN routines for performing Principal Component Analysis (PCA) and Canonical Correlation Analysis (CCA).

2008/09 Mr S. Steyn (UFS) visited Dr F.A. Engelbrecht (UP). During the visit they commenced with the coding of the algorithms that will be used in the new downscaling software that is intended for the statistical downscaling of daily rainfall fields from daily global circulation model (GCM) circulation fields.

2008/06 Dr F.A. Engelbrecht visited Dr J.L. McGregor of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Marine and Atmospheric research. During the visit the CCAM short-range, extended-range and seasonal forecasting systems running at UP were reviewed. A seminar describing the use of CCAM at UP was presented by Dr F.A. Engelbrecht at the CSIRO, which included verification results of the CCAM short-range and seasonal forecasts over South Africa.

2008/09 Dr J.L. McGregor visited UP. During this visit the focus was on the improving the CCAM seasonal forecasting system over southern Africa. Dr J.L. McGregor presented papers at the 2008 SASAS conference and the CHPC funded workshop on the use of coupled modelling in seasonal forecasting. The latter was organised by the LRF-group of SAWS and hosted at UP.

2008/11 A series of meetings was held with irrigation representatives in the Berg / Breede Catchment System. The purpose of the meetings was to collect information on the sources, allocation and distribution of irrigation water, as well the irrigation systems utilized, crops grown etc. Meetings were held in the 24 Riviere, Riebeek Kasteel, Perdeberg, Noord en Suid Agter Paarl, Banhoek, Wynland Water, Vyeboom / Houtveld, Elandskloof / Kaaimansgat, Groenland and Riviersonderend irrigation districts. A meeting was also held at Ninham Shand Consulting Services in Cape Town to collect information on the bulk water resources infrastructure in the catchment system.

2010/05 Mrs G. Zuma-Netshiukhwi attended a National Agrometeological Committee (NAC) meeting in the Free State in order to share her experiences with the use of weather / climate data.

2010/06 Dr F.A. Engelbrecht visited Dr J.L. McGregor of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Marine and Atmospheric research. During the visit the CCAM short-range and seasonal forecasting systems running at CSIR were reviewed and improved.

2010/12 Dr F.A. Engelbrecht, Dr M.A. Tadross and Mr T.G. Lumsden met to discuss the status of climate forecasts in the project and their application in agrohydrological forecasting. Issues such as frequency of updating, ensemble sizes, downscaling, hindcasting and dissemination for application in agrohydrological forecasting were discussed.

13.2 CONFERENCE PRESENTATIONS

In total 16 presentations on the project were made by team members at symposia, conferences and workshops on the project. These are listed below.

2007 Ghile, Y.B. and Schulze, R.E. Development of a framework for an integrated time-varying agrohydrological forecast system for southern Africa. *Proceedings of the 13th South African National Hydrology Symposium*, NSI, Cape Town. pp 10. On CD-Rom.

2008 Brown, N. Annual meeting of the Centre for Performance of High Computing (CHPC). University of KwaZulu-Natal, Durban, RSA.

2008 Johnston, P. *Continued challenges facing the use of seasonal forecasts for agriculture and water resources* South African Society for Atmospheric Sciences (SASAS), Pretoria, RSA.

2008 McGregor, J.L. Regional Modelling Developments at CSIRO. *24th Annual Conference of the South African Society for Atmospheric Sciences* (SASAS), University of Pretoria, Pretoria, RSA.

2008 McGregor, J.L. Coupled modelling at the CAWCR. CGCM Workshop, University of Pretoria, Pretoria, RSA.

2009 Engelbrecht, F.A. Seamless weather forecasting over southern Africa. ARC Response Farming Workshop, Pretoria, RSA.

2009 Johnston, P. Climate vulnerability and modelling progress in downscaling with a focus on agriculture in southern Africa. Advanced International Training Programme sponsored by SMHI, Walvis Bay, Namibia.

2009 Johnston, P. Farmers' forums hosted by SANLAM, NEDBANK, Price Water House Coopers.

2009 Landman, S., Engelbrecht, F.A. and Engelbrecht, C.J. Development of a short-range ensemble weather forecasting system over South Africa. Colloquium. South African Weather Service, Pretoria, RSA.

2009 Landman, S., Engelbrecht, F.A. and Engelbrecht, C.J. Development of a short-range ensemble weather forecasting system over South Africa. SRNWP Workshop, Exeter, UK.

2009 Lumsden, T.G. and Schulze, R.E. Seasonal hydrological forecasting in the Berg Water Management Area of South Africa. 12th International River Symposium, Brisbane, Australia.

2009 Nape, K.M., Steyn, A.S. and Walker, S. The Proposed use of seasonal forecasts to improve maize production in the Free State. 11th SAGA Biennial Technical Meeting and Exhibition, Royal Swazi Spa, Swaziland.

2009 Steyn, A.S., Walker, S. and Engelbrecht, F.A. Downscaling of climate change projections to daily rainfall over the Upper Olifants River Catchment. South African Society of Atmospheric Sciences (SASAS) Conference, Tulbach, RSA.

2009 Steyn, A.S., Walker S. and Engelbrecht, F.A. Afskaling van globale sirkulasie Model voorspellings na daaglikse reënval oor die Bo-Olifantsrivier Opvanggebied. Studentesimposium van die Suid-Afrikaanse Akademie vir Wetenskap en Kuns, Bloemfontein, RSA.

2010 Landman, S., Engelbrecht, F.A., Engelbrecht, C.J., Landman, W.A. and Dyson, L. A short-range multi-model ensemble weather prediction system for South Africa. South African Society for Atmospheric Sciences (SASAS) Conference, Gariep Dam, RSA.

2010 Phahlane, O. 2010. Evaluation of Weather Forecast Information Dissemination at Three Selected Towns in Mpumalanga Province. South African Society for Atmospheric Sciences (SASAS) Conference, Gariep Dam, RSA.

13.3 SCIENTIFIC PAPERS IN REFEREED JOURNALS

At the time of completing this report five papers on the project had been published in refereed scientific journals, one further paper was in preparation and several more are anticipated.

2008 Ghile, Y.B. and Schulze, R.E. Development of a framework for an integrated time-varying agrohydrological forecast system for Southern Africa: Initial results for seasonal forecasts. *Water SA* 34, 315-322.

2009 Ghile, Y.B. and Schulze, R.E. Use of an Ensemble Re-ordering Method for disaggregation of seasonal categorical rainfall forecasts into conditioned ensembles of daily rainfall for hydrological forecasting. *Journal of Hydrology*, 371, 85-97.

2010 Ghile, Y.B. and Schulze, R.E. Evaluation of three Numerical Prediction Models for short and medium range agrohydrological applications. *Water Resources Management*, 24, 1005-1028.

2010 Ghile, Y., Schulze, R.E. and Brown, C. Evaluating the performance of ground-based and remotely sensed near real-time rainfall fields from a hydrological perspective. *Hydrological Sciences Journal*, 55, 497-511.

2011 Engelbrecht, F.A., Landman W.A., Engelbrecht C.J., Landman S., Roux B., Bopape M.M., McGregor J.L. and Thatcher M. Multi-scale climate modelling over southern Africa using a variable-resolution global model. *Water SA,* 37, 647-658.

2012 Landman S, Engelbrecht F.A., Dyson L.D. and Engelbrecht C.J. (2012). A multi-model ensemble system for short-range weather prediction in South Africa. *Water SA. In preparation*.

13.4 CAPACITY BUILDING

Listed below are those post-graduate students who contributed directly and significantly to the success of this project. Numerous others, not listed below, made partial contributions to, or were beneficiaries of, the products of this research.

Degree	Name	Citizenship	Institution	Race / Gender	Status
PhD	Gobaniyi, Bode.	Nigeria	UCT	M / B	Completed
PhD	Browne, Nana	Ghana	UCT	F / B	
PhD	Ghile, Yonas	Eritrea	UKZN	M / B	Completed
PhD	Hachigonta, Sepo	Zambia	UCT	M / B	Completed
PhD	Lumsden, Trevor	South Africa	UKZN	M / W	
PhD	Zuma-Netshiukhwi, Gugu	South Africa	UFS	F / B	
PhD	McIntosh, Hayley	South Africa	UCT	F / W	
MSc	Landman, Stephanie	South Africa	UP	F / W	Completed
MSc	Nape, Moses	South Africa	UFS	M / B	Completed
MSc	Phahlane, Obed	South Africa	UFS	M / B	Completed
MSc	Le Roux, Noelien	South Africa	UP	F / W	Completed
MSc	Steyn, Stephan	South Africa	UFS	M / W	Completed
Honours	Kloppers, Pierre	South Africa	UCT	M / W	Completed
Honours	Nel, Jackie	South Africa	UP	F / W	Completed
Honours	Van der Merwe, Cobus	South Africa	UP	M / W	Completed

In summary, emanating directly from this project were 3 completed PhDs, all by African students from outside of South Africa, 5 Masters degrees and 3 Honours degrees, while 4 PhDs are in various stages of completion, 3 of which are by South Africans.

The titles of the completed PhDs are:

- Gbobaniyi, B. “Tranferability of Regional Climate Models over different climatic domains”. University of Cape Town.
- Ghile, Y.B. “Development of a framework for an integrated time-varying agrohydrological forecast system for southern Africa”. University of KwaZulu-Natal.

- Hachigonta, S. “Assessing maize water requirements in the context of climate change uncertainties over southern Africa”. University of Cape Town.

The titles of the completed MSc degrees are:

- Nape, K.M. “Using Seasonal Rainfall with APSIM to Improve Maize Production in the Modder River Catchment”. University of the Free State
- Phahlane, M.O. “A Three Month Stream Flow Forecast For Water Management in the Upper Olifants Catchment”. University of the Free State.
- Steyn, A.S. “Downscaling of Global Circulation Model Predictions to Daily Rainfall over the Upper Olifants River Catchment”. University of the Free State.
- Landman, S. “A Multi-Model Ensemble System for Short-Range Weather Prediction in South Africa”. University of Pretoria.
- Le Roux, N. “Seasonal Maize Yield Simulations for South Africa Using a Multi-Model Ensemble System”. University of Pretoria.

CHAPTER 14

SUMMARY, RECOMMENDATIONS AND CONCLUSIONS

RE Schulze and TG Lumsden

14.1 RECAPTURING THE RATIONALE AND OBJECTIVES OF THE PROJECT
14.2 ACHIEVING THE OBJECTIVES
14.3 SUMMARY OF MAIN FINDINGS
14.4 RECOMMENDATIONS FOR FUTURE RELATED RESEARCH AND DISSEMINATION OF FORECASTS
14.5 A FINAL PERSPECTIVE

14.1 RECAPTURING THE RATIONALE AND OBJECTIVES OF THE PROJECT

14.1.1 Rationale Behind the Project

The rationale of the project was the following:

- The South African climate is highly variable over short and longer periods.
- This day-by-day as well as intra- and inter-seasonal variability was likely to be amplified by the global changes in climate, along with changes in other baselines such as those of population or land use.
- Agricultural production and water management are intrinsically linked to climate variability, and many decisions are made based on weather and climate information ("now-casts", as well as short, medium and longer term forecasts), especially on assumptions regarding weather and climate in the near future.
- Farmers need such information to help them plan for operations such as planting, irrigating and harvesting of their crops.
- Weather and climate forecasting can aid users to make more informed decisions and assist in planning activities.
- Forecasts have the potential to reduce risk in the long term and improve water use efficiency, and are becoming more skilful as research efforts continue.
- However, gaps exist between the products of weather and climate forecasting, both in the links to resulting agrohydrological responses, and in the application of forecasting information to agricultural decision-making.

14.1.2 Overall and More Specific Objective

From the above, the overall objective of this project was to develop and test techniques and models for translating weather and climate forecasts in South Africa into applications for decision support at a range of spatial scales in both rainfed and irrigated agricultural production and water management, in order to reduce risks associated with vagaries of day-to-day to seasonal climate variability.

The development of a series of early warning systems was envisaged which would provide:

- different lead times and
- "translations" (including spatial and temporal downscaling) of weather and climate forecasts to intermediate parameters (such as daily precipitation amounts), and to more explicit agrohydrological outcomes including, for example, soil moisture status, growth potential, crop yield estimates and streamflows (to meet irrigation demands), as well as plant dates and fertilizer levels
- at catchment specific scales for selected critical catchments, which were to be studied in detail.

More specific objectives of the project, identified in the Project Contract, included

- engagement with stakeholders in regard to forecast needs and other issues,
- selection and configuration of the catchments for detailed study,

- updating of weather / climate data,
- acquisition, downscaling, and archiving of weather/climate forecasts,
- translation of weather / climate forecasts into agrohydrological forecasts through use of agrohydrological models,
- evaluation of downscaled weather / climate forecasts and resulting agrohydrological forecasts, including uncertainty, sensitivity and benefit/cost analyses, and
- interpretation of forecast information, with emphasis on dissemination of information in a targeted manner to stakeholders and incorporation of stakeholder feedback.

14.2 ACHIEVING THE OBJECTIVES

The contents of **Chapters 1** to **13** provides an indication of the degree to which the objectives of the project were met, some entirely and others possibly requiring follow-up research at a later stage. The project outcomes in regard to the Terms of Reference are summarised in the table below which gives chapter sections from the final report cross-referenced to the Terms of Reference.

Terms of Reference	Description of Terms of Reference / Specific Objectives	Reference to Chapter Sections in Report
1	Motivate for, and select, critical catchments for more detailed applications / stakeholder involvement	Ch 5.1, 5.2, 5.3, 5.4
2	Identify end user groupings and interact with target end users re. their forecasting needs	Ch 2.1, 2.2, 2.3, 2.4, 2.5, 2.6; Ch 3.2
3	Obtain endorsement and support from relevant end user groups	Ch 5.1, 5.2, 5.3, 5.4, 5.5
4	Inventorise / update relevant available data	Ch 11.1, 11.2, 11.3, 11.4; Ch 12.1, 12.2, 12.3
5	Update historical databases for verification	Ch 11.1, 11.2, 11.3, 11.4
6	Archive weather / climate forecasts	Ch 12.3
7	Enhance weather / climate forecasts and downscaling techniques	Ch.1; Ch 4.1, 4.2, 4.3, 4.4, 4.5; Ch 7.3, 7.4,
8	Derive daily weather inputs for different lead times for agrohydrological models	Ch 4.3, 4.4; Ch 7.1, 7.2, 7.3, 7.4; Ch 8.1, 8.2, 8.3
9	Verification of downscaling techniques and resulting forecasts, incl. uncertainty analyses	Ch 3.1; Ch 4.3, 4.4, 4.5 Ch 6.7
10	Interpret / present forecast information for users	Ch 6.1, 6.2, 6.3, 6.4, 6.5, 6.6, 6.7; Ch 9.1, 9.2, 9.3; Ch10.4
11	Link with existing dissemination initiatives	Ch 6.1, 6.2, 6.3, 6.4, 6.5, 6.6; Ch 10.4
12	Undertake benefit / cost analyses of integrated forecast systems	Ch 10.1, 10.2, 10.3, 10.4
13	Publications; capacity building	Ch 13

14.3 SUMMARY OF MAIN FINDINGS

CHAPTER 1 SETTING THE SCENE (TG Lumsden and RE Schulze)

Chapter 1 sets the scene of the project in providing information on the rationale, the objectives and scale of operation, as well as placing the project within a broader context of climate related and risk management studies in regard to timing, location, and magnitudes of climate related events in order to enhance operational reliability in the many decisions which need to be made by using either shorter or longer lead times of the forecasts, and where each decision has potential economic benefits.

CHAPTER 2 FORECASTING AS A STAKEHOLDER STRATEGY FOR VULNERABILITY MODIFICATION IN THE MANAGEMENT OF AGRICULTURAL SYSTEMS (RE Schulze, TG Lumsden and YB Ghile)

Chapter 2 addresses forecasting as a stakeholder strategy for vulnerability modification in the management of agricultural systems by first classifying types of forecasting, distinguishing clearly between weather vs. climate forecasts, then evaluating agrohydrological forecasts with respect to types (near real time vs short and medium term vs seasonal agrohydrological forecasts) and their potential applications, and thereafter providing a summary of potential forecast applications, of information requirements of farmer stakeholders and how forecasts can be disseminated

The table below summarises the vast array of potential applications, identified in various workshops held under the auspices of this project, of forecasts at different lead times for the agricultural and related water resources sectors.

Lead Time	Agriculture	Water Resources
Near Real Time (re-active decisions)	***Agronomic*** • Planting/ploughing/other land operations • Pest/disease control operations • Haymaking decisions • In-field machinery operations/trafficability • Fruit picking ***Livestock*** • Stock management and movement • Chicken farming: heating, cooling • Game capture • Sheep shearing ***Logistics/Financial*** • Energy management (e.g. irrigation) ***Natural Hazards*** • Fire suppression (SAWS/DWA, timber industry, sugar industry, fire protection agencies, farmer unions, Eskom) • Controlled burning • Pump equipment and machinery removal •	***Disaster Management*** • Evacuation (e.g. pumps, stock) • Evacuation procedures • Safety releases from reservoirs ***Streams and Dams*** • Reservoir inflows ***Irrigation*** • In-field decisions
1-6 Days (pro-active decisions)	***Agronomic*** • Aquaculture • Planting / harvesting decisions (incl. equipment maintenance) ***Livestock*** ***Logistics/Financial*** • Marketing of products (crop, wool etc.) • Energy management • Irrigation – equipment, fertigation, and labour planning	***Disaster Management*** • Preparation for flood events • Storm surge analysis • Reservoir safety releases ***Streams and Dams*** • Streamflow forecasts • Reservoir inflow forecasts • IFR releases (freshettes) ***Irrigation*** • Irrigation water orders • Irrigation scheduling

	Natural Hazards • Controlled firebreak burning • Frost probability	
7-14 Days	***Agronomic*** • Land preparation: Timing of • Crop type selection e.g. maize vs sorghum • Selection of substitute crops • Fertilizer applications • Pest/disease control operations ***Livestock*** De-stocking ***Logistics/Financial*** • Financial planning (contracts) • Futures trading ***Natural Hazards***	***Disaster Management*** • Water poverty relief planning ***Streams and Dams*** • Streamflows forecasts • Reservoir inflow forecasts • Reservoir management decisions • IFR low flow releases ***Irrigation*** • Irrigation water allocations • Irrigation scheduling decisions
1 month	***Agronomic*** • Sugarcane haulage: Truck orders • Tillage/ planting decisions • Planning of other infield operations ***Livestock*** ***Logistics/Financial*** • Crop yield estimates • Feedback on previous month's crop estimate • Fertilizer orders • Labour/equipment planning ***Natural Hazards*** Early warning: Rainfall/temperature forecasts	***Disaster Management*** • Water poverty relief planning ***Streams and Dams*** • Streamflow forecasts • Reservoir inflow forecasts • Reservoir management decisions • IFR low flow releases ***Irrigation*** • Irrigation water allocations • Planning of irrigation timing
3 months	***Agronomic*** • Crop type and plant date decisions ***Livestock*** ***Logistics/Financial*** (Strategic decisions) • Planting/ harvesting equipment orders • Fertilizer orders • Transport scheduling • Mill opening/closing decisions • Crop variety selection • Crop yield estimates • Crop storage planning (grain/ sugar) • Conservation structure maintenance ***Natural Hazards***	***Disaster Management*** ***Streams and Dams*** • Streamflows forecasts • Reservoir inflow forecasts • Reservoir management - status review - curtailment planning ***Irrigation***

In various workshops the following points emanated from stakeholders regarding the dissemination of forecasts:

- for forecasts disseminated electronically, the majority of users prefer email as the medium of dissemination, rather than the internet (which may be slow in remote areas),
- for resource poor farmers, the following channels would be suitable for dissemination of forecasts, *viz*. cellphones and radio (very important), extension services, word of mouth, written word, Agri TV, the local chief (through meetings with the community),
- indigenous knowledge is still applied in decision-making by some users,
- forecasts should be made available in local languages,
- interpretation must be included with forecasts,
- care should be taken to avoid "interpretations of interpretations" during the dissemination process (this leads to misinterpretation),
- information should be tailored, in that it is understandable and relevant to the user,
- the education level of users is an important consideration, and it needs to be ensured that forecasts are understood by the user since, an example being the concept of probability which is often not understood by users,
- training of people involved in the forecast dissemination chain is required,
- forecasts should not be prescriptive, but should rather provide users with relevant information to enable them to make their own decisions,
- forecasts need to be "in your face" and repeated a number of times in order to raise the awareness of users, and
- the products of the research should be promoted through carefully selected forums to ensure uptake.

CHAPTER 3 CHALLENGES AND APPROACHES TO MAXIMISE BENEFITS FROM AGRO-CLIMATIC FORECASTS (YB Ghile and RE Schulze)

Chapter 3 on challenges and approaches to maximise benefits from agro-climatic forecasts, elaborates in some respects on information contained in **Chapter 2** and forms the backdrop of several later chapters. It was found that the benefits which might accrue do not only depend on the scientific advances of agro-climatic forecasts, but also on an effective way of dissemination as well as on appropriate education of forecast presenters and decision makers (cf, **Chapter 2**). Apart from forecast quality considerations, the format and speed of dissemination of forecasts, as well as the willingness and ability of decision makers to make a change, are critical elements in the usefulness of forecasts. Nonetheless, the production of skilful and timely forecasts continues to be one of the major issues challenging to meteorologists. Owing to the inherent uncertainties in the weather and model limitations to account for the local rain-bearing features, weather and climate forecasts are not as accurate as desired. The accuracy of such forecasts will be further degraded during the rainfall-soil-plant transformation by agricultural models. The reason for this is that complex and non-linear processes are not always explicitly represented by many of the agrohydrological models used.

A brief review is presented in **Chapter 3** of some of the elements that contribute towards forecast uncertainties and techniques developed to minimise forecast errors, followed by the description of some commonly used verification techniques for assessing forecast quality. The chapter further describes the potential application of forecast updating by the combined use of conceptual physically based models in simulation mode plus stochastic models in the updating mode, in order to eliminate, or minimise, errors resulting from inadequacies in the hydrological model or the incorrect estimation of rainfall forecast by weather prediction models. Finally, the challenges and approaches in communication process and use of agro-climatic forecasts to modify decisions are described briefly.

CHAPTER 4 DEVELOPMENT, DOWNSCALING AND VERIFICATION OF WEATHER AND CLIMATE FORECASTS (RE Schulze, MA Tadross, AS Steyn, FA Engelbrecht, CJ Engelbrecht, WA Landman, S Landman, N Brown, B Gobaniyi, D Stone, E Marx and GGS Pegram)

The development, downscaling and verification of weather and climate forecasts is covered in **Chapter 4**. The chapter commences with an audit illustrating that there is no lack of climate forecasts available for South Africa. It is important to note that the availability of forecasting products changed rapidly during the course of the project, and may be expected to continue changing over the coming years. Such changes result from losses from the small pool of experienced climate modellers to either emigration or to a high inter-institutional turnover within South Africa, the coming and going of postgraduate and post-doctoral students at tertiary institutions, and continuing advances in supercomputing capabilities in the country (resulting in forecasts of increasingly fine spatial resolution). The consequence of the above to this project was that what was available in the form of forecasts of different lead times at the beginning of the project was not what was available at the end of the project, making the operationalising and tailoring of products to specific sectors a difficult task. This chapter focuses on the forecasting products available at the CSIR and CSAG during the final two years of the project. However, it also refers to some of the forecasting products available when the project commenced in 2006.

Chapter 4 goes on to providing an overview of downscaling techniques before describing the short range weather and seasonal forecasts from the CSIR and the University of Pretoria using the C-CAM forecasting system (including hindcasts, forecast verifications and decoding and dissemination of C-CAM data). This is followed by an outline of the seasonal climate forecasts available from the Climate Systems Analysis Group (CSAG) at UCT (including sections on the GCMs selected, implementing the SOMD statistical downscaling procedure, testing the skill of downscaled forecasts, sensitivity to horizontal resolution, forecast model verification and the development of a seasonal attribution forecast. The chapter concludes with an outline of ongoing developments on seasonal temperature forecasts from the SAWS in collaboration with the UKZN, in which a technique based on conditional merging is extended to condition coarse resolution temperature forecast fields (~ 100 km by 100 km) with detailed (i.e. ~ 1.7 by 1.7 km) mapping of temperature information.

CHAPTER 5 BACKGROUNG INFORMATION ON CASE STUDY CATCHMENTS (RE Schulze, G Zuma-Netshiukhwi, O Phahlane, DB Louw, TG Lumsden and YB Ghile)

With specific developments and applications of forecasts being tested in selected catchments, catchments in different parts of South Africa experiencing different climatic regimes and with different agricultural practices were selected. **Chapter 5** provides some background on the Modder / Riet catchment in the semi-arid parts of the Free State, the Upper Olifants in a temperate zone of Mpumalanga, the Berg / Breede in the winter rainfall region of the Western Cape and the sub-humid Mgeni catchment in KwaZulu-Natal. The descriptions cover physical as well as socio-economic background relevant to the application of forecasts.

CHAPTER 6 CASE STUDY APPLICATIONS OF WEATHER AND CLIMATE FORECASTS (G Zuma-Netshiukhwi, S Walker, O Crespo, TG Lumsden, YB Ghile and RE Schulze)

In **Chapter 6** seven case study applications of weather and climate forecasts are presented. The first is a study on the development of a tailor-made advisory for end users in the Modder / Riet catchment followed by a similar, but more detailed study of a tailor-made advisory for an individual farm, also in the Modder / Riet catchment. The third case study is on scenario development in the Modder / Riet catchment using crop growth models, followed by a study using downscaled forecasts with crop models to identify beneficial management decisions in the Berg catchment. The fifth study considers applications of scientific rainfall forecasts and indigenous knowledge in the Modder / Riet catchment, while the sixth case study is focused on applications of runoff, soil moisture and irrigation demand forecasts in the Berg / Breede catchment. The final study evaluates short and medium range rainfall forecast models in the Mgeni catchment from a hydrological perspective.

It should be noted that this is a “mixed bag’ of case studies. They are

- independent (but edited) contributions,
- some short others longer,
- some completed in the early phases of the project others at a later stage,
- some highly scientific others of a more anecdotal type
- some relating to crop yields others relating to water yield, but
- mostly taken from work undertaken by project members who have either completed or are still working towards higher degrees (MSc, PhD) under the auspices of this project.

CHAPTER 7 THE INITIAL RESEARCH BASED FRAMEWORK FOR AN AGROHYDROLOGICAL FORECASTING SYSTEM FOR SOUTH AFRICA (YB Ghile and RE Schulze)

One of the objectives of this project was to work towards developing a framework for agrohydrological forecasting for South Africa. This was achieved in two phases, the first being in the early stages of the project with emphasis on a *research* based framework for an agrohydrological forecasting system for South Africa (**Chapter 7**) with the second, building upon the first, moving towards an *operational* agrohydrological forecast framework (**Chapter 8**).

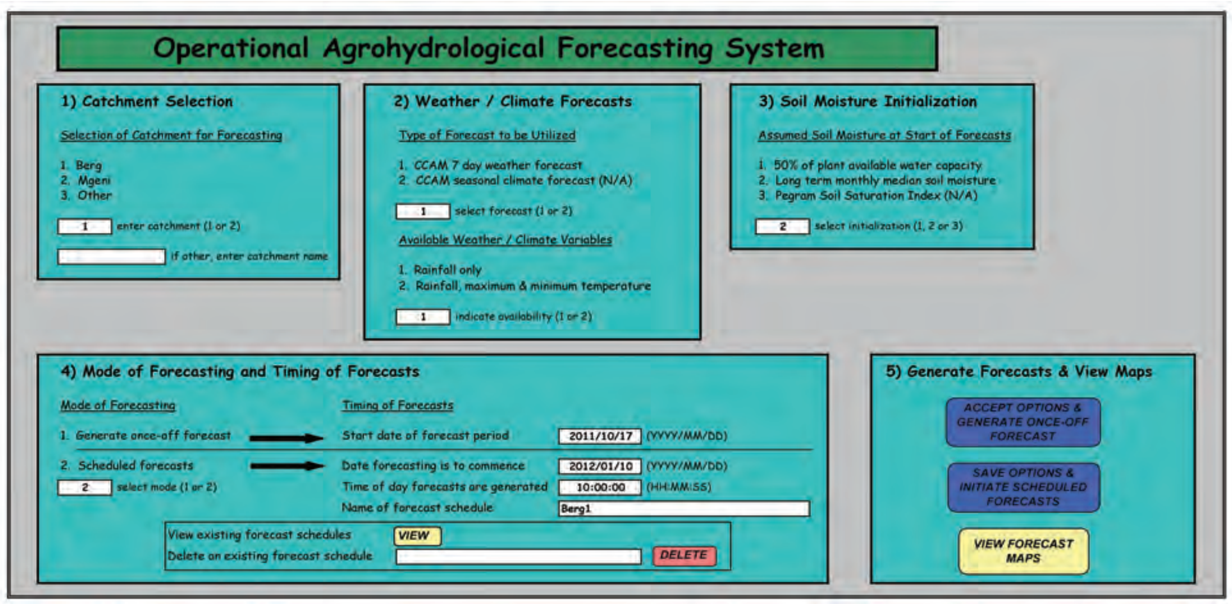
In regard to the research based forecasting framework described in **Chapter 7**, a GIS based framework was developed to serve as an aid to process all the computations required in the translation of the daily to seasonal climate forecasts into daily quantitative values suitable as input in crop or hydrological models. The framework was designed to include generic windows which allow users to process the near real time rainfall fields estimated by remotely sensed tools, as well as forecasts of weather / climate models into suitable scales and formats that are needed by many daily time step agrohydrological models. The key features of this initial framework are that it:

- facilitates the selection of near real time remotely sensed observations, as well as short term, medium term and longer term forecasts supplied by various weather and climate models from different institutions across a range of time scales;
- links to comprehensive GIS functionality that provides tools for spatial disaggregation, data structure and reformatting, as well as for post-processing of data / information through tabulation, mapping and report generation;
- translates categorical seasonal forecasts into a daily time series of values suitable for agrohydrological models through generic algorithms developed within the framework;
- converts ensembles of rainfall forecasts into suitable formats which are understood by GIS;
- downscales grid layers to Quaternary Catchments; and, finally,
- extracts rainfall data to *ACRU* model formatted text input files.

Such an application of near real, plus daily to seasonal rainfall forecasts as a nested input to one or more agrohydrological models, thereby enabling the forecasting of agrohydrological variables across a range of time scales and lead times, is a new concept in southern African context. What is presented in **Chapter 7** nevertheless remains a research tool which, with further development and refinement is considered to have the potential to play an important role in bridging the gaps that exist between outputs of weather and climate models and their practical application in agrohydrological models. The development of the research framework was viewed as a work in progress which was taken a step further from the highly versatile and highly specialised system that it was (but able to run on one computing system only, and only up until 2007 with the GIS software supported at that time), towards a more operational system in **Chapter 8**.

CHAPTER 8 TOWARDS AN OPERATIONAL AGROHYDROLOGICAL FORECAST FRAMEWORK (TG Lumsden)

The development of the more operational agrohydrological forecast framework in **Chapter 8**, of which the user interface is shown diagrammatically below, presents a much more practical approach in taking the user through steps which include generating a forecast for the first time, the various options in generating the forecast such as catchment selection, the weather / climate forecast selection, soil moisture initialisation options, the mode of forecasting and timing of forecasts, the actual forecast generation and viewing of output, steps in the forecast generation process and an overview of the software design. Examples of 7 day agrohydrological forecasts are given in the chapter.



Since the framework at this point in time represents a semi-operational system that requires further future development in a number of areas, some of these are presented, including links to a near real time system, automation of downloading the forecasts, use of near real time satellite derived soil moisture content to initialize the model, "hotstarting" of the agrohydrological model to enable the carry-over of store values from one forecast to the next, as well as the need to identify a partner to generate agrohydrological forecasts on an operational basis beyond the lifetime of the project, and the need for the development of an online portal through which the forecasts can be disseminated.

CHAPTER 9 STAKEHOLDER INTERACTIONS (G Zuma-Netshiukwi, O Phahlane, MA Tadross and P Johnston)

Practical experiences by project team members in regard to stakeholder interactions are discussed in **Chapter 9**. The ARC's experiences in the Modder / Riet catchment are the first focus, including project initiatives and presenting the "bigger picture" of climate forecasts and agricultural disaster risk management in the Free State province. Similarly, the ARC's experiences in the Upper Olifants catchment are evaluated, also from a perspective of tailor-made advisories for end users. A third set of experiences is that of the UCT group when engaging farmers and disseminating forecasts, and in this instance the farmers' problems with probabilistic seasonal forecasts is highlighted.

CHAPTER 10 BENEFIT ANALYSES OF AGROHYDROLOGICAL FORECASTING (G Zuma-Netshiukhwi, O Phahlane, KM Nape and AS Steyn)

Having utilised climate forecasts for the agricultural sector and developed an agrohydrological climate driven forecast system, a series of benefit analyses of such forecasts is presented in **Chapter 10**. From an ARC perspective the first section deals with the question as to which institutions, organisations and companies are involved in forecasting and decision-making in the Modder / Riet and Upper Olifants catchments – and the list is long. Evaluations on qualitative forecast benefits from farmer interactions in both the Modder / Riet and the Upper Olifants catchments follow. The major focus of the chapter is, however, an economic benefit analysis of maize management decisions using seasonal rainfall scenarios in which a verification study of maize yield estimates from the APSIM model is followed first by an analysis of simulated maize yields and more importantly then by a comparative economic benefit analysis of different management decisions. Here costs and benefits of different planting dates, planting densities, weeding frequencies and fertilizer application rates are assessed under various seasonal rainfall conditions. From the benefit : cost analysis, practices are recommended for rainfed maize production in the Modder / Riet catchment for a range of seasonal rainfall forecasts.

CHAPTER 11 UPDATING AND QUALITY CONTROL OF CLIMATE DATABASES FOR APPLICATION IN FORECASTING AND VERIFICATION (CJ Engelbrecht and RP Kunz)

Operational forecasting systems require continually updated daily climate data as input to their applied irrigation, soil moisture and crop yield models, especially of daily rainfall, maximum and minimum temperatures and their derivatives. The unavailability of these in South Africa formed the challenge addressed in **Chapter 11** on updating and quality control of climate databases for application in forecasting and verification. Two major initiatives were undertaken as part of this project. The first was updating and quality control of the ARC climate database, which included with a discussion on quality control procedures employed on the climate station data. The second was an updating and quality control of the SAWS rainfall database by the UKZN, in which processes of elimination of stations with poor quality, the disaggregation of accumulated totals into daily sequences and the infilling procedures for missing daily data were under scrutiny.

The lack of a national facility to update climate data and perform quality control and infilling of missing data was, once again, highlighted by these two case studies. Good quality and complete climate datasets are required in many contexts. The two case studies presented here are not the only initiatives in South Africa by research groups to embark on updating and quality controlling daily climate data. It is important to avoid duplication of effort in managing data quality, since it is a time consuming task that requires specialist skills. A single source of quality controlled and infilled data also promotes consistency in datasets.

A recommendation from this project is, therefore, that sustained and adequate funding (possibly from multiple sources) be made available for one institution in South Africa to be made responsible for the collation (from different sources) and uniform quality control of climate data, and that these data then be made freely available to all *bona fide* researchers. This would save not only the many WRC projects from major duplication of effort in updating climate related databases, but would also ensure that the same datasets be used across the many disciplines in South Africa that utilise climate data.

CHAPTER 12 ARCHIVING OF INFORMATION AND FORECASTS (RE Schulze, MJC Horan, RP Kunz, CJ Engelbrecht, FA Engelbrecht and MA Tadross)

A data and information intensive project such as this one was requires systematic archiving of information and forecasts. In **Chapter 12** the archiving of non-climatic information (e.g. the Quinary Catchments Database, the land cover and land use database as well as the soils database) is outlined, as is the archiving of historical climate information and then the archiving of original and translated forecasts from both the CSIR and the CSAG stables of weather / climate forecasts.

CHAPTER 13 WORKSHOPS, TECHNOLOGY TRANSFER AND CAPACITY BUILDING (TG Lumsden and RE Schulze)

Outreach and capacity building are important components of a project such as this one, and details of these are given in **Chapter 13**. This multi-faceted and multi-institutional project did itself proud in this regard. During the course of the project its team members initiated and / or were involved in 12 specialist workshops, in total 16 presentations on the project were made nationally and internationally by team members at symposia, conferences and workshops and at the time of completing this report five papers on the project had been published in refereed scientific journals, one further paper was in preparation and several more are anticipated. Emanating directly from this project were 3 completed PhDs, 5 Masters degrees and 3 Honours degrees, while 4 PhDs are in various stages of completion.

14.4 RECOMMENDATIONS FOR FUTURE RELATED RESEARCH AND DISSEMINATION OF FORECASTS

This multi-institutional and multiple level project highlighted that for weather and climate forecasts to be successful in agricultural decision making, six basic ingredients are necessary, *viz*.

- the forecasts have to be *accurate* at a local scale,
- the forecasts have to be *timely*,
- the forecasts have to be *understood* by all the various sectors making up the farming community,
- the *economic benefits* of applying forecasts need to be clearly demonstrated (not to forget the long term environmental spin-offs),
- the forecast systems have to be *operational* for the various sectors in agriculture for a range of lead times from days through weeks to a season ahead, and
- the *archiving* of forecasts and other research products is crucial.

On the Accuracy of Forecasts

- In order for climate forecasts to gain more acceptance among farmers (and others), continued basic research is required into minimising forecast uncertainties / forecast errors and enhancing the spatial resolution at which forecasts are presented. Such research goes beyond that which can be achieved only at the country level within South Africa and has to be undertaken by South African researchers in collaboration with international institutions which develop forecasts.
- Forecasts need to go beyond only those of rainfall, which was the focus of this project. Accurate and detailed temperature forecasts, for example, have many applications in agriculture. The developments on medium range temperature forecasts from the SAWS in collaboration with the UKZN, based on a technique of conditional merging of coarse resolution temperature forecast fields (~ 100 km by 100 km) with detailed (i.e. ~ 1.7 by 1.7 km) mapping of temperature information therefore needs to continue, become formalized as a project (as against being a sideline hobby) and needs to be extended to shorter range temperature forecasts as well.

On the Timeliness of Forecasts

- Operational forecasting systems require continually updated daily climate data as input to their applied irrigation, soil moisture and crop yield models, especially of daily rainfall, maximum and minimum temperatures and their derivatives.
- The lack of a national facility to provide up-to-date climate data (i.e. yesterday's data today in order to initialise agrohydrological forecasting systems) and perform adequate quality control and infilling of missing data was highlighted by this project. Good quality and complete climate datasets are required in many contexts. The two case studies presented in **Chapter 11** are not

the only initiatives in South Africa by research groups to embark on updating and quality controlling daily climate data. It is important to avoid duplication of effort in managing data quality, since it is a time consuming task that requires specialist skills. A single source of quality controlled and infilled data also promotes consistency in datasets.

- A recommendation from this project is, therefore, that sustained and adequate funding (possibly from multiple sources) be made available for one institution in South Africa to be made responsible for the collation (from different sources) and uniform quality control of climate data, and that these data be up-to-date and then be made freely available to all *bona fide* researchers. This would save not only the many WRC projects from major duplication of effort in updating climate related databases, but would also ensure that the same datasets be used across the many disciplines in South Africa that utilise climate data.

On the Understanding and Interpretation of Forecasts

- Since the benefits from agro-climatic forecasting which might accrue do not depend only on the scientific advances of the forecasts *per se*, further research into effective ways of disseminating and communicating the tailored forecasts, as well as on appropriate education of forecast presenters and decision makers, is required. This is the case not only for subsistence / emerging farmers, but for the commercial agricultural sector as well, as was highlighted in Chapter 9 relating to farmers' problems in understanding the nature of probabilistic seasonal forecasts.

On the Economic Benefits of Forecasting

- An important focus of this project was on economic benefit analyses of management decisions (in this case for dryland maize) using seasonal rainfall scenarios, where costs and benefits of different planting dates, planting densities, weeding frequencies and fertilizer application rates were assessed under various seasonal rainfall conditions. Such benefit analyses need to be undertaken in South Africa for crops other than maize, for regions beyond the Modder / Riet catchment, and for climate forecasts covering a range of lead times from days to weeks to months, and not only for seasonal forecasts. This is a major research undertaking, but with the potential of vast savings to the agricultural sector.

On the Operationalisation of Forecasts

- In this project a research version of a forecasting framework was demonstrated, illustrating the potential in bridging the gaps that exist between outputs of weather and climate models and their practical application through agrohydrological models. This research framework was viewed as a work in progress which was then taken a step further from the highly versatile but equally highly specialised system that it was in being able to run on one computing system only, towards a more operational system in **Chapter 8**.
- The framework at this point in time, however, represents only a semi-operational system that requires considerable further future development in a number of areas, including
  - automation of downloading the forecasts,
  - use of near real time satellite derived soil moisture content to initialise the model,
  - "hotstarting" of the agrohydrological model to enable the carry-over of store values from one forecast to the next,
  - "nesting" of short lead time forecasts (days) within longer lead time forecasts (weeks to months and up to a season ahead) or even decadal projections, and
  - tailoring the forecasts to a range of agricultural operations, regions and crops,

  as well as the need to identify a partner to generate agrohydrological forecasts on an operational basis beyond the lifetime of a research project, and the need for the development of an online portal through which the forecasts can be disseminated.
- Operationalising climate forecasts and tailoring products to specific sectors such as agriculture, and within agriculture to commercial vs subsistence farmers or irrigators vs dryland operators or those farming in the summer vs winter rainfall regions, requires *consistency in forecast products*. This remains a challenge needing to be addressed, as the experience during this project was that the availability of forecasting products changed rapidly during the course of this project, and is expected to continue changing over the coming years. Such changes result partially from advances in forecasting systems and being able to present forecasts at ever finer spatial resolutions.
- However, successfully operationalising such forecasts also implies *consistency in staffing* and *retention of skilled personnel*. This project was set back on numerous occasions by losses from the small pool of experienced climate modellers at the various institutions engaged in developing

forecasting tools to either emigration or to a high inter-institutional turnover within South Africa, as well as to the coming and going of postgraduate and post-doctoral students at tertiary institutions who all make a contribution, but their *output* does not always translate into a project's *outcomes*. In some way or other funding agencies (together with other institutions) need to address the issue of skill retention beyond only skill development.

On Archiving of Forecasts and Other Research Products

- At first glance from **Chapter 12** the archiving of research products and weather / climate forecasts appears to have been satisfactorily achieved. However, from this project some archiving occurred at universities (with knowledge of certain products frequently vested in an individual), other at parastatals and some in institutions of the State. For the sake of continuity in research and to overcome loss of institutional memory which is currently prevalent in many institutions, thought needs to be given to improving the archiving of not only this project's products, but that of many other WRC projects.

14.5 A FINAL PERSPECTIVE

Two final conclusions come to the fore:

- First, this has been a multi-institutional project addressing issues of climate forecasting on multiple levels from high level climate science to stakeholder interactions with subsistence farmers and to qualitative as well as quantitative economic benefit analyses. While multi- and trans-disciplinary research is welcomed and enriching, it is also difficult and often frustrating to manage from the researchers' perspectives. Thought should be given to engaging smaller teams with more focused outcomes.
- All TORs have been successfully addressed, some in more depth than others, and numerous ideas for further research have been proposed above. In order not to lose research momentum in this field and to gain value for monies invested thus far, the project team believes that one or more follow-up projects should be identified as soon as possible in order to achieve an operational forecast system tailor made for agricultural decision making to the benefit of individual farmers' livelihoods and the country's economy as a whole.

REFERENCES

Acocks, J.P.H. 1988. Veld types of South Africa. Botanical Research Institute, Pretoria, RSA. pp 146.

Ahrens, B. and Jaun, S. 2007. On evaluation of ensemble precipitation forecasts with observation based ensembles. *Advances in Geosciences*, 10,139-144.

Anctil, F., Perrin, C. and Andreassian, V. 2003. ANN output updating of lumped conceptual rainfall\runoff forecasting models. *Journal of the American Water Resources Association*, 39, 1269-1279.

AGIS, 2006. Agricultural Geo-Referenced Information System (AGIS). Available from http://www.agis.agric.za/agisweb/agis.html [Accessed 9 July 2006].

Anstee, S. 2004. Unpublished material. Application of numerical weather prediction to rapid environmental assessment. DSTO-GD-0403. DSTO Systems Sciences Laboratory, Department of Defence, Australia.

Banitz, E. 2001. Evaluation of short-term weather forecasts in South Africa. *Water SA,* 11, 489-498.

Bartman, A.G., Landman, W.A. and Rautenbach, C.J. de W. 2003. Recalibration of general circulation model output to austral summer rainfall over southern Africa. *International Journal of Climatology*, 23, 1407-1419.

Bekele, F. 1992. Unpublished material. Ethiopian use of ENSO information in its seasonal forecasts. National Meteorological Services Agency, Addis Abeba, Ethiopia.

Berggren, R., 1978. Economic benefits of climatological services. World Meteorological Organisation, Geneva, Switzerland, *WMO Technical Note*, 145, 27-39.

Bezuidenhout, C.N. 2005. Development and evaluation of model-based operational yield forecasts in the South African sugar industry. PhD Thesis, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, RSA. pp 137.

Bocchiola, D. and Rosso, R. 2006. The use of scale recursive estimation for short term quantitative precipitation forecast. *Physics and Chemistry of the Earth*, 31, 1228-1239.

Burger, G. 1996. Expanded downscaling for generating local weather scenarios. *Climate Research*, 7, 111-128.

Carbone, G.J. and Bramante, P.D. 1995. Translating monthly temperature from regional to local scale in southeastern United States. *Climate Research*, 5, 229-242.

Chiew, F.H.S., Srikanthan, R., Frost, A.J. and Payne, E.G.O. 2005. Reliability of daily and annual stochastic rainfall data generated from different data lengths and data characteristics. *In*: Zerger, A. and Argent, R.M. (Eds) *MODSIM 2005 International Congress on Modelling and Simulation*. Modelling and Simulation Society of Australia and New Zealand, December 2005, pp 1223-1229. ISBN: 0-9758400-2-9.

Chiew, F.H.S., Zhou, S.L. and McMahon, T.A. 2003. Use of seasonal streamflow forecasts in water resources management. *Journal of Hydrology*, 270, 135-144.

CICS, 2006. Canadian Climate Impacts and Scenarios FAQ: Downscaling Background. Canadian Institute for Climate Studies. Available from http://www.cics.uvic.ca/scenarios/index.cgi [Accessed 10 July 2006].

Clark M., Gangopadhyay S., Hay L., Rajagopalan B. and Wilby, R. 2004. The Schaake Shuffle: A Method for Reconstructing Space-Time Variability in Forecasted Precipitation and Temperature Fields. *Journal of Hydrometeorology*, 5, 243-262.

Collischonn, W., Haas, R., Andereolli, I. and Tucci, C.E.M. 2005. Forecasting river Uruguay flow using rainfall forecasts from a regional weather-prediction model. *Journal of Hydrology*, 305, 87-98.

DEAT, 2001. South African estuaries: Generalised land cover for the Mgeni catchment. Available from http://www.environment.gov.za [Accessed 13 August 2007].

Dempster, A.P., Laird, N.M. and Rubin, D.B. 1977. Maximum likelihood from incomplete data via the EM algorithm (with discussion). *Journal of Royal Statistics Society*, B 39, 1-38.

Deyzel, I.T.H., Pegram, G.G.S., Visser, P.J.M. and Dicks, D. 2004. Spatial Interpolation and Mapping of Rainfall (SIMAR). Volume 2: Radar and Satellite Products. *WRC Report* No. 1152/1/04. Water Research Commission, Pretoria, RSA.

Dunsmore, S.J., Schulze, R.E. and Schmidt, E.J. 1986. Antecedent soil moisture in design stormflow estimation. *ACRU* Report No. 23. Department of Agricultural Engineering, University of Natal, Pietermaritzburg, RSA.

DWAF, 1995. Department of Water Affairs and Forestry, Pretoria, RSA. Personal communication.

DWAF, 2004. Mooi-Mgeni River Transfer Scheme Phase 2: Feasibility Study Environmental Impact Assessment. *DWAF Report No. P WMA 07/V20/00/0504*, Landscape Dynamics in association with Eco-Agent and Isquare, Pretoria, RSA.

DWAF, 2007. Western Cape IWRM Action Plan: Status Quo Report Final Draft. Bellville, RSA.

Ebert, E.E. 2001. Ability of a poor man's ensemble to predict the probability and distribution of precipitation. *Monthly Weather Review*, 129, 2461-2480.

Engelbrecht, F.A. 2005. Simulations of Climate and Climate Change over Southern and Tropical Africa with the Conformal-Cubic Atmospheric Model. *In*: Schulze, R.E. (Ed) *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation*. Water Research Commission, Pretoria, RSA, WRC Report 1430/1/05. Chapter 4, 57-74.

Engelbrecht, F.A. 2007. Personal communication. Meteorological Group, University of Pretoria, Pretoria, RSA. 14 August 2007.

Engelbrecht, C.J., Engelbrecht, F.A. and Dyson, L.L. 2012. High-resolution model-projected changes in mid-tropospheric closed-lows and extreme rainfall events over southern Africa. *International Journal of Climatology.* DOI: 10/1002/joc.3420.

Engelbrecht, F.A., Landman, W.A., Engelbrecht, C.J., Landman, S., Roux, B., Bopape, M.M., McGregor, J.L. and Thatcher, M. 2011. Multi-scale climate modelling over southern Africa using a variable-resolution global model. *Water SA,* 37, 647-658.

Engelbrecht, F.A., McGregor, J.L. and Engelbrecht, C.J. 2009. Dynamics of the conformal-cubic atmospheric model projected climate-change signal over southern Africa. *International Journal of Climatology,* 29, 1013-1033. DOI: 10/1002/joc.1742. 29 1013-1033.

Fair, K.A. 1999. Unpublished material. Review of the operating rules of the Mgeni river system, *BKS Report No.* P671431, Pretoria, RSA.

Feddersen, H. and Andersen, U. 2005. A method for statistical downscaling of seasonal ensemble predictions. *Tellus* A, 57, 398-408.

Federico, S., Avolio, E., Bellecci, C. and Colacino, M. 2006. The application of LEPS technique for quantitative precipitation forecast (QPF) in southern Italy. *Advances in Geosciences*, 7, 1-8.

Franchini, M. 1996. Use of a genetic algorithm combined with a local search method for the automatic calibration of conceptual rainfall-runoff models. *Hydrological Science*, 4, 21-39.

Ganguly, A.R. and Bras, R.L. 2001. Distributed quantitative precipitation forecasting using information from radar and numerical weather prediction models. *Journal of Hydrometeorology*, 4, 1168-1180.

Ghile, Y.B. 2004. *An Adaptation of the SCS-ACRU Hydrograph Generating Technique for Application in Eritrea*. Unpublished MSc Dissertation, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, RSA.

Ghile, Y.B. 2008. Development of a Framework for an Integrated Time-Varying Agrohydrological Forecast System for Southern Africa. University of KwaZulu-Natal. Pietermaritzburg, RSA, PhD Thesis. pp 234.

Glantz, M.H. 1996. Forecasting El Niño: Science's gift to the 21st century. *In*: *A Workshop on Reducing Climate-Related Vulnerability in Southern Africa*, Victoria Falls, Zimbabwe. 1-4 October 1996.

Golding, B.W. 2000. Quantitative precipitation forecasting in the UK. *Journal of Hydrology*, 239, 286-305.

Goswami, M. and O' Connor, K.M. 2006. Real time flow forecasting in the absence of quantitative precipitation forecasts: A multi-model approach. *Journal of Hydrology*, 334, 125-140.

Goswami, M., O' Connor, K.M., Bhattarai, K.P. and Shamseldin, A.Y., 2005. Assessing the performance of eight real time updating models and procedures for the Brosna river. *Hydrology and Earth System Sciences*, 9, 394-411.

Habets, F., Lemoigne, P. and Noilhan, J. 2004. On the utility of operational precipitation forecasts to served as input for streamflow forecasting. *Journal of Hydrology*, 293, 270-288.

Hallowes, J.S. 2002. *Evaluation of a Methodology to Translate Rainfall Forecasts into Runoff Forecasts for South Africa*. Unpublished MSc Dissertation, School of Bioresources Engineering and Environmental Hydrology, University of Natal, Pietermaritzburg, RSA. pp 186.

Hammer, G.L., Hansen, J.W., Philips, J.G., Mjelde, J.W., Hill, H., Love, A. and Potgieter, A. 2001. Advances in application of climate prediction in agriculture. *Agricultural Systems*, 70, 515-553.

Hansen, J.W. 2002. Realizing the potential benefits of climate prediction to agriculture: Issues, approaches, challenges. *Agricultural Systems*, 74, 309-330.

Hansen, J. W. and Indeje, M., 2004. Linking dynamic seasonal climate forecasts with crop simulation for maize yield prediction in semi-arid Kenya. *Agricultural and Forest Meteorology*, 125, 143-157.

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

Hartmann, H.C., Bales, R. and Sorooshian, S. 1999. Weather, climate, and hydrologic forecasting for the Southwest U.S. CLIMAS Report Series, CL2-99, Institute for the Study of Planet Earth. The University of Arizona, Tucson, AZ 85721, USA.

Hartmann, H.C., Pagano, T.C., Sorooshian, S. and Bales, R. 2002. Confidence builders: Evaluating seasonal climate forecasts from user perspectives. *Bulletin of American Meteorological Society*, 83, 683-698.

Hay, L.E. and Clark, M.P 2003. Use of statistically and dynamically downscaled atmospheric model output for hydrologic simulations in three mountainous basins in the western United States. *Journal of Hydrology*, 282, 56-75.

Hewitson, B.C. and Crane, R.G. 1996. Climate downscaling: techniques and application. *Climate Research*, 7, 85-95.

Hewitson, B.C. and Crane, R.G. 2006. Consensus between GCM climate change projections with empirical downscaling: Precipitation downscaling over South Africa. *International Journal of Climatology*, 26, 1315-1337.

Hobbs, J.E. 1980. *Applied Climatology: A Study of Atmospheric Resources*. Dawson Westview press, Folestone, UK.

Hossain, A.N.H. 2003. Climate forecast applications in Bangladesh for water related disaster mitigation. *In*: *International Conference on Total Disaster Risk Management*, Bangladesh. 23 December 2003.

Hu, Q. and Buyanovsky, G. 2003. Climate effects on corn yield in Missouri. Journal of Appllied Meteorology, 42, 1626-1635.

Jolliffe, I.T. and Stephenson, D.B. 2003. Categorical events. In Ed. Jolliffe I.T. and Stephenson, D.B., *Forecast Verification: A Practitioner's Guide in Atmospheric Science.* Ch. 1, John Wiley and Sons Ltd., Chichester, UK.

Kabat, P. and Bates, B. 2002. The evidence *In*: Appleton, B (Ed) *Climate Changes the Water Rules: How Water Managers can Cope with Today's Climate Variability and Tomorrow's Climate Change.* Ch.1, 2 to 11, Printfine Ltd., Liverpool, UK.

Keating, B.A. and Meinke, H. 1998. Assessing exceptional drought with a cropping systems simulator: A case study for grain production in north-east Australia. *Agricultural Systems*, 57, 315-332.

Kershaw, R. 2006. Parameterization of atmospheric processes in the Unified Model. *In*: *18th BMRC Modelling Workshop 2006*: Presentations *The Australian Community Climate and Earth System Simulator (ACCESS) Challenges and Opportunities*. Bureau of Meteorology, Melbourne, Australia. 28 November – 1 December 2006.

Khaliq, P., Ahmed, S. and Cheema, N.M. 2007. Sustainable cropping system for rain-fed areas in Pothwar, Pakistan. Soil & Environment, 26, 75-80.

Kienzle, S.W., Lorentz, S.A. and Schulze, R.E. 1997. *Hydrology and Water Quality of the Mgeni Catchment*. *WRC Report* No. TT87/97. Water Research Commission Pretoria, RSA. pp 88.

Kjeldsen, T.R. and Rosbjerg, D. 2001. A framework for assessing the sustainability of a water resources system. Environment and Resources, Technical University of Denmark, DK-2800 Kongens Lyngby, Denmark.

Kleynhans, M.T., English, G., Botha, K. and Mugumo, M. 2008. Investigation of Future Surface Water Options to Augment the Western Cape Water Supply System. Western Cape Water Consultants Joint Venture for the Department of Water Affairs (Directorate Options Analysis), Pretoria, South Africa.

Klopper, E. 1999. The use of seasonal forecasts in South Africa during the 1977/98 rainfall season. *Water SA,* 25, 311-314.

Klopper, E. and Landman, W.A. 2003. A simple approach for combining seasonal forecasts for southern Africa. *Meteorology Applications*, 10, 319-327.

Kroese, N.J. 2004. Spatial Interpolation and Mapping of Rainfall (SIMAR). Volume 1: Maintenance and Upgrading of Radar and Raingauge Infrastructure. *WRC Report* No. 1151/1/04. Water Research Commission, Pretoria, RSA.

Landman, S. 2012. A multi-model ensemble system for short-range weather prediction in South Africa. MSc manuscript, University of Pretoria. *In press.*

Landman. S., Engelbrecht, F.A., Dyson, L.L., Engelbrecht, C.J. and Landman, W.A. 2012a. A short-range weather prediction system for South Africa based on a multi-model approach. *Water SA*. Submitted.

Landman, S., Engelbrecht, F.A., Dyson, L.L. and Engelbrecht, C.J. 2012. Accuracy and skill of a multi-model ensemble system for short-range weather prediction in South Africa. *Water SA*. In preparation.

Landman, W.A. 2008. Personal Communication.

Landman, W.A., Botes, S., Goddard, L. and Shongwe, M. 2005. Assessing the predictability of extreme rainfall seasons over southern Africa. *Geophysical Research Letters*, 32. L23818, DOI: 1029/2005GL023965.

Landman, W.A., DeWitt, D., Lee D.-E., Beraki, A. and Lötter, D. 2012b. Seasonal rainfall prediction skill over South Africa: 1- vs. 2-tiered forecasting systems. *Weather and Forecasting*, DOI:10.1175/WAF-D-11-00078.1.

Landman, W.A., Engelbrecht, F.A., Beraki, A., Engelbrecht, C.J., Mbedzi, M., Gill, T. and Ntsangwane, L. 2009. Model output statistics applied to multi-model ensemble long-range forecasts over South Africa. *Water Research Commission Project Report* No. 1492/1/08. Water Research Commission, Pretoria, RSA. pp 56.

Landman, W.A., Mason, S.J., Tyson, P.D. and Tennant, W.J. 2001. Statistical downscaling of GCM simulations to streamflow. *Journal of Hydrology*, 252, 221-236.

Landman, W.A., Engelbrecht, F., Park, R., Bopape, M. and Lotter, D. 2010. Atmospheric modelling and prediction at time-scales from days to seasons. *Proceedings, CSIR Biannual Conference*, August/September 2010, Pretoria, RSA. Reference NE05-P0-F.

Landman, W.A. and Goddard, L. 2002. Statistical recalibration of GCM forecast over southern Africa using model output statistics. *Journal of Climatology,* 15, 2038-2055.

Landman, W. and Goddard, L. 2005. Predicting southern African summer rainfall using a combination of MOS and perfect prognosis. *Geophysical Research Letters*, 32. L15809, doi: 10.1029/2005GL022910.

Lettenmaier, D.P. and Wood, E.F. 1993. Hydrologic forecasting. *In*: Maidment, D.R. (Ed) *Handbook of Hydrology*. McGraw-Hill, Inc. New York, USA.

Lines, G.S. and Barrow, E.M. 2002. Regional Climate Change Scenarios in Atlantic Canada Utilizing Downscaling Techniques: Preliminary Results. AMS Preprint, 13-17 January 2002, Orlando, USA.

Lines, G.S., Pancura, M. and Lander, C. 2005. Building Climate Change Scenarios of Temperature and Precipitation in Atlantic Canada using the Statistical Downscaling Model (SDSM). Meteorological Service of Canada, Dartmouth, Canada. pp 41.

Livezey, R.E. 2003. Categorical events. *In:* Jolliffe, I.T. and Stephenson, D.B. (Eds) *Forecast Verification: A Practitioner's Guide in Atmospheric Science.* Ch. 4, John Wiley and Sons Ltd., Chichester, UK.

Louw, D.B., Johnston, P., Tadross, M.A., Schulze, R.E., Lumsden, T.G., Callaway, M. and Hellmuth, M. 2011. Managing climate risk for agriculture and water resources development in South Africa: Quantifying the costs, benefits and risks associated with planning and management alternatives. Report to IDRC on Project 104 150. pp 104.

Low, A.B. and Rebello, A.G. 1996. *Vegetation of South Africa, Lesotho and Swaziland*. Department of Environmental Affairs and Tourism, Pretoria, RSA.

Lumsden, T.J. 2000. Development and evaluation of a sugarcane yield forecasting system. Unpublished MSc Dissertation, School of Bioresources Engineering and Environmental Hydrology, University of Natal, Pietermaritzburg, RSA.

Lumsden, T.G., Kunz, R.P., Schulze, R.E., Knoesen, D.M. and Barichievy, K.R. 2010. Methods 4: Representation of Grid and Point Scale Regional Climate Change Scenarios for National and Catchment Level Hydrological Impacts Assessments. *In*: Schulze, R.E., Hewitson, B.C., Barichievy, K.R., Tadross, M.A., Kunz, R.P., Horan, M.J.C. and Lumsden, T.G. 2010a. *Methodological Approaches to Assessing Eco-Hydrological Responses to Climate Change in South Africa*. Water Research Commission, Pretoria, RSA, WRC Report 1562/1/10. Chapter 9, 89-100.

Lynch, S.D. 2004. The Development of a Raster Database of Annual, Monthly and Daily Rainfall for Southern Africa, Water Research Commission, Pretoria, RSA. WRC Report 1156/1/04. pp 78.

Madsen, H. and Jacobsen, T. 2001. Automatic calibration of the MIKE SHE integrated hydrological modelling system. *In*: *4th DHI Software Conference*, Scanticon Conference Centre, Helsingør, Denmark. 6-8 June, 2001.

Maidment, D.R. 1993. *Handbook of Hydrology*. McGraw-Hill, Inc., New York, USA.

Mailier, P.J., Jolliffe, I.T. and Stephenson, D.B. 2006. Unpublished material. Quality of weather forecasts: Review and recommendations. Royal Meteorological Society, Reading, UK.

Maini, P., Kumar, A., Singh, S.V. and Rathore, L.S. 2004. Operational model for forecasting location specific quantitative precipitation and probability of precipitation over India. *Journal of Hydrology*, 288, 170-188.

Makhuva, T., Pegram, G.G.S., Sparks, R. and Zucchini, W. 1997a. Patching rainfall data using regression methods. 1. Best subset selection, EM and pseudo-EM methods: Theory. *Journal of Hydrology*, 198, 289-307.

Makhuva, T., Pegram, G.G.S., Sparks, R. and Zucchini, W. 1997b. Patching rainfall data using regression methods. 2. Comparisons of accuracy, bias and efficiency. *Journal of Hydrology*, 198, 308-318.

Mason, S.J. 2000. Definitions of technical terms in forecast verification examples of forecast verification scores. *In*: *Proceedings of the Workshop on Forecast Quality*, Palisades, New York, USA. October 10, 2000.

McGregor, J.L. 2005a. Geostrophic adjustment for reversibly staggered grids. *Monthly Weather Review*, pp 133. Chapter 7, pages 123 and 124, Chapter 4, page 27.

McGregor, J.L. 2005b. C-CAM: Geometric aspects and dynamical formulation. *CSIRO Atmospheric Research Technical Paper* No. 70. pp 41. Chapter 7, pages 123 and 124, Chapter 4, page 27.

McGregor, J.L., and Dix, M.R. 2001. The CSIRO conformal-cubic atmospheric GCM. *In*: Hodnett, P.F. (Ed) *IUTAM Symposium on Advances in Mathematical Modelling of Atmosphere and Ocean Dynamics*. Kluwer, Dordrecht, Netherlands, 197-202.

Mecklenburg, S., Joss, J. and Schmid, W. 2000. Improving the nowcasting of precipitation in an alpine region with an enhanced radar echo tracking algorithm. *Journal of Hydrology*, 239, 46-48.

Mendenhall, W. and Sincich, T. 2003. A Second Course in Statistics: Regression Analysis. 6th Edition. Upper Saddle River, Pearson, USA.

Moeller, C., Smith, I., Asseng, S., Ludwig, F. and Telcik, N. 2008. The potential value of seasonal forecasts of rainfall categories-case studies from the wheatbelt in Western Australia's Mediterranean region. *Agricultural and Forest Meteorology*, 148, 606-618.

Monteith, J.L. 1981. Evaporation and surface temperature. *Quarterly Journal of the Royal Meteorological Society*, 107, 1-27.

Murphy, A.H. 1993. What is a good forecast? An essay on the nature of goodness in weather forecasting. *Weather Forecasting*, 8, 281-293.

Murphy, J.M. 1998. An evaluation of statistical and dynamical techniques for downscaling local climate. *Journal of Climate*, 12, 2256-2284.

Nash J.E. and Sutcliffe, J.V. 1970. River flow forecasting through conceptual models, part I – A discussion of principles. *Journal of Hydrology,* 10, 282-290.

National Land Cover (NLC), 2000. Produced by CSIR and ARC consortium, Pretoria, RSA.

Nurmi, P. 2003. Recommendations on the verification of local weather forecasts (at ECMWF Member States). Consultancy Report, Reading, UK.

O' Gara, F. 2007. Irrigated maize production in the top end of the northern territory production: Guidelines and research results. http://www.nt.gov.au/dpifon (Accessed 10 February 2012).

Pannar, 2006. Seed for thought, 3, vol2, 1-12. www.pannar.com/admin/newsletters/sftv7.pdf (Accessed 20 January 2010).

Pappenberger, F., Beven, K.J., Hunter, N.M., Bates, P.D., Gouweleeuw, B.T., Thielen, J. and De Roo, A.P.J. 2005. Cascading model uncertainty from medium range weather forecasts (10 days) through a rainfall-runoff model to flood inundation predictions within the European flood forecasting system (EFFS). *Hydrology and Earth System Sciences*, 9, 381-393.

Pegram, G.G.S. 2004. Spatial Interpolation and Mapping of Rainfall (SIMAR). Volume 3: Data Merging for Rainfall Map Production. *WRC Report* No. 1153/1/04. Water Research Commission, Pretoria, RSA.

Pegram, G.G.S. and Sinclair, D.S. 2002. A linear catchment model for real time flood forecasting. *WRC Report* No. 1005/1/02. Water Research Commission, Pretoria, RSA.

Pegram, G., Sinclair, S., Vischel, T. and Nxumalo, N. 2010. Soil Moisture from Satellites: Daily Maps over RSA for Flash Flood Forecasting, Drought Monitoring, Catchment Management and Agriculture. Water Research Commission, Pretoria, RSA, WRC Report 1683/1/10. pp 191.

Pegram, G., Sinclair, S. and Wesson, S. 2005. *Daily Rainfall Mapping over South Africa: Modelling*. Water Research Commission, Pretoria, RSA, WRC Report 1425/1/06. pp 125.

Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society*, London, UK, A193, 120-146.

Piechota, T.C., Chiew, F.H.S., Dracup, J.A. and McMahon, T.A. 1998. Seasonal streamflow forecasting in eastern Australia and the El Niño-Southern Oscillation. *Water Resources Research*, 34, 3035-3044.

Pielke, R.A. 2000. Policy responses to El Niño 1997-1998. *In*: Changnon, S.A. (Ed) *El Niňo 1997/1998*. The Climate Event of the Century, Oxford University Press, New York, USA. 172-196.

Podestá, G., Letson, D., Messina, C., Royce, F., Ferreyra, R. A., Jones, J., Hansen, J.W., Llvoet, I., Grondona, M. and O'Brien, J.J. 2002. Use of ENSO-related climate information in agricultural decision making in Argentina: A pilot experience. *Agricultural Systems*, 74, 371-392.

Potgieter, 2006. Short-range weather forecasting over southern Africa with the conformal-cubic atmospheric model. MSc Thesis. University of Pretoria, Pretoria. pp 172.

Potts, J.M, Folland, C.K., Jolliffe, I.T. and Sexton, D. 1996. Revised 'LEPS' scores for assessing climate model simulations and long-range forecasts. *Journal of Climate*, 9, 34-43.

Reason, C.J.C., Engelbrecht, F., Landman, W.A., Lutjeharms, J.R.E., Piketh, S., Rautenbach, H. and Hewitson, B.C. 2006. A review of South African research in atmospheric science and physical oceanography during 2000-2005. *South African Journal of Science*, 102, 35-45.

Rebora, N., Ferraris, L., Von Hardenberg, J. and Provenzale, A. 2005. Stochastic downscaling of LAM predictions: An example in the Mediterranean area. *Advances in Geosciences*, 2, 181-185.

Rinaldi, M., Losavio, N. and Flagella, Z. 2003. Evaluation and application of CROPGRO-soybean model for improving soybean management under rainfed conditions. *Agricultural Systems,* 78, 17-30.

Ritchie, J.W., Zammit, C. and Beal, D. 2004. Can seasonal climate forecasting assist in catchment water management decision making? A case study of the border rivers catchment in Australia. *Agriculture, Ecosystems and Environment,* 104, 553-565.

Roads, J. 2004. Experimental weekly to seasonal, global to regional US precipitation forecasts. *Journal of Hydrology*, 288, 153-169.

Rural Development Services, 2002. Unpublished material. Agricultural Assessment of the Mgeni Municipality. Metroplan, Pietermaritzburg, RSA.

SAWS, 2005. Seasonal forecast for southern Africa. Long Range Forecasting Group. Available from: http://www.weathersa.co.za [Accessed 10 June 2005].

Schäfer, N.W. and van Rooyen, P.G. 1993. Operational applications of the Mgeni systems analysis. *In*: Lorentz, S.A., Kienzle S.W. and Dent, M.C. (Eds) *Proceedings of the Sixth South African National Hydrological Symposium,* 385-394. University of Natal, Pietermaritzburg, RSA. 8-10 September, 1993.

Schmidli, J., Frei, C. and Vidale, P.L. 2006. Downscaling from GCM precipitation: A benchmark for dynamical and statistical downscaling methods. *International Journal of Climatology*, 26, 679-689.

Schneider, J.M. and Garbrecht, J.D. 2003. Temporal disaggregation of probabilistic seasonal climate forecasts. *In*: *Proceedings American Meteorological Society, 14th Symposium on Global Change and Climate Variations*, Long Beach, CA, USA. February 9-13, 2003.

Schulze, R.E. 1995. *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*. Water Research Commission, Pretoria, RSA, Report TT 69/9/95. pp 552.

Schulze, R.E. 1997. Impacts of global climate change in a hydrologically vulnerable region: Challenges to South African hydrologists. *Progress in Physical Geography*, 21, 113-116.

Schulze, R.E. 2004. Determination of Baseline Land Cover Variables for Applications in Assessing Land Use Impacts on Hydrological Responses in South Africa. *In*: Schulze, R.E. and Pike, A. (Eds) *Development and Evaluation of an Installed Hydrological Modelling System*. Water Research Commission, Pretoria, RSA, WRC Report 1155/1/04. Chapter 2, 37-50.

Schulze, R.E. 2005. Development of an integrated time-varying agrohydrological forecast system for southern Africa: A Research Proposal to the Water Research Commission. *In*: *A Workshop of Water Utilization in Agriculture.* Water Research Commission, Pretoria, RSA. 29 April, 2005.

Schulze, R.E. 2006. Climate Information Needs for Integrated Risk Management of Water Resources: A South African Perspective. Presentation at International Conference on "Living with Climate Variability and Climate Change", Espoo, Finland. July 2006.

Schulze, R.E. (Ed) 2008. *South African Atlas of Climatology and Agrohydrology*. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/08 (On DVD).

Schulze, R.E. and Chapman, R.D. 2008a. Estimation of Daily Solar Radiation over South Africa. *In*: Schulze, R.E. (Ed) *South African Atlas of Climatology and Agrohydrology*. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/08. Section 5.2. pp 9.

Schulze, R.E. and Chapman, R.D. 2008b. Vapour Pressure: Derivation of Equations for South Africa. *In*: Schulze, R.E. (Ed) *South African Atlas of Climatology and Agrohydrology*. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/08. Section 11.1. pp 12.

Schulze, R.E., Hallowes, J., Lynch, S.D,. Perks, L.A. and Horan, M., 1998. Forecasting seasonal streamflow in South Africa: A preliminary investigation. *In*: Joubert, A.M. (Ed) *Forecasting Rainfall and Streamflow over South and Southern Africa*. Research Report No. TRR/T98/046, ESKOM Technology Group, Rocheville, RSA.

Schulze, R.E. and Horan, M.J.C. 2008. Soils Hydrological Attributes. *In*: Schulze, R.E. (Ed) *South African Atlas of Climatology and Agrohydrology*. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/08. Section 4.2. pp 6.

Schulze, R.E. and Horan, M.J.C. 2010. Methods 1: Delineation of South Africa, Lesotho and Swaziland into Quinary Catchments. *In*: Schulze, R.E., Hewitson, B.C., Barichievy, K.R., Tadross, M.A., Kunz, R.P., Horan, M.J.C. and Lumsden, T.G. *Methodological Approaches to Assessing Eco-Hydrological Responses to Climate Change in South Africa*. Water Research Commission, Pretoria, RSA, WRC Report 1562/1/10. Chapter 6, 55-62.

Schulze, R.E., Horan, M.J.C., Kunz, R.P., Lumsden, T.G. and Knoesen, D.M. 2010. Methods 2: Development of the Southern African Quinary Catchments Database. *In*: Schulze, R.E., Hewitson, B.C., Barichievy, K.R., Tadross, M.A., Kunz, R.P., Horan, M.J.C. and Lumsden, T.G. *Methodological Approaches to Assessing Eco-Hydrological Responses to Climate Change in South Africa*. Water Research Commission, Pretoria, RSA, WRC Report 1562/1/10. Chapter 7, 63-74.

Schulze, R.E., Horan, M.J.C., Kunz, R.P., Lumsden, T.G. and Knoesen, D.M. 2011. The South African Quinary Catchments Database. *In:* Schulze, R.E. *A 2011 Perspective on Climate Change and the South African Water Sector*. Water Research Commission, Pretoria, RSA, WRC Report 1843/2/11, Chapter 2.2, 31-37.

Schulze, R.E., Lorentz, S.A., Kienzle, S.W. and Perks, L.A. 2004. Case Study 3: Modelling the impacts of land-use and climate change on hydrological responses in the mixed underdeveloped/ developed Mgeni catchment, South Africa. *In*: Eds. Kabat, P., Claussen, M., Dirmeyer, P.A., Gash, J.H.C., Bravo deGuenni, L., Meybeck, M., Pielke, R.A Snr., Vörösmarty, C.J., Hutejes, R.W.A. and Lűtkemeier, S. *Vegetation, Water, Humans and the Climate. A New Perspective on an Interactive System*. Springer-Verlag, Heidelberg, Germany. Chapter D7, 441-453.

Schulze, R.E. and Maharaj, M. 2004. *Development of a Database of Gridded Daily Temperatures for Southern Africa*. Water Research Commission, Pretoria, RSA, WRC Report 1156/2/04. pp 83.

Schulze, R.E., Maharaj, M. and Moult, N. 2008. Reference Crop Evaporation by the Penman-Monteith Method. *In:* Schulze, R.E. (Ed). 2008. *South African Atlas of Climatology and Agrohydrology*. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/08, Section 13.3. pp 11.

Schulze, R.E., Maharaj, M., Warburton, M.L., Gers, C.J., Horan, M.J.C., Kunz, R.P. and Clark, D.J. 2008. Electronic data accompanying the South African Atlas of Climatology and Agrohydrology, Water Research Commission, Pretoria, RSA, Report 1489/1/08.

Schulze, R.E. and Perks, L.A. 2000. Assessment of the Impact of Climate Change on Hydrology and Water Resources in South Africa. University of Natal, Pietermaritzburg, RSA, School of Bioresources Engineering and Environmental Hydrology. Report to South African Country Studies for Climate Change Programme. *ACRUcons Report*, 33. pp 118.

Schulze, R.E. and Smithers, J.C. 2004. The *ACRU* Agrohydrological Modelling System as of 2002: Background, concepts, structure, output, typical applications and operations. *In*: R.E. Schulze (Ed) *Modelling as a Tool in Integrated Water Resources Management: Conceptual Issues and Case Study Applications*. Water Research Commission, Pretoria, RSA, *WRC Report* 749/2/04. Chapter 3, 47-83.

Schulze, R.E., Warburton, M., Lumsden, T.G. and Horan, M.J.C. 2005. The Southern African Quaternary Catchments Database: Refinements to, and Links with, the *ACRU* System as a Framework for Modelling Impacts of Climate Change on Water Resources. *In*: Schulze, R.E. (Ed) *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation*. Water Research Commission, Pretoria, RSA, *WRC Report* 1430/1/05. Chapter 8, 111-139.

Scott, A.J. and Collopy, F. 1992. Error measures for generalizing about forecasting methods: Empirical comparisons. *International Journal of Forecasting*, 8, 69-80.

Sinclair, S. and Pegram, G.G.S., 2010. A comparison of ASCAT and modelled soil moisture over South Africa, using TOPKAPI in land surface mode. *Hydrology and Earth System Sciences,* 14, 613-626.

Smithers, J.C. and Schulze, R.E. 1995. *ACRU Agrohydrological Modelling System: User Manual Version 3.00*. Water Research Commission, Pretoria, RSA, Technology Transfer Report TT 70/95. pp 372 (ISBN 1 86845 137 2).

Smithers, J.C. and Schulze, R.E. 2000. Long duration design rainfall estimates for South Africa. University of Natal, Pietermaritzburg, RSA, School of Bioresources Engineering and Environmental Hydrology. Report to the Water Research Commission, Pretoria, RSA, Report No. 811/1/00. pp 69 (ISBN No. 2 86845 650 1).

Smithers, J.C. and Schulze, R.E. 2004. *ACRU Agrohydrological Modelling System: User Manual Version 4.00*, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, RSA.

Tennant, W.J. 2005. Personal communication. South African Weather Service, RSA. 5 June 2005.

Tennant, W.J. 2007. Personal communication. South African Weather Service, RSA. 14 July 2007.

Tennant, W.J., Toth, Z. and Rae, K.J., 2006. Application of the NCEP ensemble prediction system to medium-range forecasting in South Africa: New products, benefits and challenges. Submitted to *Weather and Forecasting*, Revised: June 9, 2006.

Thatcher, M. and McGregor, J.L. 2009. Using a scale-selective filter for dynamical downscaling with the conformal cubic atmospheric model. *Monthly Weather Review,* 137, 1742-1752.

Thatcher M. and McGregor, J.L. 2010. A technique for dynamically downscaling daily-averaged GCM datasets over Australia using the Conformal Cubic Atmospheric Model. *Monthly Weather Review*, 139, 79-95.

Toth, Z. and Kalnay, E. 1997. Ensemble forecasting at NCEP and the breeding method. *Monthly Weather Review*, 125, 3297-3319.

Toth, Z., Kalnay, E., Tracton, S. M., Wobus, R. and Irwin, J. 1997. A synoptic evaluation of the NCEP ensemble. *Weather and Forecasting*, 12, 140-153.

Toth, E., Brath, A. and Montanari, A. 2000. Comparison of short-term rainfall prediction models for real time flood forecasting. *Journal of Hydrology*, 239, 132-147.

Toth, Z., Mendez, M.P. and Vintzileos, A. 2006. Bridging the gap between weather and climate forecasting: Research priorities for intra-seasonal prediction. *In*: *A Workshop*, 27 April 2006, Naval Weather Service, National Center for Environmental Prediction, MD, USA.

Toth, E., Montanari, A. and Brath, A. 1999. Real time flood forecasting via combined use of conceptual and stochastic models. *Physics and Chemistry of the Earth (B),* 24, 793-798.

Toth, Z., Talagrand, O. and Zhu, Y. 2005. The attributes of forecast systems: A framework for the evaluation and calibration of weather forecasts. *In*: Palmer, T.N. and Hagedorn, R. (Eds) *Predictability of Weather and Climate*. Cambridge University Press, New York, USA.

Toth, Z., Zhu, Y., Marchok, T., Tracton, S.M. and Kalnay, E. 1998. Verification of the NCEP global ensemble forecasts. Paper presented. *In*: *12th Conference on Numerical Weather Prediction*, Phoenix, Arizona, USA. 11-16 January 1998.

UKCIP, 2003. Climate adaptation: Risk, uncertainty and decision making. *In*: Willows, R.I. and Connell, R,K. (Eds) *UKCIP Technical Report*, Part 2, 41-52, UKCIP, Oxford, UK.

UK Met Office, 2007. The Unified Model. Submodels. Available from: http://www.metoffice.gov.uk [Accessed 17 July 2007].

Van Hemert, L. 2007. Personal communication. South African Weather Service, RSA. 23 September 2007.

Van Zyl, D. 2003. *South African Weather and Atmospheric Phenomena*. Printed by Creda, Cape Town, RSA.

Walker, N.J. and R.E. Schulze, R.E. 2006. An assessment of sustainable maize production under different management and climate scenarios for smallholder agro-ecosystems in KwaZulu-Natal, South Africa. *Physics and Chemistry of the Earth*, 31, 995-1002.

Warburton, M.L., Schulze, R.E. and Jewitt, G.P.W. 2010. Confirmation of *ACRU* model results for applications in land use and climate change studies. *Hydrology and Earth System Sciences,* 14, 2399-2414.

Webster, P.J. and Grossman, R. 2003. Unpublished material. Forecasting river discharge into Bangladesh on short, medium and long time scales. Georgia Institute of Technology, Atlanta, Georgia, USA.

Wei, M., Toth, Z., Wobus, R., Zhu, Y. and Biship, C. 2005. Initial perturbations for NCEP ensemble forecast system. *In*: *Proceedings for the First THORPEX Internal Science Symposium*, Montreal, Canada. 6-10 December 2004.

Weiss, A., Van Crowder, L. and Bernardi, M. 2000. Communicating agrometeorological information to farming communities. *Agricultural and Forest Meteorology*, 103, 185-196.

White, B. 2000. The importance of climate variability and seasonal forecasting to the Australian economy. *In*: Hammer, G.L., Nicholls, N. and Mitchell, C. (Eds) *Application of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems: The Australian Experience*. Kluwer Academic Publishers, Dordrecht, Netherlands.

Wilby, R.L., Barnsley, N. and O'Hare, G. 1995. Rainfall variability associated with Lamb weather types: The case for incorporating weather fronts. *International Journal of Climatology*, 15, 1241-1252.
Wilby, R.L. and Dawson, C.W. 2007. SDSM 4.2 User Manual. Available from https://co-public.lboro.ac.uk/cocwd/SDSM/ (Accessed 1 Nov 2007).
Wilby, R.L., Dawson, C.W. and Barrow, E.M. 2002. SDSM – a decision support tool for the assessment of regional climate change impacts. *Environmental Modelling and Software*, 17, 145-157.
Wilby, R.L. and Wigley, T.M.L. 1997. Downscaling general circulation model output: A review of methods and limitations. *Progress in Physical Geography*, 21, 530-548.
Wilby, R.L., Whitehead, P.G., Wade, A.J., Butterfield, D., Davis, R.J. and Watts, G. 2006. Integrated modelling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK. *Journal of Hydrology*, 330, 204-220.
Wilks, D.S. 1995. *Statistical Methods in the Atmospheric Sciences*. Academic Press, San Diego, CA, USA.
Wilks, D.S. 2006. *Statistical Methods in the Atmospheric Sciences* (2nd Edition). Academic Press. San Diego, USA. pp 627.
Willmott, C.J. 1981. On the validation of models. *Physical Geography,* 2, 184-194.
Willmott, C.J. 1982. Some comments on the evaluation of model performance*. Bulletin of the American Meteorological Society*, 63, 1309-1313.
Willmott, C.J., Ackleson, S.G., Davis, R.E., Feddema, J.J., Klink, K.M., Legates, D.R., O'Donnell, J. and Rowe, C.M. 1985. Statistics for the evaluation of model performance. *Journal of Geophysical Research,* 90, 8995-9005.
Willmott, C.J. and Matsuura, K. 2005. Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. *Climatological Research,* 30, 79-82.
Willmott, C.J., Matsuura, K. and Robeson, S.M. 2009. Ambiguities inherent in sums-of-squares-based error statistics. *Atmospheric Environment,* 43, 749-752.
Willmott, C.J., Robeson, S.M. and Matsuura, K. 2011. Short Communication: A refined index of model performance. *International Journal of Climatolology,* DOI: 10.1002/joc.2419.
WMO, 1992. International Meteorological Vocabulary. Report No. 182, Geneva, Switzerland.
Wood, A.W., Leung, L.R., Sridhar, V. and Lettenmaier, D.P. 2004. Hydrological implications of dynamical and statistical approaches to downscaling climate model outputs. *Climatic Change,* 62, 189-216.
Xiong, L., O'Connor, M. and Guo, S. 2004. Comparison of three updating schemes using artificial neural networks in flow forecasting. *Hydrology and Earth System Sciences*, 8, 247-255.
Yarnal, B. 1993. *Synoptic Climatology in Environmental Analysis: A Primer*. Belhaven Press, London, UK. pp 195.
Zhang, H. and Casey, T. 1999. Verification of categorical probability forecasts. *Weather and Forecasting*, 35, 80-89.
Zhu, Y., Toth, Z., Wobus, R., Richardson, D. and Mylne, K. 2002. The economic value of ensemble-based weather forecasts, *Bulletin of the American Meteorological Society*, 83, 73-83.
Zorita, E. and von Storch, H. 1999. The analog method as a simple statistical downscaling technique: Comparison with more complicated methods. *Journal of Climate*, 12, 2474-2489.