EVALUATION OF A METHODOLOGY TO TRANSLATE RAINFALL FORECASTS INTO RUNOFF FORECASTS FOR SOUTH AFRICA

by

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ABSTRACT

South Africa experiences some of the lowest water resource system yields in the world as a result of the high regional variability of rainfall and runoff. Population growth and economic development are placing increasing demands on the nation's scarce water resources. These factors, combined with some of the objectives of the new National Water Act (1998), are highlighting the need for efficient management of South Africa's water resources.

In South Africa's National Water Act (1998) it is stated that its purpose is to ensure that the nation's water resources are protected, used, conserved, managed and controlled in a way, which takes into account, *inter alia,*

i. promoting the efficient, sustainable and beneficial use of water in the public interest, and
ii. managing floods and droughts.

Efficient and sustainable water resource and risk management can be aided by the application of runoff forecasting. Forecasting thus fits into the ambit of the National Water Act and, therefore, there is a need for its operational application to be investigated. In this document an attempt is made to test the following hypotheses:

Hypothesis 1: Reliable and skilful hydrological forecasts have the ability to prevent loss of life, spare considerable hardship and save affected industries and commerce millions of Rands annually if applied operationally within the context of water resources and risk management.

Hypothesis 2: Long to medium term rainfall forecasts can be made with a degree of confidence, and these rainfall forecasts can be converted into runoff forecasts which, when applied within the framework of water resources and risk management, are more useful to water resource managers and users than rainfall forecasts by themselves.

The validity of Hypothesis 1 is investigated by means of a literature review. South Africa's high climate variability and associated high levels of uncertainty as well as its current and future water resources situation are reviewed in order to highlight

the importance of runoff forecasting in South Africa. Hypothesis 1 is further examined by reviewing the concepts of hazards and risk with a focus on the role of effective risk management in preventing human, financial and infrastructural losses.

A runoff forecasting technique using an indirect methodology, whereby rainfall forecasts are translated into runoff forecasts, was developed in order to test Hypothesis 2. The techniques developed are applied using probabilistic regional rainfall forecasts supplied by the South African Weather Service for 30 day periods and categorical regional forecasts for one, three and four month periods for regions making up the study area of South Africa, Lesotho and Swaziland. These forecasts where downscaled spatially for application to the 1946 Quaternary Catchments making up the study area and temporally to give daily rainfall forecast values.

Different runoff forecasting time spans produced varying levels of forecast accuracy and skill, with the three month forecasts producing the worst results, followed by the four month forecasts. The 30 day and one month forecasts for the most part produced better results than the more extended forecast periods. In the study it was found that hydrological forecast accuracy results seem to be inversely correlated to the amount of rainfall received in a region, i.e. the wetter the region the less accurate the runoff forecasts. This trend is reflected in both temporal and spatial patterns where it would seem that variations in the antecedent moisture conditions in wetter areas and wetter periods contribute to the overall variability, rendering forecasts less accurate. In general, the runoff forecasts improve with corresponding improvements in the rainfall forecast accuracy. There are, however, runoff forecast periods and certain regions that produce poor runoff forecast results even with improved rainfall forecasts. This would suggest that even perfect rainfall forecasts still cannot capture all the local scale variability of persistence of wet and dry days as well as magnitudes of rainfall on individual days and the effect of catchment antecedent moisture conditions. More local scale rainfall forecasts are thus still needed in the South African region.

In this particular study the methods used did not produce convincing results in terms of runoff forecast accuracy and skill scores. The poor performance can probably be attributed to the relatively unsophisticated nature of the downscaling and interpolative techniques used to produce daily rainfall forecasts at a Quaternary Catchment scale. It is the author's opinion that in the near future, with newly focussed research efforts, and building on what has been learned in this study, more reliable agrohydrological forecasts can be used within the framework of water resources and risk management, preventing loss of life, saving considerable hardship and saving affected industry and commerce millions of Rands annually.

PREFACE

I hereby certify that these studies represent original work by the author for post-graduate degree purposes within the School of Bioresources Engineering and Environmental Hydrology, University of Natal, Pietermaritzburg from January 1998 to December 2001, under the supervision of Prof. R.E. Schulze and co-supervision of Mr S.D. Lynch and have not otherwise been submitted in any form for any degree or diploma to any University. Where use has been made of the work of others it is duly acknowledged in the text.

Signed: ----------------

Jason Scott Hallowes

Date: -----------------

As the candidate's supervisor I hereby approve this dissertation for submission.

Signed: ----------------

Name: ----------------

Date: -----------------

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1 INTRODUCTION

Water resources, described as the limiting factor for human development (Epstein, 1998), are being placed under increasing pressure globally as growing populations are demanding more water for a range of uses, while simultaneously polluting the existing water resources, thereby decreasing usable water availability (Klohn, 1998). Morbidity and mortality, as a result of enteric diseases, are inversely correlated to quantity of running water used for domestic purposes, such as cooking and basic hygiene (Epstein, 1998; Acreman *et al.*, 2000). The temporal and spatial distributions of water have direct association with insect-borne diseases such as malaria, schistosomiasis, dengue and yellow fever; with rodent-borne diseases such as hantavirus and plague; and with water-borne diseases such as cholera, diarrhoea and skin diseases (Jury, 1996a; le Sueur and Sharp, 1996; Epstein, 1998; Acreman *et al.*, 2000). Spatial and temporal water distributions affect the agricultural potential and livestock carrying capacity, which in turn affects the ability of regions to sustain human populations (Vakkilainen and Varis, 1998). Flooding is the most common of all environmental hazards, regularly claiming 20 000 lives and effecting 75 million people per annum on a global scale (Smith, 1996). Furthermore it has been estimated that worldwide, on an annual basis, two hundred thousand people are killed and one billion people are affected by drought (Smith 1996; Acreman, *et al.*, 2000). Effective water resource and risk management therefore has the potential to save lives, spare considerable hardship and prevent financial losses, in many areas and communities throughout the world.

South Africa, along with Australia, has the highest regional variability of rainfall and runoff in the world (Haines *et al.*, 1988). Since in the hydrological cycle any changes in rainfall are amplified as changes in runoff, South Africa experiences exceptionally high coefficients of variation of runoff (Schulze, 1997a). The consequence is that for a given level of water management (e.g. impoundments, water reticulation and irrigation systems), the water resource system yields are smaller in South Africa and Australia than anywhere else in the world (Chiew *et al.*, 1997;1998). In addition, the persistence of consecutive dry and wet years, extending sometimes over several seasons, makes the operation and management of water resources in South Africa both expensive and difficult.

It has been predicted that the demand for South Africa's water resources is going to increase as a result of population growth and economic development, and that the demand for the region's water resources will outstrip the supply by the year 2030

(Shackleton *et al.*, 1996; Basson, 1997). The influence of AIDS has not been taken into account in these projections, which would result in pessimistic estimates. However, many areas in South Africa are already in a water stress situation, which is likely to deteriorate as a result of rural urban migration patterns. The National Water Act of 1998 sets aside a minimum quantity of water to sustain the aquatic environment, known as the environmental reserve. Hence, the environment is also demanding its own share of the water supply. An already vulnerable agricultural sector must adapt as the competition for the scarce water resources increases (Basson, 1997). Climate change and anticipated escalated temperatures due to the enhanced greenhouse effect could further aggravate the situation with even higher rainfall variability, increased evaporative demand and less rainfall than at present (Shackleton *et al.*, 1996; Perks, 2001). Increased competition for water in both the domestic and industrial sector, along with the increased need for food security for a growing population implies that water availability is the major natural limiting factor for development in South Africa (Watson, 1996).

Conventionally, water resource managers and system designers have erred on the side of caution when designing and managing water supply systems. Reliable forecasts would reduce a major source of uncertainty in water resource planning which could result in better designed and more viable water supply systems (Rook, 1996). The implication is that designers would be able to decrease their safety margins and build more efficient cost effective schemes. Managers, too, are able to operate their systems at more optimal capacities if risk could be reduced. The application of hydrological forecasting could increase the efficiency of current water supply schemes, making a larger proportion of the current water reserves available for use. In the past the application of forecasts in water resource management in South Africa has been limited for following reasons (Rook, 1996):

i. There has, to date been a lack of trust in the reliability of the forecasts.
ii. Both the spatial and temporal resolutions of the forecasts are very coarse and the quantities (*i.e.* percentages of normal rainfall) are not directly applicable to water resource management.
iii. A lack of flexibility exists in users' operational systems or practices, which hampers their ability to respond to forecasting information (Vogel, 2000).

However, more recently improved accuracy by forecasters and improved understanding of forecasting concepts by the user community have led to an increase in the use of rainfall forecasts in South Africa (Klopper, 1999). Even with the increased use of forecasts in

South Africa the above mentioned problems are a recurring theme that needs to be addressed to encourage further use and application of forecasts in South Africa.

In South Africa's new National Water Act (1998) it is stated that its purpose is to ensure that the nation's water resources are protected, used, conserved, managed and controlled in a way, which takes into account, inter alia;

i. The promotion of efficient, sustainable and beneficial use of water in the public interest, and
ii. managing floods and droughts.

The National Water Act (1998) also states that, as part of its water resource strategy, it wishes to promote the management of catchments in a holistic and integrated way. Forecasting, if applied within the framework of water resources and risk management, has the ability to increase water use and supply efficiencies and reduce the losses related to both flood and drought disasters, hence saving affected industries and communities large economic costs as well as preventing considerable hardship and loss of life (Vogel, 1994). Forecasting therefore fits into the ambit of the National Water Act's overall purpose and thus its operational application should be investigated in more detail.

In order to outline the objectives in this study a problem statement, illustrated in Figure OB-1, is provided. The problem statement will be used as a "road map" guiding the reader through the document, and will be referred to at the beginning of each chapter to chart the progress through the document. In this document the following hypotheses will be tested:

Hypothesis 1: Reliable and skilful hydrological forecasts have the ability to prevent loss of life, spare considerable hardship and save affected industries and commerce millions of Rands annually if applied operationally within the context of water resources and risk management.

Hypothesis 2: Long to mediun term rainfall forecasts can be made with a degree of confidence, and these rainfall forecasts can be converted into runoff forecasts which, when applied within the framework of water resource and risk management, are more useful to water resource managers and users than rainfall forecasts by themselves.

This study will begin by investigating the validity of the first hypothesis by attempting, through a literature review, to place forecasting in the context of water resource and risk management (Objective (a) in the Problem Statement, Figure OB-1), with specific reference to the South African situation. In Chapter 2, South Africa's high climate variability and associated high levels of uncertainty and risk are discussed, in order to highlight the importance of forecasting in South Africa. An overview of South Africa's current and future water resource situation is provided in Chapter 3, in order to expose the importance of runoff forecasting in water resource management in South Africa. The concepts of hazard, risk and risk management are reviewed in Chapter 4, with the focus falling on the ability of effective risk management in preventing human, financial and personal losses. The overall vulnerability to drought and floods of the people in South Africa is also highlighted in Chapter 4. This leads into the discussion of the risks associated with hydrological hazards in Chapter 5.

The latter part of the document is concerned with the testing of hypothesis 2, presented earlier. Before the hypothesis could be tested it was necessary to develop a hydrological forecasting technique that could be used operationally in South Africa (Figure OB–1). In order to develop a hydrological forecasting technique, the current methodologies used to produce hydrological forecasts were reviewed (Chapter 6). The advantages and disadvantages of each of the different techniques are highlighted in Chapter 6, in order to select an appropriate methodology for generating runoff forecasts. Chapters 7 and 8 cover the development of hydrological forecasting techniques, which use integrated model and database systems (Figure OB-1), to produce hydrological forecasts and evaluate their performance.

In Chapter 9 hypothesis 2 is tested, by evaluating the performance of the hydrological forecasting techniques developed in Chapters 7 and 8, over the South African study region. Furthermore the performance of the hydrological forecasts for different periods is investigated by comparing the hydrological forecasts for different periods to traditionally used 'forecast' quantities, such as the median value (Objective (c) in Figure OB-1). Different trends and are identified and explanations as to the possible factors influencing the different trends is provided.

Problem Statement				
Reliable, skillful hydrological forecasts have the potential to prevent loss of life, spare considerable hardship and save affected industry and commerce millions of Rands annually if applied operationally within the framework of water resources and risk management. Integrated model and database systems provide scientists and managers with tools to investigate the feasibility and applications of such systems in operational forecasting activities.				
Broad Objectives	Place forecasting within a framework of water resources and risk management in South Africa. *(a)*	Develop hydrological forecasting techniques that could be used operationally within South Africa. *(b)*	Evaluate the hydrological forecasting techniques' performance over the South Africa study region using selected forecasting periods. *(c)*	Discuss problems and shortfalls of the current methodology used to obtain the different runoff forecasts. Recommend areas of potential future research that would enable operational application of these forecasts. *(d)*
Specific Objectives	i. Review climate variability in South Africa and its associated effect on risk ii. Review the current water resource situation in South Africa iii. Review risk evaluation and management strategies with specific attention given to the role of forecasting	i. Review current methodologies used to obtain hydrological forecasts ii. Develop suitable methodologies to be used in South Africa iii. Develop unbiased techniques to evaluate the performance of the different hydrological forecasts	i. Use standard forecasting evaluation techniques to assess the performance of the hydrological forecasting techniques developed ii. Compare different hydrological forecast performances iii. Attempt to identify trends that influence forecast performance iv. Provide explanations for the different trends influencing the forecasts' performance	i. Identify shortfalls in the techniques used to translate rainfall forecasts into runoff forecasts ii. Suggest areas where improvements could be made to increase the forecasts' reliability iii. Suggest areas of future research that would lead to the operational use of the different runoff forecasts iv. Identify key sectors of the study area where the application of forecasting may be particularly beneficial

Figure OB-1: Problem Statement: General

In Chapter 10 Objective (d) of the Problem Statement (Figure OB-1) is covered by discussing the problems and shortfalls in the current methodology used to produce runoff forecasts from the rainfall forecasts. In addition recommendations for future research are made in Chapter 10. These could potentially improve the forecast methodology, thus enhancing forecast performance and lead to the operational application of forecasting in certain catchments in the South African study region.

While the forecasting technique developed and applied in this dissertation is relatively simple, it serves to highlight important aspects about forecasting runoff and helps point to those areas where further research is needed. Development on the foundations laid by this initial methodology may lead to more sophisticated runoff forecasts that could potentially be reliable enough to be placed within a framework of water resource and risk management, where they could help to enhance operations of water resource systems.

2 CLIMATE VARIABILITY OVER SOUTH AFRICA

A large number of countries in the world, especially those in the tropics and subtropics, experience problems of climate variability, often associated with conditions of extreme population pressure (Clements,1990). Climate variability, which usually cannot be predicted or accounted for, can lead to uncertainty in, for example, water supplies. Uncertainty can be construed as a component of risk, if its consequences have an impact on human affairs (Anderson, 1990). This chapter concentrates on climatic variability and risk in South Africa and addresses Objective (a)i in the Problem Statement (Figure OB-2). South Africa experiences high coefficients of variability in both rainfall and streamflow, which introduce high degree of uncertainty in water resources and risk management (Schulze, 1997a). Reliable rainfall and streamflow forecasting has the ability to reduce uncertainty, increasing water resource yields and decreasing losses associated with hydrological hazards. In this chapter a review of climate variability is provided in order to demonstrate the importance of using forecasting in water resources and risk management in South Africa. South Africa used in the context of this study, includes Swaziland and Lesotho in addition to the Republic of South Africa, while southern Africa is used to refer to all countries in Africa south of the Equator.

South Africa is a predominantly semi-arid country in which rainfall patterns are highly erratic in both space and time. The rainfall over most areas has a pronounced seasonality (Schulze, 1997b), is often concentrated within a short period of time and displays a high inter-annual variability (Tyson, 1986; Schulze, 1997b). Consequently, the inter-annual variability of southern African runoff volumes and peak discharges are about twice those of rivers elsewhere in the world (Chiew *et al.,* 1997; Thomas and Bates, 1998; Chiew *et al.,* 1998).

The inter-annual rainfall variability does, however, seem to follow several statistically significant cyclic trends (Tyson,1996; Mason and Jury,1997) :

i. A 10 -12 year oscillation accounts for 30% of inter-annual rainfall variability along the south coast of South Africa.
ii. An 18 - 20 year oscillation is evident in the north east of the country.
iii. A rainfall cycle of around two to three years, known as the Quasi Biannual Oscillation (QBO), is identifiable over South Africa and is associated with the periodic reversal of equatorial stratospheric winds.

iv. Weaker oscillations of three and a half to seven year periods are found throughout most of the region and appear to be associated with the variable fluctuations in the El Niño/ Southern Oscillation (ENSO) phenomenon.

The most pronounced variability in southern Africa is associated with the multi-decadal 18 – 20 year oscillation (Tyson et al, 2002). The other oscillations tend to be less consistent and robust and superimposing themselves onto the 18 to 20 year cycle. South Africa's rainfall variability is caused by changes in the frequency, duration and intensity of large scale weather systems that are responsible for the number of days of significant rainfall, rather than the total number of raindays or the length of the rainfall season (Mason and Jury,1997). The weather systems that are significant contributors to rainfall over southern Africa are

i. Easterly waves and lows;
ii. Westerly waves and cut off lows;
iii. Tropical Temperate Troughs (Coupling of Easterly and Westerly wave patterns);
iv. Ridging anti cyclones;
v. Mid-latitude cyclones; and
vi. Tropical cyclones (Tyson, 1996; Landman, 1997; Tennant, 1998a).

South Africa experiences predominantly high pressures throughout the year as a result of its position in the subtropics, where it receives the poleward moving descending air that has risen over the equator. During winter the Inter-Tropical Convergence Zone (ITCZ) shifts northward towards the equator and air sinks over southern Africa, causing predominantly dry conditions to prevail (Preston-Whyte and Tyson, 1988). The ITCZ is a belt of low pressure which moves about the equator and is created by the convergence of moving air from the colder subtopics. In summer, the ITCZ moves south, most notably over the eastern part of the African subcontinent, and troughs form in the subtropical high pressure belt (Mason, 1996). Changes in synoptic scale pressure patterns over South Africa and the adjacent oceans have impacts on the weather and climate of the country. On a time scale varying from months to seasons and even years, wet spells are associated with increasing pressures to the south and south west of the South Africa and a lowering of pressure over the subcontinent (Tyson, 1986; 1996). Climatological changes are also linked to changes in the tropical easterlies and attendant easterly waves and to large scale anticyclonic ridging. Changing location of westerly storm tracks and, more particularly, the location of standing westerly waves and troughs exert a significant control of current climatic variability over southern Africa (Tyson, 1996).

Problem Statement

Reliable, skillful hydrological forecasts have the potential to prevent loss of life, spare considerable hardship and save affected industry and commerce millions of Rands annually if applied operationally within the framework of water resources and risk management. Integrated model and database systems provide scientists and managers with tools to investigate the feasibility and applications of such systems in operational forecasting activities.

Broad Objectives	Place forecasting within a framework of water resources and risk management in South Africa. *(a)*	Develop hydrological forecasting techniques that could be used operationally within South Africa. *(b)*	Evaluate the hydrological forecasting techniques' performance over the South Africa study region using selected forecasting periods. *(c)*	Discuss problems and shortfalls of the current methodology used to obtain the different runoff forecasts. Recommend areas of potential future research that would enable operational application of these forecasts. *(d)*
Specific Objectives	i. Review climate variability in South Africa and its associated effect on risk ii. Review the current water resource situation in South Africa iii. Review risk evaluation and management strategies with specific attention given to the role of forecasting	i. Review current methodologies used to obtain hydrological forecasts ii. Develop suitable methodologies to be used in South Africa iii. Develop unbiased techniques to evaluate the performance of the different hydrological forecasts	i. Use standard forecasting evaluation techniques to assess the performance of the hydrological forecasting techniques developed ii. Compare different hydrological forecast performances iii. Attempt to identify trends that influence forecast performance iv. Provide explanations for the different trends influencing the forecasts' performance	i. Identify shortfalls in the techniques used to translate rainfall forecasts into runoff forecasts ii. Suggest areas where improvements could be made to increase the forecasts' reliability iii. Suggest areas of future research that would lead to the operational use of the different runoff forecasts iv. Identify key sectors of the study area where the application of forecasting may be particularly beneficial

Figure OB-2: Problem Statement, highlighting aspects covered in Chapter 2

2.1 The Influence of the ENSO Phenomenon and Rainfall Variability Over South Africa

El Niño is the term used to describe the phenomenon of anomalously high sea surface temperatures that periodically occur in the central and eastern equatorial Pacific Ocean. The Southern Oscillation Index (SOI) describes the inter-annual oscillation between sea-level atmospheric pressure measured in Darwin, Australia and Tahiti in the central Pacific Ocean (NRC, 1996). These related phenomena are, together, referred to as the El Niño/Southern Oscillation, or ENSO, phenomenon and have been linked to inter-annual changes in temperature and precipitation in many parts of the world (Ropelewski and Halpert, 1989; Sear, 1996).

2.1.1 The ENSO phenomenon

The ENSO phenomenon is a result of the coupling between the east-west atmospheric circulation in the Pacific and the current and thermal structure of the upper ocean in the central and eastern equatorial Pacific (Trenberth, 1996). For the majority of the time, strong trade winds blow from east to west across the equatorial Pacific, causing an accumulation of warm waters in the western Pacific off the coast of Australia and Indonesia (NRC, 1996). These winds drive the surface ocean currents that determine where ocean waters flow and diverge. Currents flow from east to west producing an upward slope in the sea level which is about 0.6 m higher in the west (NRC, 1996). Divergence takes place in the eastern Pacific, with cooler waters welling up from the ocean depths to replace the displaced warmer surface water, resulting in the development of a cooler area of water in the east and central Pacific (Glantz, 1996).

The gradients in the sea surface temperatures (SSTs) of the Pacific are imposed on the lower atmosphere, which are then reflected in surface pressure gradients which reinforce the strength of the easterly trade winds (NRC, 1996). Large scale cooling by the SSTs in the eastern Pacific causes air to descend and cloud-free conditions to prevail. These conditions are accompanied by surface heating, ascending air, large scale convection and associated precipitation in the western Pacific, which accentuates the east-west airflow (NRC, 1996). This circulation pattern is known as the Walker Circulation (Figure 2.1).

During El Niño events, warm waters from the western tropical Pacific migrate eastwards to the central and eastern Pacific with an associated weakening in the easterly trade winds. Strong convection preferentially occurs over areas of warmest sea surface temperatures (Mason, 1997). The SOI goes into its low phase (Figure 2.1) with pressures increasing at Darwin, Australia and decreasing in Tahiti. Associated with the eastward shift in warm SSTs there is an associated eastward shift in the location of strong convection, resulting in a shift in tropical rainfall patterns to the central and eastern Pacific. The shift in SST patterns causes changes in the Walker Circulation pattern, as seen in Figure 2.1. Changes in atmospheric circulation patterns are not confined to the tropics, but extend globally and influence the jet streams and storm tracks in the mid-latitudes (Trenberth, 1996). While, Figure 2.1 does explain some of the variation in the global climate cycle it is a conceptual simplification and is not completely demonstrated in practice.

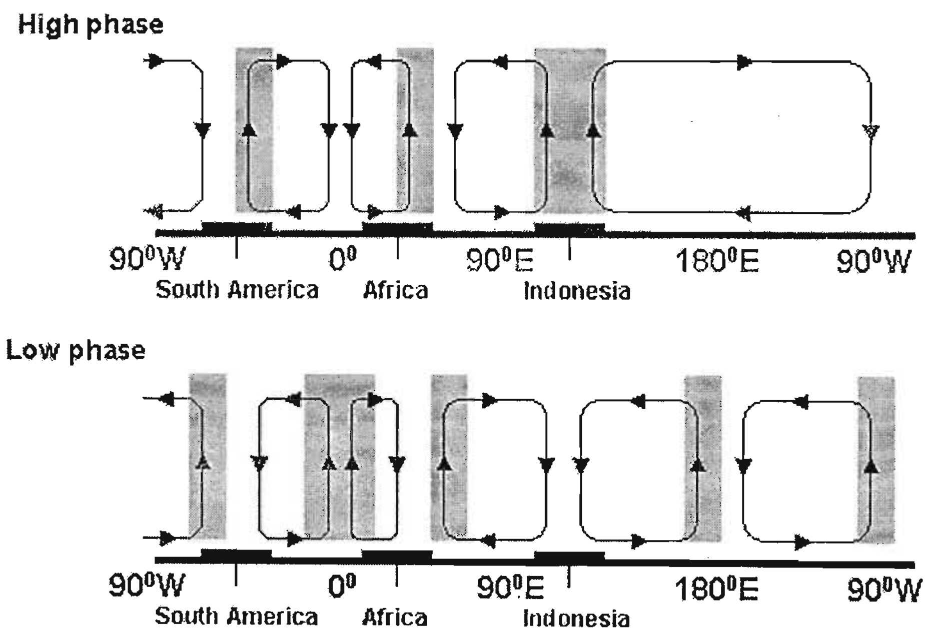


Figure 2.1 The Walker Circulation during low and high phases of the Southern Oscillation Index (after Tyson, 1986). Grey shades represent areas of preferential cloud development.

In relation to the eastward shift in the location of preferred convection in the tropical Pacific ocean during El Niño events, an eastward shift in the preferred location of convection is apparent over southern Africa (Tyson, 1986). As a result, strong convection occurs over the western Indian Ocean instead of over the subcontinent. This is partly due to an increase in SSTs in the western and central Indian Ocean, which frequently occurs during El Niño events (Mason, 1997). There is generally less rainfall over southern Africa during El Niño years as a result of the shift in the area of preferential convection. The influence of El Niño is found to be strongest in the peak summer rainfall months of December- March when ENSO events have reached maturity and the tropical atmosphere has a dominant bearing on the South African climate (Mason, 1997).

2.1.2 Links between the ENSO phenomenon and South African climate

It has been demonstrated that certain regions of southern Africa are influenced by the ENSO phenomenon (Ropelewski and Halpert, 1989). In several studies it has been demonstrated that strong teleconnections between the SOI and southern African rainfall exist (Lindesay, 1988; Ogallo, 1988; Van Heerden *et al.*, 1988; Nicholson and Kim, 1997). Lindesay (1988) showed that initial conditions of the atmosphere, as determined by whether the stratospheric QBO is in its westerly or easterly phase, significantly determines the magnitude of the influence of ENSO over southern Africa. When the QBO is in its westerly phase, more than 36% of the inter-annual variability in the late summer may be ascribed to the effect of the Southern Oscillation. In the easterly phase ENSO rainfall associations weaken, becoming almost insignificant (Lindesay, 1988). The linkage between ENSO and weather patterns over South Africa is still not completely understood and although statistically significant the physical explanation for the role of the QBO is still weak.

Summer rainfall (November to March) over the summer rainfall areas of South Africa has been found to be related to extreme phases of the ENSO phenomenon (Schulze, 1996; Landman, 1997). Sea surface temperatures in the equatorial Pacific, the Indian and the Atlantic Oceans have been linked to rainfall variability over southern Africa (Graham, 1996; Thiao, 1996; Landman, 1997). SSTs in the Indian and Atlantic Oceans have also been linked to the ENSO signal in the tropical Pacific (Nicholson, 1997). Extended research over the past two decades has provided an understanding that enables forecasters to predict major ENSO events with lead times of up to one year (Graham, 1996). Rautenbach (2001) showed that there are strong correlations between the SSTs in the Pacific Ocean and the October – March summer rainfall season over South Africa. Winter rainfall in South Africa responds poorly to global SST perturbations (Landman, 1997; Rautenbach, 2000). This suggests that relatively long lead rainfall forecasts could be obtained several months to a season in advance for summer rainfall over southern Africa.

Reliable long lead rainfall forecasts have the potential to reduce a major source of uncertainty in South Africa's highly erratic and variable climate. Rainfall forecasting, coupled with effective water demand and supply management, could therefore potentially allow hydraulic systems to be operated at more optimal capacities. Hence, a larger portion of the total water supply could be made available for consumptive use, extending the life of existing supply systems and increasing the security of the overall water supply. In the next chapter the total water demand and supply situation in South Africa will be reviewed, in an attempt to place forecasting in a more holistic perspective hydrologically.

3 SUPPLY AND DEMAND OF WATER RESOURCES IN SOUTH AFRICA

In the previous chapter an overview of the climate variability in South Africa was provided. In this chapter Objective (a)ii in the Problem Statement (Figure OB-3) is addressed by reviewing the current and future water supply situation in South Africa. An attempt will be made to expose the importance of forecasting, by highlighting the need for effective water resource management, in the context of South Africa's current and future water resource situation.

3.1 Water Supply in South Africa

There are a number of factors that exacerbate the South African water supply situation. South Africa as a whole has water resources that are scarce and limited in extent (Basson, 1997). The rainfall is poorly distributed spatially with a major part of the precipitation falling on the eastern seaboard, removed from the major centre of industrial development in the Gauteng province (Conley, 1996). In the past, water resource development has taken place largely along social and political lines, which has led to the uneven development of the resource (Barta, 1999). Industrial development has also taken place in areas where there is a predominance of mineral wealth, such as in the Gauteng urban complex, which are not necessarily in water abundant areas. This implies that in many areas of the country water utilisation has already exceeded the resource potential (e.g. in the Vaal and Crocodile catchments), necessitating the importation of water through inter-basin transfers (Basson, 1997).

South Africa's erratic precipitation and its high variability, both seasonally and inter-annually, has already been mentioned (cf. Section 2.2). Climate change and associated escalating temperatures resulting from the enhanced greenhouse effect could further exacerbate the current water supply situation with possibly even higher rainfall variability, increased evaporative demand and less rainfall than at present (Shackleton *et al.*, 1996; Schulze, 1997a, Perks, 2001). All climate change scenarios predict increased average temperatures over South Africa. It should, however, be noted that climate change scenarios are still in the preliminary stages of assessment and that these scenarios, while being plausible, are not forecasts that can be assumed to be correct. South Africa must rely on large impoundments to provide an assured supply of water and compensate for the variability of streamflow. Hence, large and well operated water schemes are a necessity, in order to ensure future development in South Africa.

Problem Statement				
Reliable, skillful hydrological forecasts have the potential to prevent loss of life, spare considerable hardship and save affected industry and commerce millions of Rands annually if applied operationally within the framework of water resources and risk management. Integrated model and database systems provide scientists and managers with tools to investigate the feasibility and applications of such systems in operational forecasting activities.				
Broad Objectives	Place forecasting within a framework of water resources and risk management in South Africa. *(a)*	Develop hydrological forecasting techniques that could be used operationally within South Africa. *(b)*	Evaluate the hydrological forecasting techniques' performance over the South Africa study region using selected forecasting periods. *(c)*	Discuss problems and shortfalls of the current methodology used to obtain the different runoff forecasts. Recommend areas of potential future research that would enable operational application of these forecasts. *(d)*
Specific Objectives	i. Review climate variability in South Africa and its associated effect on risk ii. Review the current water resource situation in South Africa iii. Review risk evaluation and management strategies with specific attention given to the role of forecasting	i. Review current methodologies used to obtain hydrological forecasts ii. Develop suitable methodologies to be used in South Africa iii. Develop unbiased techniques to evaluate the performance of the different hydrological forecasts	i. Use standard forecasting evaluation techniques to assess the performance of the hydrological forecasting techniques developed ii. Compare different hydrological forecast performances iii. Attempt to identify trends that influence forecast performance iv. Provide explanations for the different trends influencing the forecasts' performance	i. Identify shortfalls in the techniques used to translate rainfall forecasts into runoff forecasts ii. Suggest areas where improvements could be made to increase the forecasts' reliability iii. Suggest areas of future research that would lead to the operational use of the different runoff forecasts iv. Identify key sectors of the study area where the application of forecasting may be particularly beneficial

FigureOB-3: Problem Statement, highlighting aspects covered in Chapter 3

3.2 Water Demand in South Africa

South Africa's water requirements are anticipated to increase from 20 045 x 10^6 $m^3.a^{-1}$ in 1996 to 30 415 x 10^6 $m^3.a^{-1}$ by the year 2030 (Basson, 1997). The increase in demand can be attributed to population growth and economic development (Shackleton *et al.*, 1996). The South African population has increased from 22.273 million in 1970 to 40.584 million by 1996 (Orkin, 1998) at an average rate of increase of 2.4 % per annum between 1970 and 1995 (Anon, 1996). The economically active population has increased at an average rate of 1.99 % between 1991 and 1995 with employment in the manufacturing, construction and trade sectors increasing at average rates of 1.4%, 0.6% and 0.8% per annum respectively between 1970 and 1995 (Anon, 1996). The focus of this section will be on identifying how the specific sectors of the economy will demand water in future.

The historical development of water resources in South Africa has led to an uneven population distribution that reflects the physical, political, economic and social status of the past. This has led to the development of water resources according to a socio-economic scenario that favoured, for example, the reservation of water for irrigation and industries, including those involved in the production of synthetic fuels, *viz.* coal (Barta, 1999). Water demand in South Africa is currently shifting away from the dryland agricultural and irrigation sectors, which previously consumed the bulk of the surface water resources, towards the urban and industrial sectors as a result of a high rate of urbanisation and rapid industrial development (Table 3.1). In Table 3.1 it can be seen that the urban, domestic, industrial and mining sectors are expected to demand a far greater proportion of the total water supply by the year 2030 than in 1996. The greatest increase in demand comes from the urban and domestic sector, with a 12% increase. The irrigation, afforestation and environmental sectors, on the other hand, are going to have to make do with a smaller percentage of the total demand.

An increasingly important aspect in the demand for water in South Africa is that of assurance of supply. Certain industries, modern power stations, mines, sanitation works and even large irrigation projects require certain minimum amounts of water to remain operationally viable. Hence, as the economy grows and activities in these industries increase, there will be a greater demand for a certain set minimum of water to be supplied (Conley, 1996).

Table 3.1 Comparison of the 1996 water requirements for various sectors of the economy to those projected for 2030 (after Basson, 1997)

Sector of the Economy	Water requirements in 1996 (10^6 $m^3.a^{-1}$)	Projected water requirements in 2030 (10^6 $m^3.a^{-1}$)	Percentage of the total water requirement in 1996	Projected percentage of the total water requirement in 2030
Urban and domestic	2 171	6 936	10.8 %	22.8 %
Mining and industrial	1 598	3 380	8.0 %	11.1 %
Irrigation and afforestation	12 344	15 874	61.6 %	52.2 %
Environmental	3 932	4 225	19.6 %	13.9 %
Total	20 045	30 415	100.0 %	100.0 %

3.2.1 Urban and domestic water demand

The National Water Act of 1998 sets aside a certain quantity of water known as the "reserve". This reserve consists of two parts, the basic human need reserve and the ecological reserve. The basic human needs reserve provides for essential needs of individuals served by the water resource in question and includes water for drinking, for food preparation and for personal hygiene (National Water Act, 1998).

South Africa's increasing population will demand more water as a basic necessity. Rural communities are likely to place increased pressure on the groundwater and natural surface water supply as they demand their share of the reserve. However, rural communities will need to manage these resources more efficiently, as supplying water to such diffuse communities is both expensive and often impractical. The growing urban population is demanding a larger amount of potable domestic water. Many of these urban centres, such as the Gauteng urban complex, are located far from large reliable water sources. This means that large water schemes need to be implemented to assure supply in such areas (Conley, 1996).

3.2.2 Ecological demand

The ecological reserve relates to the water required to protect and sustain the aquatic ecosystem of the water resource (National Water Act, 1998). A minimum share of the water resources in South Africa is allocated to the environment. In South Africa, the protection of the natural environment is seen as a key factor in achieving sustainable development. Hence, the environmental demand will need to be factored in when assessing water supply schemes in the future (Shackleton *et al.*, 1996). The calculation of this demand is still in an initial stage and it is as yet very difficult to anticipate with accuracy the impact this demand will have on the water resources within South Africa.

South Africa's high climate variability is echoed and amplified in river flow regimes (Schulze, 1997b), which are even more variable (by a factor of 2 – 5 compared with rainfall; Schulze, 2001). The indigenous and endemic biota that live in such rivers have adapted to this high variability and require it for their survival. In order to sustain these ecosystems, it is necessary not only to provide the basic minimum amount of water, but also to maintain the variability, which allowed these systems to develop and survive. The environmental demand is hence highly erratic, varying locationally, seasonally and inter-annually. The complexity of the relationships and interactions inherent in any ecosystem makes the assessment of the environmental reserve a difficult and time consuming task.

3.2.3 Agricultural demand

Irrigation, using 54 % of the total water requirement, is the largest consumptive user of water in South Africa (Basson 1997). Food security is a major factor in the development of any country. Agriculture therefore plays an important role in the economy. Perusal of Table 3.1 indicates that agriculture and forestry, both rainfed and irrigated, use approximately 62% of the current (1996) total water demand in the country (Basson, 1997). A major portion of the agriculture and forestry sectors relies on rainfall, thus making it prone to the vagaries of climate variability. Higher future demands for water in the other sectors of the economy will increase the competition for water (Table 3.1). In the foreseeable future, the agricultural sector will have to give up the some of its share of water to the other sectors, making it a necessity for agriculture to optimise its water use (Watson, 1996).

3.2.4 Industrial demand

Industrial development is taking place at a rapid rate in South Africa. As the country develops so the industrial water demand increases. Industrial water use is predicted to increase from using 8% of the total water available in 1996 to using 11% by the year 2030 (Basson, 1997). This translates into a doubling in actual consumption, from 1 598 x 10^6 $m^3.a^{-1}$ to 3 380 x 10^6 $m^3.a^{-1}$ (Table 3.1). Water demand for industrial processes is relatively constant throughout the year, increasing linearly over time as a result of industrial expansion. Most industrial processes need a set minimum amount of water and if this is not supplied then the industry is unable to operate. Hence, the economic stability of industrial regions depends on the stability and assurance of water supply throughout the year and between years.

3.3 The Relationship Between Water Supply and Demand

When addressing the relationship between water supply and demand, supply is considered to be derived from rainfall and the demand is made up of the actual physical water quantities demanded by the various sectors of the community in a particular area. It should be noted that both the demand and supply curves in the figures presented in the ensuing pages are schematics that have been smoothed and are simplified in order to demonstrate various concepts. In addition, note that these diagrams have not been derived from actual data, but are rather conceptualisations of various principles that are being illustrated.

3.3.1 The relationship between domestic water demand and supply

Domestic demand, including non-industrial urban water usage, follows a similar pattern to that of agricultural demand in that, up to a point it fluctuates according to supply. The major difference with domestic demand and supply is that a certain set minimum must be supplied by law. In South Africa this is referred to as the basic human needs reserve and is the quantity of water required to provide for the essential needs of individuals (drinking, cooking, washing, sanitation) served by a water resource (National Water Act, 1998). The non-reserve domestic demand increases when the supply is low. The reason is similar to that for agricultural demand in that when the rainfall is low, so more water is required for non-essential uses such as gardening. The extent of the fluctuation in the domestic demand is not as pronounced as that in agriculture. The reason for this is that a certain amount of the water is used for essential operations that require a certain set amount of water. The other activities such as gardening and maintaining recreational facilities can make up a large amount of the total water use, according to socio-economic status. It is these non-essential water uses that tend to fluctuate according to the supply. These non-essential water users make up a portion of the total demand, while the other water uses remain relatively stable, implying that there is somewhat less variability in the domestic demand when compared to agricultural demand. In Figure 3.3 the consumptive patterns of urban and domestic water use are shown. The human demands in these areas (*i.e.* the set minimum) increase over time as a result of population increase and the degree of development.

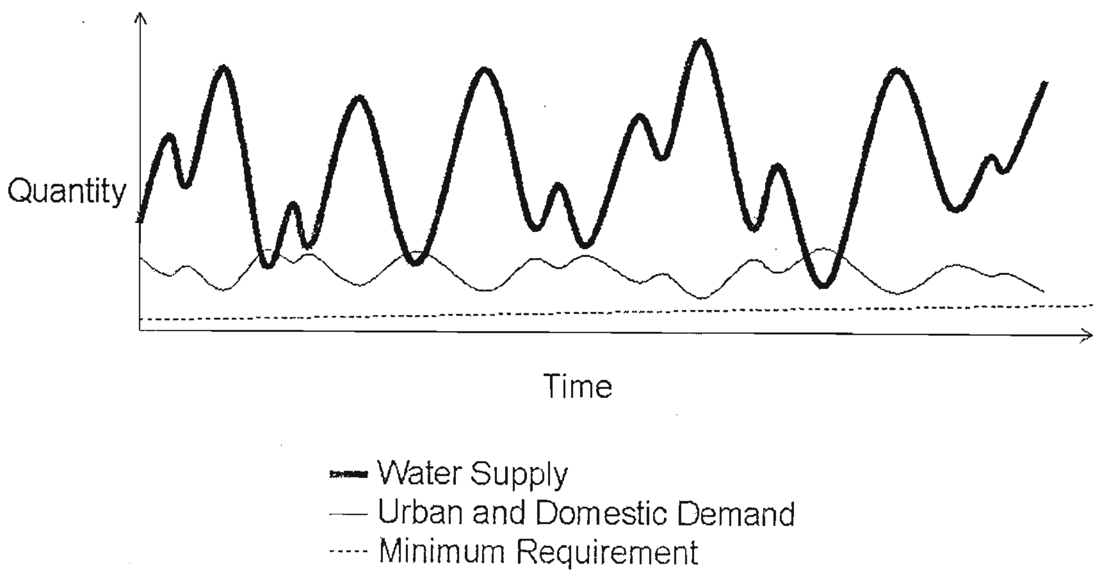


Figure 3.1 Relationships between domestic water demand against the water supply with time (schematic)

3.3.2 The relationship between ecological water demand and supply

The highly erratic nature of ecological demands and the complex interactions involved in them make the development of a formal relationship between water supply and environmental demand difficult. The environmental demand should mimic the natural hydrological cycles that occur in a particular area. This means that when the supply is low, the environmental water requirement should also follow suite and *visa versa*. However, the effects of changes in supply, i.e. rainfall, will only manifest themselves as changes in river flow once such changes have had the opportunity to filter through the catchment system. Hence, the environmental demand should essentially mirror the supply by rainfall, with consideration given to the various complex hydrological lags in an individual catchment's rainfall : runoff relationship (Figure 3.1).

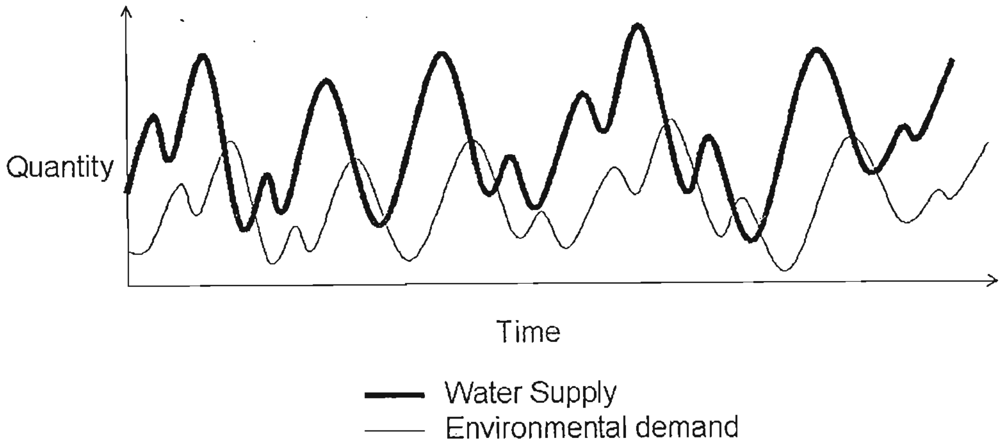


Figure 3.2 Relationships between water supply and environmental water demand with time (schematic)

3.3.3 The relationship between agricultural water demand and supply

The demand for water in agriculture is not constant, as it frequently increases when the supply is low. Plants and animals require a certain minimum amount of water to maintain production and survive. When the rainfall, and hence the supply, is low the plants and animals cannot obtain the required amount of water from their surroundings. In order to maintain a level of production when there is a deficit, the supply needs to be augmented, for example, by means such as irrigation and watering holes. This implies that there is an inverse relationship between the agricultural water demand and the water supply. This relationship is conceptualised in Figure 3.2 where, when the rainfall or supply increases, the demand decreases and *visa versa*.

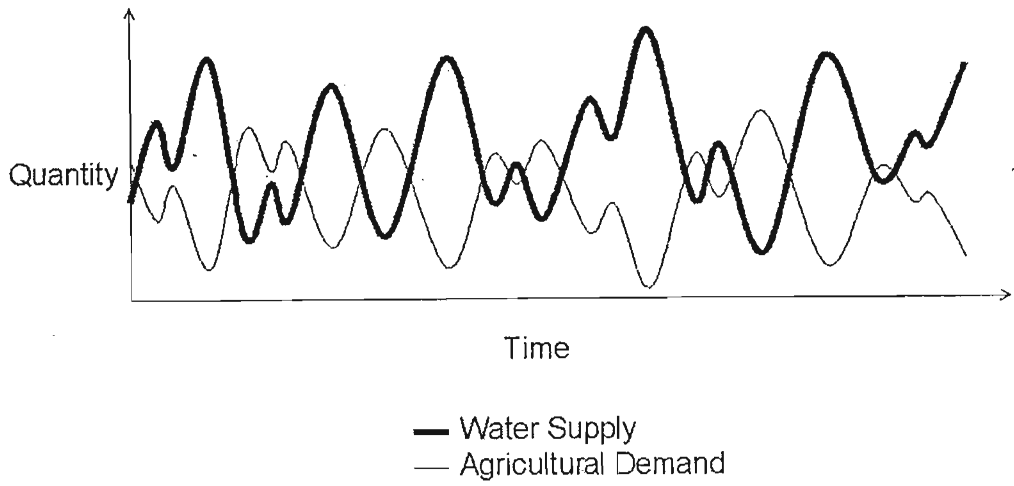


Figure 3.3 Relationships between the agricultural water demand and the water supply with time (schematic)

3.3.4 The relationship between industrial demand and supply

Most industrial processes require a certain constant amount of water throughout the year in order to operate. This implies that the industrial demand for water is relatively constant regardless of the fluctuations in the supply. This is illustrated in Figure 3.4 where the industrial demand remains constant despite the fluctuations in supply. The industrial demand increases, doubling in the next 30 years in South Africa (Basson, 1997), over time as a result of the increased industrial development in the country. On the other hand, as more efficient industrial processes are put in place, so this sector's water use may stabilise or even decrease. This will depend to a large degree on pricing structures of water.

3.3.5 Total demand compared to supply

The total water demand in an area is composed of demands from the different sectors of operating in that area. In terms of the National Water Act of 1998 the reserve must be met. This implies that the ecological and domestic sectors have preference when using the water and that their demand must be satisfied first. The estimation of the total demand is a complex task and estimating a total demand and supply curve for specific areas is difficult, as often the water demand in the various sectors of the economy responds differently to changes in supply. Water system designers need to take into account the maximum shortfall between supply and demand when designing systems, as well as the increase in fixed demand. It should also be noted that if the variability had to increase in the future, the supply would fluctuate even more and so, correspondingly, would the demand. This implies that to accompany the increased shortfall, system capacity would need to increase.

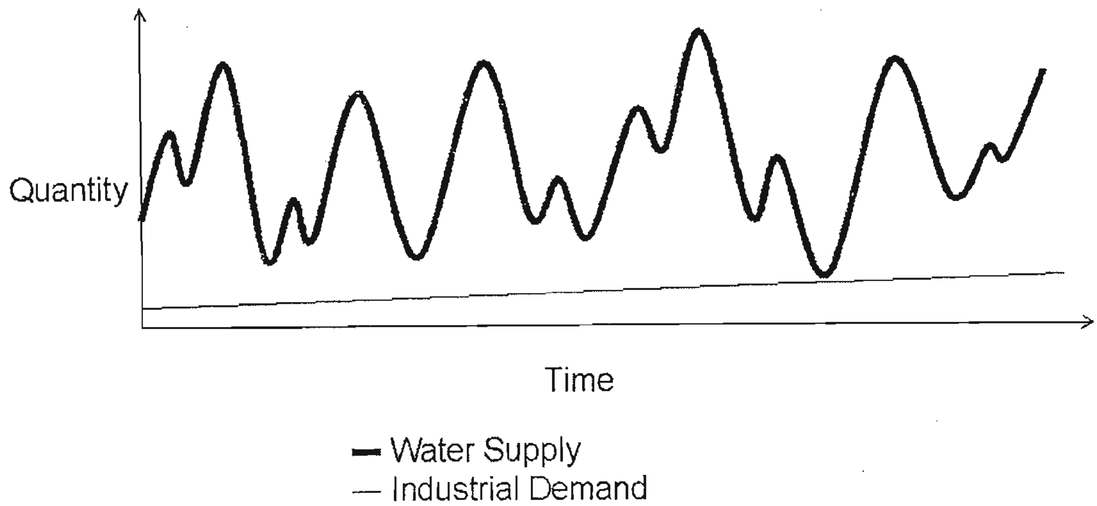


Figure 3.4 Relationship between industrial water demand and water supply over time (schematic)

Effective water resource management has the ability of increasing water resource systems operational efficiency, reducing wastages in the system and thus freeing up a greater amount of water for use. Hydrological forecasting has the ability to reduce uncertainty (associated with climate and runoff), allowing systems to be operated at a more optimal capacity, reducing safety margins/buffers in the system and thus reducing associated wastages. Identifying key sources of uncertainty enables researchers to proactively address these in the development of forecasts. While rainfall and runoff forecasting, when placed in the framework of water resources management, is seen as an effective tool in optimising systems operational efficiency, forecasting when placed in the framework of risk management can prevent loss of life, spare hardship and reduce financial losses associated with hydrological hazards. In the next Chapter the concepts of hazard and risk are reviewed, in an attempt to highlight the importance of forecasting within the framework of risk management.

4 HAZARD, VULNERABILITY AND RISK: GENERAL CONCEPTS

In the previous chapter a review of the current water supply and demand situation was provided in order to highlight the need for forecasting in water resources management. An integral part of most risk management programmes is forecasting. A basic comprehension of the concept of risk is therefore essential in gaining insight into the benefits of forecasting. However, before discussing a formal definition of risk it is prudent to investigate the concepts of hazard and Vulnerability. Hazard represents the natural and human induced threat that places a community, or area, at risk. In this section Objective (a)iii in the Problem Statement (Figure OB-4) is being addressed by reviewing hazard, vulnerability, risk and risk management with specific attention placed on the role of hydrological forecasting.

4.1 Hazard and Vulnerability

Hazard may be defined as a naturally occurring, or human induced, event that has the potential to create loss (Zhou, 1995; Smith, 1996; Fairman *et al.*, 1998). Within the scope of this study only naturally occurring and environmental hazards associated with hydrological variables (such as droughts and floods) will be reviewed. The initial definition above serves to highlight the concept that a physical process only becomes a hazard when it threatens to create some sort of loss (such as loss of life or damage to property) within the human environment (Smith, 1996). This is essentially an anthropocentric view of hazard and does not take into account the effect that an extreme natural event can have on an uninhabited area (Suter, 1993). The assessment of losses and the determination of the detrimental effects on future overall sustainability in uninhabited areas are extremely difficult to estimate and generally fall under the concept of ecological risk assessment (Suter, 1993). In this document the magnitude of a hazard is determined by the extent to which the physical event can disrupt the human environment.

A hazard is the combination of both the 'active' physical exposure to a natural process and the 'passive' vulnerability of the human system with which it is interacting (Plate, 1996).

The physical exposure is essentially the damage-causing potential of the event and is a function of both the intensity and duration of the physical process. However, although physical processes can cause damage, most physical processes produce some benefit to

Problem Statement				
Reliable, skillful hydrological forecasts have the potential to prevent loss of life, spare considerable hardship and save affected industry and commerce millions of Rands annually if applied operationally within the framework of water resources and risk management. Integrated model and database systems provide scientists and managers with tools to investigate the feasibility and applications of such systems in operational forecasting activities.				
Broad Objectives	Place forecasting within a framework of water resources and risk management in South Africa. *(a)*	Develop hydrological forecasting techniques that could be used operationally within South Africa. *(b)*	Evaluate the hydrological forecasting techniques' performance over the South Africa study region using selected forecasting periods. *(c)*	Discuss problems and shortfalls of the current methodology used to obtain the different runoff forecasts. Recommend areas of potential future research that would enable operational application of these forecasts. *(d)*
Specific Objectives	i. Review climate variability in South Africa and its associated effect on risk ii. Review the current water resource situation in South Africa iii. Review risk evaluation and management strategies with specific attention given to the role of forecasting	i. Review current methodologies used to obtain hydrological forecasts ii. Develop suitable methodologies to be used in South Africa iii. Develop unbiased techniques to evaluate the performance of the different hydrological forecasts	i. Use standard forecasting evaluation techniques to assess the performance of the hydrological forecasting techniques developed ii. Compare different hydrological forecast performances iii. Attempt to identify trends that influence forecast performance iv. Provide explanations for the different trends influencing the forecast's performance	i. Identify shortfalls in the techniques used to translate rainfall forecasts into runoff forecasts ii. Suggest areas where improvements could be made to increase the forecasts' reliability iii. Suggest areas of future research that would lead to the operational use of the different runoff forecasts iv. Identify key sectors of the study area where the application of forecasting may be particularly beneficial

Figure OB-4: Problem Statement, highlighting aspects covered in Chapter 4

the human environment with which they interact (Smith, 1996). Rainfall, for example, is Considered a benefit in that it is used in the crop growth process and it generates streamflows which feed dams which, in turn, can be used for recreation, irrigation and domestic water use. A natural process, however, becomes a hazard when it produces an event that exceeds the bounds that the environment can normally tolerate. In the case of rainfall, too much produces a flood hazard and too little a drought hazard. In Figure 4.1 the shaded area represents the tolerance limits of the variation about the average, within which the resource can be used beneficially for social and economic activities in the human environment (Plate, 1996). Hence, a process only becomes a hazard once it has exceeded a certain threshold. The magnitude by which an event exceeds a given threshold determines the damage-causing potential of such an event. The term 'intensity' refers to the severity of a natural process, thus the greater the intensity the greater the damage-causing potential (e.g. rainfall at 20 $mm.h^{-1}$ is generally less damaging than at 100 $mm.h^{-1}$ over the same time period). Duration is the other variable determining the damage-causing potential of an event. The longer the exposure to an event, the greater the damage-causing potential (Zhou, 1995; Plate,1996; Smith, 1996). The hazard intensity is determined by the peak deviation beyond the threshold (vertical scale in Figure 4.1). Hazard duration is determined by the length of time the threshold is exceeded (horizontal scale in Figure 4.1).

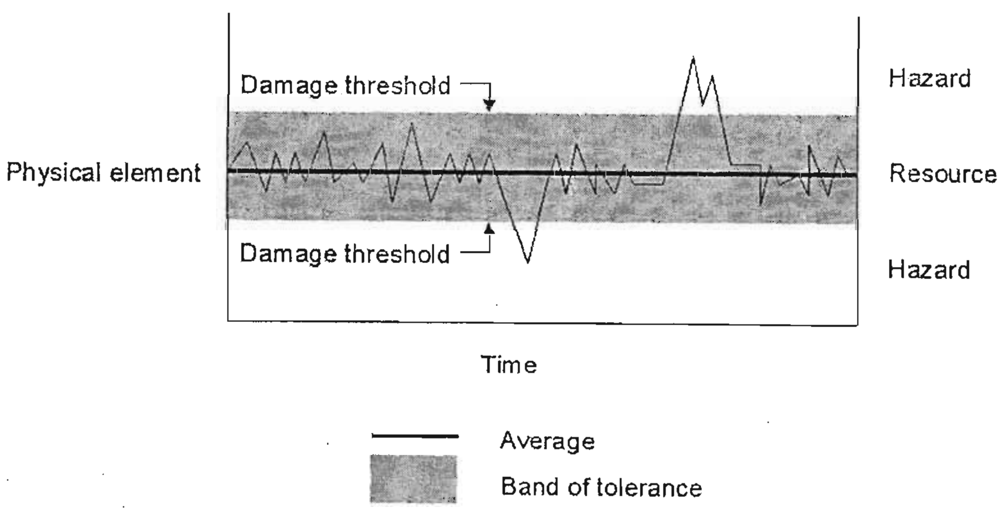


Figure 4.1 The magnitude of environmental hazard expressed as a function of the variability of physical elements and the degree of socio-economic tolerance (after Smith, 1996; Smith and Ward, 1998)

The concept of threshold also applies to the passive dimension of the vulnerability of the human system to damage from a natural process. Vulnerability is the most manipulable dimension in risk management schemes and thus assumes most importance in any hazard assessment (Smith and Ward, 1998). Vulnerability is the degree to which a system or its components react to a hazardous event (Gilard, 1996).

Vulnerability is a function of the resilience and reliability of a system. Resilience is the capacity of a system to absorb and recover from a hazardous event (Vogel, 1997). Reliability is the probability that the system, or component of the system, will perform its intended function for a specified period of time (Frankel, 1984; Plate, 1996). For example, a dam is constructed to withstand a certain flood magnitude before the wall fails; the reliability is the ability of the wall to perform this task. In terms of a so-called 'assault' event (rainfall, heat, pollution, deposit) the vulnerability threshold is determined by the system absorption and redirection capacities (Vogel, 1997). The thresholds in the case of a so-called 'deprivation' event (e.g. drought, cold, leaching, erosion) are determined by the retention and replacement capacities of the system (Smith, 1996).

Hazards represent only the potential to create loss. Loss is incurred when the hazard potential is realised. It is important to understand that not all hazards produce disasters. Disaster is the extreme form of hazard realisation, causing extensive damage and sometimes loss of life.

4.2 Risk

Risk is defined as the probability of specific hazard occurrence (Smith, 1996). Hence, risk is comprised of two factors viz., the probability of occurrence and the loss caused by the associated hazard realisation (Fairman *et al.*, 1998; Shamir, 1996). The two major factors that influence the risk associated with an event in an area are changes to the physical system affecting that area and changes to the vulnerability in that area (Vogel, 1997). In Figure 4.2 several of the possibilities that give rise to increased risk are illustrated. Case A represents a scenario where the tolerance and the variability remain constant, but there is a rise in the mean value (e.g. a trend occurs due to change in landuse). In this particular case the frequency of extreme events at one end of the scale increases. Case B shows a scenario in which both the mean and the band of tolerance remain constant, but the variability increases (e.g. change in variability associated with climate change). In this particular case the frequency of damage producing events increases at both ends of the scale. In Case C the physical variable does not change, but the band of tolerance narrows, i.e. the vulnerability of the human system increases (e.g. vulnerability increases as people locate their houses closer to a river). In this particular scenario the frequency of damage-causing events increases at both ends of the scale.

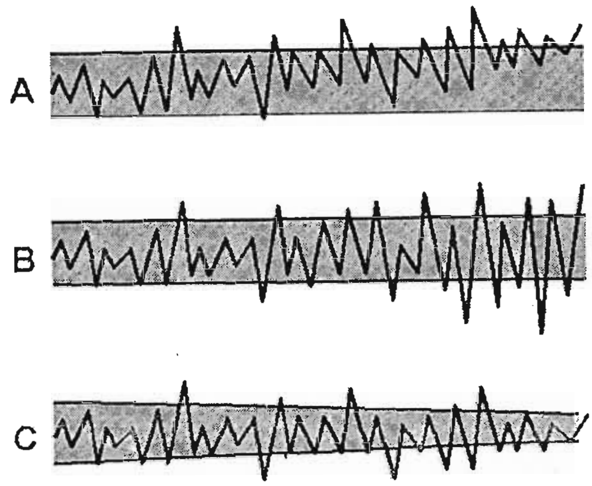


Figure 4.2 A schematic illustration in which risk changes due to variations in the physical system and socio-economic events. In all the cases risk increases over time (after Smith, 1996; Smith and Ward, 1998)

4.2.1 Risk assessment

Absolute safety is impossible as any situation, or activity, has some level of risk involved (Zhou, 1995; Plate, 1996). The concept of risk assessment is to determine the level of risk which is acceptable for any activity or situation (Fairman *et al.*, 1998). However, not all situations and activities are subject to rigorous scientific evaluation of risk. Most risk assessment takes the form of subjective evaluation of perceived risk, either by an individual or by a community (Douglas and Wildavsky, 1982). There is often a conflict between technical risk analysis and subjective risk perception. As most situations and activities are embarked upon after an evaluation of the perceived risk, it is important to understand the differences between objective and perceived risk. Along with hazard identification, risk assessment is the initial part of any risk management programme (Plate, 1996). Risk assessment in risk management programmes attempts to reconcile the differences between objectively obtained risk and perceived risk (Smith, 1996).

Objective risk analysis is usually undertaken at the initial stages of many large construction projects, or the planning of an activity involving a large number of people. In the process a certain type of hazard is identified and its probability of occurrence calculated. Suter (1993) define risk assessment as the process of assigning magnitudes and probabilities to the adverse effects of a human activity or a natural catastrophe. An objective view of risk assessment could be defined as the statistical evaluation of risk, based on mathematical theories of probability and scientific methods of identifying causal links between the different types of hazardous activity and the resulting adverse consequences (Plate, 1996; Smith, 1996). Smith (1996) identifies several distinct steps in such a scientific risk assessment, *viz*:

i. identification of hazards likely to result in loss;
ii. the estimation of the probability of such an event (i.e. the calculation of risk); and
iii. evaluation of the consequences of the derived risk (i.e. assessing the loss created by each event).

Risk, as defined earlier, is a function of probability and loss. Hence, risk could be measured (Plate, 1979; Plate, 1996; Smith, 1996; Shamir, 1996) as some factor of probability (P) and loss (L) as follows :

$$R = P \times L$$

Once the causal event, or hazard, has been defined then a probability analysis is undertaken. In the case of a flood the causal event could be heavy rainfall, or more directly, a rise in river levels. Probabilities are calculated using techniques of extreme event analysis. A record of a specific hazard threat (in the case of flooding the river stage) is ranked. The ranked record is used to calculate recurrence intervals (i.e. river stage) and probabilities. Once probabilities have been attained the losses of life, property and income are estimated to determine the expected risk associated with each event (Plate, 1979; Zhou, 1995; Plate, 1996).

There are several disadvantages in extreme event analysis that can sometimes render the results unrealistic and non-representative. An extreme event analysis is only as good as the data that are available. In many cases the record length may not be sufficient to calculate the probabilities of extremely large events with large return periods. Extrapolating beyond the bounds of the data produces major uncertainties as the trend may be different for larger events. The quality of the data is important. If data are inaccurate then the estimates will be poor. The ability of a measuring site to represent a region is important, as the extrapolation of point data to represent an area can introduce large errors. Extreme event analysis is performed on past records and will not identify trends if a system is changing over time. Hence the probability distribution could change over time. Variability could increase, resulting in an increase or decrease in the frequency of extreme events at both ends of the scale. The mean could shift, causing an increase in the number of extreme events at one end of the probability distribution, while decreasing the number of events at the lower end of the scale. Changes in the probability distribution do not cause linear changes in the extreme events. A small increase in the mean of the probability distribution could cause a large increase in the number of extreme events (Plate, 1979; Smith, 1996; Zhou, 1995; Fairman *et al.*, 1998).

There are, however, major differences between objectively calculated risk and subjectively perceived risk (Plate, 1996; Smith, 1996). Perceived risk is unique to the individual or community that is undertaking a specific activity. Subjectively determined risk is based on the experiences of the community, or individual, and may well be different to the objectively determined risk. Perceived risk can be divided into two main components, *viz.* involuntary risk and voluntary risk. Involuntary risk is risk that is not willingly undertaken by communities or individuals. It is usually associated with events of rare catastrophic potential and the person or community exposed does not know the risk involved or perceives it as uncontrollable. Voluntary risk is risk more willingly accepted by a person or community through their own actions (Douglas and Wildavsky, 1982). This type of risk is associated with less catastrophic events that occur more frequently. Perceived risk is often skewed in favour of the consequences of an event rather than its probability. The risk equation hence becomes

$$R = P \times L^{m}$$

where m is a factor > 1 and represents the weighting that a community or individual places on the loss caused by an event (Whyte and Burton, 1982). In objective analysis an event that occurs often may have the same level of risk as a rare event that causes large loss of life. However, the perceived risk would tend to favour the event that causes a large loss of life.

Hazard perception is influenced by many factors such as past experiences, present attitudes, personality, values and future expectations. The major influence on risk perception is past experience, as those with direct personal knowledge of previous events have a more accurate perception of the likelihood and magnitude of future events (Suter, 1993). When direct knowledge, or experience, with disaster is lacking individuals learn about hazards from many indirect sources such as the media. Risk perception of a group may be influenced by social and cultural factors (Douglas and Wildavsky, 1982). Risk perception can be influenced through the "locus of control" (Smith, 1996), which classifies people according to the extent that they believe a hazardous event to be dependent on fate (external control) versus it being within their own realm of responsibility (internal control).

There are three basic types of risk perception that hazard perceivers tend to adopt in order to reduce stress associated with uncertainty (Smith, 1996) :

i. A person, or group, that exercises determinate perception accepts that hazards exist, but seeks to place extreme events in an ordered manner following some sort of cycle or pattern. This does not take into account the random nature associated with most hazard threats.

ii. Dissonant perception does not recognise the possible threat of a hazard and is hence a form of threat denial. Dissonant perception can take on several forms. In many cases the hazard has not been experienced in the past and therefore its threat is not perceived. In other cases, past hazardous events may be viewed as anomalies that are unlikely to be repeated and therefore the threat tends to be denied.

iii. Probabilistic perception acknowledges that disasters will occur and accepts that certain events are random. In some cases, however, the acceptance of risk is often combined with the need to transfer the responsibility of dealing with the hazard event to a higher authority, i.e. "an act of God". The probabilistic view has sometime led to a fatalistic attitude whereby the individual feels no personal responsibility to hazard response and will avoid expenditure on risk reduction.

All three categories of risk perception produce a jaded perspective of the actual risk involved. This can lead to an increase in the vulnerability of certain communities or individuals when the risk perception is less than the actual risk threat. Several of the factors that are thought to increase or decrease risk perception are given in Table 4.1.

There is currently a paradigm shift occurring whereby hazardous events are no longer perceived as "acts of God" that are uncontrolled and unlikely to happen. Extreme events are now being viewed as part of the natural system that are likely to occur at some undetermined stage in the future (Fairman *et al.*, 1998). This view is being adopted by scientific community, which is beginning to find causal links between extreme events and natural phenomena. This perception is beginning to filter through to the educated public and is changing their risk perception. Extreme events are not only seen as certainties that will happen at some stage, but the view is held that the consequences of such events can be reduced or avoided through proper risk management.

Table 4.1 Twelve factors influencing public risk perception with some examples, in brackets, of relative safety judgements (after Whyte and Burton, 1982)

Factors tending to increase risk perception	Factors tending to decrease risk perception
Involuntary hazard (Swept away in flood waters)	**Voluntary hazard** (White water rafting)
Immediate impact (Flash flood)	**Delayed impact** (Drought)
Direct impact (Structural damage due to flooding)	**Indirect impact** (Drought)
Dreaded hazard (Flash flood)	**Common hazard** (Annual flood event)
Many fatalities per event (Major dam burst)	**Few fatalities per event** (Farm dam burst)
Death grouped in space time (Avalanche, landslide or dam burst)	**Deaths random in space time** (Drought)
Identifiable victims (People dying of hunger)	**Statistical victims** (Farmers loss of income)
Processes not well understood (Climate change impacts)	**Processes well understood** (Frontal rainfall)
Uncontrollable hazard (Tropical cyclone)	**Controllable hazard** (Dam releases)
Unfamiliar hazard (Tsunami)	**Familiar situation** (River flood)
Lack of trust in authority (Private industrialist)	**Trust in authority** (University scientist)
Much media attention (Floods in capital city)	**Little media attention** (Flood in isolated rural area)

4.2.2 Risk management

The managerial adjustments made by society to environmental hazards are a combination of risk assessment and risk perception (Smith, 1996). An objective approach to risk management is highly desirable. However, there is no universally accepted value system for risk decisions and a subjective element will inevitably be present (Plate, 1996).

In the past an effective risk management programme was seen to depend on the implementation of a sequential series of actions. However, in more recent risk management models it is recognised that the elements of a programme overlap and that their importance changes through the sequence of a hazardous event. This is known as the expand - contract model of risk management where events are managed in a parallel series of activities rather than in a sequence of actions (Anon, 1998). Risk management is seen as a continuous process where the different strands of activity continue side by side, expanding and contracting as needed (Anon, 1998). There are several key elements to any risk management programme and they form the basis of the strands of activities in the expand and contract model (Plate,1996; Smith, 1996; Anon, 1998) :

i. *The prevention and mitigation, or pre-disaster planning, strand.* The prevention aspect of this strand usually involves the establishment of defensive structures that will prevent, or reduce, the destructive ability of an extreme event (an example is the construction of dams or levees to control flood waters). The mitigation aspect involves the setting up of measures that can be taken in order to minimise the destructive and disruptive effects of hazards and thus lessen the scale of disaster. The mitigation actions are usually those involved with the formulation, dissemination and maintenance of evacuation plans.

ii. *Preparedness strand.* This action involves the ability to respond to a hazard event and reflects the degree of alertness immediately before the onset of a hazard. This action is generally concerned with the arrangements of early warning systems and the effectiveness with which institutions can implement the mitigation plans.

iii. *Response and relief strand.* This category deals with events immediately before and after they have happened, including reactions to warnings and emergency relief activities.

iv. *The rehabilitation, or relief and recovery strand.* This strand refers to the long-term activities that are designed to re-establish the affected area or community after the event. These activities usually involve the rebuilding of infrastructure and the financial support of those most affected.

Risk management is therefore a process that involves both long and short term attempts at reducing risk. There are two main loss reduction methodologies that could be followed, *viz.*

i. modification of the physical processes, or events, that create the hazard threat; and
ii. reducing the impact of the event through reducing the vulnerability of the human environment (Smith, 1996).

The major difference between the two strategies is that event modification involves some degree of direct confrontation with the hazard-causing event, whereas human vulnerability modification relies on hazard avoidance, involving mainly non-structural responses (Smith, 1996).

Physical event modification aims at reducing the damage potential associated with a particular hazard by some degree of physical control over the event involved. A strategy known as environmental control could, theoretically, be used to suppress the causes of a hazard by diffusing the releases of energy or materials over a greater area and/or period of time (Smith, 1996). However, with the current state of technology the suppression of natural events such as possible flood events is not yet possible or, alternatively, produces uncertain results. The use of such a strategy is hence extremely limited.

Event modification can also be achieved via a strategy of manipulating the secondary processes that cause a hazard, rather than attempting to attack the root cause. In the case of floods, instead of trying to manipulate the rainfall event, the runoff generation processes could be manipulated using land phase management. Hazard resistance is another form of event modification involving the construction of defensive engineering structures, the setting of building codes and retro-fitting older structures (Plate, 1996).

Vulnerability modification is a more intricate process that involves the interaction of several different interrelated factors that need to act in tandem in order to reduce the impact of a hazard event (Anon, 1998). Vulnerability modification is concerned with human reactions toward hazards and involves the changing of human attitudes and behaviour. Hazard loss reduction has been achieved through the implementation of several different measures. These include

i. community preparedness programmes;
ii. forecasting and warning systems; and

iii. legal and financial measures.

Successful risk management programmes are able to link all of these measures into one interrelated programme (Anon, 1998).

Preparedness is defined as the pre-arranged emergency measures which are to be taken to minimise the loss of life and property damage following the onset of a hazard. Preparedness programmes involve the detailed planning and testing of prompt and efficient response by both individuals and groups to hazards that have either been forecasted or have occurred. Preparedness programmes focus on public education and awareness, evacuation plans, the provision of medical and food aid as well as shelter for evacuees. Long term preparedness programmes have been implemented successfully in many of the more developed countries. The authoritarian political and under-resourced financial frameworks in many of the less developed countries have limited the development of good preparedness programmes (Smith, 1996; Okada, 1998).

Forecasting and warning systems have become increasingly important in recent decades. This can be attributed to the scientific advances in information and communications technology, such as satellites, which have improved forecast accuracy and increased the efficiency of warning systems (Tyson, 1986). However, in some cases warnings are based on predictions only, as the processes or hazards are not yet sufficiently understood to provide forecasts (Landman, 1997).

Predictions are based on statistical theory, which uses the historical records to estimate the probability of occurrence of events. The predictions are, therefore, based on average probabilities and give no indication of when a particular event may occur. Forecasts, on the other hand, tend to focus on individual events where the physical processes or statistical interlinkages are relatively well understood (Smith, 1996; Tennant, 1998a). Depending on the nature of the event being forecast, it is possible to provide information about its timing, location and magnitude. Forecasts are thus able to eliminate major sources of uncertainty and hence reduce risk (Rook, 1996). Forecasting combined with efficient warning systems are able reduce the loss of life and damage to property resulting from many hazards (Lecler *et al.*, 1996).

Legal and financial measures are designed to either avoid the settlement of individuals or communities into areas of high risk, or to provide aid that is able to accelerate the recovery of affected communities. Legal measures can, for example, involve land use planning that is designed to prevent the participation in certain activities in high risk areas, i.e. they are a form of non-structural control (Smith, 1996).

4.2.3 The major factors influencing the risk associated with environmental hazards in South Africa

In many areas throughout the world the risks associated with environmental hazards are increasing. This is a result of escalation in the probability of occurrence of extreme events as well as in an increase in the losses associated with such events (Figure 4.2). These changes in risk can either be attributed to anthropogenically induced changes to the physical system, natural changes in the physical system or to changes in the vulnerability of the human environment interacting with the physical system.

4.2.3.1 Changes occurring within the physical system

Changes in the physical system tend to influence the probability of occurrence of extreme events. This implies that they either shift the mean, or change the variability, of events associated with hazard-causing phenomena.

In South Africa climate change and anticipated escalated temperatures due to the enhanced greenhouse effect could result in higher rainfall variability, increased evaporative demand and less rainfall than at present (Shackleton *et al.*, 1996; Schulze and Perks, 2000). In drier areas the higher evaporative demand due to increased temperatures could result in enhanced desiccation, leading to greater aridity in such areas. Increases in global mean temperatures are expected to augment the water holding capacity of the air. This, in turn, could theoretically increase average amount of precipitation and result in a greater number of extreme flood producing rainfall events (Schulze, 1997a). Increases in the average SSTs could result in an intensification of the severity and a greater number of tropical cyclones. Increases in the number of tropical cyclones passing down the Mozambican channel could also significantly increase the number of flood producing rainfall events in the eastern part of South Africa. Increases in the SSTs could also result in higher average sea levels, increasing the number of coastal flooding events. These factors combine to produce more flood hazards on a global scale (IPCC, 1996b). In South Africa an increase in the number of both dry and wet extreme events could thus increasing exposure to both flood and drought hazards (Schulze, 1997a; Perks, 2001).

In South Africa population pressure and industrial development are changing the physical catchment characteristics in many areas. Land use changes resulting from development change the physical aspects of an area, which result in changes in the physical response to different hazard causing phenomenon (Kienzle *et al.*, 1997). South Africa is experiencing a high population growth rate, 2.4% between 1970 and 1995 (Anon, 1996), coupled with rapid urbanisation. The urban population expanded from 13.7 million in 1980 to 21.3 million in 1995 at a rate of over 3% per annum (Calitz, 1991; Calitz and Grove, 1991). These two factors are combining to cause land use changes in many areas throughout South Africa.

Urbanisation and resulting development increases imperviousness and decreases the hydrograph response times of catchments, resulting in the quicker onset and increased magnitude of flood events. Hence, in many areas of South Africa rapid urban development is increasing the probability of occurrence of greater magnitude flood events. Van Beek (1993) estimated that approximately 1 100 informal houses had been established below the 1:50 year flood plain near the Jukskei river in the Alexandra township, as a result of high population pressure and a high rate of urbanisation. In this area alone, it was estimated that more than 6 000 people are vulnerable to a flood hazard.

In rural areas, population pressures are placing increased demand on the natural resources with many marginal areas are now being cultivated, resulting in land denudation which is exacerbated by overgrazing and poor farming practices (Kienzle *et al.*, 1997). The decreased carrying capacity of the land increases the severity of damages associated with drought events. Vegetation removal can also increase the hydraulic smoothness of the catchment, by removing flow impeding vegetation and increasing the soil surface compaction, decreasing the time of concentration and increasing flood.

Commercial farming in South Africa is also under pressure to increase yields to support the growing population. Irrigation agriculture and forestry are major users of water resources in South Africa (Kienzle *et al.*, 1997; Schulze *et al.*,1990). Afforestation tends to reduce runoff as trees enhance the infiltrability of the catchment by retarding water surface flows and intercepting rainfall as well as trees usually having higher transpiration rates than the natural vegetation they replace (Schulze, 1995). Irrigation, on the other hand, reduces the streamflow by direct extraction from the source (Schulze et al., 1998). This could result in increased hydrological drought occurrence to downstream users.

4.2.3.2 Changes in vulnerability

Perhaps the major factor that is causing increased economic and life losses, as a result of hazards is the change in the vulnerability of the human environment. Vulnerability is essentially a combination of resilience to hazard, which is the ability to cope with hazard threats, and reliability of structures, i.e. the ability of structures to cope with disaster (UNEP, 2000). Changes in the vulnerability in South Africa can be attributed to changes in resilience as a result of changes in the population dynamics of the country. Poverty, education, culture and age all impact the vulnerability of an individual (Smith, 1996). Large rural to urban migrations that are currently taking place in South Africa are changing the population structures in many communities. Hence, the poverty, education, culture and age structures in such communities are also changing, resulting in the vulnerability changes.

Losses of life due to hazard threats are age dependent, especially in the case of drought and flood disasters. The majority of the loss of life is restricted to those people who lack the physical strength to withstand the initial disaster onset, e.g. swimming in the case of floods, or the physical robustness to withstand the results of the disaster, e.g. the ability to fight off post-event disease (Smith, 1996). The population in South Africa grew at a rate of 2.06% per annum between 1991 and 1995 (Anon., 1996). High growth rates tend to create a population distribution of predominantly young people (Figure 4.3). Over 10% of the population is below the age of 5, while more than 40% of the population is below the age of 20 (Orkin, 1999). With a predominantly young population a large number of people in the vulnerable category are exposed to hazard threats. This means that the vulnerability to hazardous events in the country as a whole increases. Whiteside and Sunter (2000) performed a study in KwaZulu-Natal having a look at the impact of AIDS. Population projections showed that without the AIDS epidemic population would grow at an average of 1.76% between 1996 and 2010. However, if the impact of the AIDS epidemic was considered the population in KwaZulu-Natal would grow at an average rate of 0.58%, with negative growth being experienced in the years 2008 to 2010 (Whiteside and Sunter, 2000). Assuming these trends could be extended to the rest of the country the population growth could slow considerably from those shown in previous census data.

The AIDS epidemic also has the potential to affect the population dynamic influencing the population pyramid significantly from that shown in Figure 4.3 (Whiteside and Sunter, 2000). Being a sexually transmitted disease it targets mainly the sexually active population, but can also be transmitted from pregnant mother to child. Whiteside and Sunter (2000) show that the AIDS is mainly targeting the sexually and economically active population with the largest number of projected aids related fatalities falling in the age groups of between 20 and 50 years of age. This means that the young, sexually active component of the population that should be most resilient to disaster, is decreasing, leaving a greater percentage of the population that is vulnerable to disaster. The infant AIDS infections also leave this already vulnerable sector of the population even more prone to disaster losses. The number of orphan infants is also increasing as the parents die due to AIDS related diseases.

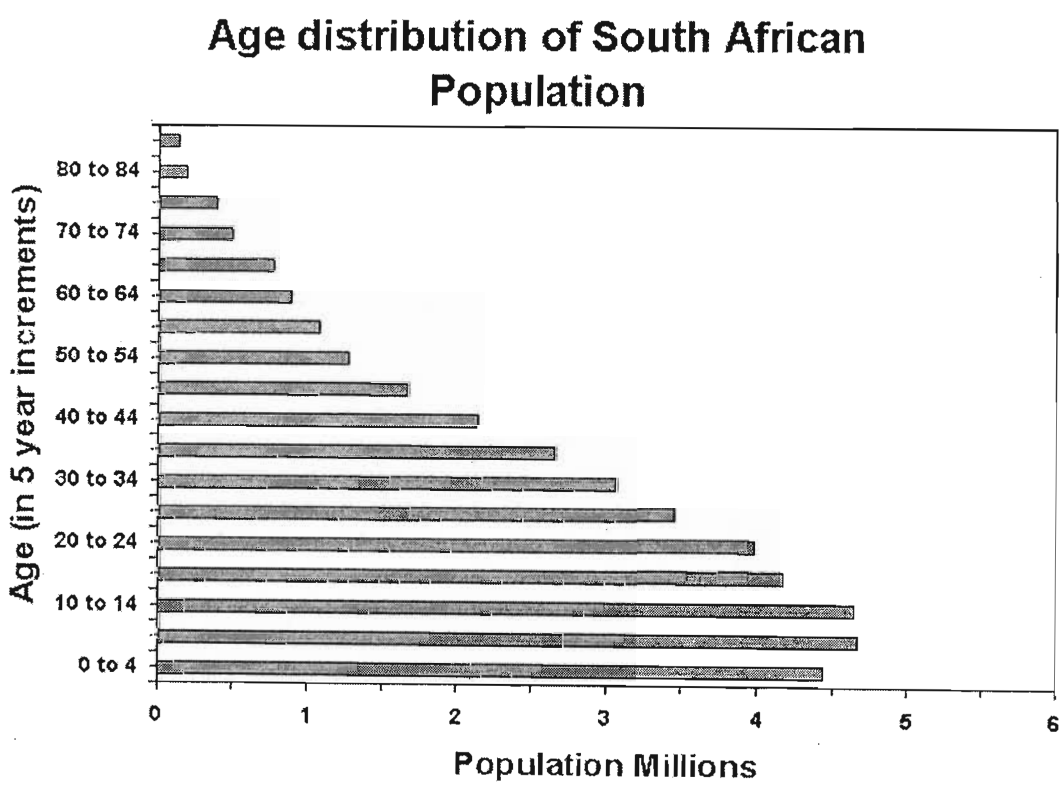


Figure 4.3 The age distribution of the South African population derived from the Population Census of 1996, with results provided in Orkin (1999)

Massive rural to urban migrations are also changing the population structures in rural communities, where the traditional social and cultural fabric is changing as a consequence. The urban population is growing at a faster rate than that of the population as a whole (Calitz, 1996). In 1995 the urban population had reached 53.7%, implying that the majority of South Africans lived in urban areas (Orkin, 1999). Figure 4.4 shows the age distribution of the urban and non-urban population for the black sector of the South African population. Proportionately, a larger percentage of the economically active population between the ages of 20 and 60 live in urban areas.

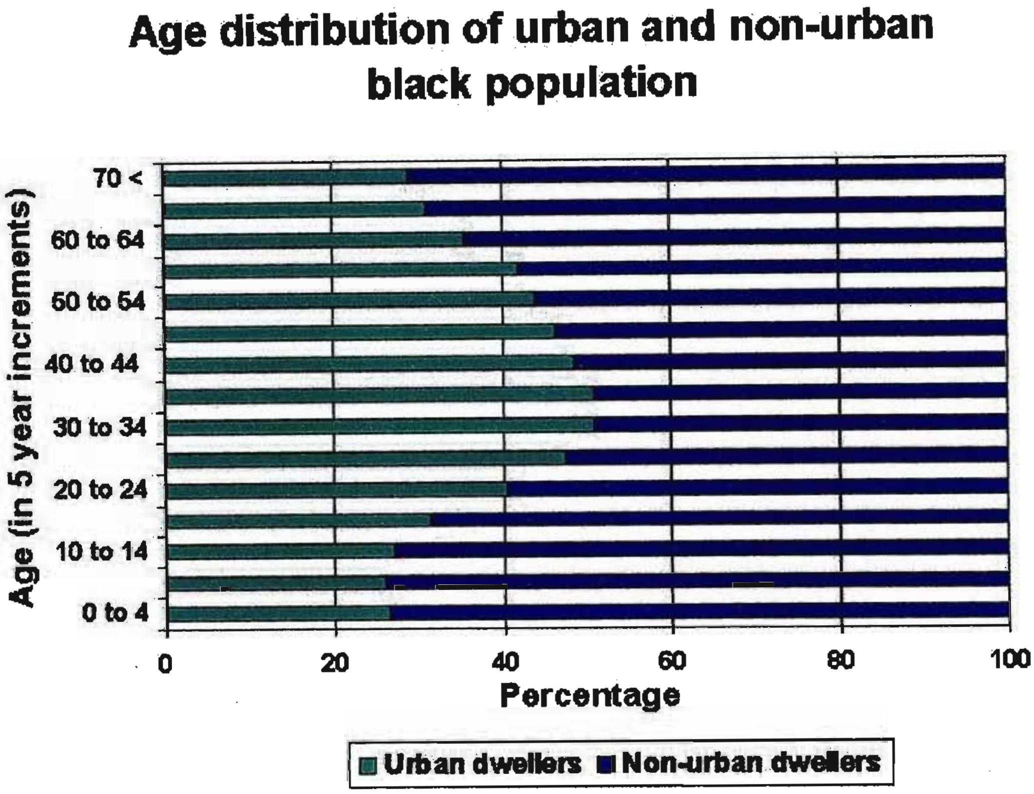


Figure 4.4 A percentage age distribution showing the urban and non-urban population distribution of the black community in South Africa (compiled from information in Orkin, 1999)

Another factor affecting the resilience of a population is poverty. The wealthy are more adept at coping with disaster as they have the financial flexibility to recover more quickly from hazard event losses. The wealthy are also able to procure better medical facilities and expertise in the case of illness of injury caused by hazard events. In general, the wealthy are also able to construct better dwellings that are better able to withstand the physical stresses caused by hazard events. The poor are hence more vulnerable to hazards. South Africa has a relatively stable economy and is wealthier than most other African nations. However, if the population growth outstrips economic growth or if the population decrease at a slower rate than economic decline as a result of the AIDS epidemic, the country as a whole will become poorer and hence its vulnerability to drought and flood disaster events increases.

Education and experience are two further major factors in the mitigation of hazard losses. The perception of hazard consequences is related to the level of education and actual experience of a hazard event (UNEP, 2000). The better educated people are the more likely they are to have gained second hand knowledge of which areas are affected by different types of hazards and the consequences of such hazards (Smith and Ward, 1998). First hand experience of a hazard event is also able to give a person a better perception of hazard consequences. In South Africa a large portion of the population is uneducated and with increased rural to urban migration taking place there is little, or no, experience of the types of hydrological hazard or their consequences as people settle into new places of domicile.

Vulnerability is further being increased by rapid development and urbanisation. In many areas settlement and development are taking place rapidly, leading to the construction of poorly designed and built dwellings (van Beek, 1993). Many of these structures do not have the ability to withstand hazards events and are more prone to failure than well designed and built structures. In South Africa rapid urbanisation and development have resulted in much uncontrolled development with the consequence of potentially greater losses to hazard threats and increased vulnerability.

In the following chapter, risk will be discussed with special reference placed on hydrological hazards, namely, floods and droughts.

5 FORECASTING, MANAGEMENT AND RISK ASSOCIATED WITH HYDROLOGICAL HAZARDS IN SOUTH AFRICA

In Chapters 2, 3 and 4 a large part of Objective (a) described in the Problem Statement (Figure OB-5) was covered, with the following aspects having been addressed:

i. Climate variability in South Africa,
ii. Water resources in South Africa, and
iii. Hazard and risk in a more generic context, with only some reference to the South African situation.

In this chapter the primary focus will be on Objective (a)iii in Figure OB-5, and will concentrate on the two most common hydrological hazards in South Africa, *viz.* droughts and floods, with specific attention given to the manner in which forecasting can be used in a broader management framework to reduce losses associated with flood and drought hazard occurrence. In the initial sections of this chapter a review of the hazards associated with excessively wet and dry periods, that have the potential to develop into flood and drought phenomena, with specific reference to South Africa, is provided. The impacts associated with these phenomena are then analysed. This is followed by a discussion of the vulnerability associated with both the flood and drought phenomena. Finally, some management strategies adopted to prevent losses associated with excessively wet and dry periods and their resultant hazards, are reviewed.

5.1 Hydrological Hazards Resulting from Floods and Droughts

5.1.1 Floods

A flood can be defined as any body of water which rises to overflow land that is not normally inundated (Ward, 1978; Acreman *et al.*, 2000). This definition of a flood is broad and covers all flooding activities that are caused by natural phenomena, including those from tsunamis, earthquakes and extreme rainfall events, or from disruptions emanating from human design shortcomings, such as dam failure. Floods can be separated into two major categories, *viz.* river floods and coastal floods. Coastal floods affect low lying coastal areas where a small increase in the sea level may cause extensive flooding (Smith and Ward, 1998). Hazards that cause coastal flooding are associated with atmospheric phenomena that result in storm surges, or with tectonic disturbances such as earthquakes that can cause tsunamis. Coastal flooding is not that great a threat in South

Africa as the country is relatively stable in tectonic terms and has reasonably steep shorelines with few extensive low lying coastal plains.

Since the primary focus of this dissertation is on the South Africa study region, the focus will be restricted to river floods, which result from the interaction between uncontrollable natural weather conditions and the characteristics of a river basin such as the topography, soil and underground water conditions, land use patterns and river morphology (Zhou, 1995). River floods are a common occurrence in South Africa and are a major source of disruption and damage in the country. Sources of river floods can be tectonic (e.g. earthquakes and landslides), technological (e.g. dam failure) and atmospheric (e.g. severe storms). The major cause of most river floods is a result of atmospheric disturbances and can be caused by either excessive rainfall, rapid snowmelt or ice jams (Smith and Ward, 1998). The latter two are not causes of floods in a South African context as temperatures are not low enough for long periods of time to sustain extensive build up of snow and ice. The majority of floods in South Africa are hence rainfall-related river floods, which are generally associated with either atmospheric standing wave disturbances in the mid-latitude Westerlies, such as cut-off lows responsible for floods in Laingsburg in 1981, KwaZulu-Natal in 1987 and in the central interior in 1988, or tropical disturbances, which caused the floods in KwaZulu-Natal through tropical cyclone Domoina in 1984 (Caelum, 1991; van Bladeren, 1993;Tyson, 1996).

Flooding is the most common of all environmental hazards, regularly claiming 20 000 lives and affecting 75 million people per annum on a global scale (Smith 1996; Acreman *et al.*, 2000). Flood losses and damages are not restricted to the immediate event in the form of drowning or damage to property. In the longer term, further deaths could result as a consequence of the spread of water-borne diseases, such as malaria and typhoid (Epstein, 1998). The breakdown of infrastructure, with resultant delays and losses in income, could affect the economy as a whole (Zhou, 1995; Smith and Ward, 1998). However, floods do also bring some benefit to the affected regions (provided they do not exceed hazard thresholds, (Figure 4.1) and may even be an integral part of their agricultural system. Floods in South Africa can carry heavy silt loads, which can help to fertilise flood plains. Floods also form an integral part of the livelihood of some people in South Africa, such as the tribes on the Maketini flats in northern KwaZulu-Natal who use the annual flooding of the Pongola river for fish harvesting.

Problem Statement				
Reliable, skillful hydrological forecasts have the potential to prevent loss of life, spare considerable hardship and save affected industry and commerce millions of Rands annually if applied operationally within the framework of water resources and risk management. Integrated model and database systems provide scientists and managers with tools to investigate the feasibility and applications of such systems in operational forecasting activities.				
Broad Objectives	Place forecasting within a framework of water resources and risk management in South Africa. *(a)*	Develop hydrological forecasting techniques that could be used operationally within South Africa. *(b)*	Evaluate the hydrological forecasting techniques' performance over the South Africa study region using selected forecasting periods. *(c)*	Discuss problems and shortfalls of the current methodology used to obtain the different runoff forecasts. Recommend areas of potential future research that would enable operational application of these forecasts. *(d)*
Specific Objectives	i. Review climate variability in South Africa and its associated effect on risk ii. Review the current water resource situation in South Africa iii. Review risk evaluation and management strategies with specific attention given to the role of forecasting	i. Review current methodologies used to obtain hydrological forecasts ii. Develop suitable methodologies to be used in South Africa iii. Develop unbiased techniques to evaluate the performance of the different hydrological forecasts	i. Use standard forecasting evaluation techniques to assess the performance of the hydrological forecasting techniques developed ii. Compare different hydrological forecast performances iii. Attempt to identify trends that influence forecast performance iv. Provide explanations for the different trends influencing the forecast's performance	i. Identify shortfalls in the techniques used to translate rainfall forecasts into runoff forecasts ii. Suggest areas where improvements could be made to increase the forecasts' reliability iii. Suggest areas of future research that would lead to the operational use of the different runoff forecasts iv. Identify key sectors of the study area where the application of forecasting may be particularly beneficial

Figure OB-5: Problem statement, highlighting aspects covered in Chapter 5

5.1.2 Drought

Drought can be defined as an unusually dry period that results in a shortage of water (Smith, 1996). In contrast to flood hazards, a drought can be defined as a "creeping" hazard because its onset and development is gradual and the drought phenomenon can last a considerable length of time (Smith, 1996). Rainfall deficiencies are the trigger causing drought, but shortage of useful water in the soil, rivers and reservoirs are what create the drought hazard (Gibberd *et al.*, 1996; Watson, 1996). It is important to appreciate that not all rainfall deficiencies result in drought. Water shortages are relative, and hence drought must not be mistaken for aridity. People, vegetation and animals adapt their water usage to the prevailing climatic conditions within an area. Hence the definition of what constitutes a drought is different in different areas and depends on what are considered the normal climatic conditions within an area (Smith, 1996). Drought impacts are essentially dynamic, resulting from interactions between demand and supply of water at a regional scale.

It has been estimated worldwide on an annual basis, that two hundred thousand people are killed and one billion people are affected by drought (Smith,1996). Although drought can cause considerable economic losses in More Developed Countries (MDC) there are virtually no deaths associated with the phenomenon in such countries (Smith, 1996). The majority of the losses are confined to Less Developed Countries (LDC) that do not have the financial and physical infrastructure to cope with drought disaster (Clements, 1990). Drought losses tend to follow socio-economic lines, with the majority of losses being confined to the rural poor. This places South Africa in a position with its disparate distribution of wealth and levels of development, exposing different sectors of the economy to the effects of drought to different degrees.

The severity of droughts in semi-arid and arid areas, which constitute the majority of South Africa, tends to be greater than in sub-humid or humid climatic zones (Schulze, 1997b). Only 7% of South Africa has a Mean Annual Precipitation (MAP) greater than 800 mm per annum while Whitmore in 1971 estimated that on average 91% of the MAP was lost to evaporation. The two major reasons for this are that climate variability tends to increase with aridity (Yair and Lavee, 1985) and that the duration of dry spells in arid areas tends to be longer than in more humid areas (Schulze, 1997b).

The impacts of droughts can affect food production on a national level and the effects can cascade throughout the economy. The impacts of such droughts are most severe for countries that have a large proportion of the economy dependent on agricultural production (Rook, 1996).

5.2 Impacts Associated with Flood and Drought Hazards

The impacts of floods and droughts can be broken down into several categories according to the nature of the impact (*direct* or *indirect*) or the measurability of the impact (*tangible* or *intangible*), as shown in Figure 5.1.

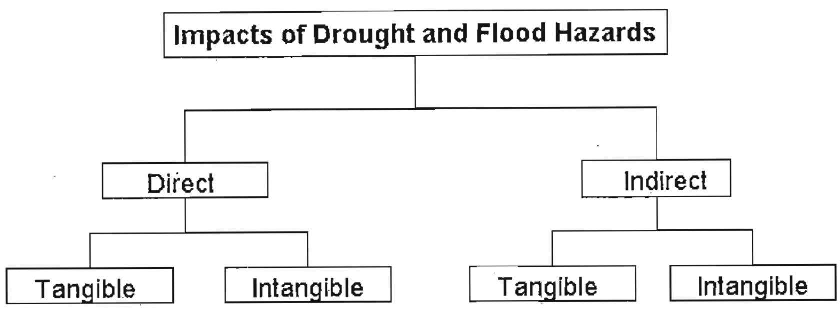


Figure 5.1 Different types of impacts of droughts and floods, classified according to the nature of the impact and the measurability of the impact (adapted from Zhou, 1995; Smith and Ward, 1998).

Direct impacts refer to those damages caused by physical contact with the assault (flood) or deprivation (drought) event, such as the collapse of a bridge caused by flood waters or crop failure due to lack of rainfall. *Indirect* impacts can be defined as the damages that result from either physical damages, such as disruption of traffic or trade in the case of a flood, or losses resulting from the hazard event, such as losses of farm income as a result of crop failure in the case of drought (Gibberd *et al.*, 1996; Zhou, 1995).

Hazard impacts that are not easily quantifiable in terms of loss of life or monetary units, such as psychological trauma or malnutrition, are considered to be *intangible* impacts. *Tangible* hazard impacts, on the other hand, are impacts that are easily quantifiable in terms of loss of life or monetary value, such as repair costs to infrastructure or crop re-establishment (Smith, 1996).

The impacts of hydrological hazards are not confined to the immediate event, such as loss of agriculture and livestock production in the case of a drought, or loss of life due to drowning and damage to property in the case of floods, but have a larger multi-dimensional impact on the community and country as a whole (Rook, 1996; Zhou, 1995).

Direct tangible flood losses are limited to those persons and properties located in the potentially inundated area and include loss of life due to drowning, physical damage to property such as buildings and their contents, damages to infrastructure (roads, railways, bridges and tunnels) and public utilities (sewage treatment, gas, electricity, water supply, telecommunications), losses of assets such as vehicles and boats, agricultural and livestock losses, and damage to the environment (Zhou, 1995; Smith and Ward, 1998).

Tangible indirect flood losses are those losses associated with the flood event but are not the immediate result of the event. They include loss of life due to illnesses resulting from a flood event (such as gastro-intestinal diseases as a result of the destruction of sanitation facilities and the outbreak of epidemics related to water-borne diseases such as cholera, typhoid and malaria) production and service losses due to the disruption of network infrastructure and public utilities as well as the cost of emergency measures (medical and financial aid) and cleanup (Zhou, 1995; Smith 1996; Epstein, 1998).

Intangible damages are usually damages that are incurred after the flooding event has taken place. These damages may only manifest themselves months, if not years, after the event and may affect the sustainability of the area as a whole. Damages can be incurred at both an individual and community level, eventually filtering through to the economy of a country as a whole (Smith and Ward, 1998). *Intangible* damages on an individual household level include health effects as a result of either physical effects (e.g. cold) or as psychological effects (irritation, grief, worry about future events, sense of inadequacy), as well as loss of memorabilia and other irreplaceable contents. They also include disruption to life and time spent getting back to 'normality'. On the other hand, *intangible* losses incurred at a community level include inconvenience due to the disruption of public utilities and infrastructure, damage to archaeological elements and other sites of historical and cultural value, damage to recreational facilities, and damages to fish and wildlife, natural vegetation and other environmental assets (Zhou, 1995).

Figure 5.2 shows the multi-dimensional impacts that drought can have on food security and the economy of a country. Drought and the resulting water shortages can have a *direct* impact on agriculture, livestock and manufacturing production, as well as on service industries such as power generation, tourism and health. The initial impact of drought on agriculture has an *indirect* effect on other economic sectors as it leads to reduced supply of raw materials to agriculturally dependent industries and demand for goods and inputs for the agricultural sector (Rook, 1996). Drought also generally increases unemployment in the agricultural sector, resulting in reduced overall income and depressed demand in the economy as a whole. Drought, although it reduces the demand of for goods and hence imports, also reduces exports and can increase imports of basic necessities, such as food, having a negative effect on the balance of payments (i.e. imports exceed exports resulting in an outflow of currency). Drought has implications for both government revenue and expenditure. There is a reduction in tax revenues as a result of lower corporate and personal earnings, reduced household consumption, corporate profits and asset values (Rook, 1996). Expenditure increases as money is poured into drought and poverty relief programmes. Droughts force food prices up as a result of lack of supply and hence have an overall inflationary effect (Rook, 1996).

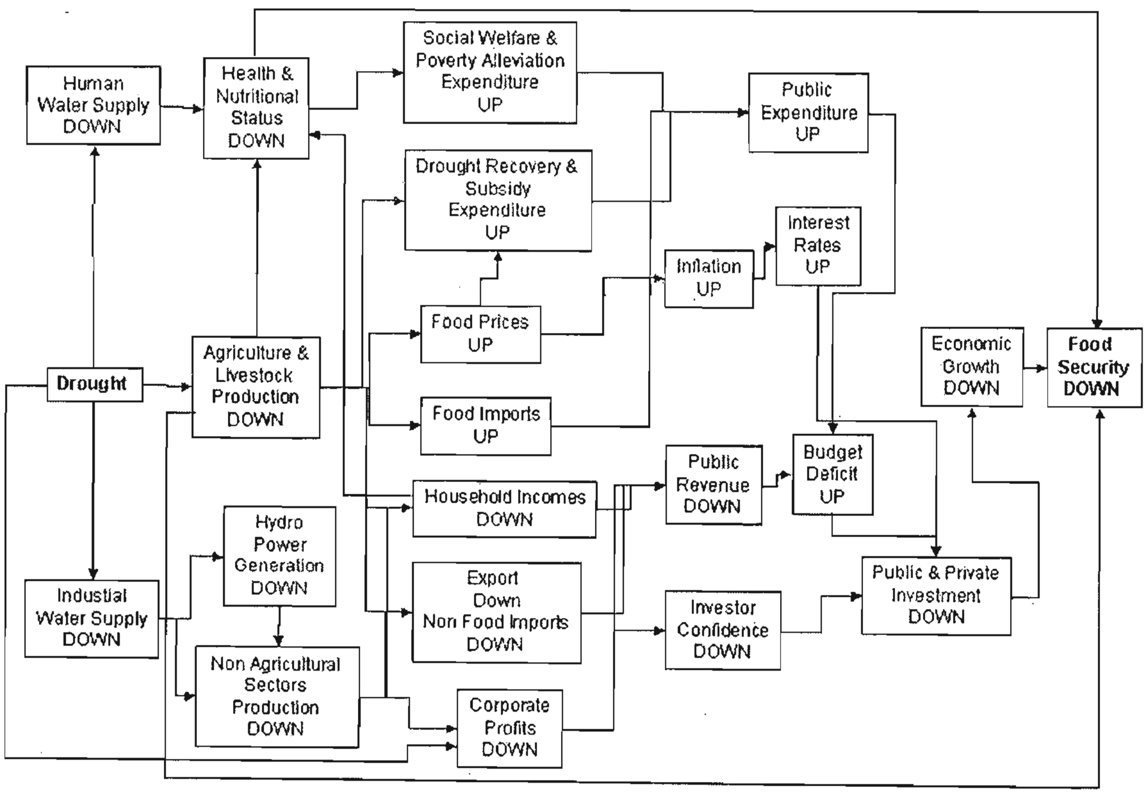


Figure 5.2 The multi-dimensional impact of drought on food security and the economy (after Rook, 1996)

5.3 Vulnerability to Floods and Droughts

As has been shown in Chapter 4 vulnerability is essentially a combination of the resilience and reliability. The reliability is essentially the ability of a system to withstand exposure to the hazard threat while the resilience is the capacity of a system to absorb and recover from a hazard event (Frankel, 1984; Plate, 1996; Vogel, 1997). Hence, vulnerability comprises an external dimension, which is the threat of an event that may increasingly predispose people to risk and an internal dimension, which is the internal capacity to absorb or respond to a hazard threat (Schulze, 2000). While, in South Africa, vulnerability is increasing largely as a result of changes in external factors such as climate and land use changes, the major impact on vulnerability is being produced by complex interactions of internal factors, and can mainly be attributed to changes in the social, political and economic dynamics within the region.

In South Africa, as in other countries in the developing world, the vulnerability to flood hazards is increasing (van Beek, 1993; Acreman *et al.*, 2000). In many developing countries, including South Africa, the increase in vulnerability associated with flood hazards is primarily due to increased population pressure, urbanisation and rapid development, which has lead to the settlement of people in, and the development of, areas prone to flooding (van Beek, 1993). Some of the high risk areas that are characterised by development in South Africa are listed below (van Beek, 1993; Smith and Ward, 1998)

i. Low lying active floodplains in both large and small river systems. These flood plains often offer good areas for settlement, as the soil is generally fertile and the land flat making it easy to cultivate and build on. The close proximity of the water source, which can be used for irrigation and essential needs, is also an advantage.
ii. Small catchments subject to flash floods, particularly in urban areas: Such areas in South Africa are particularly prone to flood disasters where the effect of convective, short duration, high intensity rainfall events, steep slopes and lack of vegetation combine to cause rapid onset flooding events. The Jukskei river in Guateng is a particularly good example, where 6 000 people live in areas below the 1:50 year flood line (van Beek, 1993).
iii. Areas below unsafe or inadequately sized dams are prone to devastating flood events. Dam failure causes rapid onset and high peak flooding events that often have a catastrophic effect on downstream communities.

iv. Alluvial fans in arid areas, where such areas often offer good drainage combined with excellent views and access to underground water, making them attractive for settlement. Flows across such features are often erratic following braided channels, which can cause extensive damage as a result of intense flow concentrations and associated high velocity flows.

Settlement in the areas mentioned above essentially increases the community's vulnerability to direct impacts of floods. Lack of infrastructure and medical facilities, especially in rural areas, increases the vulnerability of people to water-borne diseases such as cholera, typhoid and malaria.

The majority of drought losses are experienced in lesser developed countries where a large proportion of the population is dependent on agricultural production as a means of livelihood (Gibberd *et al.*, 1996). These communities do not have the financial strength and flexibility to absorb the impacts of drought. Most famine-related deaths result from complications and lack of health associated with starvation. The sectors of a community most at risk are the aged and the young who do not have the ability to fight off disease (Epstein, 1998). Hence, populations with a high number of infants and the elderly are at most risk from drought disaster. In lesser developed countries the population structure in rural areas is changing as a result of mass urbanisation, with the fit and strong young people leaving the rural areas to find work in cities (Figure 4.4). This means that rural areas are left with the elderly and young, who are the most vulnerable to drought disasters.

The primary factors that determine the level of vulnerability of a region to drought impacts are the following (Fredriksen, 1995):

i. The first is the degree to which a region is dependent on a source (or sources) of water supply. Regions where water supplies are derived from a single catchment with minimal storage or supplies and relying on marginal aquifers are obviously most vulnerable to drought.
ii. Secondly, the water distribution between different human and economic sectors within the region is important, with the percentage of domestic, urban, industrial and agricultural uses determining the degree of flexibility for response to shortages. If large portions of the water supply are used by key industries, domestic needs and other priority users, there is little buffer to protect such users in the case of water shortages.

iii. Thirdly, the level of water utilisation is an important consideration. Where a large amount of the available water resource is used, there is only a small buffer to absorb the impacts of drought.

iv. Fourthly, water quality is a major factor, as drought tends to be associated with low flows, which concentrate pollution and decrease water quality. Low quality water needs to be treated before it can be used to supply certain areas. If treatment is not possible water scarcity is increased.

v. Finally, the institutional framework in an area is a crucial factor in determining a region's level of drought vulnerability. The institutional framework can affect the response time to recognising the potential for water shortages, and means of overcoming such shortages (by rationing or inter-basin transfers). Hence it can impact the severity of such a shortage.

In South Africa vulnerability to rainfall variability is compounded by several factors, some of which are listed below (Rook, 1996; Schulze, 1997b).

i. South Africa has a large sector in subsistence agriculture with more than 50% of the population living in rural areas and largely relying on their own efforts to secure food supplies for their own families. Hence, food security for the majority of South Africans is dependent on the rainfall season.

ii. The agricultural sector plays an important role in the South African economy, employing over 16% of the economically active population as well as contributing significantly to gross national product (>4%) and export earnings (> R 10 billion in 1995).

iii. Irrigation makes up only 1.1% of the cultivated area of South Africa, implying that a large portion of the commercial agricultural production is dependent on rainfall. This means that food production is highly sensitive to rainfall fluctuations.

iv. The preferred staple food for approximately 70 % of South Africans is maize. The lack of crop diversity, particularly in subsistence agricultural production and especially the lack of cultivation of more drought tolerant crops such as sorghum, millet and cassava, increases the vulnerability of those farmers directly dependent on a fluctuating climate.

5.4 Risk Management of Flood and Drought Hazards

Risk management is the process that attempts to reduce the risk posed by hazards, both in the long and short term, by enabling decision makers and stakeholders to choose the best course of action under a given range of situations (Fairman *et al.*, 1998; Schulze, 2001). As was demonstrated in Chapter 4, there are several different models proposed for risk management which all provide a formalised framework within which decision makers and stakeholders are able to compare the potential harm posed by a hazard to the potential benefits it could provide, and enable them to choose the appropriate risk reduction measures (Gilard, 1996; Fairman *et al.*, 1998). In Figure 5.3 the main components of any risk management programme, with particular reference to hydrology, are shown. In South Africa the so-called "expand and contract" model of risk management has been adopted, by the Ministry of Provincial Affairs and Constitutional Development, in which all the different components of a risk management programme (i.e. hazard determination, risk evaluation, hazard modification and vulnerability modification) operate in conjunction with each other, but each component of the management programme takes on different levels of importance according to the progress of the hazard event (Anon, 1998).

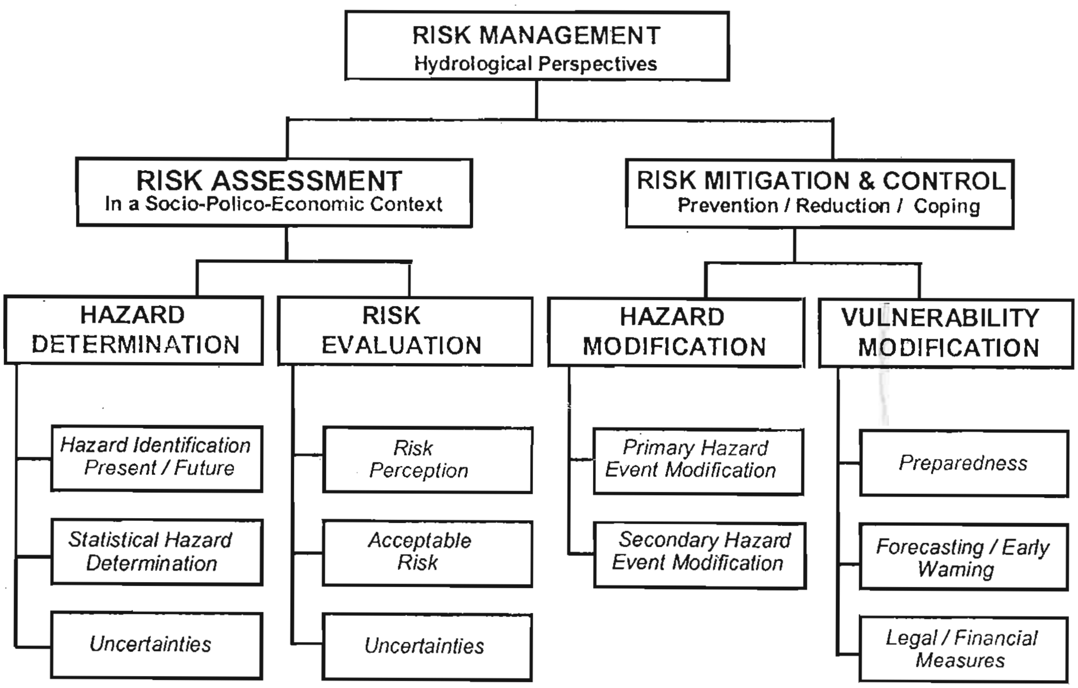


Figure 5.3 Schematic overview showing the different components of risk management programmes (Schulze, 2001)

5.4.1 Risk assessment for floods and droughts in South Africa

Hazard determination and risk evaluation in South Africa generally take on the form of statistical methods used to determine the risk associated with a certain hazard occurrence, such as a flood or drought, from past observed records of climate, such as temperature and rainfall, or other variables, such as streamflow (van Bladeren, 1993; Smithers and Schulze, 2000). Risk evaluation is usually undertaken prior to the development and construction of any large formal structures and schemes, such as dams, roads or housing developments, and usually takes the form of extreme value analysis on historical records. However, uncertainties surround the use of extreme value analysis to determine the risks associated with flood and drought hazards in South Africa. These uncertainties relate to factors such as record length, data quality and the stationarity of data (Schulze, 2001). In order to overcome some of the problems introduced by uncertainties in observed data sets, physically based hydrological and atmospheric models are now being used in South Africa. These models are often able to augment existing data records and are able to account for factors that may be changing the stationarity of existing data sets, such as the effect of land use changes on streamflow (Schulze, 1995) and the effects of climate change in the case of temperature and rainfall (Tennant, 1998a).

While formal extreme value analysis may be carried out prior to the construction of formal structures, in informal sector developments such as small houses, shacks and subsistence agricultural development, scientific methods of risk evaluation are not always followed and such developments often rely on the perceptions of risk of the responsible party. The risk determination and perception in such cases is a function of the level of education and the level of experience of specific hazards within a certain area (Smith, 1996). In South Africa population growth and urbanisation have resulted in an enormous growth in informal sector housing (van Beek, 1993) and the development of marginal areas for subsistence agriculture. Often many people in such areas have low levels of education and little experience of hazard occurrence, making them highly vulnerable to hazards threats.

5.4.2 Risk mitigation and control of floods and drought in South Africa

Risk mitigation and control can be divided into two sections, *viz.* hazard modification and vulnerability modification (Schulze, 2001; Figure 5.3). Hazard modification concentrates decreasing *direct* impacts of a hazard event and takes the form of event modification strategies that either concentrate on the primary hazard, such as high rainfall, or on the secondary hazard, such as increased river flow (Plate, 1996). Vulnerability modification, on the other hand, as discussed in Chapter 4, is primarily concerned with human reactions towards potential hazard events and is a process that involves the intricate interaction of several different but interrelated factors that are required to act in tandem in order to reduce the impact of a hazard event. Vulnerability modification programmes employ three main measures, *viz.* preparedness programmes, forecasting and warning systems and legal and financial measures, which are used to in conjunction with one another to reduce losses associated with hazard events (Smith, 1996).

5.4.2.1 Hazard modification strategies used to control flood and drought hazards

In Figure 5.3 hazard modification is divided into two different components, one being primary hazard modification and the other secondary hazard modification. As was discussed in Chapter 4, primary event modification is aimed at reducing the damage potential associated with the particular hazard by using some degree of physical control over the primary process causing a hazard event (Smith, 1996). The intention of primary event modification in an assault event (such as a flood) is to decrease the intensity of the primary event by diffusing the releases of energy over a greater area or period of time (Smith and Ward, 1998). In the case of floods, primary event modification strategies are concerned with weather modification measures aimed at decreasing rainfall intensities by inducing precipitation to fall over a longer period of time. With the current state of technology the application of this method is not yet feasible with high reliability.

In the case of a deprivation hazard event, such as a drought, the primary event modification strategies revolve around enhancing phenomena that would result in an alleviation of the hazard, such as rainfall stimulation in the case of droughts. In South Africa primary event modification has been investigated in the form of cloud seeding. Other than the potential social conflicts that may arise from cloud seeding (i.e. "my neighbour stole my rain"), its use in drought alleviation may be limited. Cloud seeding is only successful when applied to clouds with high precipitation potential, such as well developed cumulus clouds, which are lacking during a drought period (Smith, 1996).

As was discussed in Chapter 4 secondary event modification is achieved via a strategy of manipulating the secondary processes that cause the hazard, rather than attacking the primary source. In the case of flooding, event modification strategies take the form of control measures and structures, that are aimed at either reducing the flood peak or diverting the flood waters away from areas of maximum loss potential. Measures aimed at reducing flood peaks are catchment management strategies, which include land phase management, as well as the building of conservation structures, clearing/straightening channels to increase their carrying capacity and constructing flood control reservoirs designed to hold back flood volumes and attenuate flood peaks (Zhou, 1995; Smith and Ward, 1998). Diversion measures include the construction of structures such as levies and alternative channels, as well as increasing channel efficiencies to convey water past danger areas quicker.

Secondary hazard modification in the case of drought revolves around water supply augmentation and can take the form of reservoir construction or groundwater harvesting. However, augmentation measures do need to be instituted with care as they can cause secondary problems, such as water-logging and salinisation, which can reduce the carrying capacity of land and can further exacerbate drought problems (Gibberd *et al.*, 1996, Plate, 1996).

5.4.2.2 Vulnerability modification to floods and droughts

In South Africa, with its rapidly growing population and high levels of development, many areas are being utilised before a formal risk analysis has been undertaken and event modification structures can be constructed. Vulnerability modification may thus be a sound approach to follow when attempting to reduce hazard losses. As mentioned earlier, vulnerability modification has three different components, *viz.*, preparedness, forecasting/warning systems and legal/financial measures.

Preparedness, as defined in Chapter 4, includes pre-arranged emergency measures, which are taken at the onset of a hazard in order to minimise loss of life and damage to property (Smith and Ward, 1998). Preparedness programmes focus on public education and awareness, response and evacuation plans, the provision of medical and food aid, as well as shelter for victims of hazard events (Gibberd, 1996; Smith, 1996). Developing countries such as South Africa have under-resourced financial frameworks which have limited the development of good preparedness programmes (Gibberd, 1996). In many areas lack of education and experience in specific hazard occurrence has increased the vulnerability of communities and individuals who have settled or developed unsuitable areas. Sound education and awareness programmes could be used effectively to reduce vulnerability of individuals and communities, by improving response to hazard threats such as droughts and floods, and reducing associated losses. In the case of flash floods, where there are short warning times, the response of individuals and communities is important and can save many lives. Preparation is a key element in drought disaster management and involves such strategies as stockpiling and food storage, demand and supply management of, as well as the instillation of long term financial and social measures, which could reduce the impact of drought (Gibberd *et al.*,1996).

During the past 20 years forecasting and warning schemes have become a very widely applied flood mitigation measure. The two main forces behind this trend are the knowledge that improved warnings save lives, coupled with scientific and technical advances, which have led to improved short-term forecasts (e.g. String of beads rainfall model, Pegram and Clothier, 1999). The understanding of the physical systems involved in flood hydrology has developed to the point where effects of storm rainfall on runoff responses can be modelled at daily time steps with relatively high levels of accuracy (Schulze, 1995). Advances in hydro-meteorological understanding have been accompanied by improvements in flood monitoring and in real-time data handling and communication, which can increase the lead time for warnings (Jury, 1996b; Smith, 1996). Forecasting and warning systems are also an effective means of drought mitigation, by enabling the affected community to take actions that will reduce the impact of drought. Improvements in technology such as remote sensing and a better understanding of atmospheric physics have improved the accuracy of forecasts and extended their range from a few days to several months (Jury, 1996b; Landman, 1997). Prompt detection and warning against crop failure can allow individual farmers to change their management practices to reduce drought impacts

Although these systems can offer significant savings in terms of damage and loss of life, the systems are expensive to implement and maintain. The implementation of such systems in lesser developed countries such as South Africa is limited due to the financial implications. However, in many well developed countries, such as the United Kingdom and the United States of America, the systems have been implemented with a great deal of success (Smith and Ward, 1998). The development of satellite technology has increased the forecasting ability in less developed countries. However, the warning systems in such countries are not always effective and considerable losses are still experienced. In South Africa, effective radar networks have been developed in some areas, which are able to monitor indices of rainfall intensities and predict areas that may be susceptible to both flash and longer term flooding (Terblanche and Mittermaier, 1999). There is, however, often a distrust in warnings, especially if their credibility has been undermined by false warnings in the past. Nevertheless, forecasting and warning systems may still be the most cost effective measures in reducing disaster losses in many areas.

Loss sharing adjustments such as disaster aid is an important part of any drought relief programme and prevents the affected community from continuing in a downward spiral of unsustainable development which can eventually exhaust the land to the extent that it is no longer habitable. Wilhite *et al.* (1986) identified four major requirements for effective drought response by governments in order to prevent famine and severe loss:

i. Reliable and timely information on drought conditions and impacts must be developed and disseminated to allow timely responses.
ii. Impact assessment techniques need to be accurate. Accurate analysis techniques are needed to ensure that decision makers have the means to understand the severity of the drought and the agricultural impacts so that appropriate mitigation actions can be taken.
iii. The criteria for the eligibility of relief aid need to be established well in advance of a hazard event, need to be publicised adequately and applied consistently. In order to achieve this it is recommended that operational procedures be handled by one authority.
iv. In order to avoid delays in the allocation of relief aid, dissemination proceedures need to be established well in advance of the event and administered by the lead authority.

Short-to-medium term forecasting is unable to change the water supply constraints. It is, however, able to affect the demand side of water management. Improved forecasting is anticipated to affect management decisions at both the micro (farm) level and at the macro (national) level. Improved seasonal forecasting could transform early warning systems from the current function of supporting drought relief and recovery interventions into pro-active agents guiding drought mitigation and preparedness (Gibberd *et al.*, 1996). The following mitigation measures are examples of actions which agriculturalists could take when anticipating a season of below average rainfall and needing to reduce their water use to free up more water for other users (Gibberd, 1996; AgriReview, 1997):

i. Planting depth and density could be varied. Fewer plants use less water and chances of crop failure can be reduced.
ii. Weeds and other plants that may compete for the limited soil water could be actively eradicated.
iii. Marginal areas should not be planted in order to prevent costly crop failure.

iv. Irrigation farmers could decrease their irrigated areas, thereby providing fewer plants with enough water, thus decreasing consumptive water use and decreasing the risk of crop failure.

v. Water efficient tillage practices, such as conservation tillage, could be incorporated in order to decrease the water consumption.

Outside the agricultural sector, the rationing of domestic water would decrease the demand. Industry could aid in decreasing water wastage by designing water efficient systems and incorporating conservation practices. Hence, the supply of water does not change, but the demand for the water would be reduced. If forecasting were to be applied operationally it has the potential to reduce water demand.

Legal structures take the form of land use zoning and code-of-conduct measures that are designed to prevent the development of marginal areas and prevent unsuitable farming practices. This is an effective method that is implemented in many more developed countries (Smith and Ward, 1998). In lesser developed countries such as South Africa the institutional and political framework, as well as the lack scientific expertise, makes the implementation of land use planning difficult. High rates of urbanisation and the attraction of floodplain development lead to the settlement of marginal areas. In drought situations legal structures can thus effectively reduce vulnerability by preventing land degradation, which reduces the carrying capacity of the land. Financial structures increase the borrowing potential of the community, giving them more flexibility to cope with, and recover from, drought disaster.

Chapter 5 has focused on the risks associated with hydrological hazards, namely, floods and droughts. Different risk reduction strategies were discussed in the form of hazard and vulnerability modification. Forecasting was shown to fulfil an important role in vulnerability modification, where it formed an integral part of the mitigation strategies adopted by risk management programmes. In the next chapter the focus is on the different methodologies that are used to translate climate (rainfall) forecasts into hydrological (streamflow) forecasts. A review will be provided of the different methodologies and an appropriate methodology will be adopted for use in this particular study.

6 HYDROLOGICAL FORECASTING METHODOLOGIES

In the previous chapters, forecasting was placed within a broader framework of water resources and risk management in South Africa. In this chapter the initial part of Objective b in the Problem Statement (Figure OB-6), *viz.* reviewing current methodologies used to obtain hydrological forecasts, will be addressed. A broad outline on how to obtain hydrological forecasts from climate forecasts is presented. The advantages and disadvantages of the different techniques are reviewed to evaluate the suitability of generally applying the different techniques within South Africa. Each methodology is reviewed in light of its simplicity of concept, ease of use, universality and applicability in the South African context. A more detailed description of the chosen methodology is then provided in Chapters 7 and 8.

6.1 Methodologies Used to Obtain Hydrological Forecasts

In an attempt to obtain forecasts of hydrological variables two main methodologies may be followed.

i. The first approach uses statistical methods that correlate the hydrological variable (e.g. streamflow) directly with a predictor variable such as the SOI. This methodology will therefore be referred to as the direct approach and is essentially a one-step process from variable to streamflow.
ii. The second approach, referred to as the indirect approach, is a multi-layered process whereby forecasts of hydrological variables are generated from rainfall forecasts using a hydrological model. The rainfall forecasts used in the indirect approach can be produced using either statistical methods or physically based general circulation models.

Figure 6.1 shows the options available for hydrological forecasting. The direct and indirect approaches are described in more detail below in the section which follows.

Problem Statement				
Reliable, skillful hydrological forecasts have the potential to prevent loss of life, spare considerable hardship and save affected industry and commerce millions of Rands annually if applied operationally within the framework of water resources and risk management. Integrated model and database systems provide scientists and managers with tools to investigate the feasibility and applications of such systems in operational forecasting activities.				
Broad Objectives	Place forecasting within a framework of water resources and risk management in South Africa. *(a)*	Develop hydrological forecasting techniques that could be used operationally within South Africa. *(b)*	Evaluate the hydrological forecasting techniques' performance over the South Africa study region using selected forecasting periods. *(c)*	Discuss problems and shortfalls of the current methodology used to obtain the different runoff forecasts. Recommend areas of potential future research that would enable operational application of these forecasts. *(d)*
Specific Objectives	i. Review climate variability in South Africa and its associated effect on risk ii. Review the current water resource situation in South Africa iii. Review risk evaluation and management strategies with specific attention given to the role of forecasting	i. Review current methodologies used to obtain hydrological forecasts ii. Develop suitable methodologies to be used in South Africa iii. Develop unbiased techniques to evaluate the performance of the different hydrological forecasts	i. Use standard forecasting evaluation techniques to assess the performance of the hydrological forecasting techniques developed ii. Compare different hydrological forecast performances iii. Attempt to identify trends that influence forecast performance iv. Provide explanations for the different trends influencing the forecast's performance	i. Identify shortfalls in the techniques used to translate rainfall forecasts into runoff forecasts ii. Suggest areas where improvements could be made to increase the forecasts' reliability iii. Suggest areas of future research that would lead to the operational use of the different runoff forecasts iv. Identify key sectors of the study area where the application of forecasting may be particularly beneficial

Figure OB-6: Problem statement, highlighting aspects covered in Chapter 6

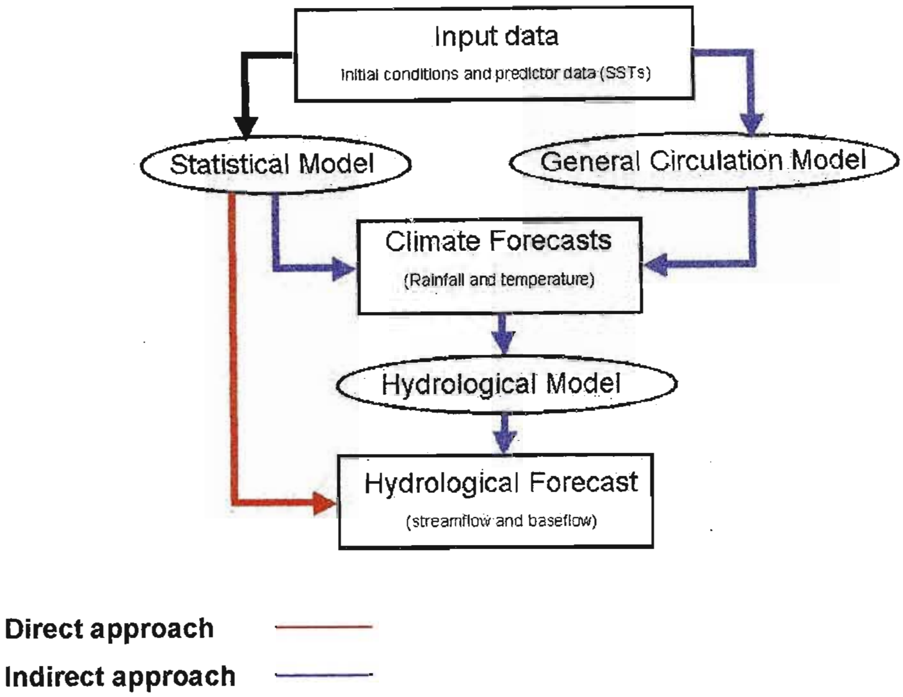


Figure 6.1 Methodologies used to generate hydrological forecasts

6.2 The Direct Approach

The direct method is a one-step approach that uses statistical methods that correlate the historical hydrological variable (predictand) values with predictor variables such as the SOI or SST data. Once the statistical model has been formulated it is used to make hydrological forecasts from the predictor variable data. Chiew *et al.* (1997;1998) have used a technique known as canonical correlation analysis (CCA) to obtain streamflow forecasts directly from ENSO variables at several sites in Australia. CCA is a multivariate regression technique that finds a linear combination of one set of variables and a linear combination of another set of variables, such that the correlation between them is maximised (Manley, 1986; Chiew *et al.*, 1997; 1998). Jury (2001) used stepwise multivariate regression techniques to obtain streamflow forecasts for a number of rivers in South Africa and gives a review of the use of statistical methods to predict streamflow in southern Africa.

The statistical approach of direct correlation between streamflow and the predictor variables has several drawbacks that make it rather inapplicable for use in the South African situation. Chiew *et al.* (1997) indicate that correlation estimates depended on the extent to which the data set used are affected by external variables. Estimates are also dependent on the quality of the data, highlighting the need for well maintained historical streamflow data sets. South Africa has a large stream gauge network. However, many of the catchments generating flow at gauging points have experienced substantial modifications in the form of land use changes and the construction of reservoirs, resulting in non-stationarity of streamflow data series (Kienzle *et al.*, 1997). Furthermore, many of these gauges are not well maintained (poor calibration and overtopping), making the data unreliable. This has been shown, for example, for gauges in the Sabie Catchment (Pike and Schulze, 2000) and in the Mkomazi Catchment (Taylor *et al.*, 2001).

Models developed using the statistical methods tend to be location specific, and therefore cannot be readily transferred to new situations, neither can they be used in a more general context (Graham, 1996; Thiao, 1996). Thus the transferability of statistical hydrological forecast models is severely limited. Maintained and undisturbed data sets are generally found in research catchments that are frequently in a reasonably pristine or unchanged condition for an extended period of time. The application of forecasts in research catchments is, however, not particularly useful as the risk to the human system is minimal. Therefore, developing forecasting models for such areas is essentially an academic rather than an operationally viable exercise. Statistical hydrological forecast models cannot be applied confidently to critical water stress areas in South Africa, such as those with high population density rural and peri-urban areas where risk is high and information is limited, owing to the lack of stationarity in the streamflow datasets found in such areas and the lack of transferability of the statistical forecasting techniques.

Finally, streamflow responses tend to be non-linear when related with other variables such as rainfall, and there is no reason to suggest that the correlation with ENSO variables is any different. Statistical models are usually based on linear associations and do not take into account the non-linear physical processes (Graham, 1996). This suggests that once the associations have been established in the model it is unlikely to improve in its accuracy, as opposed to a more deterministic, physically-based model for which simulations can be improved as the processes become more clearly understood.

6.3 The Indirect Method

The alternative method is to use the rainfall forecasts to obtain streamflow forecasts via the application of a hydrological model, which can transform rainfall quantities into simulated hydrological quantities. This method relies on the accuracy of the rainfall forecasts that may be obtained from either, or both, statistical and physical-numerical models. Although this method needs data for verification purposes, it is less reliant on good runoff data sets. The models developed using the indirect methodology are based more on physical relationships and therefore tend to be more applicable under diverse catchment conditions. Deterministic models can also account for impacts of catchment land use and its changes over time, for flow routing through channels and reservoirs as well as for abstractions and return flows from irrigated and urbanised areas. In many areas in South Africa there is also a lack of good quality streamflow data at many gauging stations, as discussed previously. These reasons suggest that the indirect hydrological modelling route is the preferred method that South Africa, and perhaps many other developing countries, should adopt.

6.3.1 Rainfall forecasting methods

Many seasonal and inter-annual climate forecast models are based on the premise that changes in the SSTs drive inter-annual climate variability (this is perhaps unjustifiable as it likely that the combined ocean-atmosphere system drives these changes). SST changes associated with the ENSO phenomenon in the tropical Pacific Ocean have become the driving factors in many Atmospheric General Circulation Models, AGCMs (Graham, 1996). Extended research in the past 15 - 20 years has provided an understanding that enables forecasters to predict major ENSO events with lead times of up to one year. The response of atmospheric circulation and associated rainfall to the global SST variability is regarded as a key factor in processing longer term forecasts, as anomalous changes in the ocean circulation evolve over longer periods than in the atmosphere (Rautenbach, 2001). The assumption that ENSO variability is associated with the dynamics of past wind forcing (dominant winds blowing over the Pacific Ocean, before the prediction period, which cause surface water to move in the prevailing wind direction) over the ocean and the atmosphere's response to changes in ocean temperatures, has contributed to the success of coupled ocean-atmosphere prediction models. Coupled ocean-atmosphere models are used in conjunction with the persistence approach to obtain predictions of SST in the Pacific and other oceans. The persistence approach simply assumes that the SST will remain unchanged for the period of the forecast (Graham, 1996).

Nicholson (1997) discusses how ENSO episodes trigger large scale changes in the tropical Atlantic and western Indian Oceans. The SSTs over these areas exert a significant influence on rainfall patterns in South Africa (Tyson, 1996). It is expected that more sophisticated forecasting techniques, rather than merely the persistence technique, will be used in the future to obtain improved forecasts of SST over the Atlantic and Indian Ocean regions.

The approach of statistically blending the coupled ocean-atmosphere SST predictions with persistence SST predictions has yielded reasonably accurate SST predictions on a global scale (Graham, 1996). The next challenge is hence to translate the SST predictions into predictions of atmospheric variables such as rainfall and temperature. Predicted atmospheric variables are obtained using either statistical-empirical methods or physical-numerical methods (Graham, 1996). These two approaches are discussed next.

6.3.2 The statistical-empirical approach

Statistical models are constructed on the basis of historical relationships between some variable for which predictions are required (the predictand data set) and factors/variables hypothesised to affect that variable (the predictor data set). Statistical methods include Canonical Correlation Analysis, or CCA (Graham *et al.,* 1987; Ropelewski and Halpert, 1989; Landman, 1997), Principal Oscillation Patterns, or POPs (Xu and von Storch, 1990) and Optimal Climate Normals, or OCNs, (Wilks, 1996). Empirical models rely on past statistical associations between lower boundary forcing, or atmospheric precursors, and the climatic variable being forecasted. They generally provide probabilistic seasonal forecasts (Mason *et al.*, 1996). Once the model is constructed, predictions are obtained by inputing predictor information, which is then transformed to return the predictand variable.

Statistical models are attractive in that they are relatively easy to construct and use. However, they are restricted by the use of historical data, which does not account for anomalous or novel situations. Statistical methods also assume linear relationships and are not based on physical principles.

The Research Group for Seasonal Climate Studies (RGSCS) of the South African Weather Service was publishing two sets of three month seasonal forecasts, one set for the three months immediately following the forecast date and another set for the following three month period, hence forecasting up to six months into the future, using a model developed by Landman (1997). The model uses the statistical technique of Canonical Correlation Analysis to make rainfall predictions from global SST data. Predictions by this technique are coarse, and are separated into three categories of expected rainfall, *viz.* Normal, Above Normal and Below Normal. Each of these categories is also given a percentage probability of occurrence (this provides an indication of the skill associated with the forecasts as it represents the number of times the forecasts where correct over a retro-active hind forecast period). At the time of evaluating these methods in 1998 to 2000 only a hind forecast data set with the expected categories was readily available, without the probabilities of occurrence, at the time of writing and testing. The addition of skill results may have improved the runoff forecasts results as it could have been factored into the hydrological forecasting methodology (cf. Chapter 7).

6.3.3 The physical-numerical approach

Physical-numerical models are based primarily on formal physical relationships rather than on statistical relationships with historical data. AGCMs apply the physical relationships governing the evolution of the atmospheric circulation. When supplied with accurate SST data the AGCMs reproduce important aspects of observed climate variability. Hence, AGCMs can be used to extrapolate the SST data into knowledge about atmospheric circulation and such variables as rainfall and temperature (Graham, 1996). In theory, AGCMs could provide higher forecast skill than statistical models because of the inherent non-linearity of the ocean-atmosphere system (Mason, 1997).

AGCMs are complex computer programs embodying a wide variety of physical laws and parameters concerning dynamic atmospheric processes such as radiation transfer and cloud physics as well as surface processes such as the influences of vegetation and soil moisture (Graham, 1996). By implication, they require a large amount of input data, substantial computer power (most GCMs at the time of undertaking this research were using CRAY supercomputers to perform simulations) and are difficult to maintain and operate. However, they are able to handle novel and anomalous situations. In the remainder of this document the terms Atmospheric General Circulation Models (AGCMs) and General Circulation Models (GCMs) will be used interchangeably.

There are several AGCMs available, all of which are still undergoing verification. The basic concept that these verification studies embody is to supply the model with the 'correct' predicted SST information (the actual observed SST data from past years) and compare the model output with observations. Atmospheric relationships tend to be chaotic, i.e. they have a built -in degree of randomness. Groups of simulations, known as ensembles, using different initial atmospheric conditions, are used to identify general trends and hence account for some of the random variability (Rautenbach, 2001). An ensemble average has been shown to yield higher forecast skills than single AGCM forecasts (Tennant, 1998a). Given the correct predicted SST patterns, most of these models reproduce many of the regional patterns of temperature and precipitation variability (Graham, 1996). This type of modelling thus meets two important requirements for good predictions:

i. They predict tropical Pacific SST with long lead times using coupled models. These predictions can be further extended to tropical and extra-tropical oceans using the concept of persistence. SST predictions in the extra-tropical oceans may improve as better understanding of their interactions with ENSO events is gained (Nicholson, 1997).
ii. Given accurate SST forecasts, relatively good simulations of regional temperature and rainfall patterns can be obtained.

Southern Africa is seen as an area where seasonal forecasts using AGCMs can successfully be developed (Mason *et al.*, 1996). The reason for this is that large scale climatic systems are the major factors that determine rainfall distribution over the country. Hence, AGCMs are tentatively postulated to be able to provide more accurate rainfall anomaly estimates than statistical models for the southern African subcontinent (Mason *et al.*, 1996). The COLA T30 is an AGCM, which has been used by Tennant (1998b) of the RGSCS to give 30 day rainfall forecasts over southern Africa. Rautenbach (2001) has employed a one-tiered climate prediction approach using a coupled ocean-atmosphere general circulation model to predict climate over South Africa.

6.3.4 Predicting streamflow from rainfall forecasts

Hydrological models generally operate at a catchment scale ranging from 10s to 1 000s of km^2. Rainfall forecasts from both statistical and general circulation models are, however, generally at a regional scale with a grid cell resolutions often at 300 - 400 km, i.e. covering 90 000 - 160 000 km^2 (Graham, 1996). The outputs from these regional scale forecast models thus need to be downscaled to catchment scale in order to run hydrological models. Regional models for southern Africa, such as the CCA model used by Landman (1997), provide output in the categorical form. The AGCM outputs produced for southern Africa by Tennant (1998b) are distributed in the form of percentages of normal rainfall for the forecast period in question. Deterministic hydrological models used in this region, such as the *ACRU* model (Schulze, 1995), require rainfall in quantitative form, i.e. mm, in order to run. The result is that the spatial downscaling problem is further compounded;

i. First, by the need to translate the temporal categorical, or percentile, rainfall forecasts into a quantitative form, and
ii. Secondly, in that the time step that many operational hydrological models use is daily (and even sub-daily), which contrasts with the forecasted outputs which usually cover a period of several days to months.

There is thus also the need to downscale the longer forecasts into daily time steps.

Forecasters use either a two-tiered or single-tiered forecast approach to obtain regional rainfall forecasts. The two-tiered approach uses predicted SSTs, obtained by using either statistical or coupled ocean-atmosphere models, as input into either statistical models or AGCMs to obtain rainfall forecasts. The single-tiered approach uses a coupled ocean-atmosphere model to obtain regional rainfall forecasts directly. One solution to the downscaling problem would be to add another tier in the form of mesoscale local atmospheric models, which could increase the resolution of the rainfall forecasts (Graham, 1996). These models could then be used to provide local scale rainfall input, which in turn, would drive catchment scale hydrological models. The complexity of such a system requires substantial computing power. This cascading approach can also lead to the compounding growth of errors which may produce inaccurate answers. The application of simpler approaches may therefore be more appropriate. Many developing countries may not have such facilities and will need to look at simpler and more robust approaches to the problem. The increased accuracy of such a meso-scale local atmospheric modelling approach needs to be weighed up against the added complexity it may present.

Statistical methods of translating the three forecast categories into actual rainfall quantities are both simple and robust. Techniques such as taking the random value or median value from ranked rainfall data sets, have been investigated for South Africa (Lecler *et al.*, 1996; Schulze *et al.*, 1998). The simplicity of these methods allows for reasonably fast computer processing and hence does not place too high a demand on computer resources. Once the rainfall quantities are established they are then run through the hydrological model, in this research the ACRU model (cf. Section 6.3.5), to generate runoff. The results of such robust techniques as mentioned above are not very precise. However, when one considers the coarseness of the rainfall forecasts these techniques have been shown to perform adequately (Lecler *et al.*, 1996). The question of whether hydrological forecasting is accurate enough to be used in water resources planning and disaster management needs to be addressed.

6.3.5 Simulating streamflow with the *ACRU* agrohydrological modelling system

In regions of highly episodic rainfall events, hydrological responses such as stormflow and baseflow, as well as sediment yield production and irrigation demand and supply, are triggered by individual events of rainfall. Monthly rainfall totals, give no real indication of antecedent catchment wetness, nor of the number or magnitude of individual rainfall events. For this reason, the multi-purpose and daily time step *ACRU* agrohydrological modelling system (Schulze, 1995) was selected for this study. Furthermore, *ACRU* is linked to an extensive database, this database containing a concurrent 44 year (1950 - 1993) quality checked daily rainfall record for each of the 1946 Quaternary Catchments making up South Africa, Lesotho and Swaziland, as well as containing information on each Quaternary Catchment's monthly means of daily maximum and minimum temperatures, mean monthly totals of potential evaporation and hydrological soils properties (Meier and Schulze, 1995; Schulze, 1997b).

6.4 Conclusions

In this study the feasibility of generating countrywide hydrological forecasts in the form of streamflow forecasts at a Quaternary Catchment scale is investigated. Owing to the complexity of catchments, which have experienced extensive landuse changes, the direct methodology described in this chapter is considered to be of little use for subsequent operational decision making. The lack of transferability of the direct approach as well as the lack of suitable stationary streamflow data sets in many areas, would mean that no suitable relationships could be established for many of the Quaternary Catchments in the country. Therefore it was decided that the indirect methodology would be the preferable streamflow forecasting technique. In the chapters which follow a more detailed description is provided on how the indirect methodology is used to generate streamflow forecasts using both the categorical rainfall forecast for the one, three and four month periods (Chapter 7) and the "percentage of normal" forecasts produced by an AGCM for 30 day periods (Chapter 8).

7 METHODS OF PRODUCING RUNOFF FORECASTS AT A QUATERNARY CATCHMENT SCALE FOR SOUTH AFRICA USING CATEGORICAL RAINFALL FORECASTS

In Chapter 6 the two main methodologies currently used to obtain hydrological forecasts were reviewed. The indirect methodology was chosen as the more appropriate method for this particular study. In this chapter Objectives (b) ii and (b) iii described in the 'Road Map' are addressed (Figure OB-7). A detailed outline of the development and application of the indirect methodology used to produce runoff forecasts from the one month, three month and four month categorical rainfall forecasts, is provided. The techniques used to produce estimates of forecast accuracy and skill (measures of forecast performance) are also discussed.

7.1 Objectives

One of the primary objectives of this investigation was to assess the use of regional, categorical rainfall forecasts of four months, three months and one month over South Africa to develop corresponding forecasts of runoff using a daily time step hydrological simulation model (as a reminder for the purpose of this study South Africa is defined as the geographical entity comprising South Africa, Lesotho and Swaziland). To do this, historical forecasts for 1981 to 1995 were used for the four month forecast period, while historical forecasts from 1987 to 1996 were used for the three month forecasts. These periods were chosen as they correspond with the representative historical rainfall forecasts sets provided by Landman from the SAWS (Landman, 1998 pers comm.).

In order to assess the methodology used to translate categorical rainfall forecasts into runoff forecasts, techniques were developed

i. to first spatially downscale the four month, three month and one month categorical rainfall forecasts, which are given for large regions of the order of 100 000 km^2 to be applicable to South Africa's operational Quaternary Catchments, which are generally of the order of 100 - 600 km^2 in extent, with approximately a third covering areas of more than 600 km^2 in area; then
ii. to temporally downscale the four month, three month and one month forecasted categorised rainfall to representative data sets of daily rainfall for the corresponding forecast period for each Quaternary Catchment; thereafter

Problem Statement				
Reliable, skillful hydrological forecasts have the potential to prevent loss of life, spare considerable hardship and save affected industry and commerce millions of Rands annually if applied operationally within the framework of water resources and risk management. Integrated model and database systems provide scientists and managers with tools to investigate the feasibility and applications of such systems in operational forecasting activities.				
Broad Objectives	Place forecasting within a framework of water resources and risk management in South Africa. *(a)*	Develop hydrological forecasting techniques that could be used operationally within South Africa. *(b)*	Evaluate the hydrological forecasting techniques' performance over the South Africa study region using selected forecasting periods. *(c)*	Discuss problems and shortfalls of the current methodology used to obtain the different runoff forecasts. Recommend areas of potential future research that would enable operational application of these forecasts. *(d)*
Specific Objectives	i. Review climate variability in South Africa and its associated effect on risk ii. Review the current water resource situation in South Africa iii. Review risk evaluation and management strategies with specific attention given to the role of forecasting	i. Review current methodologies used to obtain hydrological forecasts ii. Develop suitable methodologies to be used in South Africa iii. Develop unbiased techniques to evaluate the performance of the different hydrological forecasts	i. Use standard forecasting evaluation techniques to assess the performance of the hydrological forecasting techniques developed ii. Compare different hydrological forecast performances iii. Attempt to identify trends that influence forecast performance iv. Provide explanations for the different trends influencing the forecast's performance	i. Identify shortfalls in the techniques used to translate rainfall forecasts into runoff forecasts ii. Suggest areas where improvements could be made to increase the forecasts' reliability iii. Suggest areas of future research that would lead to the operational use of the different runoff forecasts iv. Identify key sectors of the study area where the application of forecasting may be particularly beneficial

Figure OB-7: Problem Statement, highlighting aspects covered in Chapter 7

iii. to simulate daily runoff with the *ACRU* model (Schulze, 1995) using the representative daily rainfall data sets for the forecast period; and finally

iv. to evaluate results of the forecasted runoff simulations for a selected forecast period, at both Quaternary Catchment and national scales, against runoff simulations from actual daily rainfall for the forecasted period.

The results are then used to assess where further research is needed in order to produce more reliable and applicable hydrological forecasts.

7.2 Defining forecast accuracy and skill

Forecasted predictions do not always convert to reality, and the forecasts' prediction ability has to be assessed. Therefore, before continuing to review the individual rainfall forecasts and evaluating the results of the runoff forecasts, it is important to define two terms used to assess the forecast performance, *viz. forecast accuracy* and *forecasts skill.*

i. Forecast accuracy is the average degree of correspondence between forecasts and observations and is defined as the number of times, or the percentage of occurrences, that the forecasts are correct. In terms of the categorical rainfall forecasts the number of times the forecast falls into the correct category could be defined as the forecast accuracy and for the purpose of this study will be termed the "hit rate".

ii. Forecast skill is a comparative measurement and is defined as the accuracy of a forecast relative to the accuracy of some other forecast produced by some standard procedure, such as using the median value, or chance or persistence. In this study forecast skill would be the accuracy of the runoff forecast for a given time period, as derived by hydrological modelling using the rainfall forecasts, in comparison to the median runoff for the same period. This is based on the premise that water resource managers, in the absence of reliable runoff forecasts, assume "future" runoff trends follow historical trends.

7.3 Categorical Rainfall Forecasts

The categorical seasonal rainfall forecasts in this study were obtained from the erstwhile South African Weather Bureau (SAWB), now the South African Weather Service (SAWS) (Landman, 1998 pers comm.). The forecasts have been generated using techniques described by Landman (1997). The forecasts were obtained for four month, three month and one month time periods. These forecasts place a season's rainfall into one of three categories, *viz*:

i. Above Normal, i.e. the upper (tercile) of the ranked accumulated rainfall for a specific season,
ii. Near Normal, represented by the middle tercile, and
iii. Below Normal, representing the lower tercile.

7.3.1 Procedure used to obtain operational categorical rainfall forecasts

Operational categorical rainfall forecasts ranging from one to three months have been available for several years in South Africa. In order to obtain these forecasts, Landman (1997) set up the statistical forecasting model, which uses CCA. However, in order to obtain a forecasting model, Landman (1997) first had to obtain suitable predictor and predictand data sets. These data sets were then used to train, cross-validate and independently validate the categorical rainfall forecast model.

The Global Ocean Global Atmosphere (GOGA) sea surface temperature (SST) data (Pan and Oort, 1990; Lau and Nath, 1994; cited in Landman, 1997) of the oceans adjacent to southern Africa, and those in the equatorial Pacific Ocean, were used as the predictor data in the model. The predictor data obtained by Landman for the period 1946 to 1985 were then used as the training period to establish the categorical rainfall forecast model. A further ten years of Optimal Interpolated SST data (Reynolds and Smith, 1994; cited in Landman, 1997) were obtained for the period 1985 to 1995 for independent validation purposes. The predictor ocean regions used in the study as predictors in the model are:

i. Indian Ocean: 20.25^0 N to 38.25^{0}S,
ii. Atlantic Ocean: 7.75^{0}N to 38.25^{0}S, and
iii. Equatorial Pacific Ocean: 120^{0}E to 85^{0}W, 11.25^{0}N to 11.25^{0}S (Landman, 1997).

The predictand data set was obtained from the district rainfall data of the South African Weather Bureau (van Rooy, 1972) for the same period as the predictor data set. In order to simplify processing and eliminate unnecessary data, grouping and filtering techniques were applied to the predictand fields. A rotated principal component analysis was applied to the 80 South African rainfall districts to identify relatively homogeneous rainfall regions (Landman, 1997).

A principal component analysis using Empirical Orthogonal Functions was then used to identify the variables that explain the majority of the variation in both the predictor and the predictand data sets. This is a filtering technique that allows the user to identify the most physically meaningful variables that describe the majority of the variance and hence reduce the amount of data needed to produce the statistical model (Landman, 1997).

The technique of CCA was used in order to establish relationships between the filtered predictor (SST) and the predictand (rainfall) data sets. CCA is a generalised form of multiple regression analysis in which several predictor variables are simultaneously related to several predictand variables. It determines the optimal linear combinations of two data sets by maximising the correlation (Manly, 1986). A more detailed description of the statistical techniques used by Landman (1997) can be obtained from statistical texts dealing with multivariate analysis. One recommended text on the subject is that by Manly (1986).

Landman (1997) found that rainfall variability over South Africa may be explained by several different oceans' SST values, depending on the month of the year and which area in South Africa the prediction is for. The predictability of rainfall over South Africa varies from region to region and month to month. Predictability is determined by the influence a particular area of SST has on climate variability of a region for a specific period of time. The length of a particular forecast may also affect the predictability, with periods extending for longer than a month being expected to be less predictable, since the month to month correlations are poor.

7.3.2 The four month categorical rainfall forecasts

The four month retro-active categorical rainfall forecasts were generated by Landman (1997) for six delimited forecast regions in the summer rainfall areas of South Africa. These are regions A - C and F - H in Figure 7.1. The categorical forecasts used in this study were for the period from 1 December to 31 March for the seasons commencing December 1981 to December 1995. The categorical forecasts, as well as actual rainfall categories which occurred historically in those seasons, are given in Table 7.1.

Figure 7.1	Regions delimited for the four month categorical rainfall forecast (after Landman, 1998 pers comm.)

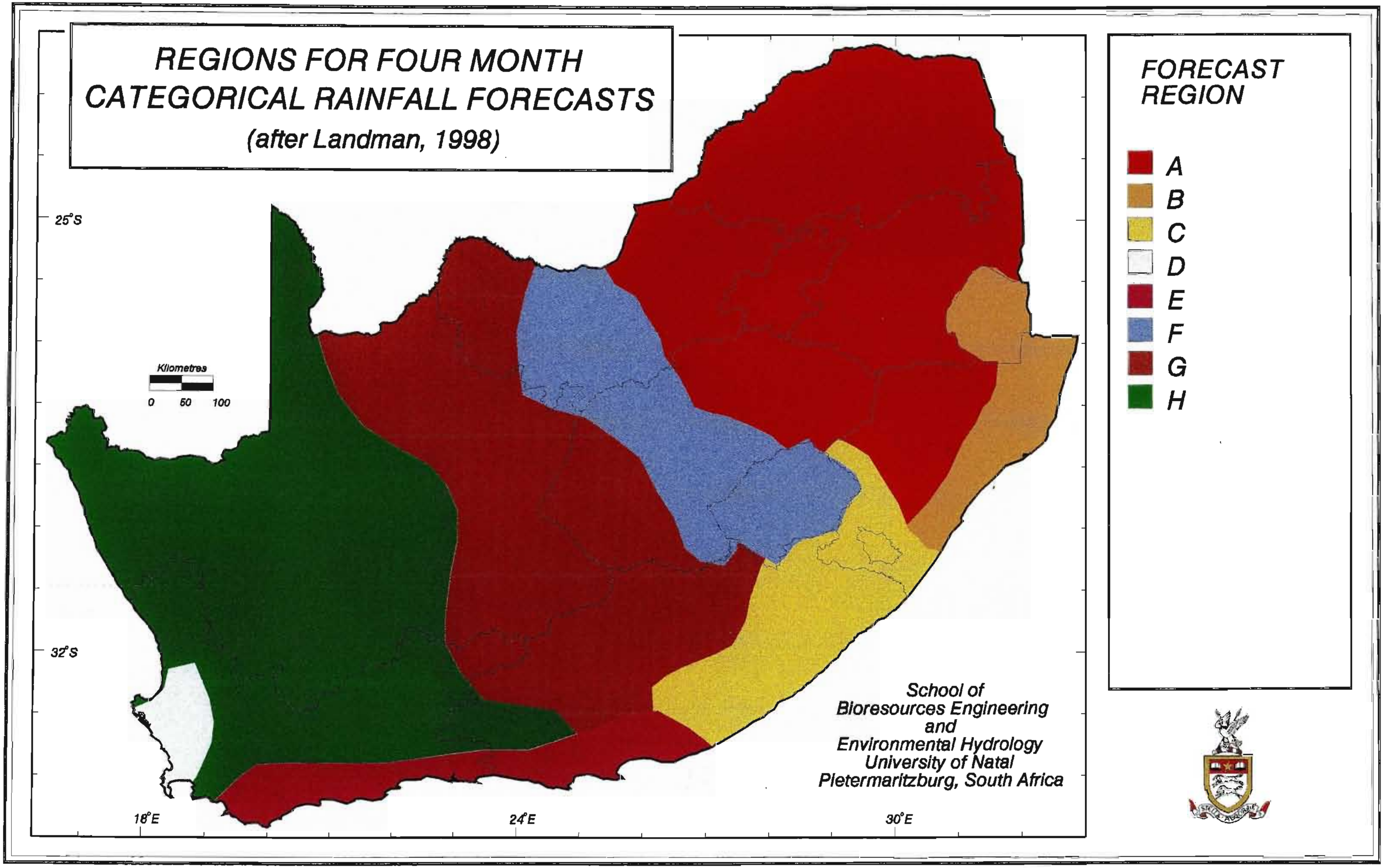

REGIONS FOR FOUR MONTH
CATEGORICAL RAINFALL FORECASTS
(after Landman, 1998)
FORECAST
REGION
A
B
C
D
E
F
G
H
Kilometres
0
50
100
25°S
32°S
18°E
24°E
30°E
School of
Bioresources Engineering
and
Environmental Hydrology
University of Natal
Pietermaritzburg, South Africa

Table 7.1 Summary of the four month categorical seasonal forecasts (top) and corresponding seasonal observations (bottom) for a 15 year period over the summer rainfall regions within South Africa (Landman and Klopper, 1998)

Region	81/ 82	82/ 83 EN	83/ 84	84/ 85	85/ 86	86/ 87 EN	87/ 88	88/ 89 LN	89/ 90	90/ 91	91/ 92 EN	92/ 93	93/ 94	94/ 95 EN	95/ 96 LN	Regional Accuracy
A	N B	B B	N N	N N	N N	B N	B A	N N	N N	B A	B B	B N	A N	B N	N A	7/15
B	N B	B B	B A	A A	A N	B N	B A	N A	A A	B A	B B	B B	N N	B B	N A	7/15
C	A B	B B	N N	A A	A A	B B	B A	A A	N N	B N	B B	B B	N A	B N	N A	9/15
F	N B	B B	N B	A B	N N	B B	N A	A A	N B	B A	B B	B B	A A	B N	N N	8/15
G	A B	B B	N B	A N	A N	B B	B A	A A	N B	B A	B B	B B	N A	B N	N N	6/15
H	N B	B B	N N	A A	A A	B B	B N	A A	N B	B N	B B	B B	N A	B N	N A	8/15
Seasonal Accuracy	0/6	6/6	3/6	4/6	4/6	4/6	0/6	5/6	3/6	0/6	6/6	5/6	2/6	1/6	2/6	50%

A = Above Normal

B = Below Normal

N = Near Normal

EN = El Niño rainy season forecast

LN = La Niña rainy season forecast

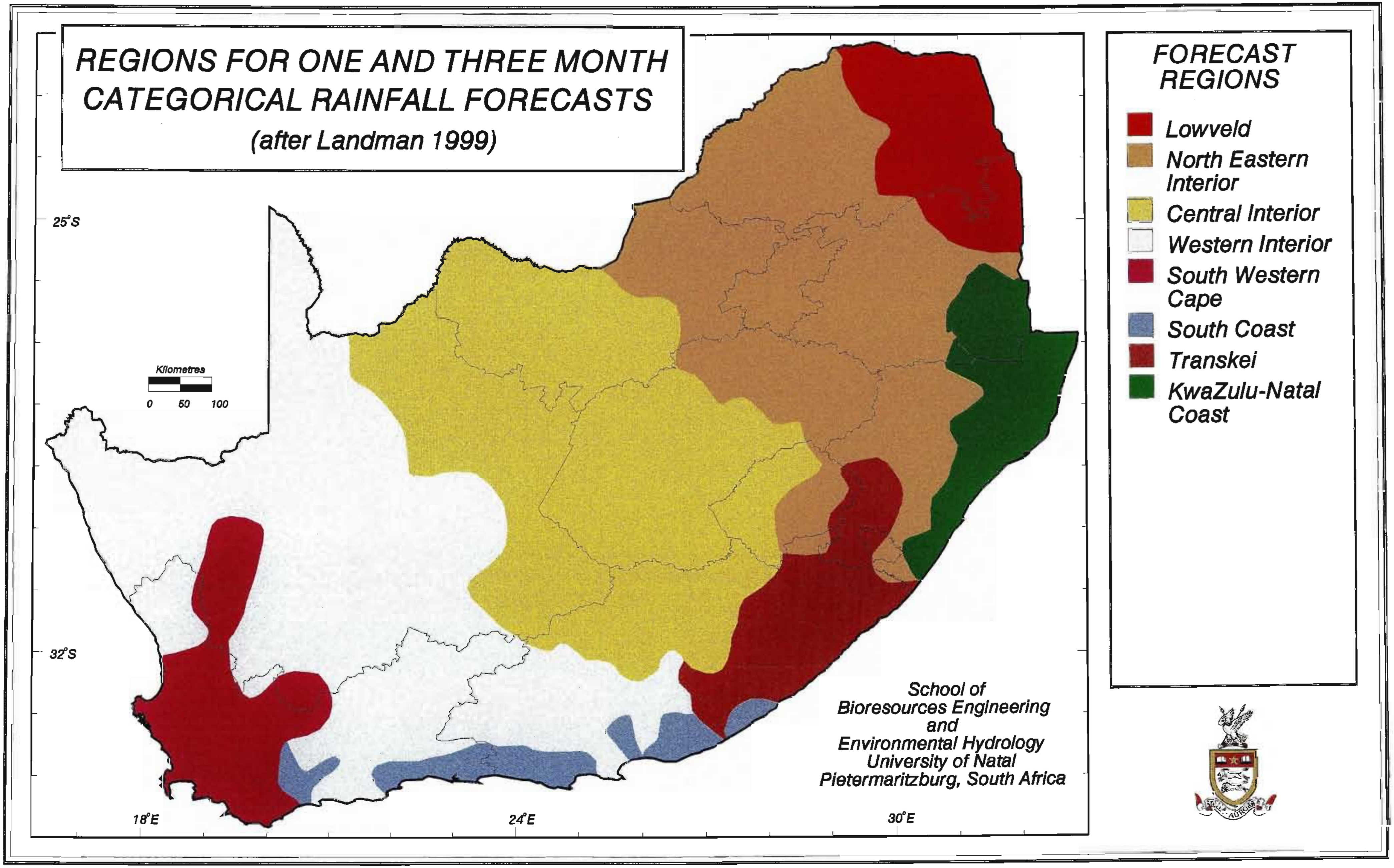
Perusal of Table 7.1 shows that within the period 1981/82 to 1995/96, four El Niño and two La Niña seasons occurred. Furthermore, in some years actual and forecasted categories corresponded very well (bold letters), while in other years the categorical forecasts were less accurate. Overall the forecasts provided were found to be correct on 50% of occasions. The regions with the highest forecast accuracies were C, F and H. The lowest accuracy of forecasts was for region G, which covers the central interior. Forecasts were correct in at least five of the six regions in 1982, 1988, 1991 and 1992 while they were incorrect in four or more of the six regions in 1981, 1987, 1990, 1993, 1994 and 1995.

The daily rainfall data sets used in simulations at the Quaternary Catchments level are readily available in quality controlled form to the end of 1993. Hence, only the forecasts up to the end of 1993 could be used in the verification studies. The last three seasons (93/94, 94/95 and 95/96) with categorical rainfall forecasts could therefore not be used. This implies that a data set of 12 seasons could be used for the verification. The overall accuracy for the 12 year period improves from 50% to 55.5%, as the last three years were poorly forecasted, with fewer than three of the six regions' forecasts being correct. The 55.5% accuracy of the forecasts is significantly better than chance, which with a three level categorisation should produce 33.3% accuracy.

7.3.3 The three month categorical rainfall forecasts for September to November

Two data sets for different three month categorical rainfall forecasts, given in Tables 7.2 and 7.3, were provided by Landman (1999, pers comm.) for eight regions covering the study area (Figure 7.2). Table 7.2 presents the retro-active categorical forecasts spanning a 10 year period from 1987/88 to 1996/97, with each forecast starting on 1 September and ending on 30 November. Forecasts were generated using the retro-active June-July-August three month SST anomaly field data for the Pacific, Indian and Atlantic Oceans using the method of CCA (Landman, 1997). The regions for the one and three month rainfall forecasts where updated from those used for the four month forecasts discussed in the previous section.

Figure 7.2	Regions delimited for the one and three month categorical forecasts (after Landman, 1999 pers comm.)


REGIONS FOR ONE AND THREE MONTH CATEGORICAL RAINFALL FORECASTS
(after Landman 1999)
FORECAST REGIONS
Lowveld
North Eastern Interior
Central Interior
Western Interior
South Western Cape
South Coast
Transkei
KwaZulu-Natal Coast
Kilometres
0
50
100
25°S
32°S
18°E
24°E
30°E
School of Bioresources Engineering and Environmental Hydrology
University of Natal
Pietermaritzburg, South Africa

For South Africa as a whole, there was only a 27.5% overall accuracy achieved for these three month categorical rainfall forecasts starting in September (Table 7.2). This accuracy is less than that of chance, which would be expected to produce forecasts of a 33.3% accuracy. The accuracy for the three month September forecasts is thus very poor and it would therefore not be recommended to use such forecasts for operational purposes. The worst forecast regions are the South Western Cape, South Coast and North Eastern Interior with accuracies in the order of 20% or less (Table 7.2). This could be due to the rainfall-producing processes in these regions being different to those in other regions. The best forecasts were achieved for the KwaZulu-Natal Coast and Western Interior, both of which achieved an accuracy of 40%. As the Quaternary Catchment daily rainfall data set only runs to the end of 1993, the last three years of the 10 year retro-active data set are excluded in verification studies. This excludes three seasons in which the forecasts were particularly poor, being correct only one out of eight times or less. For the shortened period of seven years the forecasts improve to 35.7% accuracy.

In the seven year period that could be used for verification (Table 7.2) there is one El Niño and one La Niña season. The results produced are four out of eight for the La Niña season 1987/88 and seven out of eight for the El Niño season 1991/91. Those are seasonal accuracies of 50% and 87.5% respectively. This is considerably higher than the overall accuracy. El Niño events are associated with predominantly dry conditions over much of South Africa, while La Niña events are associated with wet conditions over most of the country. Forecast accuracy is generally more valuable in cases where the season's rainfall deviates significantly from normal conditions, as such events have the potential to cause considerable damage. El Niño and La Niña years often represent years where the climate deviates far from the normal condition and therefore accurate forecasts for such years are important.

7.3.4 The three month categorical rainfall forecasts for November to January

Examination of Table 7.3 in which the three month forecasts start on 1 November and end on 31 January, reveals a forecast accuracy of only 32.5%, which is again less than the 33.3% accuracy expected to be produced by chance. The poor accuracy of these forecasts implies that similar accuracy scores are likely to be obtained from the use a

Table 7.2 The categorised retro-active three month lead forecast (top) and corresponding observations (bottom) for eight forecast regions in South Africa for a period starting on the 1 September and ending on 30 November (Landman, 1999 pers comm..)

Region	87	88 LN	89	90	91 EN	92	93	94 EN	95 LN	96	Regional Accuracy
SW Cape	A N	A N	A N	A N	**B** **B**	A B	B N	B N	B A	**A** **A**	2/10
S Coast	**N** **N**	A N	A N	B N	B A	N B	B A	B A	B N	A N	1/10
Transkei	B A	**A** **A**	A B	B N	**B** **B**	B B	B A	B N	B A	B N	3/10
KZN Coast	N A	**A** **A**	A N	B A	**B** **B**	B B	**B** **B**	N B	B A	B N	4/10
Lowveld	N A	**N** **N**	**N** **N**	B N	**B** **B**	B N	N B	N B	B A	B N	3/10
NE Interior	N A	N A	B N	B A	**B** **B**	B N	**N** **N**	N B	B A	B N	2/10
Central Interior	B A	N A	**B** **B**	B A	**B** **B**	B B	N A	N B	B A	B N	3/10
W Interior	B N	**A** **A**	**B** **B**	B N	**B** **B**	B N	N A	**N** **N**	B A	B N	4/10
Seasonal Accuracy	1/8	4/8	3/8	0/8	7/8	3/8	2/8	1/8	0/8	1/8	27.5%

A = Above Normal
B = Below Normal
N = Near Normal

EN = El Niño rainy season forecast
LN = La Niña rainy season forecast

Table 7.3 The categorised retro-active three month lead forecast (top) and corresponding observations (bottom) for eight forecast regions in South Africa for a period starting on the 1 November and ending on 31 January (Landman, 1999 pers comm..)

Region	87/88	88/89 LN	89/90	90/91	91/92 EN	92/93	93/94	94/95 EN	95/96 LN	96/97	Regional Accuracy
SW Cape	B N	A N	A N	A N	**B** **B**	**B** B	B N	A N	B A	**A** **A**	3/10
S Coast	A N	A N	A N	A N	B A	B B	B A	A A	B N	A N	2/10
Transkei	N A	**A** **A**	A B	**N** **N**	N B	**B** **B**	N A	A N	N A	A N	3/10
KZN Coast	B A	N A	**N** **N**	N A	N B	**B** **B**	N B	A B	N A	**N** **N**	3/10
Lowveld	N A	**N** **N**	**N** **N**	**N** **N**	N B	N N	N B	N B	N A	**N** **N**	5/10
NE Interior	B A	N A	**N** **N**	N A	N B	**N** **N**	**N** **N**	A B	N A	**N** **N**	4/10
Central Interior	N A	**A** **A**	A B	N A	N B	N B	N A	A B	N A	**N** **N**	2/10
W Interior	A N	**A** **A**	A B	**N** **N**	A B	N N	N A	A N	N A	**N** **N**	4/10
Seasonal Accuracy	0/8	4/8	3/8	3/8	1/8	7/8	1/8	1/8	0/8	6/8	32.5%

A = Above Normal
B = Below Normal
N = Near Normal

EN = El Niño rainy season forecast
LN = La Niña rainy season forecast

random selection process to obtain the forecasts. The highest forecast accuracy is obtained for the Lowveld region with a 50% accuracy followed by the North Eastern Interior and Western Interior with 40% accuracies. The South Coast and Central Interior produce the worst forecast accuracies at 20%. Owing to the Quaternary Catchment's daily rainfall data set ending at the end of 1993 at the time of undertaking this research, the last four years had to be discarded. The overall accuracy for the six year data set improves to 37.5%, which is only slightly better than that expected to be produced by chance.

Both the three month retro-active rainfall forecasts produce poor results with low accuracy. According to Landman and Klopper (1998) these poor results could be due to the correlation of rainfall from month to month being poor over South Africa. Landman (1997) suggests that one month rainfall forecasts over South Africa using CCA may be relatively accurate, while the forecasts extending over a range of several months may be poor. It appears that the one month (cf. section 7.3.5) forecasts perform better than the three month forecasts but worse than the four month forecasts for the forecast period.

For the La Niña event of 1988/89 the forecast accuracy was four out of eight, or 50%, which is well above the overall hit rate. However, the El Niño years of 1991/92 and 1994/95 were both poorly forecasted with accuracies of only one out of eight, which represents a score of 12.5%, which is well below the overall accuracy.

7.3.5 The one month categorical rainfall forecasts for September

Two retro-active one month categorical rainfall forecasts were provided by Landman (1999, pers comm.) for the purpose of this study (Tables 7.4 and 7.5). These forecasts are generated using three month SST fields for the three months prior to the forecast period (*i.e.* June-July-August for the September forecast and August-September-October for the November forecast). The one month forecasts are expected to yield better forecast results with higher accuracies than forecasts extending for several months, as they had been found to yield forecasts with accuracy significantly better than chance at the 95% confidence level in long term verification studies (Landman, 1997).

The 10 year retro-active categorical rainfall forecasts for the month of September (Table 7.4) deliver an overall accuracy of 33.75%, which is only slightly better than results

Table 7.4 The categorised retro-active one month lead forecast (top) and corresponding observations (bottom) for eight forecast regions in South Africa for a period starting on the 1 September and ending on 30 September (Landman, 1999 pers comm)

Region	**87**	**88** LN	**89**	**90**	91 EN	92	**93**	94 EN	**95** LN	**96**	**Regional Accuracy**
SW Cape	A N	A N	A N	A N	B B	A B	B N	B N	N A	N A	1/10
S Coast	A N	A N	A N	**N** **N**	B A	N B	B A	B A	B N	**N** **N**	2/10
Transkei	B A	**A** **A**	A B	B N	B B	B B	N A	B N	B A	B N	3/10
KZN Coast	N A	**A** **A**	A N	B A	**B** **B**	**B** **B**	N B	**B** **B**	B A	B N	4/10
Lowveld	N A	**N** **N**	**N** **N**	B N	**B** **B**	B N	N B	B B	B A	B N	4/10
NE Interior	B A	**A** **A**	**N** **N**	B A	**B** **B**	B N	**N** **N**	B B	B A	B N	5/10
Central Interior	B A	**A** **A**	N B	B A	**B** **B**	**B** **B**	**A** **A**	B **B**	B A	B N	5/10
W Interior	B N	**A** **A**	N B	B N	**B** **B**	B N	**A** **A**	B N	B A	B N	3/10
Seasonal Accuracy	0/8	6/8	2/8	1/8	7/8	3/8	3/8	4/8	0/8	1/8	33.75%

A = Above Normal

B = Below Normal

N = Near Normal

EN = El Niño rainy season forecast

LN = La Niña rainy season forecast

Table 7.5 The categorised retro-active one month lead forecast (top) and corresponding observations (bottom) for eight forecast regions in South Africa for a period starting on the 1 November and ending on 30 November (Landman, 1999 pers comm.)

Region	87	88 LN	89	90	91 EN	92	93	94 EN	95 LN	96	Regional Accuracy
SW Cape	A N	A N	A N	N N	A B	B B	B N	B N	A A	A A	4/10
S Coast	A N	A N	A N	A N	A A	B B	B A	B A	A N	A N	2/10
Transkei	N A	A A	A B	A N	N B	B B	B A	B N	A A	A N	3/10
KZN Coast	B A	A A	N N	A A	N B	B B	B B	B B	A A	A N	7/10
Lowveld	N A	A N	N N	N N	N B	N N	N B	N B	N A	N N	4/10
NE Interior	N A	A A	N N	A A	N B	N N	N N	N B	A A	N N	7/10
Central Interior	N A	A A	A B	A A	N B	N B	N A	N B	A A	N N	4/10
W Interior	A N	A A	A B	A N	N B	N N	N A	N N	A A	A N	4/10
Seasonal Accuracy	0/8	5/8	3/8	5/8	1/8	7/8	2/8	2/8	6/8	4/8	43.75%

A = Above Normal EN = El Niño rainy season forecast

B = Below Normal LN = La Niña rainy season forecast

N = Near Normal

expected from chance. The regions of the North Eastern Interior and Central Interior have the highest forecast accuracies, scoring 50%. The South Coast and South Western Cape show the lowest accuracies, with scores of 20% and 10% respectively. For the concurrent daily rainfall verification field, which runs for the seven years up to 1993, the accuracy is 39.3%. This still does not produce forecasts that are significantly better than by chance. For this particular forecast period the forecasts do not exhibit any accuracy and are not reliable enough to be used for operational hydrological forecasts. The La Niña year of 1988 produced a forecast accuracy of six out of eight, or 75%, and the El Niño year of 1991 produced a forecast accuracy of seven out of eight, or 87.5%, which are both considerably higher than the overall forecast accuracy.

7.3.6 The one month categorical forecasts for November

The one month retro-active forecasts for November deliver an overall accuracy of 43.75% (Table 7.5), which is somewhat better than chance. The regions experiencing the highest accuracy in this retro-active forecast set are the North Eastern Interior and the KwaZulu-Natal Coast, which show accuracies of 70%. The most poorly forecasted regions were the South Coast and the Transkei with 20% and 30% accuracies respectively. The overall accuracy for the concurrent verification period up to 1993 is 41.1%, which is slightly less than the overall forecast set, but still better than chance. The La Niña year of 1988 and the El Niño year of 1991 have produced forecast accuracies of five out of eight (62.5%) and one out of eight (12.5%) respectively. The overall forecasts for this 1987-96 period are thus accurate enough to produce a runoff forecasts with accuracy scores higher than chance. They could therefore prove useful operationally.

While the forecast accuracies described in Sections 7.3.3, 7.3.4, 7.3.5 and 7.3.6 are disappointing and worse than those produced by the four month forecasts in Section 7.3.2, it should be noted that the forecasts in Section 7.3.2 omit the South Western Cape (winter rainfall) and South Coast (all year rainfall) regions. Both these regions have shown little correlation with SSTs in the summer months and consistently produce poor forecasts with accuracies less than the overall country accuracy. Operational application of forecasts for these areas should therefore not be considered for the months of September and November. If forecasts for these regions are excluded from the retro-active forecast data sets the overall accuracy improves from 33.75% to 40% for the September period and from 43.75% to 48.33% for the November period.

7.4 Technique Used to Assign the Quaternary Catchments to the Categorical Rainfall Forecast Regions

The Department of Water Affairs and Forestry has delimited South Africa, Lesotho and Swaziland into Primary Catchments, each of which has been subdivided into Secondary Catchments, those in turn into Tertiary and those finally into Quaternary Catchments. In total there are 1946 Quaternary Catchments in South Africa, Lesotho and Swaziland, each with areas generally covering 100 - 600 km^2. It is possible to assign each Quaternary Catchment to a specific forecast region by overlaying the forecast regions for the four, three and one month categorical rainfall forecasts (cf. Figure 7.1 and Figure 7.2) over a map of Quaternary Catchments (an example of which is given in Schulze, 1997b). In linking a Quaternary Catchment to a forecast region, the procedure was followed that if the centroid of a Quaternary Catchment fell within a particular forecast region, the Quaternary Catchment was assigned to that region.

In this analysis the Quaternary Catchments are treated as individual hydrological entities without any Quaternary Catchment's runoff cascading, or flowing, from upstream into downstream catchments. This means that the runoffs of the Quaternary Catchments that make up the Tertiary, Secondary and Primary Catchments, are not linked and do not flow into each other in a cumulative way as occurs in reality. Furthermore, in the hydrological simulations no consideration has at this stage been given to dams, irrigation abstractions, inter-catchment transfers or impacts of land use in any of the Quaternary Catchments. The land use was assumed to be grassland (veld) in fair hydrological condition, i.e. with a canopy cover of 50 to 70% (Schulze, 1995).

7.5 Assigning Daily Rainfall Values to Categorical Rainfall Forecasts for Use in Hydrological Modelling

Each of the 1946 Quaternary Catchments in the study area has been assigned a data set of quality controlled daily rainfall from a selection of 1300 suitable SAWB rainfall stations for the period 1950 – 1993 (Meier, 1997).

In assigning the categorical retro-active rainfall forecasts for a given period to a representative daily rainfall data set for each Quaternary Catchment for the purpose of hydrological simulation the following steps, adapted from a technique presented by Lecler *et al.* (1996), were undertaken:

i. The daily rainfall for each Quaternary Catchment was accumulated for the forecast period (e.g. from 1 December to 31 March for the four month forecast) for all complete forecast periods for which daily rainfall values were readily available at the time of this research. For this study daily rainfall for 44 complete forecast periods was available.

ii. The accumulated daily rainfall totals for each Quaternary Catchment were then ranked from the highest to the lowest value for the forecast period. The ranked set of accumulated daily rainfall totals was then divided into three terciles. The upper tercile was categorised as representing the Above Normal rainfall years, the middle tercile the Near Normal rainfall years and the lower tercile as representing the Below Normal rainfall years for a specific forecast period.

iii. Using the categorical rainfall forecast for the region in which the Quaternary Catchment is located (e.g. Above Normal seasonal rainfall) the year with *median* ranked accumulated daily rainfall totals within the corresponding tercile (i.e. rank eight out of 15 Above Normal rainfall totals) was selected as being representative of the forecasted daily rainfall for the purpose of this study. The reasons for selecting the median are given later.

iv. For a given Quaternary Catchment and rainfall forecast period (e.g. 1 December 1991 to 31 March 1992) the daily time-step *ACRU* model was run as a warm up period with historically observed daily rainfall for two entire preceding chronological years (i.e. from 1 January 1989 to December 1990) and with the pre-season rainfall (i.e. up to 30 November 1991) to create representative initialisations of, for example;

    a) the groundwater store and baseflow releases
    b) the stormflow store and stormflow releases
    c) soil moisture contents in the topsoil and subsoil
    d) and, for later studies when the information becomes available for each Quaternary Catchment, the status of dams and /or irrigation demands.

v. The forecasted daily rainfalls for the forecast period in question (i.e. Above Normal rainfall in this example) were then used together with the antecedent conditions generated previously by the *ACRU* model, to generate daily runoff values for the forecast season (e.g. 1 December 1991 to 31 March 1992). For the purpose of this study runoff is defined as the sum of stormflow and baseflow for each day.

vi. The generated daily runoffs for the forecast period were then summed to give a value of accumulated forecasted runoff.

vii. These steps were repeated for the remaining Quaternary Catchments over South Africa, Lesotho and Swaziland. By way of an example Figure 7.3 shows the spatial distribution, by Quaternary Catchment, of generated runoff from both the observed and the categorical rainfall forecasts for the December 1991 to March 1992 rainy season.

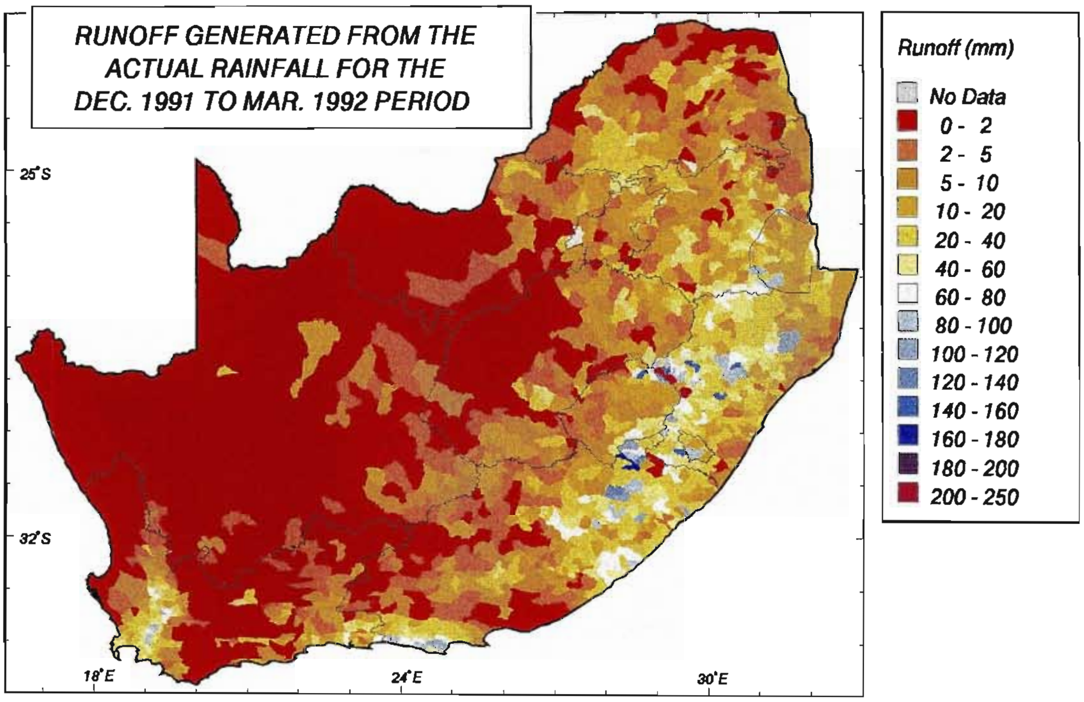
Figure 7.3	The runoff generated from the actual rainfall and the runoff generated from the categorical rainfall forecasts for the four month December 1991 to March 1992 rainfall period

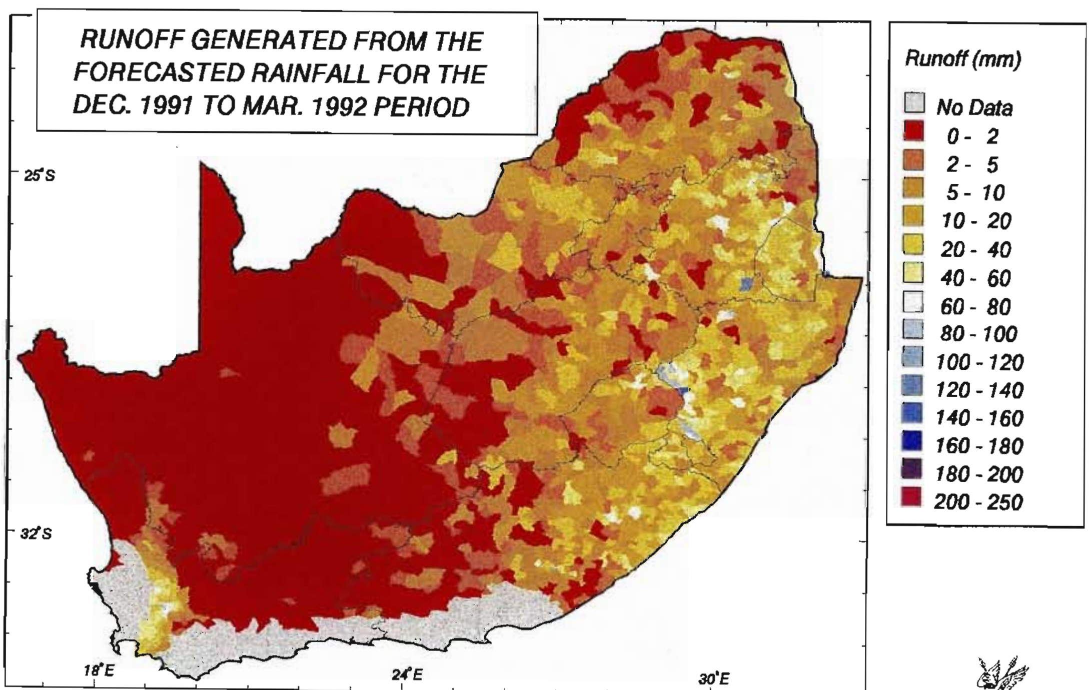
There are two main reasons that the median value of the ranked accumulated daily rainfall totals in a specific tercile was chosen to represent the forecasted daily rainfall:

i. The median value method was compared to a random selection process, which used a uniform distribution random selection algorithm to select representative daily rainfall records from those accumulated monthly values making up a tercile and used them as the forecasted daily rainfall for use in the hydrological model. Various statistical tests (Predictive Residual Error Sum of Squares (PRESS) and a Modified Student T tests) were conducted on the results, with the results from the median value method consistently outperforming those from the random selection process.

ii. The median value method was also compared against the use of the mean value as the representative daily rainfall for a given period. It was found that the mean value was influenced by outliers in the rainfall records, specifically in the lower and upper terciles, producing rainfall forecast results that tended to be either excessively low or high when forecasts were in the Below Normal and Above Normal range.

The selection of a single value (mean, median or random value) as representative of a daily rainfall forecast does not take into account the intra-forecast period variability that exists within each accumulated value making up a tercile. It might be more prudent in future to produce forecasts within a range using a standard deviation or using a method of stochastically generating a set of runoff forecasts for each tercile. The forecasting methods, which produce a range of possible runoff forecast scenarios, should perform well when probabilistic rainfall forecasts are supplied. However, probabilistic rainfall


RUNOFF GENERATED FROM THE ACTUAL RAINFALL FOR THE DEC. 1991 TO MAR. 1992 PERIOD
25°S
32°S
18°E
24°E
30°E
Runoff (mm)
No Data
0 - 2
2 - 5
5 - 10
10 - 20
20 - 40
40 - 60
60 - 80
80 - 100
100 - 120
120 - 140
140 - 160
160 - 180
180 - 200
200 - 250


RUNOFF GENERATED FROM THE FORECASTED RAINFALL FOR THE DEC. 1991 TO MAR. 1992 PERIOD
25°S
32°S
18°E
24°E
30°E
Runoff (mm)
No Data
0 - 2
2 - 5
5 - 10
10 - 20
20 - 40
40 - 60
60 - 80
80 - 100
100 - 120
120 - 140
140 - 160
160 - 180
180 - 200
200 - 250

forecasts were unavailable from the SAWB (now SAWS) for a retro-active hind forecast period at the time of this research. While methods that produce a range of runoff forecasts have been included in the programming framework developed during this project they take considerably more time to run and remain untested at present. Considering the coarse nature of the rainfall forecasts it was, therefore, decided to use the simpler method (median value) to generate the runoff forecasts and test the methodology.

7.6 Techniques Used to Evaluate the Forecasted Runoff Generated from the Categorical Rainfall Forecasts

Reliable rainfall forecasts, when incorporated effectively into water resource and risk management systems, have the potential to prevent human, environmental, social and monetary losses. Objective and unbiased techniques are essential in assessing forecast performance. The assessments of forecast accuracy and skill used in this study are derived from some selected methods used to assess the accuracy and skill of climate forecasts.

In this study several different techniques where used to evaluate the accuracy and the skill of the runoff forecasts. In the same way that the hit rate was determined in the categorical rainfall forecasts, so the accuracy of the runoff forecasts was determined using the following procedures:

i. Daily runoff was generated for each Quaternary Catchment using the *ACRU* modelling system for a concurrent rainfall period extending from 1 January 1950 to 31 December 1993.
ii. The daily runoff was then accumulated for the forecast period (e.g. 1 December to 31 March for the four month forecasts) for each of the seasons from 1950/51 to 1992/93.
iii. The total accumulated runoffs generated in each year for the forecast period were then ranked from highest to lowest.
iv. The ranked accumulated runoff data set was then split into three terciles with the upper tercile corresponding to the forecast period's Above Normal runoff, the middle tercile to Near Normal runoff and the lower tercile to the period's Below Normal runoff.
v. The runoff simulated by the observed rainfall using the *ACRU* modelling system for the period in question was extracted (Figure 7.4, top).

vi. If the forecasted runoff generated from the categorical rainfall forecast (Figure 7.4, middle), using the technique described in Section 7.5 above, fell within the same category (tercile) as the runoff generated from the observed rainfall, a "hit" was scored (Figure 7.4, bottom).

vii. This procedure was repeated for all 1946 Quaternary Catchments throughout South Africa.

viii. The results where then accumulated to obtain an overall accuracy score for the entire retro-active hind forecast data set.

Figure 7.4	Comparison of the categorical runoff produced by the actual rainfall and the forecasted rainfall for the December 1991 to March 1992 forecast period

In this study, forecast skill (as against accuracy which is the "hit" rate) is determined in relation to the long term median runoff value, by comparing the forecasted accuracy of runoff for a period against the median value of runoff for the same period. The reason for this is that a common assumption used in water resources management is

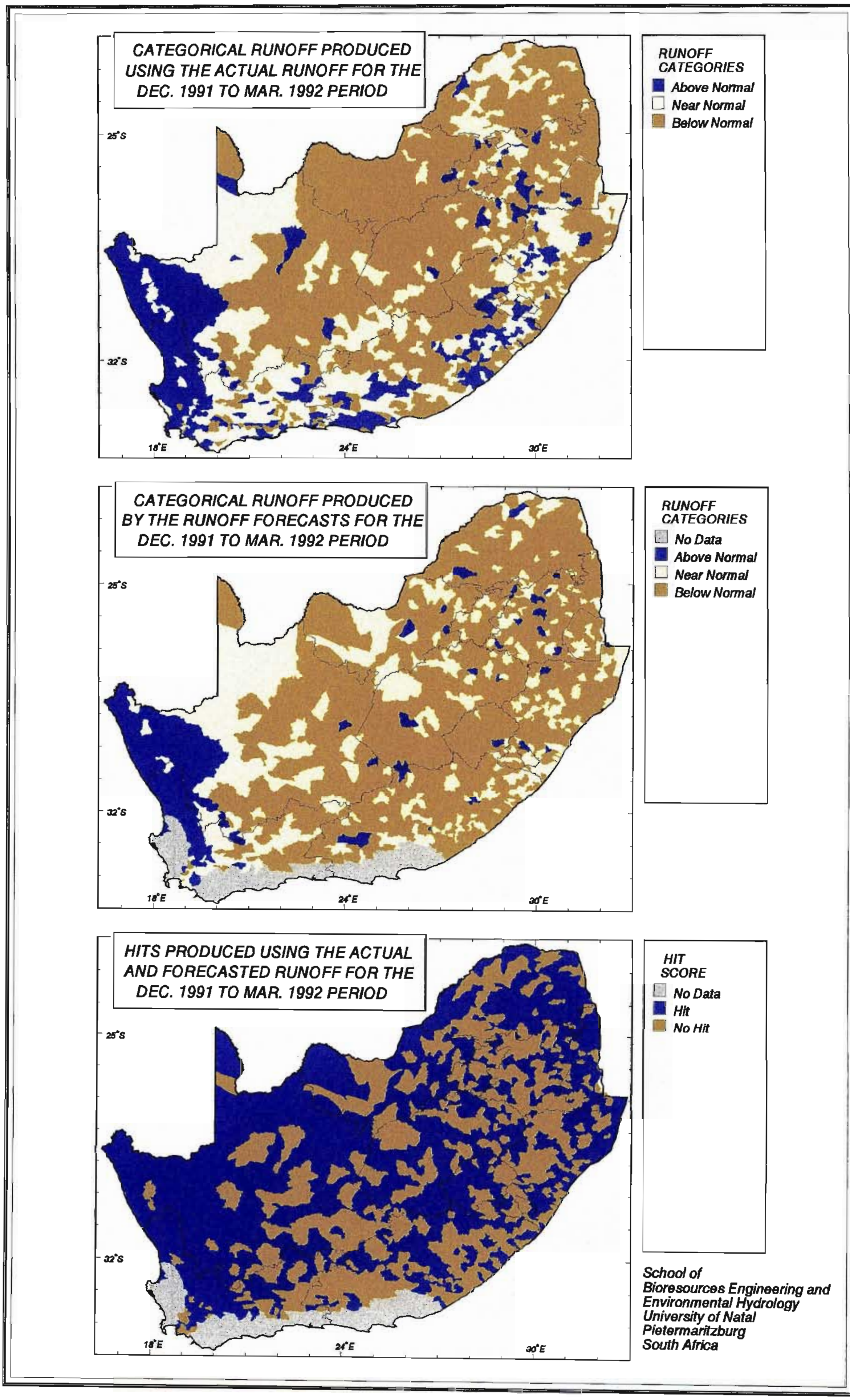
that in the absence of a rainfall (or runoff) forecast, operators assume that median runoff conditions are likely to prevail for the forecast period.

Forecast skill is assessed by what may be described as a "benefit analysis" of forecasting, whereby the results obtained by using the median runoff as the assumed forecasted value are compared to those using the forecasted runoff from the categorical rainfall forecasts. The methodology described below was used in the benefit analysis of runoff forecasting.

Three computer simulations were undertaken, as well as two further calculations being made for each Quaternary Catchment and for each categorical rainfall forecasted period, *viz*.

i. In Simulation 1 the long term (i.e. 1950-1993) accumulated *median* runoff was generated for the period in question (e.g. December to March) using historically observed daily rainfall with the *ACRU* model.

ii. In Simulation 2 the accumulated *forecasted* runoff (Figure 7.3, bottom) for the forecast period was generated using the methodologies described in the Section 7.5.


CATEGORICAL RUNOFF PRODUCED USING THE ACTUAL RUNOFF FOR THE DEC. 1991 TO MAR. 1992 PERIOD
RUNOFF CATEGORIES
Above Normal
Near Normal
Below Normal
25°S
32°S
18°E
24°E
30°E
CATEGORICAL RUNOFF PRODUCED BY THE RUNOFF FORECASTS FOR THE DEC. 1991 TO MAR. 1992 PERIOD
RUNOFF CATEGORIES
No Data
Above Normal
Near Normal
Below Normal
25°S
32°S
18°E
24°E
30°E
HITS PRODUCED USING THE ACTUAL AND FORECASTED RUNOFF FOR THE DEC. 1991 TO MAR. 1992 PERIOD
HIT SCORE
No Data
Hit
No Hit
25°S
32°S
18°E
24°E
30°E
School of Bioresources Engineering and Environmental Hydrology
University of Natal
Pietermaritzburg
South Africa

iii. Simulation 3 consisted of the generation of the assumed *actual* runoff for that forecast period, using the period's actual historical daily rainfall for that Quaternary Catchment (Figure 7.3, top).

iv. Next, an expected error was calculated. The *expected error* was defined as the absolute difference between the results of Simulation 3 (actual runoff) and the results of Simulation 1 (median runoff), i.e. |Simulation 3 - Simulation 1|. An example is given in Figure 7.5, top.

v. Finally a *forecasted error* was determined, that being defined as the absolute difference between Simulation 3 (actual runoff) and Simulation 2 (forecasted runoff), i.e. |Simulation 3 - Simulation 2|, as illustrated in Figure 7.5, bottom.

Figure 7.5	The expected error, i.e. the absolute difference between the median and actual runoff for the December 1991 to March 1992 period (top), and the forecasted error, i.e. the absolute difference between the forecasted and actual runoff for the December to March period (bottom)

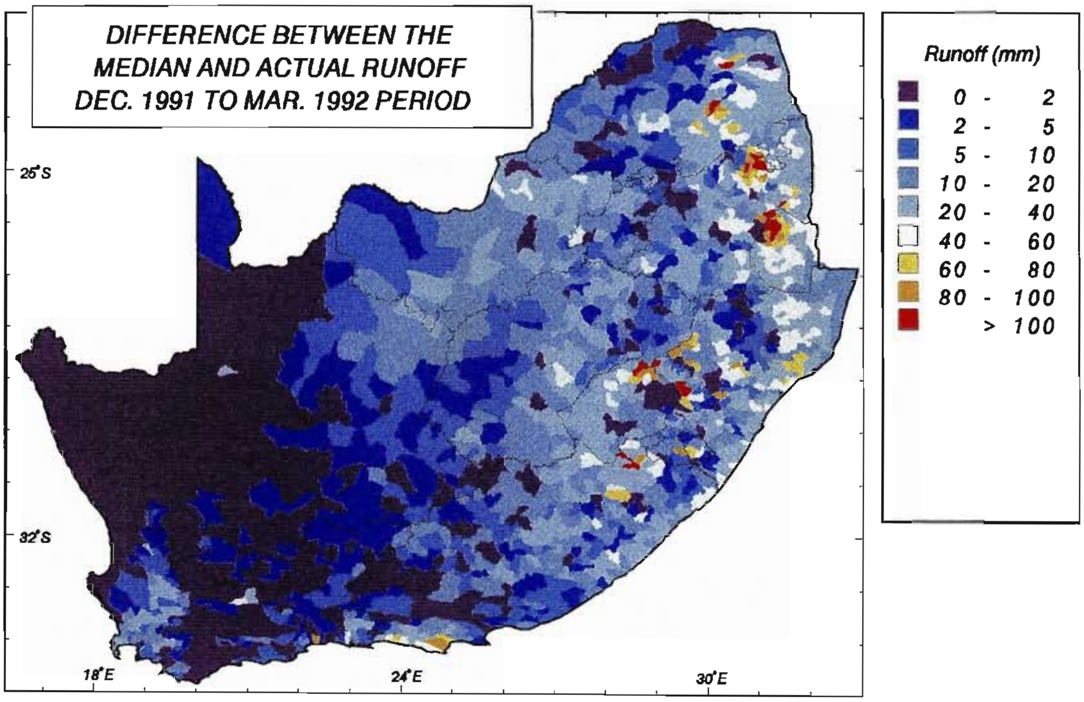
Using the results from the five steps outlined above, the following hypothesis was proposed in regard to evaluating the benefits of forecasted runoff, *viz.*

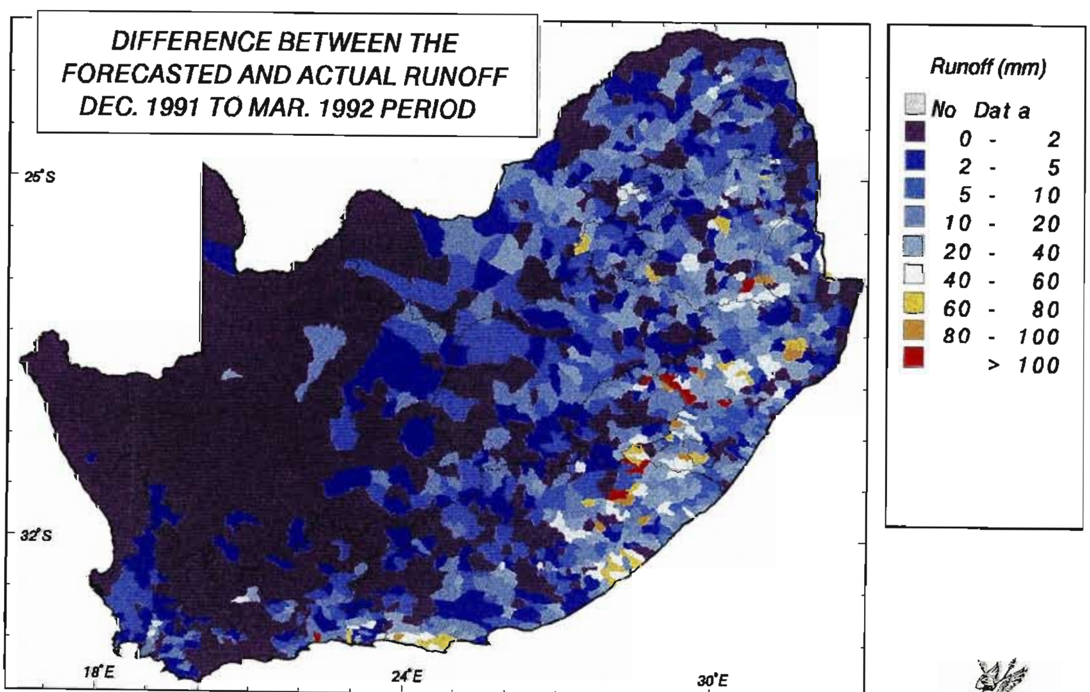
If the forecasted error of runoff is less that the expected error (as defined above), then a benefit would potentially have been derived from applying forecasting techniques, and a win is scored. If, on the other hand, the forecasted error of runoff is greater than the expected error (as defined above), then no benefit would have been derived, and a loss is recorded. If the forecasted error and the expected error are equal then a "no difference"' score is recorded.

The above steps were processed for

i. each forecast period for which forecast analyses could be made for a Quaternary Catchment, and for

ii. each of the Quaternary Catchments within the particular homogeneous rainfall forecast regions used for that particular forecast period.


DIFFERENCE BETWEEN THE
MEDIAN AND ACTUAL RUNOFF
DEC. 1991 TO MAR. 1992 PERIOD
25°S
32°S
18°E
24°E
30°E
Runoff (mm)
0 - 2
2 - 5
5 - 10
10 - 20
20 - 40
40 - 60
60 - 80
80 - 100
> 100


DIFFERENCE BETWEEN THE
FORECASTED AND ACTUAL RUNOFF
DEC. 1991 TO MAR. 1992 PERIOD
25°S
32°S
18°E
24°E
30°E
Runoff (mm)
No Data
0 - 2
2 - 5
5 - 10
10 - 20
20 - 40
40 - 60
60 - 80
80 - 100
> 100

This information allows different estimates of forecast skill to be obtained. A conceptually simple analysis of the benefit of seasonal forecasting of runoff in South Africa could be made by mapping:

i. an individual season's win vs loss for each of the Quaternary Catchments (Figure 7.6, top) and
ii. the cumulative (i.e. aggregating the 12 four month forecast periods results) win vs loss situation (Figure 7.6, bottom)

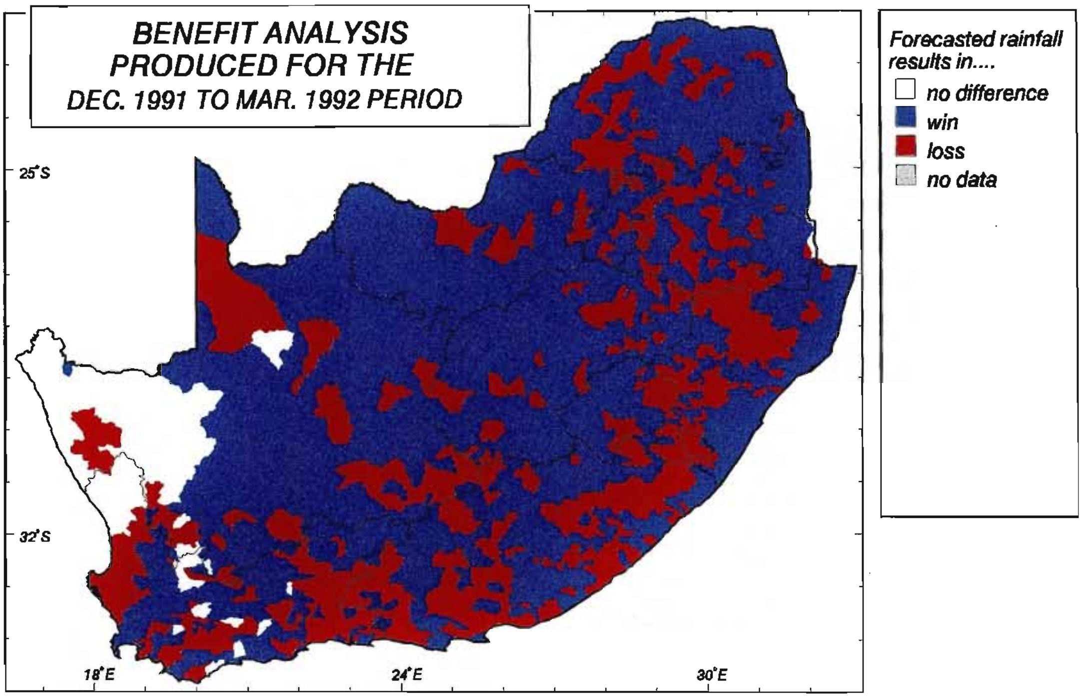
Forecast skill can also be calculated in terms of an *integer benefit analysis*, which is calculated for a single season in the same way as explained above. The single season scores are then given a value of positive one for a win, negative one for a loss scenario and zero for a no difference score. These integer values are then aggregated for the entire retro-active hind forecast dataset to create a cumulative integer benefit analysis.

Figure 7.6	Results of the benefit analysis for the December 1991 to March 1992 forecast period (top) and the cumulative benefit analysis for the entire retro-active hind forecast data set (bottom)

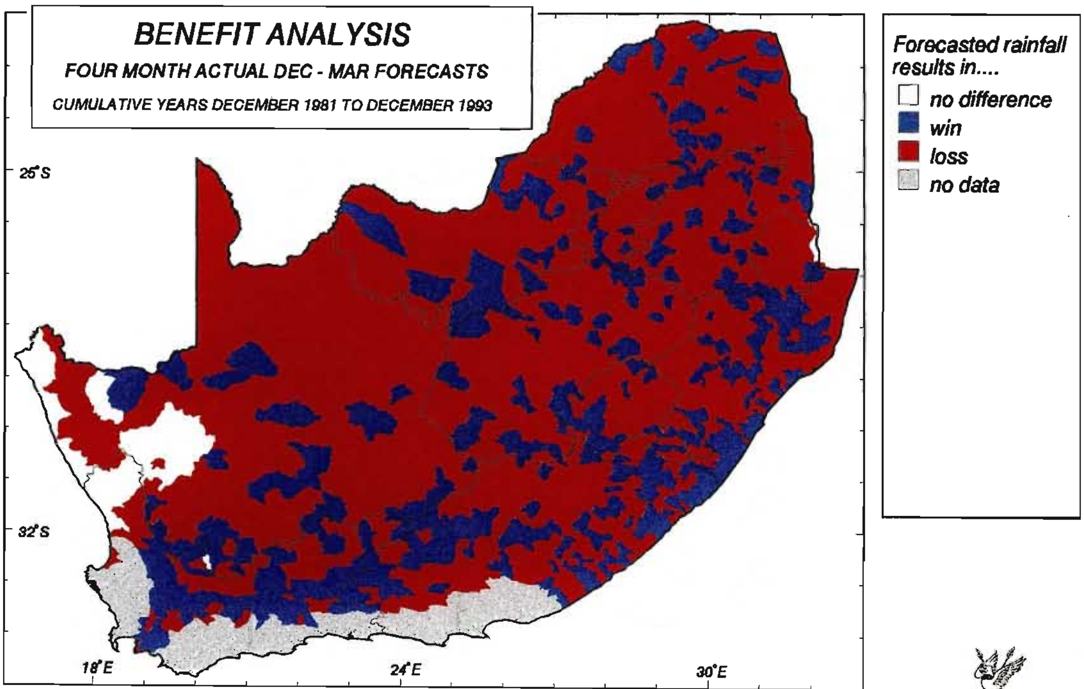
Although the cumulative integer benefit analysis and the cumulative benefit analysis are essentially measuring the same quantity, the benefit analysis gives the absolute value of comparative performance, while the cumulative integer benefit analysis estimates the number of times that one type of forecast could have outperformed another. The integer benefit analysis will eliminate the bias created if one forecast, be it median or forecasted runoff, is extremely poor.

7.7 Programming Framework Used to Generate the Runoff Forecasts from the Categorical Rainfall Forecasts

The generation of runoff forecasts for the entire South African study region required that the methodology, described in Chapter 6 and in the initial parts of Chapter 7, be implemented for each of the 1946 Quaternary Catchments. This task required a large number of iterative calculations to be performed. Added to this task was the requirement that the methodology, once tested on the retro-active hind forecasts, must also be able generate real-time runoff forecasts using the actual real-time rainfall forecasts.



BENEFIT ANALYSIS
PRODUCED FOR THE
DEC. 1991 TO MAR. 1992 PERIOD
25°S
32°S
18°E
24°E
30°E
Forecasted rainfall results in....
no difference
win
loss
no data



BENEFIT ANALYSIS
FOUR MONTH ACTUAL DEC - MAR FORECASTS
CUMULATIVE YEARS DECEMBER 1981 TO DECEMBER 1993
25°S
32°S
18°E
24°E
30°E
Forecasted rainfall results in....
no difference
win
loss
no data

A computer program was thus developed using the Fortran 90 programming language that was able to process the large number of iterative calculations and generate real time runoff forecasts from the real time rainfall forecasts. In Figure 7.7 a simplified flow chart demonstrating the structure of the programming framework developed to perform the above-mentioned tasks is depicted.

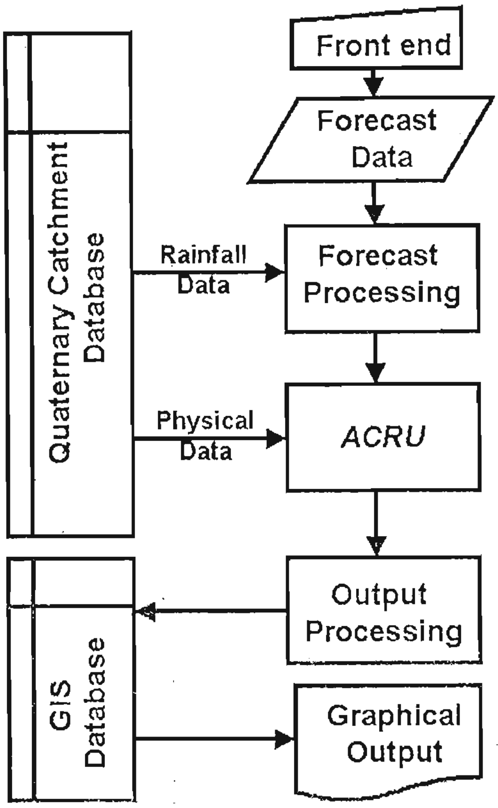


Figure 7.7 Simplified depiction of the programming framework used to produce runoff forecasts from the categorical rainfall forecasts (both real time or retro-active hind forecasts)

In its present state the program is designed to operate on a UNIX operating system and hence must be compiled and run in that environment. The program can, at a later stage and with a few minor adjustments, be made platform independent and could be compiled and run on UNIX, Windows and DOS based operating systems. Once the program is initiated, the user interacts with the program via a front end, which allows the user to select different options in the program through a series of questions (Figure 7.7). Some of the options that the user could select are:

i. Which forecast duration would one like to use, e.g. 1, 3 or 4 month?
ii. Is the forecast for the entire country or just a selection of catchments?

iii. Select the required forecast type, e.g. probabilistic or median value.

In its current form, the front end uses text and number based input, however, at a later stage a Graphical User Interface (GUI) could be designed which allows the user to select the required input information with a mouse.

Once the user has selected the appropriate options the computer program requires rainfall forecast data for the different catchment that the user has selected in order to generate runoff forecasts (Figure 7.7 illustrates option i below which was run to obtain the forecast results for this research). The rainfall forecast data can be obtained from three different sources, depending on whether the forecast is a real-time or retro-active forecast, *viz.*:

i. Categorical rainfall forecasts stored in a database containing all the retro-active categorical rainfall forecasts for each of the Quaternary Catchments in the South African study region;
ii. Manual input via the user, as this is an option that could be accessed via the front end, with this option being provided for real time forecasts where a small number of catchments are being analysed and the user knows the rainfall forecast in that region; or
iii. A real-time forecasting option, which would enable the user to input real-time categorical rainfall forecast downloaded from the SAWS. While this is an option, the step of assigning a categorical rainfall forecast to a particular Quaternary Catchment from the larger categorical rainfall forecast regions, would still need to be done manually.

Once the forecasts have been obtained for the area in question, the computer program extracts the relevant rainfall files from the Quaternary Catchment database. Each Quaternary Catchment has a specific raingauge allocated to it with, at the present time, 44 years of concurrent daily rainfall data, which is considered to represent the daily rainfall patterns that occur in that catchment. These rainfall records, extracted from the Quaternary Catchment Database, are then used in conjunction with the categorical rainfall forecast data in the forecast processing module of the program (Figure 7.7) to generate representative daily rainfall forecasts for the region in question, using the methods described in Section 7.4.

In the next step the computer program is then designed to extract information on the various biophysical characteristics, such as soils characteristics, temperature, slope and altitude, from the Quaternary Catchment Database. This information is combined with the representative daily rainfall forecasts to generate a menu (set parameters and variable inputs) that is used as an input into the *ACRU* model (Figure 7.7). The program is then designed to initiate the *ACRU* model, which uses the menu that has been generated, along with the generated representative daily rainfall forecast, to produce daily runoff for the forecast period. These techniques used to automatically update *ACRU* menus and run the model are modifications and developments on methodologies used in Schulze *et al.* (1990), Meier (1997), Schulze and Perks (2000) and Perks (2001).

The output from the *ACRU* model is then processed (Figure 7.7) in the program with the daily runoff (other outputs could be processed, such as crop yields) summed for the forecast period (simulated from observed daily rainfall) in order to obtain total runoff values for the forecast period. The forecasted runoff values are compared to the "actual" runoff experienced during the forecast period to obtain forecast accuracy scores. The accuracy scores obtained by the forecasted runoff totals are compared with the accuracy scores obtained by the median values in the output processing phase of the program, to obtain estimates of forecasting skill. The output processing has not been completely automated within the programming framework and at the time of performing the computer runs (2000) the skill and accuracy scores were calculated by initiating several other computer programs, once the main program had finished. It is anticipated that the manual output processing procedures could be incorporated as part of the main programming at a later stage.

Once the output processing has been completed the results are geo-referenced and stored in a GIS database (Figure 7.7), using the ARCINFO Geographical Information System. Following on from this step it is possible to generate different maps of the different outputs, such as runoff quantities produced by selected Quaternary Catchment, and the skill and accuracy scores produced by selected Quaternary Catchments. While there are facilities available to automatically perform this type of processing, these cannot at the time of writing be initiated from within the main computer program and must be processed separately. Automating the graphical output in order to produce maps requires integration of the main computer program with the ARCINFO GIS, which is difficult to do and beyond the scope of this project. The maps produced for this report were thus produced as a result of post processing using the ARCINFO GIS, once the outputs were added to the database.

7.8 Conclusions

In this chapter the focus has been on how the indirect methodology was used to produce one, three and four month runoff forecasts from the one, three and four month categorical rainfall forecasts. A detailed description of the hypotheses used and the methodology followed was provided, along with a simplified description of the programming framework used to produce the runoff forecasts and the results needed to evaluate the one, three and four month runoff forecasts. In Chapter 8 a detailed description of how the indirect methodology was applied to the 30 day percentage of normal rainfall forecast to obtain 30 day runoff forecasts, is provided. The forecasting evaluation methods used to assess the effectiveness of the 30 day runoff forecasts are also discussed. Finally, the programming framework developed to produce these forecasts is also discussed in the next chapter.

8 METHODS OF PRODUCING RUNOFF FORECASTS AT A QUATERNARY CATCHMENT SCALE FOR SOUTH AFRICA, USING THE 30 DAY PERCENTILE RAINFALL FORECASTS

In Chapter 7 the methodology used to obtain runoff forecasts from the four, three and one month categorical rainfall forecasts, was described. Techniques used to evaluate forecast performance where also detailed. This chapter covers Objectives (b) ii and iii of the Problem Statement (Figure OB-8) and details the methodology used to obtain the 30 day forecasted runoff values from the Centre for Ocean-Land-Atmosphere Studies (COLA) GCM 30 day rainfall forecasts. An outline of the development of an evaluation technique (similar to the one described in Chapter 7) is then provided, which will later be used on a retro-active hind forecast data set which spans 16 years from 1979 to 1995. The purpose of developing the forecast evaluation technique is to determine the accuracy and skill of the 30 day runoff forecast, which should then give some idea of the operational viability of applying this type of runoff forecast in hydrological studies.

8.1 Objectives

The major objective in this chapter is to assess the feasibility of using the Centre for Ocean-Land-Atmosphere Studies (COLA) GCM 30 day rainfall forecasts, expressed as a percentage of the normal value, for South Africa in order to develop 30 day forecasts of runoff using the *ACRU* daily time step hydrological simulation model. In doing so, simple techniques were used:

i. First, the COLA forecasts, which are provided as 18 grid cells at a resolution of 3.75^0 by 3.75^0, and thus encompass an area of approximately 130 000 km^2 each, had to be downscaled by an interpolation technique to a finer resolution of a 1' by 1' of a degree, in order to assign each of South Africa's Quaternary Catchments, which are generally of the order of 100 – 600 km^2 in area, a representative forecast value.
ii. Secondly, the 30 day percentage of normal rainfall forecasts were downscaled to representative daily rainfall data sets for all the Quaternary Catchments,
iii. The results using the forecasted daily rainfall runoff simulations at the Quaternary Catchment and regional scale were then evaluated.
iv. Finally, this analysis was then used to assess where further research was needed for more realistic and sophisticated forecasts of runoff to be made.

Problem Statement				
Reliable, skillful hydrological forecasts have the potential to prevent loss of life, spare considerable hardship and save affected industry and commerce millions of Rands annually if applied operationally within the framework of water resources and risk management. Integrated model and database systems provide scientists and managers with tools to investigate the feasibility and applications of such systems in operational forecasting activities.				
Broad Objectives	Place forecasting within a framework of water resources and risk management in South Africa. *(a)*	Develop hydrological forecasting techniques that could be used operationally within South Africa. *(b)*	Evaluate the hydrological forecasting techniques' performance over the South Africa study region using selected forecasting periods. *(c)*	Discuss problems and shortfalls of the current methodology used to obtain the different runoff forecasts. Recommend areas of potential future research that would enable operational application of these forecasts. *(d)*
Specific Objectives	i. Review climate variability in South Africa and its associated effect on risk ii. Review the current water resource situation in South Africa iii. Review risk evaluation and management strategies with specific attention given to the role of forecasting	i. Review current methodologies used to obtain hydrological forecasts ii. Develop suitable methodologies to be used in South Africa iii. Develop unbiased techniques to evaluate the performance of the different hydrological forecasts	i. Use standard forecasting evaluation techniques to assess the performance of the hydrological forecasting techniques developed ii. Compare different hydrological forecast performances iii. Attempt to identify trends that influence forecast performance iv. Provide explanations for the different trends influencing the forecasts' performance	i. Identify shortfalls in the techniques used to translate rainfall forecasts into runoff forecasts ii. Suggest areas where improvements could be made to increase the forecasts' reliability iii. Suggest areas of future research that would lead to the operational use of the different runoff forecasts iv. Identify key sectors of the study area where the application of forecasting may be particularly beneficial

Figure OB-8: Problem Statement, highlighting aspects covered in Chapter 8

8.2 General Circulation Model Rainfall Forecasts

General Circulation Models (GCMs) consist of discrete time dependent equations of motion, thermodynamics and continuity, which integrate initial conditions forward in time (Tennant, 1998a). AGCMs use surface conditions, such as SSTs, snow and ice coverage as the lower boundary conditions, which force changes in the atmosphere. Oceanic GCMs use the near surface conditions such as surface winds and temperature as the upper boundary forcing. In an attempt to formulate better simulations of global atmospheric conditions, simultaneous models assuming a coupled ocean-atmosphere are being used to provide feedback into one another (Tennant, 1998a).

At 28 day intervals the Centre for Ocean-Land-Atmosphere Studies (COLA) AGCM is used to produce the 30 day rainfall forecast fields that are used as input into the hydrological model in this study. There are two AGCMs currently used by the SAWB for monthly forecasting, the first one being the T30 version COLA AGCM and the second being the T62 version of the National Centre for Environmental Prediction (NCEP) AGCM Global Spectral Model. Although the NCEP T62 AGCM is used to produce real-time forecasts at the SAWB, there was not an extensive retro-active hind forecast period available to be used in verification studies. Hence, only output from the COLA T30 AGCM has being used in this study (Tennant, 1998a).

The COLA T30 AGCM is a spectral model with a triangular truncation at wave number 30 which produces output for a Gaussian grid consisting of 96 by 48 grid cells at approximately a 400 km resolution. The physical processes used in this GCM include deep and shallow convection, large scale precipitation, radiation, surface physics, vertical diffusion and gravity wave drag. To enable the AGCM to be used in climatological studies a simple biosphere model was included that is able to process data such as deep soil temperature, ground temperature, canopy temperature, soil moisture, liquid water storage, latest computed precipitation, roughness, maximum mixing length and sea ice temperature (Tennant, 1998a).

The initial conditions used as input data for the COLA AGCM to produce a set of 30 day retro-active hind forecasts of sea level pressure, 500 hPa heights, surface temperature, rainfall and outgoing longwave radiation were obtained from the NCEP re-analysis data set. The NCEP re-analysis data were created using a fixed data assimilation method for homogeneity and are available for every 6 hours from 1 January 1979 to 31 December 1995 (Tennant, 1998a).

Real-time forecasts are generated using initial condition data obtained from the operational Global Data Assimilation System (GDAS) at the SAWB. Global observation data are collected from the Global Telecommunications System via Washington DC, and are passed through quality control routines and are then prepared for the GDAS system that runs every six hours. These data are then used to produce 30 day forecasts using the COLA T30 AGCM at two week intervals to produce real time forecasts (Tennant, 1998a).

Tennant (1998a) produces two different types of retro-active 30 day rainfall forecasts at 28 day intervals. The first forecast set outputs rainfall forecasts into one of three possible terciles (Above Normal, Near Normal or Below Normal) using a technique similar to that of Landman's (1997), which was discussed earlier. Rainfall in this technique is estimated for seven different homogenous rainfall regions using CCA with the COLA AGCM output as a predictor set and rainfall as the predictand data set. The seven homogeneous rainfall regions were determined using a cluster analysis technique on the observed monthly rainfall data for a period of over sixty years from 510 rainfall stations throughout South Africa. Results from this technique produce an accuracy that is similar to those produced by Landman, with results being slightly better than chance and good results being around the 50% accuracy mark. With the results from the use of Landman's forecasts calling into question the appropriateness of the downscaling technique used and the representativity of the particular forecast regions to the area as a whole, it was decided to use the second type of rainfall forecasts that are produced by Tennant (1998a).

The second rainfall forecast set uses the ensemble averaged rainfall data output directly by the COLA AGCM. The rainfall forecasts produced by this AGCM generally tend to overestimate rainfall over South Africa. The rainfall data are bias corrected, in order to take the consistent overestimation into account, using simple linear regression techniques. The bias corrected rainfall data are output for the 18 grid cells which cover South Africa. The lagged average forecasting (LAF) technique is used to produce the ensemble average rainfall forecast results. The ensemble average forecasts are used as they tend to produce forecast with higher skills. The bias corrected rainfall forecasts, for each of the 18 different grid cells, are then calculated as a percentage of the normal rainfall for that region. Different interpolation techniques can then be applied to the percentage of normal rainfall forecasts to downscale forecasts to a resolution which is finer than the 18 grid cells covering South Africa.

A 16 year retro-active hind forecast data set, spanning the years 1979 to 1995, of the ensemble averaged percentage of normal rainfall forecast was provided to this study by Tennant (1999, pers comm). These forecasts were provided for a grid of 96 by 48 grid cells that represented the entire globe. South Africa experiences high spatial rainfall variability, which is maintained by multiplying the percentage of normal rainfall forecast (which is essentially a ratio) with the "normal" rainfall, i.e. 50th percentile value for a particular Quaternary Catchment. The percentage of normal forecasts were chosen for their ability to maintain the spatial rainfall variability and maintain local rainfall amounts and patterns.

8.3 "Downscaling" Percentage of Normal Forecasts from Large Area Grid Cells to the Size of the Operational Quaternary Catchments Using Interpolation

In order to obtain operational runoff forecasts it is first necessary to establish individualised rainfall forecasts for each Quaternary Catchment. It was hypothesised that the results obtained by simply assigning the value output from the COLA AGCM to a Quaternary Catchment with its centroid falling within in the region covered by a grid cell, as was done with the categorical forecast regions, would produce results that were too coarse. It was therefore decided that in order to capture more local scale variability, the COLA AGCM output should be interpolated to a finer resolution grid. The inverse distance weighting interpolation technique was therefore used to produce a 1' X 1' of an arc degree grid covering the entire region from the 3.75 X 3.75 arc degree grid output by the COLA AGCM. The 1' X 1' of a degree grid was then used to calculate the rainfall forecast values for each Quaternary Catchment by area-weight averaging the values of the grid cells that fell within each particular Quaternary Catchment.

A straightforward interpolation technique was chosen as a result of a lack of any other appropriate downscaling technique using regional climate models. The interpolation however used the percentage of normal values, which represent a ratio. These values were then superimposed on the existing rainfall patterns thus taking into account the local scale variability. The Inverse Distance Weighting (IDW) interpolation technique was chosen following a study performed by Hallowes *et al.* (1999) using several different interpolation techniques, including Spline, Kriging, trend surface analysis and IDW, to study rainfall distributions in the Kruger National Park (cf. Section 10.2.2). The Prediction Error Sum of Squares (PRESS) method was used to test the different interpolation techniques. The results showed that trend surface analysis gave the best scores followed by inverse distance weighting, Kriging and Spline. As it is was not feasible within the timeframe of this project to perform a trend surface analysis for the entire country, the inverse distance weighting technique was chosen.

8.4 Downscaling the Percentage of Normal 30 Day Rainfall Forecasts to Daily Rainfall Values that Could be Used in Hydrological Modelling

The *ACRU* modelling system requires daily rainfall input for its hydrological simulations. The precipitation forecasts produced by Tennant (1999, pers comm..) are for a period of 30 days. It is therefore necessary to translate the 30 day rainfall forecasts, which are made every 28 days, into daily rainfall quantities in order to run the hydrological model. The analogue year concept was used, as explained in Chapter 7. In downscaling the 30 day percentage of normal rainfall forecasts to representative daily rainfall values as input into the *ACRU* hydrological model the following steps were undertaken:

i. Each Quaternary Catchment's daily rainfall was accumulated for the 30 day forecast period in question (e.g. 24 January to 22 February) for each of the approximately 44 complete 30 day rainfall period windows for which daily rainfall values were available. If the forecast period overlapped the end of a year (e.g. 10 December to 8 January) then only 43 values of the 30 day accumulated daily rainfall could be extracted.
ii. This set of either 43 or 44 accumulated daily rainfall values was then ranked for each Quaternary Catchment.
iii. The median value (i.e. the value of rank 22 in a data set with 43 values) was then chosen to represent the normal rainfall.
iv. The percentage of normal rainfall forecast was then found for the particular Quaternary Catchment using the downscaling technique discussed in Section 8.3.
v. A figure of 12.5 % was added to and subtracted from the percentage of normal rainfall forecast to produce a 25% forecast range. For example, if the rainfall forecast was 85% of the normal rainfall then the values of 97.5 % and 72.5 % of the normal rainfall would represent the upper and lower bounds of the forecast range.
vi. The upper and lower bound forecast values were then converted to a ratio and multiplied by the median value, which represents the value of normal rainfall, to

produce a range of quantitative rainfall forecasts. For example, the percentages used in the example above give ratio values 0.975 and 0.725. If the normal rainfall (median) value was 160 mm, the range of rainfall forecasted would thus be between 0.975 X 160 mm = 156 mm and 0.725 X 160 mm = 116 mm.

vii. The daily rainfall data sets, from the 43 or 44 years of ranked accumulated daily rainfall, that correspond the closest to the upper and lower bounds of the range of forecasted rainfall were then selected as the daily rainfall values for the forecast period.

viii. For a given Quaternary Catchment, for a given 30 day rainfall forecast period (e.g. 24 January 1979 - 22 February 1979) the daily time step *ACRU* model was then run with historically observed daily rainfall for the two entire preceding years (i.e. from 1 January 1977 to 31 December 1978) and up to the forecast date (i.e. up to 23 January 1979) to initialise antecedent conditions and stores of, for example,

   a) the baseflow store and baseflow releases
   b) the stormflow store and stormflow releases
   c) soil moisture content in the topsoil and subsoil
   d) and, for future studies when information becomes available for each Quaternary Catchment, the status of dams and /or irrigation demands.

ix. The daily rainfall data sets representing the upper and lower bounds of forecasted daily rainfall were then applied, together with the initialised antecedent conditions generated previously (step viii) by the *ACRU* model, to generate daily runoff values which represent the upper and lower bounds of the runoff forecasting range.

x. These steps were then repeated for the remaining Quaternary Catchments over the entire region of South Africa.

Thirty day runoff forecasts were then produced by accumulating the 30 day daily runoff for the forecast period. This was done for each Quaternary Catchment in South Africa.

8.5 Methodologies Used to Evaluate the 30 Day Forecasts of Runoff

The forecast evaluations were performed using the set of 30 day rainfall forecasts produced every 28 days for the period starting on in January 1979 and ending in December 1995. There are 222 forecasts produced from this forecast set. However, as the Quaternary Catchment concurrent daily rainfall data set at the time of the computer runs ended in 1993, a shortened set of 194 forecasts was used.

Techniques similar to those used when evaluating runoff forecasts from the categorical rainfall forecasts were used to evaluate the accuracy and skill of the 30 day runoff forecasts. The output for these forecasts is slightly different, however, necessitating a modification in forecast evaluation techniques. Forecast accuracy is still determined by the hit rate. However, the forecast range is no longer represented as falling into a particular tercile, but is produced by the runoff forecast with the method described in the previous section. The following methodology is used to calculate the hit rate:

i. The accumulated forecasted runoff range is produced for each Quaternary Catchment for the forecast period in question, using the techniques described in Section 8.4.
ii. Runoff from the actual observed daily rainfall is simulated using the *ACRU* hydrological modelling system for a 43 year period from 1950 to 1993.
iii. The simulated daily runoff produced from the actual rainfall is extracted and accumulated for the period corresponding to the forecast period (e.g. 24 January to 22 February).
iv. If the accumulated simulated runoff produced from the actual observed rainfall falls within the range of the accumulated forecasted runoff (Section 7.4), then a hit is scored.
v. This is repeated for each Quaternary Catchment and for all 194 of the forecast periods which were available for this study.
vi. In this analysis hit rate was expressed as a percentage due to the large number of forecasts given in the retro-active hind forecast verification set.

In order to determine a forecast's skill, a benefit analysis was performed in which the median runoff value and forecasted runoff results were compared. The assumptions used in Chapter 7 were applied to the 30 day runoff forecasts, *viz.*

In the absence of a rainfall (or runoff) forecast, operators assume that median rainfall and runoff conditions are likely to prevail for the forecast period.

The methodology used to obtain forecast skills for the 30 day rainfall forecasts is almost identical to that used in Chapter 7. Owing to the large number of forecasts involved, automated looping procedures where established to perform the calculations. In each successive loop the following procedure was followed in order to calculate the overall, as well as the seasonal, results:

i. In Simulation 1 the long term *median* runoff was generated for the 30 day period in question (e.g. 24 January to 22 February) with the historically observed daily rainfall using the *ACRU* model.
ii. In Simulation 2 the accumulated forecasted runoff range for the forecast period was generated using the methodologies described in the Section 8.4.
iii. The values representing the upper and lower bounds of the accumulated forecasted runoff range where then averaged to obtain a single value that represents the accumulated *forecasted* runoff.
iv. Simulation 3 consisted of the generation of the assumed *actual* runoff for that season, using the season's actual observed historical daily rainfall for that Quaternary Catchment in simulations with the *ACRU* model.
v. Next, an expected error was calculated. The *expected error* was defined as the absolute difference between the results of Simulation 3 (actual runoff) and the results of Simulation 1(median runoff), i.e. |Simulation 3 - Simulation 1|.
vi. Finally a *forecasted error* was determined, that being defined as the absolute difference between Simulation 3 (actual runoff) and Simulation 2 (forecasted runoff), i.e. |Simulation 3 - Simulation 2|.

Using the results of the six steps outlined above, the following hypothesis was again postulated in regard to evaluating the benefits of forecasted runoff, *viz.*

If the forecasted error of runoff is less that the expected error (as defined above), then a benefit would potentially have been derived from applying the forecasting techniques, and a win is scored. If, on the other hand, the forecasted error of runoff is greater than the expected error (as defined above), then no benefit would have been derived, and a loss is recorded. If the forecasted error and the expected error are the same, then a benefit score of no difference is recorded.

The above steps were processed for each of the 194 forecast periods for all of the Quaternary Catchments in the study region of South Africa.

This information allows different estimates of forecast skill to be obtained. A conceptually simple analysis of the benefit of the 30 day forecasts of runoff in South Africa could be undertaken by mapping, for the study region:

i. the individual 30 day runoff forecasts' win vs loss results,
ii. the cumulative seasonal 30 day runoff forecasts win-loss situations, and

iii. the cumulative (i.e. aggregating the 194 thirty day forecast results) win-loss situations for all of the Quaternary Catchments in South Africa.

Forecast skill can also be calculated in terms of an integer benefit analysis, which is calculated for a single 30 day forecast period, in the same way as explained above. The single 30 runoff period forecast scores are then given a value of +1 for a win, -1 for a loss scenario and 0 for a no difference score. These integer values are then aggregated for the entire retro-active hind forecast data set to create a cumulative integer benefit analysis.

The large number of forecast results produced in this analysis enables one to gain better insight into the relative performance of the forecasts when compared to the median value. A percentage integer analysis was performed. In this analysis not only can one tell if the forecasted runoff value outperformed the median value, but one can also obtain an idea to the magnitude of this result.

8.6 Programming Framework Used to Generate the Runoff Forecasts from the Percentage of Normal Rainfall Forecasts

A large number of iterative calculations are required to translate the 30 day rainfall forecasts into 30 day runoff forecasts, using the method described in Chapter 6 and the initial part of Chapter 8, for all the 1946 Quaternary Catchments in the South African study region. To complicate the task even further, the large number of 30 day rainfall forecasts (194) which where received from the SAWS through Tennant (1999, pers comm) for verification purposes also needed to be processed using the methodology. The processing time on the UNIX system of the erstwhile CCWR required to generate representative daily rainfall forecasts and run the *ACRU* model to produce runoff forecasts for the study region (1946 catchments), is approximately three to seven hours, depending on available processing capacity (Assuming the average to be five hours, approximately 40 days were needed of processing time, this excluding malfunctions and shut downs). An automated process was therefore developed to automatically receive the 30 day AGCM rainfall forecasts and generate the representative daily rainfall forecasts, update the *ACRU* menu and automatically initiate the model to run all 1946 Quaternary Catchments.

As was the case with techniques described in Chapter 7, once the process had been tested on the retro-active hind forecasts, it should also be able to able generate real-time runoff forecasts using the actual real-time rainfall forecasts. The computer program discussed in Chapter 7 was modified to include the 30 day percentage of normal rainfall forecasts. The basic structure of the program did not change fundamentally, in being able to incorporate both a large number of iterations for verification purposes and be able to produce real-time forecasts. However, a looping iteration was included which was designed to automatically generate the front end inputs and forecasted daily rainfall input files, and then initiate the program to generate outputs which were again automatically stored to be processed at a later stage. In Figure 8.1 a simplified flow chart demonstrating the structure of the programming framework that was developed to perform the above-mentioned tasks is presented.

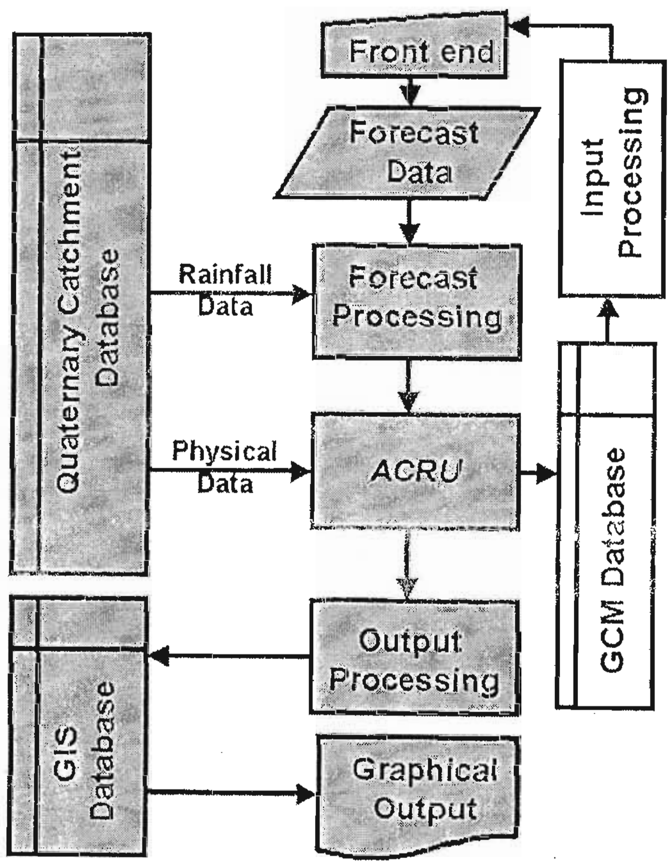


Figure 8.1 Simplified depiction of the programming framework used to produce 30 day runoff forecasts from the categorical rainfall forecasts (both real-time or retro-active hind forecasts)

The grey shaded areas in the diagram are the same as the components represented in Section 7.6. To prevent repetition, these elements will not be discussed in this section. The Reader should refer to Section 7.6 if clarity is needed on their function in the programming framework. Once again this program was designed to function on the UNIX operating system, but could be modified to initiate and run in both a DOS and Windows environment.

The addition to the original programming framework is the auto initiating looping routine, which is represented by the un-shaded elements in Figure 8.1. The program is initiated by starting a set of batch files, which contain several different executable program files. Once the program has been initiated the first program initiates the outside looping procedure, and looks for the required inputs from a General Circulation Model output database consisting of the 194 downscaled forecasts derived from Tennant's COLA T30 AGCM forecasts. The forecasts extracted from the AGCM database are then processed through the input processing routine that writes the relevant information into the correct places in the front end part of the programming framework (Figure 8.1). The model then generates the representative daily rainfall forecasts from the data in the Quaternary Catchment database. The physical attributes are then extracted from the Quaternary Catchment database and the *ACRU* model is initiated. Once the model has run, the outputs are written to a set of flat files and stored for processing at a later stage. The outside loop is initiated again, extracting the relevant forecasts from the GCM database and the entire process is repeated for all 1946 catchments and for all 194 different forecasts in the retro-active hind forecast dataset.

Once the entire looping routine was completed, the flat files were passed through the output processing routine. The results where then stored in a GIS database for graphical representation which was completed at a later stage. The output processing and the graphical representation of the results were not included in the looping procedure, as their incorporation would have unnecessarily complicated the programming framework. It was also anticipated that verification runs are a once off procedure, hence the requirement for the automated looping to include all components of the programming were unnecessary. The graphical representation component is difficult to automate in the existing programming framework as so many variables change, and this was still being done manually within the programming framework in this study.

Both Chapters 7 and 8 have given a detailed description of the methodology used to produce runoff forecasts from the categorical and percentage of normal rainfall forecasts, respectively. The techniques developed to evaluate the accuracy and skill of the different forecasts where also provided. In Chapter 9, which follows, the results produced using the methodologies and techniques described in Chapters 7 and 8, are presented. Forecast accuracy and skill scores are then used to evaluate whether, using the current forecasting techniques, forecasts are reliable enough to be used operationally in various areas within the South Africa study region.

9 RESULTS

This chapter covers Objective c in the Problem Statement (Figure OB-9), in which the results obtained from the respective methodologies and techniques used to evaluate the forecasted runoff, as explained in Chapters 7 and 8, are shown and interpreted. Results of the runoff forecasts produced using the categorical rainfall forecasts are compared to the results of runoff forecasts produced using the 100% accurate forecasts of categorical rainfall. The results of using the percentage of normal rainfall forecasts are shown for the entire forecast period as well as for different seasons. Comparisons are then made between the respective accuracy and skill scores produced using the runoff forecasts from both the categorical rainfall forecasts and the percentage of normal rainfall forecasts.

An attempt will be made to answer the following questions in this Chapter:

i. If the rainfall forecasts improve, do the runoff forecasts improve correspondingly?
ii. Do the runoff forecasts using the categorical rainfall forecasts perform better than the runoff forecast generated using percentage of normal rainfall forecasts?
iii. Is the runoff forecasts' performance dependent on the forecast period?
iv. Does the runoff forecast performance change seasonally?
v. Do forecasts perform better in wet and dry periods?
vi. Which areas in the study area produce the best runoff forecasts?

9.1 The Categorical Runoff Forecasts Produced Using the Respective Categorical Rainfall Forecasts

In this Section the results obtained from the forecasting methodology outlined in Section 7.2 will be shown. The analysis in this section should provide some answers to questions i to iv and vi listed above. Unfortunately the categorical rainfall forecasts provided only cover the spring to summer season, which implies that comparisons of forecasts performance for all seasons are not possible using the categorical runoff forecasts.

Problem Statement				
Reliable, skillful hydrological forecasts have the potential to prevent loss of life, spare considerable hardship and save affected industry and commerce millions of Rands annually if applied operationally within the framework of water resources and risk management. Integrated model and database systems provide scientists and managers with tools to investigate the feasibility and applications of such systems in operational forecasting activities.				
Broad Objectives	Place forecasting within a framework of water resources and risk management in South Africa. *(a)*	Develop hydrological forecasting techniques that could be used operationally within South Africa. *(b)*	Evaluate the hydrological forecasting techniques' performance over the South Africa study region using selected forecasting periods. *(c)*	Discuss problems and shortfalls of the current methodology used to obtain the different runoff forecasts. Recommend areas of potential future research that would enable operational application of these forecasts. *(d)*
Specific Objectives	i. Review climate variability in South Africa and its associated effect on risk ii. Review the current water resource situation in South Africa iii. Review risk evaluation and management strategies with specific attention given to the role of forecasting	i. Review current methodologies used to obtain hydrological forecasts ii. Develop suitable methodologies to be used in South Africa iii. Develop unbiased techniques to evaluate the performance of the different hydrological forecasts	i. Use standard forecasting evaluation techniques to assess the performance of the hydrological forecasting techniques developed ii. Compare different hydrological forecast performances iii. Attempt to identify trends that influence forecast performance iv. Provide explanations for the different trends influencing the forecasts' performance	i. Identify shortfalls in the techniques used to translate rainfall forecasts into runoff forecasts ii. Suggest areas where improvements could be made to increase the forecasts' reliability iii. Suggest areas of future research that would lead to the operational use of the different runoff forecasts iv. Identify key sectors of the study area where the application of forecasting may be particularly beneficial

Figure OB-9: Problem statement, highlighting aspects covered in Chapter 9

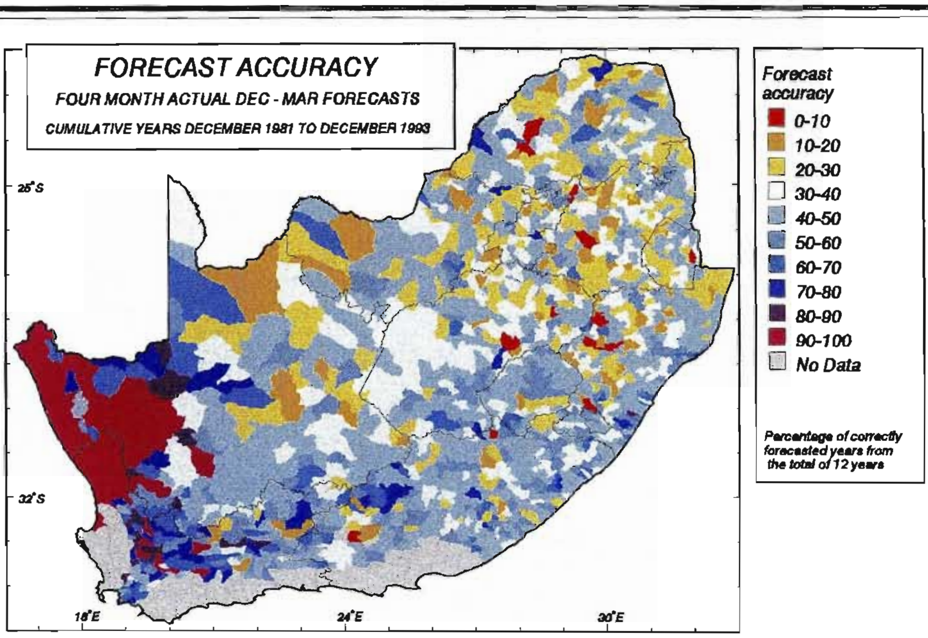
9.1.1 Evaluation of results using runoff forecasts produced with the four month categorical rainfall forecasts

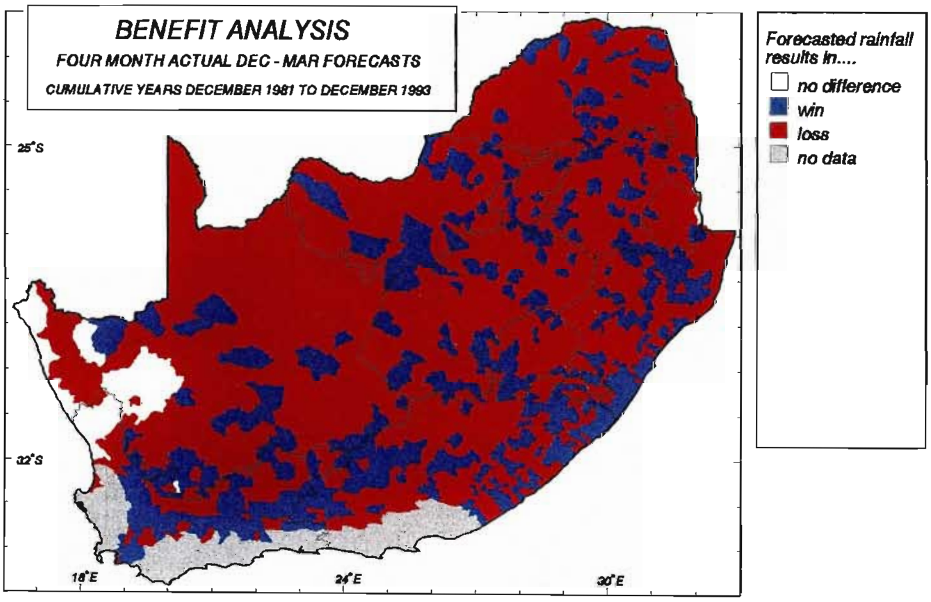
In this section the runoff forecasts using the four month December to March retro-active rainfall forecasts given in Section 7.2.2 are evaluated. Forecast accuracy and skill scores, obtained using the techniques described in Section 7.5, are displayed visually by way of maps. Forecast accuracy and skill scores using the four month forecasted categorical rainfall forecasts are displayed in Figure 9.1.

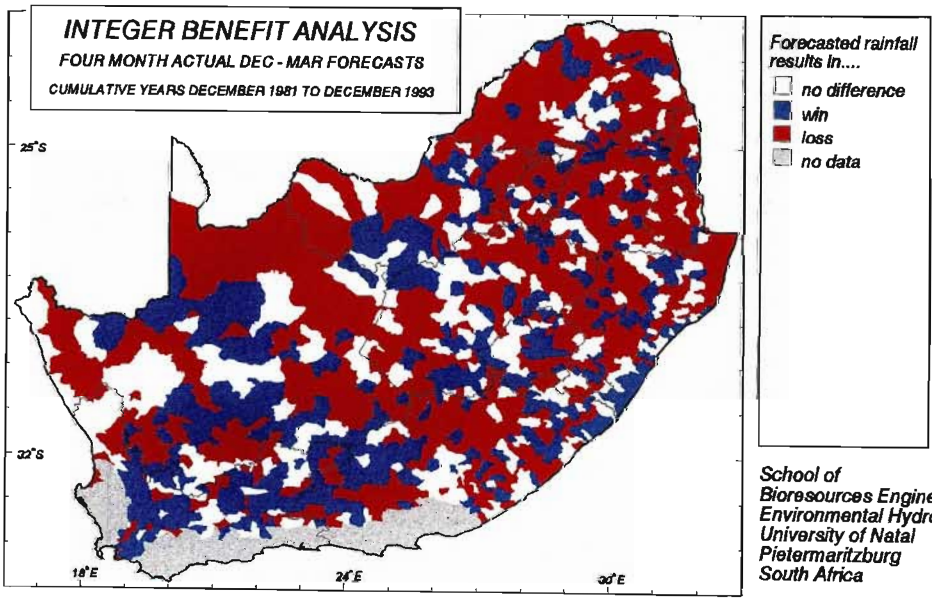
Figure 9.1	Forecast accuracy scores (%) and skill, expressed by benefit analyses, calculated using the runoff forecasts produced by the four month December to March categorical rainfall forecasts for the retro-active hind forecast period from 1 December 1981 to 31 March 1993

Figure 9.1 (top) represents the forecast accuracy, expressed as a percentage, calculated from the total number of correct forecasts (hits) out of a possible maximum of 12 four month forecast periods. The forecast accuracy is calculated using the technique described in Section 7.5. The runoff is ranked into terciles, which represent the Above, Near and Below Normal runoff categories. The forecast accuracy expected to be obtained by chance would therefore be 33.3%, i.e. 4 out of 12. The majority of the Quaternary Catchments have hit rates of five and less out of 12, which represents an accuracy of less than 50%. A large number of catchments also perform worse than chance by scoring less than 4 out of 12. The forecasts improve as they move toward the western seaboard over the drier parts of the study region, where some areas experience forecast accuracy scores of 100%. The forecast accuracy scores over the central and eastern interior of South Africa appear random, exhibiting no clear spatial patterns. Forecast accuracy does seem to improve along the eastern coastal areas where a larger number of the catchments score at a hit rate better than a 50%.

While the forecast accuracy results are encouraging it is necessary to test runoff forecasts against conventional 'forecast' quantities, such as the median value, that are often used in water resource management. In Figure 9.1 (centre and bottom) the forecast skill results are represented in the form of 'benefit' and 'integer benefit' analyses for the four month runoff forecasts, where the actual runoff is compared to the performance of the median value. These skill scores are obtained using the methodology explained in Section 7.5.







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The benefit analysis is determined using the cumulative absolute values of the differences between the actual and median runoff and the difference between the actual and forecasted runoff. The red colour on the benefit analysis map represents those Quaternary Catchments where the cumulative value of the difference between the actual and median runoff is less than the cumulative value of the difference between the actual and forecasted runoff. The red areas thus represent no benefit from forecasts, as the median values have outperformed the forecasts, and *visa versa* for the blue areas. The white areas represent catchments where the forecasted and median value produced the same skill, i.e. there is no difference between the median and forecasted values.

The integer benefit analysis (Figure 9.1, bottom) is calculated slightly differently from the benefit analysis and is represented by the cumulative number of times that the forecast outperforms the median value. It is calculated using the technique described in Section 7.5. If the number of times the forecast outperforms the median value is greater than the number of times the median value outperforms the runoff forecasts, then a win (blue) is scored. However, if the opposite is true, a loss (red) is scored. The white areas represent those places where the forecasted and the median values performed equally as well to one another.

In the benefit analysis in Figure 9.1 (middle) the majority of the area scores losses (red), implying that for the majority of the country it would have been more beneficial for the water resource managers and practitioners to have simply used the median value in their projections. The integer benefit analysis, although showing a similar trend, does not show the same results, with a larger proportion of the country showing either no difference (white) or a win (blue). This would suggest that even though in many cases the forecasts are closer to the actual runoff, the same number of times or even more often than the median value producing no difference of win results in the integer benefit analysis, they still produce a loss score on the benefit analysis. This would indicate that when forecasts are incorrect, they produce a much higher margin of error than when the median value is incorrect (this is due to forecasted category having the ability to miss the actual categorical forecast by two categories while the median, being in the middle category, can only miss by one category). The other aspect of importance to note is that although in the drier areas of the country the forecast accuracy is very high and in many of the catchments the score is 100%, the forecast's skill in these areas is the same as that when using the median value. Virtually no rainfall is recorded in these dry areas where both the median and actual forecasted values usually record little or no runoff values.

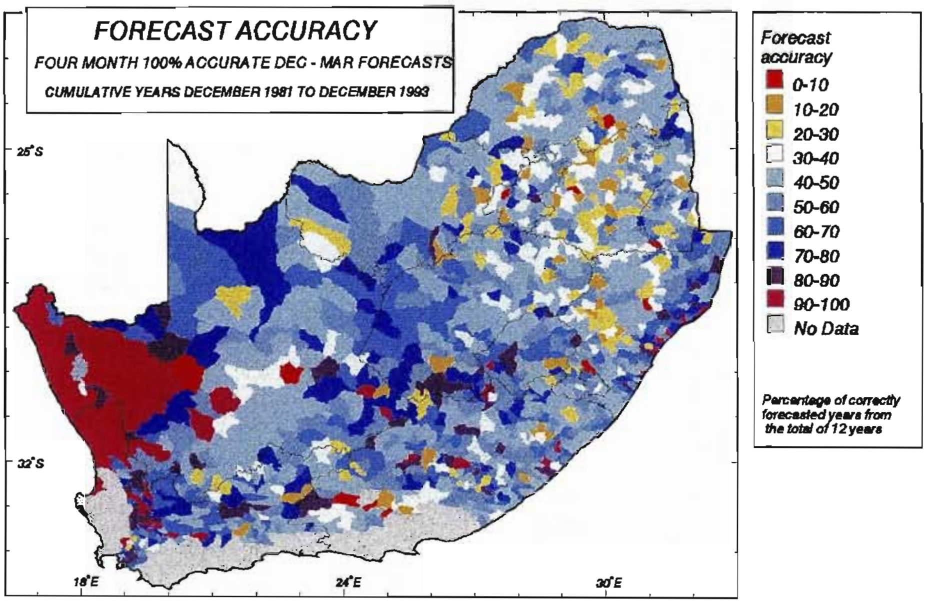
Figure 9.2 represents the skill and accuracy scores calculated for the four month runoff forecasts produced assuming that the categorical rainfall forecasts are 100% accurate. In Figure 9.2 forecast accuracy is again represented by the hit rate, while forecast skills are represented in terms of a benefit and integer benefit analyses.

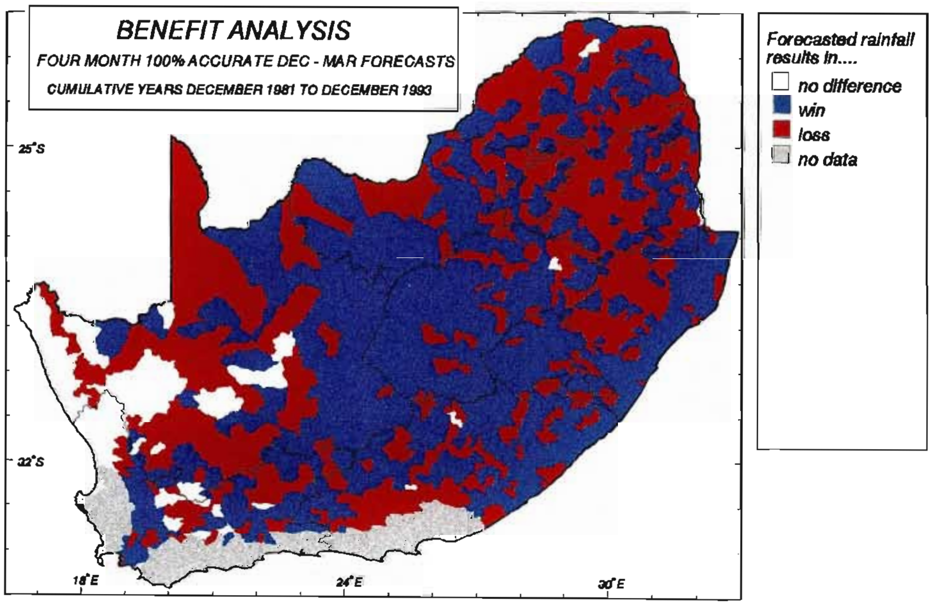
Figure 9.2	Forecast accuracy scores (%) and skill, expressed by benefit analyses, calculated using the runoff forecasts produced by the 100% accurate four month December to March categorical rainfall forecasts for the retro-active hind forecast period from 1 December 1981 to 31 March 1993

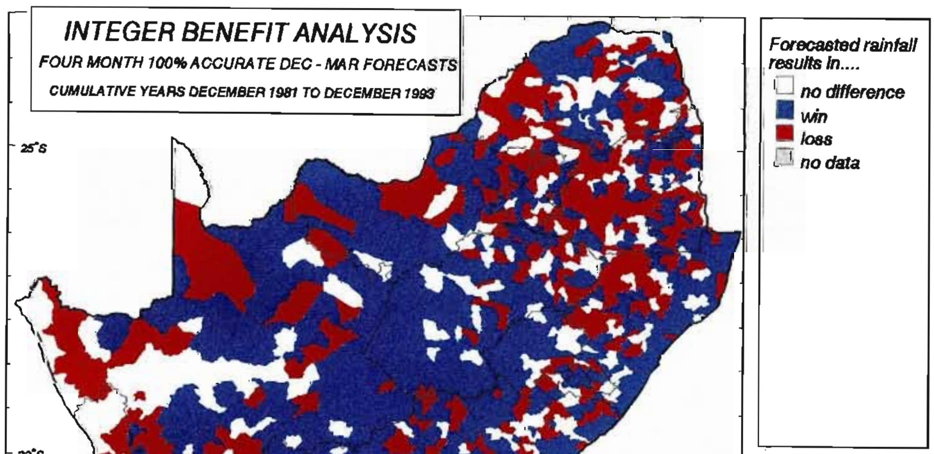
The forecast accuracy scores produced by the four month runoff forecasts assuming the 100% accurate categorical rainfall forecasts in Figure 9.2 (top) are generally higher than those produced from the actual rainfall forecasts in Figure 9.1. The majority of the Quaternary Catchments in the region show accuracy scores of six or more out of 12, i.e. > 50%. The western areas of the country still perform the best with 100% accuracy scores being achieved. The central interior and the eastern coastal areas of South Africa show an increase in forecast accuracy scores from those shown in Figure 9.1. The eastern interior, although showing a slight improvement on accuracies from those shown in Figure 9.1, still persists with low accuracy scores.

The benefit analysis in Figure 9.2 (middle) shows improved forecast skills over the majority of the region. A large portion of the region is represented by a win (blue) situation, *i.e.* where the forecasted seasonal runoffs outperform the median value. The integer benefit analysis (Figure 9.2, bottom) shows a similar pattern. The eastern interior does not show a marked improvement over the forecast skills shown in Figure 9.1, with the large majority of the area still showing a loss situation in both benefit and integer benefit analysis.

Runoff forecast accuracy and skill for the four month forecast period using the actual retro-active hind forecasts is low, indicating that runoff forecasting for this particular time period is not a good tool to use in water resource and disaster management. However, runoff forecasts improved when the categorical rainfall forecasts where assumed to be correct, indicating for the majority of the region that if rainfall forecasts where accurate, the runoff forecasts would follow suite. The regions over the eastern interior had low forecast accuracy and skill scores for both the actual and 100% accurate forecasts. The reasons for this could be several-fold:







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i. The year by year categorical rainfall data from the individual rainfall stations used to downscale the seasonal forecast categories from the forecast regions to the Quaternary Catchment scale may not be representative of those for the forecast region as a whole.
ii. The rainfall stations selected to represent a rainfall forecast region and used to produce the categorical rainfall forecasts are unable to represent the rainfall variability at the Quaternary Catchment scale.
iii. The forecast regions may therefore be too large and do not take into account the rainfall variations at a smaller, more local, scale.
iv. The downscaling technique used to generate the runoff forecasts may not, in this region, be representative enough to produce accurate results.
v. Taking the daily rainfall dataset equivalent to the median value of a particular tercile corresponding to the categorical rainfall forecast as the forecasted daily rainfall, may not take into account the variability in both the rainfall and runoff of the catchment system. Producing rainfall and runoff forecasts across a range may be a better option.
vi. The non-linearity of the runoff : rainfall relationship, especially at a daily level, may be too 'noisy' to reflect a seasonal forecast signal.

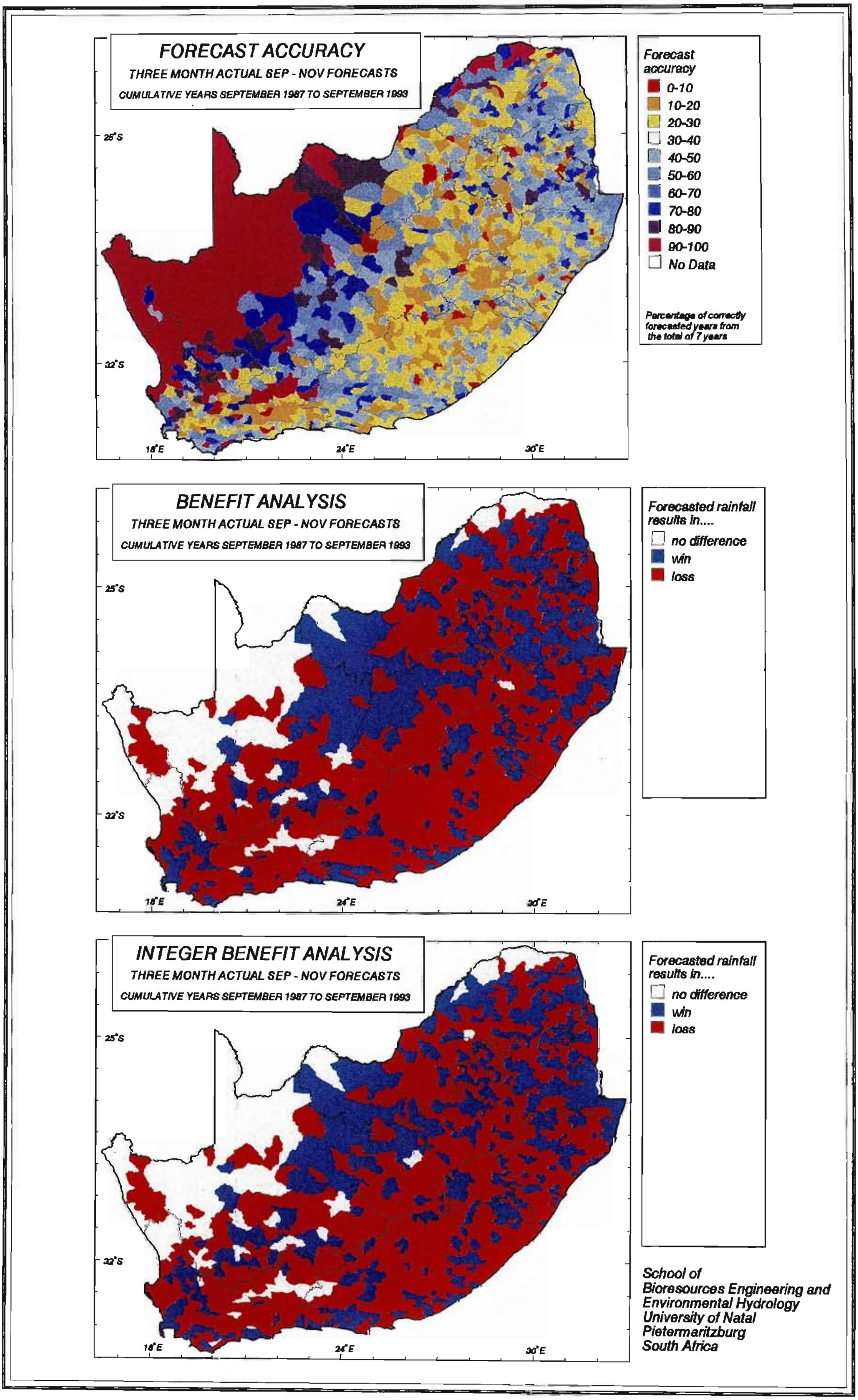
9.1.2 Evaluation of results using runoff forecasts produced with the three month categorical rainfall forecasts

In this section the accuracy and skill scores of the runoff forecasts produced using the three month categorical rainfall forecasts (Tables 7.2 and 7.3 in Section 7.2.3) are evaluated. The two sets of three month categorical rainfall periods, starting in September and November, produce accuracy scores of only 27.5% and 32.5% respectively. The runoff forecasts produced by these rainfall forecasts are expected to deliver poor results, as the statistical correlations between the different months within the forecast period is low. Forecast accuracy is expressed by the percentage forecast accuracy, i.e. the number of correct forecasts (the forecasted runoff category corresponds to the actual runoff category, Section 7.5) compared to the total number of forecasts made, in percent. Figures 9.3 and 9.4 show the skill and accuracy scores produced using the actual three month categorical rainfall forecasts for the September and November forecasts respectively.

In Figure 9.3 (top), the September to November three month runoff forecasts produced by the retro-active rainfall forecasts give an overall accuracy score of 42.9%, i.e. 3 out of 7, or less for the majority of the region. A large number of Quaternary Catchments produce accuracy scores below that expected by chance, i.e. 33.3%, or 2 or fewer hits out of 7. The eastern and central interior seem to produce the lowest accuracy scores, with the majority being two or fewer hits. The forecast accuracy scores increase toward the drier western parts of the region with some areas in the far western interior producing forecast accuracy scores of 100%. Areas in the southern Cape also display low accuracy scores of < 30%.

Figure 9.3	Forecast accuracy scores (%) and skill, expressed as benefit analyses, calculated using the runoff forecasts produced by the September to November three month categorical rainfall forecasts for the retro-active hind forecast period from 1 September 1987 to 30 November 1993

In Figure 9.3 (middle and bottom) the September to November three month runoff forecast skill results, represented as benefit and integer benefit analyses, show large areas of the region where a loss (red) is obtained. This indicates that for the majority of the country median runoff values would outperform the forecasted runoff as a predictor of expected runoff for this forecast period. Both the integer benefit and benefit analysis results show similar patterns. This would suggest that for the three month forecast period from September the errors expected to be produced from forecasting the runoff incorrectly using both the median and forecasted runoff are similar in the majority of cases. Hence, for this particular forecast period, the median value does not only outperform the forecasted runoff in absolute terms, but also produces better forecasts more often. In the western areas of the region there are large areas of the country where the forecasted and median values perform equally well. This again suggests that in dry areas high accuracy forecasts do not necessarily produce forecasts with significant skill. The higher accuracy forecast results, in the drier areas, could be attributed to the dynamics of seasonal flow generation being easier to simulate, as flow is produced by a few big events rather than many smaller events producing complex (stormflow, baseflow, antecedent conditions) interactions. The reason that both the median and forecasted values give almost identical results could be attributed to the paucity of rainfall, with normal and below normal forecasts producing very little or no runoff, implying that forecasts only become important in those years in which rainfall is well above the normal.


FORECAST ACCURACY
THREE MONTH ACTUAL SEP - NOV FORECASTS
CUMULATIVE YEARS SEPTEMBER 1987 TO SEPTEMBER 1993
Forecast accuracy
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
No Data
Percentage of correctly forecasted years from the total of 7 years
25°S
32°S
18°E
24°E
30°E
BENEFIT ANALYSIS
THREE MONTH ACTUAL SEP - NOV FORECASTS
CUMULATIVE YEARS SEPTEMBER 1987 TO SEPTEMBER 1993
Forecasted rainfall results in....
no difference
win
loss
25°S
32°S
18°E
24°E
30°E
INTEGER BENEFIT ANALYSIS
THREE MONTH ACTUAL SEP - NOV FORECASTS
CUMULATIVE YEARS SEPTEMBER 1987 TO SEPTEMBER 1993
Forecasted rainfall results in....
no difference
win
loss
25°S
32°S
18°E
24°E
30°E
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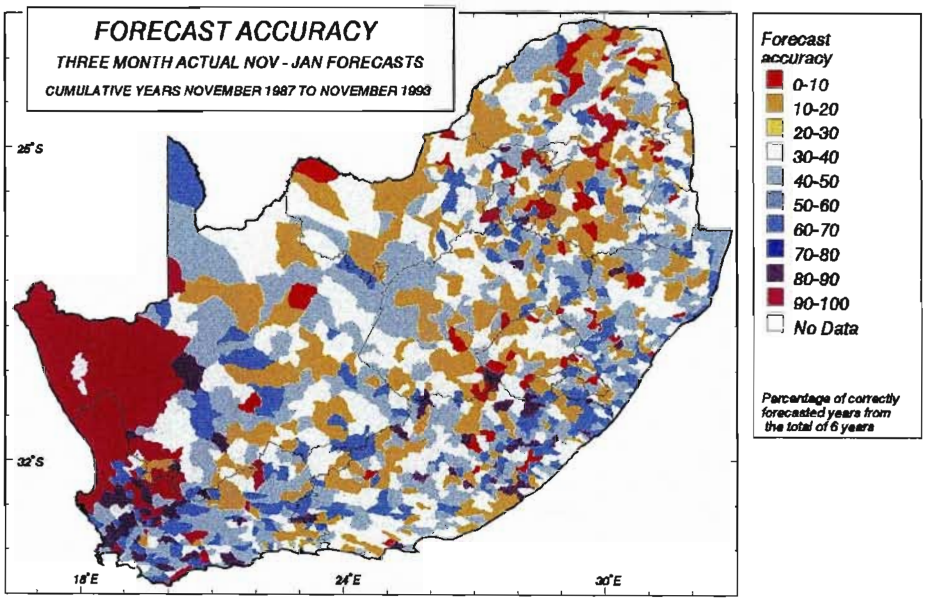
The forecast accuracy of the November three month forecasts is less than 50% for the majority of the region, with a large proportion of the area scoring values even less than 30% accuracy (Figure 9.4, top). There is a westward trend, with forecasts producing the highest accuracy scores of 100% along the dry western seaboard of South Africa. The accuracy in the western and central interior produce a fairly random pattern of forecast accuracy scores, which for the most part is in the region of the 33.3% (random) accuracy mark. The areas over the eastern interior, however, produce the lowest accuracy scores with many areas in fact producing scores of 0%.

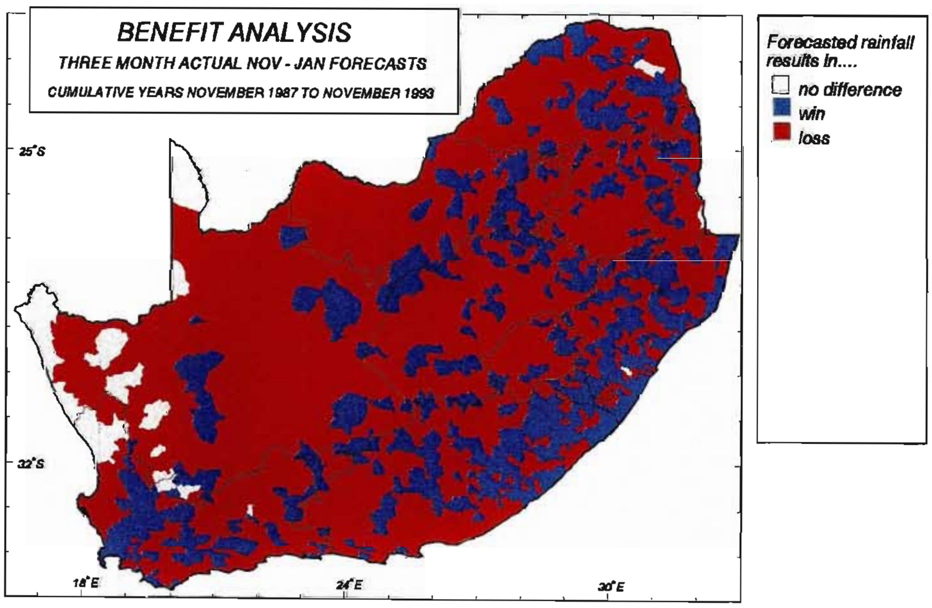
Figure 9.4	Forecast accuracy scores (%) and skill, expressed by benefit analyses, calculated using the runoff forecasts produced by the November to January three month categorical rainfall forecasts for the retro-active hind forecast period from 1 November 1987 to 31 January 1994

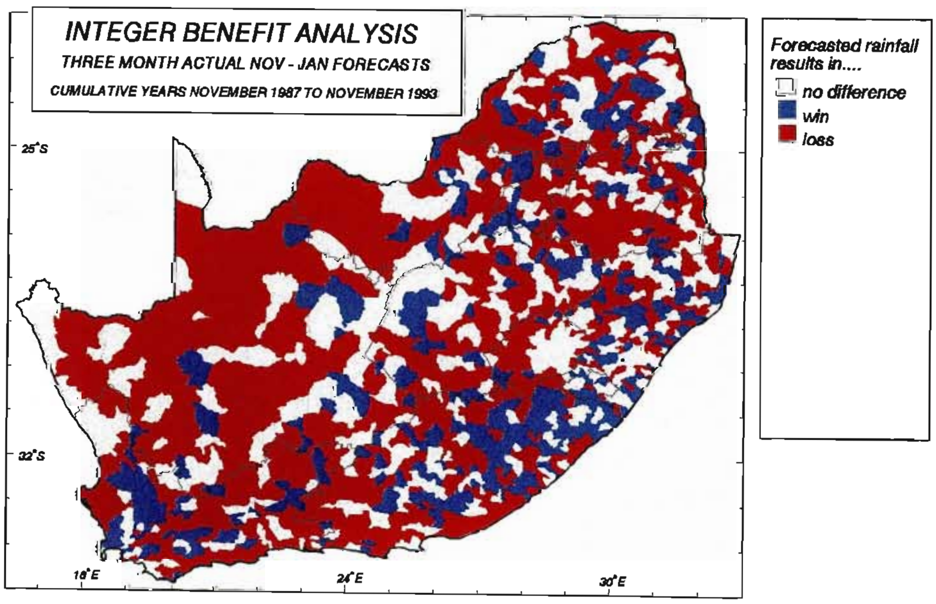
The benefit analysis in Figure 9.4 (middle) produces a "loss" scenario for large sections of the country. The forecast skill does improve along the eastern seaboard, however, where large areas record a win scenario. The integer benefit analysis (Figure 9.4, bottom) produces a better result, with the majority of South Africa still scoring losses, but with a greater proportion of the area producing no difference and win scenarios. This would suggest that for the three month November to January forecast period the expected error produced by using an incorrect forecast would be greater than the expected error produced by using the median runoff value for a three month prognosis.

Neither the three month September to November runoff forecasts (Figure 9.3) nor the three month November to January runoff forecasts (Figure 9.4) perform well enough to be used beneficially in water resource and risk management programmes for the majority of the catchments in the study region. The September toNovember forecasts, however, do seem to outperform the November to January forecasts, producing better overall skill and accuracy results.

The forecast accuracy and skill scores for the three month runoff forecasts produced by the 100% accurate categorical rainfall forecasts for September to November and November to January are given in Figures 9.5 and 9.6. A comparison of Figures 9.3 and 9.5 shows a marginal improvement in accuracy scores, for September to November, with a greater proportion of the area scoring above the 42.9%, i.e. equivalent to three out of seven hits or more.


FORECAST ACCURACY
THREE MONTH ACTUAL NOV - JAN FORECASTS
CUMULATIVE YEARS NOVEMBER 1987 TO NOVEMBER 1993
25°S
32°S
18°E
24°E
30°E
Forecast accuracy
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
No Data
Percentage of correctly forecasted years from the total of 6 years


BENEFIT ANALYSIS
THREE MONTH ACTUAL NOV - JAN FORECASTS
CUMULATIVE YEARS NOVEMBER 1987 TO NOVEMBER 1993
25°S
32°S
18°E
24°E
30°E
Forecasted rainfall results in....
no difference
win
loss

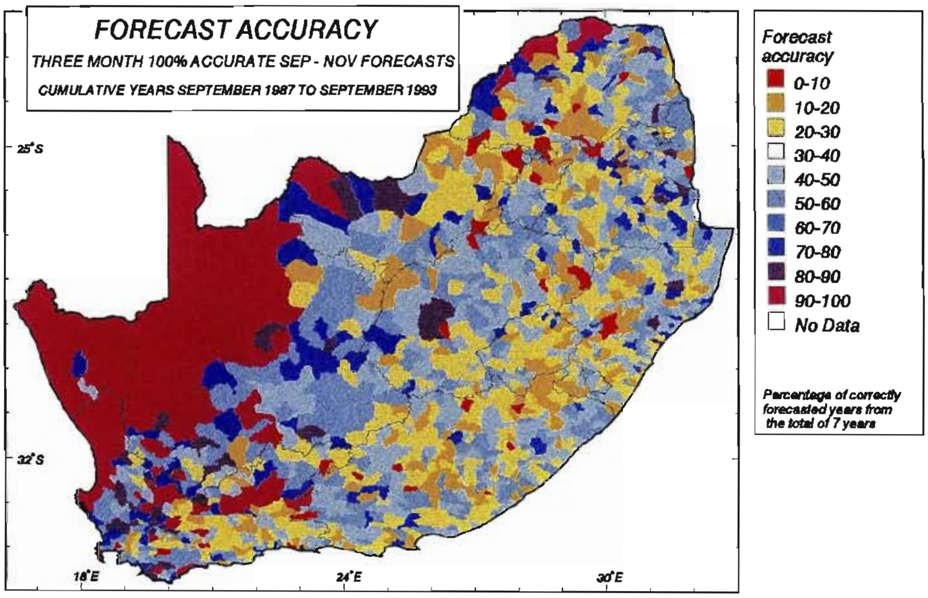

INTEGER BENEFIT ANALYSIS
THREE MONTH ACTUAL NOV - JAN FORECASTS
CUMULATIVE YEARS NOVEMBER 1987 TO NOVEMBER 1993
25°S
32°S
18°E
24°E
30°E
Forecasted rainfall results in....
no difference
win
loss

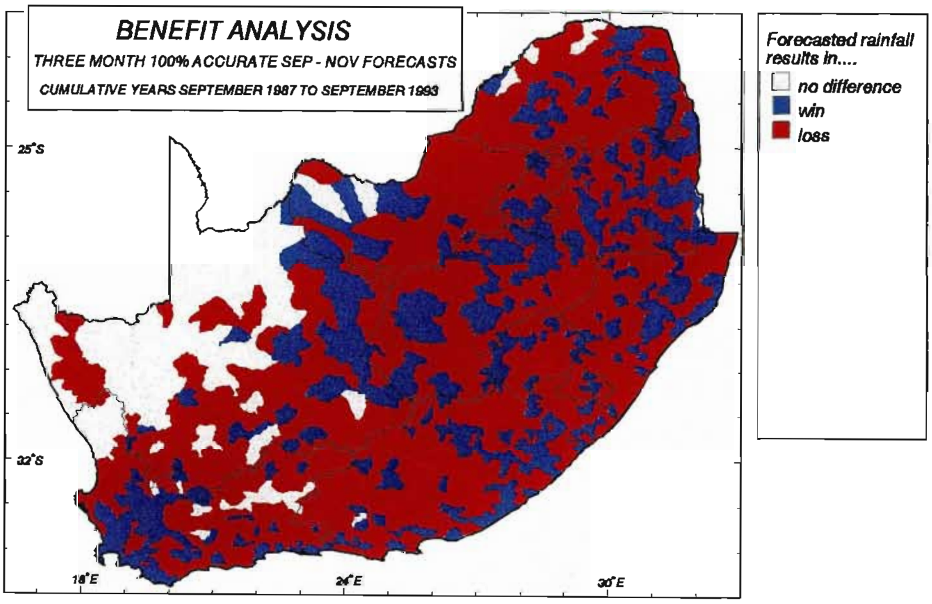
Accurate rainfall forecasts therefore produce more accurate runoff forecasts for the majority of South Africa for the three month runoff forecast period starting in September. The categorical runoff forecasts produced from 100% accurate rainfall forecasts should, in theory, yield accuracy scores of 100%. However, this is not the case and could be attributed to the complexities involved in the rainfall : runoff relationship. The improvement in forecast accuracy does not extend to the forecasts skill for the three month period starting in September. The benefit and integer benefit analysis (Figure 9.5, middle and bottom) results do not improve, with an even greater area of the country recording a loss scenario compared with the actual forecasts in Figure 9.3. The integer benefit and benefit analysis results are very similar, suggesting that for this particular forecast period the median value outperforms the forecasts both in absolute terms as well as in the number of more correct forecasts. The results produced in this analysis would seem to indicate that the technique used to produce the runoff forecasts from the rainfall forecasts is not performing well and may be flawed. The methodology used may need to be revised and account be taken of the variability that exists within the system. Instead of producing one value to represent a particular forecast (Above, Below or Near Normal), a series of forecasts should rather be produced within a range, to account for the variability.

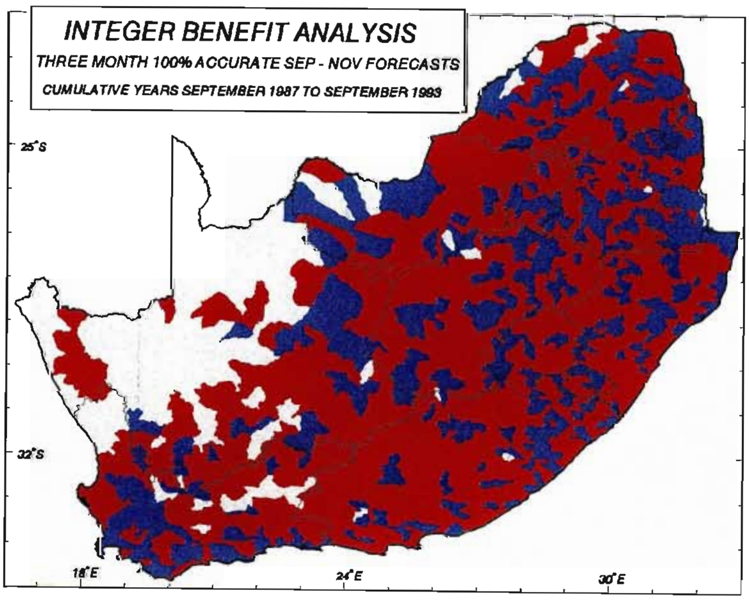
Figure 9.5	Forecast accuracy scores (%) and skill, expressed as benefit analyses, calculated using the runoff forecasts produced by the 100% accurate three month categorical rainfall forecasts for the retro-active hind forecast period extending from 1 September 1987 to 30 November 1993

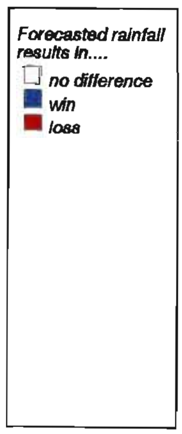
The three month forecast period starting in September therefore shows that more accurate rainfall forecasts produce more accurate runoff forecasts. This, however, does not always translate into an improvement in forecast skill. There are several factors that could contribute to these seemingly contradictory results:

i. A particular forecast region may have a high number of Near Normal runoff events, which would be conducive to the median value performance being better than that of the forecasted values.
ii. The forecast downscaling techniques used to produce runoff forecasts from rainfall forecasts may need to be improved.
iii. The forecast rainfall regions may not be representative of the region as a whole, being unable to capture much of the local scale variations in season to season rainfall.









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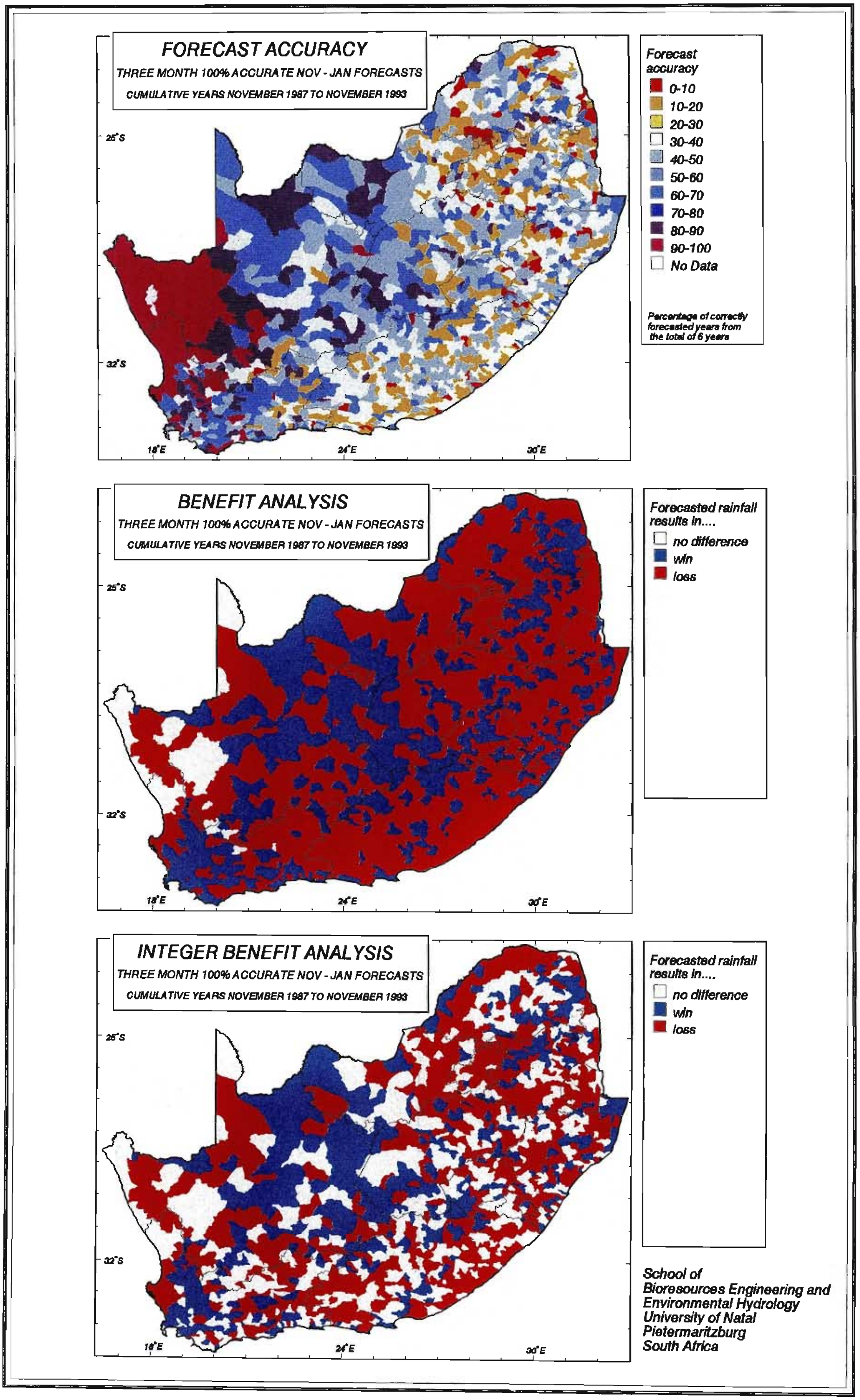
In Figure 9.6 (top) it is shown the forecast accuracy for the three month November to January runoff forecasts using the 100% accurate rainfall forecasts does not improve, when compared to results in Figure 9.4, with large parts of the central and western interior attaining accuracy scores around 50%, i.e. three out of six.

The eastern interior and eastern seaboard do not show improved forecast accuracy scores, however, with some regions even experiencing losses in accuracy when compared to the actual forecasts.

Figure 9.6	Forecast accuracy scores (%) and skill, expressed as benefit analyses, calculated using the runoff forecasts produced by the 100% accurate November to January three month categorical rainfall forecasts for the retro-active hind forecast period from 1 November 1987 to 31 January

The forecasted skill scores do not improve with the use of the 100% accurate rainfall forecasts, with a large proportion of the country experiencing loss scenarios in both the benefit and the integer benefit analysis (Figure 9.6, middle and bottom). Areas along the eastern coast, however, show a definite decrease in forecasts skill with a greater number of catchments in this region experiencing a loss scenario with perfect rainfall forecasts. This, once, again is an indication of the larger rainfall forecast regions probably being unable to capture local scale variations and suggests that the individual raingauges used to generate forecasts for this large region may not adequately represent the larger region as a whole, i.e. the year to year categories of the 510 rainfall stations used to generate the homogeneous rainfall regions (Tennant, 1998) do not necessarily correspond with those of the approximately 1300 rainfall stations used to generate runoff for the Quaternary Catchments.


FORECAST ACCURACY
THREE MONTH 100% ACCURATE NOV - JAN FORECASTS
CUMULATIVE YEARS NOVEMBER 1987 TO NOVEMBER 1993
Forecast accuracy
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
No Data
Percentage of correctly forecasted years from the total of 6 years
25°S
32°S
18°E
24°E
30°E
BENEFIT ANALYSIS
THREE MONTH 100% ACCURATE NOV - JAN FORECASTS
CUMULATIVE YEARS NOVEMBER 1987 TO NOVEMBER 1993
Forecasted rainfall results in....
no difference
win
loss
25°S
32°S
18°E
24°E
30°E
INTEGER BENEFIT ANALYSIS
THREE MONTH 100% ACCURATE NOV - JAN FORECASTS
CUMULATIVE YEARS NOVEMBER 1987 TO NOVEMBER 1993
Forecasted rainfall results in....
no difference
win
loss
25°S
32°S
18°E
24°E
30°E
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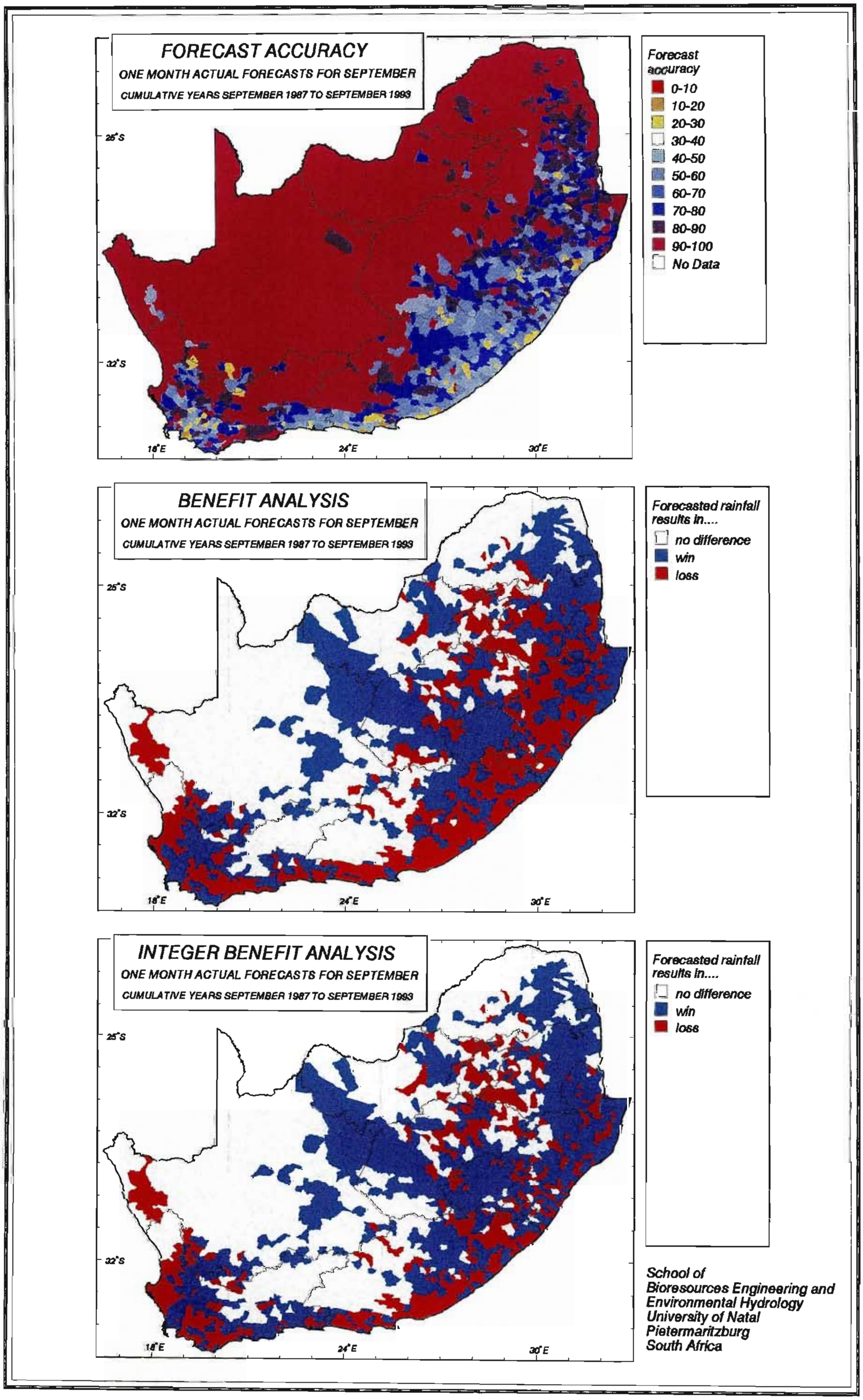
9.1.3 Evaluation of the results using the runoff forecasts produced with the one month categorical rainfall forecasts

In this section an evaluation is performed on the one month runoff forecasts produced by one month categorical rainfall forecasts for the periods starting 1 September and 1 November respectively (Section 7.2.4, Tables 7.5 and 7.6), again following procedures explained in Section 7.5. The overall rainfall forecast accuracies for these forecasts was 33.75% and 43.75% respectively, which are better than the accuracy scores produced by the three month forecasts with the same starting months. The rainfall forecast accuracy scores are, however, worse than the four month rainfall forecast accuracy scores starting in December. In Sections 9.1.1 and 9.1.2 it was shown that if the rainfall forecasts were 100% accurate then the runoff forecasts also tend to be more accurate. Hence, one would intuitively expect the one month runoff forecasts to outperform the three month runoff forecasts, but give results that are worse than those of the four month forecast period.

Figures 9.7 and 9.8 show the one month runoff forecast accuracy and skill scores generated using the one month categorical rainfall forecasts.

Figure 9.7	Forecast accuracy scores (%) and skill, expressed as benefit analyses, calculated using the runoff forecasts produced by the September one month categorical rainfall forecasts for the retro-active hind forecast period from 1 September 1987 to 30 September 1993

The one month runoff forecast accuracy scores shown in Figure 9.7 (top) are higher than those produced by any of the other forecasts periods using the categorical rainfall forecasts. For the vast majority of the region, 100% accuracy result are achieved with a hit score of 7 out of 7. The accuracy scores decrease towards the southern and eastern coastal areas, but are still generally over the 40 % accuracy mark, i.e. with a 3 out of 7 hit rate. In Sections 9.1.1 and 9.1.2 it was seen that the hit rate improved in the drier western areas of the country. In September the summer rainfall has not started over the majority of the region, with many parts in the central and western interior experiencing little or no rainfall. Hence, it would seem that forecast accuracy scores for the September month follow the general trend already shown, *viz.* that forecasts are more accurate under more arid conditions.


FORECAST ACCURACY
ONE MONTH ACTUAL FORECASTS FOR SEPTEMBER
CUMULATIVE YEARS SEPTEMBER 1987 TO SEPTEMBER 1993
25°S
32°S
18°E
24°E
30°E
Forecast accuracy
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
No Data
BENEFIT ANALYSIS
ONE MONTH ACTUAL FORECASTS FOR SEPTEMBER
CUMULATIVE YEARS SEPTEMBER 1987 TO SEPTEMBER 1993
25°S
32°S
18°E
24°E
30°E
Forecasted rainfall results in....
no difference
win
loss
INTEGER BENEFIT ANALYSIS
ONE MONTH ACTUAL FORECASTS FOR SEPTEMBER
CUMULATIVE YEARS SEPTEMBER 1987 TO SEPTEMBER 1993
25°S
32°S
18°E
24°E
30°E
Forecasted rainfall results in....
no difference
win
loss
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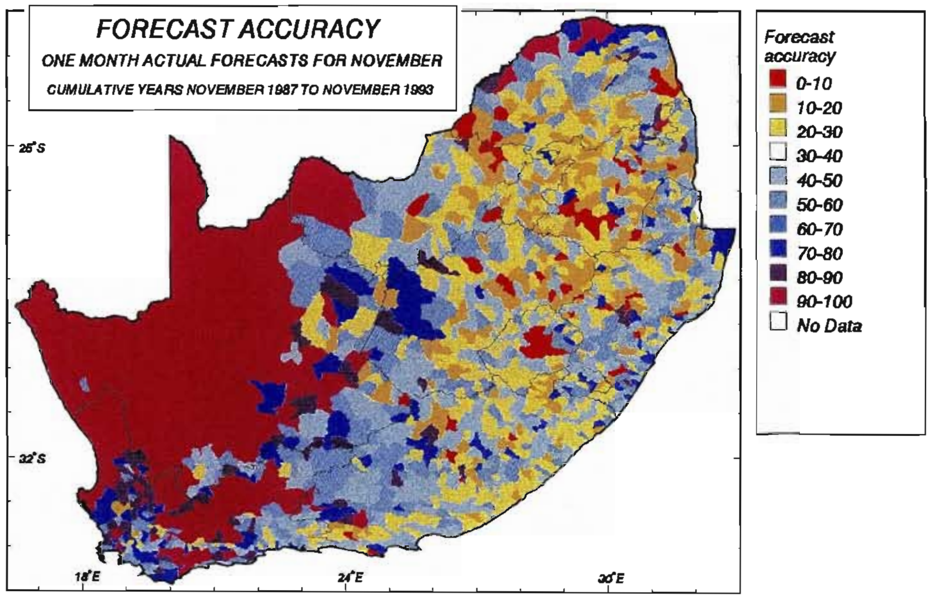
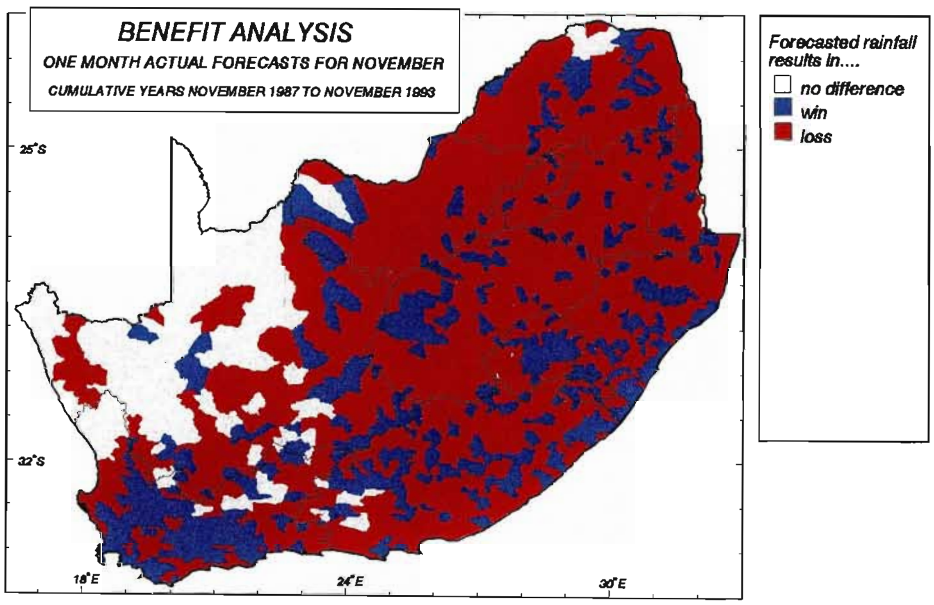
The benefit analysis and integer benefit analysis results in Figure 9.7 (middle and bottom) show almost identical patterns, with large areas of the region experiencing a "no difference" forecast result. A large proportion of the remaining areas experience a win scenario, with areas in the southern and eastern coastal areas experiencing the majority of the loss scenarios. In the drier areas covering the central and western interior the high accuracy scores do not translate into high skill forecasts. The majority of the central and western interior, experiences a "no difference" result, which indicates that the median and forecasted runoff values performed equally well. The September runoff forecasts deliver the best results thus far in terms of both forecast accuracy and skill scores. This would seem in contradiction with the general trend that has being observed, *viz*. that the runoff forecast accuracy echoes that of the rainfall forecast accuracy. The major reason for this discrepancy in results is the generally dry conditions which still prevail over most of the summer rainfall region at this time of year. The second significant, but may be expected, trend which seems to appear is that the drier the area the better the forecasts.

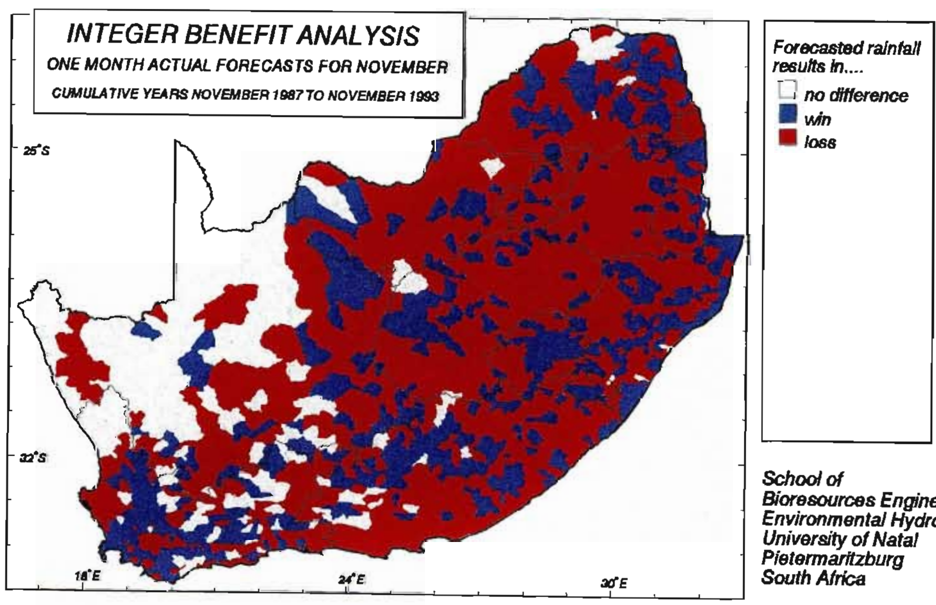
The November one month runoff forecast skill and accuracy scores are presented in Figure 9.8. In contrast to the September one month runoff forecast accuracy, which was fairly high throughout the region, the November forecasts only produce high accuracy scores in the low rainfall western areas. In Figure 9.8 the central and eastern areas experience low forecast accuracy scores with hit rates of 30%, i.e. with 2 or fewer hits out of 7.

Figure 9.8	Forecast accuracy scores (%) and skill, expressed as benefit analyses, calculated using the runoff forecasts produced by the November one month categorical rainfall forecasts for the retro-active hind forecast period from 1 November 1987 to 30 November 1993

Both the benefit analysis and the integer benefit analysis show loss scenarios over the majority of South Africa (Figure 9.8, middle and bottom). The integer benefit analysis results are only marginally better than the benefit analysis results. This would indicate that for the majority of the region the median value runoff is outperforming the forecasted runoff values, suggesting that the operational application of this particular forecast for the majority of the region is not warranted. It is also important in this investigation that a comparison of the 100% accurate forecasts is performed in order to identify the performance of the methodology for the forecast periods chosen (cf. Section 9.14).







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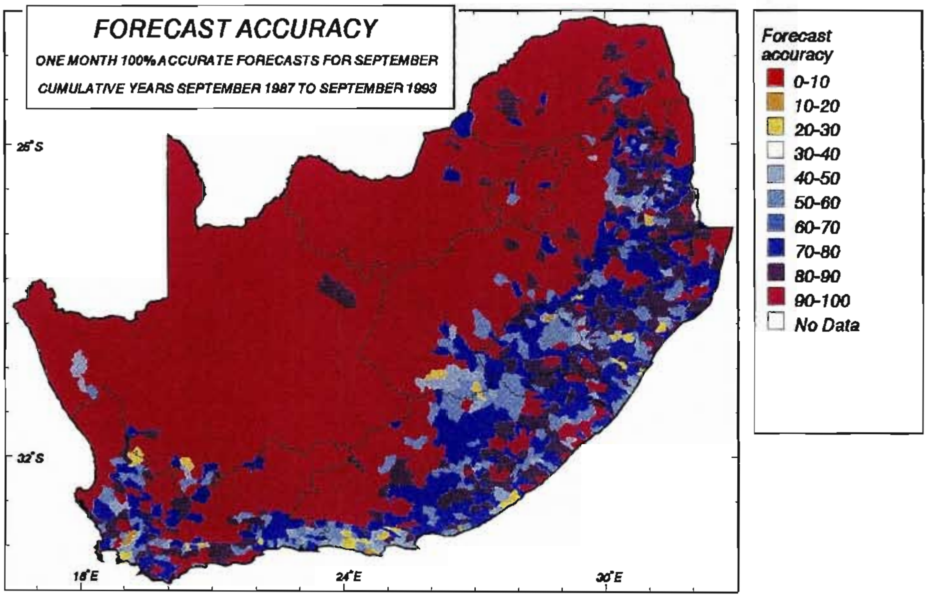
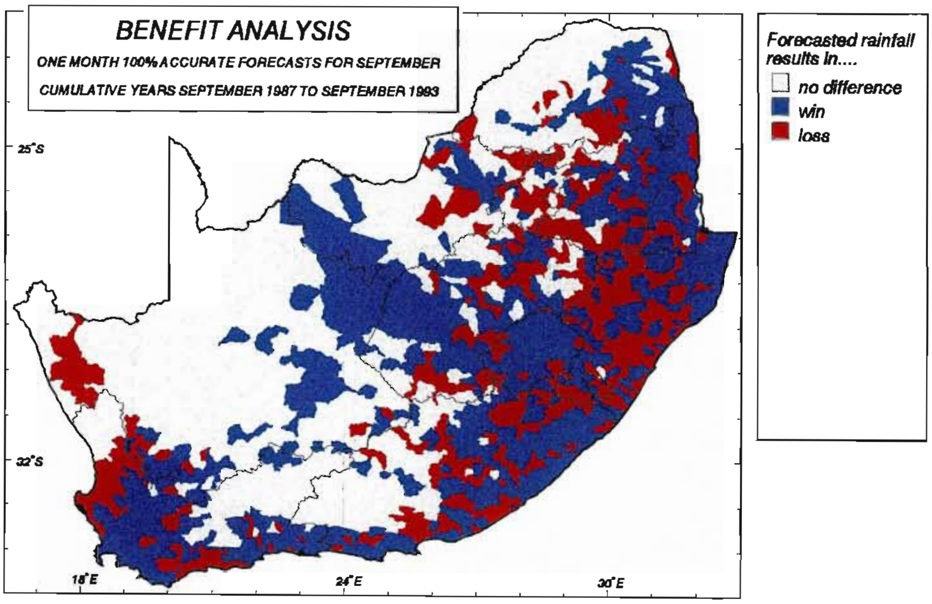
A comparison of the one month runoff forecasts obtained from the one month September and November categorical rainfall forecasts shows that the September runoff forecasts outperform those obtained in November, despite the rainfall forecasts for the November period having an overall accuracy of 43.75% against those for September with an accuracy of only 33.3%. The results obtained for the one month forecasts would seem in contrast to results obtained in the previous sections, which indicated that improvements in rainfall forecast accuracy would translate into improvements in runoff forecast accuracy. The main contributing reason to these seemingly anomalous results would be the difference in the rainfall history experienced in the months of September and November. In September the summer rainfall season has not yet started and the majority of South Africa is still experiencing dry post-winter conditions, while in November much of the region will have received at least some early summer rainfall already. It would thus seem that the forecast accuracy results are indirectly correlated to the amount of rainfall received in a region, i.e. the higher the average rainfall in an area the lower the forecast accuracies. Variations in the antecedent moisture conditions in wetter areas and in wetter periods contribute to the overall variability, making forecasts less accurate.

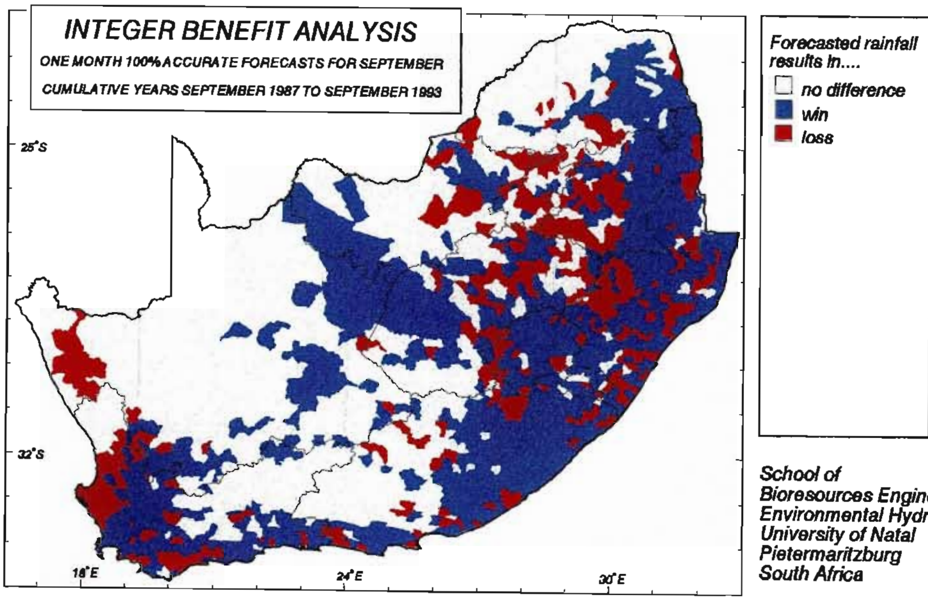
The difference in forecast accuracies between November and September could be attributed to the November period's rainfall falling on a catchment which could be either dry or wet, while in September the catchment is almost invariably dry.

Figures 9.9 and 9.10 represent the forecast accuracy and skill scores produced by the one month runoff forecasts using the one month 100% accurate categorical rainfall forecasts for September and November respectively. In Figure 9.9 a slight improvement in the forecast accuracy from that shown in Figure 9.7 can be noted in the southern and eastern coastal areas of South Africa. The majority of the country shows 100% accuracy in results.

Figure 9.9	Forecast accuracy scores (%) and skill, expressed as benefit analyses, calculated using the runoff forecasts produced by the 100% accurate September one month categorical rainfall forecasts for the retro-active hind forecast period from 1 September 1987 to 30 September 1993







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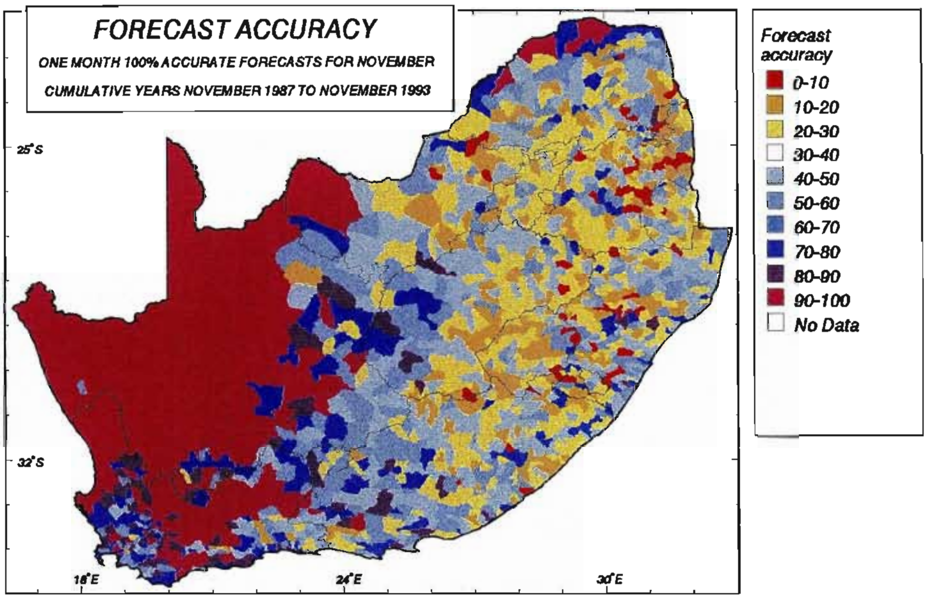
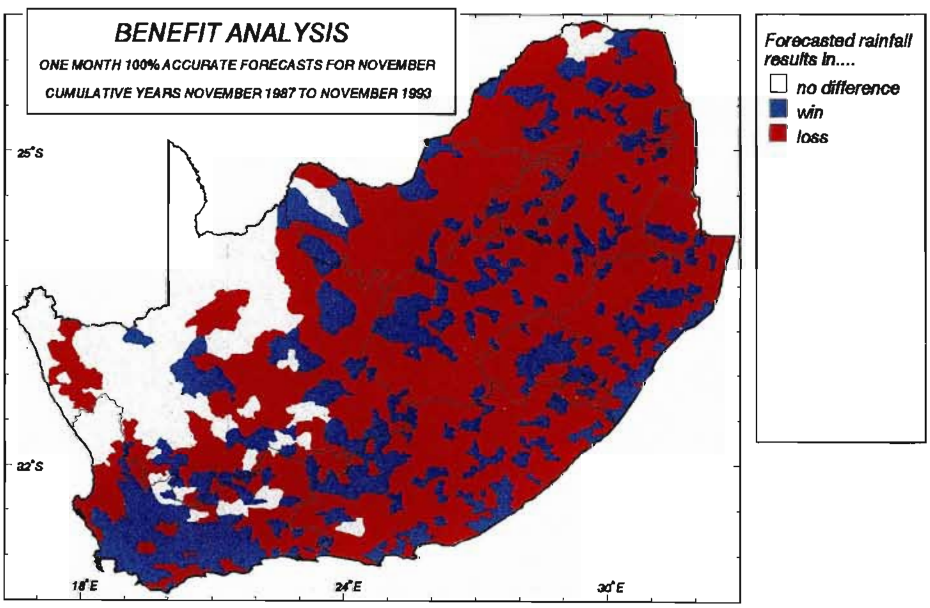
The runoff forecasts for September produced by the 100% accurate categorical rainfall forecasts also show a slight improvement in skill scores compared to those of the runoff forecast produced by the actual forecasts, shown in Figure 9.7. Both the benefit analysis and the integer benefit analysis (Figure 9.9, middle and bottom) show an increased area where a win scenario is recorded. The integer benefit analysis results are slightly better than those of the benefit analysis. This would suggest that for the September one month time period runoff forecasts could feasibly be used in operational applications for the majority of South Africa. The runoff forecasts once again improve with corresponding improvements in the rainfall forecast accuracy. There are, however, still areas in the region that still produce poor results. This would suggest that even perfect categorical monthly rainfall forecasts still cannot capture all the local scale variability of persistence of wet and dry days as well as magnitudes of rainfall on individual days and the effect of catchment antecedent moisture conditions. More local scale rainfall forecasts are thus still needed in the South African region.

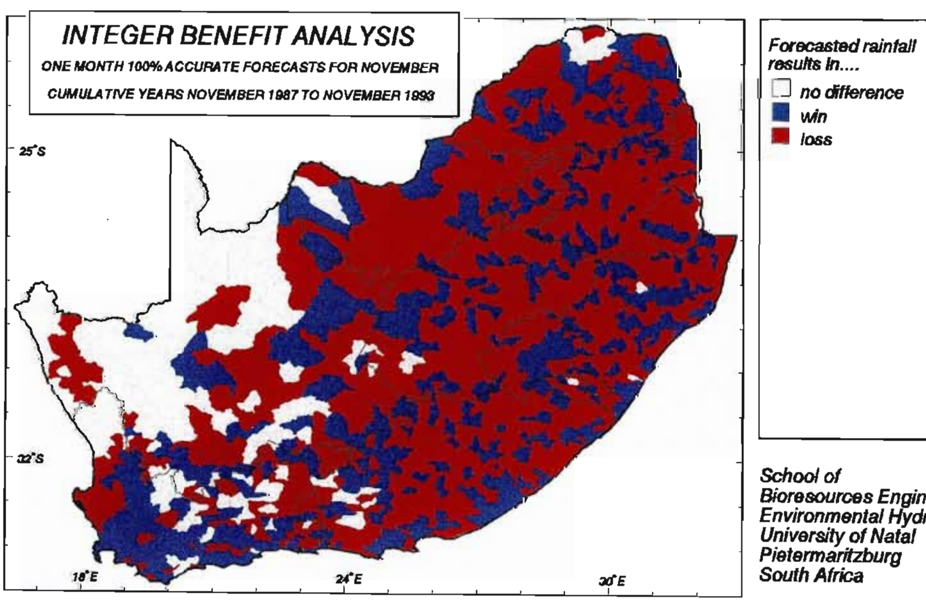
A comparison of results from Figures 9.10 and 9.8 shows that the November one month runoff forecast accuracy scores for the perfect rainfall forecasts improve only slightly over the majority of the country. The west to east decreasing accuracy trend is still maintained, with a large portion of the eastern area experiencing hit rates of 2 out of 7, or fewer. However, as has been shown before, increases in the rainfall forecast accuracies again result in increases in the runoff forecast accuracies.

Figure 9.10	Forecast accuracy scores (%) and skill, expressed as benefit analyses, calculated using the runoff forecasts produced by the 100% accurate November one month categorical rainfall forecasts for the retro-active hind forecast period from 1 November 1987 to 30 November 1993

As seen in Figure 9.10 the increases in rainfall forecast accuracy translate into slightly improved runoff forecasting skills. A loss scenario is recorded over the majority of the South African region for both the benefit analysis and the integer benefit analysis (Figure 9.10, middle and bottom). The results of both these analyses show patterns that do not differ markedly from those in Figure 9.8. This implies that the runoff forecast accuracy scores do not improve sufficiently with the 100% accurate rainfall forecasts to produce any useful skill. For most of the region the runoff values produced using the November rainfall forecasts do not outperform the median runoff value for November.







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9.1.4 Discussion of results obtained from the one, three and four month categorical rainfall forecasts

While evaluations of single forecast performances are useful, it is necessary to obtain an idea of the comparative performance of various forecasts. In Tables 9.1, 9.2 and 9.3 summary results in the form of accuracy and skill (benefit and integer benefit analyses) scores for the four, three and one month forecast periods are shown. The comparative performance of the different runoff forecasting time periods can thus be evaluated.

Table 9.1 Summary of forecast accuracy scores obtained for the four, three and one month forecast periods expressed, as a percentage of the overall number of catchments

Forecast period	4 month DJFM			3 month SON			3 month NDJ			1 month S			1 month N		
Forecast type	Act	100 %	Diff	Act	100 %	Diff	Act	100 %	Diff	Act	100 %	Diff	Act	100 %	Diff
Accuracy															
0% - 20%	6.6	4.1	-2.5	15.7	14.6	-1.1	24.4	18.9	-5.5	0.4	0.4	0.0	15.1	14.8	-0.3
20% - 40%	30.7	16.8	-13.9	27.0	23.0	-4.0	28.1	28.2	0.1	2.4	1.5	-0.9	21.7	21.3	-0.4
40% - 60%	48.0	50.0	2.0	37.8	43.9	6.1	24.1	23.8	-0.3	21.7	13.4	-8.3	39.7	37.2	-2.5
60% - 80%	8.7	19.2	10.5	8.1	7.7	-0.5	12.6	16.0	3.4	18.9	21.1	2.2	6.8	8.8	2.0
80% - 100%	6.1	9.9	3.8	11.4	10.8	-0.6	10.8	13.2	2.4	56.6	63.7	7.1	16.7	18.0	1.3

The summary accuracy scores in Table 9.1 are given as the proportion (percentage) of Quaternary Catchments out of all the Quaternary Catchments in South Africa for which forecasts where available, which produced forecast accuracy scores within a certain range. The highest runoff forecast accuracy scores, using the actual rainfall forecasts ("Act" column), are obtained for the one month September forecasts. These produce a large number of catchments scoring in the 80 to 100% accuracy range. The runoff forecast accuracy results for the one month November forecast and the four month December through to February forecast are fairly similar, with the November one month forecasts performing slightly better with more forecasts in the 80 to 100% accuracy range. The three month runoff forecasts perform poorly, with a large number of catchments producing forecasts below the 40% accuracy level. The November to September three month runoff forecasts produce the lowest accuracy results, with the majority of catchments producing accuracy scores of less than 40%.

Comparing the runoff forecasts using the actual rainfall forecasts ("Act" column) to the runoff forecasts produced using the 100 % accurate rainfall forecasts (100 % column) one can see for the most part the forecast accuracy results improve, except for the three month September to November runoff forecasts. The "Diff" column shows the difference between the forecasts using the actual rainfall forecasts and the runoff forecasts with the 100 % accurate rainfall forecasts. All five forecast periods show a negative difference in the lower accuracy ranges, i.e. < 40%, indicating that a lower number of catchments are recording forecast accuracy scores in these ranges. While positive difference results in the higher forecast accuracy ranges indicate an increase in the number of catchments producing forecasts in these ranges. The four month December through to March forecast shows the most improvement when using the 100% accurate forecasts with an increase of 14.3% resulting in a larger number of catchments recording higher accuracy results (i.e. >60%). This is followed by the September one month forecasts, which show an improvement of 9.3%. However, the other one and three month runoff forecast do not show marked improvements when rainfall forecast categories are perfect. The September to November three month forecasts show decreases in both the higher and lower accuracy forecast ranges, with an improvement being shown in the 40 to 60% forecast accuracy range. This indicates that the 100% accurate rainfall forecasts result in no real improvement in the overall runoff forecast results.

Table 9.2 Summary of forecast skill results obtained for the four, three and one month forecast periods, expressed as a percentage of the overall number of catchments which obtained total benefit forecast skill results in a specific category, *viz.* win, loss, or no difference

Forecast period	4 month DJFM		3 month SON		3 month NDJ		1 month S		1 month N	
Forecast type	Act	100 %	Act	100 %	Act	100 %	Act	100 %	Act	100 %
Skill										
Win	32.20	54.88	30.99	29.80	34.64	31.86	40.44	47.74	27.90	28.62
Loss	65.70	40.82	63.41	65.11	62.95	65.47	32.99	26.62	66.08	65.57
No diff	2.10	4.31	5.60	5.09	2.42	2.67	26.57	25.64	6.01	5.81

In Table 9.2 the total benefit analysis scores are represented as the percentage of Quaternary Catchments out of all the Quaternary Catchments in South Africa for which forecasts where available, that have recorded benefit scores within a specific category, i.e. win, loss or no difference. The September one month runoff forecasts produce the best performance with a large percentage (40.44 %) of the Quaternary Catchments producing win scenarios. The runoff forecasts for the remaining forecast periods do not perform as well as the September one month forecast, with approximately 30% of the catchments recording win results and a far larger percentage (~60 %) recording loss results. Again, the four month December to March forecast period shows the most improvement when comparing the runoff forecasts produced using the actual rainfall forecasts and the runoff forecasts produced using the 100 % accurate rainfall forecasts. The three month September to November and November to January forecasts do not show any improvement when comparing the runoff forecasts produced using the actual rainfall forecasts and the runoff forecasts produced using the 100 % accurate rainfall forecasts.

Table 9.3 Summary of forecast skill results obtained for the four, three and one month forecast periods expressed as a percentage of the overall number of catchments which obtained integer benefit forecast skill results in a specific category, *viz.* win, loss, or no difference

Forecast period	4 month DJFM		3 month SON		3 month NDJ		1 month S		1 month N	
Forecast type	Act	100 %	Act	100 %	Act	100 %	Act	100 %	Act	100 %
Skill										
Win	28.97	51.25	33.14	30.88	24.15	24.05	46.87	52.06	30.88	33.97
Loss	49.04	30.39	60.79	62.33	48.61	44.55	22.51	19.06	60.89	58.27
No diff	22.00	18.37	6.06	6.78	27.24	31.63	30.63	28.88	8.22	7.76

The integer benefit analysis (Table 9.3) produces results that are similar to the total benefit analysis, with the September one month runoff forecasts producing the best results. The biggest improvement is shown by the four month forecast when comparing the runoff forecasts produced using the actual rainfall forecasts and the runoff forecasts produced using the 100 % accurate rainfall forecasts.

The results obtained from the analyses of the different runoff forecasts produced several significant trends.

i. The September one month runoff forecast produced when using the actual categorical rainfall forecast was the only runoff forecast that produced any significant accuracy and skill for the majority of the country. This would suggest that those techniques used in this study, only the one month September forecasts produce accuracy and skill scores that are reliable enough to be used operationally in water resources management.

ii. The four month runoff forecasts for the December through March period show the most marked improvement in both accuracy and skill scores when 100% accurate categorical rainfall forecasts are used. The other forecasts studied, while generally exhibiting a slight improvement when using the 100% accurate rainfall forecasts, still produced low accuracy and skill scores (with the exception of the September forecasts). This would indicate, with the exception of the one month September and four month December to March runoff forecasts, that even with perfect rainfall forecasts the local scale runoff forecasts are too inaccurate to apply operationally. Intuitively one would expect, when using this methodology, the runoff forecasts to improve significantly when more accurate rainfall forecasts are used. This is not so in most cases, however, there are two main reasons that these seemingly anomalous results are being obtained:

    a. First, the 100% accurate forecasts (and consequently the actual forecasts) produced for homogeneous forecast regions may not be representative of the area as a whole. The forecast regions were derived from the 8 homogeneous rainfall regions which where produced using 510 rainfall stations. The Quaternary Catchment database, on the other hand uses around 1300 rainfall stations, each utilised individually. While the 100 % accurate forecast for each homogeneous rainfall forecast region, is specified in one category, e.g. Above Normal, the actual rainfall falling over the entire forecast region reported by the larger number of individual user rainfall stations in the Quaternary Catchment database may fall into different categories, e.g. Below Normal.

    b. Secondly, the forecasting methodology used may be flawed in that, by using the median value in a particular tercile corresponding to a forecast category to represent the equivalent daily rainfall forecast, the variability existing within the forecast category is ignored. This could result in poor forecasts. It may thus be better to use a range of daily rainfalls from the representative tercile as the equivalent daily rainfall forecast, to then produce a range of runoff forecasts to account for the year to year temporal rainfall variability within a tercile. This, in turn, could improve forecast accuracy results.

iii. The general trend that is exhibited is that the forecasts in the drier areas are better than forecasts in the wetter areas. This could be a result of the simpler dynamics existing in the rainfall : runoff relationship in drier areas, where runoff is only produced by a few large rainfall events which generally fall on predominantly dry soils, compared with the more complex rainfall : runoff responses in wetter areas where antecedent catchment moisture conditions ahead of individual rainfall events play an important role.

iv. The September one month runoff forecasts produce better results than the November one month runoff forecasts. This again could be attributed to a drier vs wetter situation, where drier prevailing conditions generally exist leading up to the September forecasts, while wetter prevailing conditions can already exist before the November forecast period.

v. The November one month forecasts produce the worst overall results, followed by the three month and four month forecasts, with the September one month forecasts exhibiting the best results.

9.2 Evaluation of Results Using the Runoff Forecasts Produced with the Percentage of Normal 30 Day Rainfall Fields

In this section the forecast accuracy and skill scores obtained from the 30 day runoff forecasts using the percentage of normal rainfall forecasts, as discussed in Chapter 8, are reviewed. Unfortunately, the perfect 100% accuracy retro-active forecasts are unavailable for these forecasts, implying that results from the actual rainfall forecasts cannot be compared to results produced by perfect forecasts. The retro-active hind forecast data set is more extensive than those previously used in Section 9.1, covering forecasts throughout the year from January to December for a period extending from 1979 to the end of 1993. A total of 194 runoff forecasts for 30 days are produced at 28 day intervals over this period. While the techniques used to estimate skill and accuracy scores for the 30 day forecasts differ slightly from those of the other forecasts, owing to the differences in the forecasting techniques, they are considered to still yield results that are comparable to those in Section 9.1. The fact that the forecasts cover an entire year allows comparisons to be made of seasonal trends in forecast performance. Forecast performance is expected to improve with the 30 day runoff forecasts, as the 30 day percentage of normal rainfall forecasts are essentially represented as a ratio of the expected condition compared to the normal, rather than a simple category, and are thus better able to accommodate spatial variability. The 30 day percentage of normal rainfall forecasts are determined using the COLA AGCM, which is a physically based model that is expected to produce better results than the statistical method of CCA used to produce the four, three and one month categorical rainfall forecasts. In this section the overall forecast performance will initially be assessed, followed by seasonal comparisons of runoff forecast performance.

9.2.1 Overall estimates of the 30 day runoff forecast accuracy and skill

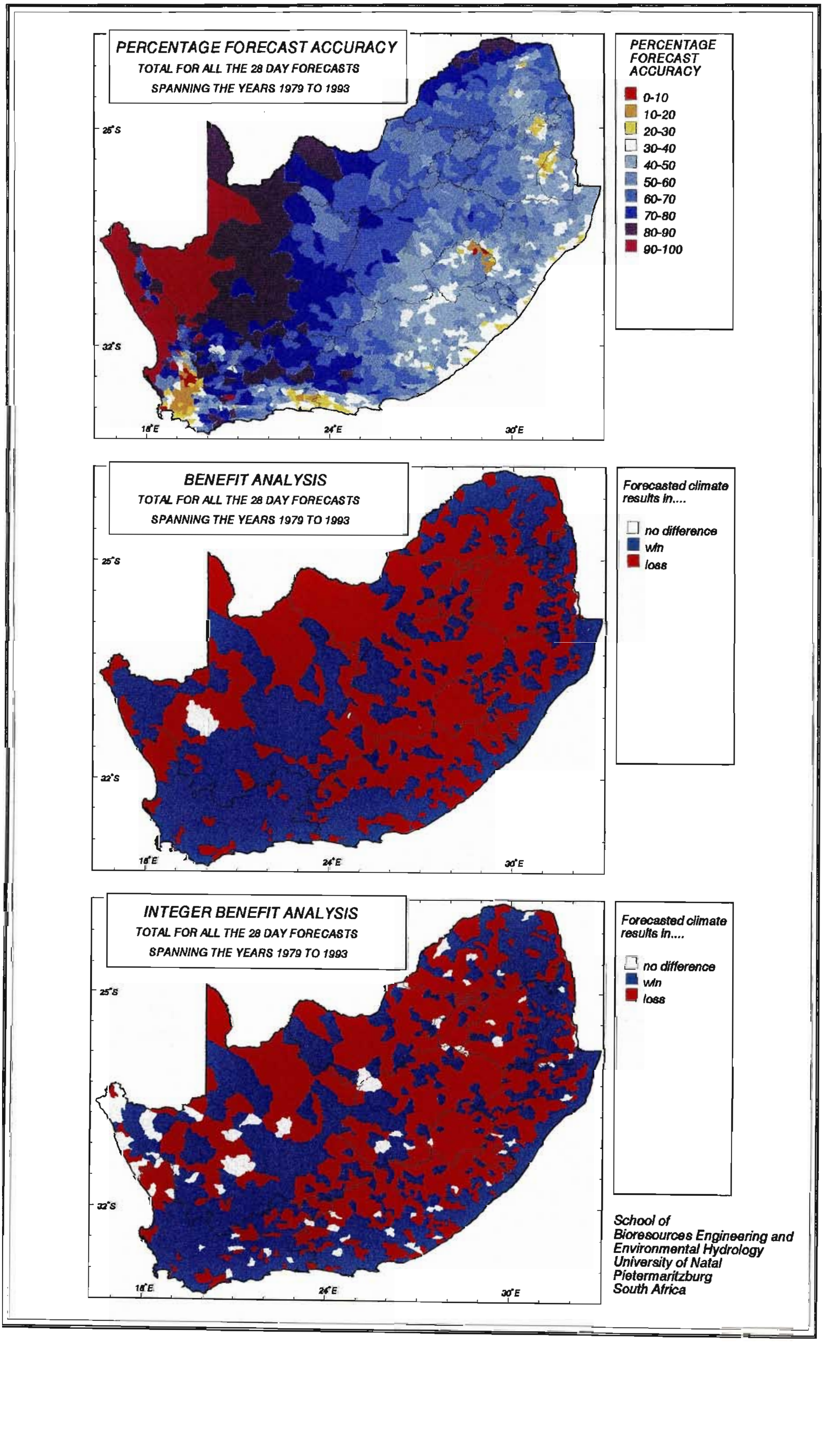
In this section and the following section the hit rate is calculated as a percentage. The hit rate is, therefore, the total number of correct forecasts divided by the total number of forecasts, expressed as a percent. The overall estimates of 30 day runoff accuracy show a higher hit rate than those obtained from the accuracy scores in Section 9.1. The majority of the study area shows percentage accuracy results of over the 50% (Figure 9.11, top). The declining west to east trend is still evident, with areas on the western parts of the region showing hit rates in the region of 90 to 100%. Hence, the forecast accuracy displays an inverse relationship with mean annual precipitation, repeating the trend that was evident in the previous section.

In Figure 9.11 it is evident that some areas in the south western Cape, along the south and east coast, on the eastern side of the Lesotho and areas of Mpumalanga and Swaziland give accuracy scores below 30%. These areas are, for the most part, expected to give anomalous results as they generally represent areas where rainfall patterns are different to the larger area as a whole. The areas in the south western Cape around Cape Town generally receive more rainfall than the surrounding Karoo interior. Areas where there is a rapid change in topography, such as areas along the coast, the steep eastern slopes of the Drakensberg and eastern parts of Mpumalanga, also seem to be giving low accuracy results.

Figure 9.11	Forecast accuracy scores (%) and skill, expressed as benefit analyses, calculated using the runoff forecasts produced by the 30 day percentage of normal rainfall forecasts for the retro-active hind forecast period extending from January 1979 through to December 1993

The COLA AGCM generates output that is representative of general rainfall patterns at a large scale. The anomalous forecast accuracies of below 30% are, for the most part, in areas where the rainfall patterns deviate from the general trend. One of the reasons for this is that the GCMs simulate large scale atmospheric processes that occur as general patterns which are represented by grid cells covering tens of thousands of square kilometres in area, and which will not identify local scale perturbations produced by smaller scale topographic or other features. It would seem that even when using relative estimates such as percentages, not much local scale variability can be accounted for. These anomalous areas, however, do occur in clusters, which suggests that local scale forecasting techniques could be used to improve forecasts in these regions.

Once again low forecast accuracies could be attributed to the regional wet : dry gradient, as the particular areas that are showing poor accuracy scores tend to be wetter than the surrounding areas. The other major factor that could be contributing to the low forecast accuracy scores is that much of the runoff in such areas is controlled by the antecedent soil water conditions, and not only by the total amount of rainfall falling in a 30 day period. The forecast accuracies will thus depend on the combination of the ability to simulate wet antecedent conditions and accurately forecast the rainfall falling over a 30 day period.


PERCENTAGE FORECAST ACCURACY
TOTAL FOR ALL THE 28 DAY FORECASTS
SPANNING THE YEARS 1979 TO 1993
PERCENTAGE FORECAST ACCURACY
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
25°S
32°S
18°E
24°E
30°E
BENEFIT ANALYSIS
TOTAL FOR ALL THE 28 DAY FORECASTS
SPANNING THE YEARS 1979 TO 1993
Forecasted climate results in....
no difference
win
loss
25°S
32°S
18°E
24°E
30°E
INTEGER BENEFIT ANALYSIS
TOTAL FOR ALL THE 28 DAY FORECASTS
SPANNING THE YEARS 1979 TO 1993
Forecasted climate results in....
no difference
win
loss
25°S
32°S
18°E
24°E
30°E
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The benefit analysis in Figure 9.11 (middle) shows that in half the areas a win (blue) scenario was recorded. It would seem that on the whole this forecasting technique yields better results than those used to produce the results in Section 9.1. In the previous section forecast accuracy and forecast skill in general followed similar trends, i.e. when the forecast accuracy was poor, the forecast skill tended to be poor. The results of the benefit analysis and integer benefit analysis shown in Figure 9.11 (middle and bottom) do not seem to follow this trend, with areas that have low forecast accuracy results yielding win scenarios. The skill scores produced in this analysis do not follow the wet : dry gradient observed in the previous section, with many of the higher rainfall areas producing higher forecast skill scores. The eastern and central interior seem to yield the majority of the loss scenario skill scores.

These trends would suggest that even though runoff forecasts produced by the 30 day rainfall forecast have low accuracy scores they still perform better than the runoff produced using the median value. This implies that even with inaccurate, or even incorrect, 30 day runoff forecasts, users could in many areas still apply them and get a better result than that of the runoff forecast from the median value. The areas of low skill in the eastern and central interior of the South African study area could be attributed to the high variability in rainfall on a daily and seasonal basis. It may also be that the GCM is unable to capture this smaller scale variability and therefore is unable to forecast accurately in these areas. The low skills in these regions could also be attributed to the high variability in the antecedent moisture conditions, which are translated into even higher runoff variability.

Perusal of these initial results seems to indicate that the runoff forecasting methodology using the percentage of normal forecasts tends to outperform the technique using the categorical rainfall forecasts. However, this initial comparison is not a true comparison as the percentage of normal forecasts cover an entire year while those produced by the categorical rainfall forecasts only represent parts of the spring and summer seasons in the South African study region. The next section therefore focuses on the seasonal forecasting results produced by the percentage of normal rainfall forecasts, which should give a better comparison of forecast performance as well as revealing seasonal trends in runoff forecasting.

9.2.2 Seasonal comparisons of the accuracy and skill scores produced by the 30 day runoff forecast

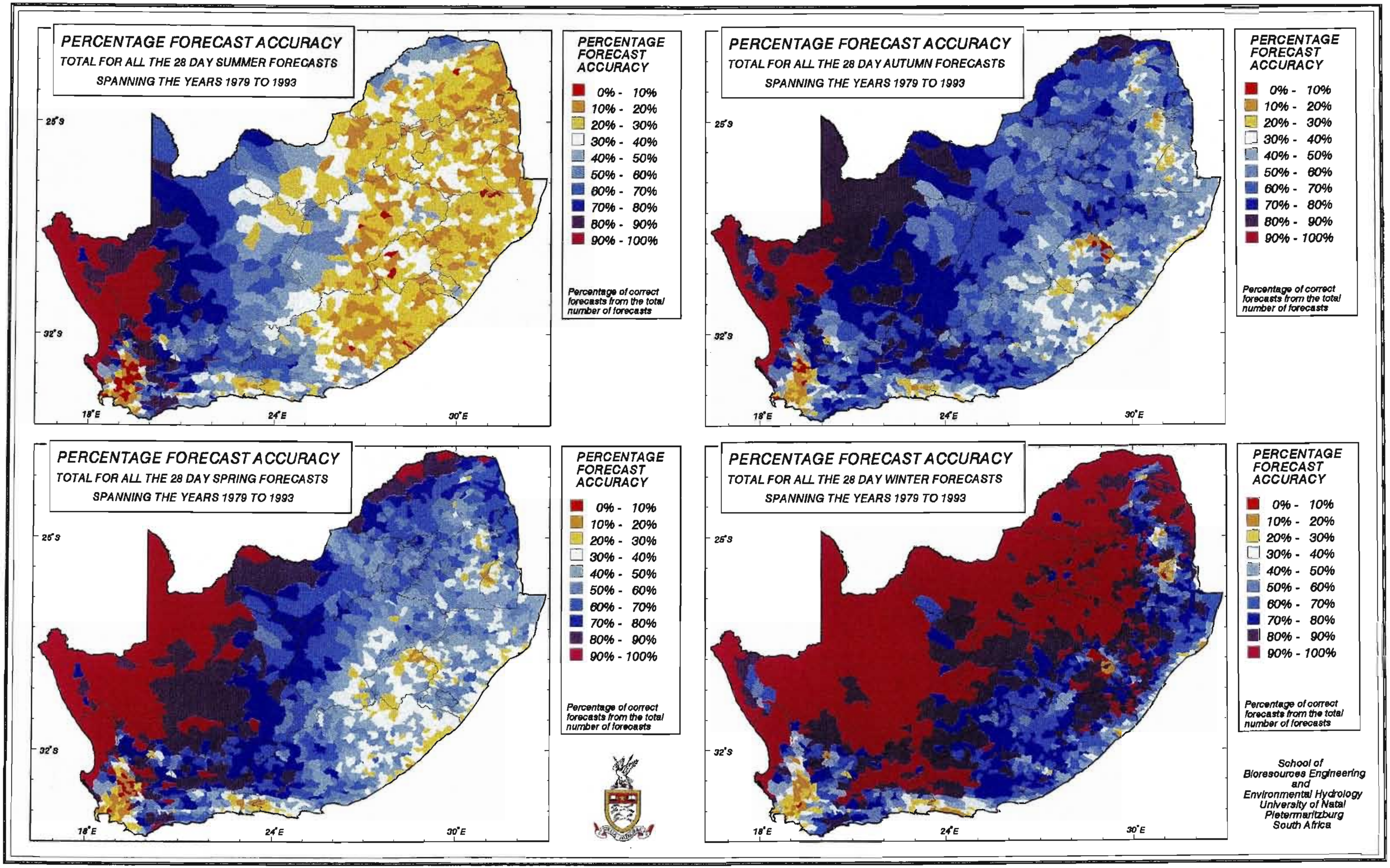
To obtain seasonal results from the 30 day runoff forecasts the year was divided into 4 periods of 3 months each to represent the major seasons. The months chosen to represent the different seasons where selected a by reviewing different literature. It was finally decided to use the same months to represent the seasons as those used by Intergovernmental Panel on Climate Change (IPCC, 1996a). The seasons are defined as follows:

i. Summer is represented by the months December through to February
ii. Autumn is represented by the months March through to May
iii. Winter is represented by the months June through to August
iv. Spring is represented by the months September through to November.

Since the 30 day forecasts do not start consistently at the same time each month throughout the simulation as they are produced at 28 day intervals, it was decide that any forecast period falling predominantly within a particular season would belong to that season. Hence, any forecast that starts on, or after, the 16th of each month before a season commences is assigned to that particular season, i.e. a forecast starting on the 16th of November would be assigned to the summer forecasts spanning the period from December to February.

Figure 9.12	Seasonal forecast accuracy scores calculated using the runoff forecasts produced by the 30 day percentage of normal rainfall forecasts for the retro-active hind forecast period extending from January 1979 through to December 1993

In Figure 9.12 the percentage forecast accuracies for the 30 day runoff forecasts are given for the four different seasons. It can be seen that the summer forecasts (Figure 9.12, top left) produce the poorest results, with a large portion of the region giving accuracies of less than 30%. The highest forecast accuracies are obtained in the winter season where the majority of the country has accuracy scores more than 80%. The forecast accuracy results for the autumn and spring are similar to one another, with spring results showing slightly higher percentage accuracy scores in most places. The east : west trend is evident for all the seasons, once again showing that forecast accuracies seem to be linked to aridity. There is an area of persistently poor forecast accuracy in the southern parts of the Western Cape Province.



PERCENTAGE FORECAST ACCURACY
TOTAL FOR ALL THE 28 DAY SUMMER FORECASTS
SPANNING THE YEARS 1979 TO 1993
PERCENTAGE FORECAST ACCURACY
0% - 10%
10% - 20%
20% - 30%
30% - 40%
40% - 50%
50% - 60%
60% - 70%
70% - 80%
80% - 90%
90% - 100%
Percentage of correct forecasts from the total number of forecasts
25°S
32°S
18°E
24°E
30°E
PERCENTAGE FORECAST ACCURACY
TOTAL FOR ALL THE 28 DAY AUTUMN FORECASTS
SPANNING THE YEARS 1979 TO 1993
PERCENTAGE FORECAST ACCURACY
0% - 10%
10% - 20%
20% - 30%
30% - 40%
40% - 50%
50% - 60%
60% - 70%
70% - 80%
80% - 90%
90% - 100%
Percentage of correct forecasts from the total number of forecasts
25°S
32°S
18°E
24°E
30°E
PERCENTAGE FORECAST ACCURACY
TOTAL FOR ALL THE 28 DAY SPRING FORECASTS
SPANNING THE YEARS 1979 TO 1993
PERCENTAGE FORECAST ACCURACY
0% - 10%
10% - 20%
20% - 30%
30% - 40%
40% - 50%
50% - 60%
60% - 70%
70% - 80%
80% - 90%
90% - 100%
Percentage of correct forecasts from the total number of forecasts
25°S
32°S
18°E
24°E
30°E
PERCENTAGE FORECAST ACCURACY
TOTAL FOR ALL THE 28 DAY WINTER FORECASTS
SPANNING THE YEARS 1979 TO 1993
PERCENTAGE FORECAST ACCURACY
0% - 10%
10% - 20%
20% - 30%
30% - 40%
40% - 50%
50% - 60%
60% - 70%
70% - 80%
80% - 90%
90% - 100%
Percentage of correct forecasts from the total number of forecasts
25°S
32°S
18°E
24°E
30°E
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The summer season 30 day runoff forecast's percentage accuracy scores (Figure 9.12, top left) correspond with those recorded for the November one month runoff forecasts (Figure 9.8, top), with the November one month forecasts possibly giving slightly better accuracy scores. These accuracy scores also approximate those obtained from the three and four month categorical runoff forecasts produced using the actual categorical rainfall forecasts (Figures 9.1, 9.3 and 9.4, top). This would suggest that, comparatively speaking, the 30 day runoff forecasts produced using the 30 day percentage of normal rainfall forecasts do not produce better results than the categorical runoff forecasts. However, this statement should be qualified by evaluating the make-up of each forecast. The categorical runoff forecasts can fall within one of three windows; therefore the statistical probability of being correct is 33.33%. The 30 day runoff forecasts have a smaller 25% window that can fluctuate anywhere between 0% of the normal to 200% or more of the normal, implying that the probability of obtaining a forecast within this window is about 12.5%. It is, therefore, more difficult to obtain an accurate forecast using the 30 day runoff forecasts.

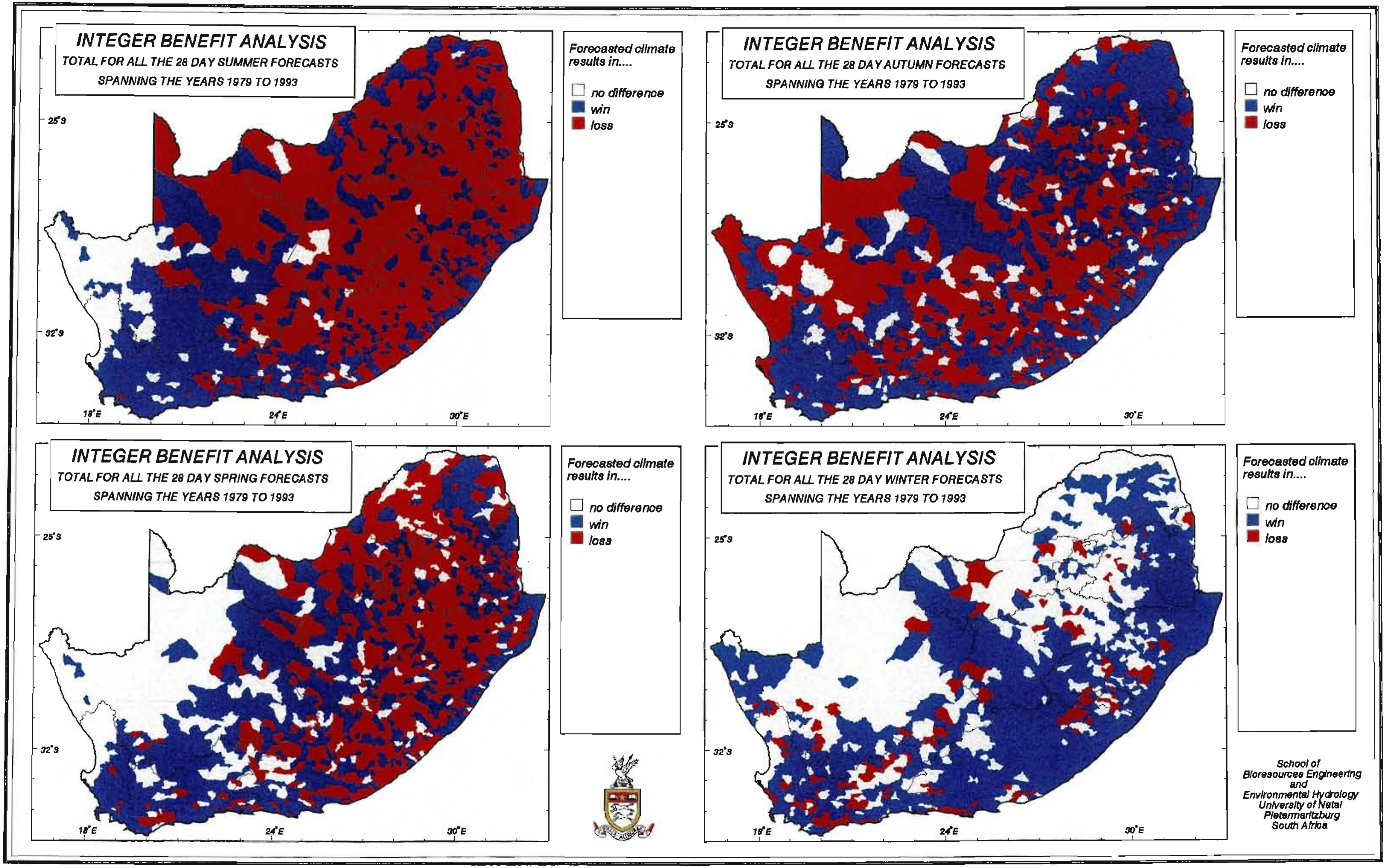
Once again the link between aridity and forecast accuracy is confirmed both temporally and spatially. The decreasing west : east trend in forecast accuracies for the 30 day runoff forecasts is visible for all four seasons in Figure 9.12. Seasonal accuracies also show a decreasing trend according to the wetness of the season, with the summer season (Figure 9.12, top left) producing the lowest accuracy results and the winter season (Figure 9.12, bottom right) the highest. Areas in the southern part of the Western Cape, along the eastern part of the Lesotho border, along the south and east coasts of South Africa, on the border of Swaziland, and in the east of Mpumalanga consistently produce low forecast results, regardless of the season. These areas are, in general, wetter than most of the surrounding area and are inclined to receive more consistent rainfall all year round. Poor forecast accuracies in wet areas could be attributed to the complexities introduced by rainfall persistencies, intensities and antecedent moisture conditions which result in higher spatial variability of runoff that cannot be accounted for by using the larger scale forecasts.

Figure 9.13 shows the integer benefit analysis results for the 30 day runoff forecasts produced from the 30 day rainfall forecasts. The east : west trend in forecast skill results is less obvious than that produced by the categorical forecasts in Section 9.1. The summer forecasts (Figure 9.13, top left) again produce the worst results, with large parts of the central and eastern interior producing a loss scenario. The areas to the west of this region as well as areas along the southern and eastern coast tend to produce a win scenario for the summer season runoff forecasts. This pattern does not wholly mimic the summer forecast accuracy pattern (Figure 9.12, top left) with some areas, particularly in the southern part of the Western Cape Province, still producing a win scenario despite having low summer runoff forecast accuracy scores. This suggests that in some regions even inaccurate forecasts will produce better results than using the runoff produced from median value rainfall.

Figure 9.13	Seasonal forecast skill scores, in the form of the integer benefit analysis, calculated using the runoff forecasts produced by the 30 day percentage of normal rainfall forecasts for the retro-active hind forecast period extending from January 1979 through to December 1993

A comparison of the results obtained in the integer benefit analysis for the 30 day summer runoff forecasts (Figure 9.13, top left) with those obtained by the four month (Figure 9.1, bottom), three month (Figures 9.3 and 9.4, bottom) and the one month November (Figure 9.8, bottom) categorical runoff forecasts show that the 30 day summer runoff forecasts produce a larger area of the win scenario. This implies that the 30 day runoff forecast performance is slightly superior to that from the categorical runoff forecasts in the summer months. There are, however, large areas of the country that still result in a loss scenario, suggesting that even though the forecasts may be an improvement on the categorical forecasts it still may not be reliable to apply operationally.

The winter period forecasts (Figure 9.13, bottom right) produce the best skill scores, with a large proportion of the country producing a win scenario. The autumn (Figure 9.13, top right) and the spring (Figure 9.13, bottom left) forecasts produce forecasts skills that are worse than the winter forecasts, with a larger area of the region recording a loss scenario. Once again the drier periods outperform wetter periods, which can be attributed to the complexities introduced by the rainfall persistencies, intensities and antecedent soil moisture conditions which result in higher runoff variability that cannot be accounted for by using the larger scale rainfall forecasts.


INTEGER BENEFIT ANALYSIS
TOTAL FOR ALL THE 28 DAY SUMMER FORECASTS
SPANNING THE YEARS 1979 TO 1993
Forecasted climate results in....
no difference
win
loss
25°S
32°S
18°E
24°E
30°E
INTEGER BENEFIT ANALYSIS
TOTAL FOR ALL THE 28 DAY AUTUMN FORECASTS
SPANNING THE YEARS 1979 TO 1993
Forecasted climate results in....
no difference
win
loss
25°S
32°S
18°E
24°E
30°E
INTEGER BENEFIT ANALYSIS
TOTAL FOR ALL THE 28 DAY SPRING FORECASTS
SPANNING THE YEARS 1979 TO 1993
Forecasted climate results in....
no difference
win
loss
25°S
32°S
18°E
24°E
30°E
INTEGER BENEFIT ANALYSIS
TOTAL FOR ALL THE 28 DAY WINTER FORECASTS
SPANNING THE YEARS 1979 TO 1993
Forecasted climate results in....
no difference
win
loss
25°S
32°S
18°E
24°E
30°E
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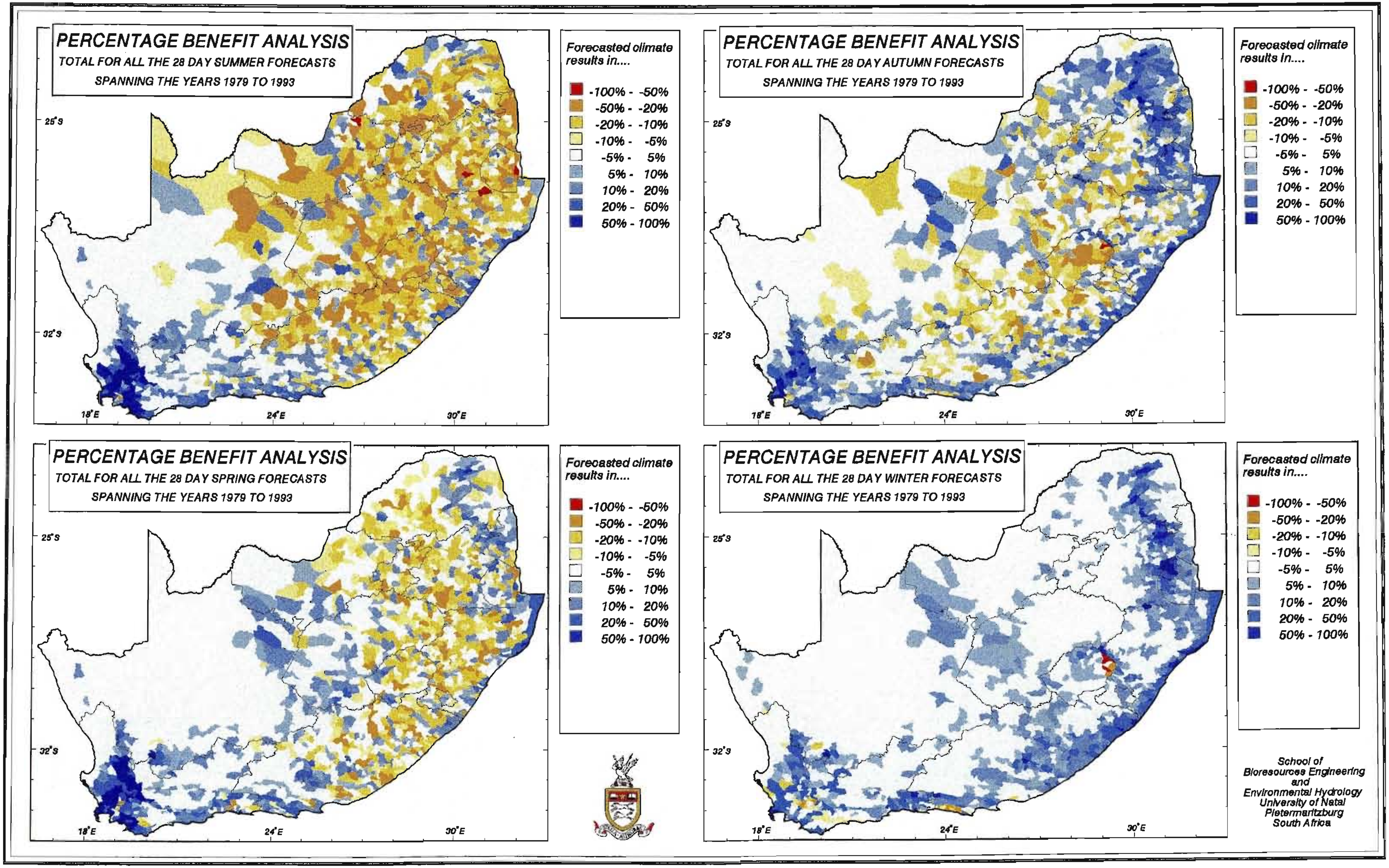
With the large number of runoff forecasts produced using the 30 day rainfall forecasts an analysis can be made which not only indicates whether the forecasts outperform the median value estimates, as was the case with the Figure 9.13 integer benefit analysis, but can also give an indication of the magnitude of this performance, i.e. how often the forecast outperformed the median value and vice versa. The percentage benefit analysis (Figure 9.14) is basically the same as an integer benefit analysis, except that it is calculated by taking the total number of times a forecast outperforms the median value, and *vice versa*, and dividing that by the total number of forecasts before converting it to a percentage. If the median value outperforms the forecast value, then a negative value is assigned to that forecast, but if the forecast outperforms the median value then a positive result is recorded. Hence, any high positive percentage values (dark blue in Figure 9.14) indicate that the forecasts have performed particularly well when compared with the median value runoff. On the other hand, any high negative percentage values (dark red) indicate that the forecasts have performed particularly poorly when compared to the median runoff values.

Figure 9.14	Seasonal forecast skill scores, in the form of a percentage benefit analyses, calculated using the runoff forecasts produced by the 30 day percentage of normal rainfall forecasts for the retro-active hind forecast period extending from January 1979 through to December 1993

During the summer period (Figure 9.14, top left) it can be seen that for the most part the median values outperform the forecasts, especially in eastern and central interior where values of between –5% and – 20% make up the majority of the area. A large part of the rest of the area records a value of between –5% and 5%, which indicates that for the majority of the country the reliability of the summer forecasts is not high enough for them to be applied operationally.

The autumn and spring 30 day runoff forecasts (Figure 9.14, top right and bottom left) show improved results compared with the summer forecasts, with a far smaller proportion of the area recording negative percentages. These are again mainly restricted to the eastern and central interior of the region. Most of the Quaternary Catchments, for both the spring and autumn periods, record a value of between –5% and 5%, indicating that for the vast majority of the region the application of forecasting is not viable for these time periods.


PERCENTAGE BENEFIT ANALYSIS
TOTAL FOR ALL THE 28 DAY SUMMER FORECASTS
SPANNING THE YEARS 1979 TO 1993
Forecasted climate results in....
-100% - -50%
-50% - -20%
-20% - -10%
-10% - -5%
-5% - 5%
5% - 10%
10% - 20%
20% - 50%
50% - 100%
25°S
32°S
18°E
24°E
30°E
PERCENTAGE BENEFIT ANALYSIS
TOTAL FOR ALL THE 28 DAY AUTUMN FORECASTS
SPANNING THE YEARS 1979 TO 1993
Forecasted climate results in....
-100% - -50%
-50% - -20%
-20% - -10%
-10% - -5%
-5% - 5%
5% - 10%
10% - 20%
20% - 50%
50% - 100%
25°S
32°S
18°E
24°E
30°E
PERCENTAGE BENEFIT ANALYSIS
TOTAL FOR ALL THE 28 DAY SPRING FORECASTS
SPANNING THE YEARS 1979 TO 1993
Forecasted climate results in....
-100% - -50%
-50% - -20%
-20% - -10%
-10% - -5%
-5% - 5%
5% - 10%
10% - 20%
20% - 50%
50% - 100%
25°S
32°S
18°E
24°E
30°E
PERCENTAGE BENEFIT ANALYSIS
TOTAL FOR ALL THE 28 DAY WINTER FORECASTS
SPANNING THE YEARS 1979 TO 1993
Forecasted climate results in....
-100% - -50%
-50% - -20%
-20% - -10%
-10% - -5%
-5% - 5%
5% - 10%
10% - 20%
20% - 50%
50% - 100%
25°S
32°S
18°E
24°E
30°E
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The winter period (Figure 9.14, bottom right) shows an even greater improvement with hardly any of the areas recording a large negative value. A large proportion of the region still, however, records a result of between –5% and 5%, indicating that for these areas the application of forecasting may not be particularly beneficial. It may, however, be feasible to use forecasting operationally in the winter season for the large majority of the country, but such forecasts would be of little value to either the water or the agricultural sector as, in the summer rainfall areas, there are not many runoff events generated in the winter months, nor crops grown.

In Figure 9.14 it can be seen that certain areas within the country perform consistently well regardless of the season. The areas in the south of the Western Cape and along the southern and eastern coast of South Africa perform consistently well, scoring values of 5% and greater. Other areas in the eastern parts of the study region, specifically in the eastern parts of Mpumalanga and the Northern Province, as well as Swaziland, record higher percentage benefit values of > 5% during the spring, autumn and winter months. It could be concluded that while the application of the 30 day forecasts may not be particularly beneficial for the majority of the country, some of the areas may well obtain substantial benefit from the use of forecasting in operational water resources planning and management.

9.2.3 General discussion of results obtained from the 30 day runoff forecasts

In this particular section seasonal and general trends could be identified. A comparison of the different forecast techniques using categorical rainfall forecasts and percentage of normal rainfall forecasts can be made. All the questions formulated in the introduction of Section 9 should be answered to satisfaction.

Table 9.4 shows the summarised results of the total benefit analysis for the 28 day runoff forecasts represented as the percentage of the Quaternary Catchments out of the total number of Quaternary Catchments in South Africa, which have recorded forecasts skill results in a specific category, i.e. win, loss or no difference. A comparison can thus be drawn between the runoff forecast results for the different seasons, as well as a comparison being drawn between the runoff forecast results produced by the 30 day GCM rainfall forecasts and those produced by the 1 month categorical rainfall forecasts.

Table 9.4 Summarised results for the total benefit analysis produced by the 30 day runoff forecasts using the 30 day rainfall GCM rainfall forecasts.

Forecast period	Summer	Autumn	Winter	Spring	Total
. Category					
Win	37.98	56.73	63.62	44.42	49.85
Loss	56.32	36.18	8.38	41.88	46.20
No Diff	5.78	7.09	28.01	13.87	3.96

The summer runoff forecasts produce the worst results with 37.98% of the catchments producing win results and 56.32% producing loss results. The forecasts do, however, improve in spring and autumn with the winter forecasts producing the best results in recording win scenarios for 56.73% of the catchments and loss results for only 8.38% of the catchments. The summer forecast results produced by the 30 day runoff forecasts are comparable to those produced by the one month November categorical forecasts. The 30 day runoff forecasts perform better than the one month November forecasts with 37.98% of the catchment producing win scenarios for the 28 day runoff forecasts as opposed to the 27.90% (Table 9.2) of the catchments producing win scenarios for the one month November forecasts. The 30 day spring season runoff forecasts are comparable with the September one month runoff forecasts. The 28 day spring season runoff forecasts producing slightly better results than the September one month forecasts with 44.42% of the catchments producing a win scenario compared to the September one month forecasts with 40.44% of the catchments producing a win scenario. In general the 30 day runoff forecasts produced using the 30 day GCM rainfall forecasts seem to perform slightly better than the statistical forecasts.

The following list summarises the results produced by the different runoff forecasts as well as attempting to answer the questions formulated in the introduction of Chapter 9:

i. The 30 day runoff forecasts produced using the 30 day percentage of normal rainfall forecasts give slightly better overall results than the runoff forecasts produced using the categorical rainfall forecast.

ii. A comparison of the results obtained for the summer season 30 day runoff forecasts produced using the percentage of normal rainfall forecasts to the results obtained using the one month November categorical rainfall forecasts, which are also for the summer period, shows that the results are similar, with the summer season 30 day runoff forecasts performing only slightly better than the runoff forecasts using the categorical rainfall forecasts.

iii. The summer season 30 day runoff forecasts produce the lowest forecast accuracy and skill scores for the majority of the study region.

iv. The winter season 30 day runoff forecasts produce the highest forecasts accuracy and skill scores for the majority of the region.

v. The spring and autumn season 30 day runoff forecasts produce very similar forecasts accuracy and skill scores, which are better than those produced by the summer season forecasts, but worse than those produced by the winter season forecasts.

vi. Forecast accuracy results are linked to aridity, both temporally and spatially. The more arid the area, the higher the forecast accuracy scores tend to be. This is confirmed by the trend where the drier western areas of the study region tend to produce higher forecast accuracy results while the wetter eastern areas tend to produce lower results. This is also confirmed by the seasonal comparisons, with the summer season forecasted runoff producing lower accuracy results than those produced by the drier winter season forecasted runoff.

vii. The trends in forecast accuracy are not mimicked in the forecast skills for the 30 day runoff forecasts, where the spatial trend is not confirmed, with some of the wetter areas actually producing high benefit scores.

viii. While for the majority of the study region the 30 day runoff forecast results were generally low, there are some areas of the study region where the application of such forecasts in an operational framework could yield benefits.

ix. The forecast accuracy and skill scores are dependent both on the type of forecasts being used as well as the time period of that forecast. The three month categorical forecasts seem to produce the worst results, followed by the one and four month forecasts, with the best results being produced by obtaining runoff forecasts from the 30 day percentage of normal rainfall forecasts.

x. More accurate rainfall forecasts tend to produce more accurate runoff forecasts. This is a general trend, with the most noticeable improvement shown in the runoff forecasts produced by the four month categorical rainfall forecasts. However, this trend does not appear in the results produced by the three month forecasts from September to November and November to January where an improvement to the rainfall forecast actually resulted in a decrease in both the skill and accuracy scores produced by the runoff forecast.

In an overall assessment of the results obtained in the whole of Section 9 it would have to be concluded that at the current levels of skill and accuracy the runoff forecasts, produced by the various methodologies outlined in Chapters 7 and 8, are as yet not reliable enough to be applied in an operational framework for the majority of the study region. A further discussion on the aspects that may have caused low accuracy and skill results will be presented in the following chapter. Chapter 10 will not only attempt to identify the various shortfalls in the current methodology used, but will also make suggestions on how these could possibly be rectified and identify potential areas of future research which might lead to the operational application of the different forecasts. Added to this, suggestions on how to asses the viability of applying forecasts in specific areas will be presented in the suggestions for further research.

10 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

In Chapter 9 the results produced using the different modelling techniques developed in Chapters 7 and 8 were presented. In this chapter, shortfalls in the current methodology used to translate rainfall forecasts into runoff forecasts will be discussed. Factors that contribute to low skill and accuracy scores will be identified and possible solutions to the problem will be provided. Factors that are affecting the operational implementation of forecasting in water resource and risk management will be identified. Suggestions will be provided as to the directions that future research should take, specifically in order to enhance the operational application of forecasts in South Africa and the surrounding areas. This chapter specifically concentrates on the objectives outlined in Objective (d) of the Problem Statement Figure (OB - 10).

10.1 Factors which could be Contributing to Low Skill and Accuracy Scores

For the majority of the area in the South Africa study region, it was concluded that with the current levels of accuracy and skill it was not feasible to use runoff forecasts within an operational framework. Hence, it is necessary to identify the factors causing these low accuracy and skill scores in order to improve future forecasts and direct further research into possible applications of runoff forecasting.

Low accuracy and skill scores could be attributed to a number of different factors, which are listed below:

i. The categorical rainfall forecast regions may not be entirely representative of the regions for which they are delimited.
ii. The rainfall forecasts are not yet accurate enough to produce reliable, accurate and skilful runoff forecasts.
iii. The large scale rainfall forecasts (both percentage of normal and categorical) do not take into account the full range of local scale climatic variability that may exist in the region.
iv. The complex, non-linear rainfall : runoff relationship may be causing perturbations in the runoff forecasts as a result of the added variability introduced by antecedent moisture conditions, as well as rainfall intensity and persistency patterns.

Problem Statement

Reliable, skillful hydrological forecasts have the potential to prevent loss of life, spare considerable hardship and save affected industry and commerce millions of Rands annually if applied operationally within the framework of water resources and risk management. Integrated model and database systems provide scientists and managers with tools to investigate the feasibility and applications of such systems in operational forecasting activities.

Broad Objectives	Place forecasting within a framework of water resources and risk management in South Africa. *(a)*	Develop hydrological forecasting techniques that could be used operationally within South Africa. *(b)*	Evaluate the hydrological forecasting techniques' performance over the South Africa study region using selected forecasting periods. *(c)*	Discuss problems and shortfalls of the current methodology used to obtain the different runoff forecasts. Recommend areas of potential future research that would enable operational application of these forecasts. *(d)*
Specific Objectives	i. Review climate variability in South Africa and its associated effect on risk ii. Review the current water resource situation in South Africa iii. Review risk evaluation and management strategies with specific attention given to the role of forecasting	i. Review current methodologies used to obtain hydrological forecasts ii. Develop suitable methodologies to be used in South Africa iii. Develop unbiased techniques to evaluate the performance of the different hydrological forecasts	i. Use standard forecasting evaluation techniques to assess the performance of the hydrological forecasting techniques developed ii. Compare different hydrological forecast performances iii. Attempt to identify trends that influence forecast performance iv. Provide explanations for the different trends influencing the forecasts' performance	i. Identify shortfalls in the techniques used to translate rainfall forecasts into runoff forecasts ii. Suggest areas where improvements could be made to increase the forecasts' reliability iii. Suggest areas of future research that would lead to the operational use of the different runoff forecasts iv. Identify key sectors of the study area where the application of forecasting may be particularly beneficial

Figure OB-10: Problem Statement, highlighting aspects covered in Chapter 10

v. The unusually high number of runoff values in the retro-active hind forecast period that fall within the Near Normal category could be producing skew in the skill results, with the forecast skills being underestimated as a result.
vi. Problems with the methodology used to translate rainfall forecasts into runoff forecasts exist.

Quantifying the exact nature and extent of each of the errors described would be valuable in focussing future research on addressing the major causes of uncertainty in the climate and hydrological system. Forecast could then be aimed at improving these elements and reducing the uncertainty. This would add invaluably to the further research in this subject.

10.1.1 Representivity of the rainfall forecast regions

In Chapter 9 it was shown, by using the research methodology outlined in Chapter 7 that in most cases, if the rainfall forecast accuracy improved the runoff forecasts followed suite. This was particularly noticeable in the case of the four month categorical runoff forecasts, where the most marked increases in forecast skill and accuracy between actual and perfect forecasts could be observed. The trend was less obvious in the cases of the one and three month categorical runoff forecasts, where the improvements between the actual and perfect forecasts were only very slight. In the case of the three month November forecast the opposite trend was observed. The number of stations used to define the forecast regions is just over 500, but they are aggregated into 8 large "homogeneous" regions, while the number of rainfall stations driving the Quaternary Catchment database used to generate the runoff forecasts is in the region of 1300, of which each is treated as and individual station. This would suggest that the rainfall stations used to define categorical rainfall forecasts regions used in the one and three month forecasts are not taking into account large amounts of the local scale variability within a forecast region and are therefore not representative of the region as a whole.

10.1.2 Rainfall forecast accuracy and skill

Runoff forecast accuracy and skill results could be improved if the rainfall forecasts were more accurate. Using the current rainfall forecasting techniques it is anticipated that the rainfall forecasts generated using the physically based GCM will increase in their accuracy as and when an improved understanding of atmospheric processes is achieved. The statistical forecast techniques used to generate the categorical rainfall forecasts are, however, not expected to improve considerably as they are limited by the statistical relationships that have been observed in the historical record.

10.1.3 Local scale variability not accounted for by the rainfall forecast regions

A major improvement could be produced in both the statistically and physically based rainfall forecasts by downscaling the various forecasts from the large rainfall forecast regions and grid cells to a more local scale, in which better account is taken of the localised spatial variability. In the case of the CCA statistical forecasts this could be achieved by using a larger data set of rainfall stations to define the different forecast regions. These regions could then be made smaller and a statistical relationship between each of these smaller regions and SSTs could possibly be established. The GCM results may be slightly more difficult to generate at a smaller scale, and this could perhaps be achieved by imbedding the GCM output as input into regional scale GCMs, which would then take into account more of the local variability.

10.1.4 Complexities introduced by the rainfall : runoff relationship

Perhaps, the most obvious trend to become evident in the results produced in Chapter 9 is the association between forecast accuracy and aridity. This trend is evident both spatially and temporally where, the drier the region or season, the more accurate the runoff forecasts are likely to be. As has already been discussed in Chapter 9, it is thought that this particular association is a result of the dynamics of the seasonal runoff generation being easier to model in drier areas, where runoff tends to be generated by several low frequency large rainfall events rather than by the more frequent smaller rainfall events that occur in wetter areas. Hence, low forecast accuracies in wet areas could be attributed to the complexities introduced by rainfall persistencies, intensities and antecedent moisture conditions which result in higher variability that cannot be accounted for by using the larger scale forecasts. Even though, with the current methodology used, the antecedent moisture conditions are taken into account by running the model for two years with the actual rainfall before the forecasted rainfall is used to generate the runoff forecasts, this period only accounts for antecedent moisture conditions prior to the onset of the forecast period, but not within the forecast period. Perhaps a more detailed modelling approach needs to be used in the wetter areas that takes into account the more complex relationship in such areas by modelling the rainfall persistency, intensity and antecedent moisture conditions more explicitly.

Lower forecast accuracy and skill results from the runoff forecasts could also be attributed to the complexity of the rainfall : runoff relationship, which is distinctly non-linear. Antecedent conditions can often have a greater influence on runoff generation than actual rainfall magnitude per event, resulting in higher runoff variability. Thus, the variability in the intra-forecast period rainfall is magnified in the runoff, making forecasting of runoff more difficult. Errors in rainfall forecasts are exaggerated in the runoff forecasts and the greater variability in runoff gives a greater range of possible runoff values and smaller probability of forecasting correctly. The accurate modelling of antecedent moisture conditions is crucial when attempting to produce accurate reliable runoff forecasts.

10.1.5 High number of runoff values in the verification data set producing runoff that could be placed in the Near Normal runoff category

The other factor that may have contributed to the low skill scores produced by the majority of the forecasts over a large portion of the study area is the high percentage of runoff generated from the actual rainfall that falls within the Near Normal category over the forecast period. Any even random distribution split into three categories produces results where 1/3 of the values fall into each category. In the case of the retro-active hind forecast period used for verification purposes a higher percentage (50% or more for most of the study area) of the runoff generated from the actual rainfall falls in the middle Near Normal category. As the median runoff will always fall within the near normal category, the median value thus appears to perform unrealistically well for the retro-active hind forecast period. This would suggest that if a longer forecast period were used the runoff forecast skill scores should correspondingly improve as a more realistic distribution of rainfall and runoff values would result.

Longer data sets and more accurate rainfall forecasts could well result in higher accuracy and skill scores for the runoff forecasts. It can be expected that further research could increase rainfall and runoff forecast accuracy. However, the question still remains as to whether more accurate forecasts will be used operationally. The next major section (Section 10.2) thus attempts to identify the factors that may influence and restrict the application of forecasting within an operational framework in the South African study region.

10.1.6 Problems with the methodology developed to translate the runoff forecasts into rainfall forecasts

There are a number of factors that could cause the methodology, currently being used to generate runoff forecasts from rainfall forecasts, to produce low accuracy and skill scores. These are discussed in greater detail in Section 10.2, but can be attributed mainly to the low level of complexity used in the technique and are mainly concerned with factors such as:

i. the lack of hydrological linking between the individual Quaternary Catchments and with that the smoothing of streamflows,
ii. the coarse nature of the spatial downscaling technique, and
iii. the inability of the temporal downscaling technique, used to obtain representative daily rainfall forecasts from the categorical rainfall forecasts, to account for variability that exists in the rainfall forecasts and consequently runoff forecasts.

In the next section recommendations on how to address shortfalls in the current forecasting methodology are addressed, and later in the chapter recommendations for future research are made.

10.2 Recommendations to Overcome Shortfalls in the Methodology Used to Translate Rainfall Forecasts into Runoff Forecasts

While the forecasting technique developed and applied in these initial simulations is relatively simple, it serves to highlight important aspects about forecasting runoff and helps to show where further research is needed. Development on the foundations laid by this initial methodology may lead to more sophisticated runoff forecasts that could potentially be reliable enough to be placed within a framework of water resource and risk management, where they could help to enhance operations of water resource systems.

Shortfalls in the current forecasting methodology may be addressed by improving the following aspects:

i. Quantify major sources of uncertainty and explore forecasting methods which address these.
ii. Improved communication of existing forecasting information would serve as a testing platform for current forecasts and lead to further improvements of the current forecasting systems.

iii. A detailed test of the forecasting methodology should be undertaken by classifying the Quaternary Catchment rainfall into the 100% accurate forecast values. These can then be used as forecasted input into the hydrological model to test the validity of the methodology. This will then provide an answer that is independent of the downscaling technique. This will allow the user to classify the major source of uncertainty identifying whether it is being introduced in the downscaling or forecasting methodology.

iv. Represent catchments as they occur in reality, with the runoff generated from different individual Quaternary Catchments cascading downstream into one another, instead of modelling them as independent individual spatial and temporal entities.

v. Improve the spatial downscaling techniques presently used to assign forecast values produced for both the categorical and percentage of normal rainfall forecasts to individual Quaternary Catchments.

vi. Improve the temporal downscaling technique, which was used in this study to produce representative daily rainfall forecasts.

10.2.1 Link the Quaternary Catchments into Primary, Secondary and Tertiary Catchment systems with the individual Quaternary Catchments' runoff cascading and accumulating downstream

In the current methodology used to translate the rainfall forecasts into runoff forecasts a major limiting factor has been not linking Quaternary Catchments into a cascading run where each catchment's runoff flows into the downstream catchment. The results that have been obtained thus far are from assuming each of the Quaternary Catchments to be an individual entity that is not linked to the upstream or downstream catchments. While internally linking the system so that each catchment flows into the next is a relatively simple process that could be done within the current programming framework, the major problem exists with the timings of the each Quaternary Catchment's forecasted rainfall.

In downscaling the forecasted rainfall from the large forecast regions and low resolution GCM grid cells to the Quaternary Catchment level, each catchment as an individual entity, produces its own forecasted rainfall for a given period based on its own rainfall station, each with its unique ranking of rainfall and therefore unique selection of median, representative years for each forecast category. This technique currently uses percentage values which represent a ratio of forecasted rainfall to compared to the median value. These are then superimposed over the actual runoff produced in each individual Quaternary Catchment thus taking into account the local scale variability. On any particular given day within the forecast period the forecasted rainfall falling on one particular catchment may thus bear no relationship to the forecasted rainfall falling on the catchments next to it. Most major rainfall events, however, cover and influence areas far larger than a single Quaternary Catchment. The runoff generated from a linked catchment system is thus a function of the areal distribution of rainfall falling over a number of catchments over the same day(s). In the current system this cannot be accounted for. Hence, linking the catchments would cause an unrealistic scenario where the timings of the different forecasted rainfall events for each individual Quaternary would not be able to mimic a single runoff producing rainfall event encompassing some or all of the linked system's area. This would likely result in an under-estimation of the forecasted runoff from a linked catchment system.

The advantage of having linked catchments cascading into each other is that the variability within a larger system is less than that existing in numerous smaller, individual Quaternary Catchment systems. Linking the catchments would decrease the variability, increasing the runoff forecasts' accuracy and skill scores, but only on condition that over a series of linked catchments the representative rainfall could also be linked to the same year's rainfall from a series of surrounding stations.

10.2.2 Improve the spatial downscaling technique used to assign forecasts from both the categorical rainfall forecasts and the percentage of normal rainfall forecasts to individual Quaternary Catchments

Another aspect that could be influencing the results is the spatial downscaling techniques used to produce rainfall forecasts at a Quaternary Catchment scale. In the case of the categorical rainfall forecasts a specific Quaternary Catchment is assigned the same rainfall forecast category as the entire rainfall forecast region, if the Quaternary Catchments centriod falls within that particular forecast region. In the case of the percentage of normal rainfall forecasts given by the COLA GCM, the large grid cells at 3.75^0 X 3.75^0 were downscaled to 0.0167^0 X 0.0167^0 grid cells using inverse distance weighting interpolative technique.

The inverse distance weighting (IDW) interpolation technique was chosen following a study performed by Hallowes *et al.* (1999) four different interpolation techniques, *viz.* Spline, Kriging, trend surface analysis (TSA) and IDW, to study rainfall distributions in the Kruger National Park. The Prediction Error Sum of Squares (PRESS) method was used to test the different interpolation techniques. The results showed that TSA gave the best scores (i.e. lowest PRESS statistic) followed by IDW, Kriging and Spline (Table 10.1). As it is was not feasible within the time frame of this project to perform a TSA, IDW as the second best of the four methods tested, was chosen.

The Quaternary Catchment was then assigned the average value of all the new grid cells that made up its area. It has already been shown that the runoff forecasts improve considerably when the rainfall forecasts are accurate. The rainfall forecast accuracy at the Quaternary Catchment scale could, and should, be improved with better techniques, which facilitate downscaling the large scale rainfall forecasts to smaller regional scale rainfall forecasts more explicitly.

Table 10.1 PRESS statistics for mean annual precipitation (MAP) and mean monthly precipitation (MM1 to MM12) for four interpolation methods used to study rainfall distributions in the Kruger National Park (Hallowes *et al.*, 1999)

Rainfall and Month	Spline	TSA	IDW	Kriging
MAP	199174.84	75856.01	93498.80	103461.92
MM1	30794.79	5480.25	24888.19	25204.83
MM2	31792.80	330.81	18148.96	20474.83
MM3	5748.03	1659.40	2567.96	2867.10
MM4	3117.23	179.94	2139.22	2653.11
MM5	1131.12	739.84	430.57	478.85
MM6	142.94	100.63	100.58	104.92
MM7	208.51	37.25	161.79	164.43
MM8	249.77	42.03	166.97	167.97
MM9	1311.90	267.00	559.91	614.42
MM10	3251.09	665.69	2445.10	2623.34
MM11	10479.13	2159.81	6477.94	6216.78
MM12	3321.65	1326.40	2077.52	2227.38

10.2.3 Improve the temporal downscaling technique used to translate both the percentage of normal rainfall forecasts and the categorical rainfall forecasts into representative daily rainfall forecast quantities

The temporal downscaling technique used to translate the four, three, one month and 30 day forecasts into daily quantities could be improved. The existing technique uses an analogue year technique, which takes the closest representative historical daily rainfall record from a ranked series as the forecasted daily rainfall. Better results may be obtained by converting the historical daily rainfall quantities, which are representative of a particular forecast, into statistical distributions and then generating a rainfall forecast, or several rainfall forecasts, with the same statistical characteristics as the original historical daily rainfall data. Probability distributions could then be used to give runoff and rainfall forecasts within a specific range and at a specific probability. This, in turn, would allow water resource practitioners to attach a level of risk to the use of the different forecasts.

While the statistical techniques suggested above may increase a forecast's accuracy and skill for each individual catchment, the same linking problem still exists where the timing of the rainfall quantities needs to be addressed to obtain realistic runoff simulations. If the linking problem is to be solved, all the different sets of linked Quaternary Catchments forming Tertiary, Secondary and Primary Catchments need to be analysed on an individual basis. Areas of similar rainfall need to be identified within each of the larger linked catchments, using techniques such as principal component and cluster analysis. Within such larger areas the different cross-correlations need to be established and daily rainfall forecasts generated which maintain the statistical properties of the historical rainfall distributions within each individual catchment. In this way a more realistic areal distribution of the rainfall patterns over the larger linked catchment as a whole could be obtained and a more realistic combined flow be generated, which could then be used for forecasting purposes.

There may, however, be more deterministic alternatives to the ideas expressed above. Rainfall forecasts may in future be generated using physical process based models (regionalised GCMs) that generate rainfall forecasts, which have defined areal distributions and that can be applied in hydrological models directly without requiring any statistical manipulation.

10.3 Factors Influencing the Application of Forecasts in Water Resources and Risk Management

While the operational application of forecasting could potentially prevent loss of life, prevent damage to property and save affected agriculture and industry millions of Rands annually, its current use in southern Africa is limited. Klopper (1999) conducted a survey of current forecast users from the climatological, energy, water, food industry, farming, construction and policy-making sectors in South Africa. Through the survey it was found that 75% of the respondents changed their decisions and strategies according to the results of forecasts. However, this survey only took into account present users of the forecasts. Vogel (2000) found that the uptake and use of forecasts remained scant for the small-scale resource poor farming community. The knowledge and ability to apply forecasts in many sectors of the country may still be lacking. In both studies cited above it was found that forecast use could be increased by addressing the following problems:

i. Both the spatial and temporal resolution of the forecasts is very coarse and the quantities (*i.e.* percentages of normal rainfall) are not directly applicable to water resource management.
ii. Information on how to respond to various forecasts scenarios is lacking, leaving users to make their own decisions on application of forecasts.
iii. A lack of flexibility exists in users' operational systems or practices, which hampers their ability to respond to forecasting information (Vogel, 2000).

In the paragraphs which follow the author looks at aspects that may be hampering the application of forecasting in water resources management, highlighting areas of potential future research, which will be elaborated on in Section 10.4.

The accuracy of forecasts and their reliability is one of the major factors that affects forecast application. Forecasts have the ability to reduce the risk associated with various management decisions. However, if the forecasts are unreliable they introduce their own element of risk, which may be too high to incorporate into management practices. In order for forecasts to be used in practice they have to be proven reliable enough to reduce risk and provide some tangible benefit from their application. Unfortunately, as the research has shown, forecasts for most areas in the country produce low accuracy, unreliable forecasts. The applications of such forecasts are therefore limited to certain areas, seasons and tasks. If forecasting is going to be applied operationally, the forecast accuracies need to improve compared to their current accuracy levels. Attaching probabilities to forecasts also may increase their operational use, as it allows users to adjust their risk level accordingly.

Reliable rainfall and runoff forecasts in isolation are not particularly useful to society. If society is to derive benefit from forecasts they need to be generated on a near real-time basis, the forecast information then needs to be communicated to different relevant institutions and to the public, who will then need to respond by taking the appropriate evasive or mitigative actions. The application of forecasts could also be improved if forecasts are accompanied with suggestions on appropriate mitigative actions and responses that could be taken. Forecasting needs to be approached from a holistic perspective, where it is integrated into various institutional structures. If any benefit is to accrue from forecasting it needs to be incorporated within a framework of water resource and risk management, discussed in Chapters 3,4 and 5 and in particular in Section 5.4.2.

10.4 Suggestions for Future Research

Forecast accuracy and skill scores, obtained by applying the methods and techniques developed in Chapters 7 and 8, vary according to the length of forecast and the time of year. While, for certain areas and forecast periods, the forecasts are relatively good, producing high forecast accuracy and skill scores, the majority of the study region and forecast periods produced low accuracy and skill scores. The foundations laid in the development of the methodology outlined in this study need to be improved upon in order to produce more reliable hydrological forecasts with higher accuracy and skill scores. It is anticipated that the following areas of future research would enhance the use and application of forecasts in water resource and risk management, by identifying potential problem areas and increasing the reliability of hydrological forecasts:

i. Improve forecasting methodology used to generate the runoff forecasts;
ii. Extend the base data sets used to generate the forecasts and test the methodology;
iii. Create a system where forecasts are automatically updated with actual observed data and other shorter period forecasts which could be used to obtain probabilities of attaining the original forecasted results;
iv. Identify areas where forecast application may be particularly beneficial;
v. Concentrate forecasting efforts on a specific catchment area where the application of forecasting has been identified as potentially beneficial, performing simulations with actual land use and operational hydrology; and

vi. Generate forecasts of variables other than runoff, such as crop yields, dam levels and water demand, all of which would all link together into an integrated forecasting framework.

10.4.1 Improve forecasting methodology used to generate runoff forecasts

Improved forecasts will enhance the reliability of forecasts rendering them useful to water resource users and managers. It is anticipated that the following recommendations would improve the forecast accuracy and skill:

i. Replace the forecasted seasonal runoff, which at present is derived from the median seasonal rainfall within a category of Above Normal, Near Normal or Below Normal, with a probability distribution of forecasted runoffs within each category.
ii. At present the *ACRU* model assessment at a Quaternary Catchment scale over South Africa is based on comparative simulations, i.e. the same model parameters for land use and hydrological response rates are used for simulations of median, actual and forecasted runoffs, assuming an unperturbed natural system. Because simulations of median, actual and forecasted runoffs are then compared in a simple win / lose benefit analysis using the same parameters, the final results are assumed to be reasonably correct on an individual Quaternary Catchment scale. However, in future for critical areas of South Africa, the model will require:
    a. Further verification studies against actual runoff observations under different hydrological regimes, with account taken of actual land uses, dam specifications, abstractions and return flows, as well as of irrigation demands/supplies and return flows, all of which perturb the natural hydrological responses, as have been undertaken already for the Mgeni, Mkomazi, Mvoti, Pongola, Sabie and Mbuluzi (Swaziland) catchments; and
    b. Cascading of runoff from one Quaternary Catchment in a nested system into the next downstream, to assess actual streamflow characteristics as they accumulate down the river system.

These facets of research still constitute a major collaborative undertaking of several years' duration.

10.4.2 Extend the base data sets used to generate the forecasts and test the methodology

A quality checked, concurrent daily rainfall data set covering a period of 44 years from 1950 – 1993 for each Quaternary Catchment in South Africa was used in this analysis. Unfortunately, the hind forecast data sets used in this project do not extend that far back, starting in the mid to early 1980s and extending beyond to beyond 1995. The result is that the overlap period is rather short and more representative results could be obtained by extending the daily rainfall database beyond the end of 1993. An extension of the daily rainfall database was not performed before the development and testing of the forecasting methodology as the data required to extend the database were not readily available at the time. In the meanwhile (2000 – 2002) a new initiative by the Water Research Commission (WRC) in South Africa titled "The Development of an Improved Gridded Database of Annual, Monthly and Daily Rainfall", will collate into a single database all the available daily rainfall observations from some 13000 rain gauges within South Africa and its neighbouring states (Lynch, 2001). The database will be more comprehensive than the existing daily rainfall database used in this study, including more stations and a longer concurrent record ending in 2000 or later. The data will be quality checked and missing or suspect data will be infilled via a hierarchical approach using a suite of different infilling techniques (Lynch, 2001). It is recommended that this database be used in further forecasting exercises and methodology testing.

10.4.3 Develop a system that automatically updates the hydrological forecasts

In the forecasting framework used in this study several different forecast time periods are used, ranging from four months down to 30 days. Tennant (1998b) produces even shorter duration forecasts of 7 and 14 days. To improve the application of forecasts in operational management of water resource systems, forecast reliability could be increased by developing a framework using several series of forecasts in conjunction with real-time observed data to continuously update the short (up to 14 days), median (up to 1 month) and longer range forecasts. Using such a structure, it is would be possible for forecasts to be updated, giving probabilities of fulfilling the original longer term forecasts. A sequence of imbedded forecasts coupled with real-time observed data could be created to run with the real data and different forecasts updating each other. The real data could be used to update the 7 day forecast and both the real data and the 7 day forecast could be used to update the 14 day forecast, which in turn could be used to update the monthly forecasts which update the three monthly forecasts and finally the four monthly forecasts. Probabilities of fulfilling the different forecasts could thus be generated and the water resource and risk managers could adjust their strategy accordingly, as longer range forecasts are updated. While, this technique would be quite valuable there may be problems with compounding errors cascading through the systems causing large in accuracies in the forecasts. This aspect therefore needs to be thoroughly investigated.

10.4.4 Identify areas where the application of forecasting may be more beneficial than elsewhere

The benefits that can be derived from forecasting are a composite of the level of risk associated with specific hazard occurrence in a particular area, and the ability to forecast the hazard occurrence in that area. The ability to reliably forecast a hazard in a particular area reduces the risk associated with that hazard, as mitigation and preventative actions can be taken to reduce losses (cf. Section 5.4.2). Risk, on the other hand, is a combination of the severity (variability or probability of occurrence) associated with particular hazard occurrence, such as a flood or drought, and the vulnerability either, or all, of the system, community or individual exposed to the hazard (cf. Chapter 4).

In the case of hydrological hazards, such as floods and droughts, the severity of the physical hazard is dependent on the particular phenomenon's sensitivity to causal phenomena such as rainfall and temperature. A direct correlation could thus be inferred, with sensitivity being used to represent severity or, alternatively, probability of occurrence.

The other dimension of risk is vulnerability, which was shown in Chapters 4, to be linked to different social, economic and physical elements such as education, poverty and population density (cf. Sections 4.2.3.2). Vulnerability indices could be created using criteria such as average income in the exposed communities, average level of education and population density in the exposed area. These criteria obviously change according to the type of hazard that is occurring, i.e. the vulnerability of people or a community to a flood may be different to that of a drought.

The level of benefit that could be derived from a forecast could thus be derived as a combination of the forecast accuracy and skill, the sensitivity to causal phenomena and the vulnerability of that particular community/ person to the hazard occurrence. In Figure

10.1 a forecast benefit matrix is shown, which could be used to in an attempt to quantify the potential benefit derived from applying forecasts over the whole of the South Africa study region.

A forecast benefit score could be derived from the matrix by creating indices of forecast accuracy and skill, sensitivity and vulnerability. High levels of benefit would be derived from a forecast if the forecast accuracy and skill scores where high, the vulnerability of a particular community was high and the sensitivity was correspondingly high, i.e. the score would occur in the upper right hand corner of the forecast benefit matrix shown in Figure 10.1 While the sensitivity and forecast accuracy results are relatively easy to obtain, as they are linked to physical attributes, the vulnerability may be difficult to determine and quantify as it is linked to social attributes (cf. Sections 4.2.3 and 5.3). Such matrices could be used to determine the forecast benefit over the South African study region. This type of research could rationalise forecasting efforts, concentrating forecasting activities in areas where the most benefit could be derived from forecasting.

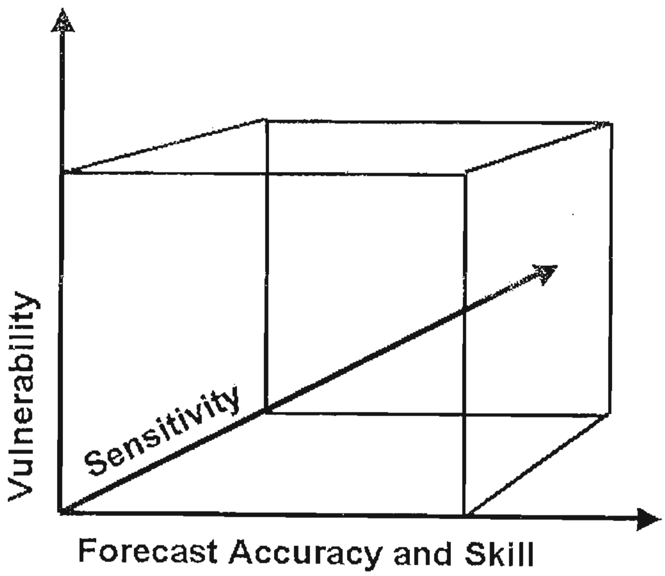

Figure 10.1 Forecast benefit matrix

10.4.5 Perform verification studies at a finer resolution on an actual operational catchment

In this study, the forecasting efforts have concentrated on producing forecasts of runoff for the South African study region. In this particular modelling set-up various assumptions were made to make the modelling runs simpler during the development of the forecasting techniques. For example, the land cover was considered homogeneous for all the catchments and was assumed to be natural grassland in fair management condition. Furthermore, hydrology-altering structures such as dams and irrigation systems were excluded from the simulations in order to prevent the perturbations which they might produce and which could complicate interpretation of results. Also, each of the catchments was considered as an entity and not as part of an interlinked hydrological system. All of these aspects, while making processing simpler, may result in unrealistic simulations of the actual conditions that are occurring in the catchments in the study region. While such simplifications in the methodology are useful to gain an overall picture of the status of forecasting within the area, the real benefit that could be derived from forecasting would result in applying forecasts at a more local scale within a catchment. This type of study should be undertaken in areas where the benefit of forecasting could be considered highest, identified using methods outlined in Section 10.4.3.

Future simulations should be undertaken on a smaller catchment system where the catchments are linked hydrologically and the catchments be divided further into discrete entities, which are able to account for the major land uses occurring. The actual land use conditions can thus be incorporated into the simulations. The simulations should also include all the different aspects of operational hydrology, including in the framework all the different reservoirs and water users such as irrigation, domestic and industrial users. Such studies have already been completed using the *ACRU* system, for example, on the Mgeni catchment (Kienzle *et al.*, 1997), the Pongola catchment (Schulze *et al.*, 1998b), the Mkomazi catchment (Taylor *et al.*, 2001), and the Sabie catchment (Pike and Schulze, 2000). Operational strategies in response to the different forecasts could thus be tested and cost benefit results generated, which would give users a better idea of the savings that could be produced by adopting different preventative and mitigative measures.

Forecasts at a specific catchment scale could be improved, as better account can be taken of the local variability. In order to link the system up so that each catchment is able to cascade into the next, the rainfall event time sequences and the spatial rainfall distribution patterns need to be maintained in the generation of the forecasted daily rainfall time sequences. For this to be achieved, it is necessary to identify different temporally homogeneous rainfall sequences within the larger catchment. This could be achieved by performing various cluster analysis techniques on the rainfall seasonal variability of the various rainfall stations or possibly by other more deterministic methods.

Once the different homogeneous rainfall zones have been identified, multivariate statistical techniques would need to be applied in order to determine the different daily cross correlations between the different rainfall stations representing the different catchments within the homogeneous forecast region. Cross correlations could also be established between the different homogeneous forecast rainfall regions within the catchment. Various regression, multivariate and interpolation techniques could then be used to produce daily rainfall fields for each of the homogeneous rainfall regions and over the catchment as a whole. Alternatively, the historical ranked rainfall fields could be extracted for an entire homogeneous rainfall region.

The simulations could then, at a later stage, be compared to actual conditions occurring in the catchment and the hydrological forecasts could be potentially used operationally in the catchment.

10.4.6 Produce more comprehensive agrohydrological forecasts

Forecasts of other components of the physical system that are dependent on rainfall (and temperature) could be obtained using the indirect methodology of passing climatic forecasts through, say, agrohydrological models. Crop yield, dam level, irrigation water use and supply are but some examples of the types of forecasts that could be produced by following the methodologies proposed and suggested above.

10.5 A Concluding Thought

In this particular study the methods used have not delivered convincing results in terms of forecast accuracy and skill. The poor performance can probably be attributed to the relatively unsophisticated nature of the downscaling and interpolative techniques used to produce daily rainfall forecasts at a Quaternary Catchment scale. It is believed that if the downscaling techniques could be improved, or forecasts produced at a more local scale, the runoff and other forecasts would improve correspondingly. It is the author's opinion that in the near future, with newly focussed research efforts, building on what has been learned in this study, reliable agrohydrological forecasts can be used within the framework of water resources and risk management, preventing loss of life, saving considerable hardship and saving affected industry and commerce millions of rands annually.

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