DETECTION OF CHANGES IN TEMPERATURE AND STREAMFLOW PARAMETERS OVER SOUTHERN AFRICA

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DECLARATION

The analytical work described in this dissertation was conducted at the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg from February 2003 to June 2005 under the supervision of Professor Roland Edgar Schulze.

These studies represent original work by the author 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.

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ABSTRACT

It has become accepted that long-term global mean temperatures have increased over the twentieth century. However, whether or not climate change can be detected at a local or regional scale is still questionable. The numerous new record highs and lows of temperatures recorded over South Africa for 2003, 2004 and 2005 provide reason to examine whether changes can already be detected in southern Africa's temperature record and modelled hydrological responses.

As a preface to a temperature detection study, a literature review on temperature detection studies, methods used and data problems encountered, was undertaken. Simple statistics, linear regression and the Mann-Kendall non-parametric test were the methods reviewed for detecting change. Southern Africa's temperature record was thereafter examined for changes, and the Mann-Kendall non-parametric test was applied to time series of annual means of minimum and maximum temperature, summer means of maximum temperature and winter means of minimum temperature. Furthermore, changes in the upper and lower ends of the temperature distribution were examined. The Mann-Kendall test was applied to numbers of days and numbers of 3 consecutive days above/below thresholds of 10th and 90th percentiles of minimum and maximum temperatures, as well as above/below threshold values of minimum (i.e. 0°) and maximum (i.e. 40°C) temperatures. A second analysis, using the split sample technique for the periods 1950 - 1970 vs 1980 - 2000, was performed for annual means of daily maximum and minimum temperatures, summer means of daily maximum temperatures, winter means of daily minimum temperatures and coefficients of variability of daily maximum and minimum temperatures. Two clear clusters of warming emerged from almost every analysis, *viz.* a cluster of stations in the Western Cape and a cluster of stations around the midlands of KwaZulu-Natal, along with a band of stations along the KwaZulu-Natal coast. Another finding was a less severe frost season over the Free State and Northern Cape. While certain changes are, therefore, evident in temperature parameters, the changes are not uniform across southern Africa.

Precipitation and evaporation are the primary drivers of the hydrological cycle, with temperature an important factor in the evaporation process. Thus, with changes in various temperature parameters having been identified over many parts of southern Africa, the question arose whether any changes were evident as yet in hydrological responses. The *ACRU* model was used to generate daily streamflow values and associated hydrological responses from a baseline land cover, thus eliminating all possible human influences on the catchment and channel. A split-sample analysis of the simulated hydrological responses for the 1950 - 1969 vs 1980 - 1999 periods was undertaken. Trends over time in simulated streamflows were examined for medians, dry and wet years, as well as the range between wet and dry years. The seasonality and concentration of streamflows between the periods 1950 - 1969 and 1980 - 1999 were examined to determine if changes could be identified. Some trends found were marked over large parts of Primary Catchments, and certainly require consideration in future water resources planning.

With strong changes over time in simulated hydrological responses already evident in certain Primary Catchments of South Africa using daily rainfall input data from 1950 - 1999, it, therefore, became necessary to examine the rainfall regimes of the Quaternary Catchments' "driver" rainfall station data in order to determine if these hydrological response changes were supported by changes in rainfall patterns over time. A split-sample analysis was, therefore, performed on the rainfall input of each Quaternary Catchment. Not only were medians considered, but the higher and lower ends of the rainfall distributions were also analysed, as were the number of rainfall events above pre-defined daily thresholds. The changes evident over time in rainfall patterns over southern Africa were found to vary from relatively unsubstantial increases or decreases to significant increase and decreases. However, the changes in rainfall corresponded with the changes noted in simulated streamflow.

From the analyses conducted in this study, it has become clear that South Africa's temperature and rainfall, as well as hydrological responses, have changed over the recent past, particularly in certain identifiable hotspots, *viz.* the Western Cape and KwaZulu-Natal where significant increases in temperature variables and changes in rainfall patterns were detected. These detected changes in climate need to be considered in future water resources planning.

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1. INTRODUCTION AND BACKGROUND INFORMATION

In May 2001, UN Secretary-General Kofi Annan, in a speech to American university students, declared that, "The evidence shows that climate change is occurring ... and we cannot wait any longer to take action" (Bergkamp *et al.*, 2003).

Concern, awareness and interest surrounding climate change and global warming is increasing. More and more media headlines and reports worldwide surrounding the issue, ranging from the sensational, informative and dismissive to the doom-laden, are becoming more frequent and are raising public awareness of the climate change phenomenon and its potential impacts. In the scientific arena climate change and global warming are hotly debated topics. As it has become progressively accepted that change is inevitable, the argument is now centred on the magnitude and timing of change, as well as the impacts of change on natural resources.

From examinations of long-term global mean temperature records since around 1860 it has become clear to, and accepted by the scientific community, that the global mean temperature has increased by ~0.6°C over the twentieth century (IPCC, 2001). Additionally, the five warmest years on record since scientific temperature observations began some 140 years ago occurred in the past ten years from 1995 to 2004 (WMO, 2005).

Not only is climate change evident through increasing global mean surface temperatures, but since the 1980s the frequency and intensity of hydrologically related extreme events have increased markedly according to reports by Munich Reinsurance (2000) and Kabat *et al.* (2003). It is not only the occurrence, and the record breaking nature, of these extreme events, but the frequency and intensity of occurrence that is concerning to hydrologists. Examples of these extremes include:

- unexpected floods in Europe in 1993 and 1995;
- flooding along the Mississippi River in 1993;
- destructive rains in Kenya in 1997;
- rain-induced mudslides in Venezuela in 1999;

- severe droughts in central and southwest Asia from 1999 to 2001;
- devastating floods Mozambique in 2000 and 2001; and
- record setting droughts and wildfires in various parts of the USA in 2003 (Glantz, 2003).

More alarming than the above examples is the sheer number of natural disasters experienced over short periods in various areas of the world, for example, in December 2004 and January 2005. December 2004 saw floods in Angola, China, Malaysia, Indonesia and Sri Lanka. Severe storms were experienced in France and Japan; flash flooding occurred in Australia, Iran, South Africa and the USA. Tropical storms ravaged the Philippines and landslides occurred in China (WMO, 2005). In January 2005 Costa Rica, Kenya and the USA experienced heavy rains, and Madagascar was the site of a severe tropical storm. Severe storms and flash flooding affected Australia, Guyana, Northern Europe, Saudi Arabia and Swaziland (WMO, 2005). Are these events already signalling the occurrence of anthropogentically forced climate change?

Climate change has become an accepted reality at the global scale (IPCC, 2001), but the question still remains: 'Is it possible to already detect, with statistical significance, climate change at a regional or local level?' It is at the regional and local level that land use and water resources management and decision-making take place. It is also at the regional level that climate interacts with geographical and socio-economic factors to influence nearly every aspect of human well-being, from health, agricultural productivity and energy use to flood control, municipal and industrial water supply, as well as fish and wildlife management (Bobba and Diiwu, 2001). Hence it is important to be able to detect climate change at the regional level, and as early as possible.

As a point of departure, prior to embarking on a literature review of, and regional study on the detection of trends in climate, an understanding is needed on what climate change and global warming are. As is an understanding of why the detection of climate change is particularly pertinent to southern Africa. Background information pertaining to a larger project of which this study on detection forms a part is also outlined.

1.1 Background Information 1: What is Global Warming?

Incoming solar radiation heats the earth's surface. From the surface of the ocean and land longwave radiation is emitted into the atmosphere. Some of this longwave radiation is absorbed by clouds and greenhouse gases, and then either reflected and/or partially re-radiated back towards the earth's surface. Clouds and greenhouse gases thus act as a partial 'blanket' for longwave radiation, warming the atmosphere. This process is termed the greenhouse effect (Glantz, 2003). It is a natural process which has warmed the atmosphere for centuries, making the earth a habitable planet.

The greenhouse gases consist primarily of water vapour and carbon dioxide, with other minor gases present in smaller quantities. These gases have been present in the atmosphere since before humans (Houghton, 1997). The amount of water vapour present in the atmosphere depends primarily on the temperature of the ocean surface, as most of the water vapour originates through evaporation from the ocean surface and is not influenced by human activities (Houghton, 1997). The amount of carbon dioxide is, however, influenced by human activities. Since the industrial revolution the amount of carbon dioxide present in the atmosphere has increased substantially from approximately 280 ppmv to a present value of around 370 ppmv as a consequence of human activities such as burning of fossil fuels and deforestation (Houghton, 1997). This increased atmospheric carbon dioxide concentration increases the 'blanket' effect, thus causing an enhanced greenhouse effect, which in theory should be increasing the earth's surface temperature, in essence resulting in global warming and changes to the earth's climatic patterns. Can such climate changes already be detected by observation?

1.2 Background Information 2: Issues of Pertinent to Africa and Southern Africa

Added to the above-mentioned general question on, already being able to detect climate change, several more specific reasons for the need to detect climate change timeously are pertinent to Africa in general, and South Africa more specifically. Africa is a continent characterised by:

- diversity in landforms, culture, and economic development;

- range of climates, which frequently display strong seasonality and are often strongly influenced by intense El Niño-Southern Oscillation (ENSO) events, rendering its present rainfall and runoff regimes already highly variable from year to year;
- a high economic dependence on local natural resources, agriculture and pastoralism, which are highly climate dependant; and
- a generally low developmental status, with the African continent including some of the poorest and least developed nations of the world (Schulze *et al.*, 2001).

Climate change is likely to render the continent even more vulnerable to the vagaries of climate than it already is. South Africa is a predominantly semi-arid region with generally a high inter-annual rainfall variability and pronounced seasonal cycles (Tyson, 1986), resulting in highly variable hydrological responses both in time and space (Schulze, 2000). In the past three decades population growth and industrial development in South Africa have placed increasing pressure on its generally scarce water resources. In the Johannesburg area alone, water consumption has more than doubled over the past thirty years (Mason and Jury, 1997).

Other pressing water related issues affecting South Africa include food security, poverty, natural resource management, energy needs, access to potable water and land use impacts on water resources (Markandya and Halsnaes, 2002). South Africa is one of only two countries in the southern African region which is able to produce food in surplus, allowing export to countries throughout the region (Glantz, 2003). This is attributable to the favourable pockets of soil and climate conditions coupled with advanced farming methods and other production factors. However, every so often severe droughts occur which affect agricultural production (Glantz, 2003). The export of surplus food is crucial for the economy of the region. Thus any statistically significant trends in temperature, rainfall characteristics, drought frequencies or streamflow regimes need to be detected as early as possible to allow planning to occur and contingency strategies to be implemented.

Is climate change therefore important? It is hypothesised that the issues raised in this introduction, coupled with the already high variability of South Africa's and Africa's present climate, render the continent particularly vulnerable to the impacts of potential climate change. This vulnerability is considered reason enough to evaluate scientifically whether climate change can already be detected at the regional scale in South Africa already.

1.3 Background Information 3: The Water Research Commission Solicited Project on Climate Change and Water Resources in South Africa

With climate change now generally being accepted as a reality, the Water Research Commission (WRC) of South Africa initiated a 2-year research project in 2003. Titled "Climate Change and Water Resources in South Africa: Potential Impacts of Climate Change and Mitigation Strategies", this project was awarded to a consortium of researchers from the Universities of KwaZulu-Natal, Cape Town, the Witwatersrand and Pretoria. The five major objectives of the project were:

- to develop plausible climate change scenarios for southern Africa;
- to investigate the potential impacts of climate change on hydrological responses and associated water resources;
- to investigate possible water related socio-economic impacts in a designated Water Management Area;
- to recommend appropriate strategies to adapt to, and cope with, water related impacts of potential climate change; and
- to determine whether effects of climate change can already be detected and to recommend appropriate monitoring systems for its detection.

The studies described in this dissertation form part of this wider ranging WRC project and address the final objective, *viz.* to establish whether or not the effects of climate change could already be detected.

1.4 The Objectives and an Outline of this Study

Two broad scientific research objectives were initially identified and addressed in the course of this study, *viz.* an analysis of observed temperature records from various stations across southern Africa (defined for this project as South Africa, Lesotho and Swaziland) to detect trends, over time and an analysis of simulated hydrological responses for 1946 Quaternary Catchments that cover southern Africa, to possibly detect trends attributable to changes in climate. A third broad objective was drawing conclusions on whether trends in temperature parameters and streamflow responses could be detected, and making recommendations for future research.

Chapters 2 and 3 address the detection of trends in temperature parameters. A review of literature pertaining to temperature detection studies, problems relating to temperature data and the dataset used in this study, as well as statistical methods used in detection studies, are presented in Chapter 2. The results of temperature trend detection studies using the Mann-Kendall non-parametric test and split-sample analysis are presented in Chapter 3.

The second broad objective is addressed in Chapters 4 and 5. A literature review of results from streamflow detection studies is given in the initial sections of Chapter 4, followed by an outline of problems relating to streamflow measurement, a discussion of the advantages of applying physical conceptual models in hydrological trend detection studies, and an outline of the southern Africa Quaternary Catchments Database which was used in, and enhanced for, this study and the inputs into this database. Lastly in Chapter 4, the re-selection of the rainfall stations for the Quaternary Catchments Database and an evaluation of South Africa's rainfall station network is presented. Chapter 5 contains results of detection studies on hydrological drivers and responses through the use of the Mann-Kendall non-parametric test and split-sample analyses.

The results from the studies on detection of changes to hydrological responses prompted an investigation into trends in southern Africa's rainfall regime, which had not been an original objective of this dissertation. These results and a review of literature pertaining to results of rainfall detection studies are presented in Chapter 6. The third broad objective is addressed in Chapter 7, in which summaries of temperature, hydrological and rainfall detection results are given, overall conclusions drawn and recommendations for future research in this field made. A "roadmap" has been prepared for readers of this dissertation, which contains not only the problem statement and broad objectives, but also specific objectives of this study. For clarity and ease of understanding, the "roadmap" is repeated before the beginning of each major section of the dissertation, *viz.* Chapter 2, Chapter 4 and Chapter 6, with relevant parts addressed in those sections highlighted.

Problem Statement: If anthropogenically forced climate change is becoming a reality, evidence of change should already be detectable in climate observations and from hydrological simulations at a regional scale

Overall Objectives: To determine whether statistical analyses already show trends in temperature parameters and hydrological responses which may be ascribed to climate change

		Broad Objectives		
		Temperature Detection Studies	**Detection Studies on Hydrological Drivers and Responses**	**Overall Conclusions and Recommendations**
Specific Objectives	**Literature Review**	i.) Review results from temperature detection studies ii.) Outline problems related to temperature data iii.) Review statistical methods used in detection studies	i.) Review results from streamflow detection studies ii.) Outline problems related to streamflow measurement iii.) Discuss the advantage of physical conceptual hydrological models in detection studies iv.) Review precipitation detection studies	i.) Changes in southern Africa's temperature regime ii.) Changes in southern Africa's hydrological drivers and responses iii.) Changes in southern Africa's rainfall regime iv.) Overall conclusions and recommendations
	Data	i.) Outline temperature dataset used for southern Africa	i.) Quaternary Catchments Database and input	
	Methods	i.) The Mann-Kendall non-parametric test ii.) Split-sample analysis	i.) Re-select rainfall station network ii.) The Mann-Kendall non-parametric test iii.) Split-sample analysis	
	Results	**Mann-Kendall Analyses** i.) Examine means of minimum and maximum temperatures ii.) Analyse percentile thresholds iii.) Analyse selected thresholds iv.) Analyse frost related parameters v.) Analyse Heat units vi.) Analyse Chill units **Split-sample analyses** i.) Examine means of minimum and maximum temperatures ii.) Analyse coefficient of variation	**Mann-Kendall Analysis** i.) Analyse accumulated streamflows **Split-Sample Analyses** i.) Reference potential evaporation ii.) Soil water content iii.) Median, 90th and 10th percentile of accumulated streamflow iv.) Range in streamflows v.) Baseflows vi.) Seasonality and concentrations of flows vii.) Irrigation water requirements **Split-Sample Analyses** i.) Median, 90th and 10th percentile of rainfall ii.) Range in rainfall iii.) Analyse selected thresholds	
	Conclusions	i.) Is southern Africa's temperature changing?	i.) Conclusions of detection studies on hydrological responses ii.) Conclusions on changes in rainfall	

2. STUDIES ON THE DETECTION OF CHANGES IN TEMPERATURE PARAMETERS OVER SOUTHERN AFRICA

2.1 Introduction

From examinations of long-term global means of temperature records since around 1860 it has become clear to, and accepted by, the scientific community that the global mean temperature has increased by ~0.6°C over the twentieth century, as shown in Figure 2.1 (IPCC, 2001). Other recent statistics indicating climate change include, for example, that the warmest year on record since scientific temperature observations began some 140 years ago was 1998, with surface temperatures averaging 0.55°C above the 1961 – 1990 annual average, that the second warmest year on record was 2002, when the global mean surface temperature was 0.48°C above the same 30-year mean and that the year 2001 was the third warmest year on record, with 2004 the fourth and 1995 the fifth (WMO, 2003; WMO, 2005)

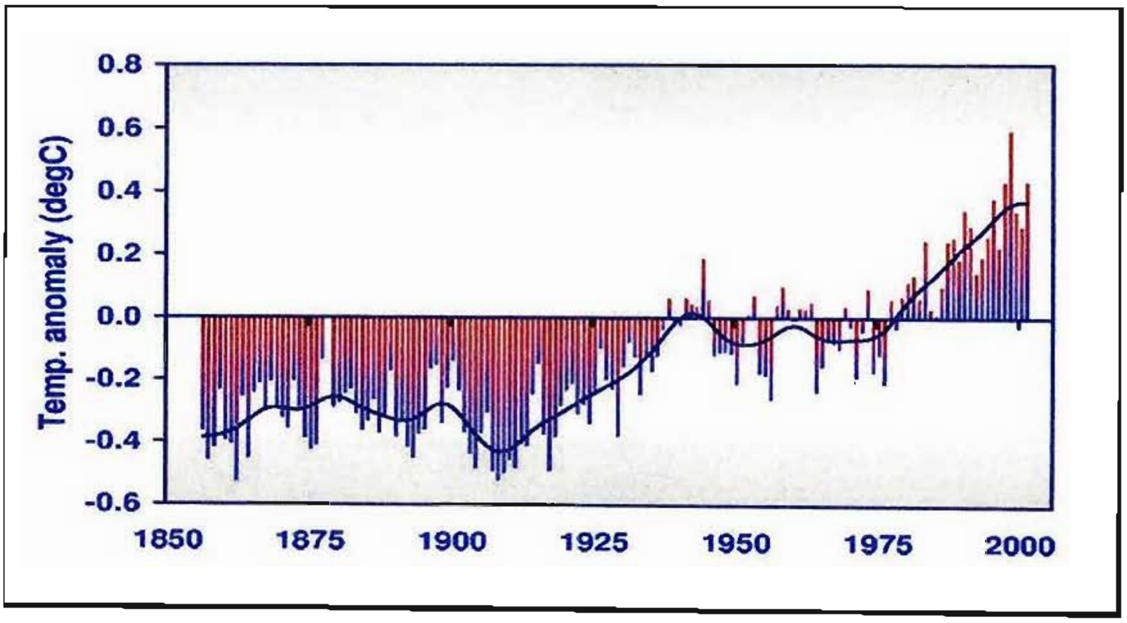

Figure 2.1 Trends in global average surface temperature, 1860-2001 (IPCC, 2001)

For South Africa in 2003, 2004 and 2005, numerous new record highs and lows of temperature have been recorded. For example, the night of 21 August 2003 was possibly the coldest night on record (Table 2.1), according to a press release from the

South Africa Weather Service (SAWS). According to other press releases from the SAWS, new record highest maximum temperatures were recorded at various locations during late 2004 and early 2005 (Table 2.2), and new record highest minimum temperatures were recorded during the same period (Table 2.3).

Such record values do not necessarily indicate a change in our climate, but they can be considered reason enough to scientifically evaluate temperature records over South Africa to determine if a change in climate can be detected. As a pre-cursor to the evaluation of the temperature records over South Africa, and as highlighted in the "roadmap", a literature review of other temperature detection studies is presented. Following this, temperature records used in this study are discussed, methods of analysis of temperature detection are reviewed, the results are presented and conclusions drawn.

Table 2.1 New and previous records of lowest minimum temperatures recorded for August for various locations in South Africa, as of August 2003 (SAWS, 2003a)

Station Name	**Previous Lowest Minimum Temperature (°C)**	**Date Recorded**	**21 August 2003 Minimum Temperature (°C)**	**Decrease (°C)**
Cape St. Lucia	7.9	1981/08/19	7.0	0.9
Oudtshoorn	-1.0	1984/08/26	-1.6	0.6
Bisho Airport	2.3	1995/08/24	1.5	0.8
Bloemfontein	-9.7	1972/08/02	-10.3	0.6
Kimberley	-6.7	1977/08/07	-8.5	1.8
Estcourt	-2.5	1975/08/03	-3.0	0.5
Bethlehem	-9.2	1985/08/04	-10.2	1.0
Welkom	-5.2	1977/08/05	-6.3	1.1
Frankfort	-10.0	1955/08/14	-10.4	0.4
Vryburg	-8.2	1955/08/08	-8.9	0.7
Ottosdal	-6.0	1977/08/05	-8.4	2.4
Potchefstroom	-7.6	1972/08/02	-7.7	0.1
Standerton	-7.9	1974/08/02	-9.5	1.6
Aliwal North	-8.2	1995/08/24	-9.5	1.3
Johannesburg	-5.0	1972/08/02	-7.0	2.0
Carolina	-4.0	1967/08/18	-6.1	2.1
Mafikeng	-4.2	1972/08/02	-5.1	0.9
Irene	-2.5	1980/08/15	-4.8	2.3
Warmbad	-5.5	1976/08/13	-5.6	0.1

Table 2.2 New and previous records of highest maximum temperatures for various locations in South Africa, as of January 2005 (SAWS, 2005a)

Station Name	**Previous Highest Maximum Temperature (°C)**	**Date**	**New Highest Maximum Temperature (°C)**	**Date**	**Increase (°C)**
Cradock	41.5	06/01/95	41.6	06/01/05	0.1
Welkom	38.3	18/01/73	38.4	06/01/05	0.1
Twee Rivieren	42.4	02/01/88	42.5	06/01/05	0.1
Willowmore	40.5	23/12/89	41.0	12/12/04	0.5
Beaufort West	40.3	12/12/65	41.0	12/12/04	0.7
Makatini	40.3	02/11/66	41.0	20/11/04	0.7

Table 2.3 New and previous records of highest minimum temperatures for various locations in South Africa, as of January 2005 (SAWS, 2005a)

Station Name	**Previous Highest Minimum Temperature (°C)**	**Date**	**New Highest Minimum Temperature (°C)**	**Date**	**Increase (°C)**
Thohoyandou	24.4	09/01/96	24.9	06/01/05	0.5
Cape Point	18.9	23/12/99	19.2	12/12/04	0.3
Mafikeng	23.2	20/11/90	23.4	27/11/04	0.2
Welkom	21.0	08/11/68	21.2	28/11/04	0.2
Cape St Francis	20.5	27/11/77	21.0	19/11/04	0.5
Cape Agulhas	19.2	26/11/77	19.6	19/11/04	0.4
Prieska	25.6	15/11/85	28.6	17/11/04	3.0
De Aar	22.6	22/11/72	23.5	17/11/04	0.9

2.2 Literature Review: Climate Change Detection Studies on Temperature

An increase in global mean surface temperature has been established (Section 2.1, Figure 2.1; IPCC, 2001). However, regional detection studies for temperature worldwide have shown varying results. Results from temperature change detection studies for various countries will be discussed first, followed by results from studies undertaken for Africa and southern Africa. Whether or not any of the changes in temperature reviewed in this chapter are a consequence of anthropogenic influences, is not at issue; the literature review merely sets out what has been found in various studies.

For the USA, Easterling (2002) showed a substantial warming for most of the country. Averaged for the USA as a whole a small, but significant, trend of 0.8 fewer days of frost per decade was detected. A significant change to a later first-autumn frost, when averaged across the entire USA, was also found. Cooter and LeDuc (1995) illustrated that the frost-free season in the northeastern USA had occurred 11 days earlier in the mid-1990s than in the 1950s. DeGaetano and Allen (2002) showed the occurrence of decreasing maximum and minimum temperatures at nearly 80% of the 361 stations they examined. Of these stations, 15% showed statistically significant decreases in the occurrence of cold extreme temperatures. Similarly, a decrease was found in the number of ≥ 2 day runs, and ≥ 3 day runs of extreme cold temperatures occurring across the country. Contrary to this, Easterling *et al.* (2000) found no clear trends in maximum temperatures to be evident for the USA.

In an examination of the minimum temperature records for Venezuela and Colombia, Quintana-Gomez (1999) found a statistically significant positive trend in the annual mean of minimum temperatures. Rusticucci and Barrucand (2004) analysed trends in the mean, standard deviation and extremes (5th and 95th percentiles) of maximum and minimum temperature over Argentina for the period 1959 to 1998. Positive trends of approximately 4°C per century were found for minimum temperature in summer. Maximum summer temperatures displayed strong negative trends. None of the other variables considered presented significant trends.

Balling Jr. *et al.* (1998) analysed a long-term temperature record for Europe, and a warming of 0.5°C over the period 1751 to 1995 was found. Wibig and Glowicki (2002) examined trends in maximum and minimum series for nine stations in Poland. The mean of maximum temperatures was shown to exhibit a slight increasing trend at all nine stations; however, the increasing trend was only statistically significant at one station. For the mean of minimum temperatures a statistically significant increasing trend at all stations was found, ranging from 0.14°C per decade to 0.31°C per decade. A decrease in the annual frequency of the number of days with minimum temperature below 0°C was also noted. In examining daily climate data from 305 weather stations in China, for the period 1955 to 2000, Lui *et al.* (2004) found that the surface air temperatures of China had increased, especially in the last decade of the twentieth century. It was found that the daily minimum temperature increased at a rate of 1.27°C per century and daily minimum temperature increased at 3.23°C per century.

Easterling *et al.* (2000) produced the information contained in Table 2.4 from a literature review of temperature detection studies. The table shows that for all countries reviewed, the number of frost days per year had decreased.

Table 2.4 A summary of findings by Easterling *et al.* (2000) from climate change temperature detection studies for various countries

Country/ Region	Frost Days	Extreme Min. Temp.	Extreme Max. Temp.	Cold Waves	Heat Waves
Australia	Fewer		Up		
China	Fewer	Up	Down	Fewer	
C. Europe	Fewer				
N. Europe	Fewer				
New Zealand	Fewer		Up		
U.S.A	Fewer	Up	No trend	No trend	No trend

King'uyu *et al.* (2000) examined daily maximum and minimum temperature records for eastern Africa from 1939 to 1992. They found a significant rise in the minimum temperature at several locations over eastern Africa. However, the warming trends were not geographically uniform, with coastal locations and those near large water bodies indicating cooling trends. Although a significant warming of minimum temperatures at several locations was evident, no clear trend could be found in maximum temperatures.

Hughes and Balling's (1997) work over South Africa showed a warming in excess of 1°C; Hulme *et al.* (1996), however, only showed a warming of 0.5°C over southern Africa as a whole. The warming over southern Africa has not been even (Mühlenbruch-Tegen, 1992; Levy, 1996) and is believed to be partly attributable to an urban effect (Hughes and Balling, 1997), but with evidence of a signal of greenhouse warming evident at some locations (Mason and Jury, 1997).

A non-peer reviewed report by Gill (2005) examined whether the first ten days in June 2005 deviated from the normal condition for the past 30 years over South Africa and Lesotho. The long-term daily average temperatures for 87 stations across the country was calculated for the first 10 days of June and compared to the daily average temperature for the first ten days of June 2005. The results (Figure 2.2) showed that the northern parts of South Africa and some of the central regions experienced temperatures in excess of 2°C higher than the 30 year average for the first ten days of June. In parts of the Limpopo Province temperatures in excess of 4°C of the 30 year average were experienced. These results established that South Africa experienced an extensive, pronounced warm spell in early June 2005, however, they do not necessarily signify a trend.

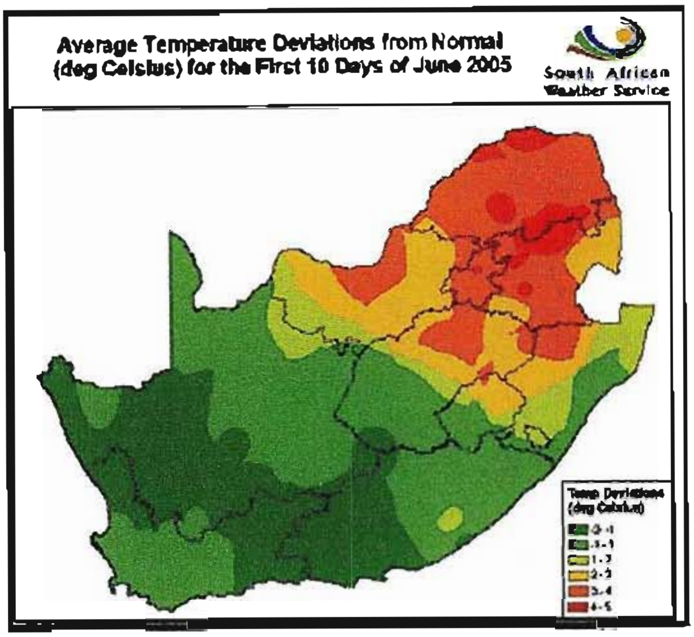

Figure 2.2 Deviations of the daily average temperatures for the first ten days of June 2005 from the 30 year average of daily temperatures for the first ten days in June (Gill, 2005)

From the above literature review it has become evident that a trend in minimum temperatures is more likely to be found than a trend in maximum temperatures. Furthermore, when conducting detection studies at a regional level, local influences such as those of large water bodies and urbanisation must be borne in mind.

2.3 Temperature Data and Climate Change Detection

Analysis of trends in observational records can provide insights into the characteristics and magnitude of global and regional climatic variations during the past decade to century (Frei and Schar, 2001). However, most attempts to characterise trends in climatic parameters have been plagued by the lack of long-term, high quality daily datasets (DeGaentano and Allen, 2002). With this in mind, problems relating to temperature datasets such as those mentioned above are discussed in this section and the temperature dataset used in this study is described.

2.3.1 Data problems to be aware of

No extensive temperature dataset can be totally void of any errors. However, with knowledge of the manner by which likely errors could arise and by careful quality control, the errors can be minimised and more confidence placed in the integrity of the dataset. Often the data available contains inhomogeneities as a result, *inter alia*, of changes in observational practices, changes in instrumentation type, instrument exposure, changes in location or changes in a location's characteristics, for example urbanization (Akinremi *et al.*, 1999; King'uyu *et al.*, 2000). Furthermore, if data are available, they are often not available in electronic form and/or the quality of the data are often questionable (Easterling *et al.*, 2000). For example, of 973 temperature stations in South Africa with daily records used in a study by Schulze and Maharaj (2004), only 299 stations were actually recording in the year 2000 and only 22 stations have actual (i.e. non-infilled or extended) records longer than 50 years. Furthermore, an apparent availability of data can be misleading, as in many parts of the world the spatial distribution of climate stations is uneven, with a high proportion of stations located close to urban areas and along coastlines (Groisman and Legates, 1995).

Other problems relating to data include the following:

- The exchange of international data is often hampered by cost recovery policies for high-resolution historical climate records.
- Data on short-term weather events (e.g. tropical cyclones) are largely unavailable owing to an absence of electronic or automatic recording instruments.
- A major problem affecting virtually every analysis of climatic records relates to undocumented or unknown effects of inhomogeneities in the datasets (Karl and Easterling, 1999).

To address the problems of inhomogeneities in datasets, a set of climate monitoring principles was proposed by Karl and Easterling (1999). The principles are aimed at reducing inhomogeneities in climatic records in order to allow unbiased analysis of these records to take place and trends in climatic variables to be detected. The principles include the following:

- An overlapping period of measurement for both old and new observing systems should be standard practice prior to implementing changes, in order to develop appropriate transfer functions from the old to new observing systems.
- Calibration, validation, processing algorithms, knowledge of instrumentation, station history and any other information relevant to interpreting the measured variable should be mandatory information that is recorded and archived with the original data.
- Routine assessment of both the random and systematic errors should take place in order to adequately monitor environmental variations and change.
- Observation stations with long, uninterrupted records should be maintained and protected to ensure a long-term homogenous climate record from that station.
- When implementing or installing new observation systems, priority should be given to either data poor regions, variables or regions sensitive to change or key measurements with inadequate temporal resolution.
- Data management systems should be guided by freedom of access, low-cost mechanisms that facilitate use and quality control (Karl and Easterling, 1999).

These principles, in particular the principles relating to the protection of stations and data management systems, should be applied to observing climatic variables in South Africa. Discussed below is the temperature dataset used for this study.

2.3.2 Temperature dataset used in this study

Daily maximum and minimum temperature records were obtained from a CD-ROM which accompanied a recently completed report to the Water Research Commission (WRC) titled "*The Development of a Database of Gridded Daily Temperature for Southern Africa*" (Schulze and Maharaj, 2004). This report formed a component of a WRC project titled "*The Development of a Revised Spatial Database of Annual, Monthly and Daily Rainfall and other Hydroclimatic Variables for South Africa.*" The project developed procedures to infill missing daily maximum and minimum temperature values and to extend temperature records to a common, preselected base period from 1950 to 2000, for those stations qualifying on the strength of existing records.

Daily temperature data were obtained from three main sources, *viz.* the South African Weather Service (SAWS), the Institute for Soil, Climate and Water (ISCW) and the South African Sugarcane Research Institute (SASRI). Of the 1053 stations which initially qualified following quality control of data, only 23 had a record length of greater than 50 years of daily temperature data, with only 4 stations having a record length in excess of 75 years of daily data. The network of temperature stations is densest in the KwaZulu-Natal, Gauteng and Western Cape provinces and sparsest in the Northern Cape province and Lesotho (Schulze and Maharaj, 2004).

Following initial quality controls, further stringent quality controls were undertaken on all daily temperature data included in the database. Thereafter, missing or discarded temperature values were infilled and records extended by using data from nine control stations for each target station, selected according to criteria, distance from the target station and difference in altitude. Infilling/record extension of the target station was undertaken by using the "difference in standard deviation method" (described in Schulze and Maharaj, 2004) after adjusting the control stations records' for differences in altitude using regional and monthly lapse rates. Where the target station could not be infilled using this method, Fourier Analysis was used (Schulze and Maharaj, 2004).

For this study on detection of trends in temperature a 51-year record of daily temperature for the common period 1950 to 2000 was extracted from the database of daily temperatures for southern Africa (Schulze and Maharaj, 2004) for stations with an actual data record length of 20 years or longer. Furthermore, stations were eliminated if any of their records were infilled using Fourier Analysis, as the infilled values of temperature for a given day of the year remain the same year to year, and, therefore nullify any trend. Following this elimination process, each station's record of monthly means of daily values (e.g. as in Table 2.5 for one station) was checked manually. Any anomalies found in the time series plots were then investigated at a daily level. As a result, five stations in Lesotho, *viz.* 0204819_A, 0207337_W, 0263859_W, 0267137_W and 0297083_W were identified as stations with questionable data.

A further data check undertaken was to identify the land use surrounding each temperature station, using the 1996 Landsat TM National Land Cover Image from the CSIR. If the land use was urban, the station was flagged, as the temperature record could have been influenced by an urban heat island effect. Owing to the small number of stations located in heavily built-up urban areas, the effect of land use was not considered any further at this stage.

The initial 1053 temperature stations whose records qualified were reduced to 342 once further quality controls had been effected and a minimum 20 year actual record length was considered. These 342 stations were further reduced to 209 when those stations with records which at any stage in the 51 year period 1950 – 2000 had been infilled/extended by Fourier Analysis had been removed. Thus the temperature stations used in the analysis contained few infilled values.

Following this data collation and quality control, the next step was to analyse the datasets for trends over time, using the methods outlined in Section 2.4 below.

2.4 Methods of Analysis to Detect Climate Change in Temperature Records

With quality datasets established and stored, the next step was to apply statistical techniques to detect whether trends over time were evident. These methods are reviewed below. The methods reviewed are simple statistics, moving averages, linear regression and the Mann-Kendall non-parametric test.

First, before evaluating relevant statistics, the question 'What constitutes an extreme event?' needs to be answered. There are two types of extreme events, the first being a single day event in which an observation of a variable (e.g. temperature) on a given day equals or exceeds a specified threshold. The second is a so-called run event for which each day's value of the variable equals or exceeds a specified threshold for that variable for a specified number of consecutive days, for example 3 or 5 or 7 days (Colombo *et al.*, 1999). The threshold value could be either an absolute value, e.g. five consecutive days each above 30°C, or it could be a percentile, e.g. the 1st, 5th, 95th or 99th percentile value of the long term series (Groisman *et al.*, 2001; DeGaetano and Allen, 2002).

Table 2.5 Example of monthly means of daily maximum temperatures, from which suspect values were then re-analysed for any anomalies at a daily level

```
0239482_A CEDARA - AGR                        29°32' 30°17' 1134m
YEAR  JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP   OCT   NOV   DEC   ANN
1950  23.9  25.6  26.4  22.5  20.5  20.5  19.0  19.4  23.2  23.3  24.0  23.7  22.7
1951  22.5  26.3  23.9  23.3  20.2  19.4  17.8  19.4  21.2  22.5  26.7  24.8  22.3
1952  24.6  24.0  25.1  23.5  20.9  19.9  18.5  21.6  22.5  25.0  23.2  23.5  22.7
1953  25.8  24.2  23.7  23.1  22.7  19.6  19.3  19.6  21.8  24.2  24.0  24.7  22.7
1954  22.6  24.2  24.1  22.9  21.8  17.8  18.4  21.2  22.8  21.1  22.5  25.5  22.1
1955  23.6  23.9  23.4  22.5  20.6  18.3  20.0  20.2  22.8  21.1  21.0  23.8  21.8
1956  27.1  24.9  24.7  23.1  20.1  18.1  20.4  21.0  20.9  22.2  22.3  21.7  22.2
1957  26.1  26.4  23.8  21.9  21.6  18.1  19.9  20.2  21.2  22.4  25.3  25.8  22.7
1958  25.1  25.7  25.4  23.8  22.3  18.9  20.7  21.8  21.9  22.7  25.9  25.2  23.3
1959  24.7  25.0  25.4  24.4  20.1  20.4  20.2  21.1  23.7  23.4  21.9  24.0  22.9
1960  25.1  24.0  25.7  20.7  20.5  19.5  19.4  21.6  22.4  24.4  24.0  23.5  22.6
1961  26.4  26.0  24.7  22.6  20.3  19.5  19.4  19.8  23.7  22.4  22.8  23.6  22.6
1962  24.1  25.0  25.3  23.4  20.7  20.4  20.9  22.6  26.2  24.1  23.9  25.2  23.5
1963  24.2  25.6  22.3  21.8  20.4  17.9  17.3  21.0  26.0  23.9  24.1  26.8  22.6
1964  24.7  25.8  26.1  21.4  21.4  18.4  18.8  19.9  22.1  20.7  23.5  24.0  22.2
1965  24.9  26.2  26.7  22.7  21.5  16.5  19.5  21.9  22.8  21.2  21.5  25.0  22.5
1966  26.6  23.4  27.1  20.5  20.5  19.7  20.1  21.2  21.7  22.9  23.1  25.3  22.7
1967  24.7  23.6  23.4  21.5  20.6  18.5  17.4  21.4  22.5  23.3  23.9  24.8  22.1
1968  26.0  25.1  22.4  20.2  19.8  16.9  19.7  19.5  21.5  22.9  22.4  25.8  21.8
1969  28.3  27.1  23.7  21.0  19.1  18.2  19.9  22.0  20.1  22.7  23.4  24.4  22.5
1970  24.9  24.9  25.3  24.0  22.0  19.0  19.3  21.3  23.5  21.1  22.9  26.0  22.8
1971  24.6  24.1  25.2  23.8  20.0  19.2  19.2  19.9  20.3  22.7  22.7  23.9  22.1
1972  26.7  23.8  24.4  23.2  19.7  17.7  19.5  19.4  23.8  24.1  22.7  26.0  22.6
1973  24.9  24.8  25.6  20.8  19.4  19.7  19.4  19.2  20.2  22.6  22.6  24.0  21.9
1974  25.5  24.6  24.6  21.1  19.6  18.9  19.2  20.3  22.9  24.9  23.3  24.0  22.4
1975  24.2  22.9  22.6  22.6  21.2  20.1  20.0  21.2  21.2  21.5  22.0  22.7  21.9
1976  23.9  25.0  24.5  22.1  19.1  18.4  19.3  18.8  23.3  20.9  23.6  25.4  22.0
1977  25.6  26.0  23.1  24.0  20.9  20.4  19.6  19.5  23.4  23.4  23.3  26.5  23.0
1978  24.1  25.1  25.7  21.1  21.0  18.4  19.6  20.8  21.5  20.9  22.8  24.8  22.1
1979  24.5  26.7  24.4  24.2  20.6  19.1  17.3  19.8  19.8  22.4  22.9  24.3  22.2
1980  24.0  26.4  25.7  24.1  22.0  19.5  20.0  21.4  19.2  23.1  23.7  25.7  22.9
1981  26.1  23.8  24.3  24.9  20.0  18.4  19.1  18.6  19.5  22.0  25.0  24.8  22.2
1982  24.5  26.6  23.9  21.0  21.4  19.5  19.7  21.4  22.5  23.2  23.5  26.5  22.8
1983  26.1  26.2  26.3  25.4  21.9  19.9  19.4  19.3  24.2  21.5  22.3  24.9  23.1
1984  24.7  24.3  23.5  23.0  20.8  18.7  18.7  20.4  23.2  23.0  22.3  25.6  22.4
1985  27.0  25.4  24.5  24.4  20.4  20.2  19.8  23.8  23.2  24.9  24.7  24.0  23.5
1986  25.2  24.8  25.9  23.5  23.1  20.1  20.4  21.8  22.4  22.5  22.3  24.8  23.1
1987  24.5  27.7  24.7  23.8  23.6  19.0  18.8  19.3  19.6  20.5  22.9  26.0  22.5
1988  25.8  25.6  25.1  22.1  21.3  18.0  20.1  21.9  22.5  21.7  22.8  22.9  22.5
1989  24.5  23.2  25.2  22.8  21.1  18.2  18.6  24.0  22.2  21.8  21.8  25.1  22.4
1990  25.0  23.8  22.9  23.0  20.6  19.0  19.6  19.3  20.8  20.6  24.6  22.9  21.8
1991  25.9  25.4  23.3  24.7  22.1  17.6  19.9  20.9  21.7  21.2  23.5  25.3  22.6
1992  25.1  26.9  26.2  25.6  23.2  20.7  21.4  19.9  22.7  24.2  24.5  26.1  23.9
1993  26.7  25.1  25.0  23.8  22.1  19.8  21.1  21.0  24.1  21.7  23.9  24.5  23.2
1994  24.9  24.4  24.5  22.7  22.0  18.8  19.1  20.4  24.4  21.2  25.2  26.5  22.8
1995  26.1  28.5  23.8  21.0  20.3  18.3  18.8  22.8  23.7  22.4  23.7  22.8  22.7
1996  24.5  25.1  23.8  21.0  20.1  19.0  15.1  18.6  23.5  21.0  23.9  26.0  21.8
1997  24.8  25.0  23.5  21.5  18.9  18.6  17.8  21.9  20.5  22.8  21.5  24.8  21.8
1998  25.2  25.9  24.5  24.5  21.4  21.0  19.6  21.1  22.2  22.8  25.0  23.4  23.0
1999  25.9  26.0  26.7  24.5  22.1  20.9  21.6  22.6  23.5  23.3  25.3  25.2  24.0
2000  23.2  25.8  24.0  20.5  17.8  19.6  19.4  22.5  22.3  22.0  22.2  24.6  22.0
```

2.4.1 Simple statistics

Simple statistics that can be used include the mean, median, standard deviation and range. Other simple statistics include counts of days above pre-specified thresholds, for example, the number of days per year or month with daily maximum temperature above 40°C (Osborn *et al.*, 2000). These simple statistics are, in themselves, insufficient to determine trends in data, but they form a starting platform for more detailed analyses.

2.4.2 Moving averages

Time series data can be represented graphically in a line diagram, but often the only striking feature of such a representation is the very erratic behaviour of the observations in relation to time. A moving average is a method used to clarify any inherent patterns in a time series by smoothing the erratic behaviour (Anderson, 1989).

A moving average is obtained when a single observation is replaced by the mean of a number of observations centred on the observation in question (Anderson, 1989). For example, the 5-year moving average of a time series of maximum mean annual temperature for station 0317447_A in South Africa from 1980 to 2000 is shown in Table 2.6. Figure 2.3 demonstrates the smoothing effect of using a moving average.

Naturally some data points at the beginning and end of the time series are lost by the moving average technique, but this may not be of great importance in a long time series. The number of observations used to produce each average is a matter of judgement. If the period is too short, little smoothing will be achieved. If the period is too long, meaningful irregularities may be flattened out to an almost meaningless near-straight line, and there will be considerable gaps of data usage at each end of the series (Anderson, 1989). For example, King'uyu *et al.* (2000) used a 5-year moving average to smooth out trends in an inter-annual temperature time series. Genta *et al.* (1998) used a 30-year moving average to smooth variability in climatic records, while Bobba and Diiwu (2001) used a 10-year moving average to identify trends in meteorological time series.

Table 2.6 Time series of annual means of daily maximum temperature from 1980-2000 for station 0317447_A and the 5-year moving average of the annual means of daily maximum temperatures

Year	Temperature (°C)	5-year Moving Average (°C)	Year	Temperature (°C)	5-year Moving Average (°C)
1980	28.47		1990	28.00	27.88
1981	27.58		1991	27.66	27.99
1982	28.39	28.24	1992	28.43	28.15
1983	28.17	28.23	1993	28.53	28.22
1984	28.60	28.44	1994	28.14	28.06
1985	28.41	28.48	1995	28.33	27.99
1986	28.61	28.45	1996	26.86	27.99
1987	28.63	28.20	1997	28.09	27.98
1988	28.00	28.11	1998	28.55	27.82
1989	27.32	27.92	1999	28.08	
			2000	27.50	

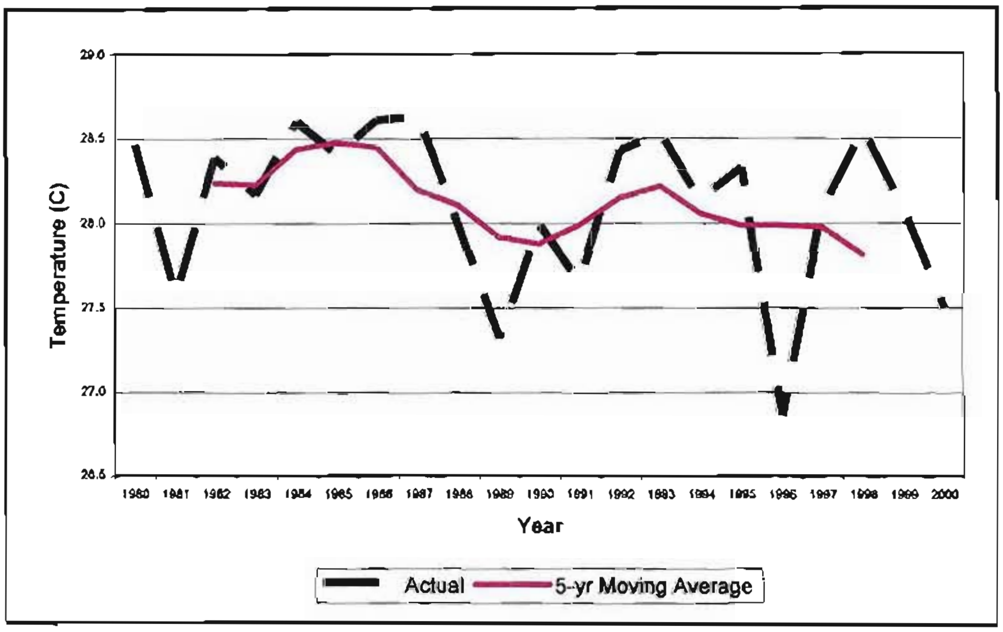

Figure 2.3 Actual annual means of daily maximum temperature for station 0317447_A and the 5-year moving average of the same temperature series, demonstrating the smoothing effect of using a moving average

Moving averages provide a simple technique of smoothing out erratic behaviour in a time series. This allows a trend to be identified graphically. However, the magnitude of the trend is not determined, nor is it possible to determine whether or not it is statistically significant. Hence, moving averages provide a starting platform only for further trend analysis.

2.4.3 Linear Regression

The simplest form of regression is simple linear regression, which is used to model the relationship between one response (or dependent) variable 'y' and one predictor (or explanatory) variable 'x'. The aim is to use the explanatory variable to predict and describe 'y'. It is assumed that the relationship between 'x' and 'y' is linear. The model is:

$$y_i = \beta_0 + \beta_1 x_1 + \varepsilon_1 \qquad \text{......... (2.1)}$$

where

y_i = the value of the response variable of the *i-th* observation,

β_0 = the intercept of the regression line,

β_1 = the slope of the regression line,

x_i = the value of the explanatory variable of the *i-th* observation, and

ε_i = the error term associated with the *i-th* observation.

Easterling (2002) fitted simple linear regression equations to time series of the number of frost days per year to examine trends in the data from the USA. Akinremi *et al.* (1999) used simple linear regression analysis to establish linear trends in precipitation amounts, number of precipitation events and variance of precipitation for the Canadian prairies.

In order to evaluate trends in meteorological variables, Bobba and Diiwu (2001) used another form of regression, *viz.* Robust Locally Weighted Regression (RLWR). The RLWR technique combines locally weighted regression with polynomial smoothing. The technique involves determination of the order of the polynomial to be fitted locally to each point of the scatter plot, the weighting functions to be used at each point of the scatter plot, and the number of iterations to be performed in the fitting procedure. The closest neighbours of each point are assigned the least weights. This minimises the effects of outliers on the fitted curve. At each point the polynomial to be fitted is of the general form (Bobba and Diiwu, 2001):

$$y_k = \beta_0 + \beta_1 x_k + \beta_2 x_k^2 + \ldots + \beta_d x_k^d \qquad \text{......... (2.2)}$$

where

β_i = parameters to be determined by weighting least squares, $w_k(x_i)$, at each point (x_k, y_k).

i = i th value

Frei and Schar (2001) used logistic linear regression to estimate and test long-term trends in count records of meteorological variables. Logistic regression is a specialised case of a formal generalisation of linear regression concepts. The logistic trend model expresses a transformed form of the expected value of counts (or, equivalently, the event probability) π as a linear function of time:

$$\eta(\pi) = \alpha + \beta \times t \qquad \text{......... (2.3)}$$

where

t = time (year of the period)

α, β = the regression intercept and coefficient to be estimated from the data, and

η = the prescribed monotonic link function (Frei and Schar, 2001).

The essence of a link function is to provide a transformation from the value range $\pi\varepsilon[0;1]$ onto the real axis, in order to ensure compatibility with the linear model. The link function in this case is:

$$\eta(x) = \log it(x) = \log\left[\frac{x}{1-x}\right] \qquad \text{......... (2.4)}$$

Therefore,

$$\pi(t,\alpha,\beta) = \exp\frac{(\alpha+\beta+t)}{[1+\exp(\alpha+\beta\times t)]} \qquad \text{......... (2.5)}$$

The magnitude of the trend, as given by the model parameter β, is expressed as the odds ratio, θ, *viz.*

$$\theta = \frac{\left[\pi(t_2) \big/ 1-\pi(t_2)\right]}{\left[\pi \big/ t_1 \big/ 1-\pi(t_1)\right]} = \exp[\beta(t_2 - t_1)] \qquad \text{......... (2.6)}$$

The odds ratio, according to Frei and Schar (2001), represents the relative change in the ratio of the events against non-events during the period (t_1, t_2).

2.4.4 The Mann-Kendall Non-Parametric Test

Fitting a linear relationship line to data determines the slope of the trend. However, in the case of a time series in which data are distributed non-normally, it is valid to supplement a linear regression model with a non-parametric model to assess the significance of the trend, because a non-parametric model makes no assumptions regarding the data distribution (Suppiah and Hennesy, 1998). Both the Spearman Rank Correlation and Mann-Kendall test are examples of non-parametric models. The Mann-Kendall test will be discussed here.

The Mann-Kendall test is a simple rank-based procedure suitable for non-normally distributed data, censored data, or non-linear trends (Bobba and Diiwu, 2001; Molnar and Ramirez, 2001). The test is used to determine whether a time series is moving upward, downward or remaining relatively constant over time. In order to accomplish this, a statistic based on all possible data pairs is computed. This statistic represents the net direction of movement of the time series. All possible differences $(x_i - x_j)$ are calculated, where x_j precedes x_i in time. This difference is either positive if $x_i > x_j$, negative if $x_i < x_j$, or zero $x_i = x_j$, for each of the pairs. The number of positive differences minus the number of negative differences is then calculated. This becomes the Mann-Kendall test statistic S (Bobba and Diiwu, 2001).

Stated in statistical terms, the null hypothesis of randomness, H_0, states that the data $(x_1, x_2, \ldots\ldots, x_n)$ are a sample of n independent and identically distributed random variables. The alternative hypothesis, H_1, states that the distributions of x_i and x_j are not identical for all $i, j, \leq n$ with $i \neq j$ (Molnar and Ramirez, 2001). The test statistic is defined as:

$$S = \sum\sum Sgn\left(x_i - x_j\right) \qquad \ldots\ldots\ldots (2.7)$$

where Sgn ( ) is the sign function.

$$Sgn(\theta) = \begin{cases} 1 & \text{, if } \theta > 0 \\ 0 & \text{, if } \theta = 0 \\ -1 & \text{, if } \theta < 0 \end{cases} \qquad \ldots\ldots\ldots\ldots (2.8)$$

$$\varepsilon(S) = 0 \qquad \ldots\ldots\ldots\ldots (2.9)$$

$$Var(S) = \frac{n(n-1)(2n+5)}{18} \quad \text{......... (2.10)}$$

If S has an approximate normal distribution, then the test statistic z is,

$$z = \begin{cases} (S-1)/(Var(S))^{0.5} & , \text{if } S > 0 \\ 0 & , \text{if } S = 0 \\ (S+1)/(Var(S))^{0.5} & , \text{if } S < 0 \end{cases} \quad \text{......... (2.11)}$$

where z is the value of the standard normal variate with zero mean and unit standard deviation (Bobba and Diiwu, 2001; Brunetti *et al.*, 2001; Molnar and Ramirez, 2001).

In a two-sided test for trend, the null hypothesis is rejected at significance level α if $|z| > z_{(1-\alpha/2)}$, where $z_{(1-\alpha/2)}$ is the value of the standard normal distribution with a probability of exceedance of $\alpha/2$. A positive value of z indicates an upward trend; a negative value indicates a downward trend in the tested time series (Molnar and Ramirez, 2001).

The Mann-Kendall test was chosen to analyse the temperature records as it is a simple statistical test of trend that is not affected by non-normally distributed data. It was chosen as it can be applied to a time series and as it assumes the sign values are not skewed by extreme events. Thus the Mann-Kendall test is considered an appropriate statistical test for trend and is complemented by linear regression, which is used to determine the magnitude of the trend. However, for analysis of observed rainfall and simulated streamflow, a split-sample analysis was used as the large number of 'zero' values influenced the Mann-Kendall test.

3. RESULTS OF AN ANALYSIS OF TRENDS IN SOUTHERN AFRICAN TEMPERATURE DATA

The temperature stations included in this analysis were those from South Africa, Lesotho and Swaziland which had an actual record length of 20 years or longer and were not infilled using Fourier Analysis. Using procedures described in Section 2.3.2 of Chapter 2, those stations which required it, had their records extended to a common base period from 1950 – 2000 and any missing and/or poor quality data were infilled. This elimination process resulted in 209 temperature stations, each with 51 years of daily data, being available for analysis of trends.

Two different forms of identifying changes in the temperature records at southern African stations were used. In the first analysis, the Mann-Kendall test was used to detect trends in the temperature data. Given the changes already identified in the global mean temperature (IPCC, 2001), the initial step of this regional temperature change analysis was to evaluate whether any changes in means are evident. Therefore, the Mann-Kendall test was used to detect whether any trends had occurred in the annual means of minimum and maximum temperatures, the summer means of maximum temperatures and the winter means of minimum temperatures. Besides changes in means, it is hypothesised that the extreme ends of temperature distributions will change under conditions of global warming. To detect whether changes in the extremes of temperatures were evident as yet for South Africa, the Mann-Kendall test was used to detect trends in:

- the number of days in winter (i.e. June, July and August) below the 10th percentile of winter minimum temperatures
- the number of occurrences of 3 consecutive days in winter below the 10th percentile of winter minimum temperatures
- the number of days in summer (i.e. December, January and February) above the 90th percentile of summer maximum temperatures
- the number of 3 occurrences of consecutive days in summer above the 90th percentile of summer maximum temperatures
- the number of 3 occurrences of consecutive days below thresholds of -2.5°C, 0°C, 2.5°C, 5°C, 7.5°C and 10°C

- the number of 3 occurrences of consecutive days above thresholds of 20°C, 25°C, 30°C, 35°C and 40°C
- the number of frost occurrences per season
- the first frost date and last frost date, and
- Heat Units and Positive Chill Units (defined in Section 3.7 and 3.8 respectively)

Only trends at a 95% confidence level were considered to be significant and, thereby, indicative of a significant change in that temperature station's record. The percentile thresholds were calculated using the temperature records from 1950 –2000.

In the second type of analysis, two relatively short 21 year periods of data, namely 1950 – 1970 and 1980 – 2000, were extracted from the 51 year record period. The later period was compared to the earlier period for:

- annual means of daily maximum and minimum temperature
- summer means of daily maximum temperature
- winter means of daily minimum temperature, and
- coefficients of variation of daily maximum and minimum temperature

to determine if any warming (or cooling) was evident between the two relatively short periods, or if temperature had become more variable.

The results from each of the above-mentioned analyses are discussed below. In each of the figures which follow, the expected outcome under climate change conditions is indicated by a red triangle at a station's location if the trend is statistically significant at the 95% confidence level, while the opposite outcome (i.e. a significant trend, but the reverse to what is expected under global warming) is indicated by a blue square, and a green circle indicates that no statistically significant trend was detected at the 95% confidence level. The shading shown in the figures has no statistical significance; it is a by-eye grouping of stations with a significant trend in the direction expected under climate change conditions. Figure 3.1 shows the study area, *viz.* South Africa, Lesotho and Swaziland. The provinces of South Africa, which are referred to in the discussion of the results, are also labelled.

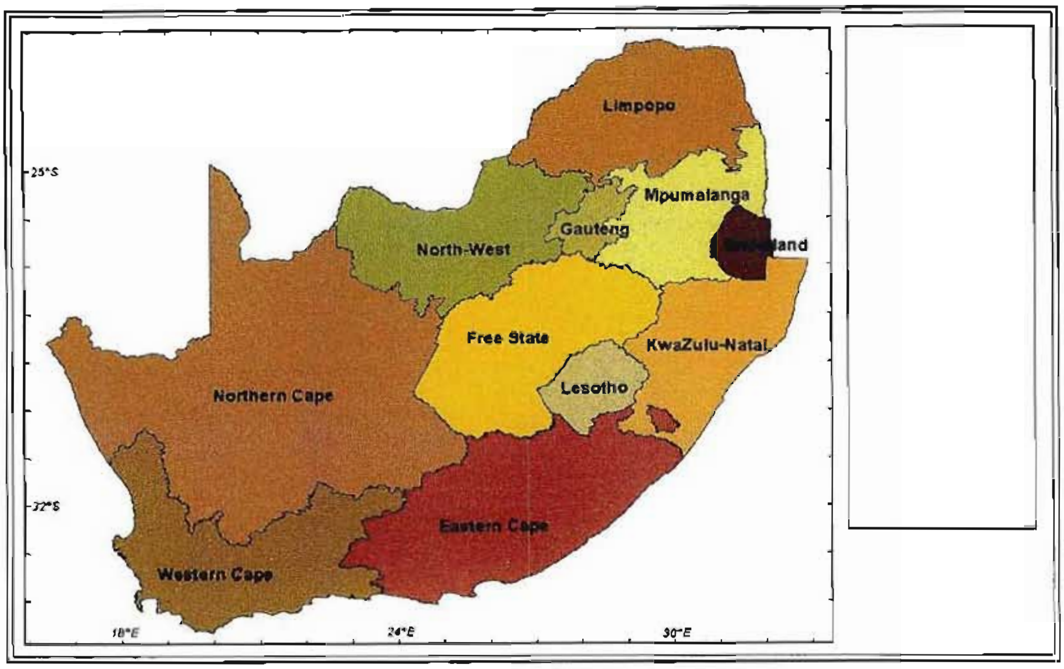

Figure 3.1 South Africa, with provinces labelled, as well as Lesotho and Swaziland

3.1 Trends in Annual Means of Daily Minimum and Maximum Temperatures

Under conditions of climate change it is hypothesised that the annual means of daily maximum temperatures would increase. Shown in Figure 3.2 are the results from the trend analysis of annual means of daily maximum temperature. As may be seen from the shaded areas, there is a scattering of locations which show an increasing trend across the region. In particular, a cluster of stations in the southeast of the Western Cape shows an increasing trend. Furthermore, a large proportion of the stations in the Eastern Cape, Northern Cape and Free State show a trend over time.

Figure 3.3 displays the results of the trend analysis of annual means of daily minimum temperature. Under climate change conditions it is hypothesised that minimum temperatures would increase. Two clusters of stations in Figure 3.3, the first in the Western Cape and the second along the KwaZulu-Natal coast and midlands area, indicate distinct areas of warming. Another grouping of stations with an increasing trend is evident in the Gauteng/Free State areas. It is important to note that a few stations show a cooling trend, one of these stations being a Lesotho station with questionable data.

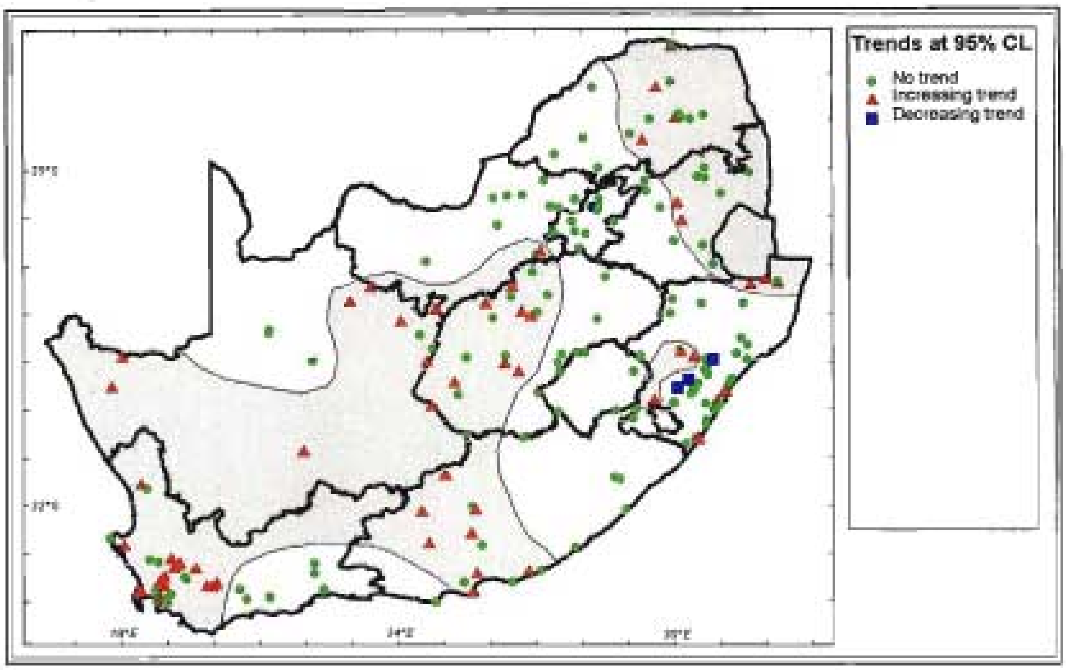

Figure 3.2 Trends over southern Africa at the 95% confidence level in the time series of annual means of daily maximum temperatures

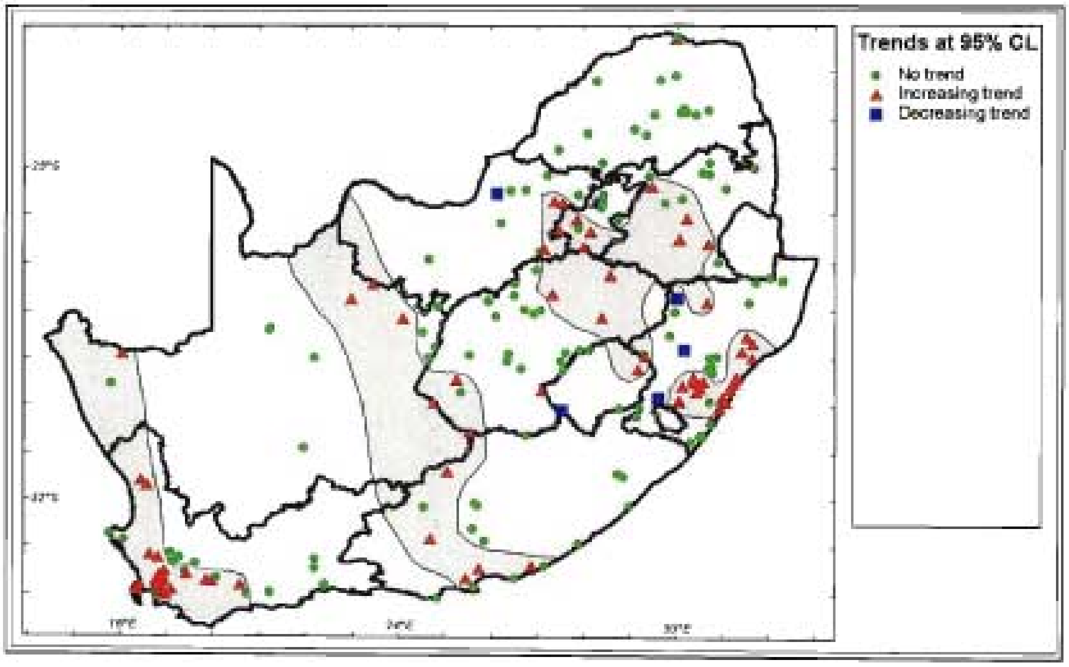

Figure 3.3 Trends over southern Africa at the 95% confidence level in the time series of annual means of daily minimum temperatures

3.2 Trends in Summer Means of Daily Maximum Temperatures

For this analysis of a southern hemisphere region, summer is defined as the months of December, January and February. These are the warmest months of the year in South Africa (Schulze, 1997a). In order to determine whether an increasing trend in maximum temperatures could be detected, as expected under climate change conditions, data for these months were analysed collectively. A clear band of stations along the KwaZulu-Natal coast shows significant warming trends (Figure 3.4). A group of stations between the Eastern and Northern Cape, as well as a small group of stations in the Western Cape, show a statistically significant warming trend. It is interesting to note that no stations in the interior provinces of Gauteng, Free State, North-West and Northern Province display statistically significant trends in summer means of daily maximum temperature.

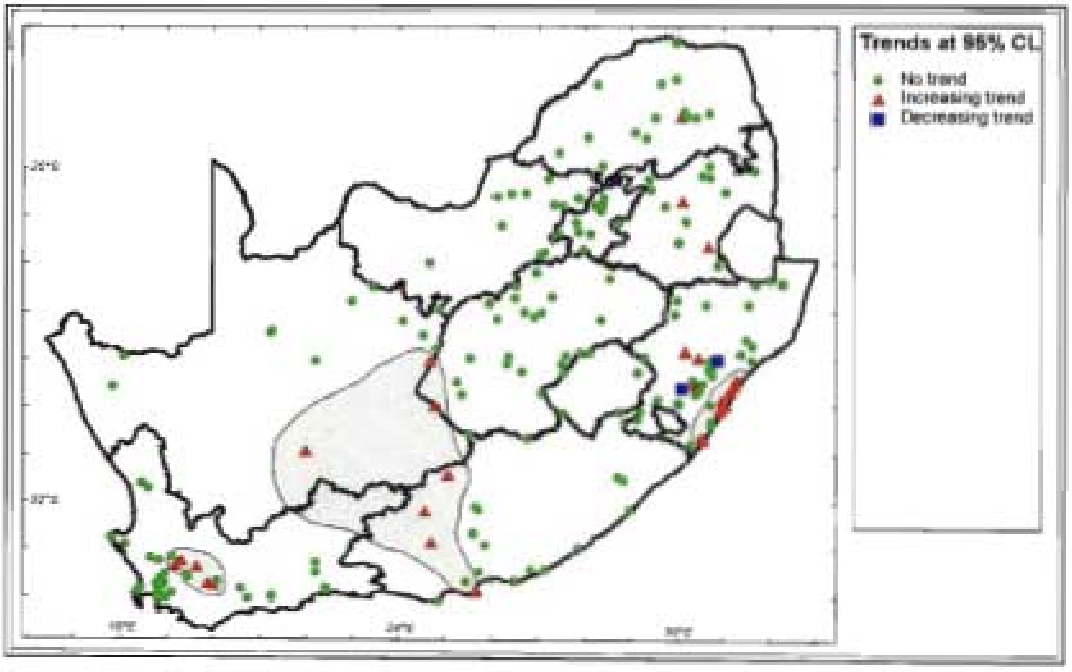

Figure 3.4 Trends over southern Africa at the 95% confidence level in the time series of summer (December, January and February) means of daily maximum temperatures

3.3 Trends in Winter Means of Daily Minimum Temperatures

The coldest months of the year over South Africa are June, July and August (Schulze, 1997a); thus for this analysis winter is defined as being these three months. As may be seen in Figure 3.5, the pattern of warming is very different to the analysis of summer maximum temperatures. For winter means of daily minimum temperatures a large number of stations over the interior of the country show warming trends. In particular, a large percentage of stations in the Free State, Northern Cape, Mpumalanga and North-West provinces show statistically significant warming trends. In KwaZulu-Natal for winter means of minimum temperatures a cluster in the interior north and west of the province show statistically significant warming.

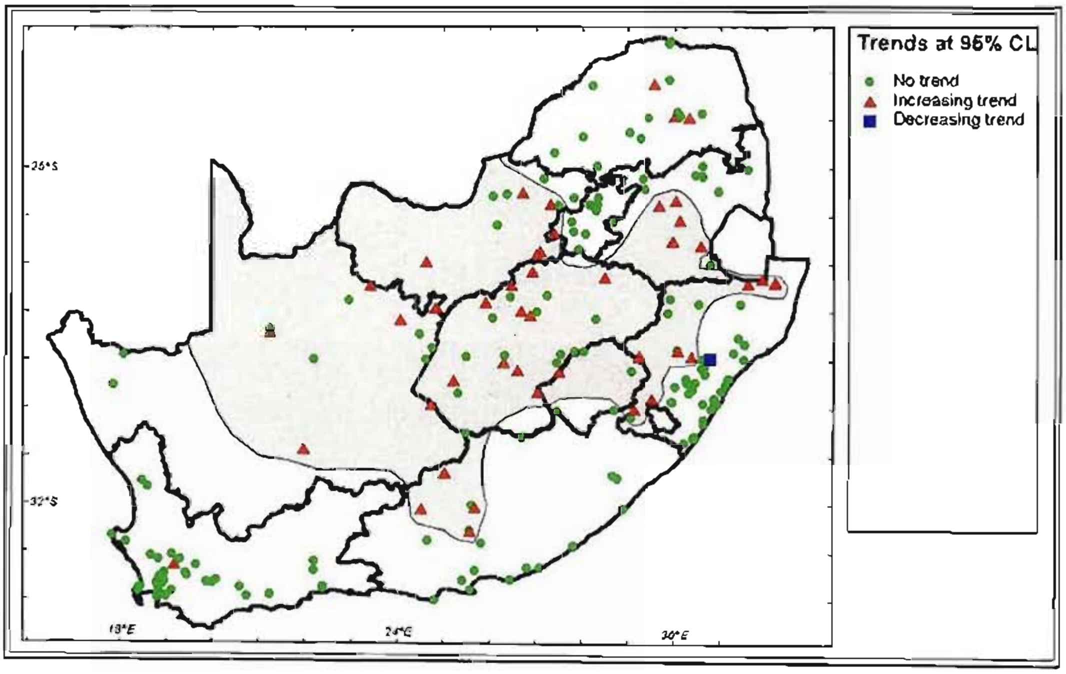

Figure 3.5 Trends over southern Africa at the 95% confidence level in the time series of winter (June, July, August) means of daily minimum temperatures

3.4 Trends in Occurrences of Temperatures Above/Below Selected Percentiles

With climate change it is believed that temperatures at the extremes of occurrences will change. In order to examine this hypothesis, trends in the number of days above and below selected percentiles were analysed. Taking the common 51 year period of daily temperature values, records for the winter months were extracted and the 10th percentile of daily minimum temperatures was calculated for the entire record length at a station. Following this, the number of days per winter season below the overall 10th percentile was calculated, as was the number of occurrences of three consecutive days per winter season below the 10th percentile of minimum temperatures.

Figure 3.6 shows the spatial distribution of the results of the trend analysis of the number of days below the 10th percentile and Figure 3.7 shows the trend analysis results of the number of occurrences of three consecutive days below the 10th percentile of winter minimum temperatures.

Under climate change conditions the number of these events is expected to decrease. A cluster of stations in the southeast of the Western Cape shows statistically significant decreasing trends for both single and three consecutive days below the 10th percentile. A band of stations through the Northern Cape and Eastern Cape show decreasing trends in the number of days below the 10th percentile. This same pattern is evident for three consecutive days below the 10th percentile; however, the band is smaller in spatial extent. A number of stations in KwaZulu-Natal display a statistically significant decreasing trend in number of days below the 10th percentile, but with fewer stations with three consecutive days displaying the same trend. What is important to note is that there are stations in the Western Cape and KwaZulu-Natal that display statistically significant increasing trends in both single days and occurrences of three consecutive days below the 10th percentile of winter minimum temperatures.

These results suggest that at a number of locations extremes of minimum temperatures may be reducing while at other locations minimum temperatures may be becoming more extreme.

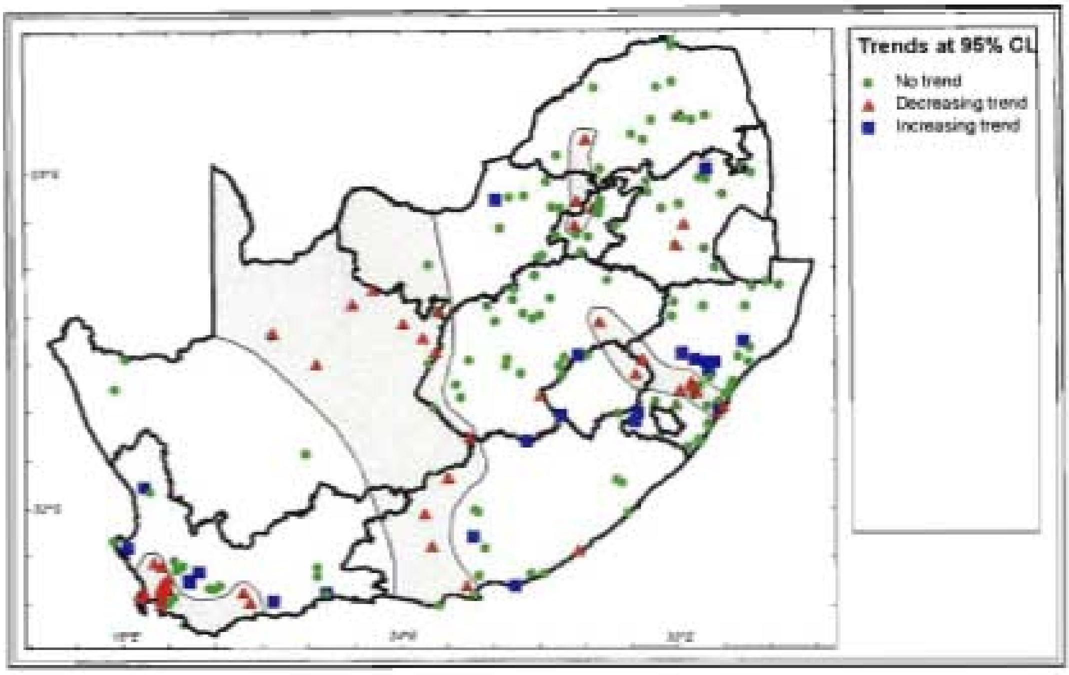

Figure 3.6 Trends over southern Africa at the 95% confidence level in the time series of the number of days per year below the 10th percentile of winter (June, July, August) daily minimum temperatures

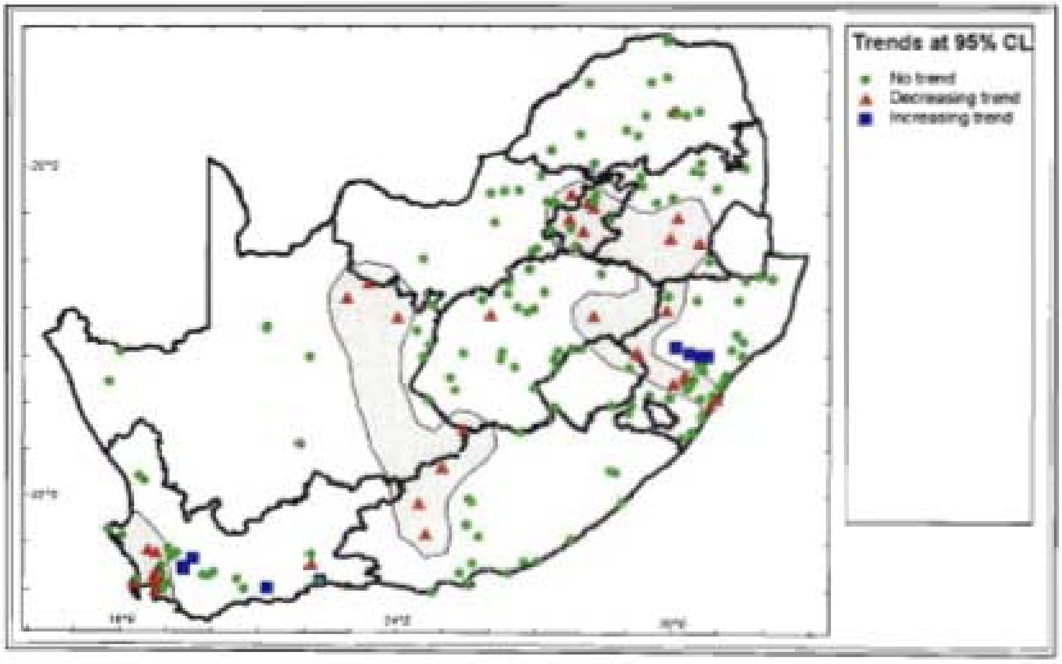

Figure 3.7 Trends over southern Africa at the 95% confidence level in the time series of number of occurrences of three consecutive days per winter season (June, July, August) below the 10th percentile of winter daily minimum temperatures

After evaluating minimum temperature trends at their extremes, the next step was to assess maximum temperatures at their extremes. Therefore, the 90th percentile of summer (i.e. December, January and February) daily maximum temperatures was calculated for the entire 51 year record at each station, and trends in the number of days and number of occurrences of three consecutive days above the 90th percentile were analysed.

Figure 3.8 displays the results of the time trend analysis of number of days with maximum temperatures above the 90th percentile spatially across South Africa, Lesotho and Swaziland. Under climate change conditions the number of these events is expected to increase. As may be seen in Figure 3.8, a large percentage of stations in the Western Cape and Eastern Cape show a statistically significant increasing trend in maximum temperatures exceeding the 90th percentile, as do stations in a distinct band along the KwaZulu-Natal coast, with a few stations in the Free State and Northern Cape also displaying an increasing trend.

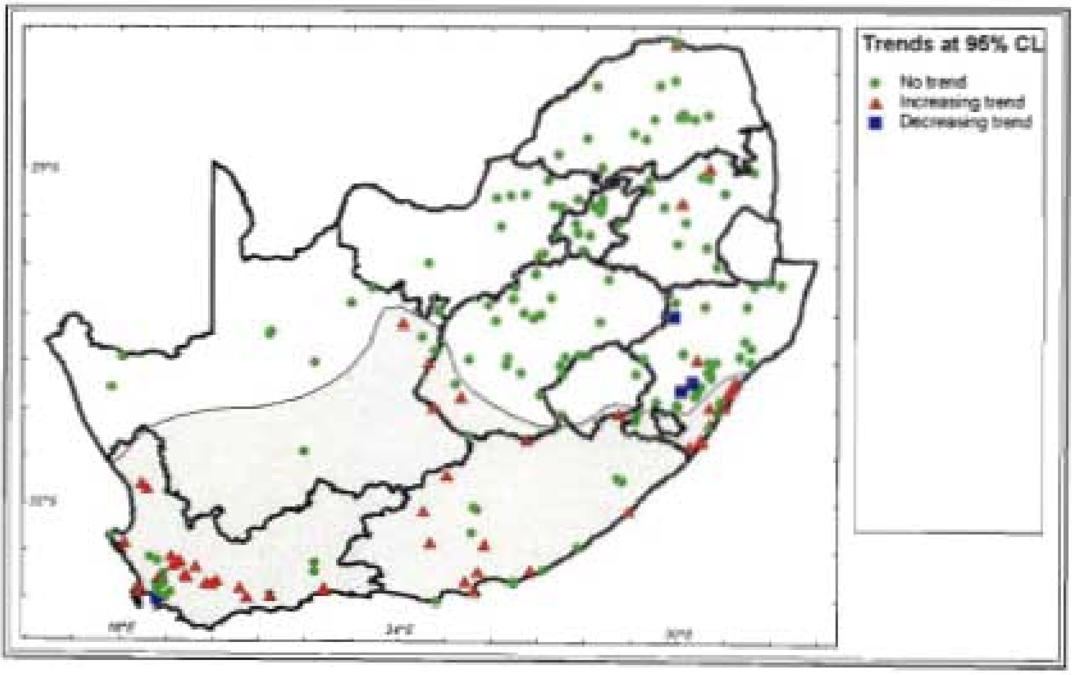

Figure 3.8 Trends over southern Africa at the 95% confidence level in the time series of number of days per year above the 90th percentile of summer (December, January, February) daily maximum temperatures

Figure 3.9 shows the trends in the number of occurrences of three consecutive days above the 90th percentile of summer month maximum temperatures. As may be seen, far fewer stations' records display an expected increasing trend over time, with those displaying a statistically significant trend located in the Western and Eastern Cape in a rather random scatter.

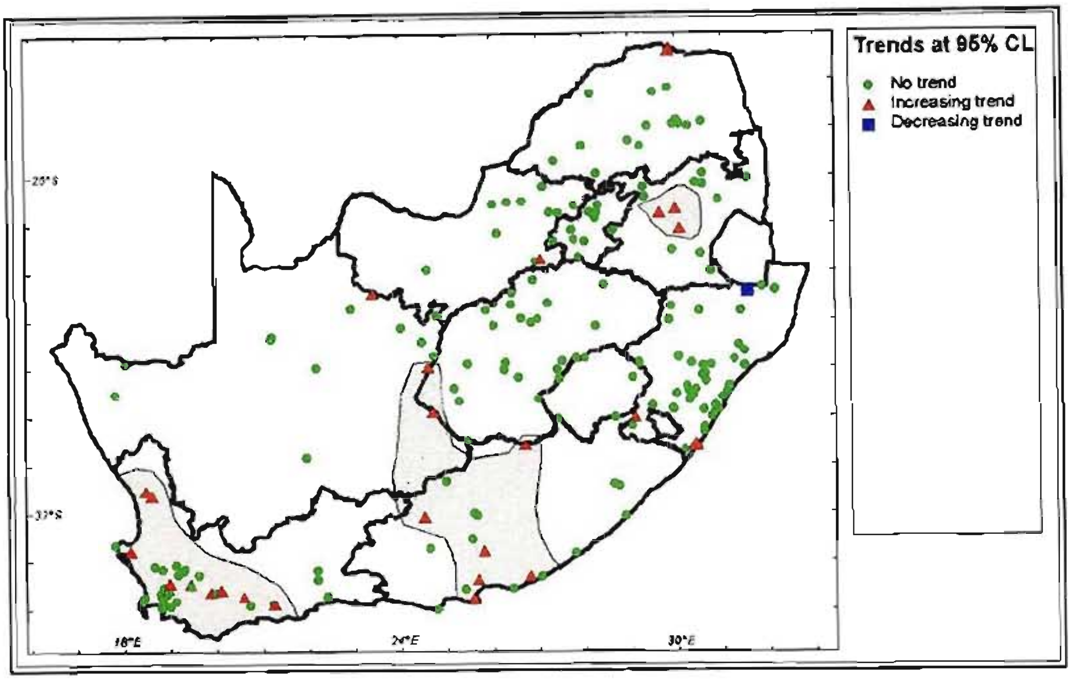

Figure 3.9 Trends over southern Africa at the 95% confidence level in the time series of number of occurrences three consecutive days per year above the 90th percentile of summer (December, January, February) daily maximum temperatures

3.5 Trends in the Number of Days Above/Below Predefined Temperature Thresholds

Temperature thresholds of -2.5°C, 0°C, 2.5°C, 5°C, 7.5°C, 10°C, 20°C, 25°C, 30°C, 35°C and 40°C were chosen, and trend analyses performed on the number of occurrences of three consecutive days above or below the thresholds. This analysis was designed to complement the percentile analysis in Section 3.4 in which changes in temperatures at the extremes of their distribution were investigated. Under climate change it is hypothesised that the means of temperatures will increase over time.

Therefore, it could be argued that temperature values at the 10th and 90th percentiles will increase over time. A threshold value is independent of the temperature dataset and thus may be a more objective analysis of trends in temperature at their extremes. The disadvantage of time trend analysis based on threshold temperatures compared to a percentile value is that the threshold is an arbitrary selected value, with no consideration given to an individual station's location or quality of record.

Following a preliminary analysis, the lower thresholds of -2.5°C and upper thresholds of 35°C and 40°C were disregarded as too few of these events occurred in southern Africa. Additionally, the threshold of 20°C was also disregarded as too many of these events occurred. For this analysis a new symbol is used in the figures. A black circle indicates that the station record does not exceed that specified threshold in the entire 51 years and therefore did not qualify for analysis.

Figure 3.10 depicts spatially the results of the time trend analysis of the number of occurrences of three consecutive days with minimum temperatures below 0°C. Under conditions of climate change the number of these events is expected to decrease. A large proportion of stations in Gauteng display a statistically significant decreasing trend. A scattering of stations throughout the Mpumalanga, Northern and Eastern Cape provinces also show decreasing trends in the number of three consecutive days with minima below 0°C, while a few stations in KwaZulu-Natal in fact show a statistically significant increasing trend of this temperature parameter.

Trends in the number of occurrences of three consecutive days with minimum temperatures below 2.5°C are shown in Figure 3.11. A distinct cluster of stations in the Western Cape shows a statistically significant decreasing trend, as does a grouping of stations from Mpumalanga/Gauteng, through the Free State into KwaZulu-Natal. A further scattering of stations with a decreasing trend is identified in the Northern and Eastern Cape, as well as in the Free State. In the Western and Eastern Cape, and KwaZulu-Natal, a few stations with a statistically significant increasing trend occur.

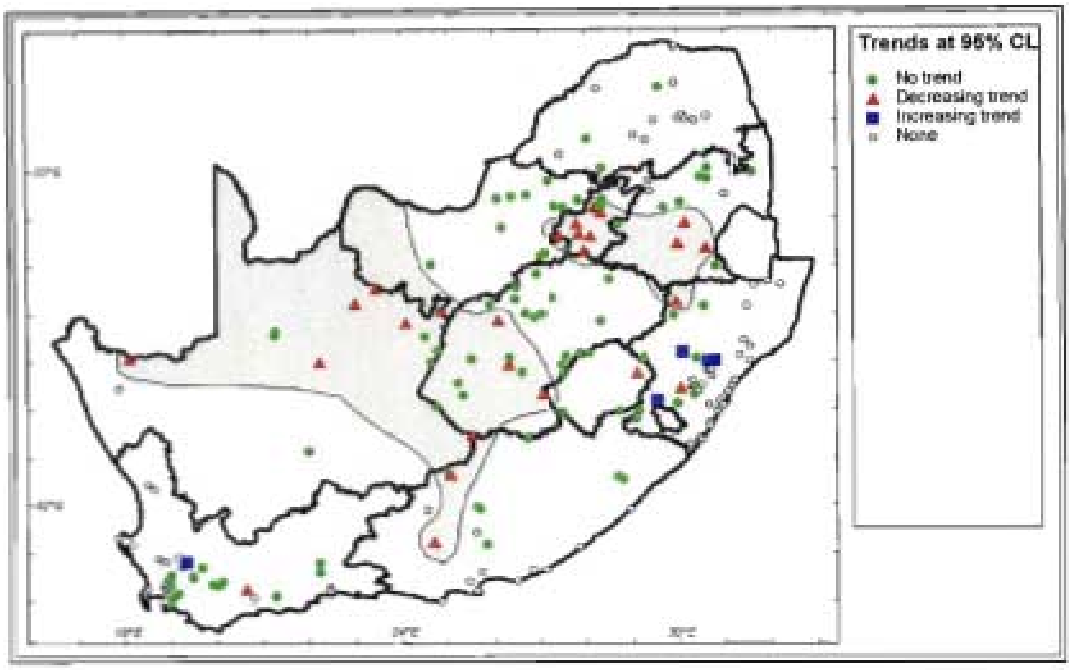

Figure 3.10 Trends over southern Africa at the 95% confidence level in the time series of number of occurrences of 3 consecutive days per year with minimum temperatures below 0°C

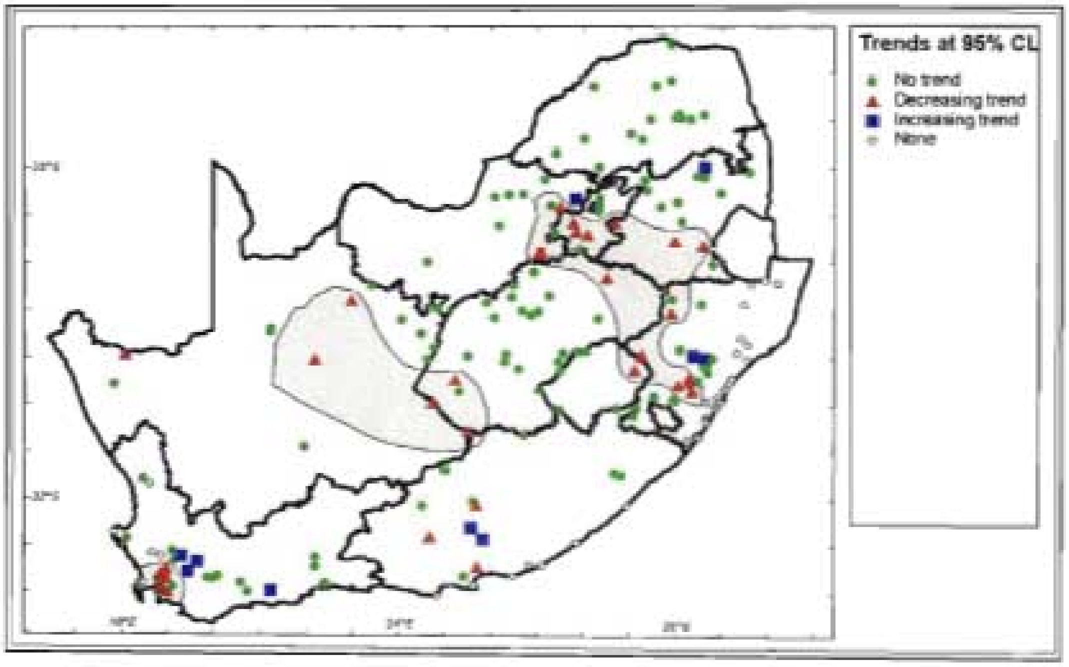

Figure 3.11 Trends over southern Africa at the 95% confidence level in the time series of number of occurrences of 3 consecutive days per year with minimum temperatures below 2.5°C

Under climate change conditions the number of occurrences of three consecutive days with minimum temperatures below 5°C is, once again, hypothesised to decrease. The results of the time trend analysis for this threshold are shown in Figure 3.12. In comparison to the threshold analysis at 2.5°C, the cluster of stations in the Western Cape showing a decreasing trend of minimum temperatures below 5°C has increased, as has the number of stations in KwaZulu-Natal. Fewer stations in Gauteng display a decreasing trend, and this could be due to a threshold of 5°C being a near-everyday occurrence in those areas (cf. Schulze, 1997a). A scattering of stations in the Free State province show a decreasing trend. Still present, however, are a few stations in the Western Cape, Eastern Cape and KwaZulu-Natal which display a statistically significant increasing trend.

Figure 3.13 displays the results of the time trend analysis for the number of occurrences of three consecutive days with minimum temperatures below 7.5°C. As with a threshold of 5°C, a large number of stations in the Western Cape and KwaZulu-Natal show statistically significant decreasing trends, as would be expected with global warming. The cluster in the midlands area of KwaZulu-Natal is, in particular, very distinct. A scattering of stations in the Free State and Mpumalanga provinces show statistically significant decreasing trends in the number of occurrences of three consecutive days with minimum temperatures below 7.5°C. No stations in Gauteng show any trend, possibly attributable to a threshold of 7.5°C being a near-everyday occurrence (i.e. it is not an 'extreme' event).

The last 'cold' threshold analysed was the number of occurrences of three consecutive days with minimum temperatures below 10°C (Figure 3.14). Immediately evident again are the clusters of stations in the Western Cape and KwaZulu-Natal provinces, showing statistically significant decreasing trends, as would be hypothesised to occur under conditions of climate change. A scattering of stations throughout the rest of the region shows a decreasing trend. In the colder areas of southern Africa, the stations' records display no trend, as a 10°C threshold is too common a minimum temperature (cf. minimum temperature maps for winter months in Schulze, 1997a).

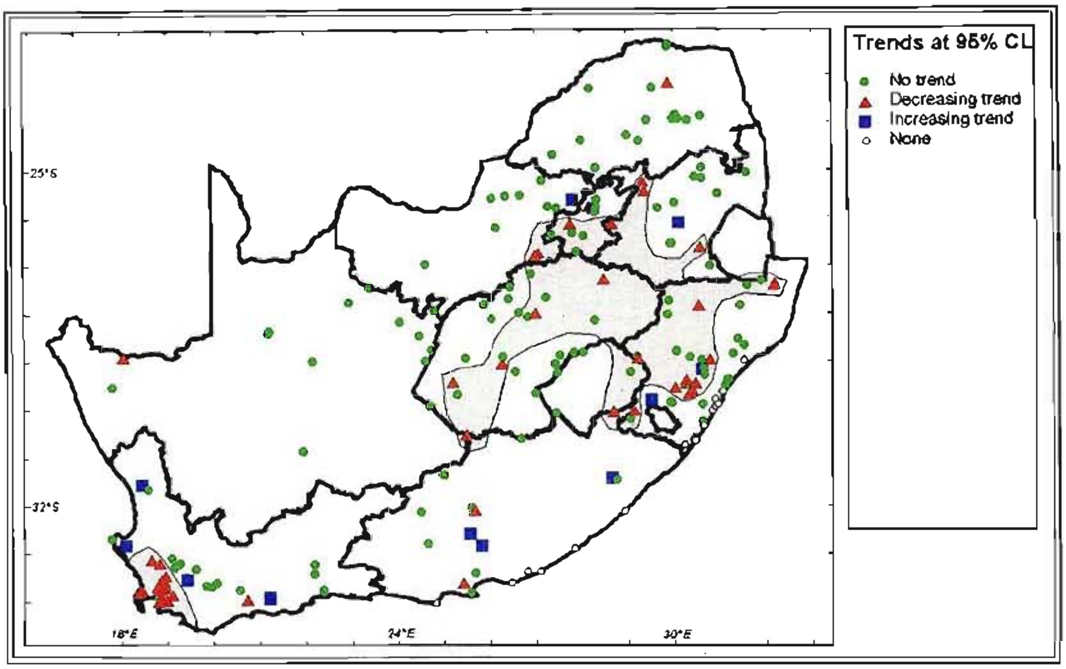

Figure 3.12 Trends over southern Africa at the 95% confidence level in the time series of number of occurrences of 3 consecutive days per year with minimum temperatures below 5°C

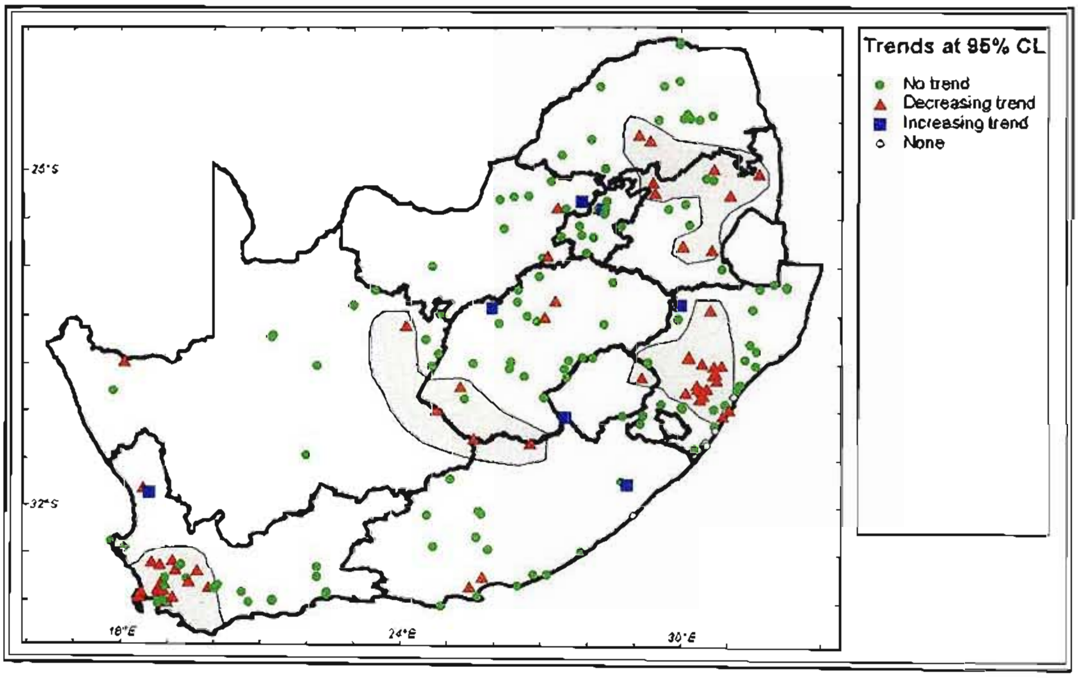

Figure 3.13 Trends over southern Africa at the 95% confidence level in the time series of number of occurrences of 3 consecutive days per year with minimum temperatures below 7.5°C

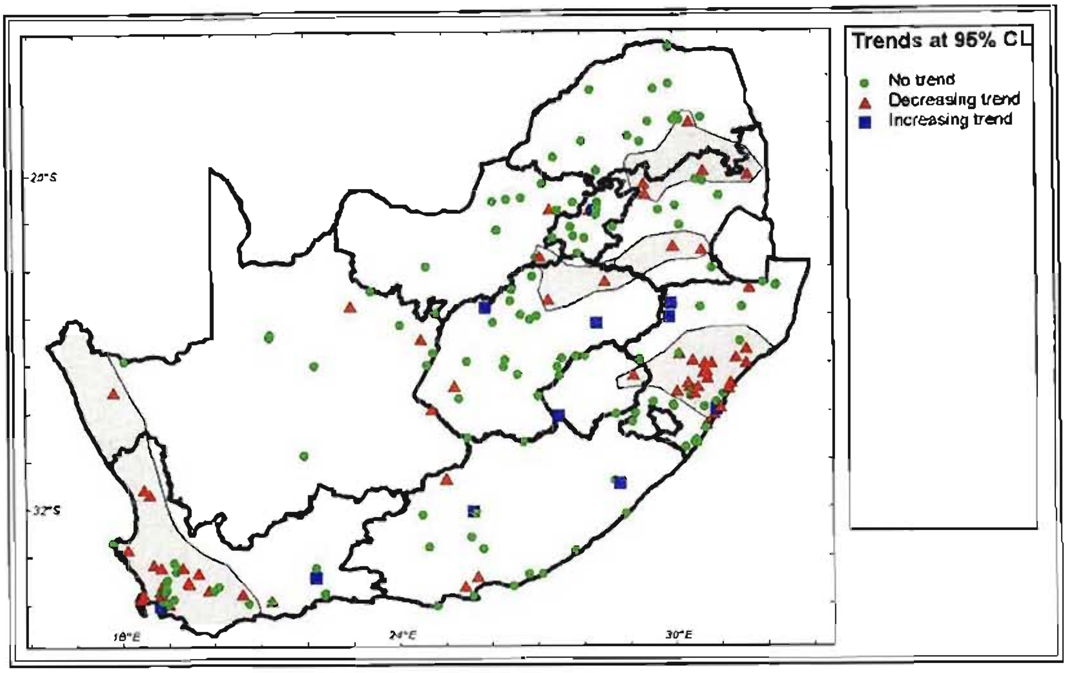

Figure 3.14 Trends over southern Africa at the 95% confidence level in the time series of number of occurrences of 3 consecutive days per year with minimum temperatures below 10°C

A comparison of Figure 3.10 to 3.14 shows that there are stations in several areas exhibiting a decrease in the more extreme low temperature events. As the thresholds of minimum temperatures change, so do the spatial patterns of stations which exhibit a statistically significant decreasing trend in number of occurrences below the threshold. At the lower thresholds the colder areas of the region display warming trends when consecutive days below selected minimum temperatures are analysed, e.g. at 0°C, but as the threshold increases the trends shift to the warmer areas, with colder areas then displaying no warming trend. From a threshold of three consecutive days with minimum temperatures below 2.5°C an increasing number of stations showing a statistically significant increasing trend in the number of three days consecutive days above threshold through to a threshold of 10°C. The Western Cape clearly shows a decreasing trend of statistical significance in 'extreme' cold temperature events. Similarly, KwaZulu-Natal emerges as a province which is experiencing a decreasing trend in the number of 'extreme' cold temperature events as well, as would be expected if global warming is already occurring.

The occurrence of 'extremes' in warm temperature events was considered next. The two threshold temperatures analysed were daily temperature maxima above 25°C and 30°C. Under conditions of climate change the number of occurrences of three consecutive days above these thresholds is hypothesised to increase. Figure 3.15 shows spatially the results of the trend analysis for the number of occurrences of three consecutive days with temperature maxima above 25°C, and in Figure 3.16 the results for the threshold of 30°C are presented. For both thresholds very few stations show any trend. The one exception is a band of stations along the KwaZulu-Natal coast and a cluster in northern KwaZulu-Natal which display a statistically significant increasing trend for the number of occurrences of three consecutive days with maxima above 25°C. These results do not indicate that the more 'extreme' warm temperatures events are not changing, as it may well be that the chosen thresholds were incorrect in relation to the temperature records.

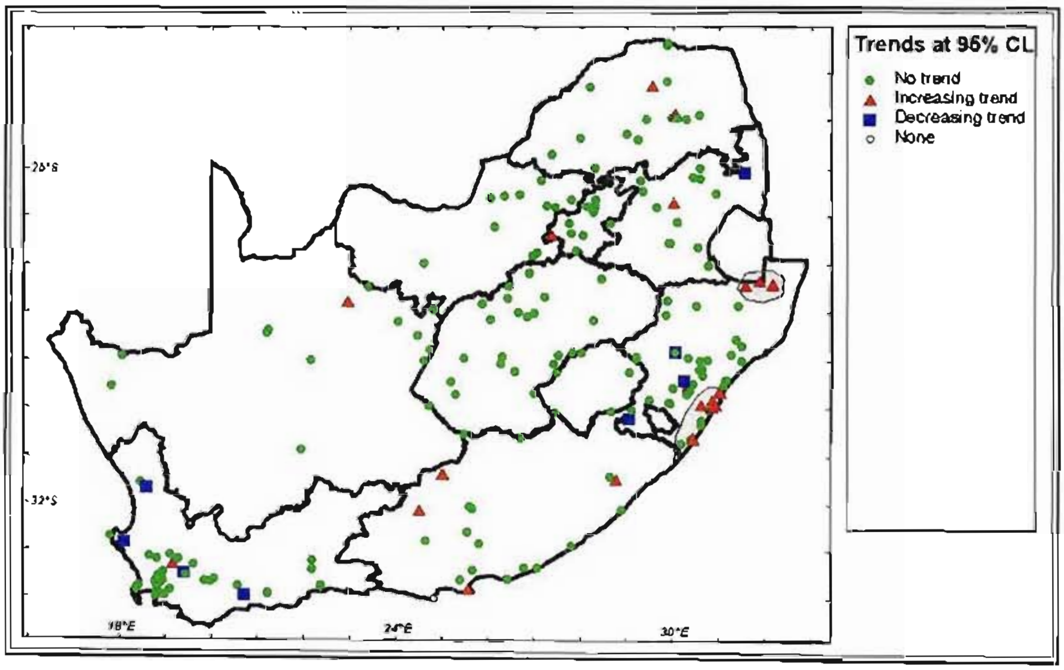

Figure 3.15 Trends over southern Africa at the 95% confidence level in the time series of number of occurrences of 3 consecutive days per year with maximum temperatures above 25°C

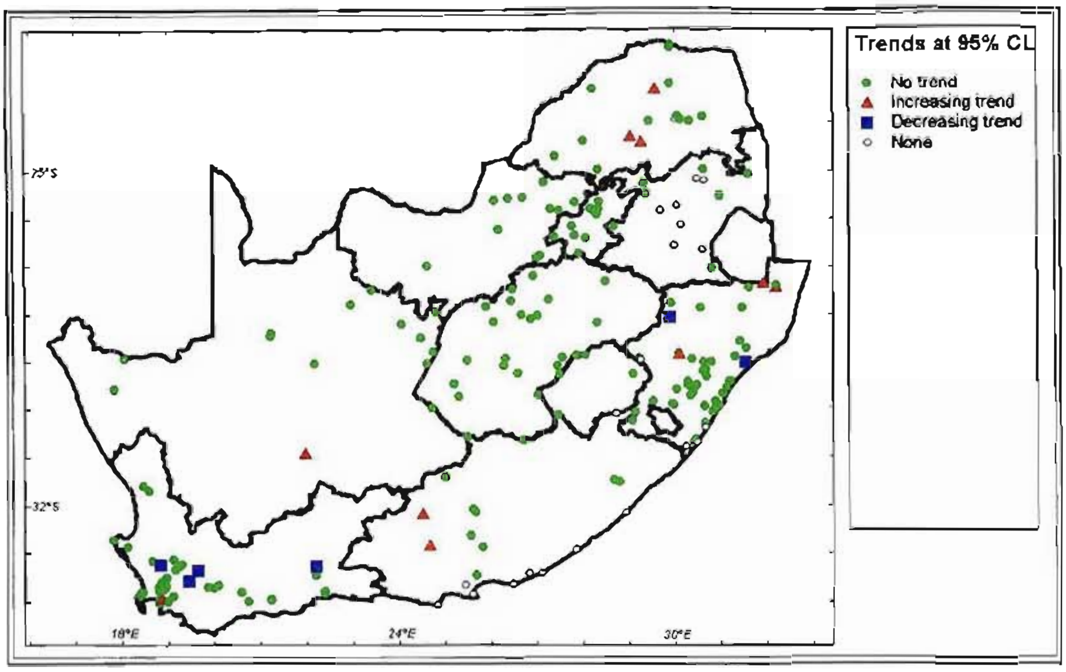

Figure 3.16 Trends over southern Africa at the 95% confidence level in the time series of number of 3 consecutive days per year with maximum temperatures above 30°C

3.6 Trends in Occurrences of Frost and the Length of the Frost Season

To evaluate whether changes in frost patterns over time could be detected in southern Africa, statistics of three temperature parameters were analysed, *viz.* the number of frost occurrences per frost season, the date of the first frost, and the date of the last frost. A frost event was considered to occur when the minimum temperature dropped below 0°C. Any station that experienced fewer than 20 individual frost events over the 51 year period of record was considered to be in a frost-free area.

Figure 3.17 shows spatially the results of the trend analysis for the number of frost occurrences per season. Under climate change conditions the number of frost occurrences is hypothesised to decrease. Immediately evident from Figure 3.17 is the large number of stations across the country displaying statistically significant decreasing trends in the number of frost occurrences per season. In particular, the majority of stations in the Northern Cape, Free State and Gauteng display this decreasing trend. A few stations, however, in the Western Cape, KwaZulu-Natal and

Lesotho display statistically significant increasing trends. The Lesotho stations could be disregarded as the data from these stations are suspect.

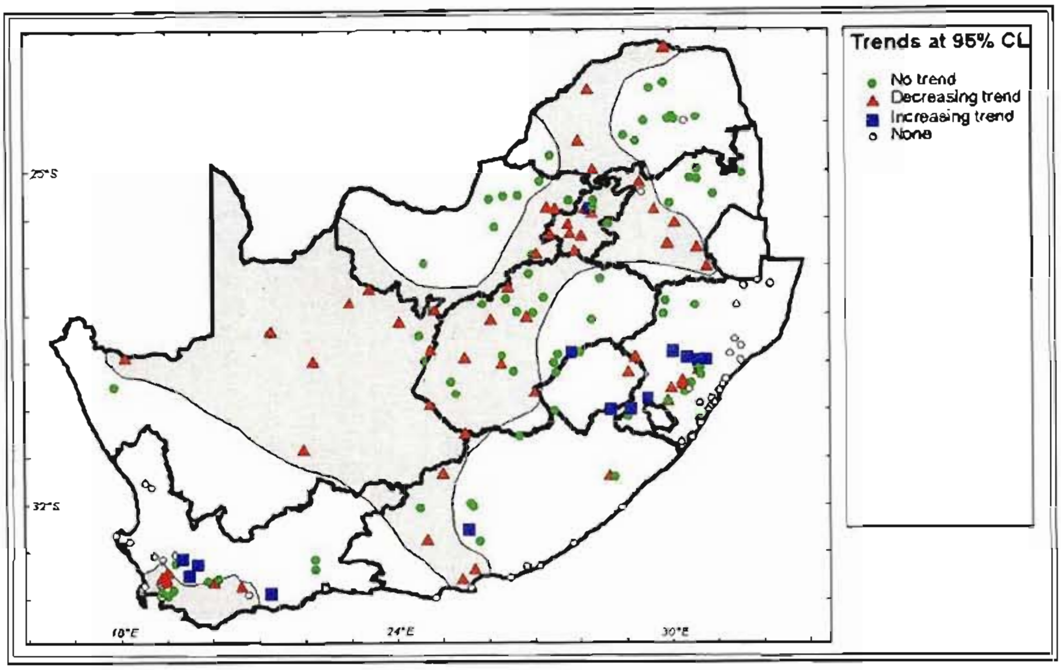

Figure 3.17 Trends over southern Africa at the 95% confidence level in the time series of number of frost occurrences (i.e. daily minimum < 0°C) per season

With changes in the number of frost occurrences per season in certain locations being evident, the next step was to analyse whether changes in the duration of the frost season could be detected. This was achieved by analysing whether or not trends in the first frost date and last frost date could be identified. Under climate change conditions it is hypothesised that the frost season will become shorter, i.e. a later first frost date and an earlier last frost date are hypothesised to occur.

Figure 3.18 displays spatially the results of the trend analysis of the date of the first frost. A grouping of stations over the interior of the country show a statistically significant later first frost date to occur over time. Against the hypothesis, is the large number of stations showing a statistically significant earlier first frost date to be occurring.

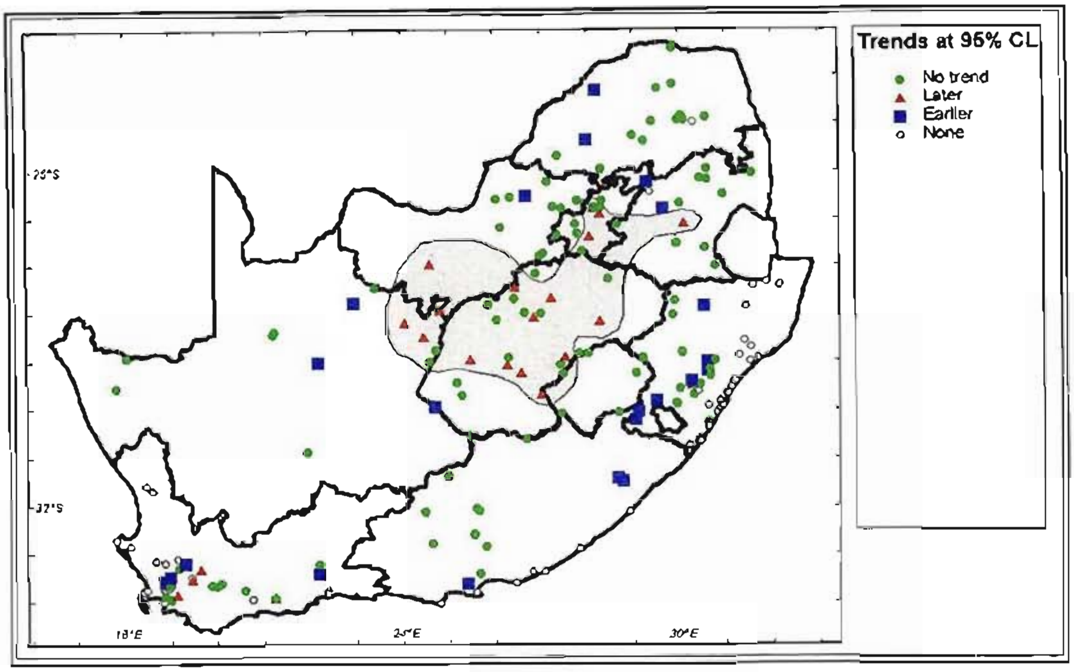

Figure 3.18 Trends over southern Africa at the 95% confidence level in the time series of the date of the first frost per season

Figure 3.19 shows trends in the date of the last frost. The majority of stations in the Northern Cape, Eastern Cape, Free State, North-West and Mpumalanga provinces display a statistically significant earlier date of the last frost in a season.

From these results, it is suggested that the frost season over the interior of the country, in particular over the Free State, is becoming shorter through a decrease in the number of frost occurrences per season and an earlier end to the frost season. At other locations it could be surmised that the frost season is becoming more severe, or is shifting to earlier in the year. Further analysis is required to draw clearer conclusions regarding changes in frost patterns over time.

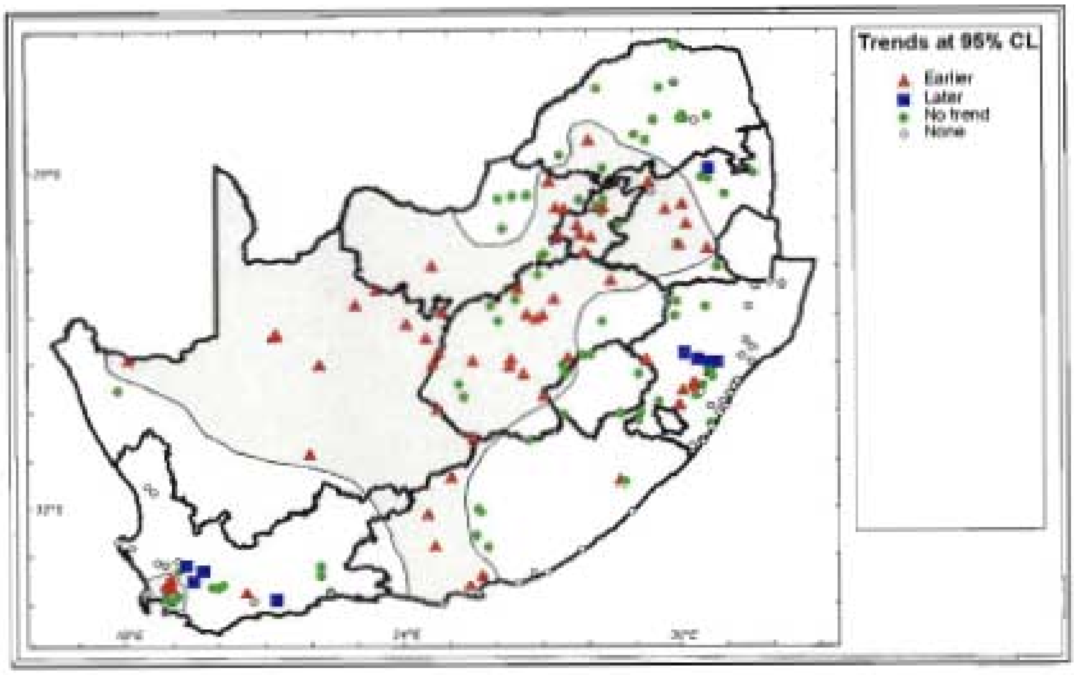

Figure 3.19 Trends over southern Africa at the 95% confidence level in the time series of the date of the last frost per season

3.7 Trends in Heat Units

Heat units, expressed as degree days, are the accumulation of mean temperatures above a specified lower threshold, below which no active plant growth/development takes place, and below an upper limit, above which active development similarly ceases (Schulze, 1997a). Accumulated degree days are applied in the selection of crop planting dates, modelling the development of crop canopy, prediction of harvest dates and estimation of yield as well as in the estimation of life cycles of crop pests.

Using a lower threshold average daily temperature of 10°C, the trends in heat units for the summer and winter seasons of southern Africa were analysed. The summer months, in this instance, were October to March, with winter being from April to September. Under climate change conditions it is hypothesised that in both summer and winter there will be an increasing trend over time in heat units.

Figure 3.20 shows the results of the trend analysis for heat units in the summer season. A large number of stations in the Western Cape show statistically significant increasing trends over time in heat units, as does a band of stations along the KwaZulu-Natal coast.

Another band of stations with increasing trends are shown stretching through the Northern Cape and Eastern Cape. A few stations in Gauteng also display an increasing trend. Only three stations display a statistically significant decreasing trend and they are located in KwaZulu-Natal.

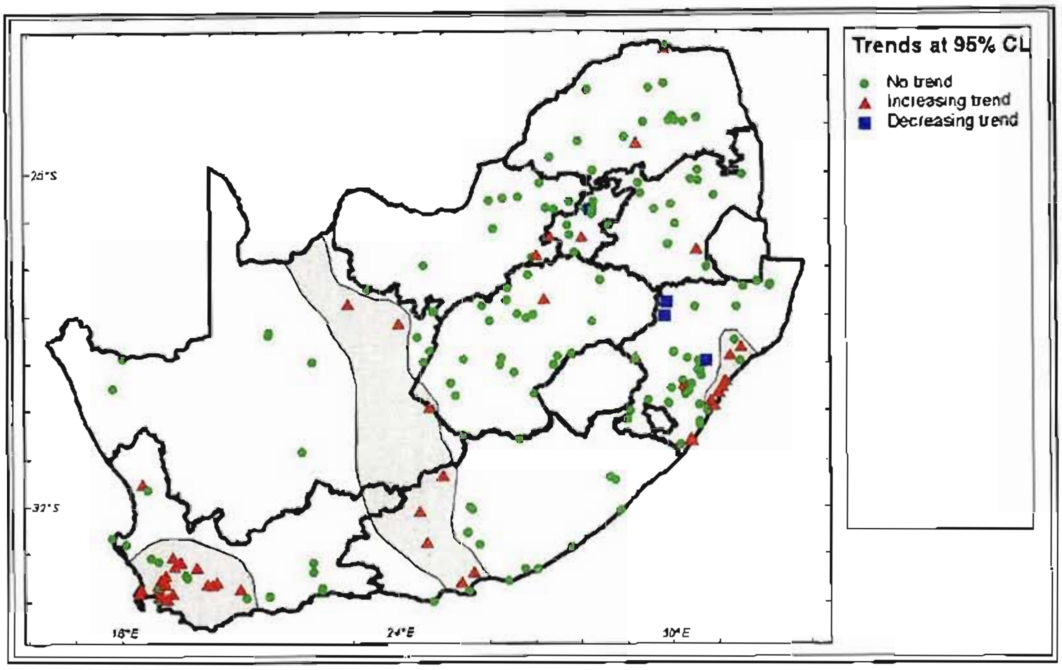

Figure 3.20 Trends over southern Africa at the 95% confidence level in heat units (base 10°C) for the summer season (October to March)

The spatial distributions of trends for heat units in the winter season are shown in Figure 3.21. Immediately evident is the large proportion of stations over South Africa displaying a statistically significant increasing trend in winter heat units. In particular, distinct clusters of stations in the Western Cape and KwaZulu-Natal (along the coast and inland) show increasing trends over time. The majority of stations in the Northern Cape also show increasing trends.

The trends in heat units seem to mimic the changes found in other temperature variables, with greater changes evident in winter and two clear areas of warming emerging, *viz.* the Western Cape and KwaZulu-Natal. Increasing trends in heat units have implications for viability of crops to be grown in certain areas and the occurrences of crop pests. For example, the coddling moth develops and thrives between a lower threshold of 11°C and an upper threshold of 34°C (Schulze, 1997a). With an increase in heat units, areas which previously were not affected by this crop pest may now be. Maize requires 1 700 heat units to mature. Previously, certain areas in KwaZulu-Natal and the Western Cape did not achieve this (Schulze, 1997a), but with an increase in heat units they may now be viable areas for maize farming.

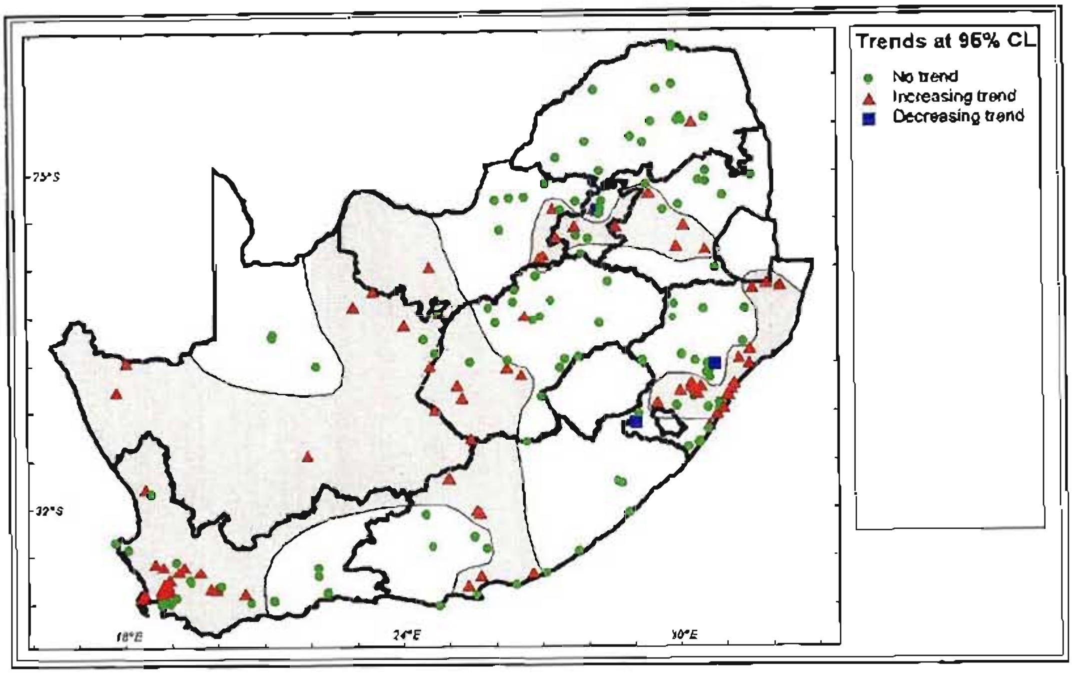

Figure 3.21 Trends over southern Africa at the 95% confidence level in heat units (base 10°C) for the winter season (April to September)

3.8 Trends in Positive Chill Units (PCUs)

Certain perennial plants have a dormant season during the winter months and require a critical period of accumulated minimum temperatures below a threshold in order to stimulate growth, develop leaves, flower or set fruit (Schulze, 1997a). The measure of these accumulated minimum temperatures is the positive chill unit (PCU), which can be computed from daily maximum and minimum temperatures (Schulze, 1997a).

To determine positive chill units, hourly values of temperature were determined from daily minimum and maximum temperatures by using the sine log equations derived by Linsley-Noakes *et al.* (1995; as cited by Schulze, 1997a). These hourly temperatures were then converted into PCUs according to intervals suggested by Richardson *et al.* (1974, as cited by Schulze, 1997a), modified and used by Linsley-Noakes *et al.* (1994;

as cited by Schulze, 1997a) and Linsley-Noakes *et al.* (1995; as cited by Schulze, 1997a), such that when

$2.4^{\circ}\mathrm{C} < T_t < 9.1^{\circ}\mathrm{C}$ then PCU = 1.0
$1.4^{\circ}\mathrm{C} < T_t < 2.4^{\circ}\mathrm{C}$ then PCU = 0.5
$9.1^{\circ}\mathrm{C} < T_t < 12.4^{\circ}\mathrm{C}$ then PCU = 0.5
$12.4^{\circ}\mathrm{C} < T_t < 16.0^{\circ}\mathrm{C}$ then PCU = 0.0
$T_t < 1.4^{\circ}\mathrm{C}$ then PCU = 0.0
$16.0^{\circ}\mathrm{C} < T_t < 18.0^{\circ}\mathrm{C}$ then PCU = -0.5
$18.0^{\circ}\mathrm{C} < T_t$ then PCU = -1.0 (Schulze, 1997a)

From the hourly PCU calculations, daily PCUs were accumulated, from which summer and winter seasonal totals could be obtained.

Shown in Figure 3.22 is the spatial distribution of the trend analysis for accumulated positive chill units for the period May to September. Under climate change conditions it is hypothesised that PCUs will display a decreasing trend. A grouping of stations in the Western Cape displays a statistically significant decreasing trend, as does a scattering of stations through the Northern Cape, Eastern Cape, KwaZulu-Natal, Free State and Mpumalanga.

The deciduous fruit industry in the Western Cape is highly concerned with the changes in climate. Deciduous trees need a certain period of winter chilling for completion of their seasonal dormancy. The required amount of chilling for completion of the rest period varies between species, cultivars and different locations. For peaches, for example, temperatures between approximately 2.5°C and 9.0°C have been identified as optimum for contributing to rest completion (Schulze, 1997a). As seen in Figure 3.22, it is in the Western Cape that PCUs are decreasing, possibly making this area less suitable for deciduous fruit farming in future, or at least increasing the risk associated with deciduous fruit farming.

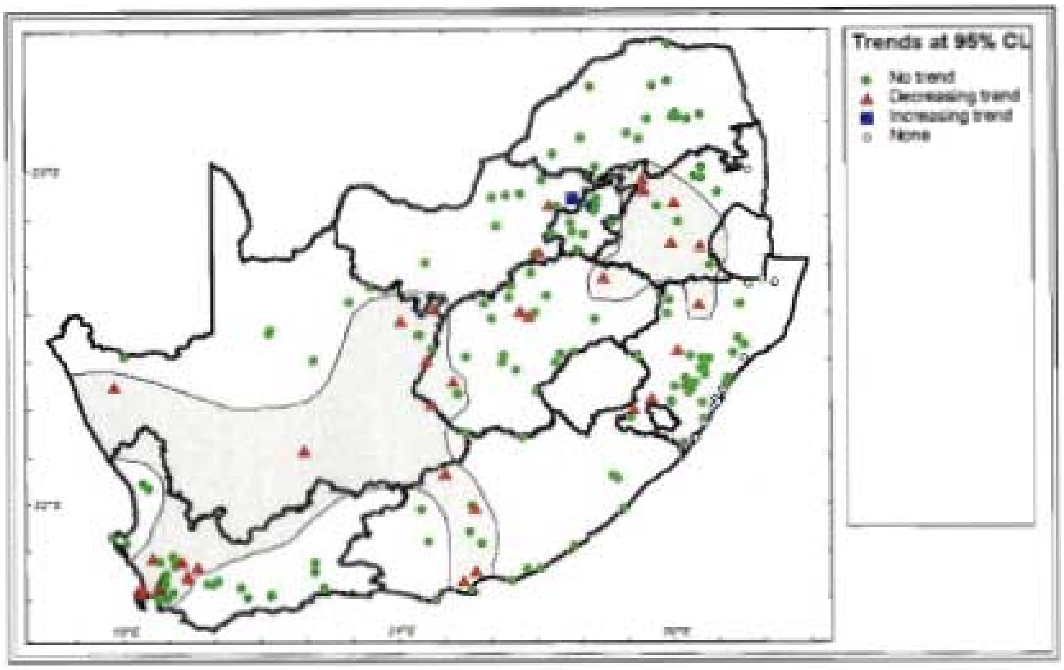

Figure 3.22 Trends over southern Africa at the 95% confidence level in accumulated positive chill units for the period May to September

3.9 A Comparison of Means of Daily Minimum and Maximum Temperature for 1950 – 1970 vs 1980 – 2000

A final step in the temperature trend analysis was to split the data series into two relatively short periods of 21 years each, *viz.* an earlier period from 1950 – 1970 and a later period from 1980 – 2000, and to compare the means for these periods. This analysis has no particular statistical significance, but shows spatially the magnitude of any change which may have occurred in the means of daily temperatures at the stations' locations. The comparison was carried out for:

- annual means of daily maximum temperatures,
- annual means of daily minimum temperatures,
- summer means of daily maximum temperatures, and
- winter means of daily minimum temperatures.

Under conditions of climate change it is hypothesised that the mean temperatures will increase. For this analysis the changes were grouped into five classes of change, *viz.*:

- no change, which is indicated by a green circle and defined as an increase or decrease of less than 0.2°C between the two periods of record,

- an increase in mean temperature of 0.2°C to 0.6°C in the later 21-year period, indicated by a small red triangle,
- an increase in mean temperature of greater than 0.6°C in the later 21-year period, indicated by a big red triangle,
- a decrease in mean temperature of 0.2°C to 0.6°C in the later 21-year period, indicated by a small blue square, and
- A decrease in mean temperature of greater than 0.6°C in the later 21-year period, indicated by a big blue square.

Figure 3.23 shows results for annual means of daily maximum temperatures. A cluster of stations in the Western Cape clearly shows a warming in the later 21-year period. A large percentage of stations throughout the Northern Cape, Eastern Cape, Free State, Northern Province, Mpumalanga and KwaZulu-Natal also show a warming in the later period of record. A few stations do show a decrease, however, two of these stations are Lesotho stations with suspect data, which can thus be disregarded.

Figure 3.24 shows changes in the annual means of daily minimum temperatures between the 1950 – 1970 and 1980 – 2000. The cluster of stations in the Western Cape with an increase in annual mean daily minimum temperatures for the 1980 – 2000 period is indicative of warming in this area. Another clear cluster of stations indicating warming is evident in KwaZulu-Natal. A scattering of stations through the Eastern Cape, Free State, Northern Cape, Gauteng and Mpumalanga also show an increase in annual means of daily minimum temperatures in the later period. A number of stations in KwaZulu-Natal show a cooling in the later period, as do a few in the Eastern Cape and North-West. The Lesotho stations showing a cooling can be disregarded as these stations have been shown to have suspect data.

Figure 3.25 displays differences in summer means of daily maximum temperatures between 1950 – 1970 and 1980 – 2000. Again, the stations in the Western Cape and KwaZulu-Natal clearly indicate a warming in the later 21-year period. A number of stations over the remainder of the region indicate a warming in the later 21-year period, in particular, stations in the Northern Cape and Northern Province. A few stations in KwaZulu-Natal indicate a cooling in the latter period.

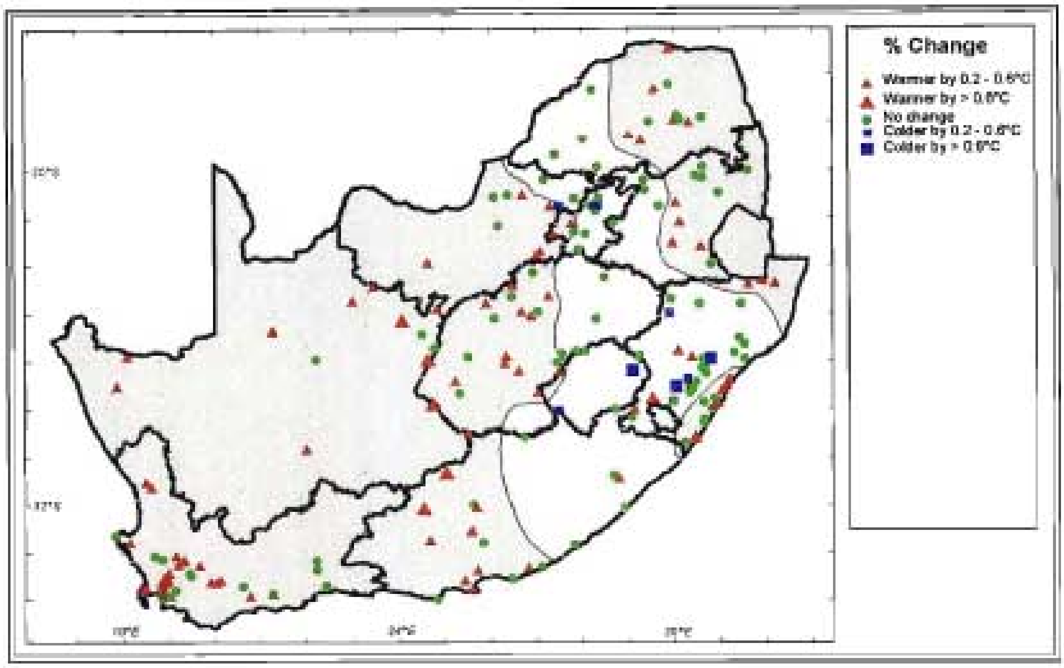

Figure 3.23 Comparison of annual means of daily maximum temperatures over southern Africa between 1950 – 1970 and 1980 – 2000

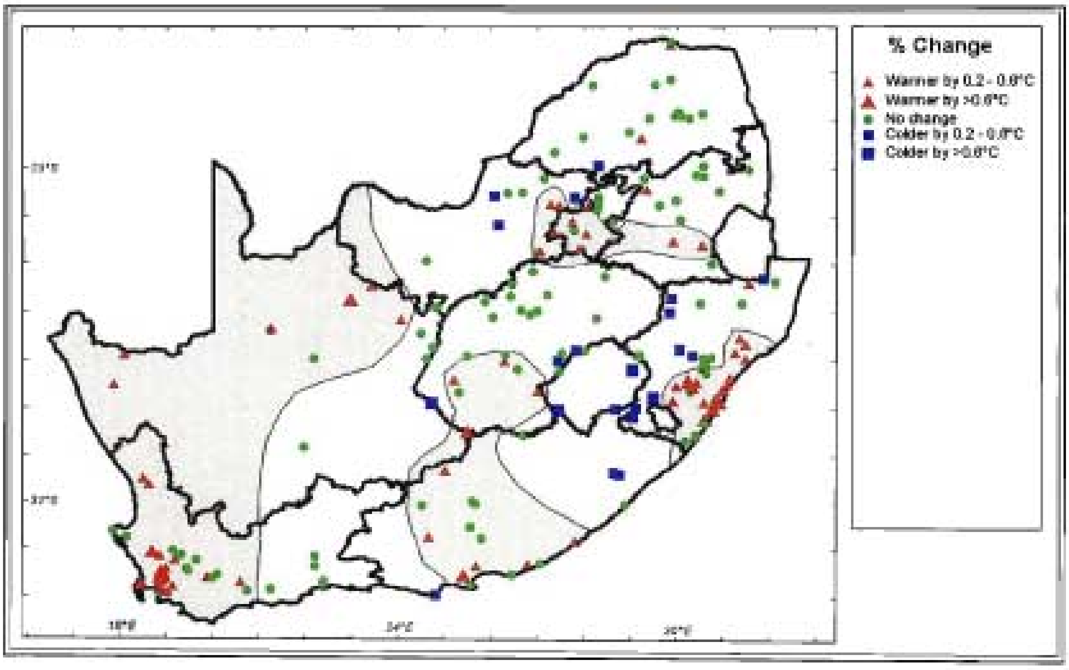

Figure 3.24 Comparison of annual means of daily minimum temperatures over southern Africa between 1950 – 1970 and 1980 – 2000

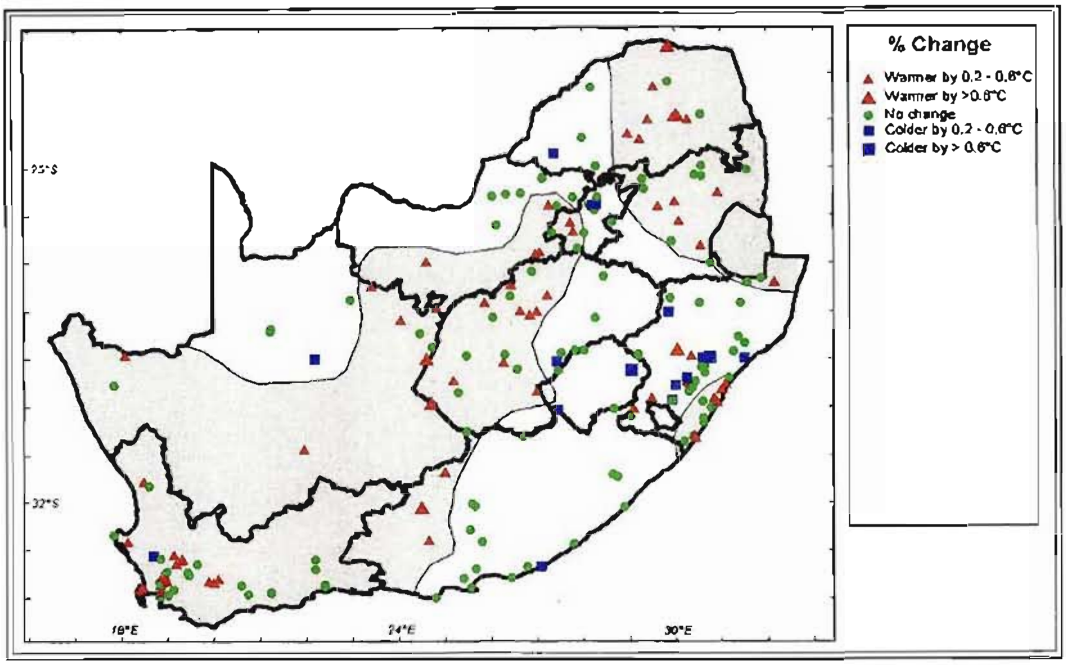

Figure 3.25 Comparison of summer means of daily maximum temperatures over southern Africa between 1950 – 1970 and 1980 – 2000

In Figure 3.26 winter means of daily minimum temperatures are compared for the earlier vs later period of record. Yet again, the warming in the Western Cape and KwaZulu-Natal is clear, with large clusters of stations showing a warming of at least 0.2°C in 1980 – 2000 in comparison to 1950 – 1970. A surprising observation is the number of stations across the country indicating a cooling in the later 21-year period. A cooling of winter means suggests that although the annual means of temperature may be increasing, the winter temperatures on average may be reducing (i.e. temperatures may be becoming more extreme), and summer temperatures warming substantially. However, further analysis is needed to confirm this.

The comparison of 1950 – 1970 vs. 1980 – 2000 temperatures seems to mimic spatially the statistical analysis using the Mann-Kendall test, with stations in the Western Cape and along the KwaZulu-Natal coast, as well as those in the midlands of KwaZulu-Natal, showing a warming and the remainder of the country showing no clear pattern.

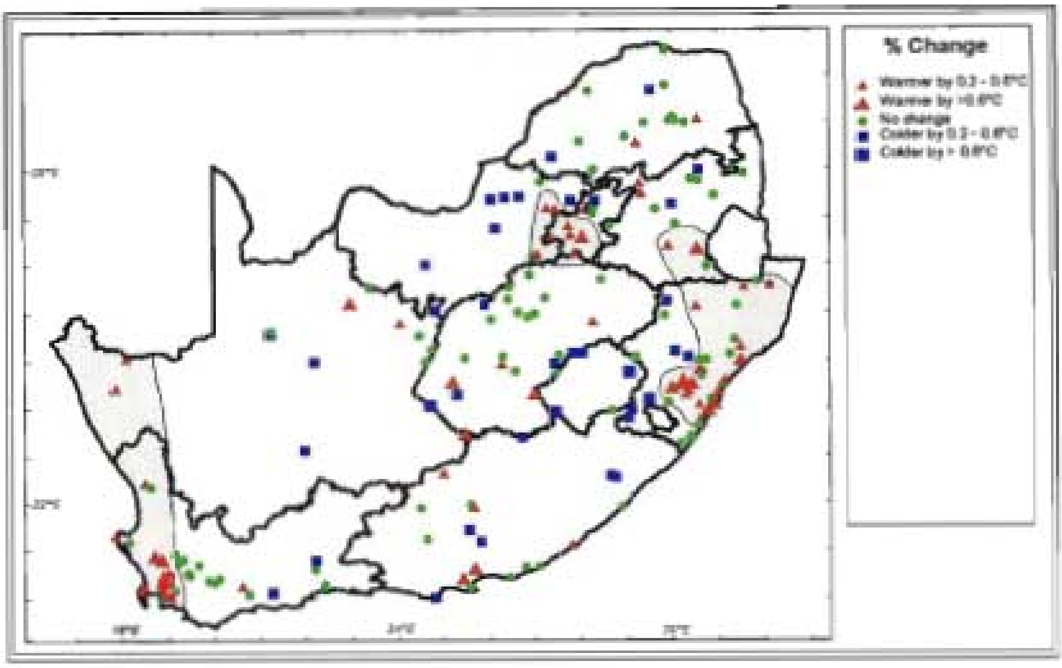

Figure 3.26 Comparison of winter means of daily minimum temperatures over southern Africa between 1950 – 1970 and 1980 – 2000

3.11 Is South Africa's Temperature Changing: A Summary of Findings

In almost every analysis performed two clear clusters of warming emerge, these being a cluster of stations in the Western Cape and a cluster of stations around the midlands area of KwaZulu-Natal, along with a band of stations along the KwaZulu-Natal coast. The clusters show up clearly in the analyses of annual means of both minimum and maximum temperatures, in the threshold analyses, in the percentile and set value analyses for cold spells, as well as in the heat unit analysis. Another distinct conclusion that can be drawn is the warming over the interior of the country when analysing frost occurrence, where the Free State and Northern Cape provinces stand out in this regard. It must be noted, however, that according to the data there appears to be a shift towards an earlier ending of the frost season, but nevertheless a shorter frost season with fewer frost occurrences is evident.

In the comparison of annual means of daily maximum temperatures between 1950 – 1970 and 1980 – 2000 a larger percentage of stations across the country shows a warmer later 21-year period. Nevertheless, in the comparison of annual means of daily minimum temperature there are a number of stations with a cooling trend. Again, trends in warming appear in the Western Cape and KwaZulu-Natal provinces, with distinct clusters evident there. From this analysis of temperature records it becomes clear that changes in certain temperature parameters are occurring across southern Africa. However, these changes are not uniform across the region. Consistent areas of warming are present, these being in the Western Cape and KwaZulu-Natal. Another clear conclusion is the decrease in severity of the frost season over the Free State and Northern Cape provinces, with the number of frost occurrences having decreased, and the frost season ending significantly earlier.

Temperature is a basic climatological parameter that has a direct effect on all forms of life on earth (Schulze, 1997a). Temperature affects a wide range of processes and activities such as human comfort and, consequently, energy supply and demand for heating and cooling, crop and animal responses as well as incidences of pests and disease (Schulze, 1997a). Temperature is one driver of evaporation from water surfaces, soil surfaces, intercepted water and transpiration, thus the changes shown in temperature will have important hydrological repercussions, through influencing potential evaporation, total evaporation and soil moisture. As a consequence, runoff generation will possibly be altered through drier antecendent soil moisture conditions, irrigation demands may possibly increase due to greater transpiration and evaporation rates, and less groundwater is likely to be available in the long run due to reduced groundwater recharge as a result of lower soil moisture. With changes in temperature evident, and with that possible changes in hydrological responses, the logical next step is to apply the daily temperature data (Schulze and Maharaj, 2004) together with daily rainfall data (Lynch, 2004) in the South African National Quaternary Catchments Database (Schulze *et al.*, 2004) and analyse whether any changes in streamflow and other hydrological indicators could be detected already.

As highlighted in the "roadmap" which follows, Chapter 4 contains a literature review of streamflow detection studies, an outline of the problems relating to streamflow measurement and a discussion of the advantages of physical conceptual modelling. Chapter 4 also addresses the QCDB and input used in this study, as well as a detailed discussion of the re-selection of the rainfall station network. In Chapter 5 results from the analysis for hydrological drivers and responses are presented.

Problem Statement: If anthropogenically forced climate change is becoming a reality, evidence of change should already be detectable in climate observations and from hydrological simulations at a regional scale

Overall Objectives: To determine whether statistical analyses already show trends in temperature parameters and hydrological responses which may be ascribed to climate change

		Broad Objectives		
		Temperature Detection Studies	**Detection Studies on Hydrological Drivers and Responses**	**Overall Conclusions and Recommendations**
Specific Objectives	**Literature Review**	i.) Review results from temperature detection studies ii.) Outline problems related to temperature data iii.)Review statistical methods used in detection studies	i.) Review results from streamflow detection studies ii.) Outline problems related to streamflow measurement iii.)Discuss the advantage of physical conceptual hydrological models in detection studies iv.)Review precipitation detection studies	i.) Changes in southern Africa's temperature regime ii.) Changes in southern Africa's hydrological drivers and responses iii.) Changes in southern Africa's rainfall regime iv.)Overall conclusions and recommendations
	Data	i.) Outline temperature dataset used for southern Africa	i.) Quaternary Catchments Database and input	
	Methods	i.) The Mann-Kendall non-parametric test ii.) Split-sample analysis	i.) Re-select rainfall station network ii.) The Mann-Kendall non-parametric test iii.) Split-sample analysis	
	Results	**Mann-Kendall Analyses** i.) Examine means of minimum and maximum temperatures ii.) Analyse percentile thresholds iii.)Analyse selected thresholds iv.)Analyse frost related parameters v.) Analyse Heat units vi.)Analyse Chill units **Split-sample analyses** i.) Examine means of minimum and maximum temperatures ii.) Analyse coefficient of variation	**Mann-Kendall Analysis** i.) Analyse accumulated streamflows **Split-Sample Analyses** i.) Reference potential evaporation ii.) Soil water content iii.) Median, 90th and 10th percentile of accumulated streamflow iv.) Range in streamflows v.) Baseflows vi.) Seasonality and concentrations of flows vii.)Irrigation water requirements **Split-Sample Analyses** i.) Median, 90th and 10th percentile of rainfall ii.) Range in rainfall iii.) Analyse selected thresholds	
	Conclusions	i.) Is southern Africa's temperature changing?	i.) Conclusions of detection studies on hydrological responses ii.) Conclusions on changes in rainfall	

4. CLIMATE CHANGE DETECTION STUDIES: A REVIEW OF LITERATURE AND AN OVERVIEW OF TOOLS AND METHODS USED

4.1 Introduction

Streamflow responses are highly sensitive to and amplified by, changes in precipitation as a result of rainfall thresholds for stormflow and groundwater recharge having to be exceeded, scale issues and antecedent catchment conditions (Schulze, 2005). Furthermore, streamflow responses to changes in precipitation are complex in that changes in precipitation may imply changes not only in magnitude, but also precipitation intensity (i.e. rainfall per event) or in precipitation persistencies (i.e. sequencing of wet/wet, wet/dry, dry/wet and dry/dry days; Schulze, 2003a).

Even small changes in precipitation attributes maybe amplified through the hydrological cycle and may become evident in trends in observed runoff and groundwater recharge records (Schulze, 1995). Thus an analysis of observed streamflow records may reveal trends that are not immediately evident in rainfall totals alone. Streamflow is, however, not as widely a measured variable as rainfall or temperature and, in addition, most observed streamflow records, apart from being relatively short, are non-homogeneous in that upstream land use and channel changes are common for the period of record. In the literature, only detection studies relating to the Americas have been found; hence these will be reviewed below (*cf.* roadmap). Following this, the advantages of using hydrological simulation modelling to obtain streamflow values to analyse for trends is elaborated upon (as highlighted in "roadmap"). The uncertainties in hydrological modelling are explored, prior to the South African Quaternary Catchment Database and its inputs being outlined.

4.2 Literature Review: Climate Change Detection Studies for Streamflow

As mentioned above only detection studies relating to the Americas were found in the literature searched, and these are discussed below. For the contiguous USA, 395 climate-sensitive streamflow gauging stations, some with datasets dating back to 1914, have been analysed by Lins and Slack (1999). It was found that streamflow in the USA was generally increasing. While the USA is generally getting wetter, the events are apparently less extreme. Slight decreases in total streamflows were, however, noted for parts of the northwest and southeast (Lins and Slack, 1999). In a more detailed analysis, Groisman *et al.* (2001) analysed area-averaged monthly streamflow time series in the USA. For the 70 years of data analysed, a steady increase in runoff was found for the southern and southeastern parts as well as the Upper Mississippi River Basin in the USA.

In the northwestern USA and Missouri River Basin an increase in streamflow was reversed during the past 25 years of the 70 year period, as a result of an earlier onset of spring snowmelt, according to Groisman *et al.* (2001). For the Rio Puerco Basin in New Mexico, none of the streamflow records analysed by Molnar and Ramirez (2001) for the 1952 to 1986 period displayed any statistical significant trends in annual streamflows.

Genta *et al.* (1998) examined long-term observed streamflow records from four rivers in southeastern South America, *viz.* the Uruguay, Negro, Paranà, and Paraguay Rivers. All four rivers displayed a statistically significant increasing trend in streamflows, and all but the Negro River displayed a significant decrease in the amplitude of the seasonal cycle.

Although the natural hydrological cycle amplifies changes in rainfall parameters, it must be recognised that streamflow is influenced by numerous human activities such as catchment land use changes, inter-basin water transfers, other abstractions, return flows or reservoir construction followed by controlled releases. These may conceal, or obliterate, or even reverse, natural trends. Other factors that could disguise trends in streamflow records are that the streamflow records tend to be relatively short, and that streamflow is the integration of several aspects of climate over both time and space. Hence, trends in one climate driver may be offset by opposite trends in another climate driver (Arnell, 2002).

These factors could help to explain why so few trends in streamflow have been detected, and these issues must be borne in mind when conducting detection studies for streamflow. It is for the above reasons and others, that physical conceptual hydrological simulation modelling has been chosen to generate streamflow records for this detection study in southern Africa, and this is discussed further in the following section.

4.3 Problems in Streamflow Measurements and the Advantages of Physical Conceptual Models for Streamflow Estimates

The streamflow gauge network in South Africa, like that of many other countries, is relatively sparse. Where gauges do exist, they are often poorly maintained and neglected (Arnell, 2002). Frequently it is also the case in developing countries that streamflow measurements are made at a time scale coarser than at a daily scale. Added to this is that the existing streamflow records are often characterised by inhomogeneities, due to overtopping of the gauging structures, incorrect calibration of the recording device, or mistakes in conversion of data to digital format. For example, in South Africa many streamflow gauges can only measure streamflow events to a certain threshold limit before overtopping (Smithers and Schulze, 2003).

Other problems include the length of record, which is often too short for detection analysis, and changes in the land use upstream from the gauge that affect streamflow. In climate change detection studies it is these last two problems that are of the greatest concern. A short record does not allow trends to be detected adequately, and any changes in land use in the catchment affect the volume, peak and seasonality of streamflow. When attempting to detect trends attributable to climate change, this becomes a major problem as it becomes unclear whether an observed change in streamflow is due to change in land use or to climate. This brings to the fore the advantages of using a physical conceptual hydrological model to generate streamflow records.

A hydrological model can be described as a collection of physical laws, physically based equations and empirical relationships which are written in mathematical terms and combined in such a way as to produce a set of results from a set of known or assumed conditions (Schulze, 1995). A conceptual hydrological model is one that averages inputs and/or outputs over an area and integrates several hydrological processes and their variability such that their parameter expressions are indices rather than physically meaningful or true values (Bergström, 1991). However, for a physical conceptual model, the hydrological system is conceived in a way that important processes and couplings are idealised and the physical processes are represented explicitly (Schulze, 1995).

Using a hydrological model to generate streamflow records has the following advantages (Schulze, 1989):

- There are no missing days of data in the generated streamflow records.
- The generated streamflow record can be longer than the actual streamflow record, as rainfall records are usually longer.
- Modelling is efficient and cost effective as there are no maintenance and monitoring costs for gauging structures.
- A generated streamflow record has no introduced inhomogeneities from weir structures, calibration of recording devices or keying in errors.
- The land use of the catchment can be held constant in a model at a land cover prior to human influence, i.e. the streamflow record can be generated for baseline, or reference, conditions.
- There are limitations to hydrological measuring techniques (i.e. one cannot measure everything one would like to know about hydrological systems; Beven, 2000), but generating hydrological output from a model allows other information and statistics to be generated that are useful in climate change detection studies, such as peak flow, baseflow and sediment yield.

4.4 Uncertainties in Hydrological Modelling

Many uncertainties exist in hydrological modelling. The perfect hydrological model, and according to Beven (2000, p 304), is an unreachable goal as 'we have neither the model structures nor the data to identify that complex, unique, single realisation that is the real catchment'. Suter (1993) identifies four sources of uncertainty in hydrological modelling, *viz.:*

1. Stochasticity (the inherent unknowable randomness, e.g. of rainfall);
2. Ignorance (the imperfect or incomplete knowledge of things potentially knowable, e.g. having only short records);

3. Human errors (including poor quality control of model input); and
4. Both up- and down-scaling.

In hydrological modelling, three major categories of uncertainty exist, namely, uncertainty in inherent components of the system, uncertainty in the datasets used in the modelling and uncertainty resulting from the model's conceptualisation of processes (Schulze, 2005).

When considering the uncertainties in the components of the system, two sources of uncertainty are important, climate drivers and catchment conditions. The uncertainty introduced by climate drivers centres around the amount, seasonal timing, duration, intensity, persistence and spatial duration of rainfall. The uncertainty introduced by catchment conditions stems from the non-stationary nature of catchments in terms of antecedent wetness before an event, channel manipulations over time, and runoff changes resulting from land use change over time (Schulze, 2005).

Uncertainties in the datasets used in modelling stem from issues such as data length, data quality and the data network density, while the uncertainties resulting from the model's conceptualisation of processes include the level of detail of process representation and parameterisation of land use and soil input, both of which contain point uncertainties and a degree of spatial randomness which are seldom considered in modelling (Schulze, 2005).

Given the problems associated with gauged streamflow measurements it was decided that, for the purposes of this study on detection of hydrological responses, streamflow would be simulated using the daily timestep physical-conceptual *ACRU* agrohydrological model (Schulze, 1995) linked with the southern African Quaternary Catchments Database (QCDB; Schulze *et al.*, 2004). The *ACRU* model, which has been widely tested, was the only model used and thus many of the uncertainties that may occur will be consistent and in comparative studies are largely self-cancelling. What follows below are discussions on the QCDB and the *ACRU* model.

4.5 The South African Quaternary Catchments Database

The QCDB (Schulze *et al.*, 2004) may be used for agrohydrological detection, sensitivity and impact studies anywhere in South Africa, Lesotho and Swaziland. It consists of an *ACRU* input database which is used to perform spatially comparative simulations with the *ACRU* model of, for example,

- streamflow accumulated from all QCs upstream of a point,
- stormflow from an individual QC,
- baseflow from an individual QC,
- impacts of land use change,
- impacts of climate change (including transpiration feedbacks under enhanced $C0_2$ concentrations,
- soil moisture status,
- recharge to the vadose zone,
- crop yield,
- sediment yield or
- irrigation demand

at spatial scales of either

- individual Quaternary Catchments into which the region has been sub-delineated, or
- hydrologically linked, cascading catchments.

The definition and numbering system of Quaternary Catchments is discussed below, followed by a brief overview of the *ACRU* agrohydrological model.

4.5.1 The concept of the Quaternary Catchment

The South African Department of Water Affairs and Forestry (DWAF) has delineated South Africa, Swaziland and Lesotho into a hierarchical system of catchments, from Primary Catchments (Figure 4.1), which are disaggregated into Secondary, then Tertiary and finally Quaternary Catchments (Figure 4.1). The Quaternary Catchment is the smallest operational catchment area which DWAF uses for general planning purposes (Midgley *et al.*, 1995).

Quaternary Catchments are numbered in a downstream order. For example, the Quaternary Catchment numbered V32E would be interpreted as follows:

- The letter 'V' denotes that the Quaternary Catchment is in Primary drainage region V, which is the Thukela catchment. There are 22 Primary drainage regions which cover southern Africa, numbered alphabetically from A to X, but excluding the letters I and O.
- The number '3' denotes that the Quaternary Catchment is in the Secondary drainage region number 3 of the Primary drainage region V. There are, at maximum 9 Secondary drainage regions (1-9) per Primary drainage region.
- The number '2' denotes that the Quaternary Catchment is located in the Tertiary drainage region number 2 of the Secondary drainage region number 3. Again, there are a maximum of 9 Tertiary drainage regions per Secondary drainage region.
- 'E' denotes the Quaternary Catchment *per se*. There are at most 12 Quaternary Catchments per Tertiary drainage region, labelled A to M, with I omitted (Midgley *et al.*, 1995).

In total there are 1946 Quaternary Catchments covering South Africa, Lesotho and Swaziland. The QCDB thus contains the input variables needed for the *ACRU* agrohydrological model for all 1946 Quaternary Catchments.

The concepts and structure of the *ACRU* agrohydrological model are discussed briefly below.

4.5.2 The ACRU Agrohydrological Simulation Model

The *ACRU* model is a daily timestep, physical-conceptual, multi-purpose model (Figure 4.2) which is able to give output of daily streamflow (which includes flows from all upstream catchments), stormflow, baseflow, peak discharge, sediment yield, groundwater recharge, reservoir status, irrigation water supply and demand, as well as seasonal crop yields at any location within a catchment, in addition to other output options (Schulze, 1995; Schulze and Smithers, 2004).

The *ACRU* model revolves around a daily multi-layered soil water budget (Figure 4.3) and is structured to be sensitive to climatic and to land cover or land use changes on the soil water and runoff regimes. The water budget, furthermore, is responsive to supplementary watering by irrigation, to changes in tillage practices and the onset and degree of plant stress (Schulze, 1995).

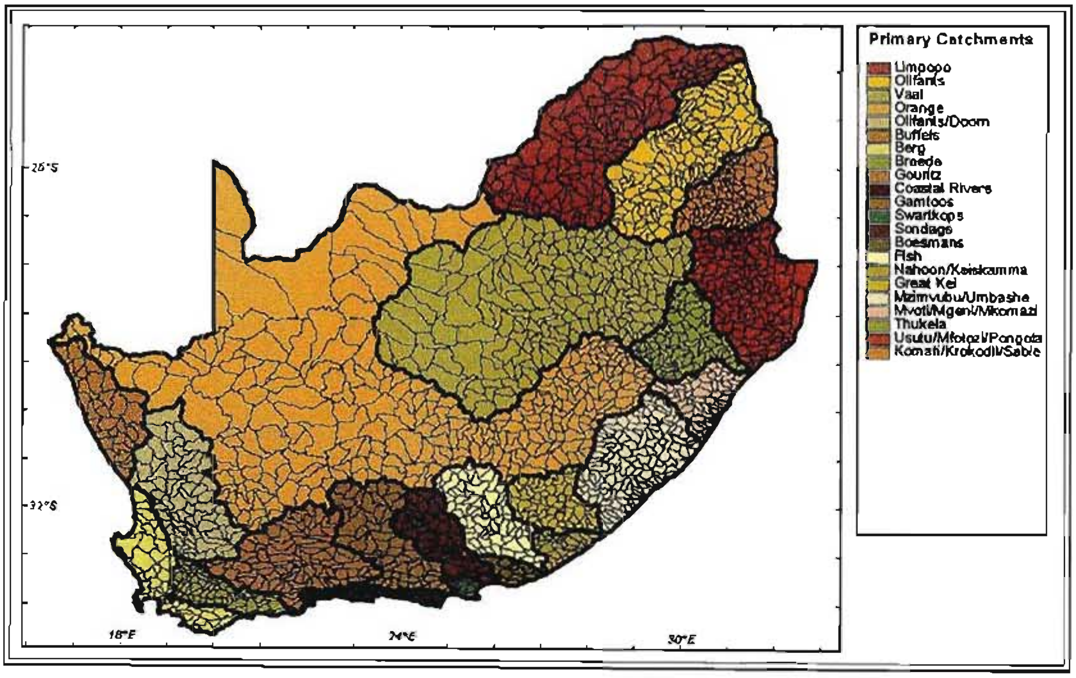

Figure 4.1 Delimitation of Quaternary Catchments in South Africa, Lesotho and Swaziland, with Primary Catchments distinguished by different shading (after DWAF, 2005)

4.5.3 QCDB: The *ACRU* input database used for this study

4.5.3.1 Daily rainfall input per Quaternary Catchment

A refinement to the *ACRU* input database, which formed part of this project, was a re-selection of the rainfall stations for each QC (as highlighted in the methods section of the "roadmap" which appeared at the end of Chapter 3), the data from which were used to 'represent' the various Quaternary Catchments. This re-selection procedure is discussed in detail in Chapter 4.5.

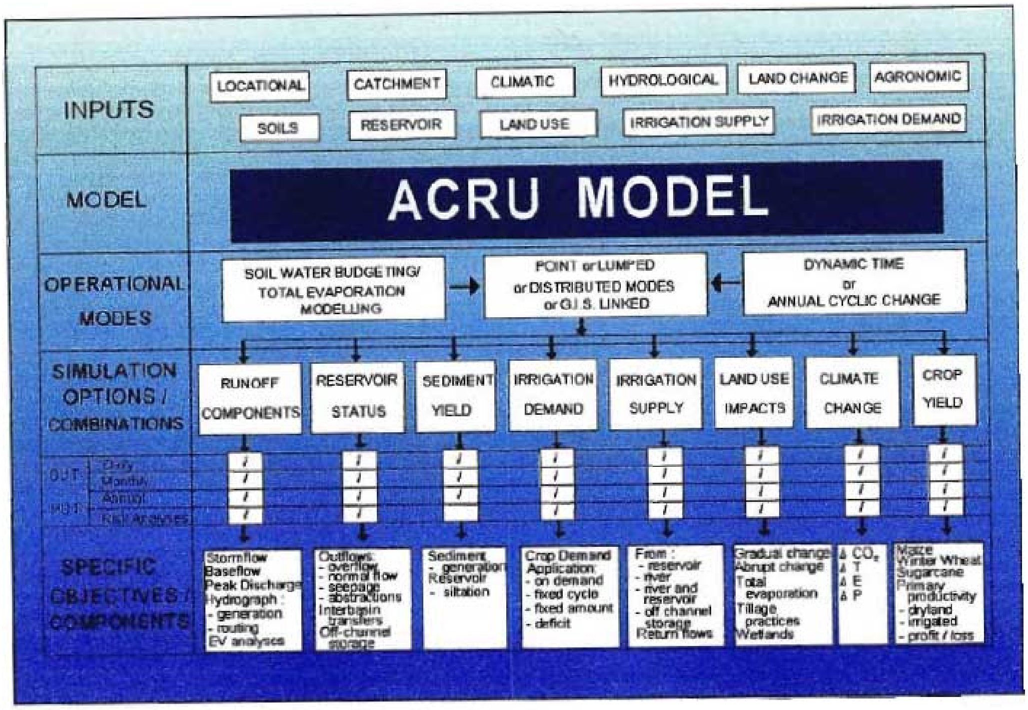

Figure 4.2 *ACRU*: Concepts of the modelling system (Schulze, 1995)

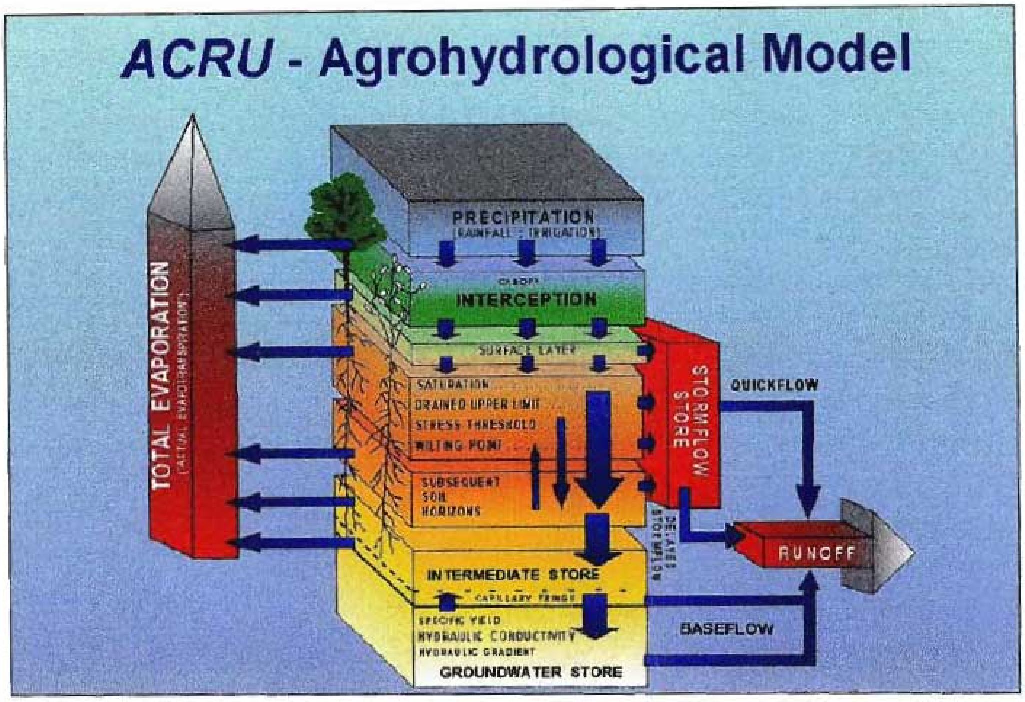

Figure 4.3 *ACRU*: Model structure (Schulze, 1995)

Once the rainfall stations had been re-selected to represent each of the Quaternary Catchments, a 50-year record of daily rainfall was extracted for each station. The *ACRU* model provides an option for the daily rainfall record to be adjusted by a month-by-month multiplication factor. If the chosen rainfall station is located outside of the QC, or the rainfall record is not representative of the catchment's areal precipitation, this adjustment factor renders the rainfall records more representative of the catchment's rainfall. This monthly adjustment factor is obtained by dividing the catchment's mean monthly rainfall obtained from a recent detailed study by Lynch (2004) by the rainfall station's mean monthly rainfall.

4.5.3.2 Daily temperature input per Quaternary Catchment

In the absence of spatially and temporally detailed input information on daily potential evaporation (E_p) for each of the 1946 Quaternary Catchments, these values have to be derived from widely tested and verified temperature based E_p equations applicable to South Africa, e.g. from the Hargreaves and Samani (1985) equation. This requires daily values of maximum and minimum temperatures.

A recently completed WRC project titled "The Development of a Database of Gridded Daily Temperature for Southern Africa" (Schulze and Maharaj, 2004) facilitates the generation of a 50-year historical series (1950 – 1999) of daily maximum and minimum temperatures at any unmeasured location in southern Africa at a spatial resolution of 1' by 1' latitude/longitude (i.e. ~ 1.6km x 1.6km). For each QC, a representative altitude was computed from a 200 m DEM and for this altitude the 50 – year series of daily maximum and minimum temperatures was generated at the centroid of the QC (Schulze *et al.*, 2004).

4.5.3.3 Reference potential evaporation

The *ACRU* model, as operated for this project, uses daily unscreeded A-pan equivalent evaporation as the reference for potential evaporation. Since the 1946 Quaternary Catchments did not each have daily A-pan evaporation records, an equivalent reference potential evaporation needs to be obtained from an equation and needs for detection purposes, to be applied consistently. *ACRU* provides a suite of equations to calculate A-pan equivalent potential evaporation at both a daily and monthly level (Schulze, 1995). For the purposes of this project the Hargreaves and Samani (1985) daily equation was selected.

Hargreaves and Samani (1985) developed a simple and practical equation to estimate crop water requirements using a minimum of climatological data. This method estimates daily or monthly A-pan equivalent evaporation using readily available data, and requires little or no local calibration (Schulze, 1995). The equation is given by:

$$E_{apan} = 1.25 \times K_{HS} . R_a . T_r^{0.5} (T_a + 17.8) \qquad \text{..........} \; 4.1$$

where

E_{apan} = A-pan equivalent reference potential evaporation (mm.day^{-1}),

K_{HS} = local or regional calibration co-efficient for the Hargreaves and Samani equation,

R_a = extra-terrestrial solar radiation (mm equivalent.day^{-1}), computed for any location as a function of latitude and day of year,

T_r = range of daily (or monthly) air temperature (°C), and

T_a = daily (or monthly) mean air temperature (°C).

The output from the primary equation is adjusted by the Hargreaves and Samani (1985) factor 1.25, since the original equation represented maximum crop-related evaporation rather than A-pan equivalent potential evaporation. The values of K_{HS} were calculated for various locations in the USA and a mean value of 0.154 with a standard deviation of 0.019 was determined (Hargreaves and Samani, 1985). The Hargreaves and Samani (1985) daily A-pan equivalent potential evaporation equation was chosen for this study as it requires only daily temperature parameters as input variables and was found by Bezuidenhout (2005) to mimic the Penman-Monteith values of potential evaporation well in South Africa using the two adjustment factors discussed above.

ACRU provides the option to calculate soil water evaporation (E_s) and transpiration (E_t) as a combined entity or separately. In this study the soil water evaporation and transpiration components of total evaporation are calculated as separate entities. At a fraction of 0.4 of plant available water it is assumed that the total evaporation (i.e. 'actual evapotranspiration') will commence to decrease linearly below its maximum evaporation (i.e. potential evaporation).

4.5.3.4 Land cover variables

A major objective of this study is to determine whether hydrological responses have altered between the periods 1950 – 1969 and 1980 – 1999 as a consequence of any changes in climate (Chapter 5). In order to eliminate the effects which changing land cover may have on hydrological responses over time, it was decided that for each Quaternary Catchment the spatially most dominant baseline land cover, represented by the respective Acocks' (1988) Veld Type, would be selected as the baseline, or reference, land cover for the entire period of analysis.

ACRU requires hydrological attributes of the land cover in order to simulate hydrological responses. In South Africa, the 70 Acocks' (1988) Veld Types have become the *de facto* recognised baseline land cover in hydrological impact studies (Schulze, 2004). Based on a set of working rules for determining the water use coefficient, interception per rainday, root mass distribution in the top- and subsoils, a coefficient of infiltrability and index of suppression of soil water evaporation by a litter/mulch layer, month-by-month values of these attributes were developed by Schulze (2004) and are incorporated into the QCDB for each of the 70 Acocks' Veld Types covering southern Africa.

4.5.3.5 Soils

The *ACRU* model revolves around a daily multi-layer soil water budget, and operates with a surface layer and two active soil layers, topsoil and subsoil, in which rooting development and soil water extraction take place through evaporation and transpiration, as well as soil water uptake and drainage (Schulze, 1995). Therefore, the model requires the thickness of the topsoil and subsoil, as well as soil water content at the soil's lower limit (i.e. permanent wilting point), its drained upper limit (i.e. field capacity) and saturation for both the topsoil and subsoil; also the fraction of 'saturated' soil water (above drained upper limit) to be redistributed daily from the topsoil to the subsoil, and from the subsoil into the intermediate/groundwater store (Schulze, 1995). For this study the soils information from the 84 Broad Natural Homogenous Soil Zones of South Africa were used (Scotney, 1989, as cited by Schulze, 1997a). The area weighted average was calculated for each Quaternary Catchment for each of the abovementioned soils parameters, extracted and entered into the input database.

4.5.3.6 Streamflow control variables

The *ACRU* model contains a number of variables which control the generation of streamflow and runoff. The variables and input values used in this study are given in the paragraph which follows.

It is assumed that 30% of the total stormflow generated in a Quaternary Catchmnet would exit the Quaternary Catchment on the same day as the rainfall event which generated the stormflow. This is a value typical of the spatial scale of Quaternary Catchmnets (Schulze *et al,* 2004). On any particular day it is assumed that 0.9% of the groundwater store will become baseflow. This default value has been found to be representative of large parts of southern Africa (Schulze *et al,* 2004). The depth of the soil from which stormflow generation occurs is set to the thickness of the topsoil. The coefficient of initial abstraction is a variable in *ACRU* which is used to estimate the rainfall abstracted by interception, detention surface storage and initial infiltration before stormflow commences (Schulze, 1995). In this study it varies from month-to-month and between Quaternary Catchments as it is based on the land cover with values being input per QC according to Schulze (2004). Impervious areas were assumed to be negligible in this study and were, therefore, not considered.

4.5.3.7 Irrigation variables

For this study, irrigation of a unit of 1 hectare of a maize-equivalent crop in summer and a wheat equivalent crop in winter was simulated in each Quaternary Catchment. Irrigation was allowed in all months of the year were except April and October when tillage was assumed to take place. Demand irrigation scheduling was assumed, i.e. refilling of the soil profile to its drained upper limit as soon as the soil water content in the zone of maximum rooting activity had fallen below 50% of plant available water. For the purposes of this study the irrigation water was assumed to be provided from an unlimited supply of water.

4.5.3.8 Other input variables

Although *ACRU* provides the option of including inputs relating to peak discharge, sediment yield, wetlands and reservoirs, none of these were considered for this study on the detection of changes in hydrological responses over time.

4.6 Enhancement of the QCDB Rainfall Input Database Undertaken as Part of this Research

An important component of this dissertation project was the re-selection of the rainfall stations used to represent, or 'drive', rainfall in the various Quaternary Catchments. Previously, single rainfall stations had been selected to represent each of the 1946 Quaternary Catchments in the region (Meier, 1997). These stations contained infilled daily records from 1950 to 1993 and were part of the monitoring network of only the South African Weather Service (SAWS). In a recently completed WRC project, Lynch (2004) compiled a comprehensive up-to-date database (1950 – 2000) of infilled rainfall station data. This daily rainfall database consists of more than 300 million rainfall values from 12 153 rainfall stations. This database represents a considerably denser network of stations than that used in the original selection by Meier (1997) as it contains not only data collected by the SAWS, but also by various other organisations. Before discussing the method used to re-select the "driver" rainfall stations, some problems and basic requirements of rainfall networks are outlined and the rainfall network of southern Africa is evaluated.

4.6.1 Problems and basic requirements of rainfall networks

The measurement of rainfall is a simple procedure, provided that accuracy is not essential. Uncertainties in point rainfall measurement are the result of random and systematic errors (Schultz, 1985). Random errors include misreading of the raingauge, faulty instrumentation or incorrect data entry (Groisman and Legates, 1995). Systematic errors are attributable to the following:

- wind effects;
- wetting and evaporation losses;
- splash–in and –out effects;

- the contribution of fog;
- monitoring techniques;
- changes in the raingauge type; and/or
- changes in the environment surrounding the raingauge (Groisman and Legates, 1995).

Additionally, errors are introduced when extrapolating point rainfall data to an areal value (Boughton, 1981) to represent, for example, a Quaternary Catchment's daily rainfall.

In daily timestep hydrological modelling, the daily rainfall is the most important input, and daily rainfall is the most sensitive "driver" of hydrological responses. Bearing this and the problems mentioned above in mind, when a rainfall "driver" station is selected for a Quaternary Catchment, the rainfall station should

- have an already existing long and uninterrupted record of daily rainfall;
- display high quality and reliability of data; and
- be representative of the areal rainfall of the Quaternary Catchment.

4.6.2 The South African rainfall network

The comprehensive daily rainfall database compiled by Lynch (2004) contained data from rainfall stations of the monitoring networks of the SAWS, the Agricultural Research Council (ARC), the South African Sugarcane Research Institute (SASRI) and from municipalities, private companies and individuals. The breakdown of the number of rainfall stations per organisation for which daily rainfall data were available is given in Table 4.1.

Table 4.1 Number of rainfall stations per organisation in the southern African daily rainfall database (Lynch, 2004)

Organisation	Number of rainfall stations
SAWS	8281
Agricultural Research Council	2661
South African Sugarcane Research Institute	161
Private Individuals	1050
Total	12 153

The locations of all the rainfall stations across southern Africa, regardless of record quality and length, are shown in Figure 4.4a. The quality and length of record of these stations varied greatly. As mentioned, the length and quality of the rainfall record is of major concern in hydrological modelling, and also in climate change detection studies. In Figure 4.4 (top) the rainfall station coverage of southern Africa appears adequate. However, when only the rainfall stations with a usable record length of 50 years and longer (Figure 4.4 middle) are considered, the spatial distribution is significantly changed. The coverage is far sparser, with no usable stations in Lesotho and a very sparse coverage in the Northern Cape and Limpopo provinces. When mapping rainfall stations with a record length of 75 years and longer (Figure 4.4 bottom), the coverage of southern Africa is sparser still. KwaZulu-Natal has only two and the Limpopo province only three rainfall stations with a usable daily rainfall record longer than 75 years.

The daily rainfall data from all available rainfall stations were checked exhaustively by Lynch (2004) for various errors and anomalies, with missing or suspect data infilled using the following hierarchy of infilling techniques:

1. Expectation maximisation algorithm;
2. Median ratio method;
3. Inverse distance weighting; and a
4. Monthly infilling technique (Lynch, 2004).

Although every effort was taken by Lynch (2004) to remove, or correct for, various identified errors and anomalies, a rainfall database of this magnitude can never be rendered totally error free. From this database, a single rainfall station had to be selected to represent each Quaternary Catchment, with its data considered representative of the daily rainfall of that Quaternary Catchment. Bearing in mind the problems identified in Sections 4.5.1 and 4.5.2, the method of re-selection of rainfall stations is discussed below.

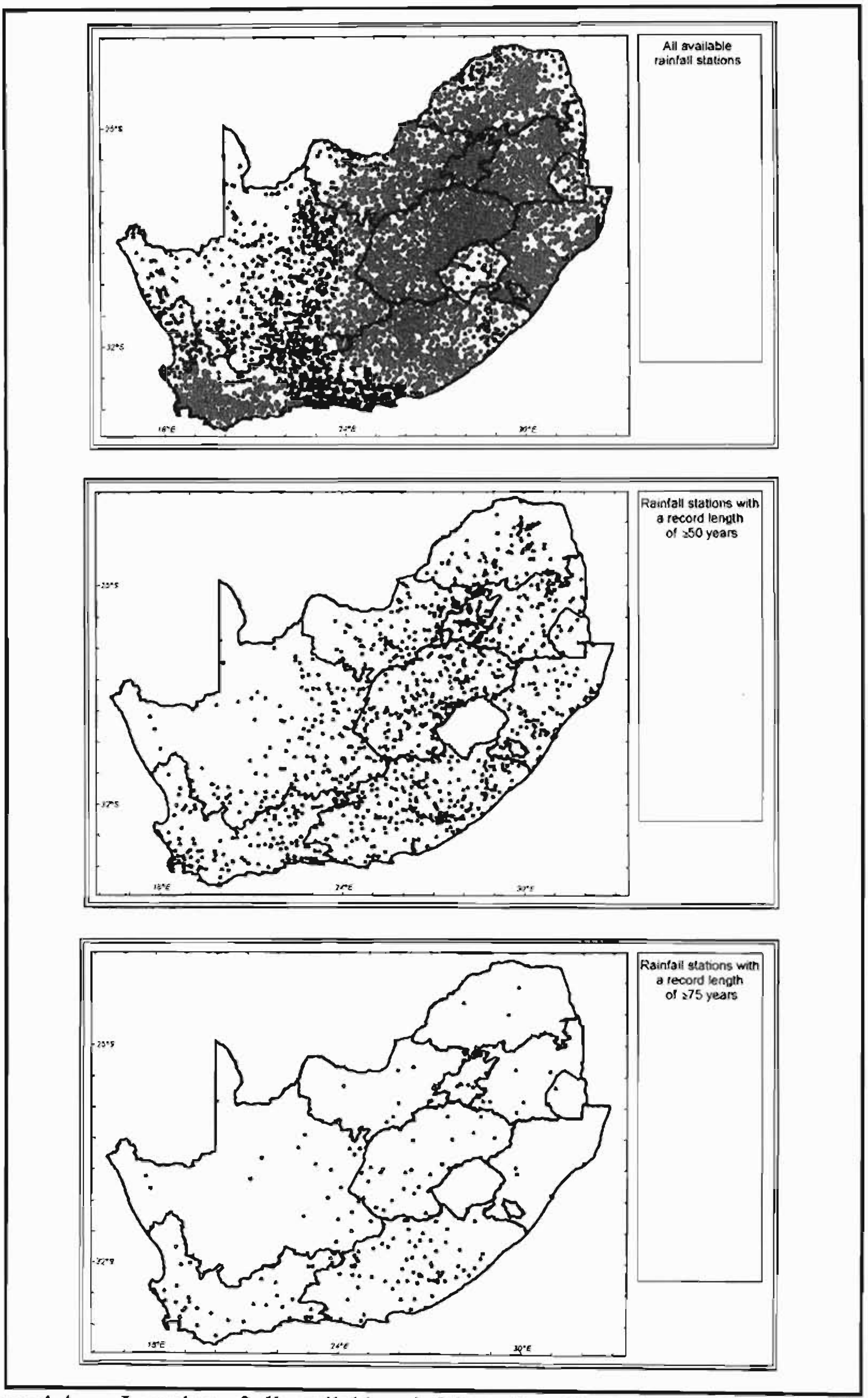

Figure 4.4 Location of all available rainfall stations (top), those with a record length of ≥ 50 years (middle), and with a record length of ≥75 years (bottom)

4.6.3 Method of analysis for re-selecting the Quaternary Catchments "driver" rainfall stations

The catchment centroid was determined for each of the 1946 Quaternary Catchments (QCs) using ArcView GIS. Using these co-ordinates, the Daily Rainfall Extraction Utility developed by Kunz (2004) was used to extract the 10 closest rainfall stations to each pair of the centroids' co-ordinates. These 10 stations are ranked by the Daily Rainfall Extraction Utility (Kunz, 2004) using the following 10 criteria:

1. Distance from the rainfall station to the point of interest, with this criterion being given the highest weighting;
2. Stations that are operational at the end date of the required period (i.e. the year 1999 in this study) are given a maximum score;
3. If the start year of the rainfall record is earlier than the start year required by the user (in this case the year 1950), the station is given a maximum score;
4. If the end year of the rainfall record is later than the end year required by the user (in this case the year 1999), the station is given a maximum score;
5. Stations with relatively long rainfall records compared to other stations nearby, are given maximum scores;
6. The 1' x 1' grid value mean annual precipitation (MAP; determined by techniques described in Lynch, 2004), for the point of interest (i.e. the centroid of the QC, in this case) is compared to the grid MAP of the station's location; if the two are similar a maximum score is given;
7. The 1' x 1' grid value MAP for the point of interest (the QC centroid) is compared to the observed MAP of the rainfall station whose suitability is being tested. If the two are similar a maximum score is given;
8. The higher the reliability (i.e. the higher the percentage of actual data vs infilled values) of the rainfall station's record, the higher the score given;
9. The lower the fraction of infilled record (as a result of poor quality data or missing values), the higher the score given; and
10. The lower the portion of missing record (i.e. years missing from the requested period), the higher the score given (Kunz, 2004).

Although the Daily Rainfall Extraction Utility's method of ranking the stations is comprehensive and thorough, there are certain factors which it does not compensate for. These include

- not taking account of the siting of the rainfall station within the catchment with regard to local topographic features and/or prevailing weather conditions;
- the method's being restricted to extracting and analysing daily rainfall from only the nearest 10 raingauges when there may be more rainfall stations in the Quaternary Catchment, or in the vicinity of the Quaternary Catchment, that may be better suited to act as the "driver" station; and
- the method's not including a 'human experience' factor.

Therefore, it was decided that the best ranked station by the Kunz (2004) Daily Rainfall Extraction Utility would not automatically be chosen as representative of the Quaternary Catchment's rainfall, but rather that each Quaternary Catchment's selection of rainfall station should, in addition, be evaluated manually.

Using ArcView with a MAP grid, a Digital Elevation Model (DEM) at 200 m spatial resolution, the Quaternary Catchment's shapefile and the rainfall station shapefile, along with the 10 rainfall stations extracted by the Daily Rainfall Extraction Utility (Kunz, 2004), each of the 1946 Quaternary Catchments was examined manually and the best rainfall station for that Quaternary Catchment was decided upon by considering the following:

- the reliability of the record;
- the ranking given by the Daily Rainfall Extraction Utility;
- the topography of the catchment, i.e. the altitude of the rainfall station compared to the average altitude of the catchment;
- prevailing weather direction; and to a large extent
- hydrological knowledge/experience of a team of evaluators at the School of Bioresources Engineering and Environmental Hydrology.

If the QC contained more rainfall stations then the 10 extracted, or if the reliability of each of the 10 rainfall stations was poor, the catchment was flagged, and the station selection procedure re-visited. In these cases the Daily Rainfall Extraction Utility

(Kunz, 2004) was re-run, and 20 rainfall stations (instead of 10) were extracted, with the representative rainfall station then being chosen according to the criteria listed above.

4.7 An Evaluation of the Re-Selected "driver" Rainfall Stations

Shown in Figure 4.5 are the selected "driver" rainfall stations and the Quaternary Catchment boundaries. As may be seen, for some QCs no suitable "driver" rainfall station was found within the QC. For such QCs the "driver" rainfall station would, therefore, be located outside of the QC and may represent the rainfall of more than one QC. This does not imply that no rainfall stations exist in that QC, although this may be the case. It simply means that the best representative rainfall station of that QCs rainfall is not located within the QC. By the techniques described in Chapter 4.5.3, 1 248 rainfall stations were chosen to 'drive' the rainfall of the 1 946 QCs. Nearly twenty-five percent (or 486) of the chosen "driver" rainfall stations represented more than one QC. There are two rainfall stations which 'drive' 7 catchments each, and a further two rainfall stations which 'drive' 6 catchments each. Table 4.2 provides a breakdown of the number of rainfall stations, the data from which are 'driving' the hydrology of more than one Quaternary Catchment.

Table 4.2 Breakdown of rainfall stations used to 'drive' the hydrology in the more than one Quaternary Catchment

No. of QCs a Rainfall Station Drives	No. of Rainfall Stations	% of Total No. of Stations Used
2	334	17.16
3	110	5.65
4	30	1.54
5	8	0.41
6	2	0.10
7	2	0.10
Total	486	24.96

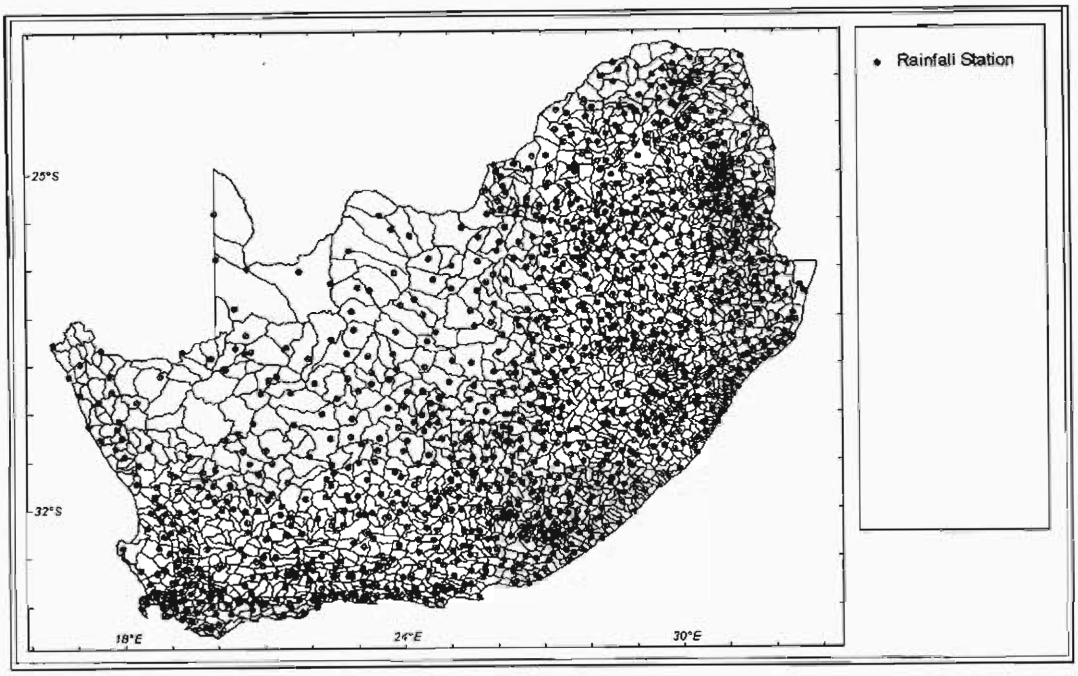

Figure 4.5 Selected "driver" rainfall stations for Quaternary Catchments

As already mentioned, the reliability of a station's record was an important selection criterion. The reliability of the rainfall record is the percentage of days in a required data period (in this case 1950 – 1999) for which there is a reliable observed rainfall record. The reliability of the rainfall record is an important factor, as a sample error in rainfall will be amplified when the record is used for hydrological modelling purposes to generate simulated streamflow or other variables. The average reliability of the rainfall stations selected was 79.2 %, with the highest reliability of a chosen station being 100% and the lowest reliability of a chosen rainfall station being 23.9%. Nearly 50% of the selected rainfall stations had a reliability of 95% or higher. The breakdown of the reliability of the rainfall stations' records is shown in Table 4.3. Other factors considered in the re-selection were the rankings given to the rainfall station by the Rainfall Extraction Utility. Of the selected rainfall stations, 73.23% were ranked number 1. The distance of the rainfall station from the centroid was also considered. However, only 20.5% of the chosen rainfall stations were closest to the centroid. Again that breakdown is shown in Table 4.4.

Table 4.3 Breakdown of rainfall station reliability

Reliability (%)	% of selected stations
100 – 95	49.589
95 – 90	8.532
90 – 80	12.077
80 – 70	12.334
70 – 60	8.687
60 – 50	5.959
50 – 30	2.335
< 30	0.469
Total	100

Table 4.4 Statistics of the selected rainfall stations according to the ranking given by the Daily Rainfall Extraction Utility of Kunz's (2004)

Rank	No. of Stations	% of Total	Average Reliability (%)	% Closest to Centroid	Average Record Length (years)
Rank 1	1425	73.23	87.6	25.75	111
Rank 2	261	13.41	82.4	9.58	108
Rank 3	56	2.88	75.5	8.93	102
Rank 4	23	1.18	76.9	8.70	92
Rank 5	4	0.21	63.9	0.00	103
Revisited	177	9.10	88.9	0.00	
Total	1946	100	79.2	20.50	110

Figure 4.6 illustrates the reliability of the chosen rainfall stations for the QCs in South Africa, Lesotho and Swaziland. What is immediately evident is the large portion of the region covered by rainfall stations with a reliability in excess of 90%. The cluster of QCs in the Drakensberg mountains/Lesotho region, represented by rainfall stations with a poor reliability, is also clearly evident. Other clusters of low reliability are evident in parts of the Western Cape mountains region, and along the northeastern border of South Africa with Mozambique. The repercussions of poor data reliability in the two specific mountainous high rainfall and runoff regions could be immense, because the Drakensberg/Lesotho region supplies water to the Lesotho Highlands Water Scheme and to South Africa's economic heartland of Gauteng while the Western Cape region is already a highly water stressed one.

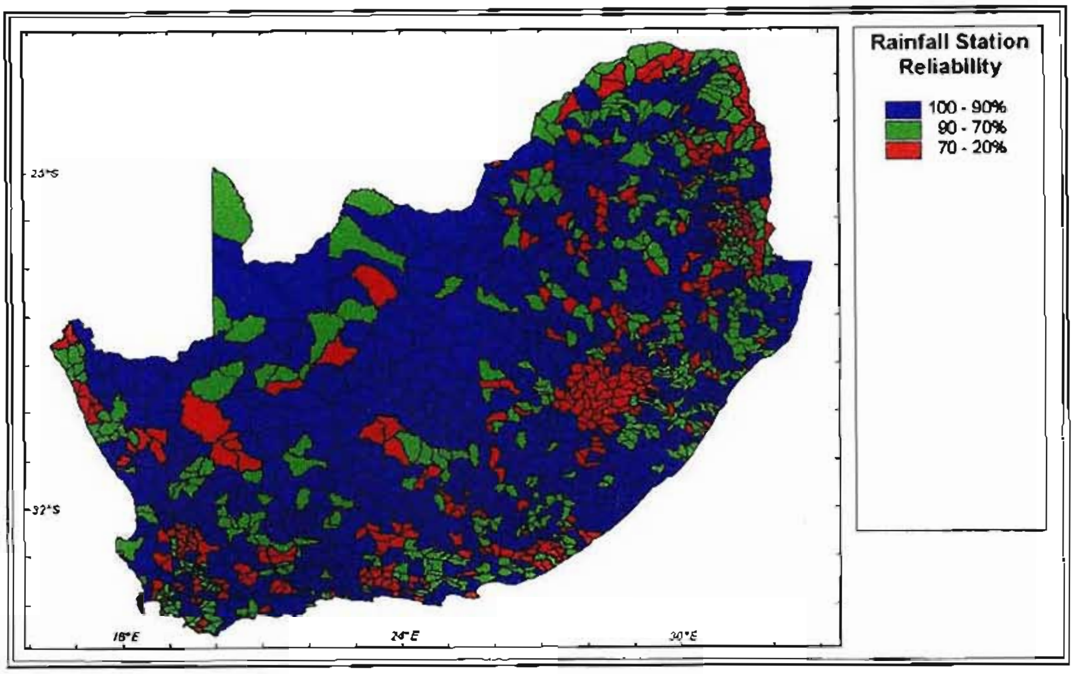

Figure 4.6 Reliability of daily rainfall at stations selected to represent each Quaternary Catchment in southern Africa

Since the rainfall stations selected were from the rainfall database developed by Lynch (2004), the length of the rainfall record is not the actual length, but rather the length of the observed plus infilled record. Figure 4.7 shows those "driver" rainfall stations which have a record length (observed and infilled) of 75 years and longer in addition to having a reliability of 95% and greater. These "driver" rainfall stations have each been allocated a 35 km radius buffer, representing an area of 3 850 km^2 per raingauge, which is far in excess of the 'ideal' area to be represented by one raingauge in a region with largely convective rainfall, and considerably larger than the average area of a QC, which is 651 km^2 . Even with this unrealistically large area represented by a single rainfall station, there are many QCs not covered by a high quality "driver" rainfall station. Most of the QCs in Lesotho, much of Swaziland and the Northern Cape are not covered by a high quality raingauge, neither are QCs along the Limpopo/Mozambique border or in the Western Cape mountain regions. If, however, each raingauge is buffered by a 10 km radius, which could represent an individual thunderstorm cell, then Figure 4.8 clearly shows that the rainfall station network is not yet ideal for detailed regional distributed hydrological modelling.

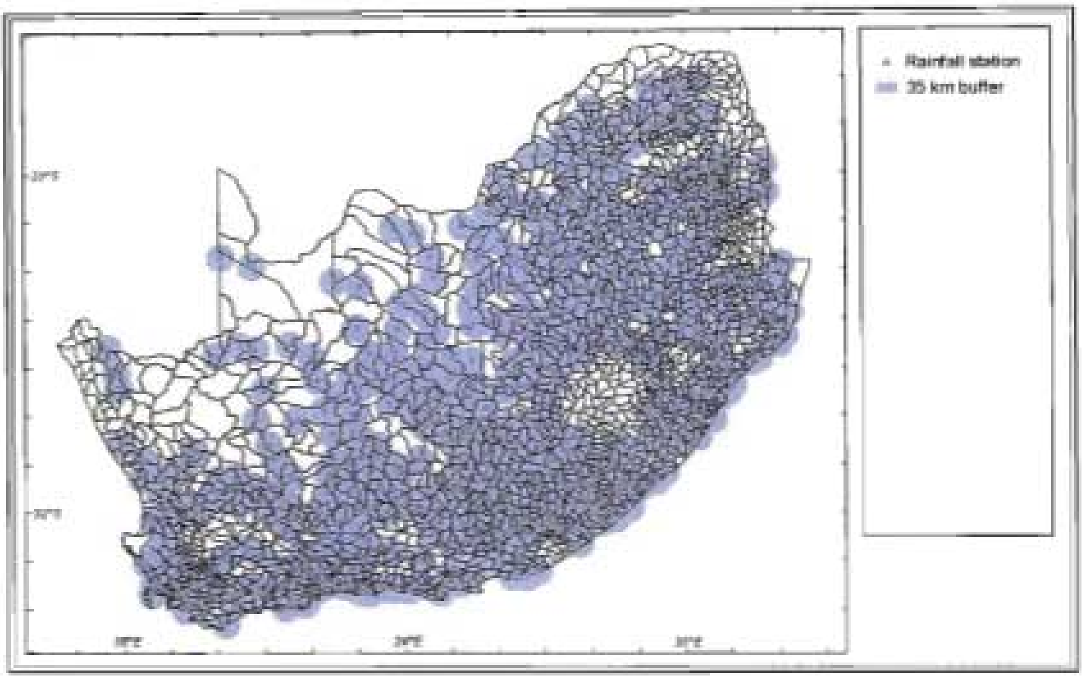

Figure 4.7 "Driver" rainfall stations with a record length (observed and infilled) of 75 years or more and a reliability of 95% or more, with a buffer of 35 km radius

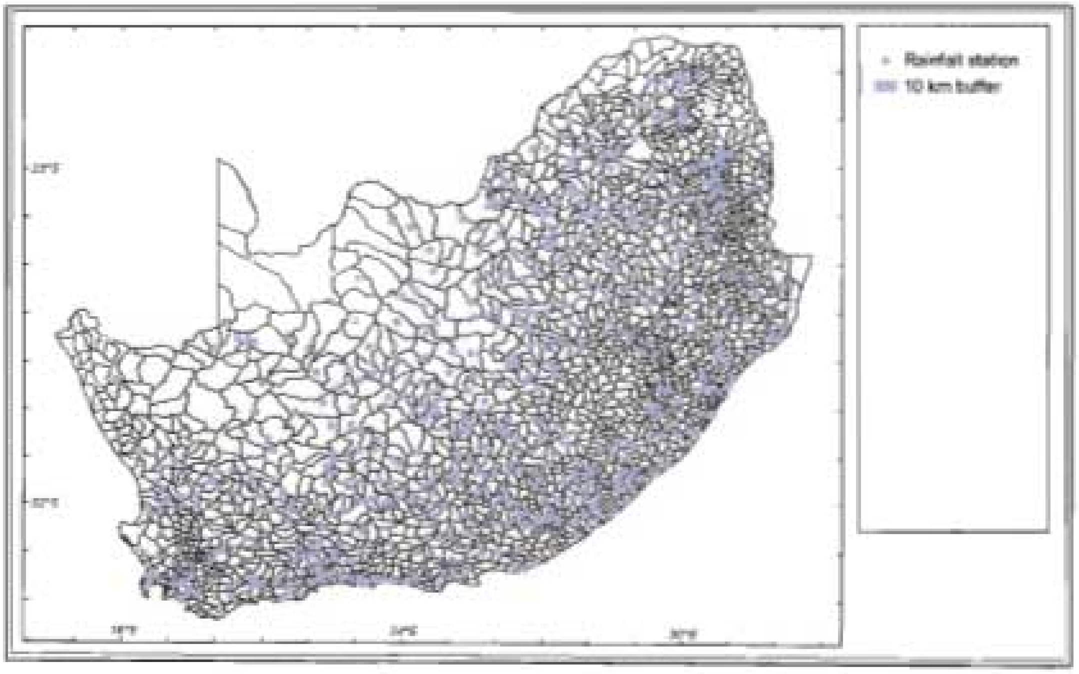

Figure 4.8 "Driver" rainfall stations with a record length (observed and infilled) of 75 years or more and a reliability of 95% or more, with a buffer of 10 km radius

The occurrence of QCs whose hydrology is 'driven' by data from rainfall stations with low reliability in the high lying areas of the Western Cape and Drakensberg mountains (Figure 4.6) leads to the suggestion that rainfall station reliability may be inversely related to altitude. This hypothesis would also be supported by hydrological intuition, for high lying areas are not densely inhabited, nor are there extensive road networks and the areas tend to be rugged. These factors make siting of rainfall stations difficult; furthermore, reading the gauge on a daily basis is often not feasible due to problems of access. Additionally, to place a recording raingauge in mountainous regions is seldom feasible, as instrument vandalism is common. However, when plotting rainfall station reliability against rainfall station altitude (Figure 4.9) no relationship between the two is evident.

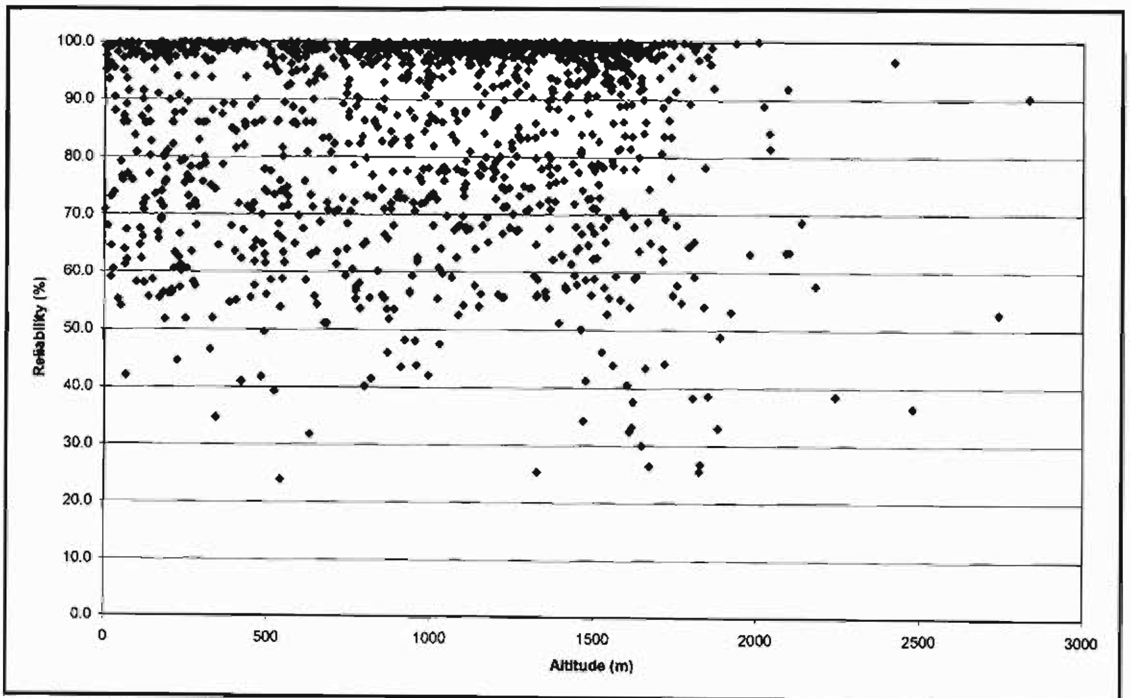

Figure 4.9 Plot of reliability of "driver" rainfall station data vs rainfall station altitude

Appendix 1 lists the rainfall station the data from which 'drives' each QC, the reliability of the rainfall station, the rainfall station's record length, distance from the centroid, the rainfall station MAP and the catchment MAP.

4.8 Concluding Remarks on the Re-Selection of the "Driver" Rainfall Stations for the QCDB

The selected rainfall stations for each Quaternary Catchment generally have data of high quality, with adequate reliability and record length. The rainfall station selection was based on a number of possible influences on the quality of the record. As already highlighted, the Drakensberg and Western Cape mountain areas and the northernmost parts of South Africa need to be evaluated in regard to their rainfall station networks, as in those areas the reliability of data at the rainfall stations is low. A considerable proportion of southern Africa's water resources have their origin in such high lying areas, and it is in these areas that the rainfall, and thus runoff, gradients are the steepest and the strong curvilinear relationship between rainfall and runoff is at the high end of the curve. The high lying mountainous areas are critical areas that are highly sensitive to climate or land use change; however, these are the areas which have the lowest rainfall network reliability.

All rainfall stations selected is this study need to be considered in regard to the monitoring network in South Africa and should, if at all possible, be retained as high quality rainfall stations, as they are crucial in the region's climate change detection and hydrological studies. This re-selection of the rainfall stations is likely to be used extensively for the next five to ten years. It is for that reason that great care and a large amount of time were invested in making what is believed to be the best selection possible.

The principles suggest by Karl and Easterling (1999), as outlined in Section 2.3.1 of Chapter 2, should be applied to all rainfall stations selected by this study. A management plan needs to be drawn up to address the implementation and maintenance of raingauges, especially in high lying areas, otherwise any detection of changes in rainfall characteristics *per se*, or hydrological manifestations of changes in rainfall patterns through modelling, may be missed.

5. DETECTION OF TRENDS OVER TIME IN HYDROLOGICAL DRIVERS AND RESPONSES OVER SOUTHERN AFRICA

5.1 Hypotheses on Changes in Hydrological Drivers and Responses with Global Warming

The hydrology of a landscape is characterised as a dynamic, non-linearly lagged and cascading system with complex feedforwards and feedbacks (Schulze, 1995). It may be expressed by the hydrological equation, which, when reduced to its simplest form for an undisturbed catchment with no dams, abstractions or interbasin water transfers, can be described as:

$$Q = P - E \pm \Delta S$$

where

Q = streamflow (mm equivalent),
P = precipitation (mm),
E = total evaporation (mm), previously termed "actual evapotranspiration," and
ΔS = changes in water storages (surface, soil, groundwater).

If streamflow is regarded the main hydrological response variable in water resource management, the driver variables of the hydrological equation are precipitation and total evaporation. Total evaporation comprises three components, *viz.* plant transpiration, soil water evaporation and open water evaporation from water surfaces or water intercepted by vegetation before it reaches the ground (Schulze, 1997b). A primary driver of all three components of total evaporation is temperature (Schulze *et al.*, 2001), either when used directly or as a surrogate in, for example, estimations of net radiation. Changes in various temperature parameters over the past 51 years over many parts of southern Africa have already been identified (Chapter 3). These include changes in the means of minimum and maximum temperature as well as changes in the ends of the temperature distribution. These changes in temperature are hypothesised to manifest themselves in changes in the evaporation components.

Changes in storages have an effect on the streamflow of a catchment. The changes in storage comprise changes in surface water storage, soil water storage and groundwater storage. Soil water content is the most variable of the three on a day-to-day basis. It is primarily determined by transpiration and soil water evaporation losses, balanced by recharge from precipitation. Temperature is a primary determinant of soil water evaporation and, as found in Chapter 3, changes over time in the temperature regime have been noted. Thus, if precipitation has remained reasonably constant, changes in soil water content are hypothesised to have occurred over time.

The magnitude of streamflow generated depends primarily on the amount of precipitation in an event, with this streamflow responding non-linearly to the precipitation, largely according to antecedent soil moisture conditions. With temperature considered to be one of the primary determinants of evaporation, and consequently of soil water content, it is hypothesised on the basis of temperature changes alone (precipitation presumed constant) that changes in streamflow may already have become noticeable in the past 50 years. Such changes may manifest themselves as changes in the medians of annual streamflows, the 90th or 10th percentiles (i.e. highest flows in 10 years and the lowest in 10, respectively) of annual, summer or winter streamflows, or the variability of flows, which may be expressed as the range between the 90th and 10th percentiles of streamflows. Changes in streamflows may, furthermore, be evident through shifts in the seasonality of streamflows (i.e. the time period in which highest flows occurs) or the concentration of the streamflow (i.e. the magnitude of flow during the period of highest flows in relation to annual flow).

Irrigation water demands by crops are controlled by the interplay of precipitation, soil water content and evaporation (both transpiration and soil water evaporation). Thus, as temperature has a direct effect on both the evaporation process and soil water content, it is hypothesised that with changes in temperature already evident (*cf.* Chapter 3), changes over time in irrigation water demand may already be evident. It should, however, be noted at this juncture that with enhanced atmospheric concentrations of CO_2 anticipated in a future climate, the CO_2 "fertilization effect" will not only have an effect on photosynthetic rates, but that with plant stomatal resistance hypothesised to increase, a reduction in transpiration is set to occur, with this relationship, however, being complex.

Following on the above discussion on possible changes to hydrological drivers and responses, the next section outlines the types of analyses carried out to determine whether these hypothesised changes are evident as yet in southern Africa.

5.2 Analyses Undertaken to Determine Whether Changes in Hydrological Drivers and Responses are Evident Yet

The results presented in this chapter are based on agrohydrological simulations and not on observations. Although observed streamflows are available at the outflows of a number of Quaternary Catchments, there is no explicit method of removing the effects land use activities (e.g. urbanisation, afforestation, overgrazing, tillage practices) and channel flow manipulations (e.g. reservoirs, abstractions, return flows, inter-basin transfers) have had on the observed record of streamflow over time. It is for these reasons that simulated, rather than observed, streamflows are used for the analyses as the physiography, land use and channel characteristics can then be held constant over the simulation period, in this case the 50-year period 1950-1999, with all human impacts being nullified and any changes manifested thus being attributable directly to changes in the climate record, i.e. daily precipitation and temperature.

Two forms of analyses were explored, *viz.* the application of the Mann-Kendall test for trends in a time series and a split-sample analysis. The Mann-Kendall test, as outlined in Section 2.4.4, was applied to the annual accumulated daily streamflow values for the 1946 Quaternary Catchments (QCs) for a 50 year daily climate record. However, owing to the high inter- and intra-annual variability, and the large number of zero flows, in the streamflow simulations the Mann-Kendall test was found to be too stringent in identifying trends over time. The alternative analysis selected was therefore a split-sample analysis. Two periods of climate input data, *viz.* 1950-1969 and 1980-1999, representing an earlier and a more recent time period, were extracted and comparisons made for various hydrological drivers and responses. This second method was found to be more robust and appropriate to hydrological trend analysis.

The medians, rather than the means, of the various hydrological drivers and responses were compared since the mean, unlike the median, is highly influenced by outliers in a non-normally distributed series such as streamflow, which has a lower value (zero) but no upper limit. It is equidistant from both extremes.

Furthermore, instead of comparing the coefficients of variation for the two respective periods, the range between the 10th and 90th percentiles of the two periods was compared. The coefficient of variation is a measure of dispersion of the values for a particular variable and is therefore affected by the outliers and extremes. The range between the 10th and 90th percentiles of the selected variables is not affected by outliers, and thus was chosen as a more robust measure of changes in distribution.

5.3 Modelling Assumptions Made

The *ACRU* model (Schulze, 1995 and updates) was selected for trend detection studies when using the split-sample method. The model requires various inputs to simulate streamflow and other variables. Presented here is a short summary of the inputs used. Daily maximum and minimum temperature were obtained for each QC from a database developed recently by Schulze and Maharaj (2004). Daily rainfall data from stations derived to be representative of a QC's rainfall were obtained from a database developed by Lynch (2004), with the rainfall station selection described in Chapter 4.

As neither daily nor monthly A-pan nor Penman-Monteith type evaporation records existed for all 1946 QCs, a temperature-based potential evaporation equation was used to generate reference potential evaporation. The chosen equation was the Hargreaves and Samani (1985) daily equation, which has been found to give more realistic values in South Africa than other temperature-based equations of similar level of sophistication when compared with measured A-pan values (Pike, 1988) and with simulated values from the Penman-Monteith equation (Bezuidenhout, 2005). It is a conceptually based temperature driven method of calculating potential evaporation in which direct account is taken of daily extra-terrestrial radiation and implicit account is taken of vapour pressure deficit and net radiation by various temperature-based parameters.

Of importance when generating streamflows are the inputs for land cover and soils. For these analyses a baseline land cover was used, in this case Acocks' (1988) Veld Type.

For each QC the spatially dominant Veld Type was assigned. The monthly values used for the hydrological attributes of the baseline land cover, as required by the *ACRU* model, were those developed by Schulze (2004). With regard to the soils, the 84 Broad Natural Homogenous Soil Zones of the Institute for Soil, Climate and Water (ISCW) (Scotney, 1989, as cited by Schulze, 1997a) were used, with soils' hydrological information for each Soil Zone determined by Schulze (1997a). The Soil Zones were area-weighted for each QC and values for the thicknesses of the topsoil and subsoil, soil water content at permanent wilting point, drained upper limit and saturation for both the topsoil and subsoil, the fraction of 'saturated' soil water to be redistributed daily from the topsoil to the subsoil, and from the subsoil into the groundwater store were obtained from values published in Schulze (1997a). Both the soils and baseline land cover were assumed to remain constant over the 50 year simulation period.

The irrigation routine in the *ACRU* model was invoked for this study. A unit area of maize in summer, rotating with pasture in winter was irrigated for all months except April and October when lands were assumed to be tilled. The irrigated soil was set to be a standard sandy clay loam of 0.8m depth for all QCs to circumvent the problem of different soils in this climate-driven trend analysis. The irrigation schedule selected was demand irrigation, with the soil profile being filled to the drained upper limit of the soil when the soil water content in the zone of maximum rooting activity fell below 50% of plant available water.

Using the parameters described in summary form above, and in greater detail in Chapter 4, daily streamflow values and other hydrological outputs were obtained from the daily timestep *ACRU* agrohydrological model. Presented below are mapped results of an analysis of the daily output expressed as a ratio of output for the period 1980 – 1999 to the period 1950 – 1969. The blue scale on the maps indicates an improvement, or positive change, in the later period while a red scale indicates a worsening, or negative change, in the later period. The darker borders surrounding QCs designate the Department of Water Affairs and Forestry (DWAF) Primary Catchments. For simplicity the Keiskamma/Nahoon Primary Catchment will be referred to as the Keiskamma, the Mzimvubu/Umbashe Primary Catchment will be referred to as the Mzimvubu, the Mvoti/Mgeni/Mkomazi Primary Catchment will be referred to as the Mvoti, the Mfolozi/Pongola/Usutu Primary Catchment will be referred to as the

Mfolozi, and the Komati/Krokodil/Sabie Primary Catchment will be referred to as the Komati. These Primary Catchments are shown in Figure 5.1.

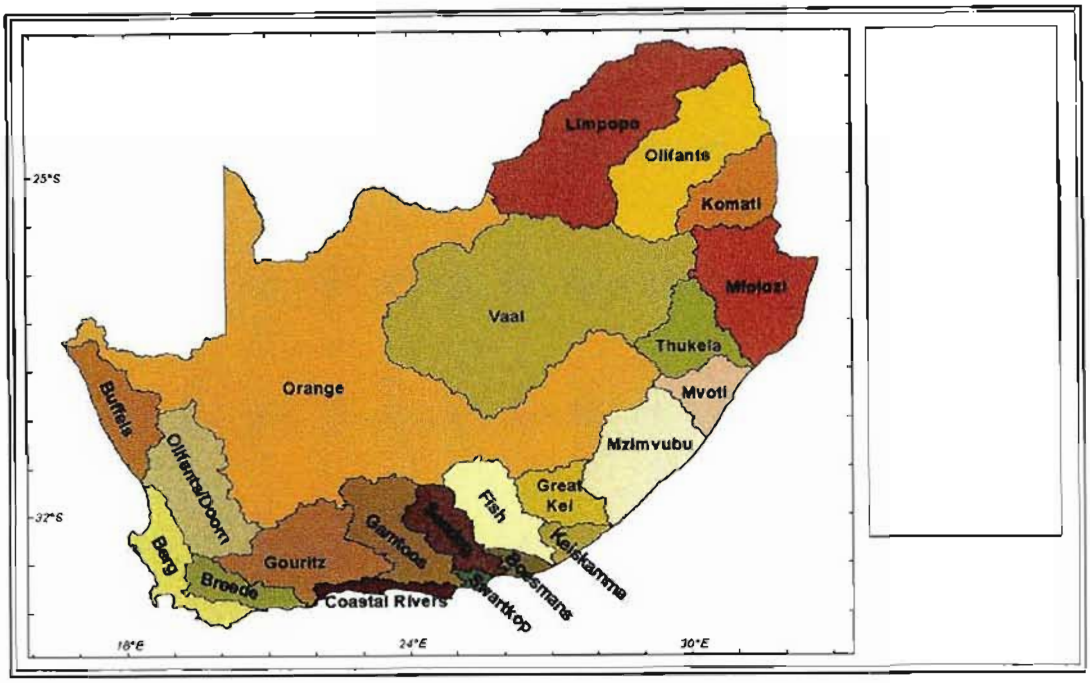

Figure 5.1 DWAF Primary Catchments, labelled as referred to in Chapter 5

5.4 Analysis of Simulated Median Annual Reference Potential Evaporation

Temperature is a primary direct and/or indirect driver of potential evaporation. As concluded in Chapter 3, changes in the temperature time series have been noted. The aim of this section is to determine whether these changes in temperature have manifested themselves as changes in simulated reference potential evaporation over southern Africa. Potential evaporation is the input to computing transpiration, total (i.e. "actual") evaporation and consequently soil moisture. It is therefore one of the determinants of changes in streamflow generation and irrigation water demand by crops. For purposes of this study the Hargreaves and Samani (1985) daily potential evaporation equation was used as the reference for potential evaporation (*cf.* Section 5.3). No verifications of this equation were carried out against observed data, as that did not constitute a part of this study.

Figure 5.2 shows the ratio of change in the simulated median annual reference potential evaporation between a later period, 1980 – 1999, and an earlier period 1950 – 1969.

The interior of the region shows an increase in the simulated median annual reference evaporation in the later period, particularly in the Vaal, Orange and Sondags Primary Catchments, as would be expected if climate change effects are already detectable.

The coastal areas, however, show a decrease in the median reference potential evaporation, particularly in the coastal areas of the Thukela, Mvoti, Boesmans, Great Kei, Swartkops, Breede and Berg Primary Catchments. This latter finding is somewhat unexpected since it was in the KwaZulu-Natal and Western Cape regions, which include the Thukela, Mvoti and Berg Primary Catchments, that increases in temperature were noted (*cf.* Chapter 3). These changes are relatively small, and by themselves are unlikely to have a marked hydrological impact. Hence, soil water content is analysed.

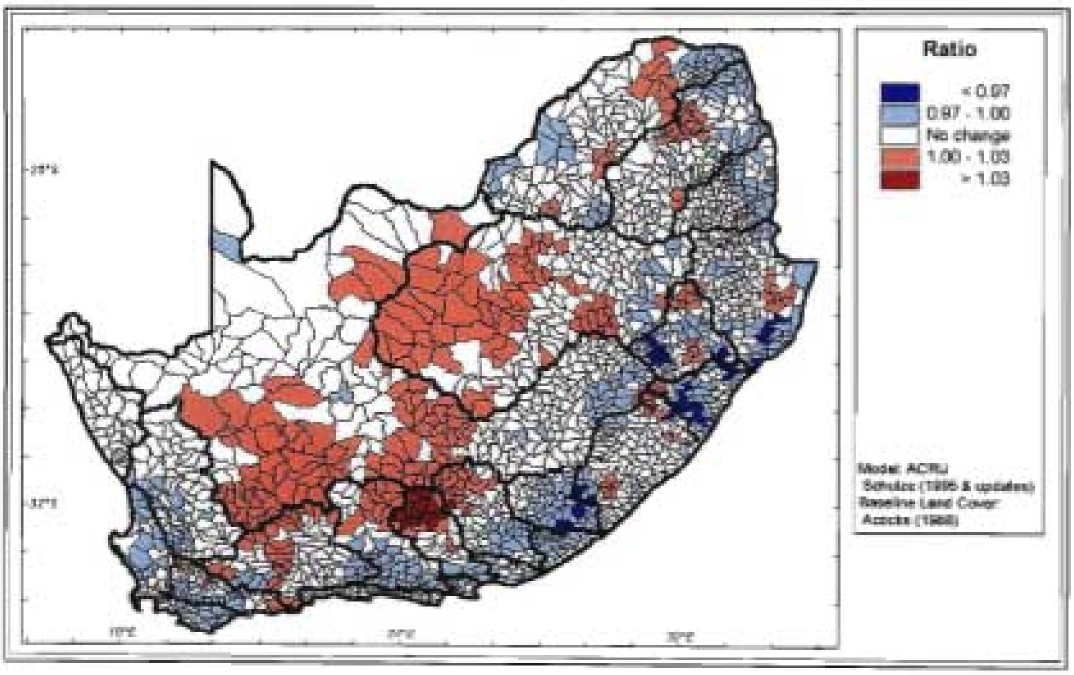

Figure 5.2 Ratio of later (1980 – 1999) to earlier (1950 – 1969) median annual reference potential evaporation

5.5 Analysis of Median Annual Soil Water Content of the Topsoil Horizon

As noted above, soil water content is dependent, *inter alia*, on potential evaporation. For this analysis, changes in water content of the topsoil was selected, as moisture content of topsoil is more dynamic than that of the subsoil. It is from the topsoil that soil water evaporation takes place; it is also the horizon in which most plant-water interactions occur, where the majority of root activity is, where recharge from rainfall first occurs, and where changes are thus more likely to be evident.

Figure 5.3 illustrates the ratio of change in the median annual soil water content of the topsoil horizon between a later period, 1980 – 1999, and an earlier period 1950 – 1969. Although it may seem that a number of QCs show a change in median annual soil water content, changes are not substantial, the value for the later period mostly being within 5% of that found for the earlier period. Most QCs in the Primary Catchments of the Berg and Olifants/Doorn show small increases in the median annual soil water content in the topsoil in the later period, which is consistent with the decreased reference potential evaporation in the later period in this area, while some QCs in these primary catchments show a decrease in median annual soil water content of the topsoil horizon. The slight changes noted in median annual soil water content of the topsoil horizon can be explained by the soil water content having a small range, with the median of the daily soil water content, over a year, tending to be near the middle of the range.

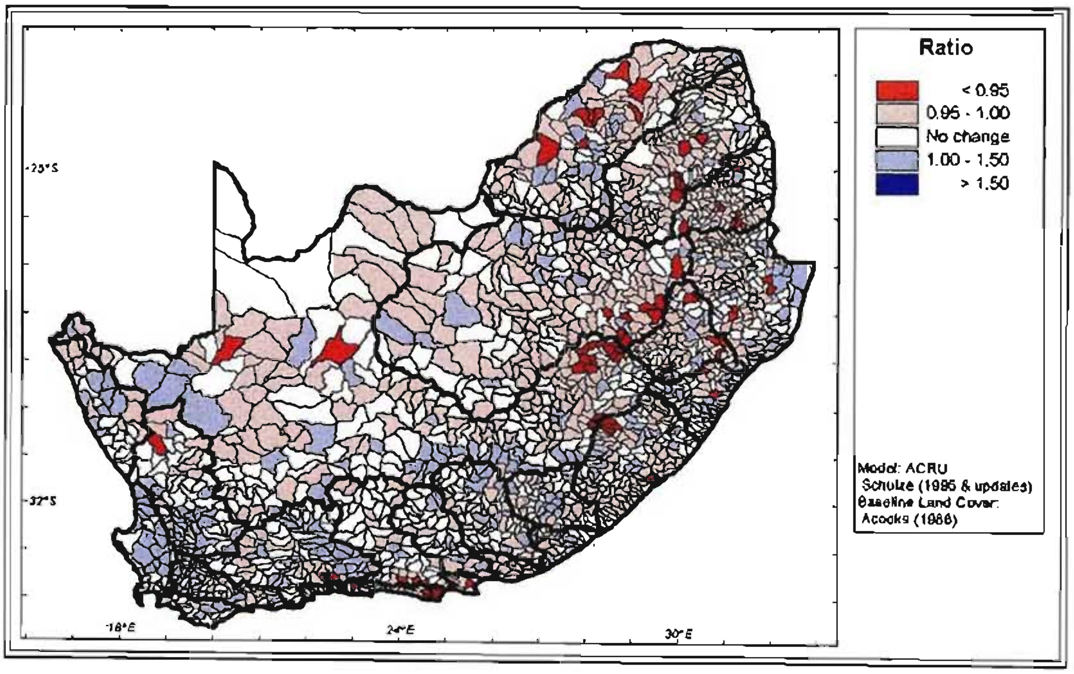

Figure 5.3 Ratio of later (1980 – 1999) to earlier (1950 – 1969) annual median soil water content in the topsoil

5.6 Trends over Time in Annual Accumulated Streamflows

Streamflows, as simulated by the *ACRU* model, consist of runoff from the QC under consideration plus any runoff contributions from all upstream QCs (Schulze, 1995). Runoff, i.e. the water yield from a given QC, is made up of stormflows plus baseflows as well as any seepage, normal flows and outflows from any reservoirs within a QC (Schulze, 1995). However, no reservoirs are considered in this study, thus runoff consists solely of stormflow and baseflow. Of importance to the streamflow generation in the *ACRU* model (beside input climatic data as well as land cover and soils information) is that

- a same-day stormflow response factor of 30% was assumed for each QC, with the remaining stormflow generated by a rainfall event "decaying" at 0.3 per day; and that
- the effective depth of soil from which stormflow generation took place was set to the thickness of the topsoil;
- that adjunct and disjunct impervious areas were considered to be negligible; and that
- the monthly value of the coefficient of initial abstraction varied seasonally according to the values assigned to the respective Acocks' Veld Types (Schulze, 2004).

The Mann-Kendall test as described in Chapter 2 was applied to annual totals of accumulated daily streamflows. Under conditions of climate change, changes in streamflows are hypothesised to occur, with decreases in streamflows in winter rainfall areas anticipated, but an unclear picture remaining over the summer and all year rainfall zones of southern Africa, however with decreases dominating (Engelbrecht, 2005; Hewitson *et al.*, 2005).

Figure 5.4 depicts the trends in annual accumulated streamflows which are statistically significant at the 95% confidence level. Red indicates a statistically significant decreasing trend, while blue indicates a statistically significant increasing trend, with light grey indicating that the QC showed no statistically significant trend.

The upper Orange Primary Catchment has a cluster of QCs showing a statistically significant decreasing trend in annual accumulated streamflows. This area is an important runoff generation area feeding into the Caledon River. Along the boundaries of the Orange and Mvoti Primary Catchments there are clusters of QCs showing a statistically significant increasing trend, as do clusters of QCs in the northern and southern Thukela Primary Catchment. Along the coast in the Mfolozi Primary Catchment there is a grouping of QCs showing a statistically significant increasing trend. The areas showing an increasing trend are already relatively wet compared to the remainder of South Africa, and if this trend continues it could cause problems to inhabitants of floodplains in impoverished areas.

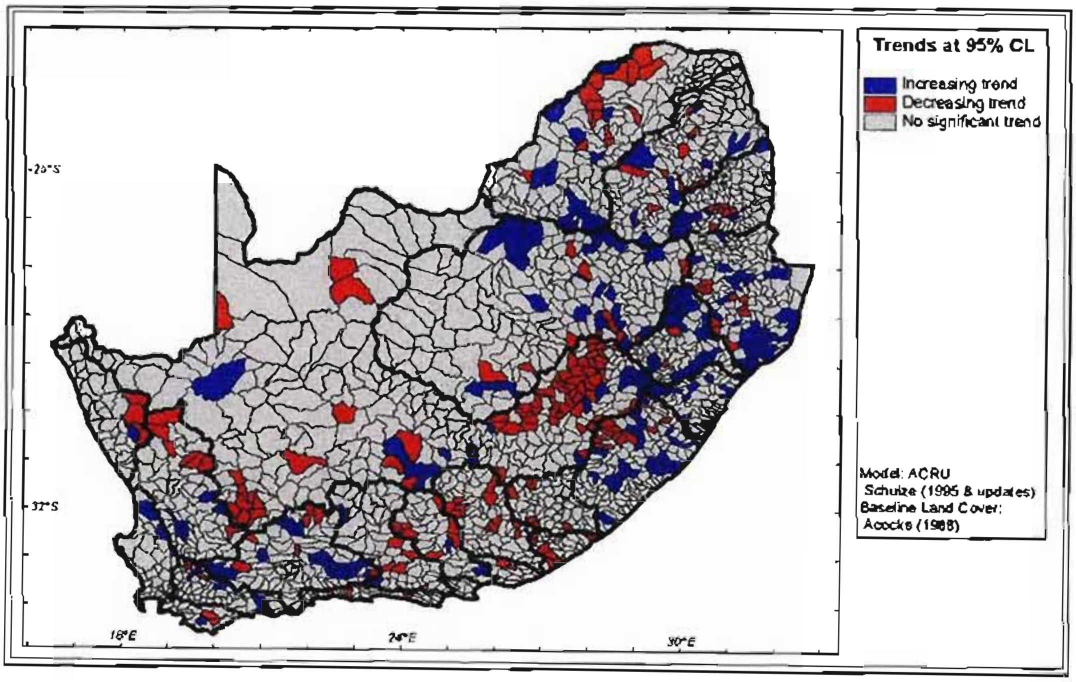

Figure 5.4 Trends over time at the 95% confidence level in accumulated annual totals of daily streamflows

5.7 Accumulated Streamflows in Median, Dry and Wet Years

The streamflows considered here are the total streamflows from the respective Quaternary Catchment, including contributions from all upstream Quaternary Catchments, as described in Chapter 5.6. Accumulated streamflow is an essential variable to consider because it integrates all upstream runoff which has been generated from spatially variable precipitation, physiography and land cover. It constitutes the total available water resource at any 'point' in a series of interlinked and cascading Quaternary Catchments, and it is therefore essential that water resource managers are aware of any climate-related changes which may have occurred over the 50 year time period. Again, the accumulated streamflows for which trends are analysed are simulated under baseline land cover conditions, and are not observed streamflows. Any changes identified may thus be attributed solely to changes in climatic variables as a given QC's physiography, soils and land cover were held constant for the entire period of analysis and the same model, with its inherent strengthens and weaknesses, was used throughout.

Figure 5.5 depicts a comparison of the median annual accumulated streamflows between 1950 to 1969 and 1980 to 1999, expressed in terms of a ratio increase or decrease in 1980 – 1999 values relative to those of 1950 – 1969. From Figure 5.5 it may be seen that no clearly defined large regions of increases or decreases in the median annual accumulated streamflow are evident, with many QCs not showing any significant change in flows. However, there are smaller clusters of QCs within various Primary Catchments displaying either increases or decreases in median annual accumulated streamflows in the later period. The Thukela, Mvoti, Mfolozi, Mzimvubu, Gouritz are all Primary Catchments that have a number of QCs with an increasing trend in median annual accumulated streamflows in the later period.

The Orange catchment has a number of QCs displaying a decrease in median annual accumulated streamflow in the later period, with a cluster of QCs in the upper reaches of the Orange basin showing a reduction of half or less of the median annual streamflow of the earlier period experienced in the later period. This is viewed as of particular importance as this is the area which feeds the Caledon subcatchment of the Orange, a vital source of water for major dams downstream. However, moving towards the mouth of the Orange catchment there are a few QCs that show an increase in median annual accumulated streamflow, of which some show the later period to be experiencing three times the median annual streamflow of the earlier period. These areas of the Orange Catchment are, however, arid and thus with little runoff generated. A small absolute increase or decrease may therefore be manifested as a large relative change, but with the increase or decrease having little impact on the available/usable surface water resources of the area. Other basins which have a number of QCs showing a decreasing trend are the Olifants/Doorn, Buffels and Gamtoos Primary Catchments.

Although changes in median flows are important, it is often the streamflow changes in the more 'extreme' years that are crucial to water resources planners and designers of hydraulic structures. Structures such as dams are designed to withstand conditions at the ends of distributions of flows. However, if these have changed over time, additional stress is placed on the structures and failures could occur, both with respect to more severe droughts and to more severe high flows. In regard to water resources planning, changes in the more extreme years can have far reaching effects on water allocations. Thus changes in the lowest flows in 10 years (10th percentile) and highest flows in 10 years (90th percentile) of annual accumulated streamflows between 1950 – 1969 and 1980 – 1999 are analysed. Changes in the range between the driest year and the wettest years in 10 are discussed in Section 5.8.

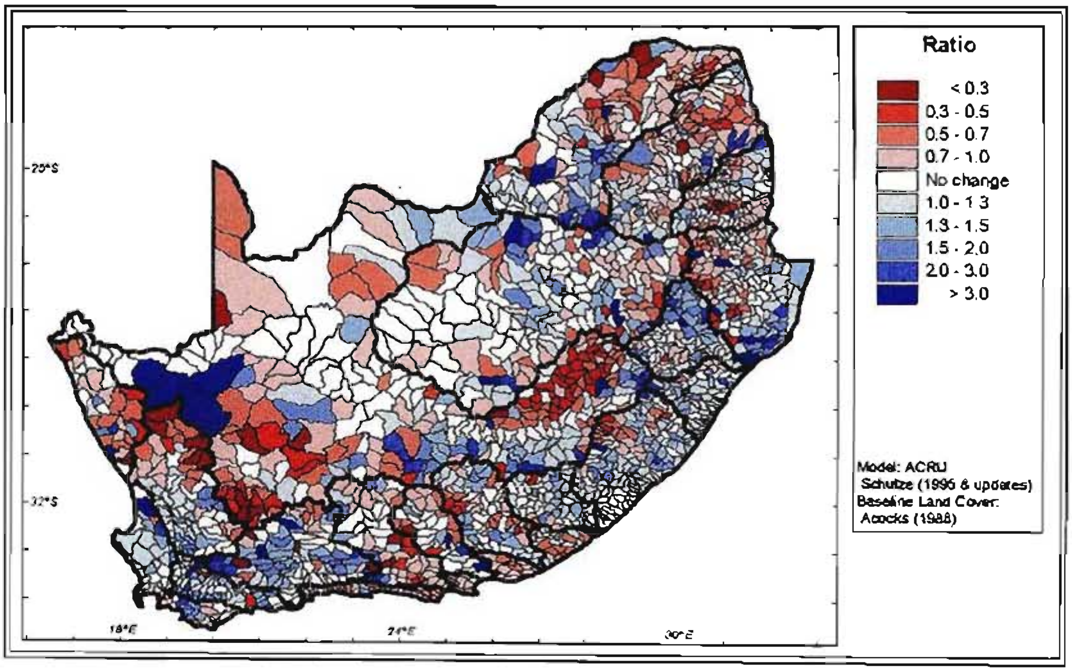

Figure 5.5 Ratio of later (1980 – 1999) to earlier (1950 – 1969) annual medians of accumulated streamflows

Figure 5.6 displays changes, expressed as a ratio, of the driest year in 10 of accumulated annual streamflow between a later period (1980 – 1999) and an earlier period (1950 – 1969). Changes in this variable indicate whether the dry periods are becoming more severe or not.

The red scale indicates a decrease in 1980 – 1999 flows in comparison to those of 1950 – 1969. The first noticeable difference results from the comparison in the 'driest' year in 10 to the medians is the amount of red displayed in the low flow years (Figure 5.6). There are a number of clusters of QCs showing a decrease in values of the lowest flow in 10 years in the later period. These are the Mfolozi, Komoti, Limpopo, Great Kei, , Keiskamma, Gamtoos and Vaal, and particularly the Sondags, Fish and Orange Primary Catchments where some QCs show less than a third of the earlier periods' streamflow in the later period.

The Primary Catchments with QCs showing an increase in the later period are the Berg, Breede and Gouritz basins. The increases shown are high, in the order of two to three times greater low flows in the later period. These Primary Catchments fall into the winter rainfall region, whereas the basins showing a decrease in the later period are in the summer rainfall region.

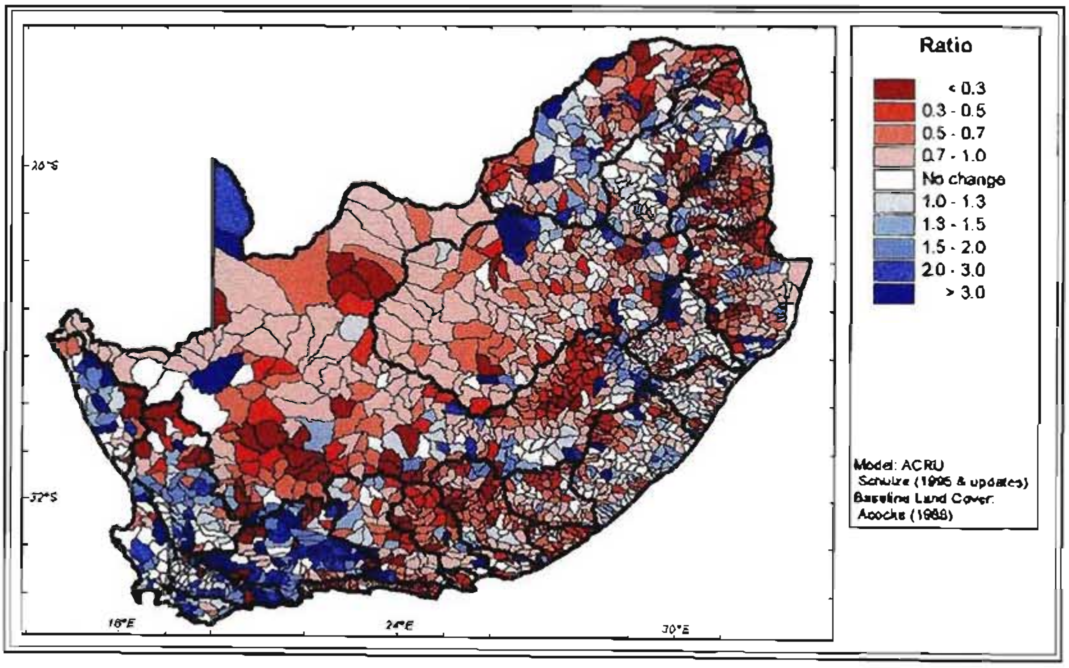

Figure 5.6 Ratio of later (1980 – 1999) to earlier (1950 – 1969) lowest annual accumulated streamflows in 10 years

Figure 5.7 shows a comparison of the highest accumulated annual streamflows in 10 years, expressed as the ratio between 1980 – 1999 flows with those of 1950 – 1969. Evident from Figure 5.7 are the large number of QCs showing an increase in highest flows in 10 years in the later period. The Primary Catchments in particular which have a large number of QCs displaying an increase in the later period are the Thukela, Mvoti, Mfolozi, Gouritz and Gamtoos. The Vaal Primary Catchment contains a number of QCs displaying an increase in the later period; however they are scattered throughout the basin rather than being clustered. The Mvoti, in particular, shows large increases in the order of 1.5 to 3 times greater in the later period.

QCs in the Olifants/Doorn and Buffels Primary Catchments show decreases in years with the highest flows in 10 years in the later period. Again the area which feeds the Caledon catchment, in the Orange Primary Catchment, shows decreases in the later period. The cluster of QCs showing decreases in the later period in the Olifants/Doorn, Buffels and lower Orange catchments tend to be in semi-arid areas, and thus the accumulated volume changes may be small despite the ratio changes being large. The overall impact this has on the water resources of the area may, therefore, not be significant.

The changes in median annual accumulated streamflows did not provide a strong signal as to whether an increase or decrease in streamflows had occurred. However, there is a strong indication from the analyses of the lowest flows in 10 years and highest flows in 10 years, that the more extreme flows at either end of the distribution are becoming even more extreme in the summer rainfall region, i.e. the low flows are decreasing in volume and the high flows increasing in volume.

The Mvoti and Thukela Primary Catchments are particularly prominent in showing increases in the highest flows in 10 years in the later period. The question arises that if increases in very high and decreases in the very low annual flows are already evident, sometimes in the order of greater than twice that of the earlier period, what the future may hold?

With evidence of differences between summer and winter rainfall regions in regard to increases and decreases in the 'driest' year in 10 and 'wettest' year in 10 between 1950 – 1969 and 1980 – 1999, the respective summer and winter season's lowest flows in 10 and highest flows in 10 are considered for this analysis. The summer months are defined as December, January and February and the winter months as June, July and August.

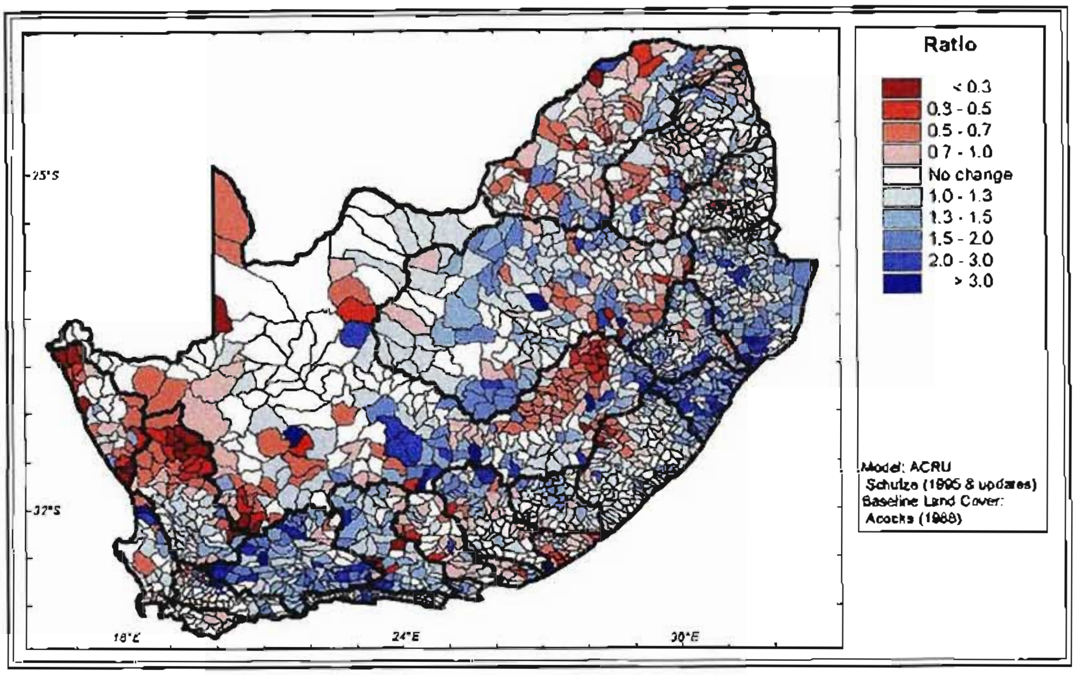

Figure 5.7 Ratio of later (1980 – 1999) to earlier (1950 – 1969) highest annual accumulated streamflows in 10 years

Figure 5.8 depicts spatially the ratio of 1980 – 1999 to 1950 – 1969 accumulated streamflows for the driest season in 10 of the summer months. From Figure 5.8 it may be seen that no clear spatial pattern of increases or decreases in the later period emerges, with most of the Primary Catchments displaying a patchwork of QCs with either no substantial change, or with decreases or increases in the later period of varying magnitudes, except in the southern most parts of the country where increases in the later period are evident.

The Buffels, Olifants/Doorn, Berg, Breede and Gouritz Primary Catchments, in the southern most parts of the country, each show a number of QCs with increases in the driest season in 10 of summer months' accumulated streamflows for the later period. A similar pattern is evident in the Thukela Primary Catchment. The QCs in the Orange Primary Catchment in the area of the Caledon tributary show a decrease in the lowest summer season flows in 10 years in the later period.

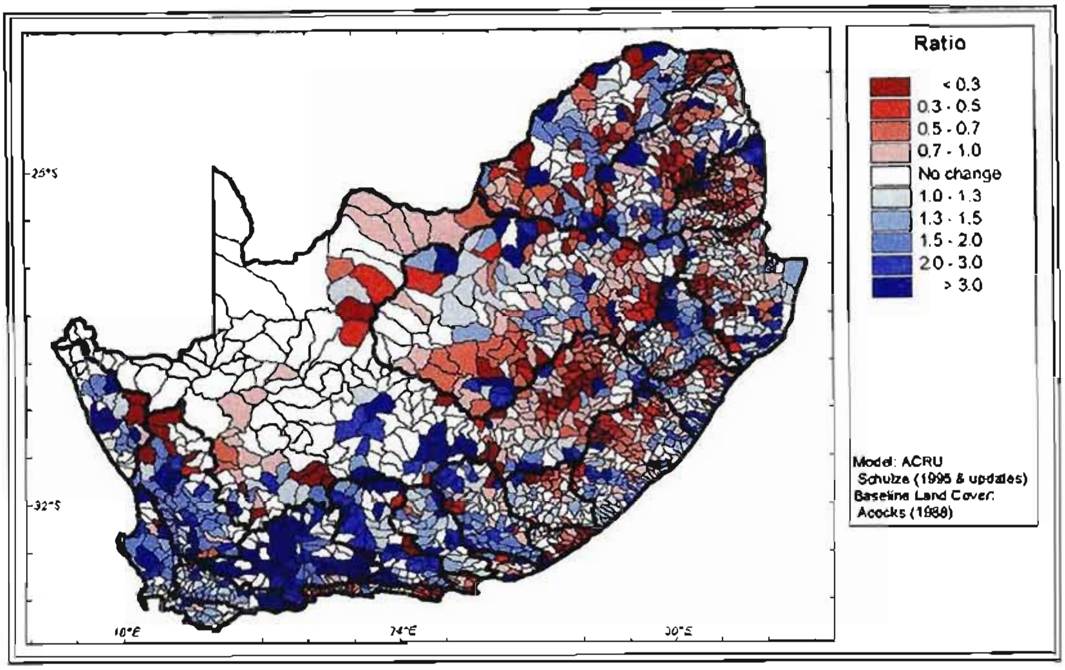

Figure 5.8 Ratio of later (1980 – 1999) to earlier (1950 – 1969) lowest accumulated summer months' streamflows in 10 years

Figure 5.9 depicts spatial changes in the ratio of accumulated streamflows for the wettest season in 10 of summer months in 1980 – 1999 vs 1950 – 1969. Immediately evident from Figure 5.9 are the QCs along the east coast of South Africa, which show an increase in the later period. The Mfolozi, Thukela, Mvoti, Mzimvubu, Great Kei, Fish, Sondags and Gouritz Primary Catchments have a majority of their QCs displaying an increase in the wettest season in 10 of summer months' accumulated streamflow in the later period. The increase in later period becomes greater when moving towards the coast and the outlets of the catchments. In the upper reaches of the Primary Catchments the later period is 1.3 to 2 times greater than the earlier period, at the outlets the later period is often 3 times greater.

The Orange Primary Catchment shows a mixture of QCs with increases or decreases in the later period. Again, the area of the Orange Primary Catchment which feeds the Caledon tributaries shows significant decreases in the later period. However, in the lower Orange Primary Catchment the QCs are showing an increase in the wettest season in 10 of summer months' accumulated streamflow in the later period. The Buffels Primary Catchment shows predominantly decreases in the wettest season in 10 in the later period.

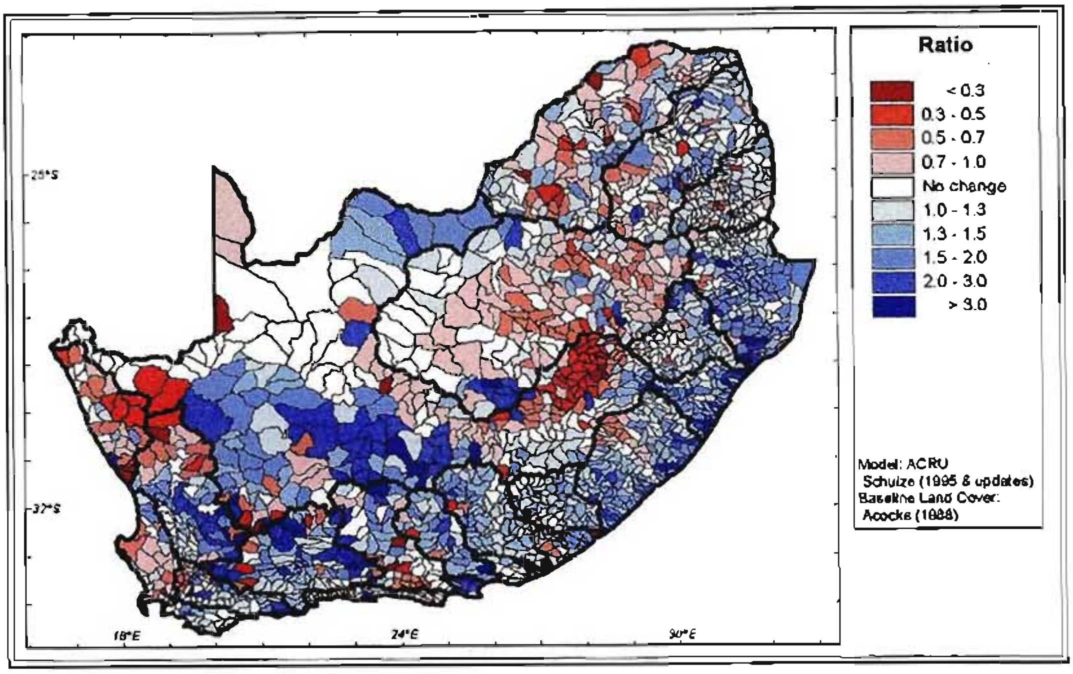

Figure 5.9 Ratio of later (1980 – 1999) to earlier (1950 – 1969) highest accumulated summer months' streamflows in 10 years

Figure 5.10 illustrates spatial changes in the ratio of 1980 – 1999 vs 1950 – 1969 of the lowest accumulated winter months' streamflows in 10 years. Figure 5.10 indicates that the winter rainfall region has already experienced an increase in the lowest accumulated winter months' streamflows in 10 years in the later period, while the summer rainfall region is tending towards a decrease in the lowest accumulated winter months' streamflows in 10 years in the later period.

The Berg and Breede Primary Catchments have a number of QCs showing strong increases in the lowest accumulated winter streamflows in 10 years in the later period, the increases in the later period being in the order of twice the magnitude of the earlier period and greater. The Olifants/Doorn Primary Catchment has a cluster of QCs in the lower reaches of the catchment showing a strong increase in the later period. These Primary Catchments all fall within the winter rainfall region of South Africa.

The Coastal Rivers, Swartkops, Fish, Mzimbubu, Mvoti, Mfolozi and Komati Primary Catchments have a number of QCs displaying a decrease in the driest season in 10 of the accumulated winter months' streamflows in the later period. The Orange Primary

Catchment has a number of QCs which too show a decrease in the later period, with the Caledon River Basin area again showing decreases.

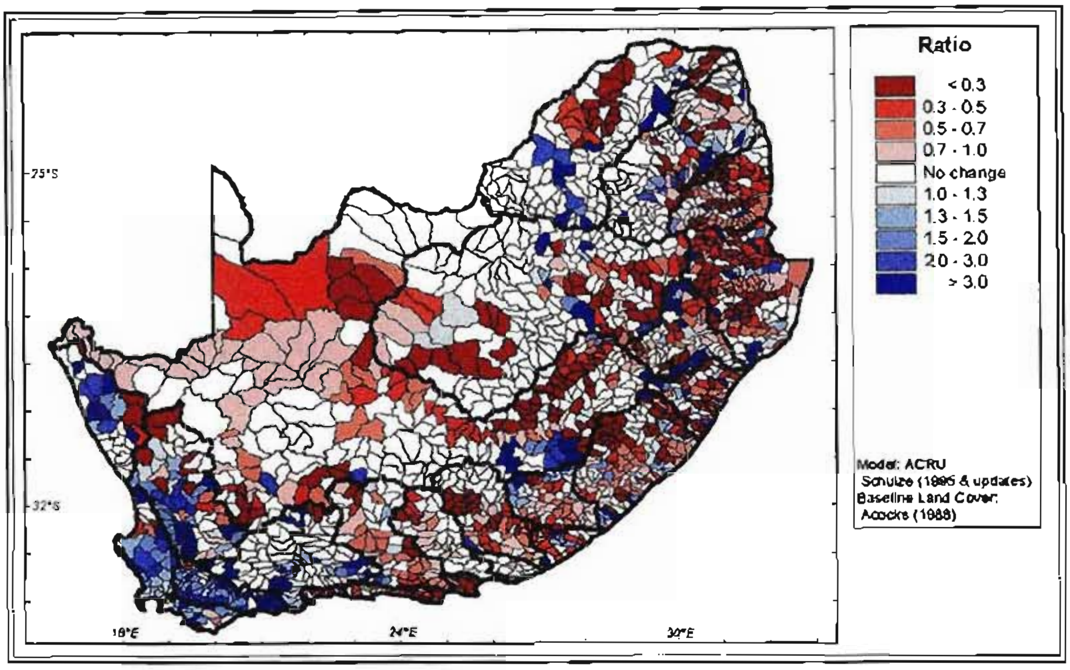

Figure 5.10 Ratio of later (1980 – 1999) to earlier (1950 – 1969) lowest accumulated winter months' streamflows in 10 years

Figure 5.11 shows ratio of the highest flow season in 10 of accumulated winter months' streamflows between the periods of 1980 – 1999 and 1950 – 1969. The Orange Primary Catchment shows both increases and decreases in the highest flows in 10 years of accumulated winter streamflows in the later period. The increases in the later period tend be more in the upper reaches of the catchment, while the decreases are in the lower reaches, with the latter seeming to be more predominant.

The Vaal Primary Catchment shows a mixture of increases and decreases in the highest flows in 10 years of accumulated winter streamflows in the later period. In the upper reaches of the Vaal Catchment a cluster of QCs display decreases of more than half of the earlier periods flows in the later period. In the lower reaches of the Vaal Catchment, QCs tend to show an increase in the later period.

In the Limpopo, Buffels, Olifants/Doorn, Sondags, Mzimvubu and Boesmans Primary Catchments the majority of QCs show a decrease in the highest flows in 10 years of accumulated winter months' streamflows in the later period. The Gouritz Primary Catchment has a cluster of QCs at its outlet showing a decrease in the highest flows in 10 years of accumulated winter streamflows in the later period.

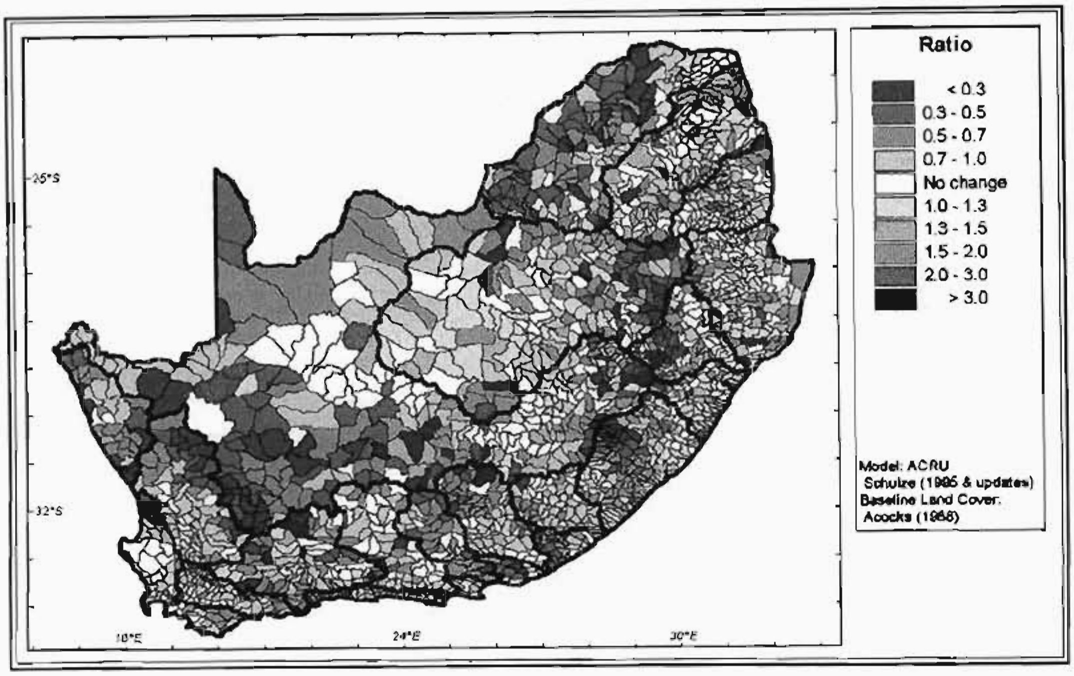

Figure 5.11 Ratio of later (1980 – 1999) to earlier (1950 – 1969) highest accumulated winter months' streamflows in 10 years

5.8 Ranges of Streamflows between High and Low Flow Years

Structures are designed to accommodate streamflows at both ends of the streamflow distribution. If, therefore, low flows are becoming more severe and simultaneously high flows are becoming more severe, structures have to be designed to accommodate a wider range of events, and the designs of both reservoir capacity and spillways need to be more conservative. Changes the lowest flows in 10 years and highest flows in 10 years, annually and seasonally for winter and summer months, have been shown to occur (*cf.* Figures 5.6 to 5.11). For that reason changes in the range between the lowest and highest flows in 10 years for annual streamflows, as well as for summer and winter seasons, are analysed.

Figure 5.12 shows changes in the range between the lowest and highest flows in 10 years of accumulated annual streamflows in terms of a ratio of 1980 – 1999 vs 1950 –

1969. This analysis gives an indication of whether the flow extremes are changing. An increase in the range is of concern for storage structures in particular.

The Primary Catchments which have most of their QCs showing an increase in the range between the lowest and highest flows in 10 years in the later period are the Vaal, Mvoti, Thukela, Mfolozi, Gouritz, Gamtoos, Coastal Rivers, Great Kei and Fish Catchments. The Mvoti and Mfolozi Primary Catchments, in particular, display an increase in the later period for most of its QCs, and the increases are in the order of 1.5 times and greater.

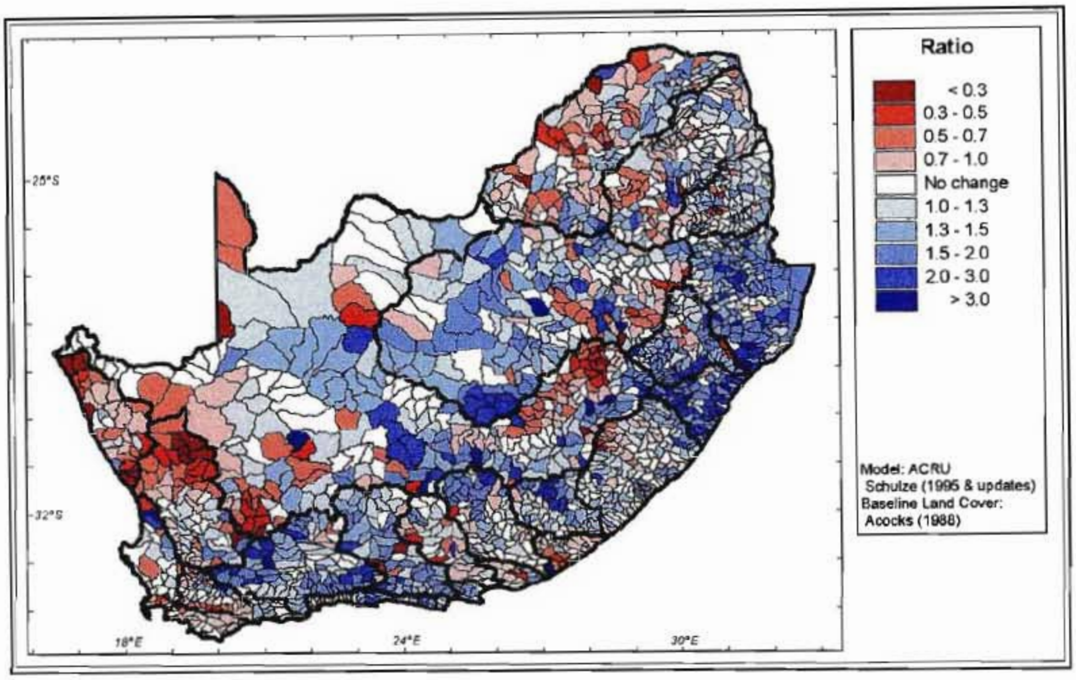

Figure 5.12 Ratio of later (1980 – 1999) to earlier (1950 – 1969) range of the lowest and highest accumulated annual streamflows in 10 years

The Olifants/Doorn, Buffels and Keiskamma Primary Catchments have QCs which show a decrease in the range between the lowest and highest flows in 10 years in the later period. The Orange Primary Catchment has QCs showing both an increase and decrease, and notable is the decrease in range in the area of the Caledon tributary which feeds the Orange Catchment. This area shows decreases in the lowest flows in 10 years in the later period as well as a decrease in the highest flows in 10 years in the later period; thus the 'dry' periods are increasing in severity and the 'wet' periods are decreasing in severity. However, the range between the lowest and highest flows in 10 years is decreasing. The QCs in the lower Orange, Olifants/Doorn and Buffels Primary Catchments which show decreases in the range in the later period are in semi-arid areas, and thus again it is unlikely that the changes there will have significant impacts on the water resources.

Figure 5.13 depicts ratio of the range between the lowest and highest flows in 10 years of accumulated summer streamflows between the periods 1980 – 1999 and 1950 – 1969. The Mfolozi, Thukela, Mvoti, Mzimvubu, Great Kei, Sondags, Fish and Gouritz Primary Catchments have a majority of their QCs displaying increases in the range in the later period.

The Orange Primary Catchment shows a mixture of increases or decreases in the later period. Again the Caledon River catchment in the Orange Catchment shows a marked decrease in the later period. However, in the lower Orange Catchment QCs are showing an increase in the range between the lowest and highest flows in 10 years of accumulated summer streamflows in the later period. The Olifants/Doorn Primary Catchment shows increases in the range between the lowest and highest flows in 10 years in the lower reaches, while in the upper reaches decreases in the range in the later period are evident. The Buffels Primary Catchment shows decreases in the range between the lowest and highest flows in 10 years of accumulated summer streamflows in the later period for the majority of its QCs.

Figure 5.14 depicts changes in the ratio of the range between the lowest and highest flows in 10 years of accumulated winter months' streamflows for the periods 1980 – 1999 vs 1950 – 1969. The patterns shown in Figure 5.14 are similar to those shown in Figure 5.11 in which changes in the highest flows in 10 years of accumulated winter streamflows are illustrated. The Limpopo, Buffels, Olifants/Doorn, Breede, Sondags, Boesmans, Keiskamma and Mzimvubu Primary Catchments all have QCs showing a decrease in range in the later period. The Gouritz Primary Catchment also has a cluster of QCs towards the outlet of the catchment which shows a decrease in range in the later period.

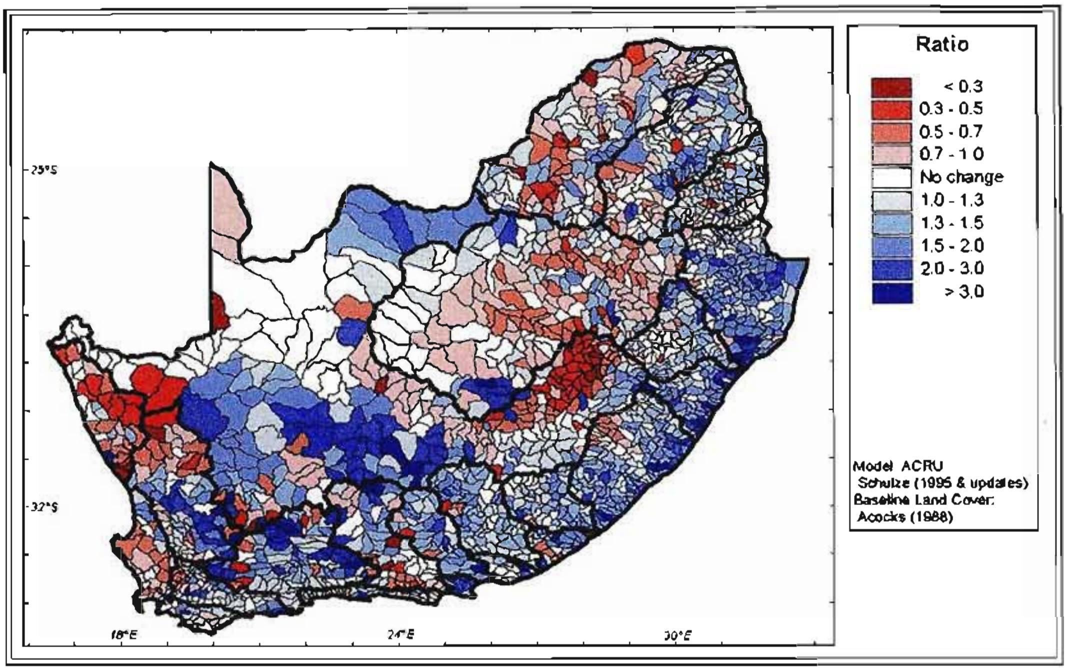

Figure 5.13 Ratio of later (1980 – 1999) to earlier (1950 – 1969) ranges between lowest and highest accumulated summer months' streamflows in 10 years

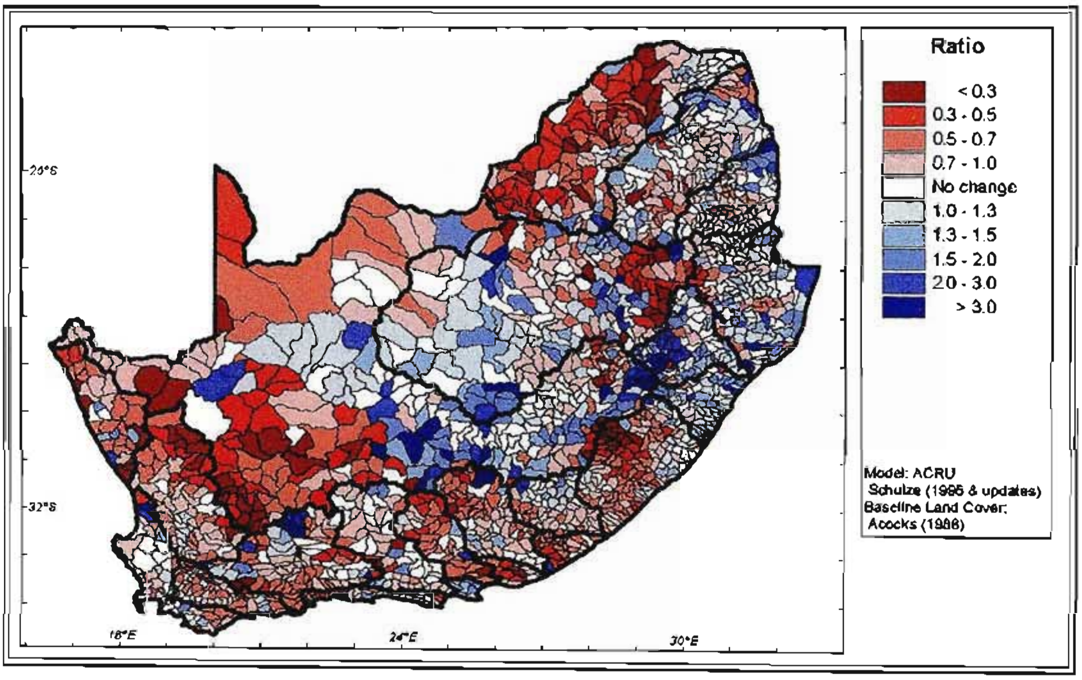

Figure 5.14 Ratio of later (1980 – 1999) to earlier (1950 – 1969) ranges between lowest and highest accumulated winter months' streamflows in 10 years

In the upper reaches of the Orange Primary Catchment, the QCs show an increase in range in the later period, while in the lower reaches the QCs tend to show a decrease in the later period in the range. The Vaal Primary Catchment has QCs in its upper reaches which show a decrease in the range between the lowest and highest flows in 10 years of accumulated streamflows in the later period, while in the lower reaches the QCs show an increase in the later period. The Thukela and Mvoti Primary Catchment show increases in the range between the lowest and highest flows in 10 years of accumulated winter streamflow in the later period.

5.9 Analysis of Baseflows

Baseflow, in the manner in which it is generated in the *ACRU* model, consists of water from previous rainfall events that has percolated through the soil horizons into the intermediate and groundwater zones and then contributes as a delayed flow to the streams within a QC on a daily basis (Schulze, 1995). The intermediate and groundwater stores are recharged by drainage from the subsoil horizon when its soil water content has exceeded the drained upper limit (Schulze, 1995). The coefficient of baseflow response, which is the variable in *ACRU* that determines the fraction of water from the intermediate and groundwater stores that becomes part of streamflow on a particular day, was set to the experimentally determined default value of 0.9%. Baseflow maintains the streamflow between rainfall events and during dry periods.

Shown in Figure 5.15 is the ratio of median annual baseflows for the later period, 1980 – 1999, vs the earlier period of 1950 – 1969. QCs in the Vaal, Orange, Limpopo and Olifants Primary Catchments generally tend to indicate a decrease in the median annual baseflows in the later period. This is a cause for concern as flows in many rivers in these areas are made up virtually entirely of baseflow contributions. A number of QCs in the Gamtoos Primary Catchment show a decrease in the later period. The remainder of the Primary Catchments show a mixture of QCs with both increases and decreases in the later period, or no change.

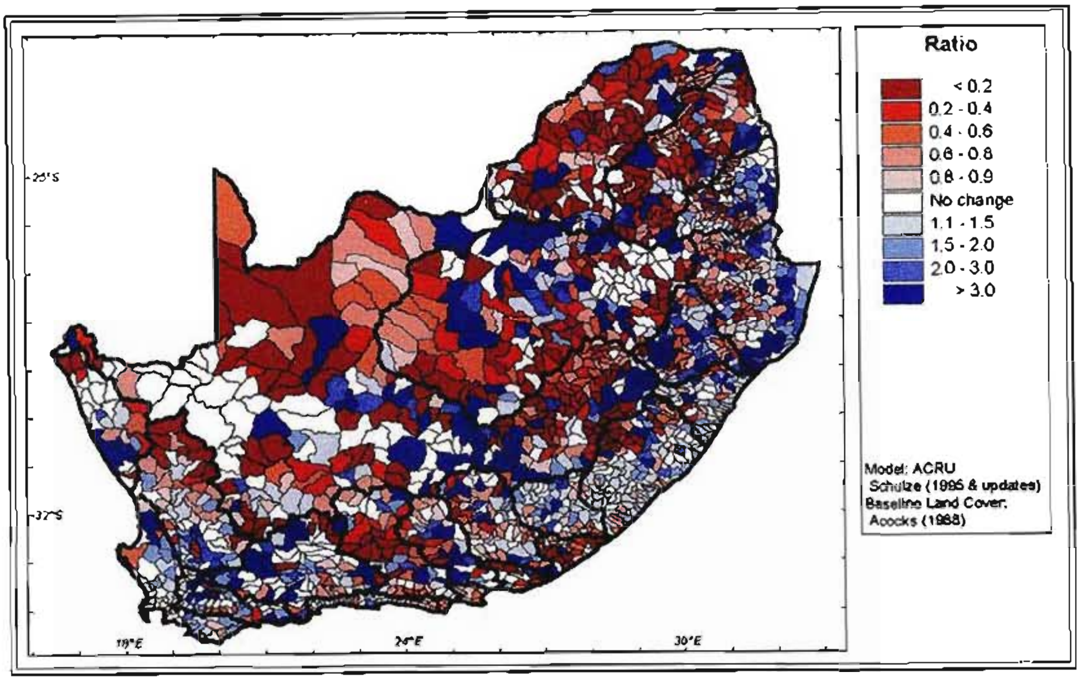

Figure 5.15 Ratio of later (1980 – 1999) to earlier (1950 – 1969) median annual baseflows

5.10 Changes in the Seasonality of Streamflows

Under conditions of climate change it is hypothesised that the timing of periods of high flows and low flows could shift. Such shifts in the timing of critical flow periods are important to water resources planners, as they may need to adjust operating rules of water supply reservoirs to accommodate these shifts. The influences of changes in the seasonality of flows may also have environmental implications in regard to aquatic habitats. In addition, changes in seasonality of flows may have implications for satisfying irrigation water demands and domestic and industrial water supply. For irrigation, it may occur that the peak water demand periods no longer coincides with the highest flow period, with evaporative demands increasing while with the flows during the same period are decreasing. The interactions between timing of flows, water requirements and environmental factors are complex.

In order to determine whether any shifts in the timing of summer streamflows have been evident already, the median monthly accumulated streamflows for the months of November, December, January, February, March and April were extracted for two 20-year periods, *viz.* 1950 – 1969 and 1980 – 1999. The sum of each three consecutive months of median accumulated streamflow was calculated to determine which three month period produced the highest summer streamflow, i.e. November, December and January flows were summed, then those for December, January and February, followed by those for January, February and March and lastly February, March and April.

Shown in Figure 5.16 is the comparison of the time of occurrence of the 3 months with the highest accumulated median streamflows for summer between 1950 – 1969 and 1980 – 1999. The Gouritz, Gamtoos, Sondags, Fish, Keiskamma and Great Kei Primary Catchments exhibit QCs in which the 3 months of highest streamflows are one, two or three months earlier in the 1980 – 1999 period. A cluster of QCs in the Orange Primary Catchment show a shift of one month later in the 1980 – 1999 period. The Vaal Primary Catchment has a number of QCs whose 3 months of highest streamflow are now one month later in the more recent period.

The Limpopo Primary Catchment has a number of QCs whose 3 months of highest summer streamflows are now one to two months later when compared with 1950 – 1969. All Primary Catchments hitherto mentioned with regard to Figure 5.16 fall into the area of all-year rainfall or summer rainfall. Primary Catchments in the winter rainfall region show no changes in the 3 month summer period of highest accumulated median flows. This is the low flow season for the winter rainfall region and the timing of low flows has not altered.

To determine whether any changes in the timing of winter streamflows could be noticed, the same procedure as used for summer streamflows was followed. The median monthly accumulated streamflows for the months of May, June, July, August and September were extracted for two 20- year periods, *viz.* 1950 – 1969 and 1980 – 1999. The sum of three consecutive months of accumulated median streamflows was calculated to determine which three month period produced the highest winter streamflows, i.e. May, June and July flows were summed, then those for June, July and August, and lastly for July, August and September. The highest three month streamflow period was determined for both 1950 – 1969 and 1980 – 1999, and compared.

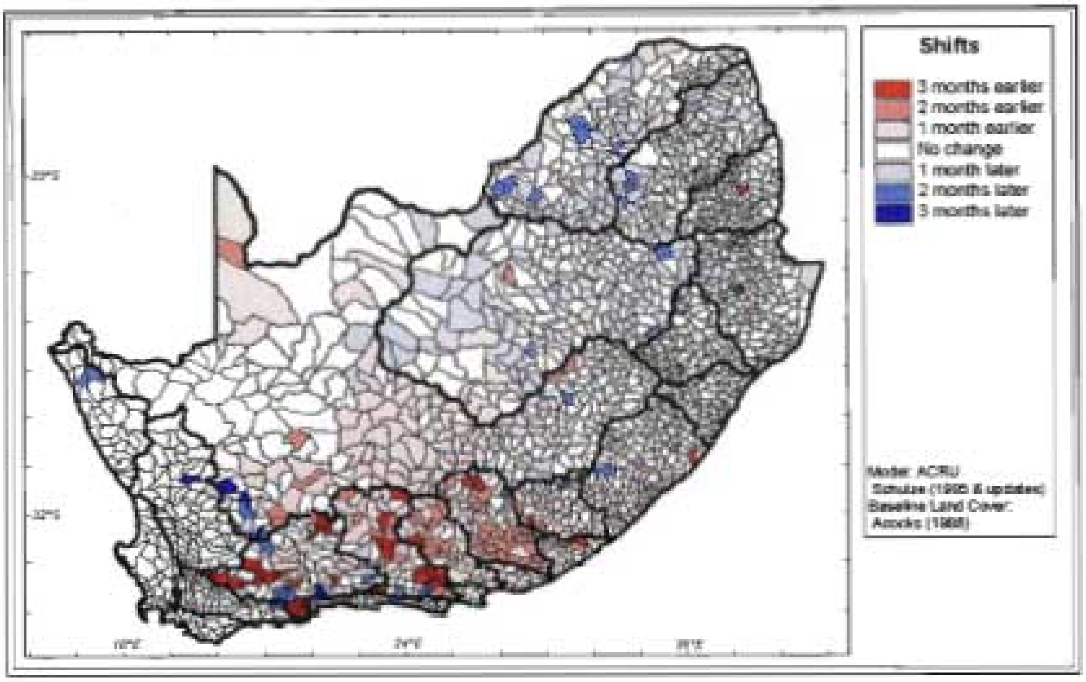

Figure 5.16 Shifts in timing between 1950 – 1969 and 1980 – 1999 of the three summer months with the highest accumulated median streamflows

Shown in Figure 5.17 is the comparison between 1980 – 1999 and 1950 – 1969 of the timing of the 3 months of highest accumulated median winter streamflows. The majority of QCs across southern Africa show no shifts in the timing of the 3 months of highest accumulated winter streamflows. The Vaal and Upper Orange Primary Catchments indicate a shift to 2 months later in the 3 months of highest accumulated winter streamflows in the later period.

The Olifants/Doorn and Buffels Primary Catchment have QCs which show a shift to 1 month later for the 3 months of highest accumulated winter streamflows in the later period. There are a few QCs in the Thukela, Mvoti, Mzimvubu, Great Kei, Fish, Sondags and Breede Primary Catchments which show a shift to 2 months earlier for the 3 months of highest accumulated winter streamflows. By implication the low flows in the summer rainfall regions of the Vaal and upper Orange Primary Catchment seem to be occurring 2 months later in 1980 – 1999 compared with the 1950 – 1969 period.

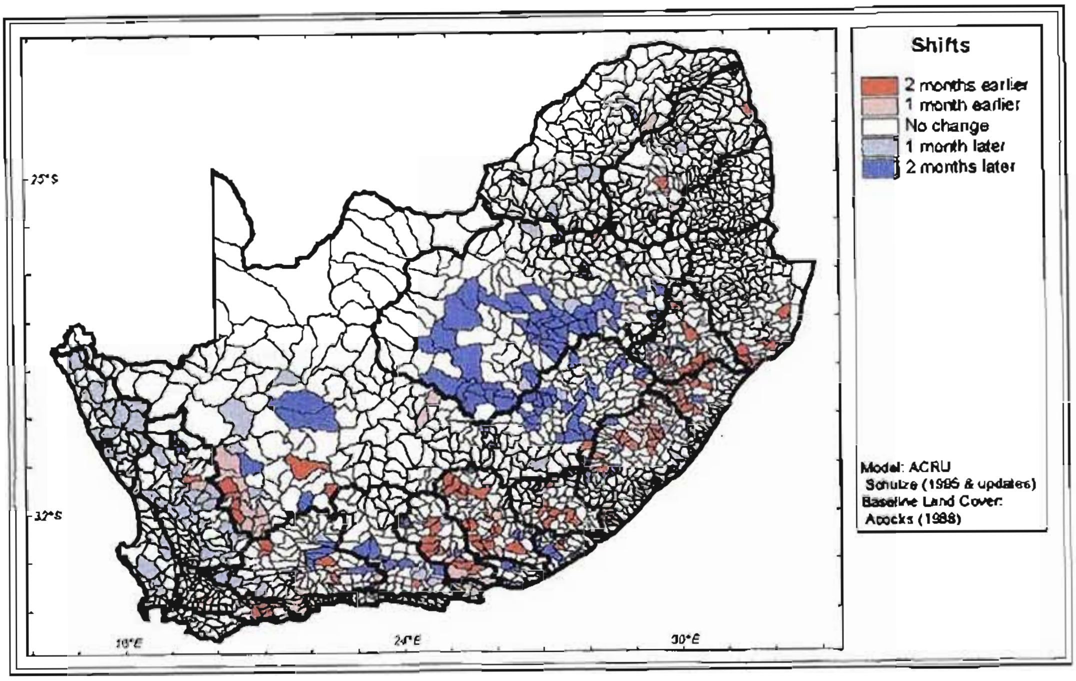

Figure 5.17 Shifts in timing between 1950 – 1969 and 1980 – 1999 of the three winter months with the highest accumulated streamflows

5.11 Changes in the Concentrations of Streamflows

As was mentioned above, changes in the timing of high and low flows are important to water resources planners. Changes in the concentration (i.e. the magnitude) of streamflows of defined periods of high and low flows are equally crucial. Therefore, an analysis was undertaken to compare the concentration of flows for the 3 month period with the highest accumulated of flows in 1980 – 1999 vs 1950 – 1969.

Figure 5.18 illustrates the ratio between the concentrations of the 3 months of highest accumulated streamflows for summer for 1980 – 1999 vs 1950 – 1969 periods. The Mvoti, Mzimvubu, Great Kei, Breede and Gouritz Primary Catchments contain QCs with an increase in flow concentration in summer in the later period. The Breede and Gouritz Primary Catchments show increases of twice and greater the magnitude of the earlier period in the later period in the summer flow concentrations. The Gouritz Primary Catchment, as seen in Figure 5.16, has a number of QCs where the 3 months of highest summer flows occur 1 to 2 months earlier in 1980 – 1999. Additionally, the streamflows have been shown to display a higher concentration.

In Figure 5.18 the upper Orange Primary Catchment shows a cluster of QCs displaying a reduction in the concentration of the 3 months of highest accumulated summer streamflows. In the upper reaches of the Olifants/Doorn Primary Catchment the QCs show a decrease in the summer flow concentrations. This is a winter rainfall region and thus the summer period corresponds with the low flow period in this region. The decrease in the low flows could be of great concern.

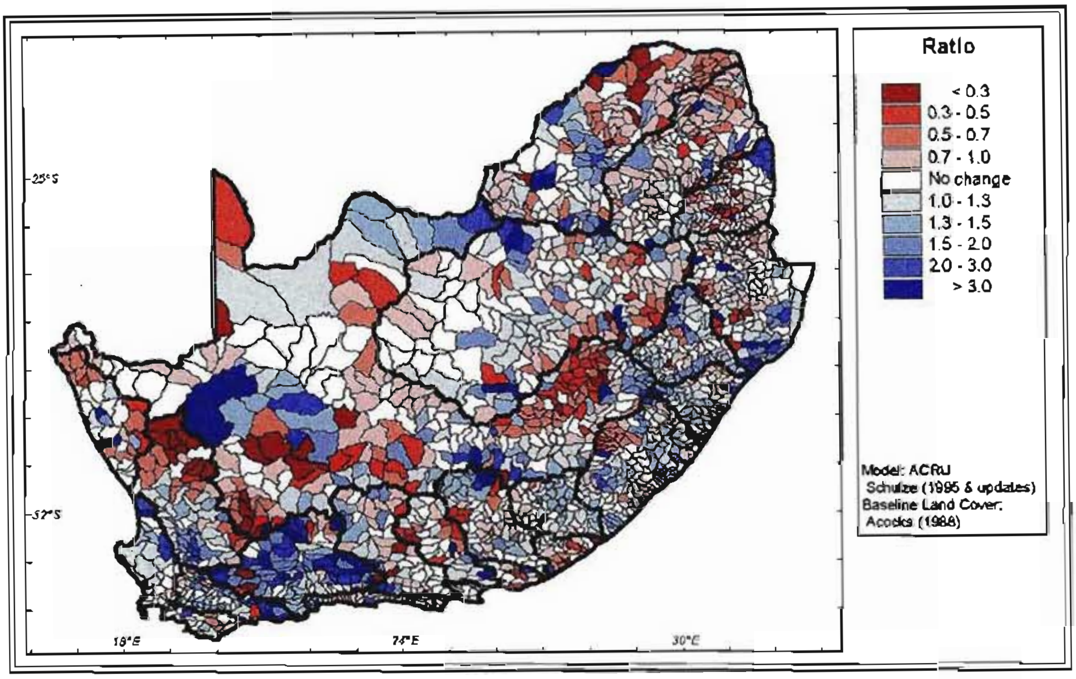

Figure 5.18 Ratio of later (1980 – 1999) to earlier (1950 – 1969) concentration of the 3 months of highest accumulated summer streamflows

Figure 5.19 illustrates the ratio of the winter flow concentration for 1980 – 1999 vs 1950 – 1969. Immediately evident are the large number of QCs in the Vaal, Orange, Limpopo, Olifants, Buffels, Mzimvubu, Keiskamma and Boesmans Primary Catchments showing a decrease in the concentration of the 3 months of highest winter accumulated streamflows in the later period. In the upper Olifants/Doorn the trend is also for a decrease in the later period. QCs in the Gouritz Primary Catchment show an increase in the winter flow concentration in the later period. Along the coast of the Mfolozi Primary Catchments, QCs also show an increase in the winter flow concentration.

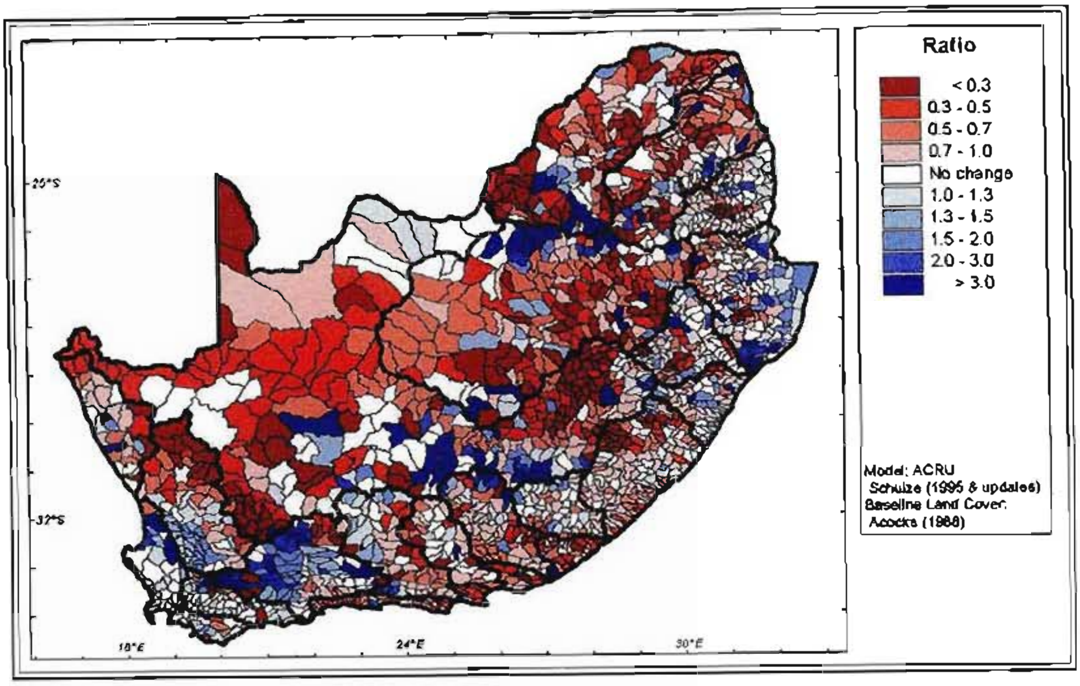

Figure 5.19 Ratio of later (1980 – 1999) to earlier (1950 – 1969) concentration of the 3 months of highest accumulated winter streamflows

5.12 Analysis of Changes in Irrigation Water Demand

The *ACRU* agrohydrological model's irrigation routines consider the water "consumption" by the plant through transpiration, water lost through evaporation from the soil surface, recharge of the soil profile through rainfall, soil water content of the active root zone, and the amount of soil water depletion needed for plant stress to commence (Schulze, 1995).

For the purposes of this study two crops per annum were considered to be irrigated. In summer the crop considered was maize, planted in November and with a 140 day growing season. In winter the crop considered was winter pasture. Irrigation was considered to be applied in all months except April and October, when fields were being prepared. An unlimited supply of water for irrigation was assumed. The chosen method of irrigation was demand irrigation, whereby the soil profile is refilled by irrigation to the drained upper limit once the plant available water has dropped to 50%. The soil assumed was a typical sandy clay loam soil of 0.8 m depth and its attributes were held constant over the 50 year simulation period for all QCs.

In Figure 5.20 the ratio of later (1980 – 1999) and earlier (1950 – 1969) median annual irrigation water demands is illustrated. As may be seen, the majority of QCs across southern Africa show small increases or decreases in irrigation water demand in the later period, of the order of less than 0.05 of the earlier period. A few QCs in the Mvoti Primary Catchment show stronger increases in the later period, while QCs in the Mzimvubu, Thukela and Mfolozi Primary Catchments show a mixture of stronger increases and decreases. No large clusters of QCs showing either substantial increases or decreases in the later period are evident. However, it is interesting to note that the few QCs showing a substantial change occur in the summer rainfall region.

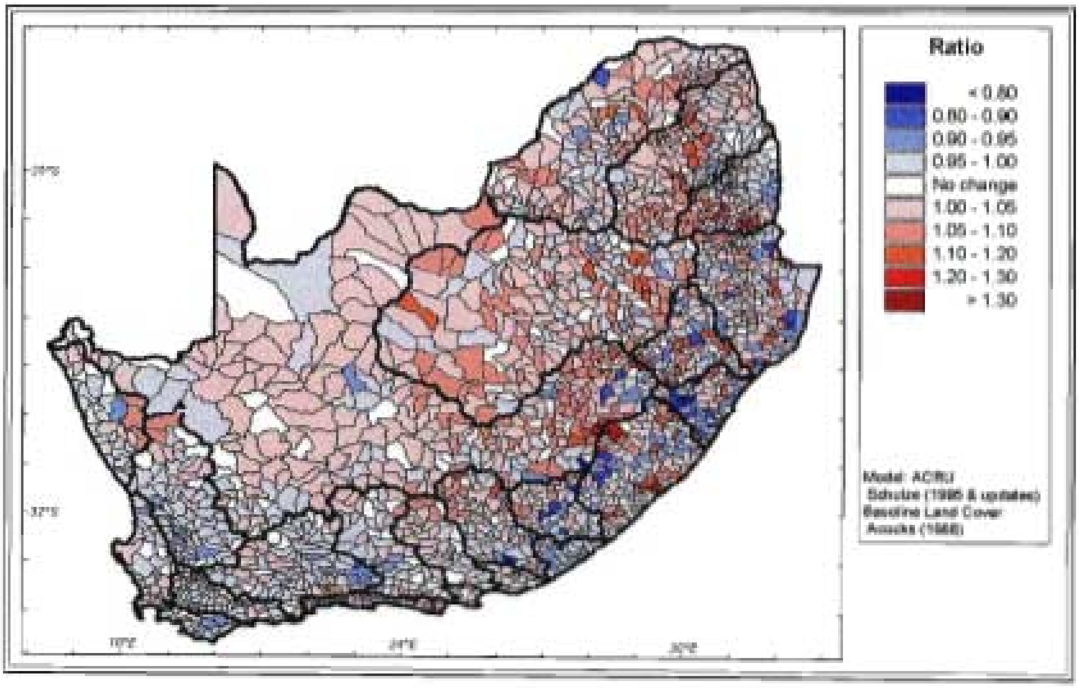

Figure 5.20 Ratio of later (1980 – 1999) to earlier (1950 – 1969) median annual irrigation water demands

Figure 5.21 shows the ratio of later (1980 – 1999) and earlier (1950 – 1969) median summer month irrigation water demands. The summer months for irrigation are taken as November through March. In the Mzimvubu, Mvoti, Thukela, Mfolozi, Komati and Olifants Primary Catchments a number of QCs show either substantial increases or decreases in summer irrigation water demands in the later period. The remainder of the Primary Catchments show no substantial changes, or have scattered QCs showing either substantial increases or decreases in median summer irrigation water demands.

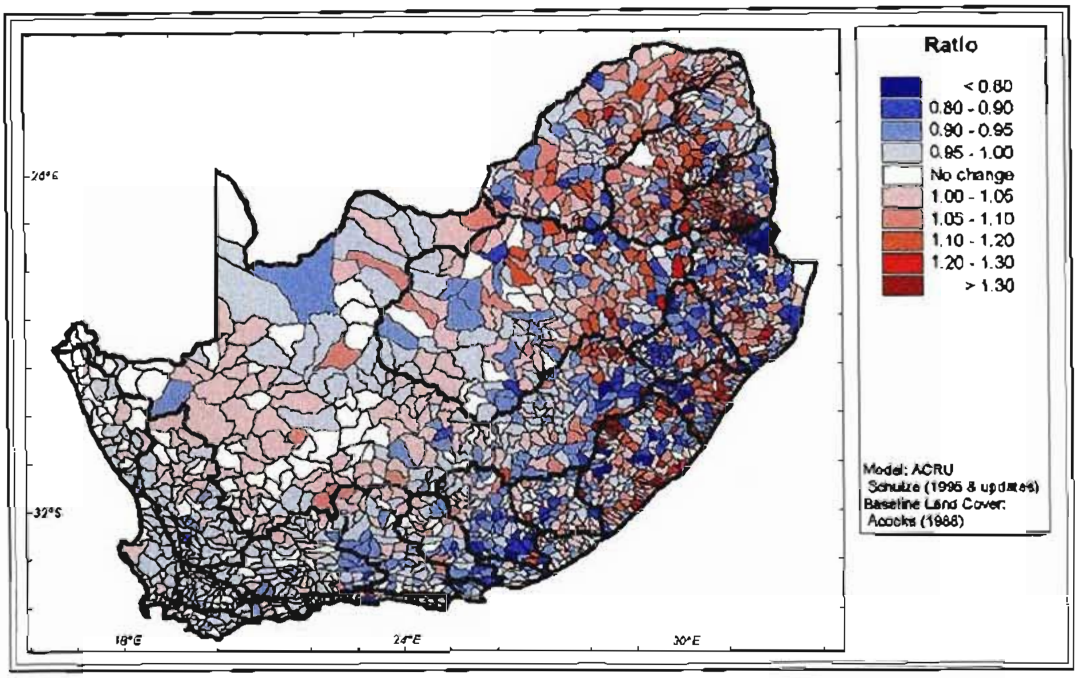

Figure 5.21 Ratio of later (1980 – 1999) to earlier (1950 – 1969) summer months' (November-March) median irrigation water demands

Figure 5.22 depicts the ratio of later (1980 – 1999) and earlier (1950 – 1969) median winter months' irrigation water demands. The winter months for irrigation are taken as May through September.

The Primary Catchments in the summer rainfall region predominantly have QCs which show increases in median winter months' irrigation water demand, of the order of 1.05 to 1.20 times greater than the earlier period. The exception is a cluster of QCs in the upper Orange Primary Catchment which show a decrease in the later period. The Buffels, Olifants/Doorn, Berg, Breede and Gouritz Primary Catchments in the winter rainfall region tend to show a decrease in median winter months' irrigation water demand in the later period.

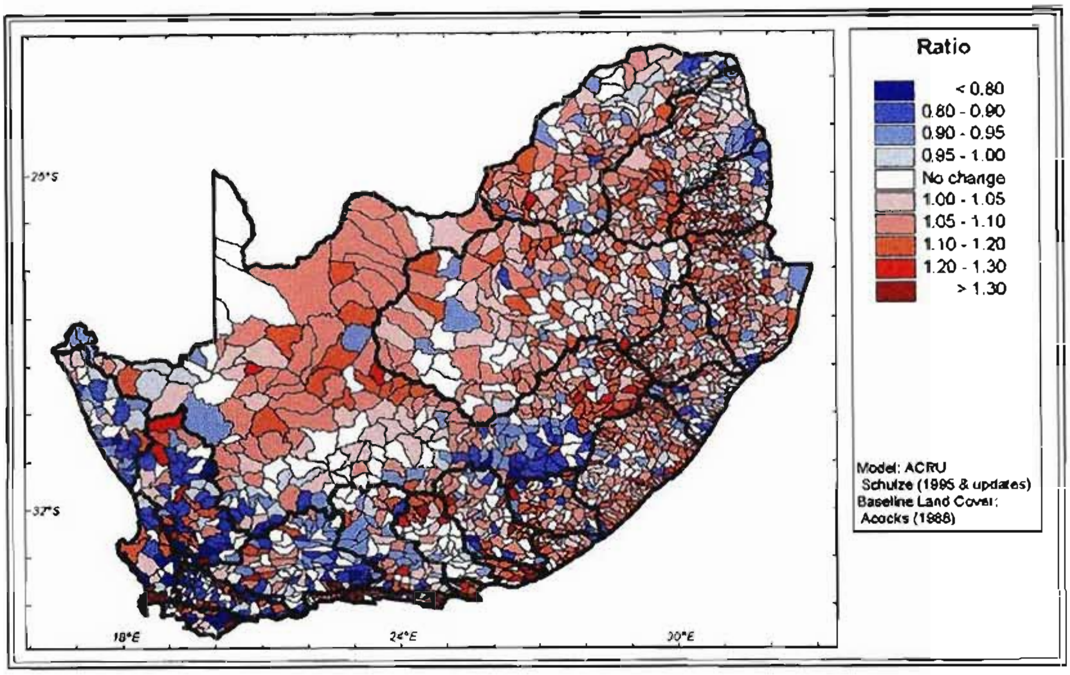

Figure 5.22 Ratio of later (1980 – 1999) to earlier (1950 – 1969) winter months' (May-September) median irrigation water demands

5.13 What Changes Have Been Observed in Southern Africa's Hydrological Drivers and Responses? A Summary of Findings

For purposes of this summary of findings, which is aimed also at non-hydrology audiences, changes are described by province rather than by Primary Catchment. In summary, the split-sample analysis of simulated hydrological responses for the 1980 – 1999 vs 1950 – 1969 periods, yielded ratios which vary in relation to climate, as all human influences on the catchment and channel had been eliminated from simulations. These ratios show that:

- simulated potential evaporation has increased very slightly over the central areas of southern Africa (Figure 5.2);
- simulated accumulated streamflows in the 'driest' year in 10 have increased over large parts of the winter rainfall region while decreasing markedly over parts of the Northern Cape, Eastern Cape, eastern Free State, Swaziland and parts of Limpopo (Figure 5.6);
- on the other hand, simulated accumulated streamflows in the 'wettest' year in 10 have increased over much of the summer rainfall region, especially over KwaZulu-Natal, but with notable decreases over the southeastern Free State (Figure 5.7);

- simulated summer month streamflows in the 'driest' season in 10 have increased markedly over the winter rainfall region, while decreases are evident in the southeastern Free State (Figure 5.8);
- simulated winter month streamflows have increased in the 'driest' season in 10 in the winter rainfall region, but decreases are evident along most of the east coast of southern Africa (Figure 5.10);
- however, simulated winter months streamflows in the 'wettest' season in 10 have decreased over the winter rainfall region, as well as much of the Northern Cape, Eastern Cape, Limpopo and North-West Provinces (Figure 5.11);
- the range of simulated streamflows between low and high flow years, indicative of a change in streamflow variability, has generally increased over the summer rainfall region, especially over KwaZulu-Natal (Figure 5.12);
- the range of simulated streamflows between low and high flow years in the winter months has decreased over the Western Cape, Eastern Cape, Northern Cape and Limpopo Provinces (Figure 5.14);
- periods of highest simulated summer streamflows have tended to become earlier by 1 – 3 months in the Eastern Cape, but later by 1 – 2 months over much of the central and north-eastern parts of southern Africa (Figure 5.16);
- concentrations of flows in summer months have increased in magnitude over much of the southern and eastern parts of South Africa, with decreases over the southeastern Free State (Figure 5.18); and
- concentrations of flows in winter months have decreased markedly in magnitude over most of the interior of southern Africa (Figure 5.19).

The changes seen in simulated streamflows are relatively large, often being in the order of 2 to 3 times the initial streamflows. In some instances, particularly in the drier areas of southern Africa, although the ratio changes may be large the actual change in mm or m^3 equivalents may be small.

The extent to which these trends over the past 50 years are related directly to climate change is not immediately clear. However, some trends are very marked over significantly large parts of Primary Catchments and certainly require bearing in mind in future water resources planning and management.

What has caused these various hydrological changes identified in this Chapter, and summarised above? Changes in reference potential evaporation, which reflect, *inter alia*, changes in solar radiation and temperature patterns, have been observed. However, these changes, at approximately 1 – 3% are very small and the hypothesis outlined in Section 5.1, *viz.* that on the basis of temperature changes alone, changes in streamflow may already be noticeable, does not hold. Therefore, rainfall needs to be examined, as it is the only other driver of the hydrological cycle in the context of simulation modelling with *ACRU*. It is a well recognised hydrological phenomenon that the hydrological cycle amplifies any changes in rainfall. For example, a unit change in rainfall results in changes in runoff by 2 – 4 times the change in rainfall over most areas of South Africa, and with a 4 – 5 fold sensitivity along the South African west coast (Schulze, 2005). A climate change detection study on rainfall over southern Africa is therefore conducted in Chapter 7.

As highlighted in the "roadmap" below, a review of precipitation detection studies is presented, followed by a split-sample analysis of the rainfall, examining medians, 10th and 90th percentiles as well as events above selected thresholds. Lastly, conclusions regarding the rainfall detection study are drawn.

Problem Statement: If anthropogenically forced climate change is becoming a reality, evidence of change should already be detectable in climate observations and from hydrological simulations at a regional scale

Overall Objectives: To determine whether statistical analyses already show trends in temperature parameters and hydrological responses which may be ascribed to climate change

		Broad Objectives		
		Temperature Detection Studies	**Detection Studies on Hydrological Drivers and Responses**	**Overall Conclusions and Recommendations**
Specific Objectives	**Literature Review**	i.) Review results from temperature detection studies ii.) Outline problems related to temperature data iii.)Review statistical methods used in detection studies	i.) Review results from streamflow detection studies ii.) Outline problems related to streamflow measurement iii.)Discuss the advantage of physical conceptual hydrological models in detection studies iv.)Review precipitation detection studies	i.) Changes in southern Africa's temperature regime ii.) Changes in southern Africa's hydrological drivers and responses iii.) Changes in southern Africa's rainfall regime iv.)Overall conclusions and recommendations
	Data	i.) Outline temperature dataset used for southern Africa	i.) Quaternary Catchments Database and input	
	Methods	i.) The Mann-Kendall non-parametric test ii.) Split-sample analysis	i.) Re-select rainfall station network ii.) The Mann-Kendall non-parametric test iii.)Split-sample analysis	
	Results	**Mann-Kendall Analyses** i.) Examine means of minimum and maximum temperatures ii.) Analyse percentile thresholds iii.)Analyse selected thresholds iv.)Analyse frost related parameters v.) Analyse Heat units vi.)Analyse Chill units **Split-sample analyses** i.) Examine means of minimum and maximum temperatures ii.) Analyse coefficient of variation	**Mann-Kendall Analysis** i.) Analyse accumulated streamflows **Split-Sample Analyses** i.) Reference potential evaporation ii.) Soil water content iii.) Median, 90th and 10th percentile of accumulated streamflow iv.) Range in streamflows v.) Baseflows vi.) Seasonality and concentrations of flows vii.)Irrigation water requirements **Split-Sample Analyses** i.) Median, 90th and 10th percentile of rainfall ii.) Range in rainfall iii.) Analyse selected thresholds	
	Conclusions	i.) Is southern Africa's temperature changing?	i.) Conclusions of detection studies on hydrological responses ii.) Conclusions on changes in rainfall	

6. A CLIMATE CHANGE DETECTION STUDY IN SOUTHERN AFRICA ON PRECIPITATION

6.1 Introduction

In a split-sample hydrological simulation for the 1 946 interlinked Quaternary Catchments, into which South Africa, Lesotho and Swaziland have been delimited, the trends over time noted in reference potential evaporation and hydrological responses were significantly large for certain variables and certain areas within the Primary Catchments of the region. Although changes over time in temperature have been detected for certain areas of southern Africa (Chapter 3), these changes by themselves are insufficient to account for the noted changes in hydrological responses in Chapter 5. This prompted a need to investigate whether changes in rainfall patterns were the cause of the hydrological changes and whether such changes, if present, could already be observed.

As was the case with temperature, new record highs of maximum 24 hour rainfall were recorded at various locations in South Africa in 2004 (Table 6.1; SAWS, 2005b). For example, a new record maximum 24 hour rainfall of 199.2 mm was recorded for Knysna in the Western Cape on 22 December 2004; this was 127.4 mm greater than the previous maximum 24 hour rainfall. New climate records are continually being set, and have been throughout the history of observations; however, the number and magnitude of the new records being set in the recent past suggest a possible shift in southern Africa's precipitation patterns.

Southern Africa experiences a high inter-annual and intra-annual variability of precipitation under present climatic conditions (Schulze *et al.*, 2001). This renders the detection of changes in rainfall patterns, which are hypothesized to result from global warming, very difficult. Any changes in precipitation patterns, however, have important implications for the hydrological cycle and for water resources, as precipitation is the main driver of responses in the water balance, over both time and space, and it is this water balance upon which humans and the environment depend (IPCC, 2001). Any change in precipitation over space and time through total amounts, frequencies or rainfall above certain thresholds, persistence of wet or dry day combinations or the onset and duration of the rainy season has amplifying consequences for runoff responses (Schulze *et al.*, 2001). It is a well-established hydrological characteristic that a 10% change in precipitation over South Africa can result in a streamflow change of up to 30% and more (Schulze, 1995; Schulze, 2005). Precipitation and water resources are inextricably linked with food security, human health and environmental protection (Appleton, 2003). Therefore, detection of changes in precipitation characteristics becomes important to humans and the environment alike. Literature on detection of recent changes in rainfall characteristics includes Hewitson et al. (2005) who show changes to have occurred in southern Africa's rainfall in the period 1950 – 1999. The review of literature is followed by a climate change detection analysis of precipitation records from the Quaternary Catchments Database over southern Africa.

Table 6.1 The old and new records of maximum 24 hour rainfall records for various locations in South Africa, as of January 2005 (SAWS, 2005b)

Station Name	Old Maximum 24 Hour Rainfall (mm)	Date	New Maximum 24 Hour Rainfall (mm)	Date	Increase (mm)
Cape St Lucia	105.0	1988/12/16	153.5	2004/12/23	48.5
Riversdal	67.2	1994/12/23	126.6	2004/12/22	59.4
Knysna	72.0	1970/12/06	199.2	2004/12/22	127.2
McGregor	51.0	1994/12/23	79.5	2004/12/22	28.5
Robertson	52.5	1994/12/23	185.0	2004/12/22	132.5
Humansdorp	104.6	1889/12/20	118.0	2004/12/06	13.4
Swartkops (PE)	47.5	1994/12/23	55.1	2004/12/06	7.6
Estcourt	53.0	1975/11/01	65.0	2004/11/08	12.0
Simon's Town	39.4	1884/10/10	40.0	2004/10/20	0.6
Hopefield	35.3	1924/10/24	40.0	2004/10/20	4.7
Darling	41.5	1984/10/04	46.5	2004/10/20	5.0
Moorreesburg	34.0	1984/10/04	41.5	2004/10/20	7.5
Cape Columbine	30.0	1984/10/04	35.0	2004/10/20	5.0
Lamberts Bay	18.0	1995/10/11	28.0	2004/10/20	10.0
Lutzville	21.0	1996/10/18	22.0	2004/10/20	1.0
Calvinia	21.0	1984/10/10	25.6	2004/10/20	4.6
Loeriesfontein	27.9	1942/10/09	32.0	2004/10/20	4.1
Hondeklip Bay	12.0	1982/10/11	32.0	2004/10/20	20.0
Henkries	13.0	1981/10/14	20.6	2004/10/20	7.6

6.2 Literature Review: Climate Change Detection Studies on Precipitation

During the 20th century precipitation totals have increased significantly over most of the contiguous USA during all seasons except their winter. The increasing trends range from 7% to 15% during summer, spring and autumn (Groisman *et al.*, 2001). The trends in one-day and multi-day heavy precipitation events are showing a tendency towards more days with heavy 24-hour precipitation totals (Karl and Knight, 1998). In support of this is the finding by Groisman *et al.* (2001) that the number of days per year exceeding the 90th and 95th percentile of 24-hour precipitation and the 1-year annual maximum daily precipitation amounts have been increasing.

Another source of support for increasing rainfall trends is research by Karl *et al.* (1996) which shows the number of days annually exceeding a threshold value of precipitation, *viz.* 50 mm per day, to be increasing. With regard to multi-day precipitation events, the 2- to 7-day precipitation totals exceeding station-specific thresholds for 1 in 1-year and 1 in 5-year recurrence intervals are increasing (Karl and Knight, 1998).

An increasing, and statistically significant, trend has also been detected for the Rio Puerco basin in New Mexico, USA. After analysis of the 1947 to 1997 period, a consistent increase in the annual precipitation was found which results from an increase in precipitation during the autumn and spring months. Most notable was an increase in the number of rainy days in the Rio Puerco basin (Molnar and Ramirez, 2001).

Akinremi *et al.* (1999) concluded that there has been a significant increase in both the number of precipitation events and precipitation amounts for the Canadian prairies over the past 75 years, after examining records from 37 stations located in the area. It was concluded that the increasing number of precipitation events was due to an increase in the number of low-intensity precipitation events.

The United Kingdom has shown an increasing trend in annual precipitation (Osborn *et al.*, 2000). The upward trend is particularly evident in the mean winter precipitation and in the western and more mountainous regions of the UK. The increase of precipitation in the western UK is manifested by a combination of more frequent wet days and more precipitation on those wet days. However, the increase in precipitation in the eastern UK is driven solely by an increase in the amount of precipitation that falls on a wet day (Osborn *et al.*, 2000).

In Switzerland evidence has been found of an increasing trend in intense precipitation over the 20th century, as well as an increase in the mean winter precipitation (Frei and Schar, 2001).

For eastern China a significant negative trend in precipitation was found for the 1950s to mid-1970s period, while a positive trend was found to occur since the 1970s, and it is this positive trend that is more prominent (Gong and Wang, 2000). During the 1977 to 1998 period the number of stations with severe wet conditions increased at a rate of 20.3 per decade. The mean precipitation for the eastern China region for the 1990 to 1998 period was higher than that in any other decade on record in the past 100 years. The linear trend of the annual precipitation for the 33 stations analysed by Gong and Wang (2000) during the 1977 to 1998 period was an unprecedented +47.5 mm per decade. In contrast, Zhai *et al.* (1999) did not find any evidence of changes in China's total annual precipitation, nor any evidence of changes in precipitation extremes for 1- and 3-day events. Similarly, an analysis of India's 1-day, 2-day, and 3-day precipitation totals showed no distinct trends (Kumar *et al.*, 1997).

In Africa, Hulme (1992) compared two successive 30-year climatologies, namely 1931 – 1960 and 1961 – 1990. Hulme (1992) found that African rainfall had changed substantially over the previous 60 years to 1990. The most noticeable change had been a 30% decline in rainfall over tropical North Africa for the 1961 to 1990 period compared to the 1931 to 1960 period. Rainfall increases have occurred in equatorial East Africa, *viz.* an increase of 15%, and in the southern coastal region of West Africa, with an increase of 10% for the 1961 to 1990 period compared to that of 1931 to 1960. Along with increases in the means, the variability of rainfall between the two periods has increased in general for Africa, the most notable locations for increased inter-annual variability being Tunisia, Algeria, and the Nile Basin.

For South Africa, Mason *et al.* (1999) found that significant increases in extreme rainfall events have taken place between two 30-year periods, namely 1931 to 1960 and 1961 to 1990. Over large areas of South Africa it was found that the intensity of the 10-year high rainfall event has increased by over 10% (Mason *et al.*, 1999). Widespread flood-producing rainfall events over South Africa have been analysed by Alexander (2001) on a regional basis. Events of 4 days' duration were divided into 6 classes, 0 to

5, with Class 5 experiencing the most extreme rainfall, i.e. with 60% of the stations recorded >99 mm, 32% >199 mm, 16% >299 mm, 12% >399 mm and 4% >499 mm over a 4 day period. From this analysis Alexander (2001) noted that over time the total number of Class 3-5 events appeared to be increasing, particularly since 1970.

However, for the tropical margins of southern Africa annual rainfall has decreased by 5% (Hulme, 1992). For the eastern parts of South Africa a decrease of approximately 10% in mid-summer rainfall between the 1931 – 1960 and 1961 – 1990 periods has taken place. A decrease in mean annual rainfall is also evident over the eastern Lowveld of South Africa (Mason, 1996). Along with this, rainfall variability over South Africa is increasing (Hulme, 1992; Mason, 1996). The Global Circulation Models (GCMs) predict a decrease in total rainfall for South Africa (IPCC, 2001). However, in contrast to this, Lynch (2004) found an increase in annual rainfall since the 1980s for six rainfall stations, each with record lengths of over 70 years, in the Potchefstroom area of the North-West Province.

In more recent research, Hewitson *et al.* (2005) assessed trends in rainfall over a 50 year period (1950 – 1999) for southern Africa. No strong trends in annual totals were noted; however, trends on the sub-annual and seasonal scales were strong (Figure 6.1). Also strong trends in the derivative statistics from daily data, such as changes in the number of raindays per month (Figure 6.2) and days with rainfall greater than 2 mm (Figure 6.3), dry spell duration (Figure 6.4) and the magnitude of the 90th percentile event (Figure 6.5) were found. For the summer rainfall region, Hewitson *et al.* (2005) noted increases in the late summer dry spell duration (Figure 6.4). On the other hand, in the winter rainfall region the mountainous areas received more raindays per month and increased totals, in contrast to the neighbouring coastal plains which they found to be experiencing the reverse (Figures 6.2 and 6.5). The arid areas, according to Hewitson *et al.* (2005), are receiving more raindays (Figure 6.2). In each of Figures 6.1 to 6.5, DJF denotes December, January and February (i.e. summer months) statistics, MAM denotes March, April and May (i.e. autumn months) statistics, JJA denotes June, July and August (i.e. winter months) statistics and SON denotes September, October and November (i.e. spring months) statistics.

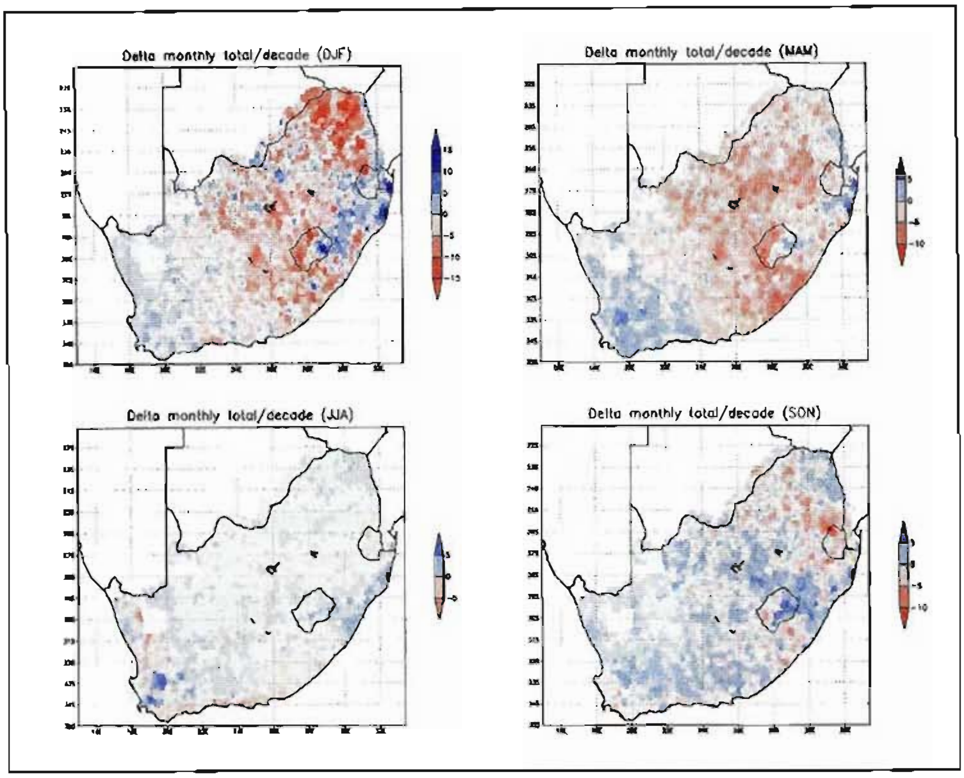

Figure 6.1 Historical trend (1950-1999) of change per decade of mean monthly precipitation totals (mm; Hewitson *et al.*, 2005)

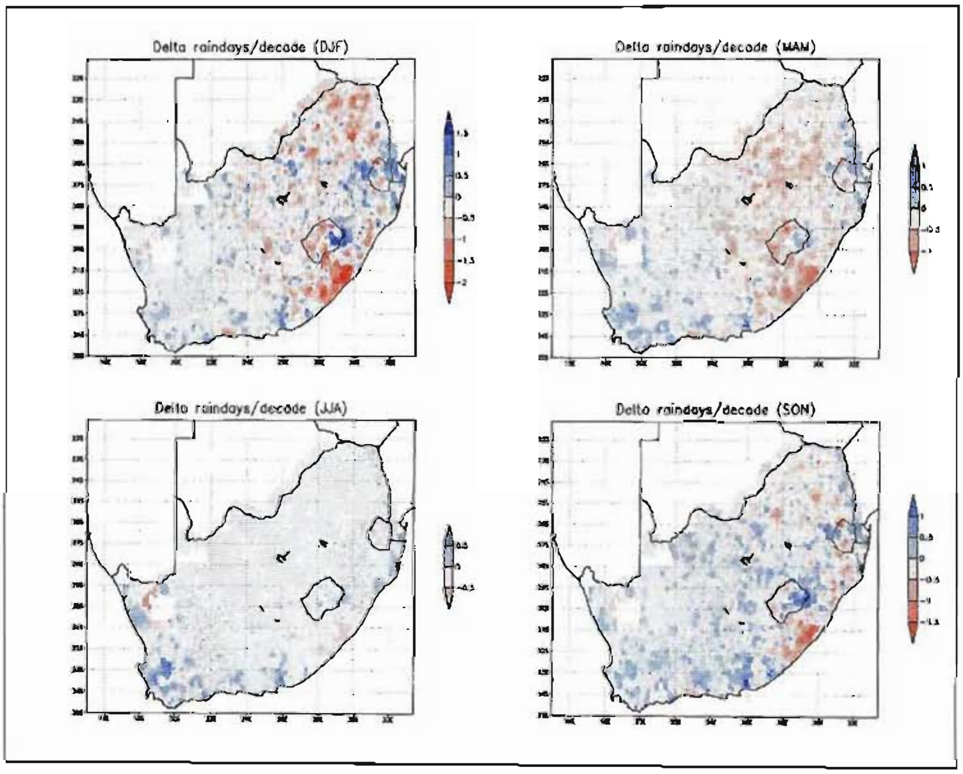

Figure 6.2 Historical trend (1950-1999) of change per decade of mean monthly number of raindays (> 0 mm; Hewitson *et al.*, 2005)

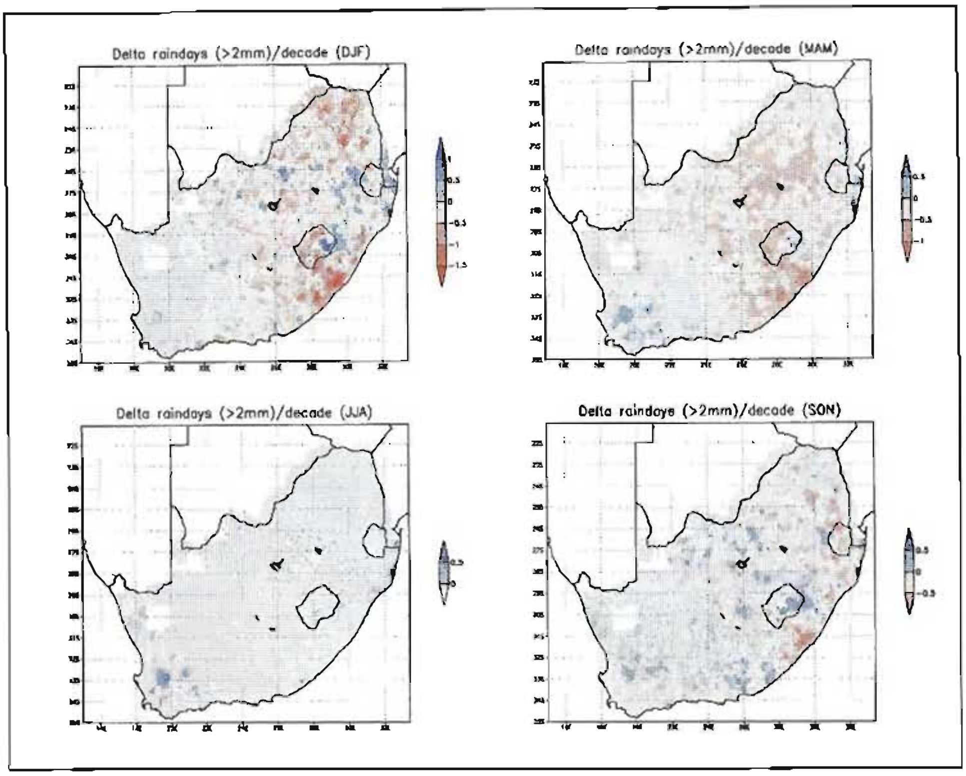

Figure 6.3 Historical trend (1950-1999) of change per decade of mean monthly number of raindays (> 2 mm; Hewitson *et al.*, 2005)

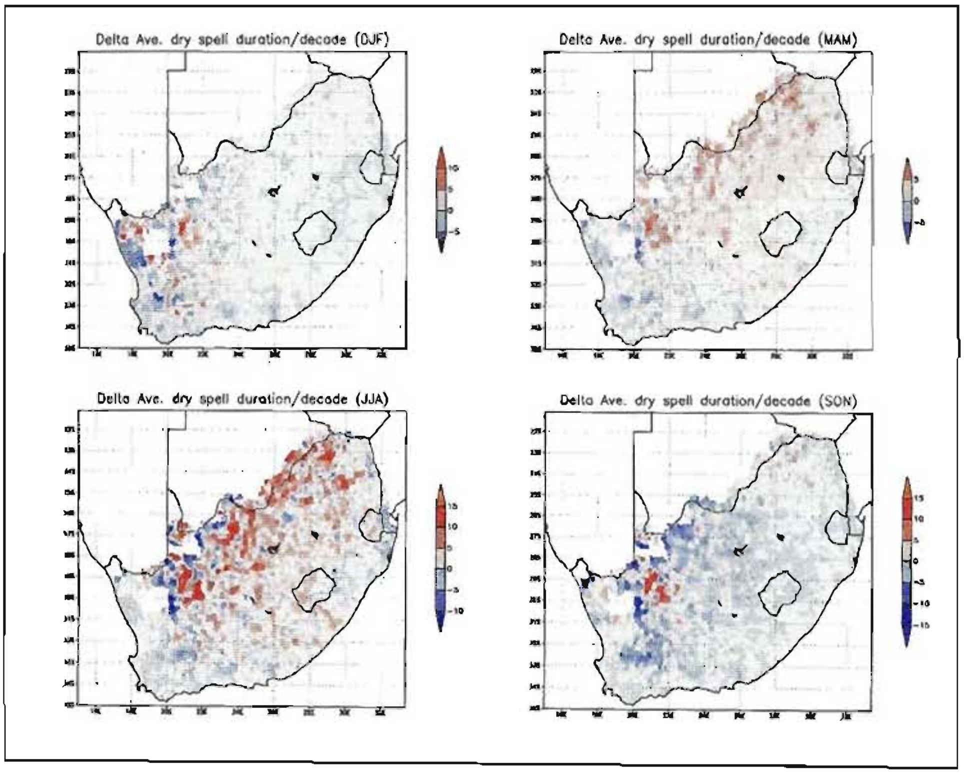

Figure 6.4 Historical trend (1950-1999) of change per decade of mean monthly dry spell duration (days; Hewitson *et al.*, 2005)

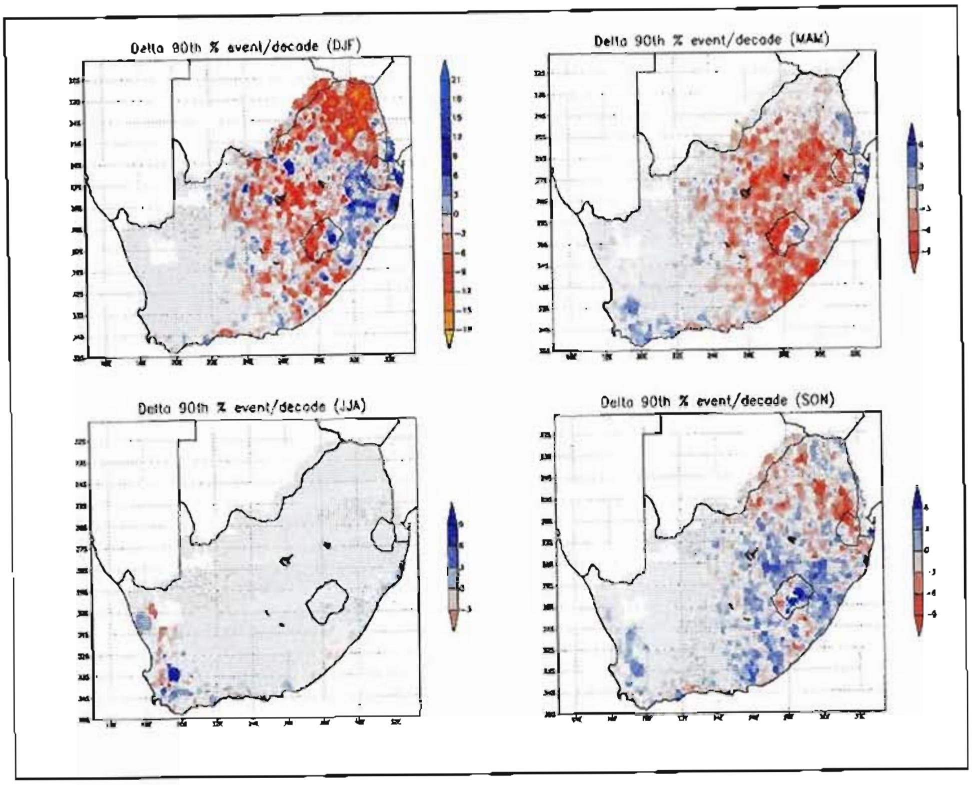

Figure 6.5 Historical trend (1950-1999) of change per decade of mean monthly 90th percentile magnitude precipitation event (mm; Hewitson *et al.*, 2005)

6.3 Data and Methods Used

As outlined in Chapter 4 and 5, the *ACRU* model (Schulze, 1995) was used to simulate whether changes in hydrological responses over time had occurred across southern Africa. In Chapter 4 the inputs used for the *ACRU* model simulations are also outlined. One requirement of the model is a daily rainfall record for each of the inter-linked catchments considered, which in this study are the 1 946 Quaternary Catchments into which southern Africa has been delineated. A component of the hydrological detection study in Chapter 5 was the enhancement of the daily rainfall input through a re-selection of the "driver" rainfall stations for each of the 1 946 QCs from a more comprehensive, up-to-date and quality controlled database than that used in the previous rainfall station selection by Meier (1997). The method of re-selection is outlined in detail in Chapter 4 (Section 4.5), with an evaluation of the re-selected "driver" stations given in Section 4.6. The evaluation highlighted the generally high quality, long daily records from the rainfall "driver" stations, and the exception to this being the rainfall records in the Drakensberg and Western Cape mountain areas.

It must be noted that the daily rainfall analysed in this Chapter is that from the South African Quaternary Catchments Database (Chapter 4) as used by the *ACRU* model. These daily rainfalls differ from the "driver" stations' original records, in that the observed daily point rainfall value of the "driver" station have, for certain QC's, been adjusted by a month-by-month multiplication factor to give a more realistic representation of the QC's areal rainfall from the point rainfall source. The adjustment factor is calculated by dividing the mean annual precipitation (MAP) of the QC (as obtained from a set of 1' x 1' latitude x longitude (~ 1.6 km x 1.6 km) gridded values determined by Lynch, 2004) by the MAP of the "driver" rainfall station. The adjustment factor does not alter any trends over time, should they be present, as it is a simple point to area multiplier.

As already alluded to above Hewitson *et al.* (2005) showed changes in South Africa's historical precipitation for 1950 – 1999 based on an analysis which used robust regression with an interpolated 0.1° gridded precipitation data set that draws from approximately 3 000 rainfall stations records across South Africa. The analysis discussed here differs from theirs in that, only the "driver" rainfall stations of the Quaternary Catchments are considered, and the method evaluating changes of rainfall over time is a split-sample analysis. The primary difference is the objective of the analysis; Hewitson *et al.* (2005) established changes in the historical rainfall from a climatology perspective as a context for understanding future rainfall projections. The objective in this Chapter is to support and explain the significant changes noted in hydrological responses, i.e. the perspective is a hydrological one.

It is hypothesised that an analysis of the daily rainfall records for each of the 1 946 QCs covering southern Africa will provide an objective indication of whether changes in the rainfall regimes of the QCs can be detected already, where, and to what extent. The analysis used for this study was a split-sample analysis, with the periods considered being 1950 – 1969, considered representative of an earlier period, and 1980 – 1999, considered representative of a later period. The parameters analysed corresponded to the parameters analysed for changes in hydrological responses over time. The parameters were:

- median, as well as lowest and highest annual rainfalls in 10 years;
- median, as well as lowest and highest summer season rainfalls in 10 years;

- median, as well as lowest and highest winter season rainfalls in 10 years;
- ranges between lowest and highest rainfalls in 10 years; and
- the number of rainfall events above pre-defined threshold amounts of 10 mm and 25 mm per day.

Median rainfalls are defined as the 50th percentile rainfall value as computed in a frequency analysis, the lowest in 10 years as the 10th percentile and the highest in 10 years as the 90th percentile in a frequency analysis. The results are expressed as a ratio of the later (1980 – 1999) to earlier (1950 – 1969) period. Decreases in the parameter analysed in the later period are displayed as a red scale, and increases in the later period are displayed as a blue scale, on figures which follow.

6.4 Results of an Analysis of Southern Africa's Rainfall Regime

6.4.1 Changes in median annual as well as lowest in 10 and highest in 10 year annual rainfalls

Figure 6.6 shows the ratios of median annual rainfall for 1980 – 1999 vs 1950 – 1969. Decreases in median annual rainfall are evident in the Limpopo, Keiskamma and lower Vaal Primary Catchments. Two areas in the Orange Primary Catchment show decreases, one cluster in the area which feeds the Caledon River Catchment and another in the lower Orange.

The majority of QCs in the Berg, Breede and Gouritz Primary Catchments show increases in median annual rainfall in the later period. The remainder of the Primary Catchments have QCs showing a mixture of increases or decreases in the later period. The increases and decreases evident over the interior of the country are greater in magnitude than those evident in coastal areas; however, no clear spatial patterns of increases or decrease are evident.

It is hypothesized that changes in the ends of rainfall distributions will be evident prior to changes in the means and medians. Hence the lowest and highest rainfalls in 10 years in the two periods selected are analysed next. Figure 6.7 illustrates the ratios of lowest annual rainfall in 10 years for 1980 – 1999 vs that of 1950 – 1969. Clearly evident, is the divide across southern Africa with the winter rainfall, western area of

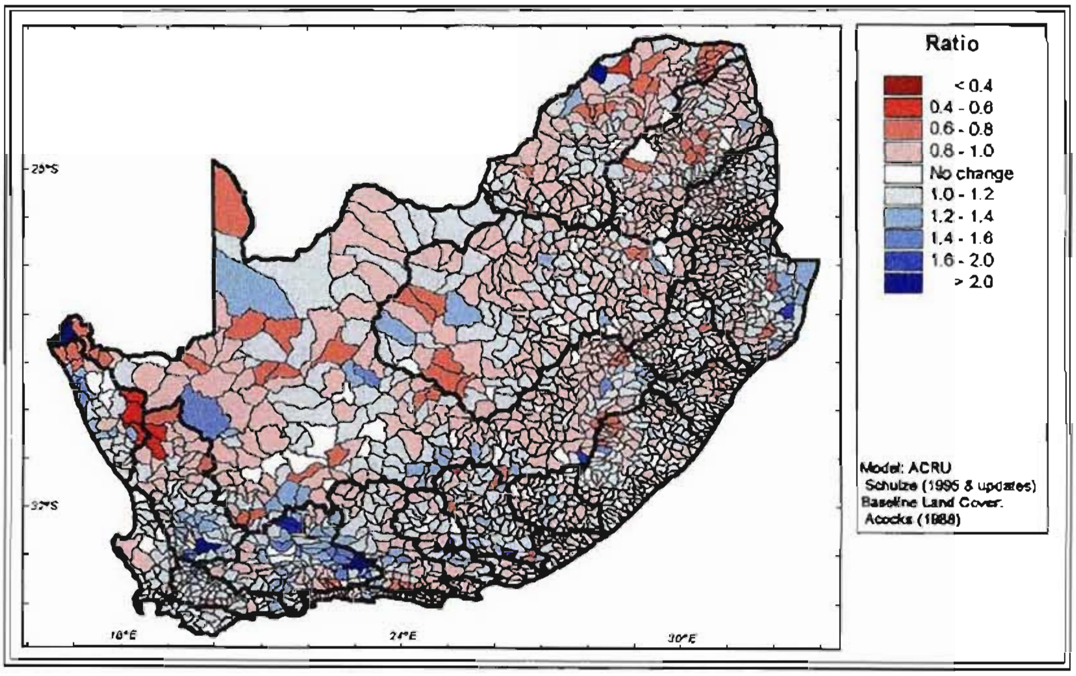

Figure 6.6 Ratios of later (1980 – 1999) to earlier (1950 – 1969) median annual rainfall

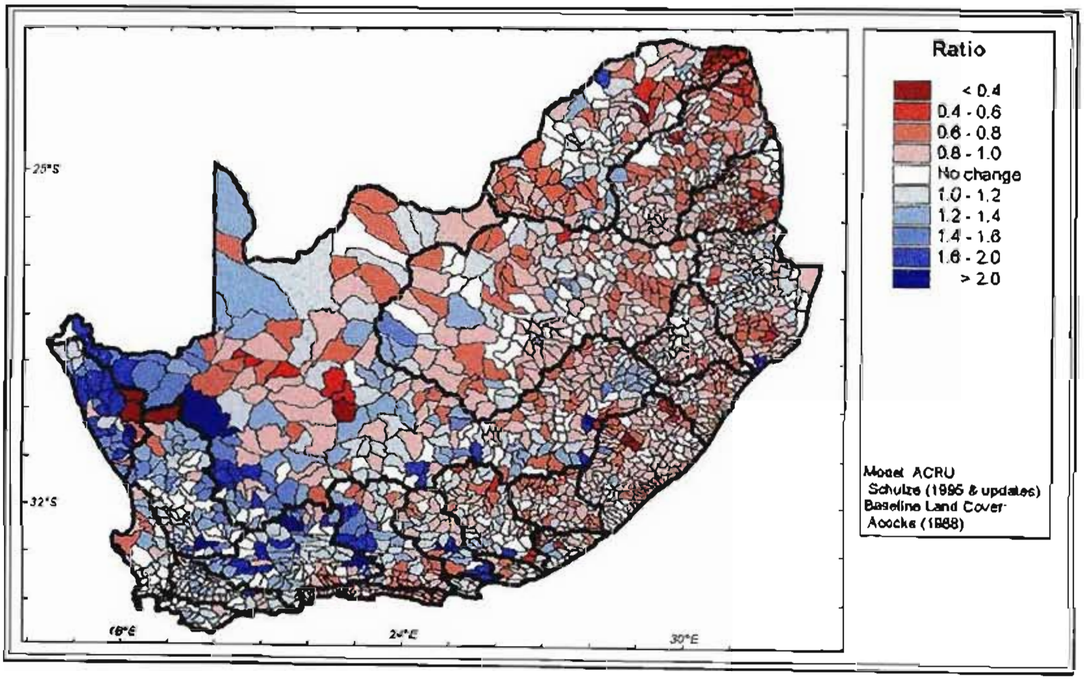

Figure 6.7 Ratios of later (1980 – 1999) to earlier (1950 – 1969) lowest annual rainfall in 10 years

southern Africa showing increases in the later period and the summer rainfall, eastern region of southern Africa shows decreases in the later period. In particular, the lower Orange and Buffels Primary Catchments show large increases in the later period. It is important to note that the changes evident here are greater than those observed in annual median rainfall. Large decreases are evident in the Great Kei, Mzimvubu, Komati and Olifants Primary Catchments.

The ratios of highest annual rainfall in 10 years between the periods 1980 – 1999 and 1950 – 1969 are shown in Figure 6.8. The changes evident are small, with many QCs showing no change between the earlier and later periods. The majority of QCs in the Mfolozi, Thukela, Mvoti, Olifants/Doorn and Gouritz Primary Catchments show slight increases in the highest annual rainfall in 10 years in the later period. A number of QCs in the Limpopo and Orange Primary Catchments show decreases in the later period.

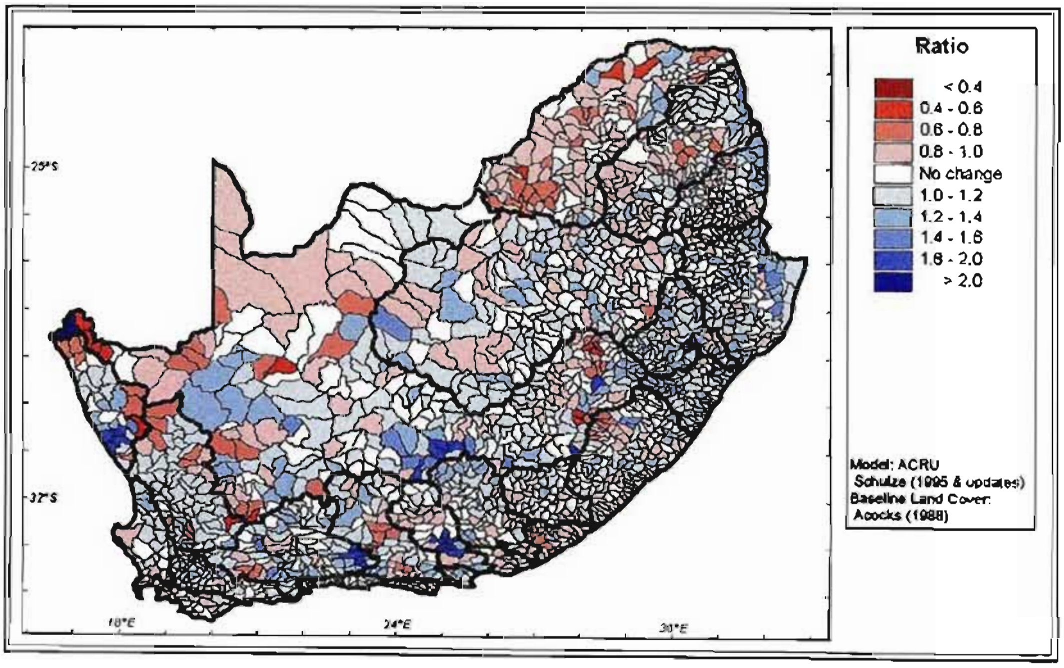

Figure 6.8 Ratios of later (1980 – 1999) to earlier (1950 – 1969) highest annual rainfall in 10 years

6.4.2 Changes in summer median, lowest and highest rainfalls

For the purposes of this study, December, January and February were defined as the summer months. Figure 6.9 shows ratio changes between 1980 – 1999 and 1950 – 1969 of median summer rainfall. A division across South Africa is evident, with the southwest showing increases in median summer rainfall in the later period, and the northeast decreases. The Gouritz, Berg, Breede, Buffels, Gamtoos, Sondags and lower Olifants/Doorn Primary Catchments show increases in the later period in the south-western winter rainfall region of southern Africa.

On the other hand, QCs along the borders of southern Africa with Zimbabwe and Mozambique show decreases in the later period. The area of the Orange Primary Catchment which feeds the Caledon River Basin, and the upper Olifants/Doorn and lower Orange Primary Catchments, also shows decreases in median summer rainfall in the later period, as do a number of QC's in the Vaal Primary Catchment.

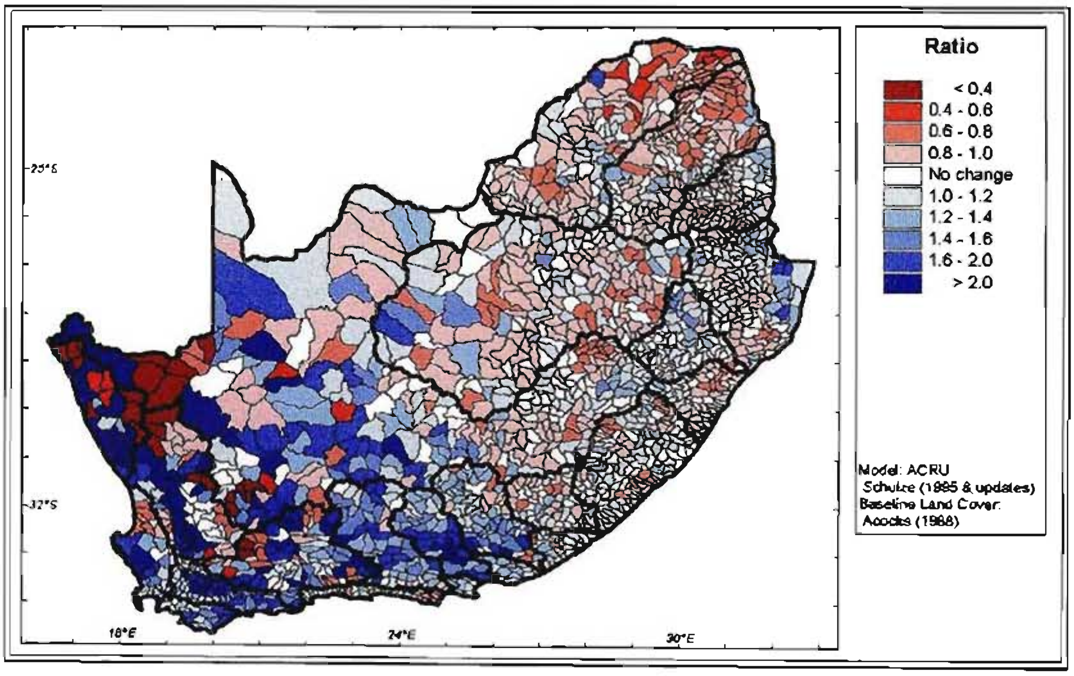

Figure 6.9 Ratios of later (1980 – 1999) to earlier (1950 – 1969) median summer (December, January, February) rainfall

Figure 6.10 illustrates the ratios of later (1980 – 1999) to earlier (1950 – 1969) lowest summer rainfall in 10 years. The striking feature of Figure 6.10 are the strong increases, up to 3 times greater in the later period than the earlier, in the lowest summer rainfall in 10 years for the Berg, Breede, lower Gouritz, Gamtoos, Sondags and Fish Primary Catchments, located mainly in the winter and all-year rainfall regions. The

Thukela and Mfolozi Primary Catchments have a number of QCs showing a smaller increase in the later period.

The Orange Primary Catchment has a few QCs displaying strong increases or decreases in the later period. The Great Kei, Mzimvubu, Mvoti, Limpopo and Olifants Primary Catchments show predominantly QCs with decreases in lowest summer rainfall in 10 years in the later period.

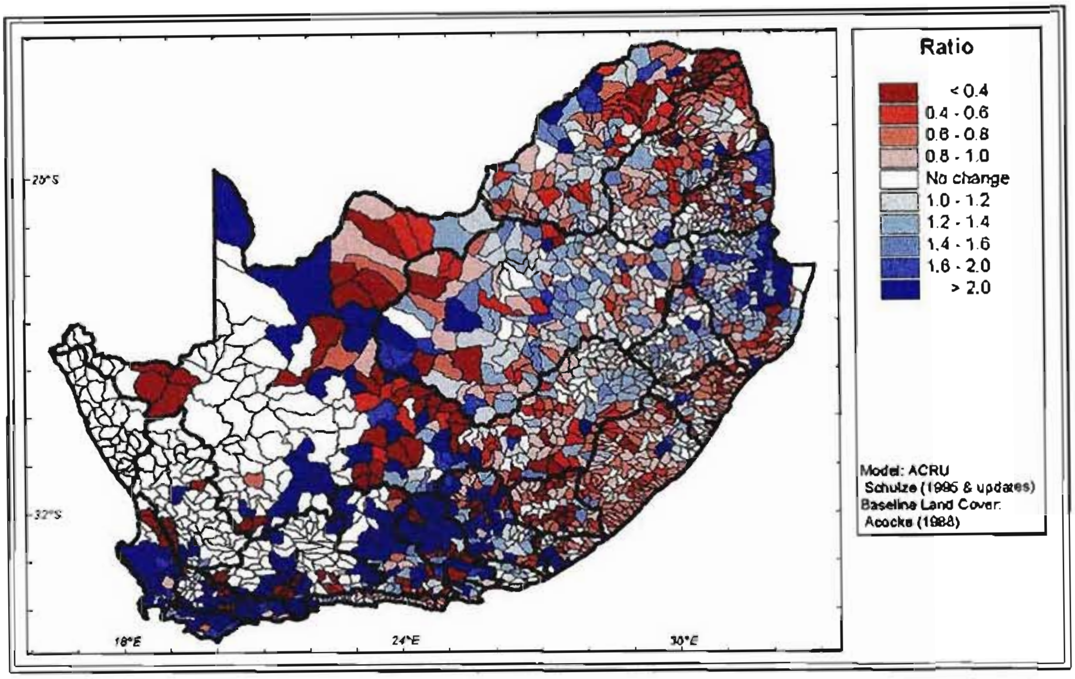

Figure 6.10 Ratios of later (1980 – 1999) to earlier (1950 – 1969) lowest summer (December, January, February) rainfall in 10 years

Figure 6.11 shows ratio changes in the highest summer rainfall in 10 years between 1980 – 1999 and 1950 – 1969. The changes evident are not as marked as those for the lowest summer rainfall in 10 years. The Limpopo and Olifants Primary Catchments tend to show decreases in the later period, as does the area of the Orange Primary Catchments which feeds the Caledon River Basin. A number of QCs in the Vaal Primary Catchment also show a decrease in highest summer rainfall in 10 years in the later period.

Quaternary Catchments in the Mgeni, Great Kei, Lower Orange, Sondags, Gouritz and Breede Primary Catchments tend to show slight increases from 1.1 to 2 times the highest summer rainfall in 10 years of 1950 – 1969s rainfall in the later period.

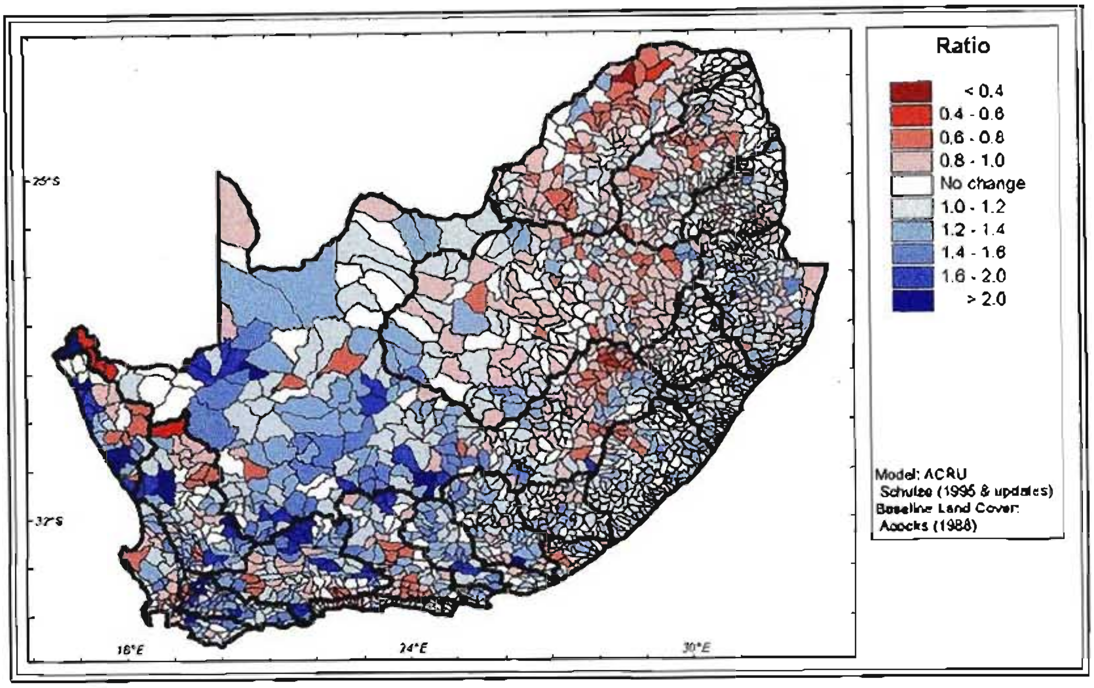

Figure 6.11 Ratios of later (1980 – 1999) to earlier (1950 – 1969) highest summer (December, January, February) rainfall in 10 years

6.4.3 Changes in winter median, lowest and highest rainfalls

The winter months are defined as June, July and August for the purposes of this study. Figure 6.12 displays the ratios of later (1980 – 1999) to earlier (1950 – 1969) winter median rainfall. The Primary Catchments along the east coast of southern Africa do not show strong changes in median winter rainfall in the later period; neither do the Primary Catchments along the west coast of southern Africa or those in the Western Cape region, the latter two being the winter rainfall region of southern Africa.

Over the interior of the country and stretching up to the border of South Africa with Mozambique, the changes evident in winter median rainfall are substantial, but with a mixture of increases and decreases in the later period. The only Primary Catchments showing a predominant change in one direction are the Thukela and Sondags Primary Catchments, which show predominantly an increase in the later period. However, rainfall in this period in the Sondags and Thukela Primary Catchments is low, as this is a summer rainfall region, and thus changes are likely to be hydrologically insignificant

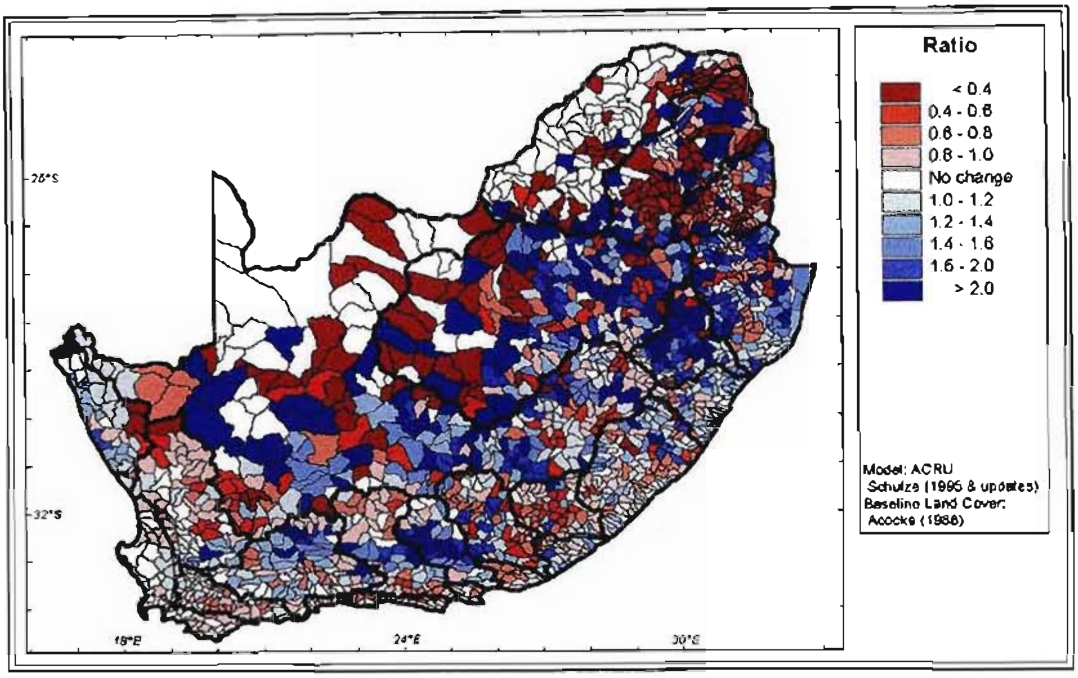

Figure 6.12 Ratios of later (1980 – 1999) to earlier (1950 – 1969) median winter (June, July, August) rainfall

Figure 6.13 shows the ratios of the lowest winter rainfall in 10 years between 1980 – 1999 vs 1950 – 1969. The interior of southern Africa shows no changes in the lowest winter rainfall in the later period. This is not altogether surprising, as this variable is the 10th percentile of winter rainfall which, in this area, is most likely zero and remains so in both periods. QCs along the east coast of southern Africa, particularly those in the Mgeni, Mzimvubu, Fish, Boesmans, Swartkops and Gamtoos Primary Catchments, show significant decreases in the lowest winter rainfall in 10 years in the later period, in many instances the QC only experiences a third of the earlier periods lowest rainfall in 10 years in the later period.

In the winter and all year rainfall regions a mixture of increases and decreases in the later period of lowest winter rainfall in 10 years are evident, however, QC's showing increases in the later period are more prevalent and indicated stronger changes than the QC's displaying decreases in the later period.

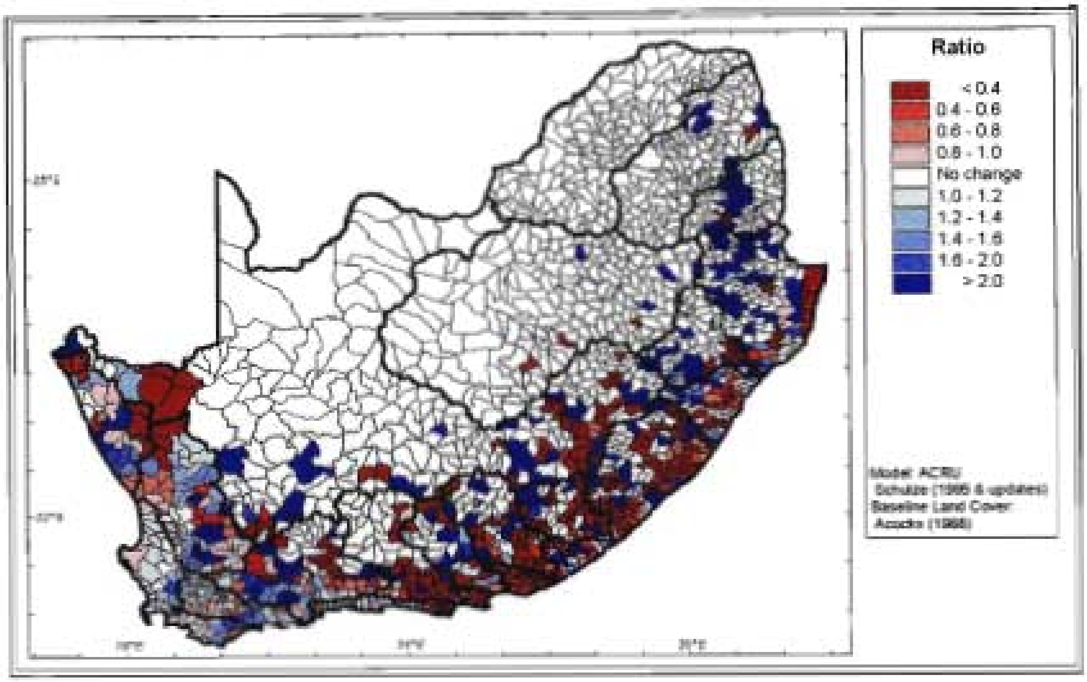

Figure 6.13 Ratios of later (1980 – 1999) to earlier (1950 – 1969) lowest winter (June, July, August) rainfall in 10 years

Figure 6.14 displays the ratio of highest winter rainfall in 10 years between the 1980 – 1999 and 1950 – 1969 periods. The pattern shown is markedly different to the pattern shown for lowest winter rainfall in 10 years. Decreases in the later period are evident in the majority of QCs in the Komati, Vaal and Mzimvubu Primary Catchments. Quaternary Catchments in the Orange and upper Limpopo Primary Catchments, along the border of South Africa with Botswana and Zimbabwe, show significant decreases in the highest winter rainfall in 10 years in the later period. A number of QCs in the Mgeni, Great Kei and north-eastern Orange Primary Catchments show slight increases in the later period.

QCs in the winter rainfall region are showing decreases in the highest winter rainfall in 10 years in the later period, these decreases are slight, and a few QC's in the region indicate increases in the later period.

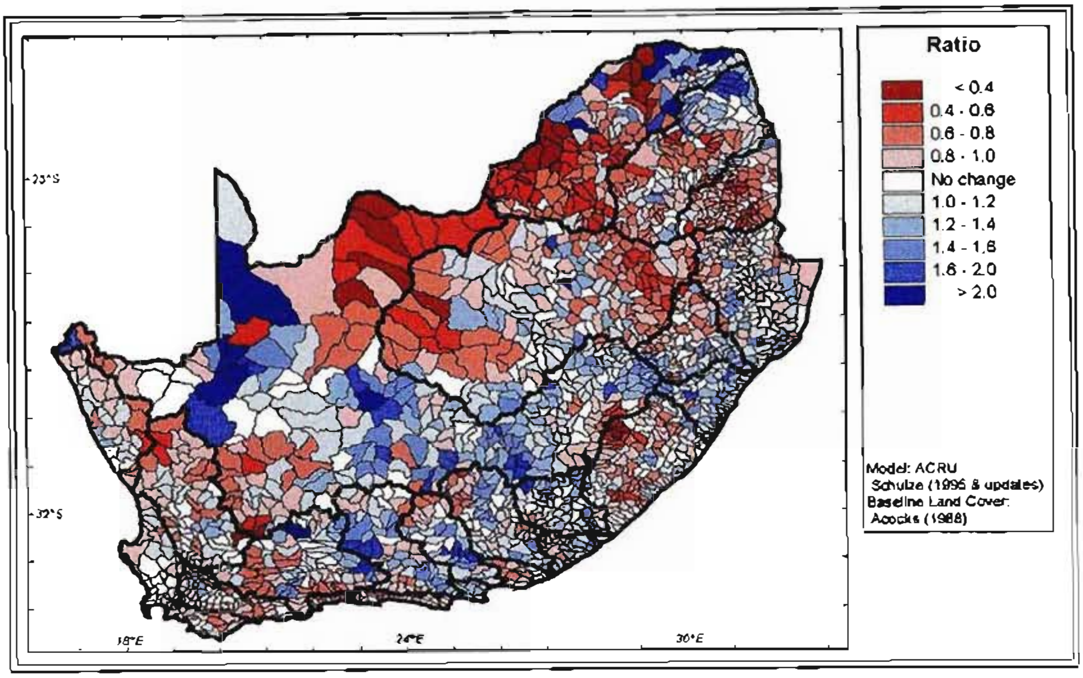

Figure 6.14 Ratios of later (1980 – 1999) to earlier (1950 – 1969) highest winter (June, July, August) rainfall in 10 years

6.4.4 Ranges of rainfall between years with low and high rainfalls

Rainfall at the upper end of the distribution results in flooding, while sustained lack of rainfall at the lower end of the distribution results in droughts. Structures are designed to accommodate rainfall generated runoff at both ends of the distribution. If, therefore, lowest rainfalls in 10 years are becoming more severe and simultaneously the highest rainfalls in 10 years are becoming more severe, structures have to be designed to accommodate a wider range of resulting runoffs, and the designs need to be more conservative. Spatial changes in the lowest rainfalls in 10 years and highest rainfalls in 10 years, for both winter and summer seasons, have been shown to occur (*cf.* Figures 6.9 to 6.14). On the basis of these changes, changes in the range between the lowest and highest rainfalls in 10 years for summer and winter seasons are analysed below.

Figure 6.15 shows the ratio of the range between the lowest and highest summer rainfalls in 10 years for 1980 – 1999 vs 1950 – 1969. The pattern of changes is similar to changes in the highest summer rainfall in 10 years. A number of QCs in the Limpopo, Olifants and Vaal Primary Catchments show decreases in the summer range in the later period, as do the QCs in the Orange Primary Catchment in the area that feeds the Caledon River Basin.

The Mgeni, Mzimvubu, Great Kei, Sondags, Gouritz, Breede and lower Orange Primary Catchments contain a number of QCs showing an increase in the range between the lowest and highest summer rainfalls in 10 years in the later period. The increases evident are larger in the lower Orange, Breede and Sondags Primary Catchments, where the range in the later period is often up to twice that of the earlier period.

At quick glance, the picture for the range between the lowest and highest summer rainfalls in 10 years is one of increases in the later period for the east coast and western regions of southern Africa, with decreases over the north-eastern regions.

Figure 6.16 illustrates the ratio of the range between the lowest and highest winter rainfall in 10 years for 1980 – 1999 vs 1950 – 1969. The pattern is similar to that shown in Figure 6.14. The majority of QCs in the Vaal, Komati, Olifants, Mzimvubu and Limpopo Primary Catchments show decreases in the range between the lowest and highest winter rainfall in 10 years in the later period. The QCs in the Orange and Limpopo Primary Catchments that are situated in the area of the South African borders with Botswana and Zimbabwe show significant decreases in the later period; however, as the magnitude of rainfall in the winter months in this area is small these changes are most likely hydrologically insignificant.

A number of QCs in the Mgeni and north-eastern Orange Primary Catchments show increases in the range between the lowest and highest winter rainfalls in 10 years in the later period. The area of importance is the winter rainfall region where QC's show primarily decreases in the range between lowest and highest winter rainfall in 10 years in the later period. The remainder of Primary Catchments show a mixture of QCs with either increases or decreases in the later period.

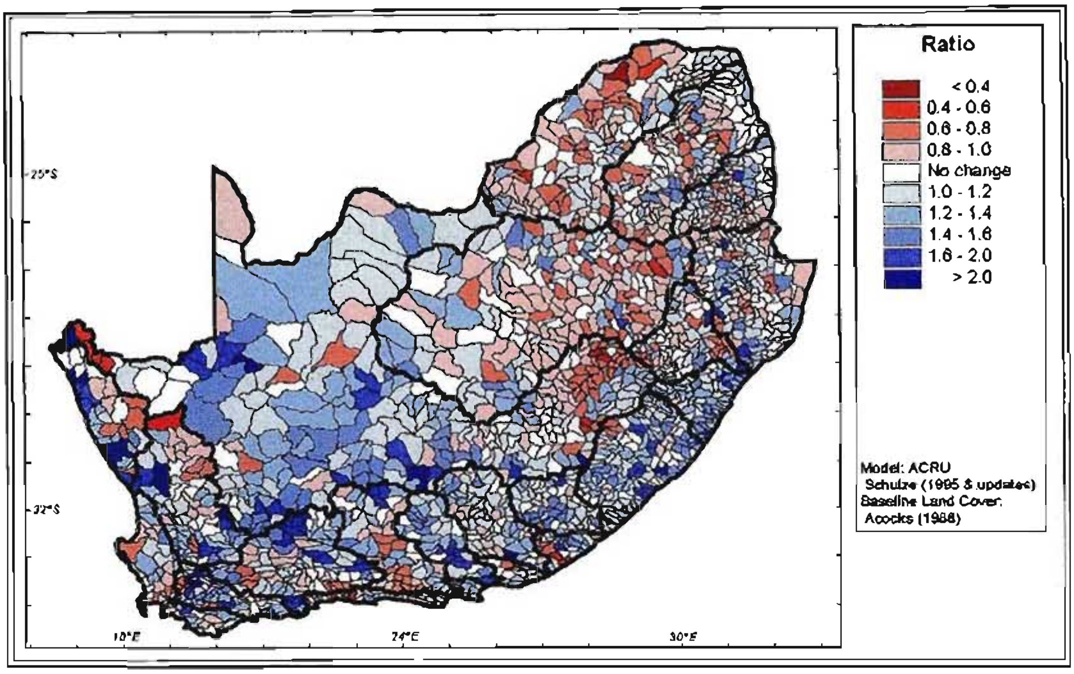

Figure 6.15 Ratios of later (1980 – 1999) to earlier (1950 – 1969) range between lowest and highest summer (December, January, February) rainfall in 10 years

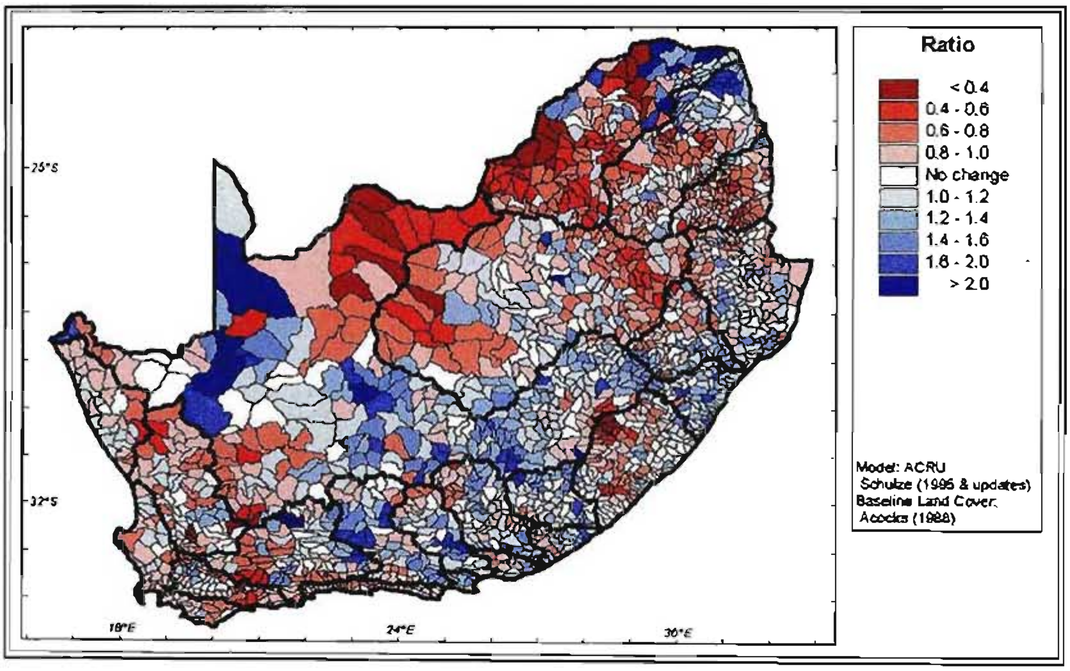

Figure 6.16 Ratios of later (1980 – 1999) to earlier (1950 – 1969) range between lowest and highest winter (June, July, August) rainfall in 10 years

6.4.5 Analysis of the number of rainfall events above predefined threshold amounts

Climate change will mostly likely be evident in more extreme rainfall events prior to being evident in the annual or seasonal averages. It is also hypothesised that with climate change the number of large rainfall events will increase in frequency and magnitude, as already shown from pixel averaged Regional Climate Model values over southern Africa by Englebrecht (2005). To assess whether the frequency of large runoff-producing rainfall events has changed, two rainfall thresholds, *viz.* 10 mm and 25 mm per day, were chosen and the number of rainfall events exceeding these two thresholds were assessed for the two time slices, 1950 – 1969 and 1980 – 1999, for both summer (December, January and February) and winter (June, July and August). This was expressed as a ratio of the number of events in the later (1980 – 1999) period to the number of events in the earlier (1950 – 1969) period.

Figure 6.17 illustrates the ratio of the number of rainfall events greater than 10 mm in summer. At first glance the pattern evident is one of increases in the later period in the winter rainfall region of the country and decreases in the northern most part of the country. In more detail, the Limpopo and Olifants Primary Catchments show primarily decreases in the number of rainfall events greater than 10 mm in summer in the later period. The area of the Orange Primary Catchment which feeds the Caledon River Basin shows decreases in the later period.

Quaternary Catchments in the winter and all year rainfall region, particularly the Sondags, Olifants/Doorn, Gouritz, Coastal Rivers, Breede and Berg Primary Catchments, show a clear, cohesive increase in the number of rainfall events greater than 10 mm in summer in the later period.

The remainder of the Primary Catchments over central southern Africa have QCs showing no substantial change, increases and decreases in the later.

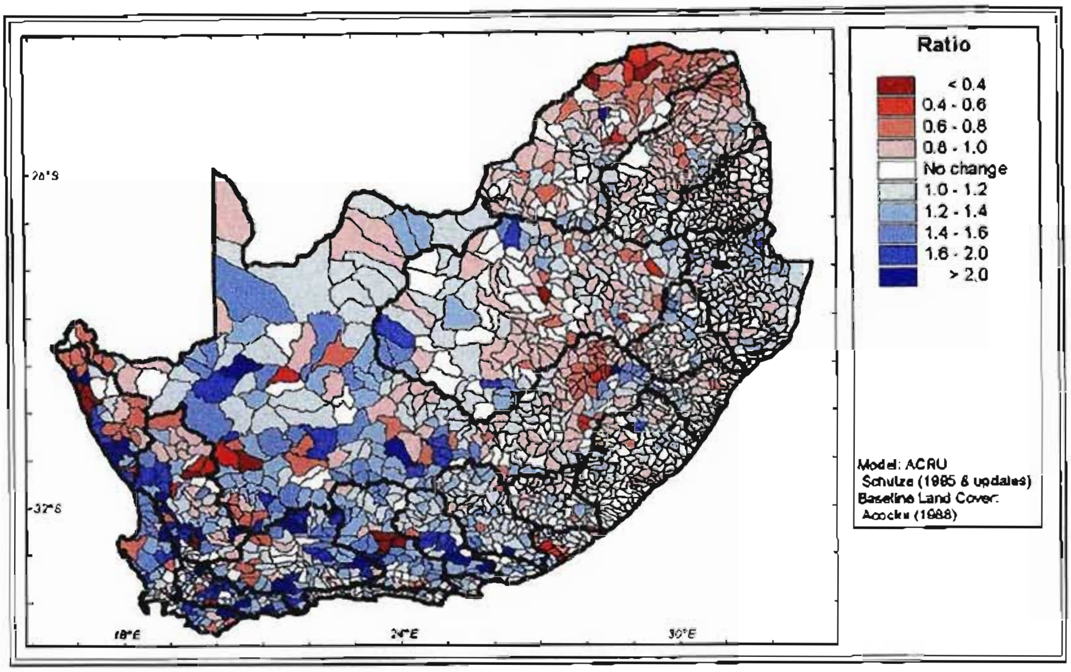

Figure 6.17 Ratios of later (1980 – 1999) to earlier (1950 – 1969) number of rainfall events greater than 10 mm in summer (December, January, February)

Figure 6.18 displays the ratio of changes in the number of rainfall events greater than 25 mm in summer for the periods 1980 – 1999 vs 1950 – 1969. In comparison to changes in the number of events greater than 10 mm in summer, the changes evident in the number of events greater than 25 mm in summer are larger. However, few clear clusters of change are evident.

One clear cluster of QCs showing a change in one direction is the area of the Orange Primary Catchment which feeds the Caledon River basin shows decreases in the number of events greater than 25 mm in summer, where the later period only experiences a third of the number of events that the earlier period does. Decreases in the later period are also evident in the QCs in the northern regions of the Limpopo Primary Catchment. The Thukela Primary Catchment shows fairly uniform increases in the later period. Although, significant increases and decreases in the later period are evident in various QCs, there is no spatial pattern to these changes.

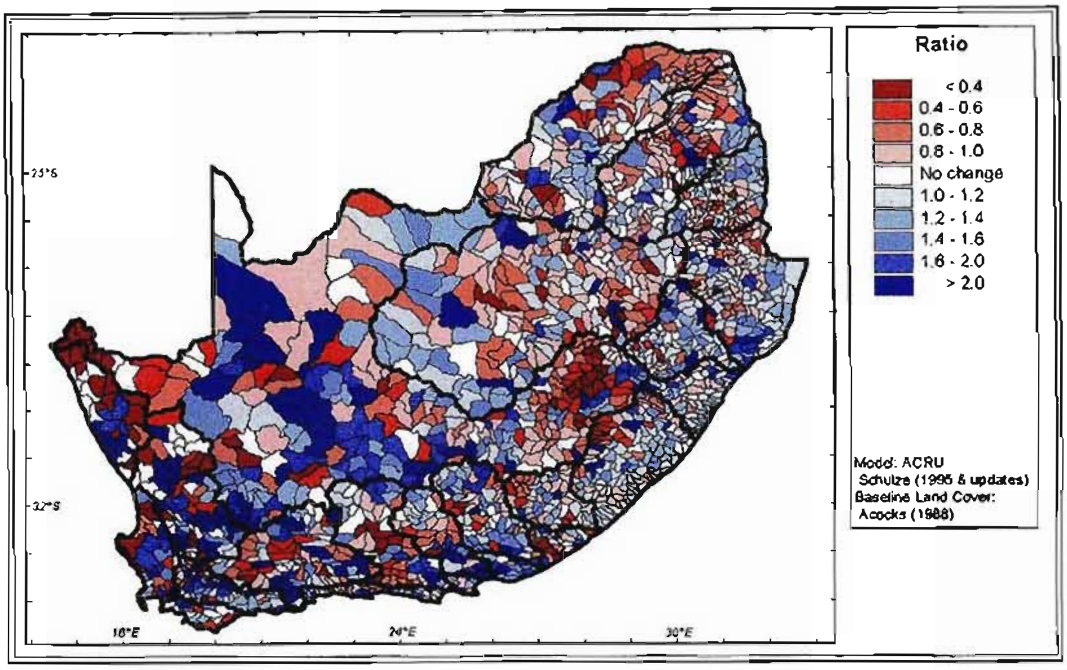

Figure 6.18 Ratios of later (1980 – 1999) to earlier (1950 – 1969) number of rainfall events greater than 25 mm in summer (December, January, February)

Figure 6.19 shows the ratio of later (1980 – 1999) to earlier (1950 – 1969) changes in the number of rainfall events greater than 10 mm in winter. The QCs in the area of the upper Limpopo and Orange Primary Catchments, stretching into the Vaal Primary Catchment on the South Africa border with Botswana and Zimbabwe show significant decrease in the number of rainfall events greater than 10 mm in winter in the later period.

The Komati, Breede and upper Olifants have a number of QCs which show a decrease in the later period. The area of the Orange Primary Catchment which feeds the Caledon River Basin also experiences decreases in the later period. However, the remainder of the Orange Primary Catchment not mentioned above, tends to experience increases in the number of rainfall events greater than 10 mm in winter in the later period.

The south-western Cape or winter rainfall region of southern Africa shows largely decreases in the number of rainfall events greater than 10 mm in winter in the later period.

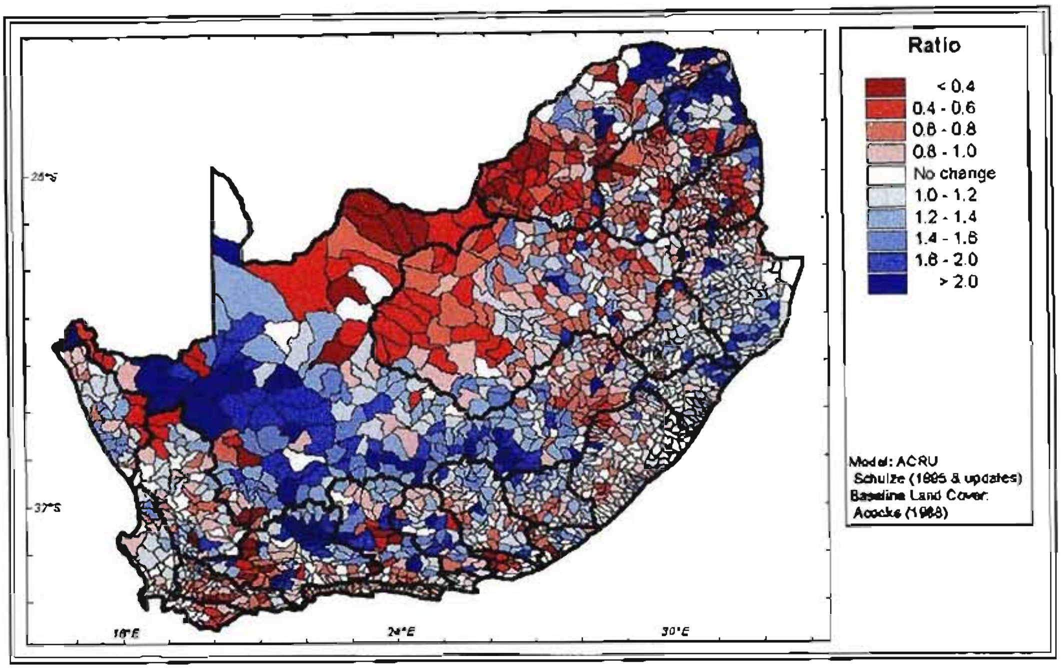

Figure 6.19 Ratios of later (1980 – 1999) to earlier (1950 – 1969) number of rainfall events greater than 10 mm in winter (June, July, August)

In Figure 6.20 the ratio changes between number of rainfall events greater than 25 mm in winter for a later (1980 – 1999) vs an earlier (1950 – 1969) period is shown. The changes shown here are greater than the changes noted at a threshold of 10 mm in winter. Again, the same area on the South African borders with Botswana and Zimbabwe show significant decreases in the later period.

Of marked importance are the decreases evident in the winter rainfall region. Decreases are evident in the Primary Catchments of the Breede, Buffels, Berg and parts of the Gouritz in the number of rainfall events greater than 25 mm in winter for the later period. This tends to suggest that the winter rainfall region is experiencing fewer large rainfall events in winter. A number of QCs in the Great Kei and remainder of the Orange Primary Catchments show increases in the later period.

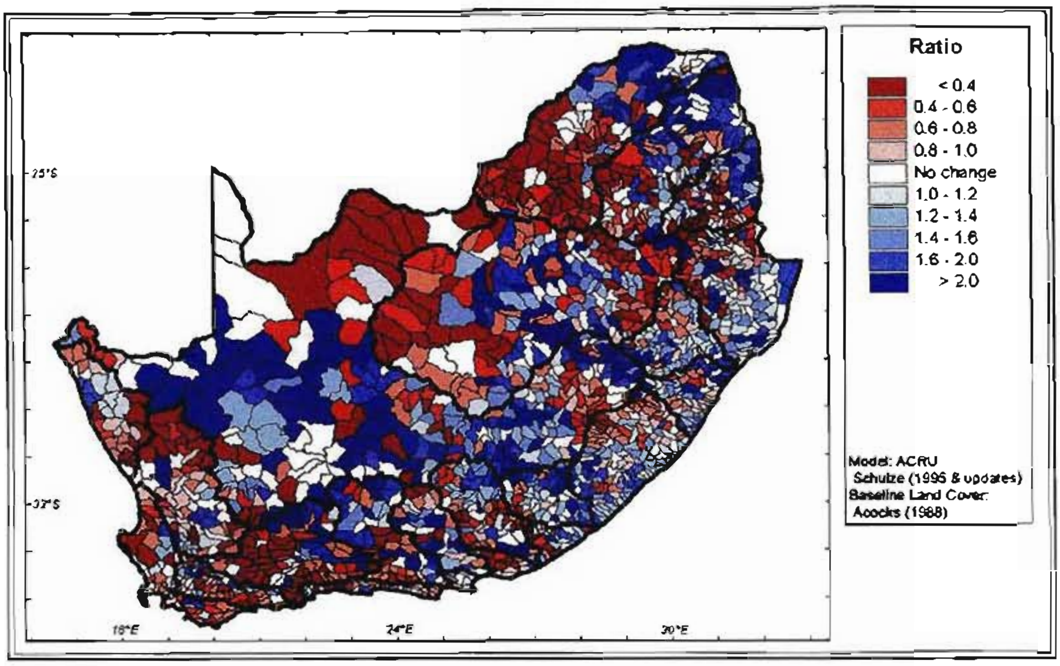

Figure 6.20 Ratios of later (1980 – 1999) to earlier (1950 – 1969) number of rainfall events greater than 25 mm in winter (June, July, August)

6.5 Can the Changes Evident in Hydrological Responses be Explained by Changes in the Rainfall Regime? A Discussion

The analysis of each Quaternary Catchment's rainfall in Section 6.3 was prompted by the substantial changes evident in hydrological responses between the periods 1980 – 1999 and 1950 – 1969 (*cf.* Chapter 5), with the objective being to determine if these substantial hydrological changes could be supported with observed changes in rainfall. Thus, the dominant changes noted in Chapter 5 in hydrological responses will be repeated in this section. First, however, the dominant changes evident in rainfall patterns will be highlighted. As in the case of the summary of findings in Chapter 5, this summary is intended also for non-hydrologists and is therefore given by province rather than Primary Catchment.

The split-sample analysis of Quaternary Catchments' rainfall, displayed diagrammatically as a ratio of 1980 – 1999 vs 1950 – 1969 values, shows that:

- median annual rainfall has decreased over the Limpopo and North-West Provinces, with decreases evident in the southeastern Free State as well, but with increases in the winter rainfall region (Figure 6.6);

- the lowest annual rainfall in 10 years shows increases in the Western Cape and along the west coast of South Africa, with decreases over the southeastern Free State (Figure 6.7);
- the lowest rainfall in 10 years in the summer months shows substantial increases in the Western and Eastern Cape (Figure 6.10);
- the highest summer rainfall in 10 years shows similar increases over the Northern, Western and Eastern Cape provinces; decreases are evident, however, over the north-eastern regions of southern Africa (Figure 6.11);
- winter median rainfall showed both substantial increases and decreases over the interior of southern Africa, with the only clear area of uniform change being KwaZulu-Natal, where increases are evident (Figure 6.12);
- the lowest winter rainfall in 10 years indicated increases in the winter rainfall region and marked decreases along the east coast of southern Africa (Figure 6.13);
- the range between one in ten low and high summer rainfalls showed increases in the Northern and Western Cape, as well as over KwaZulu-Natal; again with decreases evident in the southeastern Free State (Figure 6.15);
- for the threshold analyses, the changes observed became more substantial as the threshold amount increased; and
- rainfall events in excess of 25 mm in winter are decreasing along the borders of South Africa with Botswana and Zimbabwe, with decreases also evident in the Western Cape, but increases evident over parts of the Northern Cape (Figure 6.20).

The changes evident in rainfall patterns vary from relatively unsubstantial increases or decreases to significant increases or decreases. As mentioned previously, changes in rainfall are amplified by the hydrological cycle, with a unit change in rainfall frequently resulting in changes in runoff by 2 – 4 times the change in rainfall over most areas of South Africa, and with a 4 – 5 fold sensitivity along the west coast (Schulze, 2005). To support the changes evident in hydrological responses (Chapter 5), certain hydrological responses and related changes in rainfall are highlighted.

Median annual accumulated streamflows decreased over the southeastern Free State and Limpopo provinces, with half to a third of the earlier period's streamflows experienced in the later period (Figure 5.5). A corresponding decrease in annual rainfall was noted in the southeastern Free State and Limpopo Provinces, where in places less than third of the 1950 – 1969 rainfall was experienced in 1980 – 1999. Both median annual streamflows and median annual rainfalls indicate increases in the winter rainfall region.

The lowest annual streamflows in 10 years indicated increases in the winter rainfall region, as did the lowest annual rainfalls in 10 years show increases in the Western Cape and southern Northern Cape. Decreases in the lowest annual rainfall in 10 years were evident over eastern South Africa, in the order of 80 to 50% of 1950 – 1969 rainfall in the 1980 – 1999 period and this is mirrored in the decreases in lowest annual streamflows in 10 years with, in places, only 30% of the earlier period's streamflows occurring in the later period.

Both lowest summer rainfalls and streamflows in 10 years showed substantial increases in the winter rainfall region. However, these have little hydrological significance as the rainfall thus runoff during summer is low. Increases were also evident for both lowest winter rainfalls and streamflows in 10 years for the winter rainfall region, while marked decreases for both were also evident for the highest winter rainfall in 10 years. Events above thresholds in the winter rainfall region for winter tend to indicate decreases, thus it appears that the winter rainfall region is experiencing more raindays, but with less rainfall on those days.

In regard to the inter-annual range of rainfall, decreases in the summer range between the lowest and highest rainfalls and streamflows in 10 years were noted in the southeastern Free State, while increases were evident in KwaZulu-Natal.

The changes in rainfall patterns certainly support the changes observed in hydrological responses, with similar hotspots of change noted in both analyses. Increases in both hydrological responses and rainfall are evident in the winter rainfall region; decreases are evident in the southeastern Free State, Limpopo and North-West provinces. Not all areas of southern Africa are experiencing changes in rainfall as yet, and the direction of rainfall change is not uniform across the country.

In Chapter 7, which follows, observed changes in temperature (Chapter 3), observed changes in hydrological drivers and responses (Chapter 5) and observed changes in rainfall (Chapter 6) are summarised. Recommendations regarding the direction and areas which future research in climate change detection in South Africa should move are made, as are recommendations on the rainfall monitoring network covering South Africa. The roadmap given overleaf places the final chapter in perspective with regards to the overall project.

Problem Statement: If anthropogenically forced climate change is becoming a reality, evidence of change should already be detectable in climate observations and from hydrological simulations at a regional scale

Overall Objectives: To determine whether statistical analyses already show trends in temperature parameters and hydrological responses which may be ascribed to climate change

		Broad Objectives		
		Temperature Detection Studies	**Detection Studies on Hydrological Drivers and Responses**	**Overall Conclusions and Recommendations**
Specific Objectives	**Literature Review**	i.) Review results from temperature detection studies ii.) Outline problems related to temperature data iii.)Review statistical methods used in detection studies	i.) Review results from streamflow detection studies ii.) Outline problems related to streamflow measurement iii.)Discuss the advantage of physical conceptual hydrological models in detection studies iv.)Review precipitation detection studies	i.) Changes in southern Africa's temperature regime ii.) Changes in southern Africa's hydrological drivers and responses iii.) Changes in southern Africa's rainfall regime iv.) Overall conclusions and recommendations
	Data	i.) Outline temperature dataset used for southern Africa	i.) Quaternary Catchments Database and input	
	Methods	i.) The Mann-Kendall non-parametric test ii.) Split-sample analysis	i.) Re-select rainfall station network ii.) The Mann-Kendall non-parametric test iii.)Split-sample analysis	
	Results	**Mann-Kendall Analyses** i.) Examine means of minimum and maximum temperatures ii.) Analyse percentile thresholds iii.)Analyse selected thresholds iv.)Analyse frost related parameters v.) Analyse Heat units vi.)Analyse Chill units **Split-sample analyses** i.) Examine means of minimum and maximum temperatures ii.) Analyse coefficient of variation	**Mann-Kendall Analysis** i.) Analyse accumulated streamflows **Split-Sample Analyses** i.) Reference potential evaporation ii.) Soil water content iii.) Median, 90th and 10th percentile of accumulated streamflow iv.) Range in streamflows v.) Baseflows vi.) Seasonality and concentrations of flows vii.)Irrigation water requirements **Split-Sample Analyses** i.) Median, 90th and 10th percentile of rainfall ii.) Range in rainfall iii.) Analyse selected thresholds	
	Conclusions	i.) Is southern Africa's temperature changing?	i.) Conclusions of detection studies on hydrological responses ii.) Conclusions on changes in rainfall	

7. OVERALL CONCLUSIONS AND RECOMMENDATIONS

The last broad objective (*cf.* roadmap) of this dissertation was to draw conclusions as to whether changes in temperature and hydrological parameters could be detected already at the regional scale of southern Africa. The objective also included making recommendations for future research. Prior to drawing final conclusions, summaries of the temperature and hydrological detection studies are presented.

7.1 Summary of Temperature Changes Evident over Southern Africa

The Mann-Kendall non-parametric test and a split-sample analysis were applied to a high quality, daily 51 – year record of minimum and maximum temperatures for 209 stations across southern Africa in order to determine if trends in temperature parameters could be detected already. Not only were annual, summer and winter means considered, but percentile threshold analyses, predefined threshold analyses, frost related analyses, chill unit analyses and heat unit analyses were also conducted, as it hypothesised that climate change will be evident in the extremes of temperature parameters prior to being evident in their means.

For almost all the analyses performed two clear clusters of warming emerged, these being a cluster of stations in the Western Cape and a cluster of stations around the midlands of KwaZulu-Natal, along with a band of stations along the KwaZulu-Natal coast. These clusters showed up clearly in the analyses of annual means of both minimum and maximum temperatures, in the percentile and predefined threshold analyses for cold spells, in the heat unit analyses and split-sample analyses of annual means of daily minimum temperature.

Another distinct conclusion drawn is that warming over the interior of southern Africa is already occurring, and when analysing frost occurrences, the Northern Cape and Free State provinces stood out in this regard. A shift towards an earlier frost season was also noted. From the analyses of temperature records it became clear that certain changes in temperature parameters are occurring across southern Africa. However, these changes are not uniform across the region. The identified hotspot areas of warming were the Western Cape and KwaZulu-Natal.

7.2 Summary of Changes Evident in Hydrological Responses over Southern Africa

The *ACRU* model was used to simulated streamflows and various other hydrological responses and drivers for the period 1950 – 1999. In this analysis, all human impacts were eliminated from simulations. Two periods of data, *viz.* 1980 – 1999 and 1950 – 1969 were extracted and split-sample analyses performed on the various hydrological responses and drivers. Analyses were conducted on reference potential evaporation, soil water content, median, lowest and highest accumulated streamflows in 10 years, ranges between high and low streamflows, baseflows, timing and concentration of streamflows and irrigation water demand.

The winter rainfall region emerged through all the analyses as an area experiencing increased flow parameters in the later period. Increases in the later period were observed in median annual accumulated streamflows, lowest summer accumulated streamflows in 10 years, lowest winter accumulated streamflows in 10 years and concentration of summer flows. Decreases in the later period, however, were observed in the winter range between the lowest and highest flows in 10 years.

The southeastern Free State, the area which feeds the Caledon River Basin, exhibits decreases in the later period in almost every analysis of hydrological responses conducted, be it in medians, extremes or ranges, and the decreases noted are substantial.

The east coast of southern Africa, in particular that of KwaZulu-Natal, showed marked increases in the upper end of the streamflow distribution. Increases in the later period in the annual highest accumulated streamflows in 10 years were evident, as were increases in the summer highest accumulated streamflows in 10 years. The range between the lowest and highest flows in 10 years for summer in the later period had also increased in this region.

The changes seen in streamflow were relatively large, and often the later period experienced more than twice the streamflows of the earlier period. These results however, may be an artefact of the two relatively short periods used in the split-sample analysis, for which the trends observed may not necessarily have statistical significance. The extent to which the trends over the past 50 years are directly related to climate change is not clear. However, some trends are very marked over significantly large parts of Primary Catchments, with the hotspots of change being the winter rainfall region, KwaZulu-Natal and the southeastern Free State.

7.3 Summary of Changes in Rainfall Regimes

The substantial changes evident in hydrological responses prompted an exploration of changes in rainfall patterns. Daily rainfall values for each of the 1 946 Quaternary Catchments were extracted from the *ACRU* model rainfall files for the periods 1980 – 1999 and 1950 – 1969. A split-sample analysis was performed, and the results displayed as a ratio. The changes evident in rainfall vary from unsubstantial increases or decreases to significant increase and decreases. The winter rainfall region of southern Africa seems to be experiencing more rainfall in the 1980 – 1999 period compared with the 1950 – 1969 period. It is experiencing an increased median annual, lowest annual rainfall in 10 years, an increase in summer median and lowest summer rainfall in 10 years. The lowest winter rainfall in 10 years in the winter rainfall region is increasing, however, the highest winter rainfall in 10 years is decreasing, as is the number of events above thresholds of 10 mm and 25 mm.

The area of the southeastern Free State which feeds the Caledon River Basin, consistently indicates a decrease in rainfall in the later period for almost all rainfall parameters analysed. The Limpopo and North-West provinces, along the borders of South Africa with Botswana and Zimbabwe, stretching into the Northern Cape, represents another area consistently showing a decrease in rainfall in the later period for the various parameters analysed. The changes evident in daily rainfall varied spatially across the country, with hotspot areas in the Western Cape, southeastern Free State, Limpopo and North-West Provinces being identified.

7.4 Are Changes in Climate Already Evident over Southern Africa at a Regional Scale?

Changes in southern Africa's temperature, hydrology and rainfall have been shown in Chapters 3, 5 and 6. These changes, however, are not consistent spatially within the region, nor in direction and magnitude of change. However, hotspots or clusters of substantial change have been detected.

The Western Cape region is viewed as a definite hotspot of change. In almost every temperature parameter analysis performed warming was observed. Streamflows in the Western Cape are increasing, in particular low flow. The rainfall regime in the Western Cape has also been shown to be increasing. Another hotspot of detected change is KwaZulu-Natal, where strong increases in temperatures are evident, along with increases in the upper ends of the streamflow distribution. Increases in rainfall were also evident in this region.

In rainfall and hydrological detection studies, a hotspot showing substantial decreasing trends was the southeastern Free State. The Limpopo and North-West provinces were also identified as areas showing marked decreases in rainfall and hydrological responses.

From the analyses conducted in this study, it has become clear that South Africa's temperature and rainfall, as well as hydrological responses, have changed over the recent past in certain identifiable hotspots, *viz.* the Western Cape and KwaZulu-Natal. These detected changes in climate need to be considered in all future water resources planning.

7.5 Recommendations Regarding the Rainfall Monitoring Network in South Africa

For each Quaternary Catchment the "best" representative rainfall station of that catchment was selected in this study from a more comprehensive and up-to-date database than that used in a previous selection of stations. The selection was based on a number of possible influences on the quality of the rainfall stations' records. The rainfall stations selected to 'drive' each Quaternary Catchment generally had a long reliable and high quality record of daily rainfall.

However, an analysis of the rainfall network highlighted that low rainfall station reliability existed in the Western Cape and Drakensberg mountain areas and in the northernmost parts of South Africa. As a considerable portion of southern Africa's water resources have their origin in such high lying areas where the rainfall, and thus runoff, gradients are at their steepest and the strong curvilinear relationship between rainfall and runoff is at the high end of the curve, it is crucial that the reliability of the rainfall network in these areas be improved.

The rainfall stations selected in this study need to be highlighted in terms of the monitoring network in South Africa and should, if at all possible be, retained as high quality rainfall stations, as they are crucial in the region's future climate change detection and hydrological studies.

7.6 Recommendations for Future Climate Change Detection Studies in Southern Africa

Future research in detection studies in southern Africa should focus first on using the results of detected changes in climate parameters from this and other studies to convince roleplayers in national, regional and local governments and water resources managers that climate change has become a reality already, and can no longer be ignored.

Hydrological detection studies in future need to consider the impacts which actual catchment conditions, including present (and projected) land uses, dams, irrigated areas, inter-basin transfers and return flows, have had on the hydrological regime, and whether changes in the catchments hydrological responses, over and above these anthropogenic impacts, are present which can be attributed to changes in climate.

An in-depth examination of actual rainfall records from high quality rainfall stations, which have a homogeneous record of at least 50 years, needs to be undertaken. Water is crucial to human existence; hence, it is essential that changes in rainfall regimes are detected early.

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