CONCEPTUALISATIONS AND APPLICATIONS OF ECO-HYDROLOGICAL INDICATORS UNDER CONDITIONS OF CLIMATE CHANGE

KR BARICHIEVY

DISSERTATION

Submitted in partial fulfilment of the requirements
for the degree of MSc in Hydrology

School of Bioresources Engineering and Environmental Hydrology
University of KwaZulu-Natal
Pietermaritzburg
July 2009

ABSTRACT

Anthropogenically-induced climate change has the potential to have serious implications on aquatic ecosystems and may ultimately affect the supply and quality of freshwater lakes and rivers throughout the world. As a class of ecosystems, inland waters are vulnerable to climatic change and other pressures, due to their small size and their position in the landscape. There is therefore a need to assess the impact of projected climatic change on aquatic ecosystems. Owing to this need, ecological indicators have been developed as a method of quantifying, identifying, monitoring and managing the ecological integrity of aquatic environments. The aim of this research was to develop techniques in order to conceptualise the higher order impacts of projected climate change on environmentally related streamflows and water temperature in South Africa, and to simulate these using an appropriate hydrological model.

For this dissertation the downscaled daily climate output from the ECHAM5/MPI-OM General Circulation Model (GCM) was used as an input into the daily time step conceptual-physical *ACRU* Agrohydrological Modelling System in order to simulate the impacts of projected climate change on selected eco-hydrological indicators at the Quinary Catchment spatial scale. In this research these indicators were grouped into two broad categories:

1. Ecological Flow Indicators and
2. Water Temperature Indicators.

The results of this research took the form of maps and time series graphs. The ecological flow indicator results investigate the magnitude and duration of flow events and were analysed spatially for the 5 838 hydrologically interlinked and cascading Quinary Catchments constituting the southern Africa study region. The ECHAM5/MPI-OM GCM projects the magnitude and duration of both annual subcatchment runoff and accumulated streamflows to increase in the eastern parts of southern Africa for the intermediate future climate scenario (2046 - 2065), with this trend strengthening in the distant future climate scenario (2081 - 2100).

The computationally intensive water temperature indicator results were analysed spatially at the scale of the Thukela Catchment. The Thukela catchment was selected as a case study area because of its diversity - in altitude, rainfall, soils and ecological regions, as well as in its population geography and levels of education and employment. This diversity presents a challenge to studies of impacts of projected climate change, including its potential impacts on water temperatures. The spatial analyses indicate that subcatchment runoff, accumulated streamflows and mixed maximum water temperature are all likely to increase under projected future climate conditions.

A temporal investigation, in the form of time series analyses, focused on four water temperature indicators and was performed for 15 selected Quinary Catchments, located within the Thukela Catchment. These temporal analyses indicate that the absolute variability (i.e. standard deviation) of both individual subcatchment runoff and accumulated catchment streamflows, are projected to increase in the future, while the relative variability (i.e. coefficient of variation) is likely to remain much the same or even decrease slightly over time period. These temporal analyses also indicate that there is a noticeable difference in the mixed maximum water temperature within a single Quaternary Catchment due to hydrological flow routing, with an increase in water temperatures as the water cascades downstream from the upper Quinaries to the Quinaries at lower altitudes. The techniques developed and used in this research could aid decision makers involved in ecological and water management planning.

PREFACE

The work described in this dissertation was carried out in the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal, Pietermaritzburg, from February 2006 to December 2008, under the supervision of Professor R.E. 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.

Signed: …………………………… Date: ……………
K.R. Barichievy (Author)

Signed: …………………………… Date: ……………
R.E. Schulze (Supervisor)

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation and gratitude to the following people and institutions for the assistance rendered during this study:

Professor R.E. Schulze, School of Bioresources Engineering and Environmental Hydrology, for supervising this project and providing invaluable assistance throughout the duration of this study,

Professor G.P.W. Jewitt, School of Bioresources Engineering and Environmental Hydrology, for his co-supervision,

Mr R.P. Kunz, School of Bioresources Engineering and Environmental Hydrology, for his assistance in programming and modelling which made this project possible,

Mr. T.G. Lumsden, School of Bioresources Engineering and Environmental Hydrology, for his assistance in programming and modelling,

The School of Bioresources Engineering and Environmental Hydrology, for providing the working environment and resources making this study possible, as well as the South African Water Research Commission, for funding and supporting this project,

To Dad, Mom, Michelle, friends and family, for all the support, encouragement and sacrifices made throughout my time at University.

TABLE OF CONTENTS

LIST OF FIGURES

PAGE

LIST OF TABLES

1. INTRODUCTION

There has been growing concern that over the past few decades the phenomenon of climate change has already occurred and will continue to do so more rapidly than has been recorded in geological history (Levine, 1992). This has been observed in measurements of, *inter alia*, atmospheric CO_2 concentrations increasing from 280 parts per million (ppm) since the dawn of the Industrial Revolution to approximately 380 ppm at present, and also in global temperature records, with global mean surface air temperatures having increased by between 0.2 and 0.6 °C since the late 19th century (IPCC, 2001; 2007). There is apprehension about climate change and the many uncertainties that surround it imply that its full impacts are, to date, still inadequately understood (IPCC, 2007). Major concerns surround the concept of increasing temperatures and associated shifts in precipitation attributes and patterns, which are likely to result in significant changes in water quantity and quality (Schulze *et al*., 2005b). Despite these uncertainties the evidence for potential large scale climatic change is now sufficiently strong to justify further investigations not only of the causes, but particularly of its consequences in a variety of environments (Melack, 1992). Aquatic ecosystems are anticipated to respond to climate change both thermally and hydrologically. Many aquatic ecosystems are vital components in the landscape and are generally excellent candidates for research on global climate change (Dahm and Molles, 1992).

Climate is one of the most important extrinsic drivers which determine hydrological regimes (e.g. the quantity and temporal distribution of streamflow). Even relatively subtle regional shifts in climate may alter not only the quantity of runoff, but also its variability and timing. Because ecological processes are regulated by the quantity and the temporal distribution of streamflows, major climate change-driven alterations in hydrological regimes are likely to result in modifications of freshwater ecosystem structure and function (Poff, 2002). Essentially, ecological responses will depend on the magnitude, direction, rate and spatial extent of any climatic change.

In South Africa there is a need to gain an insight into how projected climate change could impact on hydrology and aquatic systems. To date South African research has been focussed on the primary impacts of climate change on hydrological responses (e.g. Schulze *et al*., 2005b). The research conducted in this dissertation investigates effects of climate change on second (i.e. higher) order impacts, which include ecological flows and water temperature characteristics. The research presented in this dissertation builds on previous climate change research completed at the School of Bioresources Engineering and Environmental Hydrology (BEEH) and is focussed on scientific techniques and methods such as using a finer spatial scale of investigation and output from more advanced climate models as an input into an appropriate hydrological model.

The aim of this project, therefore, is to conceptualise the higher order impacts of projected climate change on environmentally related streamflows and water temperature parameters in southern Africa, and to simulate these using an appropriate hydrological model. In order to achieve this goal, the downscaled climate output from the ECHAM5/MPI-OM General Circulation Model (GCM) is used an input into the daily time step *ACRU* hydrological model (Schulze, 1995 and updates) in order to simulate impacts of climate change, as projected by this particular GCM, on selected eco-hydrological indicators at a fine spatial scale. These indicators can be grouped into two broad categories:

1. Ecological Flow Indicators and
2. Water Temperature Related Parameters.

In this dissertation on the modelling of projected climate change impacts on eco-hydrological indicators, **Chapter 2** provides a review of the concepts surrounding climate change and its projected impacts by investigating literature relating to natural and anthropogenic climate change as well as general circulation and regional climate predictions. **Chapter 3** focuses on aquatic ecosystems within the context of climate change by exploring the broad concepts surrounding impacts of climate change on these systems. **Chapter 4** proposes the use of flow and water temperature related parameters to assess the impacts of projected climate change. **Chapter 4** also includes a review of the relevant literature regarding the methods and models used estimate water temperature in lotic systems. **Chapter 5** focuses on the scale issues surrounding the techniques of modelling and mapping of eco-hydrological indicators. This chapter also introduces the concept of the sub-delineating Quaternary Catchments into smaller and more homogenous Quinary Catchments. **Chapter 6** summarises the relevant databases, models and techniques used in this project to assess the projected impacts of climate change on eco-hydrological indicators. The modelling results for the magnitude and the duration of flow events for southern Africa are presented in **Chapter 7**. The results are presented by means of maps at the scale of Quinary Catchments. The results of the water temperature analysis for the Thukela Catchment are presented in **Chapter 8**, again by means of maps while in **Chapter 9** time series graphs are used to describe water temperature parameters for 15 selected Quinary Catchments. A discussion and conclusion of this project, as well as recommendations for future research, is provided in **Chapter 10**.

2. MODELLING THE IMPACTS OF CLIMATE CHANGE

"Climate change is as old as the atmosphere itself. That climates have changed radically in the past in southern Africa is indisputable; that they will change again in the future is certain" (Tyson and Preston-Whyte, 2000 p305).

2.1 What is Climate Change?

Climate change, neither a new nor a recent phenomenon, is a natural process which in the past has been broadly cyclical in nature with both warmer and colder cycles occurring. In recent times, however, scientists have come to realise that the rate of climate change is accelerating unnaturally as a result of global warming emanating from the enhanced greenhouse effect, and that this is consequently disrupting these natural cycles. Climate change refers to a statistically significant change/trend in either the mean state of the climate or in its variability for an extended time period, typically decades or longer (Kabat *et al.*, 2003). This mean state is calculated using climatic variables which are represented by data pertaining to parameters of temperature, precipitation, atmospheric pressure, wind and humidity (Waugh, 1995). Climate change spans time scales of decades to centuries, is permanent and essentially irreversible (Schulze, 2003).

Climate variability differs from climate change and refers to variations in the mean state and other statistics of climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system or to variations in natural or anthropogenic external forcing (Kabat *et al.*, 2003). Furthermore, climatic variability is generally experienced over a shorter time frame when compared to that of climate change, *viz*. from diurnal variations to years, and it is generally cyclical, reversible and thus not permanent (Schulze, 2003).

In the post-industrial era, scientists generally use the term climate change in the manner defined by The United Nations Framework Convention on Climate Change (UNFCCC) in which "climate change" is a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is, in addition to natural climate variability, observed over a prolonged (and comparable) period of time (Hardy, 2003).

2.2 Natural Climate Change

Although it is accepted that climatic fluctuations occur across a range of time scales, there is as yet no single explanation for the onset of major climatic changes (Waugh, 1995). Many scientists believe that large climatic changes (i.e. glacial and interglacial periods) are caused by slight variations in the Earth's orbit and by so doing these variations create small changes in seasonal incoming solar radiation rates. Over time these small changes in the radiation received cause the temperature to either increase, when the Earth moves slightly closer to the sun, or decrease when the Earth moves further away (Arnell, 1996). There are other suggestions that may cause variations in global climate characteristics, and these include continental drift, varying sunspot activity, volcanic dust, natural variations in atmospheric carbon dioxide concentration, changes in ocean currents and shifts in jet streams (Waugh, 1995). All these naturally occurring mechanisms play a role in altering long term climatic variables on a global scale. However, in the past 150 years humans have become the new and dominating force in terms of climate change and as a result we have accelerated and altered natural climatic cycles.

2.3 Anthropogenic Impacts

Anthropogenic emissions of greenhouse gasses have already produced a discernible human influence on the world's climate, with atmospheric concentrations of carbon dioxide, methane and nitrous oxide having increased markedly since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years (IPPC, 2007). Measured warming of the climate system is unequivocal, with a total global temperature increase of between 0.57 and 0.95 °C since 1850 (IPCC, 2001; **Figure 2.1)** and with 11 of the 12 warmest years in the global temperature record up to the end of 2006 having occurred in the 12 year period 1995-2006 (IPCC, 2007; Jones and Palutikof, 2006; **Figure 2.2**). NASA's Goddard Institute for Space Studies (GISS) found that the highest globally averaged surface temperature in more than a century of instrumental measurements was recorded in 2005. The analysis used by the GISS is considered the most comprehensive to date and incorporates measurements on land, satellite measurements of the sea surface and ship-based analyses. The

GISS believes that the recent warming coincides directly with rapid increase in human-made greenhouse gases (Bhattacharya, 2006).

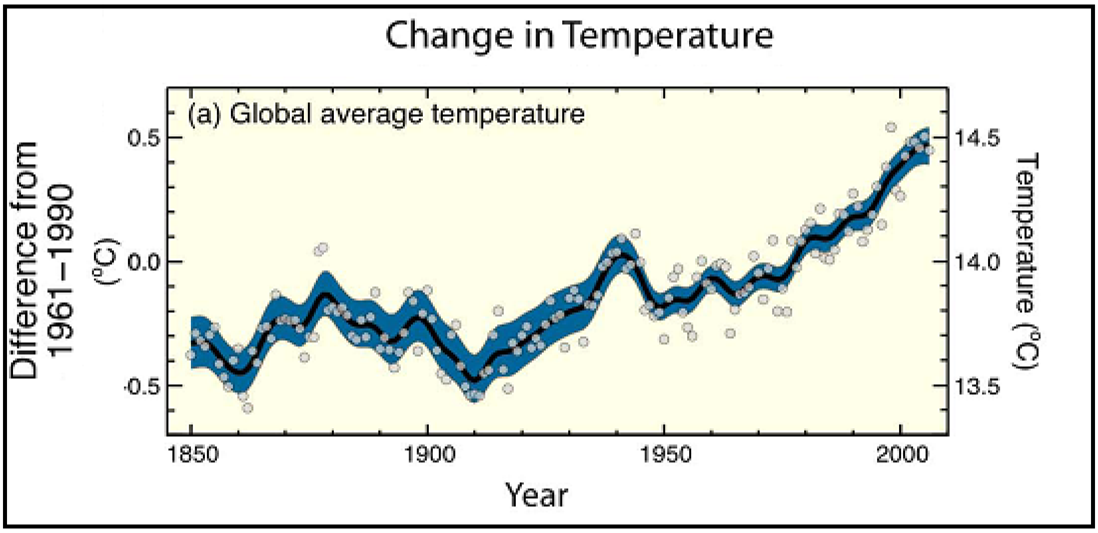

Figure 2.1 Observed changes in global average surface temperature between 1850 and 2005 (from IPCC, 2007)

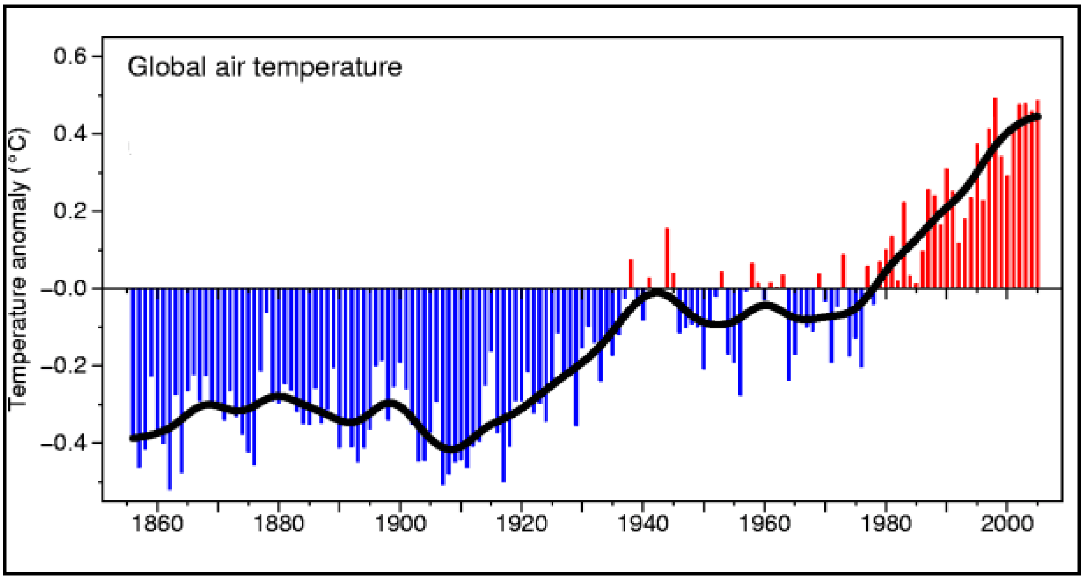

Figure 2.2 Global temperature increases between 1856 and 2005 (Jones and Palutikof, 2006)

The unnatural warming of the atmosphere via anthropogenic impacts is known as global warming. Global warming has only really occurred over the past 120 or so years and it is caused by the enhancement of the greenhouse effect **(Figure 2.3)**.

The greenhouse effect is a natural occurrence and is required to maintain life on earth. The greenhouse effect is a complex phenomenon and is initiated by incoming solar radiation. The sun gives off shortwave radiation during the day and this passes through the Earth's atmosphere without warming it. Once it reaches the Earth's surface it is re-radiatated into the atmosphere as longwave radiation and this warms the atmosphere. The longwave radiation continues to rise in the atmosphere until it reaches a band of gases known as greenhouse gases, which include water vapour, carbon dioxide, methane, nitrous oxide and CFCs (Waugh, 1995). At this point some of the outgoing longwave radiation is "trapped" within this layer of gases, is partially re-radiated downwards and this consequently results in further warming of the atmosphere. Greenhouse gases act like the glass panes of a greenhouse, thus giving this process its name: the greenhouse effect. In the atmosphere's natural state most of the longwave radiation is lost to outer space and the relative temperature balance is maintained. It must be noted that without the greenhouse effect the temperature of the earth would be approximately 33 °C cooler than it is with greenhouse gases being present in the atmosphere (Arnell, 1996; Hardy, 2003).

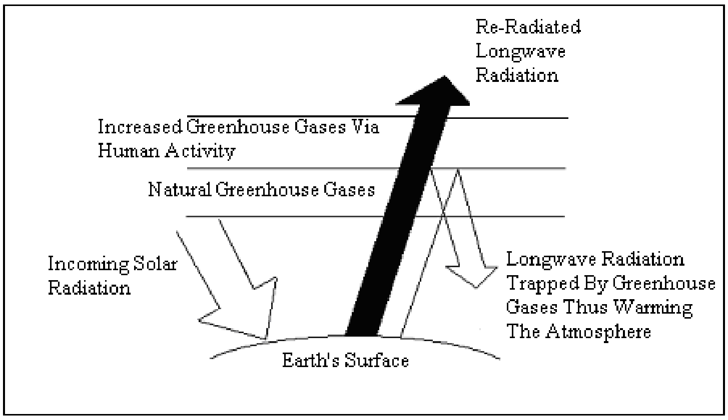

Figure 2.3 Simplified diagram of the enhanced greenhouse effect (after Waugh, 1995, pg 236)

The accelerating rise in the world's population and the associated increase in agricultural and industrial activity have upset the temperature balance within the atmosphere (Waugh, 1995). Industrial and agricultural activities emit large quantities of greenhouse gases **(Table 2.1)**. The marked increases in industrialisation, commercial agriculture and population are all contributing to increasing the concentration of greenhouse gasses in the atmosphere and are adding to the global warming problem. Measurements indicate that global atmospheric concentrations of methane and nitrous oxide have both increased since the beginning of the industrial revolution. Methane levels have increased from a pre-industrial value of 715 parts per billion (ppb) to 1774 ppb in 2005, while nitrous oxide has increased from a value of 270 ppb to 319 ppb in over the same time period (IPCC, 2007).

Table 2.1 Sources of various greenhouse gases (after Waugh, 1995)

Gas	Sources
Water vapour	Evaporation from the ocean and total evaporation from land
Carbon dioxide	Burning of fossil fuels (power stations, industry, transport), burning of rainforests, respiration
Methane	Decaying vegetation (peat and swamps), farming, sewage disposal and landfill sites
Nitrous oxide	Vehicle exhausts, fertilizer production, nylon manufacture, power stations
CFCs	Refrigerators, aerosol sprays, solvents and foams

Water vapour, found naturally within the atmosphere, provides the majority of the natural greenhouse effect. Its concentration in the atmosphere is not directly a result of human activities (Hardy, 2003). Water vapour is a result of the natural evaporative process and its amount within the global context remains relatively constant. However, it may be argued that a warmer atmosphere implies that the atmosphere's capacity and ability to hold water vapour will increase. Hence, water vapour may ultimately become the most important greenhouse gas. Carbon dioxide is a natural component in the atmosphere and is produced naturally by respiration and latterly by industrial processes and combustion of fossil fuels. During the past 150 years humans have increased the concentration of atmospheric carbon dioxide. The global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280 part per million (ppm) to 379 ppm in 2005 (IPPC, 2007). As more greenhouse gases are released, more longwave radiation is "trapped" within atmosphere, therefore causing unnatural warming of the atmosphere. Rising temperatures can lead to fluctuations in climatic and environmental components and thus alter environmental cycles, such as the hydrological cycle.

In years to come, increasing atmospheric carbon dioxide and greenhouse gas concentrations will enhance the greenhouse effect and accelerate global warming. Enhanced greenhouse gas concentrations may lead to different responses in climate related parameters. Each of these responses has an individual as well as a combined effect on the local environment. The main responses include changes in temperature, which in turn result in changes in precipitation patterns and characteristics and thus in climatic systems (Schulze, 2003). In order to predict the future state of the Earth's climate, complex atmospheric models are used. A short description and critique of atmospheric models is presented in **Section 2.5**.

2.4 Review of Relevant Climate Change Impact Studies in South Africa

Global climate change research has been driven by numerous sections of the scientific community which includes the Intergovernmental Panel on Climate Change (IPCC), the International Geosphere-Biosphere Programme (IGBP) and International Dialogue on Water and Climate (DWC). In regard to South Africa, research to date has been focussed mainly on the primary impacts of climate change. Interest in potential impacts of global warming on hydrological responses in southern Africa was first kindled at an IGBP workshop in Swaziland for Southern Hemisphere scientists in 1988 (Schulze, 1989). In the early 1990s a number of sensitivity studies investigated climate change and hydrological responses in southern Africa (e.g. Schulze, 1990; 1991a; 1991b). Subsequently a number of significant studies, which focused on primary impacts of climate change, were undertaken at the former University of Natal and are summarised below:

- In 1993 R.P. Kunz completed the first MSc at the same institution investigating the impact of climate change and hydrological responses.
- In 1997 K.L. Lowe also completed an MSc at the former University of Natal which analysed the agrohydrological sensitivity with regard to projected climate change in southern Africa. Both Kunz and Lowe used relatively simple techniques and only examined the first order impacts of projected climate change.

- Between 1998 and 2000 the South African Country Study was performed with a section focusing on water resources and this study was built on by L.A Perks, who in 2001 completed her PhD at the School of Bioresources Engineering and Environmental Hydrology (School of BEEH) at the former University of Natal. This comprehensive document investigates methods of refining modelling tools to assess potential agrohydrological impacts of climate change in southern Africa. This was the first study to explore the impacts of climate change with more advanced Global Circulation Models at a scale of a Quaternary Catchment (**Section 5.3**).
- In 2002 a Water Research Commission (WRC) funded projected titled *"Climate Change and Water Resources in South Africa: Potential Impacts of Climate Change and Mitigation Strategies"* and was awarded to the University of Natal. In 2005 this research culminated in a 470 page WRC report (number 1430/1/05) which included an investigation of the potential impacts of climate change on first order hydrological responses.
- In 2003 the "Thukela Dialogue" workshop, funded by the International Dialogue on Water and Climate (DWC), was held and focused on managing climate variability and climate change in water resources. From this workshop 18 papers were published in a proceedings (Schulze, 2003), most of them being directly related to hydrology and water resources, and including papers on policy, surface water, groundwater, agriculture, water for the poor and environmental water.
- A full sequence of events related to climate change and water resources in southern Africa up to 2007 is summarised in Schulze *et al*. (2007).

From the above list of previous climate impact studies it is clear that there is a need for research to shift from simply evaluating first order impacts, such as changes in streamflow patterns, to determining the effects of climate change on second (i.e. higher) order impacts, which include aquatic ecological flows and water temperature characteristics. The relevant attributes and coupling of the second order impacts in aquatic ecosystems are at present relatively poorly articulated by current research. The research presented in this dissertation builds on previous research completed at the School of BEEH and provides additional scientific techniques and workable scientific results which could aid decision makers involved in ecological and water management planning.

It is intended to achieve this goal by using a finer spatial scale of investigation and more advanced climate models as an input into an appropriate hydrological model than previous climate change studies.

2.5 General Circulation and Regional Climate Change Prediction Models

Projections of future climates rely on numerical computer models, referred to as General Circulation Models (GCMs), which simulate the Earth's climate system (Hardy, 2003). GCMs are based on the physical laws of energy conservation, which describe the redistribution of heat, water vapour and momentum by atmospheric motions (IPCC, 1990). Climate change impact studies rely on outputs from GCMs and the regionalised, downscaled versions of GCMs, which are known as Regional Climate Change Prediction Models (RCCPMs). This section briefly describes the importance of GCMs in climate change as well as some of the problems and uncertainties associated with large scale GCMs, and how RCCPMs attempt to overcome these shortcomings.

2.5.1 General Circulation Models

In order to reach credible conclusions in the water system regarding variations in precipitation, it is of vital importance to be able to estimate natural climatic changes (Tomasion and Dalla Valle, 2000). Hydrological models, through their applications with outputs from GCMs, are used to predict the impacts of possible future change in hydrological responses. GCMs have been widely used to generate climate expectations for both past and future climates. The most recent and complex GCMs currently in use consist of a coupled atmosphere-ocean general circulation model and they are used to simulate the variability and rate of change of physical processes within this coupled climate system over an extended period of time. GCMs are cartesian grid-point models, which can be run at a variety of horizontal and vertical resolutions (Hansen, 2006). Essentially, the goal of using a GCM is to project future climatic conditions with a global spatial coverage over a temporal time period stretching over many years. Generally GCMs perform well when predicting first order atmospheric processes such as surface heat and vapour fluxes (Hardy, 2003). GCMs are, however, less successful in predicting second order processes such as precipitation. Furthermore, there are some drawbacks when trying to use GCM output in catchment based projects and these problems are summarised in the following section.

2.5.2 Problems with General Circulation Models

GCMs are highly complex models which attempt to simulate present and future states of global climate conditions over extended periods of time. This is a daunting task owing to the range of scales and the unpredictability of global atmospheric systems involved in such modelling and, as such, any result from a GCM simulating present climate conditions has some uncertainty attached to it. Any attempt at predicting future conditions will contain even more uncertainties. Still greater uncertainty exists in predications of the subsequent consequences of climate change for sea level changes and ecosystems (Hardy, 2003).

In addition to general uncertainties, other problems are inherent in GCMs when attempting to simulate future precipitation patterns. First, GCMs cannot simulate individual convective rainfall events and this is problematic, as in many parts of the world (including most of southern Africa) convective rainfall is the dominant form of precipitation. Furthermore, climatological variables representing other atmospheric conditions that lead to high magnitude precipitation and flood producing events cannot generally be obtained from GCMs (Grimm *et al.*, 1997). These two factors decrease both the accuracy of precipitation output and, therefore, the usability of GCM results in hydrological studies. In addition, it is difficult to use GCM outputs directly in catchment studies as GCMs do not necessarily mimic local climates well, owing to their coarse spatial resolution (Arnell, 1996). The question of scale in atmospheric modelling is an important issue and is discussed further in **Section 4**.

All these above-mentioned problems associated with GCMs point to one conclusion, *viz*. that GCM outputs *per se* should only be used in continental to sub-continental scale projects where their coarse resolution has less influence on more local hydrological responses. To help solve this lack of regional detail required in hydrological (and other) studies, GCM outputs therefore have to be downscaled to operate at finer spatial resolutions and such models are known as Regional Climate Change Prediction Models (RCCPMs).

2.5.3 Regional Climate Change Prediction Models

Local climate is influenced greatly by local topographic features such as mountains, valleys and proximity to the ocean. This is problematic as these features cannot be well represented in global models with to their coarse resolution. To overcome this, RCCPMs, with a higher spatial resolution (typically 10 - 50 km) are downscaled from GCMs for limited areas and run for shorter periods of around 15 - 30 years (Hadley Centre, 2006). The fundamental rationale for downscaling is that the raw outputs of climate change experiments from GCMs are an inadequate basis for assessing the effects of climate change on hydrological processes at regional scales (Wilby *et al*., 1999). Therefore, RCCPMs are being developed to improve spatial detail and investigate local and regional changes. RCCPMs reveal a number of differences in climate variables between regions. For example, when compared to a global mean, warming will be greater over land areas, especially at high latitudes (Hardy, 2003). The above example shows that RCCPMs can provide more regionally relevant answers than GCMs. There is a need to co-ordinate RCM simulation efforts and to extend studies to more regions so that ensemble simulations, with different models and scenarios, can be developed to provide useful information for impact assessments (IPCC, 2001).

In South Africa, a critical need exists for the development of regional scenarios from GCM climate change simulations, as well as for analysis of uncertainty surrounding the regional scenarios, and also for developing a better understanding of the physical processes and changes in the climate system that give rise to shifts in future climate (Hewitson *et al.*, 2005). Development of RCCPMs is essential for climate change impact studies because they are capable of producing climate information for present and future climate scenarios at a resolution fine enough that they can be used for environmental applications such as modelling ecologically related flows (Hay and Clark, 2003).

For purposes of this project, 14 RCCPMs were developed at the University of Cape Town (UCT) for application in southern Africa using empirical downscaling techniques. These RCCPMs have spatial resolutions of 1/4° latitude/longitude, i.e. grid cells of approximately 25 km x 25km, and this scale is appropriate for investigations into the more local influences of climate change on ecological components. Engelbrecht (2005) has also developed a high-resolution RCCPM (1/2°, or approximately 50 km) for southern Africa that employs numerical downscaling as well a cumulus parameterisation scheme which makes it suitable for universal use. All these RCCPMs are capable of producing daily rainfall and temperature values for present and future climates at a resolution fine enough for application in hydrological and ecological impact studies at operational catchment scale which, in southern Africa, has to date been the so-called Quaternary (or fourth level) Catchment. By using RCCPM outputs as a climate input into an appropriate daily time step hydrological model, such a model can then be used not only to undertake sensitivity studies, but also to simulate the potential effects of climate change *per se*, and this at spatial scales which have not been achieved before in southern Africa (Gray, 2005). The scale at which present and future climates are modelled will have to become increasingly finer to enable better decisions to be made surrounding the impacts of climate change on environmental systems.

*****

In this chapter some of the major concepts regarding climate change were introduced. These concepts included distinguishing between climate change and climate variability, in addition to making the distinction between natural and anthropogenic climate change. In the remainder of the chapter the major climate change studies undertaken in South Africa were reviewed and the use of both GCMs and RCCPMs in climate change impact studies was outlined. **Chapter 3** focuses on aquatic ecosystems in the context of climate change by reviewing the potential impacts of climate change on aquatic ecosystems.

3. AQUATIC ECOSYSTEMS WITHIN THE CONTEXT OF CLIMATE CHANGE

Aquatic ecosystems consist of biological organisms, biota, as well as the physical non-living (abiotic) environment, i.e. the rocks, soils and water (Cotgrave and Forseth, 2002; Clausen *et al*., 2004). Aquatic ecosystems range from open oceans to freshwater lakes (lentic systems), streams and rivers (Giller and Malmqvist, 1998). This chapter will focus on running freshwater, or ‘lotic’, systems and the term “aquatic ecosystem” will be used in specific reference to these flowing freshwater habitats. In this chapter the roles and benefits provided by aquatic ecosystems, and the manner in which the system’s flow regime plays a critical role in maintaining a healthy aquatic ecosystem, are investigated. Finally the potential impacts of climate change on aquatic ecosystems are discussed.

Flowing water systems come in many shapes and sizes and comprise a large array of intergrading types of water channels, including streams, drains, tributaries and/or floodplain rivers (Downes *et al*., 2002). Water is the primary driving force within this habitat and determines the soil, vegetation and organism characteristics found within aquatic ecosystems. Both the vegetation and soil found in aquatic ecosystems play critical roles in determining adequate hydrological functioning and it is the integrated relationships between vegetation, soil and water that determine many hydrological attributes found within freshwater ecosystems. These attributes include the flow velocity of the water, as well as the frequency, duration, magnitude, timing and rates of change of flows. Aquatic ecosystems provide many goods and services which benefit both humans and the environment, and this role is investigated in order to understand the importance of these systems.

3.1 The Roles and Benefits of Aquatic Ecosystems

Although aquatic ecosystems and other similar wildlife habitats have long been valued for their aesthetic values, they are also critical components of the global environment and essential contributors to biodiversity and ecological productivity (Poff *et al*., 2002). More than this, aquatic ecosystems have socio-economic importance, and humans have come to realise that aquatic ecosystems are a large source of natural products that they can utilise. The rise in awareness of the importance of aquatic ecosystems has much to do with an enhanced appreciation of their many positive, ecological and environmental functions and values (Williams, 1991). In South Africa, and around the world, human-induced pressures on freshwater ecosystems have increased with the ever-increasing human population and associated agricultural and industrial development.

Aquatic ecosystems benefit humans in various ways and the most important of these is as a water resource. A river, or water impoundment, lies at the heart of all aquatic ecosystems. River water is seen as a usable renewable resource, which can be utilised for drinking, food production and recreation (Boon, 1992; Poff *et al*., 2002). Another benefit provided by rivers is the fact is that flowing water is able to remove and dilute waste and can also be used as a transportation medium of solutes and sediments.

Rivers form part of complex systems and generally represent an extremely important resource that humans can utilise. It is therefore not surprising that it has been recognised that humans have used rivers more than any other type of ecosystem (Boon, 1992). Rivers are an important source of nutrition as there are many species of fish, amphibians, crustaceans and molluscs that inhabit these rich ecosystems. Hunting of game animals like antelope and water birds also occurs in order to supplement the diets of the people living in close proximity to the aquatic ecosystem. Building materials such as wood and thatch grass can often be found in abundance near rivers and the extraction of these natural products is yet another benefit of aquatic ecosystems to humans.

A detailed list of services from freshwater ecosystems includes many items that are undervalued in economic terms and often are unrecognised and unappreciated (IPCC, 2001). Although aquatic environments cover only a very small portion of the Earth, they play a vital role in many environmental cycles and related processes. For example, inland waters play a major role in biogeochemical cycling of elements and compounds such as carbon, sulphur, nitrogen, phosphorous and toxic substances (Stumm and Morgan, 1996 cited in IPCC, 2001).

Other than the benefits provided via physical functioning, rivers also provide the habitat for biota, be they plants, invertebrates, fish or mammals. Many species are adapted to the aquatic environment and cannot move into another habitat, which leads to a high level of endemism. Plants have adapted to this wet environment by being able to float, having long oxygen transporting tubes or having pnematophores, which are above-ground root structures. All these adaptations allow a greater chance of plant survival in saturated habitats. The riparian zone is the source of extremely important structural components, such as aquatic debris, which is the main source of nutritional substrate for aquatic biota (Franklin, 1992). The success of aquatic biota is a function of a number of interrelated factors which are driven by hydrological conditions which, in turn, are determined largely by the overriding climate regime.

There are many factors which affect the health, composition and diversity of biota found within an aquatic ecosystem.

- *Foods (i.e. nutrients)* play an important role in determining the population size and diversity of biota in a given aquatic ecosystem. Essentially, the more food that is available, the greater the population of biota a given ecosystem can sustain.
- *Channel substrate* (includes both sediment and organic matter) is important to biota in the running water environment, as most organisms are closely connected to sediment availability. Channel substrate provides raw materials that create habitat structure, refugia and breeding grounds for aquatic organisms. Furthermore, channel substrate supplies and stores nutrients that sustain aquatic plants and animals (Baron *et al*., 2003).
- *The water depth and streambed width* of a river defines the physical space of an aquatic ecosystem, and thus can be a limiting factor to biota populations.
- The *velocity* of the water current is important for transport of resources to organisms. These resources can be in the form of both dissolved nutrients and prey. Water velocity can also be a potential hazard and a limiting factor for biota. Water velocity has both a higher and lower threshold through its effect on turbulence and laminar flow as represented by measures such as Froude and Reynolds numbers, which affects both biota population and diversity.
- *Water temperature* plays a major role in all processes in an aquatic environment (Coulson and Joyce, 2005). Temperature and light characteristics regulate metabolic processes, biota activity levels, growth rates, distribution and productivity of aquatic organisms (Baron *et al*., 2003; Clausen *et al*., 2004).

- *Water quality* is vital for aquatic ecosystems and is influenced by nutrients, water velocity and temperature. Dissolved oxygen and pH levels are often used to indicate water quality (Clausen *et al*., 2004).

These six factors are determined directly from the flow regime of the given river system. These factors influence environmental variables within a river and thus influence aquatic communities within these systems and form a continuous gradient of conditions along a river's longitudinal axis (Rivers-Moore, 2003). This is the essence of the *River Continuum Concept* (Vannote and Sweeney, 1980), according to which biological communities form a spatial and temporal continuum, and species dynamics are in equilibrium with the dynamic physical conditions of the river channel. Thus biotic communities are predictably structured along a river's profile because of the relative uniformity of the abiotic conditions (Vannote and Sweeney, 1980).

Therefore, it can be concluded that the concept of a river's flow regime must be investigated in order to understand the complex nature of aquatic ecosystems.

3.2 The Flow Regime

Freshwater ecosystems require certain elements to continue providing the valuable goods and services described in **Section 3.1**, above. One of the most important elements that maintains a healthy aquatic ecosystem is its flow regime. Hydrological regimes influence all ecosystem components as well as the evolutionary adaptation by the biota inhabiting the ecosystem (Naiman *et al.,* 1992). A flow regime consists of five components, *viz*.

- Magnitude,
- Frequency,
- Duration,
- Timing, and
- Rate of change (Poff *et al.*, 1997; **Figure 3.1**).

The flow regime of a freshwater ecosystem is critical for regulating biological productivity and biological diversity, particularly in lotic systems. These aspects include baseflow, annual or more frequent intra-annual floods, rare and more extreme inter-annual flood events, the seasonality of flows and inter-annual flow variability (Baron *et al.*, 2003). Furthermore, hydrological patterns of ecologically healthy catchments are strongly related to the timing and quantity of flows, characteristics of seasonal water storage, the source area of streamflows and the dynamics of surface and subsurface flow exchanges (Naiman *et al.,* 1992). Natural hydrological regimes vary from catchment to catchment and thus water quality, the physical habitat and biotic interactions also differ from river to river, often showing regional patterns which result from similar influencing factors such as climate and topography.

Through the construction of and abstractions from dams, irrigation abstractions, canalisations, urban and irrigation return flows, inter-catchment transfers and other abstractions which may be unsuitable/disruptive for the aquatic habitats, humans have altered the natural flow regime in many rivers systems and have thus compromised the ecological integrity of these aquatic ecosystems. The construction of large water impoundments has probably had the greatest impact on river flow regimes and many of the world's and South Africa's rivers have effectively become anthropogenically-controlled water engineered systems. Anthropogenically-driven landuse change is also a major driver of flow regime alteration. Landuse change such as deforestation, poor land management, over grazing, urban expansion and uncontrolled burning regimes have all played a role altering natural flow regimes.

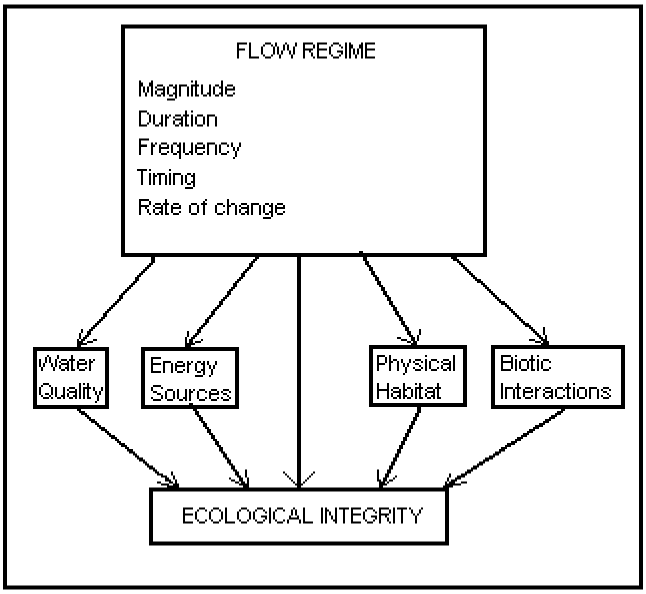

Figure 3.1 The effects of flow regimes on components which influence ecological integrity (after Karr, 1991)

In South Africa the concept of instream flow requirements has been introduced in order protect aquatic ecosystems. This concept attemps to mimic a river's natural flow regime, albeit at a reduced volume if there is an upstream impoundment, using controlled releases from dams and thus attempting to maintain some element of ecological integrity. Many years of streamflow measurement are required to describe the characteristic patterns of a river's flow such as its flow quantity, timing and variability (Poff *et al*., 1997).

A river's natural flow regime is complex, and is described by both intra- and inter-annual flows patterns. Intra-annual flows occur within a single year and show seasonal variation, i.e. periods of low and high flows. Many fundamental ecological processes are influenced by temporal flow variations which affect

- Availability and persistence of habitats,
- Species' access to habitats required for specific life stages, and
- Fluxes of nutrients, materials and organic matter.

Temporal variations in streamflow occur naturally within a catchment in response to seasonal and inter-annual climate variation. For example, some species require high flows at specific times of the year in order to reproduce and sustain their populations and in the absence of high flows they do not sustain their populations (Meyer *et al*., 1999).

A river's natural flow regime also contains chronic events such as flooding or extreme droughts, and these are required to maintain ecological complexity. Extreme flows (floods) are one of the key components found in a river's natural flow regime. Extreme flows are referred to as a "disturbance" when it causes significant loss of individuals from a community (Biggs *et al.,* 1999). The response of ecosystems/organisms to extreme flows depends on the biota characteristics as well as the timing, magnitude and frequency of the extreme flow (Clausen *et al*., 2004). Ecologically healthy aquatic ecosystems are dependent on natural hydrological disturbances. Extreme flows impact on spatial heterogeneity and temporal variability to the physical components of the system. This is reflected in the life history strategies, productivity and biodiversity of the biotic community. This natural disturbance creates the dynamic equilibrium (Naiman *et al.,* 1992). Disturbances such as floods increase the level of ecosystem complexity. An example would be chronic events, i.e. high intensity floods, which import material and woody debris during storm episodes. They shape the environment and cause alterations in channel morphology. Annual floods create freshly disturbed habitats for plant colonisation, increase the area of land under water and form travel routes to breeding sites (Franklin, 1992). Extreme flows are generally part of the long-term flow regime and, while they are usually short-term, they have a major effect on the ecosystem. Both seasonal flow variation and chronic events are vital for the long-term sustainability of aquatic ecosystems and need to be reflected in a river's flow regime.

A flow regime of any river reach is dependent on upstream hydrology and the overriding climatic drivers such as the day-to-day variations in temperature and precipitation. Additional variations in these drivers, caused by anthropogenically induced climate change, will undoubtedly alter a river's flow regime and thus impact upon the aquatic ecosystems upon which society and aquatic biota are so dependent. This is particularly significant in South African rivers due to their inherent high variability in terms of quantity, frequency and timing of flows thus making them more susceptible to small changes in climate.

3.3 The Potential Impacts of Climate Change on Aquatic Ecosystems

Anthropogenic climate change (**Section 2.3**) has the potential to have serious implications on aquatic ecosystems and will ultimately affect the supply and quality of freshwater lakes and rivers throughout the world (Chu *et al*., 2005). In addition to the challenges posed by land use change, environmental pollution, water storage and diversion, aquatic systems are expected to soon begin experiencing the added stresses of global climate change (Poff *et al*., 2002). Effects of change in the physical and chemical properties of the atmosphere present many uncertainties for future catchment management (Dolph *et al*., 1992; Risser, 1992). The direct effects of increasing greenhouse gases in the atmosphere on aquatic ecosystems is not known. The overall impacts of climate change on catchments are likely to be diverse (Dolph *et al*., 1992). Ecosystems require some disturbance regime to maintain complexity, but in reality climate change may cause too much ecosystem disturbance, which may exceed the *ecosystem's resilience* (i.e. the ability of an ecosystem to recover) and thus permanently alter the aquatic ecosystem and reduce its ability to function and provide goods and services on which we as humans depend (Stanford and Ward, 1992).

3.3.1 Increasing air and water temperatures

Climate change is expected, *inter alia*, to increase global and thus local air temperatures, accelerate the retreat of mountain glaciers, reduce Arctic and Antarctic sea ice and alter the frequency and intensity of climatic phenomena, especially those related to rainfall, from daily events to inter-seasonal ones such as the El Niño phenomenon (McGinn, 2002). Greenhouse gas induced warming, in some areas more than others, will lead to higher surface temperatures and greater potential evaporation, hence reduce soil moisture and result in increasingly frequent droughts (Hardy, 2003; Schulze, 2003). Results from recent RCCPM scenarios for southern Africa substantiate many of these assumptions (Schulze *et al*., 2005b; see also **Section 2.4**).

As a class of ecosystems, inland waters are vulnerable to climatic change and other pressures, owing to their small size and position downstream from many human activities. Impacts of a warmer climate on inland waters are already being observed in many part of the world. A trend observed in 26 lakes and rivers in the northern hemisphere shows that at present the lakes, on average, freeze 9 days later and ice break-up is 10 days earlier than 150 years ago as a result of a 1.8 °C increase in air temperature (IPCC, 2001). Continued warming will alter the thermal structure of aquatic ecosystems and will impact upon the aquatic species which inhabit these waters. Individual aquatic species, including fish and invertebrates, have an optimum range of temperatures for growth and reproduction, i.e. their thermal habitat. Increased global temperatures will likely shrink thermal habitats for many aquatic species (Hardy, 2003). Warming could lead to changes in species composition and density, sex ratio, stability and food web dynamics of aquatic ecosystems (Beisner *et al*., 1997, cited in Hardy, 2003).

Increases in water temperatures as a result of climate change are projected to alter fundamental ecological processes and the geographic distribution of aquatic species. Rates of nutrient removal/accumulations and primary production are also a function of water temperature, and these may well be altered by climate change. A changing climate may intensify threats to aquatic ecosystems. For example, a warmer climate may increase habitat fragmentation (Meyer *et al*., 1999). Such impacts and threats may be ameliorated if species attempt to adapt by migrating to more suitable habitats. However, human alteration of potential migratory corridors may limit the ability of species to relocate, increasing the likelihood of species extinction and loss of biodiversity (Meyer *et al*., 1999; IPCC, 2001; Poff *et al*., 2002). This problem is exacerbated in the case of aquatic ecosystems, where many species are confined to the riparian zone of a stream, which makes migration laterally (i.e. from one river system to the next) impossible. Furthermore, many aquatic species are highly specialised, making them more susceptible to habitat alteration.

A warmer world does not only threaten the natural environment, but also the usefulness of the aquatic ecosystem in terms of its utilisation potential for anthropogenic activities. Climate change alterations in some streams may decrease the potential for irrigation abstractions and waste disposal. There may also be a reduction of the flush effect to remove human wastes, if future flows decrease, with possible impairments to ecosystem services (Hardy, 2003). A reduced flush effect could lead to increased biological water quality problems, e.g. an increase in the presence of *E. coli*.

3.3.2 Changes in precipitation patterns

Changes in seasonal patterns of precipitation and runoff will alter hydrological characteristics of aquatic systems, affecting species composition and ecosystem productivity. Populations of aquatic organisms are sensitive to changes in the frequency, duration and timing of extreme precipitation related events, such as floods or droughts. Changes in the seasonal timing of snowmelt in areas where snow is a significant contributor to the hydrological regime, will alter streamflow patterns, potentially interfering with the reproduction of many aquatic species (Poff *et al*., 2002). Anthropogenic climate change that alters dominant patterns of precipitation and runoff therefore presents a real threat to the structure and function of aquatic ecosystems, including rivers, lakes, wetlands and coastal systems (Meyer *et al*., 1999).

Environmental variability (including flooding) plays a critical role in structuring aquatic and riparian ecosystems through mediating the directions and outcomes of ecological processes at multiple scales of hierarchical ecological organisation (Poff, 2002). A change in environmental drivers, such as climate, modifies the core of a given ecosystem. This in turn, modifies the relative outcomes of ecological processes, resulting in a change in ecological structure and function. This is the basic conceptual model for ecological response to environmental alteration, such as rapid climate change, where the regimes of one or more of the environmental drivers may be expected to change on a regional scale and thereby modify river ecosystems (Poff, 2002). Climate change has the potential to disrupt and even decrease aquatic ecosystem productivity and, as such, there is a need to establish methods which can be used to assess these impacts.

*****

In this chapter the roles and benefits provided by aquatic ecosystems, and the manner in which the flow regime plays a critical role maintaining a healthy aquatic ecosystem, were investigated. Finally the potential impacts of climate change, on aquatic ecosystems, through an increase in temperature and changes in precipitation patterns were discussed.

Ecological indicators are a tool commonly used in environmental assessments and their usefulness in climate change impact studies is discussed in the following chapter.

4. ECO-HYDROLOGICAL INDICATORS

Anthropogenically-driven climatic change (**Section 2.3**) may disrupt normal ecological functioning and thus compromise valuable ecosystem goods and services on which human society depends. There is a need to assess the impact of climatic change on aquatic ecosystems. Recent ecological research has developed methods of identifying, monitoring and managing the ecological integrity of aquatic environments through the use of ecological indicators (Fanelli, 2006). Ecological indicators are suitable for use in impact studies where one needs to determine how certain ecological components respond to a change in environmental conditions over an extended period of time. Ecological indicators have also been suggested as useful tools in environmental assessments (Manoliadis, 2001). However, ecological responses to change are often unknown and therefore difficult to assess either with, or without, indicators. Even so, the development and validation of such indicators on a national scale could help form sound environmental policies and thus facilitate better adaptation and preparation for potential environmental problems (Andreasen *et al*., 2001). In this chapter the concept of ecological indicators, how they are selected and how they can be used in climate change impact studies are reviewed. This is followed by a section on so-called Indicators of Hydrologic Alteration and water temperature as an eco-hydrological indicator.

4.1 What are Ecological Indicators?

Ecological indicators are measures used to describe the state of a nation's or region's ecological status (Andreasen, 2001). Indicators are used in many sectors of environmental science and generically they are seen as a distance measure from a goal, or target, against which aspects of policy performance should be assessed (Manoliadis, 2001). More specifically, however, an ecological indicator is a "characteristic of an ecosystem that is related to, or derived from, a measure of a biotic or abiotic attribute that can provide quantitative information on ecological condition, structure and function" (EPA, 2006).

Ecological indicators have numerous functions, but most importantly should inform the user easily and quickly of the state (health) of the environment. They can also be used to assess vulnerability, risk and damage to ecosystems, to monitor trends over time and to provide early signals of changes (Karr, 1991). It is of vital importance that ecological indicators detect and summarise patterns of ecosystems and show when environmental problems are occurring (Fanelli *et al*., 2006).

There are two principal types of indicators, *viz*. condition indicators and stressor indicators.

- *Condition indicators* are biotic or abiotic characteristics of an ecosystem that can provide an estimate of the condition of an ecological resource with respect to some environmental value, such as ecosystem integrity.
- *Stressor indicators*, on the other hand, are characteristics that are expected to change the condition of a resource if the intensity or magnitude is altered (EPA, 2006).

Aquatic biota and water quality are often used to indicate a river's health in aquatic ecosystems studies. For example, biota such as frogs are known as indicator species and if these specific species start to disappear this indicates that the ecosystem's overall health and functionality may be decreasing. In some cases water quality can also be used to indicate ecosystem health because it effectively integrates the full range of geomorphological, hydrological and biological processes (Hem, 1985). A change in water quality usually indicates a change in some aspect of the terrestrial, riparian, or in-channel ecosystem. Water temperature, a component which forms part of the generic term *water quality*, is easily measured and greatly affects the rate of chemical and biological processes, and it can initiate certain functions once the temperature is above or below a certain threshold. Stream temperature is a relatively sensitive indicator of riparian conditions and is controlled by climatic and atmospheric inputs (Naiman *et al*., 1992). However, it is important to note that ecological functioning depends on many inter-related processes and not just on a single indicator such as water temperature.

No matter how good an indicator is, no single indicator can be expected to measure everything about the ecological health of an area. Thus, a suite of ecological indicators must be selected, in the first instance to encompass the phenomena of interest and, secondly, to correspond to stated policy goals and/or research and management questions related to these goals (Andreasen, 2001). There are literally hundreds of both qualitative and qualitative indicators which can be used to illustrate ecosystem health and thus the selection of suitable ecological indicators is of vital importance.

4.2 Selection of Indicators

The use of ecological indicators relies on the assumption that the presence or absence of, and fluctuations in, these indicators reflect changes taking place at various levels in the ecological hierarchy, from genes to species and ultimately to entire regions (Noon *et al*., 1999 cited in Dale and Beyeler, 2001). The problem with using ecological indicators is that there is no universal set of indicators that is equally applicable in all cases (Manoliadis, 2002). Therefore, the ideal suite of indicators should represent key information about ecosystem structure, function and composition. Appropriate indicators should deal with the complexity of ecological systems. There have been numerous attempts at developing criteria to select the most appropriate indicators for environmental projects (e.g. World Bank, 1999; Methratta and Link, 2006). However, one of the most comprehensive set of criteria to select the most suitable indicators has been developed by Dale and Beyeler (2001):

- *Ease of measurability:* The indicator should be straightforward and relatively inexpensive to measure. The metric needs to be easy to understand, simple to apply and, most importantly, relevant.
- *Sensitivity to stresses on the system*: The ideal ecological indicator is responsive to stresses placed on the system by human actions, while also having limited and documented sensitivity to natural variation (Karr, 1991). While some indicators may respond to all of the more dramatic changes in the system, the most useful indicator is one that displays high sensitivity to a particular stress, thereby serving as an early indicator of reduced system integrity.
- *Response to stress in a predictable manner*: The indicator response should be unambiguous and predictable, even if the indicator responds to the stress by a gradual change. Resource managers may uncritically assume that indicators give unbiased estimates of the true biological condition, but this assumption is largely untested. The use of biased indicators could lead to ineffective and potentially damaging management (Cao and Hawkins, 2005). Ideally, there is some threshold response level at which the observable response occurs before a level of concern is reached.
- *Ability to be anticipatory, i.e. signify an impending change in key characteristics of the ecological system*: Change in the indicator should be measurable before substantial change in ecological system integrity occurs.

- *Be integrative, i.e. with the full suite of indicators providing a measure of coverage of the key gradients across the ecological systems (e.g. gradients across soils, vegetation types, temperature, space, time, etc.)*: The full suite of indicators for a site should integrate across key environmental gradients. For example, no single indicator is applicable across all spatial scales of concern.
- *Have a known response to disturbances, anthropogenic stresses, and changes over time*: The indicator should have a well-documented reaction to both natural disturbance and to anthropogenic stresses in the system. Focal indicator species are often the only types of species that have a foundation of information large enough to indicate long-term trends and responses to change.
- *Have low variability in response*: Indicators should have a small range in response to particular stresses in order to allow for changes in the response value to be better distinguished from background variability.

All these criteria should be taken into account before the final indicators are selected. A major challenge is to derive a manageable set of indicators that meets these criteria and links closely to project objectives and environmental problems being addressed.

4.3 The Use of Ecological Indicators in Climate Change Impact Studies

There is a need to predict the potential impact of climate change on aquatic ecosystems as natural resource managers and policy makers require information regarding ecosystems conditions, trends and future status. However, ecological systems are inherently complex in being composed of many interacting biological and physical components. Predicting the impact of climate change on such complex systems is difficult, owing to issues regarding scale and not knowing exactly what to measure (Andreasen, 2001).

Research should attempt to develop suitable indicators of ecosystem integrity for impending ecological change resulting from both natural variation and future anthropogenic activities. Furthermore, using a multidisciplinary approach along with performing ecosystem analysis at an appropriate scale will, hopefully, result in robust techniques for ecosystem monitoring and evaluation (Debusk *et al*., 2001).

4.4 Indicators of Hydrologic Alteration

The so-called Indicators of Hydrologic Alteration, or IHA, (e.g. Richter *et al*., 1996; 1997; Taylor, 2006) are commonly used in eco-hydrological studies for assessing quantitatively the characteristics of natural and altered hydrological regimes. The power of the IHA method is that it can be used to summarise long time series of daily hydrological observations or simulated output into a much more manageable series of ecologically relevant hydrological parameters. The IHA consists of a total of 67 statistical parameters used to describe hydrological regimes (The Nature Conservancy, 2005). The IHA indicators represent the five components of the streamflow regime, *viz*.

- Magnitude,
- Frequency,
- Duration,
- Timing, and
- Rate of change (c.f. **Section 3.2**)

In the following section the descriptions of the five components of a flow regime, as given by Richter *et al*. (1996; 1997) and Taylor (2006), are summarised.

(a) The *magnitude of the monthly means of daily flows* represents average daily flow conditions for a specific month and defines such habitats attributes as wetted area within a channel or the availability of aquatic habitat area for that month. Generally the greater the flow magnitude the greater the availability of habitat area. The degree to which the means of flows of a given month vary from year to year indicates the inter-annual variation of streamflow conditions, which in the IHA is defined by the Coefficient of Dispersion (**Section 6.8**)

(b) The *magnitude and duration of extreme annual conditions* are a measure of different environmental disturbances, or stresses, such as levels of inundation or desiccation. The durations comprise of the 1 day, 3 day, 7 day (weekly), 30 day (monthly) and 90 day (seasonal) extremes. The 1 day events are the maximum and minimum daily streamflow values that occur in any given hydrological year, and the multi-day events are the highest and lowest multi-day means of flow occurring in any given hydrological year. These values are then averaged for the years that are being analysed. As a measure of inter-annual variation, the Coefficient of Dispersion can be calculated from each year's values for each duration (e.g. 1 day, 3 day…90 day) of extreme annual maximum and minimum conditions.

(c) The Julian date of the 1 day maximum and minimum flow events represents the *timing of the annual extreme conditions* within annual cycles and provides a measure of the seasonal nature of environmental stresses, or the likelihood of mortality associated with flow extremes such as droughts or floods. The timing of these flows can also determine whether certain lifecycle requirements are met i.e. biological cues.

(d) The *frequency of conditions* during which the magnitude of streamflows exceeds an upper threshold (high flow) or falls below a lower threshold (low flow) within a hydrological year, and the *average duration of such occurrences* together reflect the pulsing behaviour of the streamflow regime within a given year. The frequency of occurrence of these high and low pulses can influence the reproduction and mortality rates, and thereby influence population dynamics, of aquatic habitats.

(e) The *rate and frequency of change in conditions* measures the number and average rates of both positive and negative changes (i.e. reversals) in streamflows between consecutive days. These changes in the hydrograph trend indicate the intra-annual fluctuation of the streamflow regime and can also be tied to the stranding of certain aquatic organisms along the water's edge.

In this research a subset of the 67 IHA indices was used to determine how the selected indictors may change under conditions of projected climate change. The selection of the final set of indicators used in this project can be found in **Section 6.8.1**.

4.5 Water Temperature as an Eco-Hydrological Indicator

In this section the importance of water temperature as an eco-hydrological indicator is described, along with the factors which affect water temperature and thermal regimes.

Subsequently the projected impact of climate change on water temperature is explored and selected methods on how to model water temperature in lotic environments.

4.5.1 The importance of water temperature

Water temperature in streams and rivers is an important attribute of water quality and it controls the overall health of freshwater ecosystems (Morrill *et al*., 2005). Except for birds and mammals, all organisms associated with freshwater ecosystems are *poikilothermic*, i.e. they are unable to control their body temperatures and, therefore, their body temperatures are the same as that of the ambient water temperatures (Dallas and Day, 2004). Essentially aquatic organisms are therefore inextricably linked to the ambient water temperature in which they exist.

There are a number of ways in which water temperature impacts upon aquatic ecosystems and associated aquatic biota. The most obvious effects of stream water temperatures on aquatic organisms is in their growth rate, behaviour, survival and development (Elliot and Hurley, 1997). Aquatic organisms have a specific range of temperatures which they require to function optimally. Once outside this temperature range, vital functions such as reproduction and metabolism may be hindered or may not occur at all.

Water temperature does not only affect aquatic organisms directly, but also influences their habitat and, in fact, determines the limits of thermal habitat space for many aquatic organisms (Erickson *et al*., 2000). The minimum and maximum points in this temperature range are known as the lethal limits and vary from species to species (Dallas and Day, 2004). Water temperature also influences many chemical and biological processes present in river systems. This makes water temperature a key indicator in aquatic ecosystem studies (Webb, 1987; Erickson *et al*., 2000; Caissie *et al*., 2001; Mosheni *et al*., 2002; Rivers-Moore, 2003), as well being important to the kinetics of chemical reactions, the solubility of gases and the toxicity of some elements within an aquatic environment (Erickson *et al*., 2000). In the following section the effects which temperature variations have on aquatic biota and ecosystems will be investigated further.

4.5.2 The effects of temperature variation on aquatic biota and ecosystems

All lotic (i.e. running waters, e.g. rivers) and lentic (i.e. standing waters, e.g. reservoirs) systems have natural thermal regimes, which mimic seasonal temperature changes, i.e. water temperatures tend be highest in late summer and coldest in late winter. Aquatic organisms are adapted so that seasonal changes in water temperatures act as cues for various stages of development, such as the timing of migration, spawning and emergence. Natural thermal characteristics of lotic systems are dependent on the interaction between hydrological, climatological and structural features of the region and catchment (Dallas and Day, 2004). Anthropogenic impacts such as land use changes and climate change have already begun to alter this natural thermal regime in catchments around the world. For example, the construction of large reservoirs has played an enormous role in altering both the flow and thermal regimes of rivers downstream of their walls. Deforestation is another process which can greatly alter the thermal regime of a stream and thus influence the integrity of that same ecosystem. Studies show that stream temperatures increase after logging, largely because of the increased exposure of the stream surface to solar radiation (e.g. Cafferata, 1990).

Changes in water temperature regimes may have an effect on an organism, a species or an entire community. Increased water temperature variation may expose organisms to potentially lethal or sub-lethal conditions. Temperature variation, in turn, affects the aquatic biota in regard to physiology, life cycle, competitive abilities, and community structure (Dallas and Day, 2004). Most temperature variation in aquatic ecosystem occurs during summer due to climatic and hydrological factors and it is important to note that temperature varies both temporally (e.g. daily and seasonally) and spatially along river reaches (Caissie *et al*., 2001).

In general, water temperatures in streams are expected to rise due to anthropogenic impacts (e.g. global warming; deforestation) and, as such, the focus will be on the impacts of higher temperatures on aquatic biota. High stream temperatures can have adverse effects on fishery resources by limiting habitats and can, in some cases, result in fish mortality. Poikilothermic organisms are very susceptible to changes in water temperature and an increase in 10˚C may lead to a doubling in the metabolic rate (Hellawell, 1986). An increase in water temperature decreases oxygen solubility and may increase the toxicity of certain chemicals as well as increasing the stress on aquatic organisms (Dallas and Day, 2004). As a result, even if food is abundant at higher temperatures, decreases in dissolved oxygen (DO) may stress certain aquatic organisms metabolically, thereby increasing their susceptibility to disease (Dallas and Day, 2004). Increasing water temperatures could also lead to an augmented distribution of water-borne diseases such as Bilharzias and malaria and thus have serious social and financial implications.

In order to address potential problems associated with rising stream water temperatures, resource managers need to incorporate stream temperature objectives in their operations models and management decisions. This requires the ability to predict stream temperature in order to model and assess different scenarios.

Because the prediction will be used in daily operating decisions, the prediction must meet the following specific requirements, *viz*. it must be

- quick,
- accurate,
- easy to use, and
- spatially and temporally consistent with the operations models.

4.5.3 Factors affecting water temperature and thermal regimes

Ambient water temperature has been shown to be one of the most important factors affecting the success of aquatic life. Land use activities, water abstractions, streamflow alterations, dam construction and associated water releases as well as natural factors all affect a stream's water temperature within a catchment. For simplicity, Dallas and Day (2004) have categorised the factors which influence the thermal characteristics of lotic systems into three major divisions related to hydrological, climatological and structural features. These major features and the associated factors which affect thermal regimes of rivers are summarised in **Table 4.1**.

The hydrological feature in **Table 4.1** groups all flow-related factors which influence water temperature. With particular reference to South Africa, the source of water is mostly from surface runoff, ground water contributions and dam releases and rarely includes snowmelt as a source. Thus the interactions between surface and groundwater, along with dam releases, are critical to the thermal regime of South African rivers. Turbidity, along with flow characteristics such as flow rate, volume and water depth also fall within hydrological features which influence water temperature and, as a consequence, need to be carefully considered when examining water temperature.

The climatological feature in **Table 4.1** groups all meteorological and climatological parameters together. Incoming solar radiation and air temperature play the most critical roles in determining the ambient water temperature in aquatic environments (**Figure 4.1**).

Table 4.1 Major factors affecting the thermal regime of rivers (after Dallas and Day, 2004)

Feature	**Factor**
Hydrological	Source of water (snowmelt, dam outlet)
	Groundwater contribution
	Flow rate and discharge
	Water volume and depth
	Turbidity
Climatological	Latitude and altitude of river
	Cloud cover
	Wind speed
	Vapour pressure and relative humidity
	Precipitation events
	Incoming solar radiation and air temperature
Structural	Catchment and river topography
	Vegetation cover and characteristics
	Channel form

At the catchment scale, differences are driven by variation in climate, geography, topography and vegetation (Poole and Berman, 2001). At a river scale, variation occurs longitudinally down a river system, with headwaters typically at lower temperatures than water found closer to the coast. Maximum temperatures increase downstream (Ward, 1985), while the maximum range in temperatures is often found in the middle reaches of a river (Vannote and Sweeney, 1980). The temperature of larger rivers and smaller streams is also influenced by the surrounding landscape and reflects the characteristics and condition of the stream and its valley (Beschta et al., 1987), with the alteration of aquatic environments generally causing an increase in water temperature. It is for these reasons that structural factors (**Table 4.1**) need to be considered when investigating the thermal regime of rivers and streams. Structurally-based factors tend to have more impact on thermal regimes at small (river reach) scale. For example, shading and sheltering can greatly influence water temperature at small scales and many environmental sectors, including forestry, recognise the need to maintain riparian trees in order to provide direct shade and prevent elevation of water temperature.

Anthropogenically-induced changes of catchment and atmospheric conditions can also influence the temperature regime of lotic systems by processes such thermal pollution, timber harvesting and climate change (Cassie *et al*., 2001). Hostetler (1991) found that water temperature could be increased by 8 °C within a distance of 1.3 km of where trees had been removed from the river banks, mainly due to a decrease in water surface shading (Caissie *et al*., 2001).

It is apparent that there are many factors which need to be considered when investigating, or estimating, water temperature. It is even more evident that estimating water temperature at different scales requires different techniques. By ranking the factors which influence water temperature by how sensitive daily mean water temperature is to changing these factors, one is able to understand which factors drive water temperature in lotic systems (**Figure 4.1**).

Figure 4.1 illustrates that air temperature above the stream surface is the most important factor in increasing water temperatures, followed by relative humidity, shading and streamflow. Thus, in order to estimate water temperature, these more influential factors need to be quantified. These above-mentioned variables can be divided into drivers (e.g. solar radiation) and buffers (e.g. flow volume) and in terms of modelling buffers are easier to manage for.

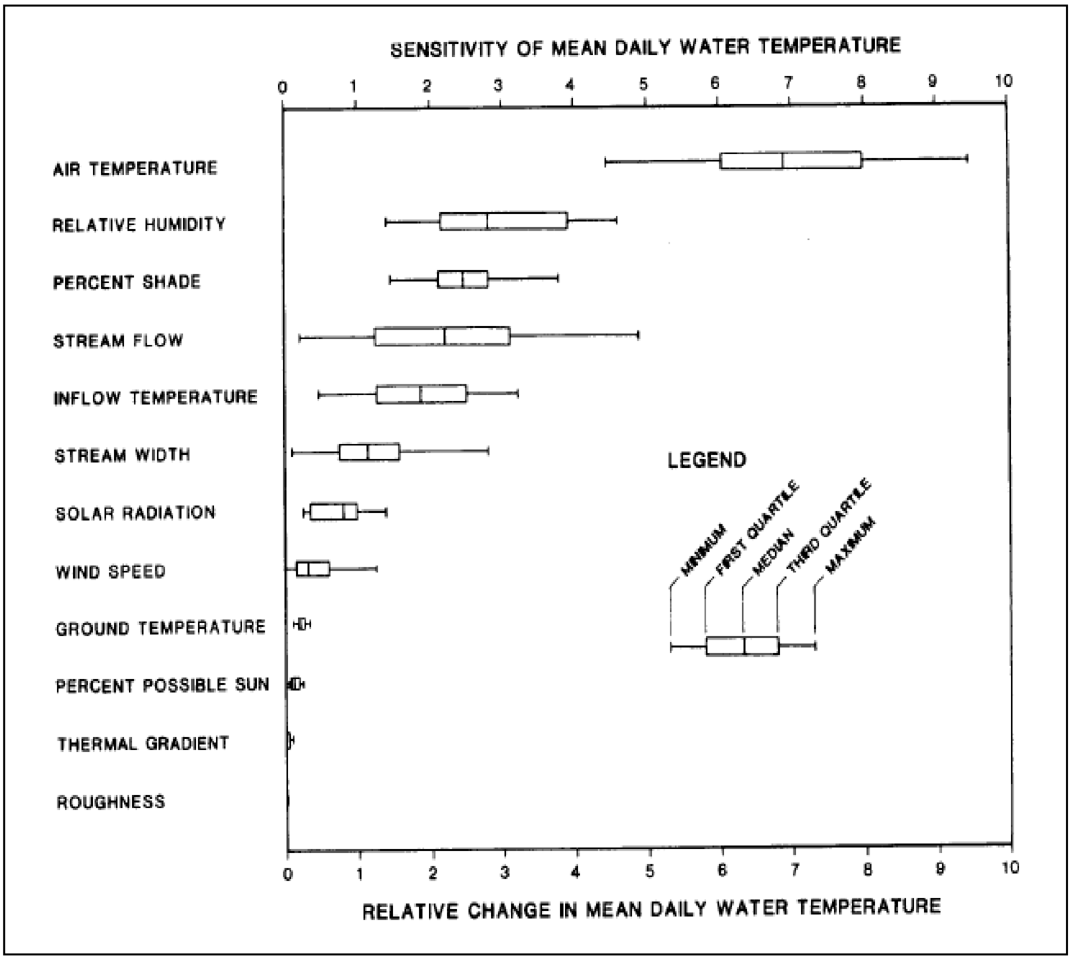

Figure 4.1 Factors that influence stream temperature (Bartholow, 1989).

4.5.4 Water temperature and climate change

Impacts on water temperature may be direct, which include thermal discharges, or indirect, which include land use changes, irrigation return flows, flow modifications (such as river regulation), inter-basin water transfers, modification to riparian vegetation and global warming (Dallas, 2008). The implications of projected climatic changes on water resources and on natural ecosystems are a matter of great environmental concern (Avila *et al*., 1996). In the post-industrial era, scientists generally use the term climate change in the manner defined by the United Nations Framework Convention on Climate Change (UNFCCC), in that it is a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is, in addition to natural climate variability, observed over a prolonged and comparable period of time (Hardy, 2003).

The main response to the alteration of the atmospheric composition (i.e. increase in greenhouse gases) includes changes in temperature which, in turn, results in changes in precipitation attributes and hence in entire climatic systems (Schulze, 2003). The recent Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007) projects that global average temperatures by 2100 will be between 1.8 - 4.0 °C higher than the 1980 – 2000 average (i.e. the best estimate, with a likely range of 1.1 - 6.4 °C). Sea levels are projected to rise 0.18 - 0.59 m by 2100. Furthermore, it is *very likely* that temperature extremes at the high end, prolonged heat waves and heavy precipitation events will continue to become more frequent (EEA, 2007).

Anthropogenic climate changes and their likely impacts, as summarised above, have the potential for serious implications on aquatic ecosystems and could ultimately affect the water supply and quality of freshwater lakes and rivers throughout the world (Chu *et al*., 2005). A rise in air temperatures is expected to increase stream temperatures (Mohseni *et al*., 1998). Increases in water temperatures as a result of climate change will alter fundamental ecological processes (e.g. reproduction, migration and metabolism) as well as the geographic distribution of aquatic species. This may have a profound effect on water quality and the availability of habitat for aquatic organisms, including fish (Bogan *et al*., 2006). Stream temperatures are, therefore, of great ecological importance, especially under conditions of a projected warmer climate (Mosheni *et al*., 2002). A sound knowledge of river water temperature modelling is, consequently, essential in the management of aquatic resources and in addressing climate change issues (Caissie *et al*., 2001).

4.5.5 Modelling water temperature

Modelling water temperature in lotic systems is far more difficult than in open water systems. According to Handcock *et al*. (2006), a stream is a more complex environment than an impoundment because it is usually much smaller and its temperatures are often not resolved at the spatial resolution as those in impoundments. Streams often have a complex morphology of braided channels, islands and in-stream rocks, and they vary greatly in hydrological and hydraulic characteristics such as inputs from groundwater, water depth, water velocity and turbulence fluctuations. They also vary in the amount of bank vegetation present and the percentage of shading, which influence the amount of incoming solar radiation on streams.

Along with experimental approaches, the prediction of the long term responses of aquatic ecosystems to climate change requires the use of models (Avila *et al*., 1996). There are two major approaches to modelling water temperature which are summarised below, *viz.*

- Deterministic i.e. process based approaches and
- Statistical approaches.

(a) Deterministic approaches focus on creating a conceptual energy balance between all the factors which influence water temperature. This approach is essentially a cause and effect relationship between site conditions and meteorological parameters and their influences on water temperatures (Caissie *et al*., 2001). In **Table 4.2** the advantages and disadvantages of using deterministic approaches to modelling water temperature are summarised. A study undertaken by Huguet *et al*. (2008) which attempts to estimate high river temperatures for future decades used the CALNUT model to compute a complete temperature series for a site which had an unreliable historical data series. The CALNAT model (**Equation 4.5.1**) calculates the temperature in a point of the river in a deterministic manner, integrating the equation of the temperature evolution (see Gras, 1969):

$$\frac{\partial T}{\partial t} + U\frac{\partial T}{\partial x} = \frac{\partial}{\partial x}\left(K\frac{\partial T}{\partial x}\right) + \frac{1}{\rho C H}(SR + AR - WR - C - E) \qquad [4.5.1]$$

where

U = river velocity,
K = thermal diffusivity along the river,
ρ = mass of water per unit volume,
C = specific heat capacity of water and
H = depth of river thermal inertia.

The five thermal fluxes SR, AR, WR, C and E are caused by solar radiation, atmospheric radiation, water radiation, wind convection and evaporation, respectively (Huguet *et al*., 2008). The output from the CALNUT model and 11 stations, which had reliable historical data, were combined with the unreliable data from the site in question, in order to identify trends in the historical temperature records. The CALNUT model is good example of a deterministic type approach to estimating water temperature and uses many input parameters to estimate water temperature at a single point of interest.

Table 4.2 Comparison between deterministic and stochastic approaches to modelling water temperature (after Caissie *et al*., 2001)

Approach	**Advantages**	**Disadvantages**
Deterministic	Well adapted to effluent-type problems (mixing temperatures)	High complexity of model development and application
	Usually scenario based problems, with many parameters, e.g. solar radiation, wind speed	Large number of input parameters, which can lead to calibration problems
	Cause and effect water temperature modelling	Data often unavailable for study area
	Can aid in management decisions	Applied over very small areas
Statistical	Requires few input parameters	Simplistic
	Generally used in simple applications	Generally not as accurate as deterministic methods
	Shows good results with air temperatures as sole input	Based on the assumption that air and water temperatures are highly correlated throughout the study area
	Well adapted to climate change studies, as GCMs simulate air temperature better than other climate variables (Lau *et al*., 1996)	
	Can be applied over a large area	
	Large datasets availability from climate stations	
	Generally based on few parameters	

(b) Statistical approaches relate water and air temperatures, since both are responding to similar energy balance components. When applying statistical regression models the timing of the event is not particularly important (Caissie *et al*., 2000). In **Table 4.2** the advantages and disadvantages of using a statistical approach to modelling water temperature are summarised. One such approach, developed by Moshseni *et al*., (1998), uses an S-shaped logistic function derived from daily air temperatures (**Equation 4.5.2**) to estimate stream temperature:

$$Ts = \mu \ - \frac{\alpha \quad \mu}{1 + \ ^{\gamma(\beta \quad a)}} \qquad [4.5.2]$$

where

Ts is the estimated stream temperature,

Ta is the air temperature measured at or near the stream gauging site,

α is the estimated maximum stream temperature,

μ is the estimated minimum stream temperature,

γ is a measure of the steepest slope of the logistic function and

β represents the air temperature at the inflection point (or curve midpoint).

Compared to the deterministic CALNUT model (**Section 4.5.5a**) this statistical approach is simpler with fewer input parameters, making it more attractive for large scale investigations into stream temperature estimation.

Statistical linear correlation between water and air temperature falls within the statistical approach and it can be applied at large scale with few input parameters and this approach is described in greater detail in **Section 4.5.7**.

4.5.6 Modelling water temperature using climate change scenarios

Modelling water temperature when using simulated climate change inputs narrows the choice of approach which can be applied, owing to the limited range of output variables from GCMs. Thus, in order to estimate water temperature as an eco-hydrological indicator, statistical methods with their more limited input requirements are more attractive to use than deterministic approaches. Linear regression models of stream temperature versus air temperatures are attractive for climate change impact studies because only one input variable, *viz*. air temperature, is used and GCMs simulate this variable better than other climate variables (Lau *et al*., 1996). In studies of the potential effects of global climate change on freshwater ecosystems, water temperature has been shown to be a primary factor (Mohseni and Stefan, 1999). Linear regression models using air temperatures as a surrogate for stream temperature have been applied successfully under various climate change scenarios, for example, doubling of atmospheric CO_2 (Mohseni and Stefan, 1999). One of the most common approaches to modelling water temperature under climate change thus uses input of air temperature as the primary input in a linear correlation analysis. Webb and Nobilis (1997) examined the relationship between monthly mean air and water temperatures for a small catchment in Austria over a time period of 90 years, and found a significant relationship between monthly water and air temperatures.

4.5.7 Linear correlation between water and air temperatures

The goal of regression models is to fit a set of data with an equation, the simplest being a linear regression equation (Neumann *et al*., 2003). Research has shown that there is a strong correlation between stream and air temperatures between 0 and 25 °C and that linear regression models can indeed be used to determine stream water temperatures from daily air temperatures (Morrill *et al*., 2005). Furthermore there is, intuitively, a statistical linear correlation between air and water temperatures (Mosheni and Stefan, 1999) and it has been shown that air temperature can be a good and reliable indicator of stream temperature across a wide range of environmental settings, especially at weekly and monthly time scales in which temperature extremes are averaged and smoothed (Erickson *et al*., 2000).

Pilgrim *et al*. (1998) used data from 39 Minnesota streams and found a near-linear relationship between stream and air temperatures for weekly and monthly data, but this relationship correlated less well at the daily time step. In a similar study, Webb (1987; 1992) found a more or less 1:1 relationship between weekly and monthly averages of stream and air temperature for 36 streams in the United Kingdom. Thus the temporal scale selected for the linear correlation between water and air temperatures is extremely important and care needs to be taken to ensure the correct temporal scale is used to match the nature of the investigation. Developing a linear regression model between water and air temperatures as also been attempted in South Africa. Rivers-Moore *et al*. (2005) developed a linear regression model for estimating maximum water temperature from data recorded over a period of 33 months at nine sites within the Sabie Catchment, which is situated in the Mpumalanga Province, South Africa. The model uses locally calibrated coefficients to estimate maximum water temperature with **Equation 4.5.3**, *viz*.

$$WT_{max} = 2.425 + 0.977\, AT_{mean} \qquad [4.5.3]$$

where

WT_{max} = the daily maximum water temperature and

AT_{mean} = the mean daily air temperature (Rivers-Moore *et al*., 2004).

This equation has been found to be fairly robust and has been used in other climatic areas, including catchments located in the Eastern Cape (Rivers-Moore *et al*., 2007).

By developing a predictive relationship between only air temperature and stream temperature it is implicitly assumed that air temperature is the most influential factor in determining stream temperature (Morrill *et al*., 2005), and this has been shown in **Figure 4.1**. Factors such as stream boundaries, groundwater inflows, dam releases and thermal pollution compound the linear fit between water and air temperature and the influences of these factors therefore need to be carefully considered when using a linear correlation approach to modelling water temperature (Bartholow, 1989) as an eco-hydrological indicator. A good correlation between water and air temperatures can be achieved if the water in the stream under investigation is considered to be well mixed in both vertical and transverse directions, and perfect mixing is typically assumed when using statistical linear correlation. On the other hand, poor correlations between water and air temperatures can be caused by dam releases, groundwater inflows, unique local climates, industrial activity, shading, sheltering and deforestation (Erickson *et al*., 2000).

******

In this chapter the use of flow and water temperature related indicators in climate change impact studies was investigated. This chapter also introduced the concepts surrounding the modelling of water temperature using deterministic and stochastic approaches. It concluded that employing linear correlation between water and air temperatures was the most effective method of modelling water temperature when using climate change scenarios at a large spatial scale. In the chapter which follows the issues of scale in atmospheric and streamflow modelling are investigated.

5. MAPPING ECOLOGICAL INDICATORS UNDER REGIMES OF CLIMATE CHANGE: SCALE ISSUES

The term "scale" is used here to refer both to the magnitude of a study (e.g. its spatial/geographic extent) and also to the degree of detail (e.g. its level of geographic resolution) and is undoubtedly one of the most fundamental aspects of any hydrological research (Quattrochi and Goodchild, 1997). The essence of environment-based research consists of dealing with nested systems across spatial (space) and temporal (time) scales as well as the linkages and intricacies among and between various environmental components (Jewitt *et al*., 1998). Selecting and using an appropriate scale throughout a study is of the utmost importance, especially when relating ecologically relevant responses to climatic change. This chapter initially focuses on the issues of scale in atmospheric and ecological modelling and subsequently investigates the need and methods of sub-delineating Quaternary Catchments into finer and more detailed Quinary Catchments.

5.1 The Issues of Scale in Atmospheric Modelling Revisited

Modelling likely future climates scenarios with General Circulation Models (GCMs; **Section 3.1**) raises problems in the usability of the GCM output related directly to spatial scale. In 1996 the IPPC stated that the spatial resolution of then current GCMs at 2 - 3° latitude/longitude was very coarse for hydrologically-related studies, which meant that their outputs were not regionally specific and that they did not allow small-scale or local investigations. It is for this reason that empirical and numerical downscaling techniques have, more recently, been developed in order to convert coarse scale GCM output into regionally relevant output through Regional Climate Change Prediction Models (RCCPMs; **Section 2.5**).

5.2 The Issue of Scale in Ecologically Related Streamflow Modelling

Ecology and hydrology (with its link to climatology) are often at opposite sides of the scale spectrum (Jewitt *et al*., 1998). The reliable modelling of eco-hydrological processes with respect to atmospheric phenomena is a complex problem, owing to the immense range of scales involved, and the differences that appear when the phenomena are viewed at different space and time scales (Global Atmospheric Research Programme, 1972; Smagorinsky, 1974; Dooge, 1982; 1986; 1992 cited in Panagouliaa and Dimoub, 1997). Essentially a complete theory of hydrology, relevant to climate modelling, would have to be considered in order to cover phenomena from the scale of the water molecule to the grid scale of a GCM. Thus, to build up a model at a given scale, one must either:

- parameterise laws established at a finer micro-scale to predict the key variables at the required scale; or
- disaggregate models validated at a coarser scale to produce more detailed predictions at the required more detailed scale; or
- attempt to establish new laws at the required scale and validate them by measurements at that scale (Panagouliaa and Dimoub, 1997).

Furthermore, to accurately establish relations and valid scientific conclusions one cannot assume that information gathered at one scale relates to information at other scales (Kershner and Snider, 1992). Users of information must ensure they do not “jump scales” and thus violate scale representations by assuming that point processes apply to large-scale catchments (Schulze, 2000; 2005).

Scale issues in ecological flow and water temperature modelling are not so much a problem at the phase of linking processes within a modelling system, but more at the phase of deciding which is an appropriate scale at which to work, i.e. at what scale does one need to simulate processes affecting the aquatic ecosystem (Jewitt *et al.,* 1998). It is, therefore, of the utmost importance that planners of in-stream flow studies determine what scale(s) of physical and biological functions are required to make accurate assessments of flow changes and it effects on aquatic ecosystems (Kershner and Snider, 1992).

Approaches to ecological in-stream flow and water temperature studies have been performed across a range of scales, but generally these have either been at large- or micro-scale. Planning-level studies (i.e. at large scales) are often used to investigate annual flows in a catchment while micro-scale studies use measurements/estimates of velocity, depth, substrate and cover at individual stream transect scales to quantify habitat attributes for aquatic species at different flows. Such micro-scale hydro-ecological studies are highly time consuming, detailed and intensive and thus impossible to perform on a countrywide scale (Kershner and

Snider, 1992). When small-scale predictions of flow depth and velocity have been attempted along transects where no direct measurements have been made, the input requirements and complexities of the models involved have effectively made them unusable (Gan and McMahon, 1990; King and Tharme, 1993 cited in Jewitt *et al*., 1998). The complexities of scale in impact studies cannot be overstressed and sufficient consideration needs to be given to these issues (Schulze, 2000).

5.3 The Southern African Quaternary Catchment Sub-Delineation in the Context of Climate Change Impact Studies

The publications on the Surface Water Resources of South Africa (WR90; Midgley *et al*., 1994) have provided a valuable source of baseline regional hydrological and water resource information, which has been used in various hydrological and ecological modelling exercises. Part of the WR90 monthly time series of flows were generated using consistent approaches and cover the whole of South Africa, Lesotho and Swaziland based on a spatial sub-division into 1 946 hydrologically interlinked Quaternary Catchments, QCs (**Figure 5.1**), which vary in size from 50 to 18 000 km^2 (Hughes, 2006). The School of Bioresources Engineering and Environmental Hydrology (BEEH) at the University of KwaZulu-Natal has developed a comprehensive Quaternary Catchment database (e.g. Schulze and Perks, 2000; Schulze *et al*., 2005b) in order to aid various hydrological modelling projects for South Africa (e.g. Gush *et al*., 2002) This database contains a vast amount of data and information regarding soils, land cover, daily climate data and hydrological parameters for each of the 1 946 QCs. The database, which is linked to the daily time step *ACRU* model (Schulze, 1995 and updates), allows one to simulate the entire South Africa at the one end of the spectrum, or simply one single QC at the other end of the spectrum. Schulze *et al*. (2007) state that the objective of developing the Quaternary Catchment database is to be able to perform spatially comparative simulations of, for example,

- stormflow,
- baseflow, or
- total runoff, as well as
- impacts of land use change on hydrological responses, or of
- climate change on hydrological responses, of

- crop yields,
- sediment yield,
- irrigation water demand, or
- hydrological risk analyses.

The aforementioned studies which have all utilised the Quaternary Catchments database, identified problems associated with using the Quaternary Catchment as the scale of investigation for hydrological and these problems are outlined in the next section.

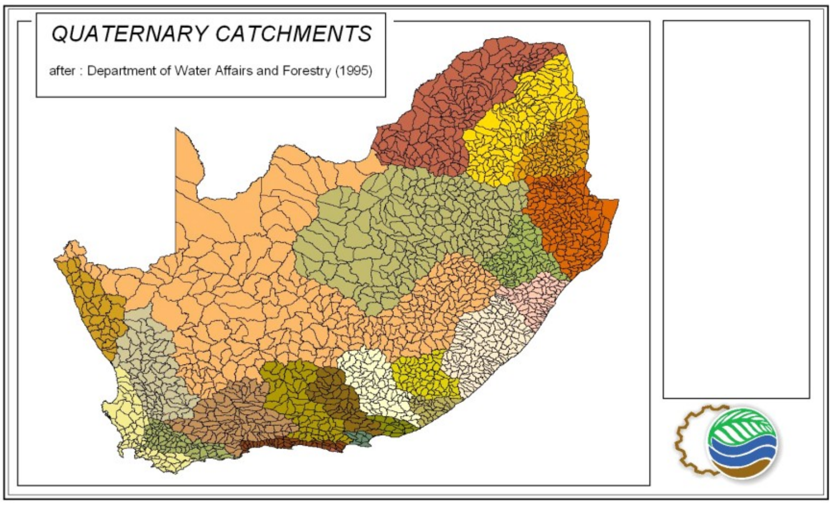

Figure 5.1 Delimitation of Quaternary Catchments in South Africa, Lesotho and Swaziland, with Primary Catchments distinguished by different shading.

5.4 Applications of RCCPMs at Quaternary Catchment Scale: The Scale Dilemma and the Need for Spatial Disaggregation into Quinary Catchments

The scale of investigation in any project using atmospheric models should, ideally, be constrained by the resolution of the RCCPM output from the GCMs. In previous South African climate change impact studies, the outputs from a range of GCMs/RCCPMs were used to investigate the impacts of climate change on South African hydrology (e.g. Schulze and Perks, 2000; Schulze *et al.*, 2005b). One such RCCPM, which was developed in Australia, is the Conformal-Cubic Atmospheric Model (C-CAM). Engelbrecht (2005) modified this model for southern Africa to a spatial resolution of 0.5° (approximately 50 km or 2 500 km^2), with daily climate data for both present (1975-2005) and future (2075-2100) climate scenarios. Quaternary Catchments that cover southern Africa have a median area of

620 km^2. Using RCCPMs with this particular spatial resolution and applying them at the scale of Quaternary Catchments has given rise to a number of scale related issues. For example when using a spatial resolution of 0.5° many QCs will have inadequate RCCPM raster points to create a comprehensive picture of the impact of climate at Quaternary Catchment level since QCs range in scale from 50 km^2 to 18 000 km^2. This conflict of spatial scales has lead to a so-called "scale dilemma" in climate change impact studies. The dilemma that arises is two-fold:

- In large QCs there will be more than a single raster point from a RCCPM within a QC.
- In smaller and physiographically more complex QCs no single raster point from a RCCPM may fall within the QC boundary. This is critical as those QCs were delimited to be small because of the general hydrological heterogeneity of the region and that was where spatial detail was going to be of paramount importance.

In both cases the question arises as to how one selects raster points to represent the QC. To resolve this problem one needs to investigate the merits of modelling at QC scale or whether, alternatively, to select a more appropriate spatial scale.

There are both advantages and disadvantages to modelling hydrological systems at QC scale. One advantage is that modelling at this scale is relatively straightforward, as the flow path network of QCs has already been put into place from past nationwide hydrological studies (e.g. Schulze, 2005). The other major advantage is that the QC datasets are of a high quality and are easily accessible.

A disadvantage of modelling at QC scale is that appropriate hydrological processes are not always well represented at QC scale. Thus, when modelling at the scale of a QC, all catchment characteristics and processes are area-averaged and this can mask responses at the outer limits of the hydrological spectrum and it is these "extremes" which frequently determine hydrological and ecological decisions. Another disadvantage is that many QCs are physiographically diverse and are therefore neither climatologically nor hydrologically homogenous, and thus not representative of a single hydrological regime assumed for a QC. For example, statistical analysis has shown that intra-QC variability of one arc minute (~1.7 x1.7 km) gridded altitude and rainfall values is high enough for approximately 1 000 of the 1 946 QCs to require subdivision into smaller, more homogeneous response units on the grounds of natural hydrological variability alone (Schulze, 2004). This is illustrated in **Figure 5.2**, in which differences in gridded altitude values between the 90th and 10th percentiles are shown for each QC, depicting the many QCs with altitudinal ranges in excess of 400 m which may need to be discretised further when based solely on the influence which altitude has on drivers of runoff such as rainfall, and on buffers on runoff such as soils properties and potential evaporation (Schulze, 2004). From this example it is clear that QC sub-delineation needs to be undertaken, since improving downscaling technologies allow for the superior fine-scaled resolutions from RCCPMs. Completing these tasks will certainly improve our modelling simulations and ultimately our decision-making regarding the impact of climate change on aquatic ecosystems.

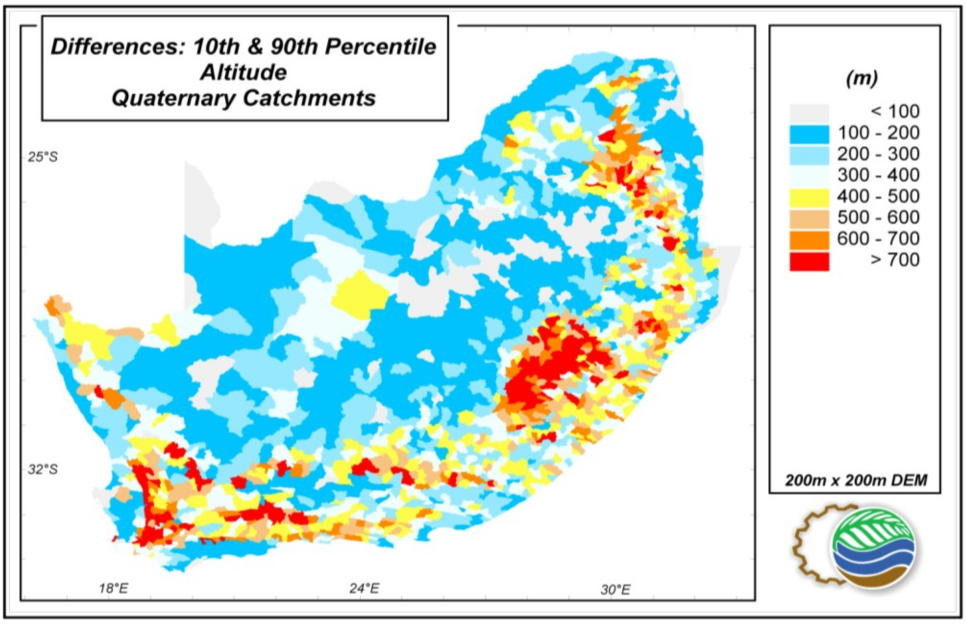

Figure 5.2 Differences between the 10th and 90th percentile values of one arc minute gridded altitudes per Quaternary Catchment (after Schulze, 2004)

5.5 Approach Taken for a Sub-Delineation of Quaternary Catchments into Quinary Catchments

The scale dilemma, outlined in the previous section, has illustrated the problems associated with modelling climate change impacts at the scale of a fourth level QC and thus the need to sub-delineate QC into smaller, more detailed subcatchments at the fifth level of disaggregation, *viz*. Quinary Catchments. The remainder of **Sections 5.5** and **5.6** are extracted from Chapter 5 (Schulze and Horan, 2009) of WRC Report 1562/01/09 (Tadross and Schulze,

2009) - a report to which the author of this dissertation made a major contribution. In order to achieve consistent methodologies of sub-delineating QCs into Quinary Catchments according to altitude criteria, each Quaternary was therefore subdivided consistently into three Quinaries, i.e. an upper, middle and lower Quinary, of unequal area but of similar topography, by applying the Jenks' optimisation procedures available within the ArcGIS software suite, and which are based on a sub-delineation according to "natural breaks" in altitude (Schulze and Horan, 2009). The individually determined natural breaks between adjacent Quaternaries were then edge-matched. The entire concept is illustrated in **Figure 5.3** for two Quaternary Catchments, with altitude shown in the left hand map, the three-fold sub-delineation by natural breaks of altitude by Jenks' procedures in the middle map and the flowpaths of runoff from the upper to middle and middle to lower Quinary in the right hand map (Schulze and Horan, 2009).

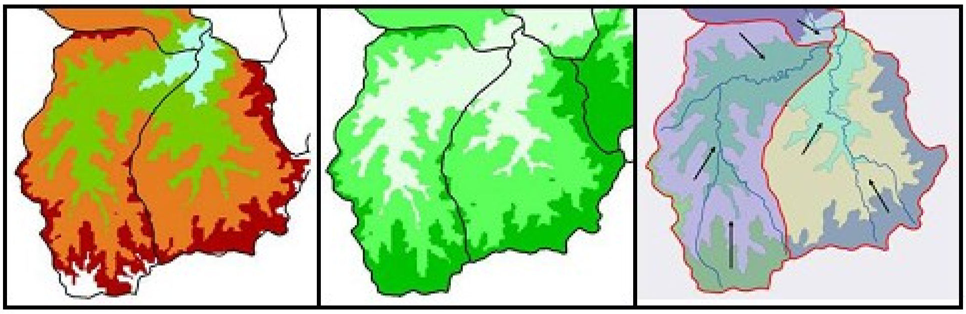

Figure 5.3 Sub-delineation of Quaternary Catchments (left) from altitude, (middle) into three Quinaries by natural breaks and (right) with flow paths of water (Schulze and Horan, 2009)

Two points need to be stressed in regard to the sub-delineation into Quinaries:

- The three Quinaries within each QC are delineated by natural altitude breaks. A specific Quinary may thus be made up of one or more discrete spatial units, i.e. polygons, as in the example of the upper Quinary in **Figure 5.3** (middle). These polygons are nevertheless conceptualised as *one single spatial entity* for purposes of hydrological simulations, with all runoff generated from those polygons flowing into the next downstream Quinary (Schulze and Horan, 2009).
- The outflow of the lower Quinary of a QC (irrespective of whether that QC is an "external" or "internal" Quaternary), does *not* enter the upper Quinary of the next

downstream Quaternary Catchment, because that upper Quinary may be at a higher altitude than the lower Quinary of the upstream Quaternary. Therefore, the outflow of the lower Quinary has been configured to rather enter the downstream Quaternary at its exit. A schematic of the flowpath configuration between Quinaries and Quaternaries, taken from the Upper Thukela Catchment, is given in **Figure 5.4** (Schulze and Horan, 2009).

5.6 Outcomes of the Delineation of Quaternary into Quinary Catchments

The sub-delineation of Quaternary into Quinary Catchments, outlined in **Section 5.5**, has four primary outcomes:

- The first is that the RSA, Lesotho and Swaziland have now been delineated into 5 838 hydrologically interlinked and cascading Quinaries (**Figure 5.5**) from exterior through interior subcatchments, with water eventually flowing out to sea or into neighbouring countries (such as Mocambique), or into international border rivers (such as the Limpopo).
- The second is that the Quinary Catchments are deemed to be more homogeneous than the Quaternaries in their altitudinal range. This is illustrated clearly when comparing the much lower altitudinal ranges of the Quinaries shown in **Figure 5.6** with the much higher ones of the Quaternaries in **Figure 5.2** (Schulze and Horan, 2009).
- The third is that, especially in higher altitude runoff-producing Quaternary Catchments, the differences between hydrologically relevant attributes of the three Quinaries within a Quaternary can be highly significant (Schulze and Horan, 2009). The three Quinaries could therefore yield markedly different hydrological responses than the Quaternary they make up.
- The fourth is that certain land uses within a Quaternary Catchment are often dominant within specific Quinaries of that QC (Schulze and Horan, 2009).

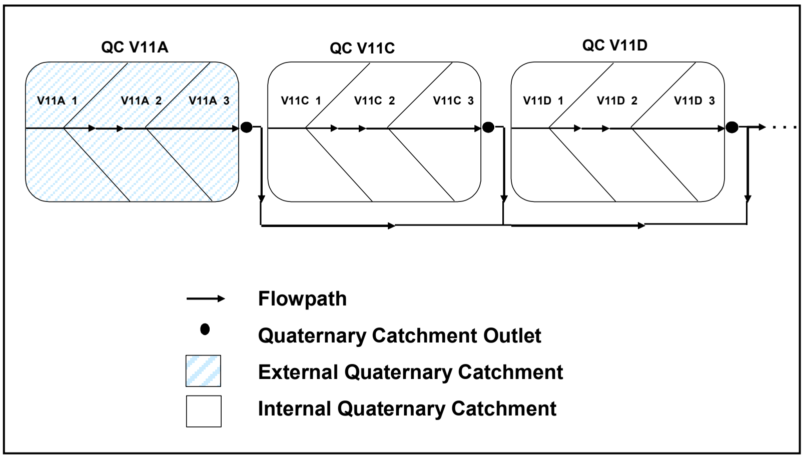

Figure 5.4 Example of flowpaths between Quinary and Quaternary Catchments in the Upper Thukela Catchment (Schulze and Horan, 2009)

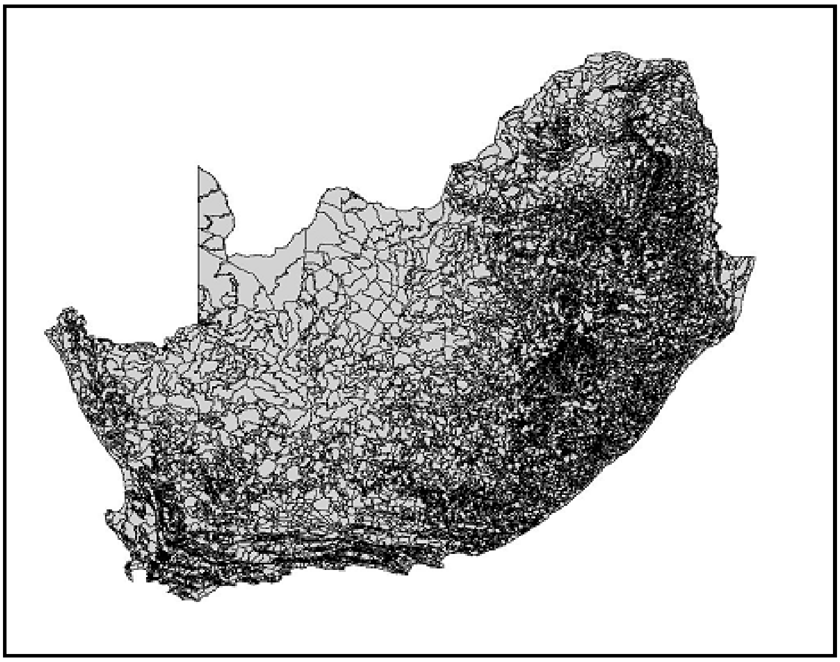

Figure 5.5 Delineation of the RSA, Lesotho and Swaziland into 5 838 hydrologically interlinked and cascading Quinary Catchments (Schulze and Horan, 2009)

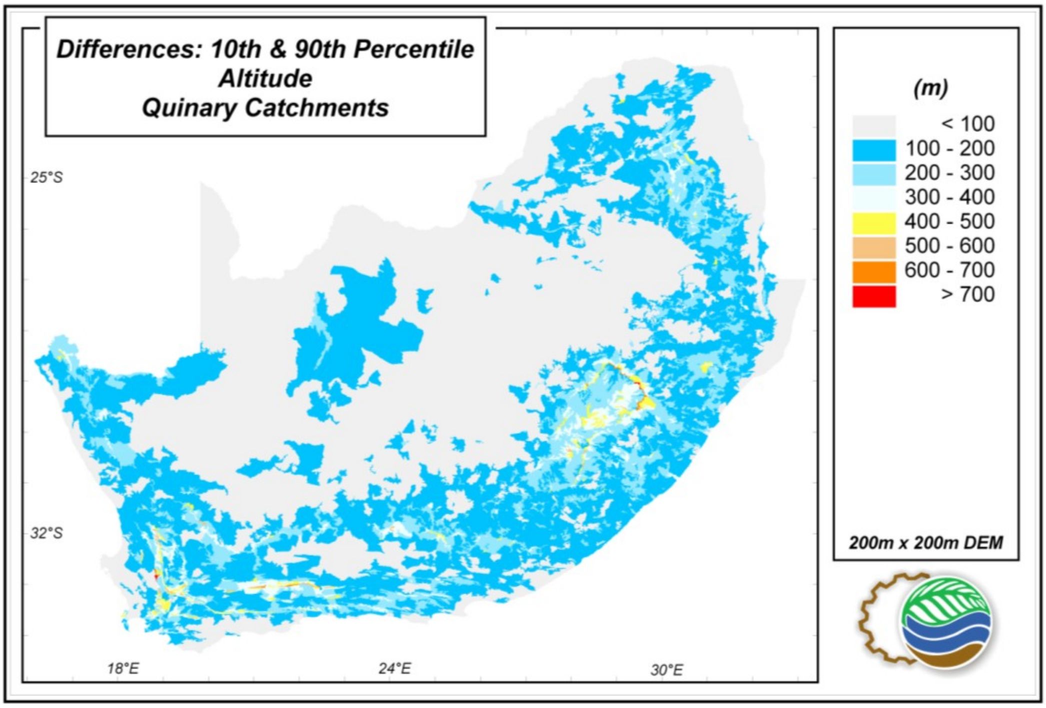

Figure 5.6 Differences between the 10th and 90th percentile values of one arc minute gridded altitudes per Quinary Catchment (Schulze and Horan, 2009)

*****

In **Chapter 5** the issues of scale in atmospheric and streamflow modelling were investigated. The delineation of South Africa into Quaternary Catchments and the problems of using this spatial scale for climate change impact studies were then discussed. In order to address this problem there was a need to spatially disaggregate Quaternary Catchments into smaller and hydrologically more homogenous spatial units, known as Quinary Catchments. Finally the outcomes of this new delineation into Quinary Catchments were outlined using the work compiled by Schulze and Horan (2009) as a source of reference. In the following chapter the development of the Quinary Catchments Database is outlined, as is the methodology used to assess projected impacts of climate change on environmentally related flows and water temperature indicators.

6. THE METHODS USED TO MODEL ECO-HYDROLOGICAL INDICATORS UNDER CONDITIONS OF CLIMATE CHANGE

The accuracy with which ecological and hydrological activities can be modelled depends largely upon the accuracy of the climatic databases, on the process representations of the simulation models used as well as on the spatial and temporal resolutions used in modelling (Hull, 2008). The databases, models and techniques that were used to assess the projected impacts of climate change on flow and water temperature related indicators are described in this chapter.

6.1 The Development of the Quinary Catchments Database

For a number of years now many assessments of hydrological and agricultural responses over southern Africa have been made using the Southern African Quaternary (i.e. 4th level) Catchments Database (**Section 5.3**). Following the delineation of the RSA, Lesotho and Swaziland into hydrologically interlinked Quinary Catchments (**Section 5.6**) imbedded within Quaternaries, the Quaternary Catchments Database has now been expanded to the Southern African Quinary (i.e. 5th level) Catchments Database (QnCDB). The QnCDB is an essential data source for this research project and was used to model the flow and water temperature indicators under projected conditions of climate change. In **Sections 6.2 - 6.6** the focus is on baseline historical climatic conditions and in these sections only the climate inputs that were applied to this specific research project are described. The preparation of climate inputs derived from climate change scenarios are discussed only briefly in **Sections 6.2 - 6.6**, with greater detail being provided in **Section 6.8** for the primary variables of rainfall and temperature. It should be noted that the information in **Sections 6.2 - 6.6** has been largely extracted and summarised from Chapter 6 by Schulze *et al*. (2009b) of the WRC Report 1562/01/09 currently in preparation under editorship of Tadross and Schulze (2009). The research findings described in this dissertation make up a component of this WRC project.

6.2 Daily Rainfall Input per Quinary Catchment

6.2.1 Estimations of daily rainfall values for simulations under baseline climatic conditions

In 2004 Lynch compiled a comprehensive database (1950 - 2000) of quality controlled (and where necessary infilled) rainfall data consisting of more than 300 million rainfall values from 12 153 daily rainfall stations in southern Africa. From this database, a rainfall station had to be selected for each of the 5 838 Quinary Catchments, with that station's data considered to be representative of the daily rainfall of that Quinary (Schulze *et al*., 2009b).

This was achieved by assuming that the previously selected station representing the rainfall of the parent Quaternary Catchment would also represent the three Quinary Catchments which in each case make up the Quaternary. The selection of the stations representing the Quaternary Catchments was described in Schulze *et al.* (2005b) and involved first determining the centroid of each of the Quaternary Catchments. The Daily Rainfall Extraction Utility (Kunz, 2004) was then used to extract the 10 closest rainfall stations to each catchment's centroid. These 10 stations were ranked by Kunz's (2004) Utility using 10 reliability criteria, with the best ranked station being subjected to further manual evaluation. In total, 1 244 stations were selected, the daily rainfall values from which were to "drive" the hydrology of the 1 946 Quaternaries. Reliability tests (Warburton and Schulze, 2005) showed the average reliability of the rainfall stations selected to be 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 (Warburton and Schulze, 2005), with poorest reliability found to be in Lesotho, the Western Cape fold mountains region and along the northeastern border of the RSA with Mozambique. By implication, one rainfall station often had to "drive" the hydrology of numerous Quaternaries (Schulze *et al*., 2009b).

In response to further research during the course of this project, the representative (or "driver") station for 11 Quaternary Catchments was changed in order to improve the representation of rainfall in those catchments. This resulted in the total number of driver stations being reduced from 1 244 to 1 240. Data from these 1 240 stations were then used to generate the daily rainfall of the 5 838 Quinary Catchments according to the assumption made above, *viz*. that each Quaternary Catchment driver station would also represent the rainfall of the associated three Quinary Catchments (Schulze *et al*., 2009b).

Multiplicative rainfall adjustment factors were then determined for each Quinary Catchment and applied to the driver station's daily records in order to render the driver station's daily rainfall to be more representative of that of the Quinary. In this way a unique 50 year daily rainfall record was created for each of the 5 838 Quinaries for application in hydrological simulation modelling. The adjustment factors were derived by first calculating the 12 spatial averages of all the one arc minute (~1.7 x 1.7 km) gridded median monthly rainfall values (determined by Lynch, 2004) within a Quinary Catchment. The ratio of these catchment average median monthly rainfalls to the driver station's median monthly rainfalls was then calculated to arrive at 12 monthly adjustment factors (Schulze *et al*., 2009b).

6.2.2 Estimations of daily rainfall values for simulations with future climate scenarios

For climate change studies a similar approach was adopted, whereby suitable driver stations were identified from the 2 642 stations for which "present climate" (1971 - 1990) daily rainfall values, as well as those for an "intermediate future" (2046 - 2065) and a more "distant future" climate (2081 - 2100), had been empirically downscaled to station level for the ECHAM5/MPI-OM Global Climate Model (used exclusively in this project, cf. **Section 6.8**) as well as four other GCMs supplied to the School of BEEH by the Climate Systems Analysis Group (CSAG) at the University of Cape Town. In total 1 061 driver stations were identified, of which 1 023 were also used in representing the baseline (historical) climate above. As was the case for the baseline historical climate, the data for the above 1 061 driver stations were adjusted to better represent the rainfall of each Quinary Catchment, resulting in the development of a unique representative rainfall record for each Quinary.

It was assumed that the monthly adjustment factors calculated for the baseline historical climate would also be applicable under the GCM derived climates considered (present, intermediate future and distant future). This assumption was made in the absence of *fine resolution* (e.g. one arc minute) national grids of median monthly rainfall for these "present climate", "intermediate future" and "distant future" periods which would be required if adjustment factors specific to those periods were to be calculated (Schulze *et al*., 2009b).

6.3 Daily Air Temperature Input per Quinary Catchment

6.3.1 Estimations of daily values of maximum and minimum air temperatures for simulations under baseline climatic conditions

Daily maximum and minimum temperature values facilitate estimations to be made, implicitly or explicitly, of solar radiation, vapour pressure deficit and potential evaporation (Schulze, 2007) and with those variables plus rainfall as input into hydrological models such as *ACRU*, the generation of soil moisture content, runoff and/or irrigation demand becomes possible (Schulze *et al*., 2009b).

Procedures outlined in detail by Schulze and Maharaj (2004) enable the generation of a 50-year historical time series of *daily* maximum and minimum air temperatures at any unmeasured location in the RSA, Lesotho and Swaziland at a spatial resolution of one arc minute of latitude/longitude (~1.7 x 1.7 km) for the 429 700 grid points covering the region. In summary, the underlying temperature database was made up of daily, quality controlled records from > 970 temperature "control" stations, extended to a common 50 year period, *viz*. 1950 - 1999 (Schulze and Maharaj, 2004). Infilling and/or extension of records to the common 50 year period at each of the control stations took account of independent month-by-month maximum and minimum temperature lapse rates (i.e. rates of change of temperature with altitude) from 12 lapse rate regions identified in southern Africa (Schulze, 1997), and from carefully chosen target stations at which similarities in the variability of daily temperature values with those from the control station was the key criterion. At each of the 429 700 grid points the maximum and minimum temperatures were computed for each day of the 50 year data period from two selected, independent (i.e. in different quadrants), temperature stations. The daily values from these two stations were then averaged in order to modulate any biases (from lapse rates or station data) emanating from either of the two stations' generated records (Schulze *et al*., 2009b).

Suitable grid points from the study of Schulze and Maharaj (2004) were determined to represent each of the 5 838 Quinary Catchments covering the study area, The selection of these representative grid points was achieved by first calculating the mean altitude of each Quinary from a 200 m Digital Elevation Model. Grid points with altitudes similar to those of the catchment means and located as close as possible to the catchment centroids were then selected to represent each of the Quinary Catchments (Schulze *et al*., 2009b).

In summary, the above determination of daily maximum and minimum temperatures for the Quinary Catchments represents a two-step approach with:

- first, the generation of a 50 year daily maximum and minimum temperature dataset at 429 700 raster points from > 970 control stations (with data quality checked and infilled) and
- second, the selection of individual grid points to represent each Quinary Catchment.

Based on the results of tests performed, the algorithm applied to select grid points (second bullet point, above) incorporated an exponential decay in the influence of altitude with distance from the point of interest, rather than the linear decay employed when selecting target stations for infilling of missing values at the control stations (control stations were used in the generation of the temperature grid; bullet point one, above). The resulting 50 year series of daily maximum and minimum temperatures for each Quinary Catchment was then also used in the generation of daily estimates of solar radiation and vapour pressure deficit, and from these, the daily values of reference potential evaporation as well as potential crop evapotranspiration could be computed on a Quinary Catchment-by-Catchment basis (Schulze *et al*., 2009b).

6.3.2 Estimations of daily values of maximum and minimum air temperatures for simulations with future climate scenarios

For climate change studies, empirically downscaled daily maximum and minimum temperature values from 404 stations were supplied by CSAG for "present climate" (1971 - 1990) daily air temperature values, as well as those for an "intermediate future" (2046 - 2065) and a more "distant future" climate (2081 - 2100). Two stations were selected to represent daily maximum and minimum air temperatures in each of the Quinary Catchments. The selection algorithm developed for this purpose was, as in **Section 6.3.1**, was based on distance between the stations and the Quinary centroids, together with the difference in altitudes of the stations relative to the catchment's mean altitude. The same month-by-month maximum and minimum lapse rates which were applied in the generation of the temperature grid of Schulze and Maharaj (2004) were applied to the daily values from the two selected temperature stations. A weighted average of the adjusted temperatures from the two stations was then calculated to represent air temperature in each Quinary Catchment. A 20 year time series of daily maximum and minimum temperature values was generated for the ECHAM5/MPI-OM

GCM for the three climatic periods for each of the 5 838 Quinary Catchments covering southern Africa (Schulze *et al*., 2009b).

6.4 Hydrological Soil Attributes

Hydrological models require amongst other variables, soils information as input. Being a threshold-based model, *ACRU* (Schulze, 1995 and updates) needs input values on the following soils variables:

- thicknesses (m) of the topsoil and subsoil;
- soil water contents (m/m) at
  - saturation (porosity),
  - drained upper limit (also commonly referred to as field capacity), and
  - permanent wilting point (i.e. the lower limit of soil water availability to plants);
- rates of "saturated" drainage from topsoil horizon into the subsoil, and from the subsoil horizon into the intermediate groundwater zone, and the
- erodibility of the soil.

Values of these variables were derived by Schulze and Horan (2007) using the AUTOSOILS decision support tool (Pike and Schulze, 1995 and updates) applied to the soils database from the Institute for Soil, Climate and Water (SIRI, 1987 and updates) for each of the soil mapping units, called Land Types, which cover South Africa, on the basis that the hydrological properties of all the soil series making up an individual Land Type were area-weighted. For each Quinary Catchment the values of the hydrological soils variables required by the *ACRU* model were derived from the Land Types identified in that Quinary, again on an area-proportioned basis (Schulze *et al*., 2009b).

6.5 Hydrological Attributes of Baseline Land Cover Types

In any hydrological impact studies the hydrological attributes of baseline land cover types are required in order to simulate any changes in hydrological responses when the baseline land cover is converted to new land uses, or new forms of land management. For South Africa, Lesotho and Swaziland the 70 Acocks' (1988) Veld Types are a recognised baseline (i.e.

reference) of land cover for application in hydrological impact studies (cf. Schulze, 2004; Schulze *et al*., 2007).

Based on a set of working rules for determining the water use coefficient, interception per rainday, root distribution, a coefficient of infiltrability, an index of suppression of soil water evaporation by a litter/mulch layer and a soil loss related vegetal cover factor, month-by-month values of these attributes, given in Schulze (2004; 2007), were incorporated into the Quinary Catchments Database for each of the 70 Acocks' Veld Types covering southern Africa. For each of the 5 838 Quinaries in the database the spatially most dominant Veld Type was then selected as the representative baseline land cover (Schulze *et al*., 2009b). In this research the land cover is assumed to stay constant throughout all climate change scenarios.

6.6 The Hydrological Model

In order to simulate possible impacts of climate changes on flows and water temperature related indictors, the *ACRU* agrohydrological modelling system (Schulze, 1995; Schulze and Smithers, 2004 and updates) was selected. The *ACRU* model has been, and is currently being, used extensively in integrated water resources management and climate change studies in southern Africa (c.f. **Section 2.4**). The *ACRU* model is a deterministically based, physical-conceptual and integrated multi-purpose modelling system, revolving around a daily time step, multi-layer soil water budget (Schulze, 1995; **Figures 6.1 and 6.2**). Internal state variables (for example, soil moisture), model components (e.g. interception) as well as the model output (e.g. streamflow; peak discharge; sediment yield) have been widely verified under different hydrological regimes throughout the world (Schulze *et al*., 1995; Schulze and Smithers, 2004).

The standard *ACRU* model as also been modified to undertake climate change impact simulations, for example, by being able to take account differentially of enhanced CO_2 for C_3 and C_4 plants. A critical characteristic of the *ACRU* model is that it can operate at multiple scales as a *point* model, or as a *lumped* small catchments model, or as a *distributed* cell-type model on large catchments, or at national scale, with flows taking place from "exterior" through "interior" cells (i.e. sub-catchments) according to a predetermined configuration scheme, with the facility to generate individually requested outputs at each subcatchment's exit (Schulze, 2007). The *ACRU* model has been linked to the Southern African National Quinary Catchments Database for applications at a range of spatial scales in the RSA, Lesotho and Swaziland for climate change impact studies such as this one.

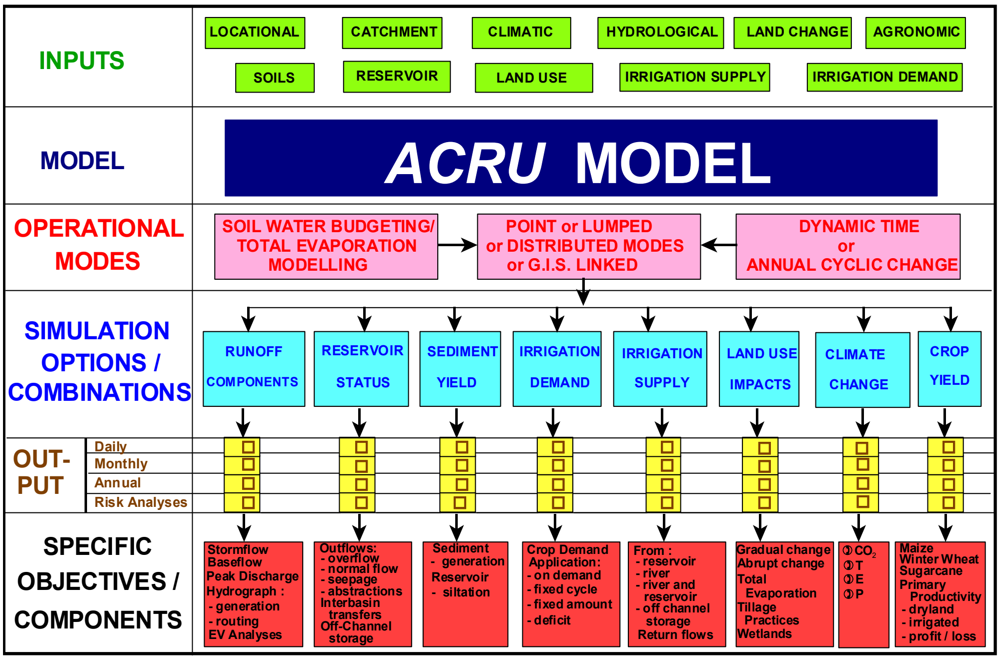

Figure 6.1 The *ACRU* agrohydrological modelling system: Concepts (after Schulze, 1995)

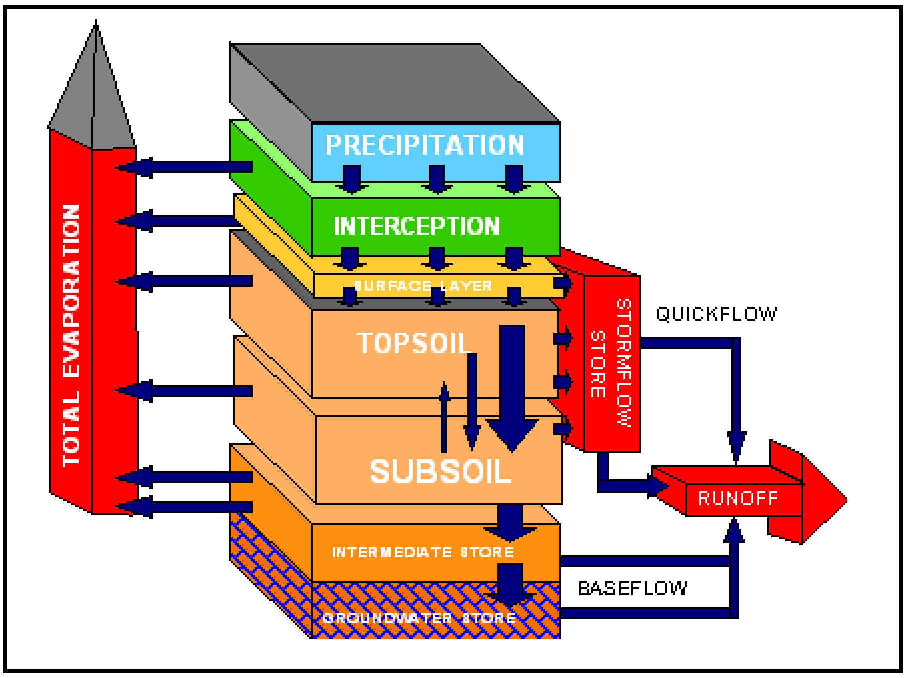

Figure 6.2 The *ACRU* agrohydrological modelling system: General structure (after Schulze, 1995)

The methods used by *ACRU* to simulated runoff and streamflow are critical to this project and these, as well as some of the model's shortcomings, are summarised below from Schulze (1995; 2007):

The *ACRU* model accounts explicitly for stormflow generation and for recharge into the intermediate and groundwater zones. However, processes involving baseflow releases and interflow contributions are still represented by simple algorithms only, and which require more research. *ACRU* operates simultaneous runoff generating routines for the pervious fraction of the catchment (stormflow, baseflow) and the impervious fraction (connected and unconnected to the channel system) in addition to separate routines for stormflow, percolation and return flows from irrigated areas.

The model contains the option (applicable mainly to larger catchments) of distinguishing between:

- landscape-based processes (by disaggregating the catchment into interlinked and relatively homogeneous response units such as Quinary Catchments),
- channel-based processes (including a separate reservoir water budget which can account also for gains through inter-basin transfers and losses by evaporation, seepage, abstractions and environmental demands), and the
- transitional zones of wetlands and riparian zones, while hillslope processes at this stage distinguish only between the riparian and non-riparian zones .

Several processes require further refinement, e.g. channel transmission losses, interflow and hillslope processes in general. Despite these limitations, *ACRU* is nevertheless believed to be a modelling system highly suitable for evaluating impacts of climate change on the hydrology and water resources of southern Africa (Schulze 1995; 2007).

6.7 The Climate Model and Scenario Representation

6.7.1 The ECHAM5/MPI-OM General Circulation Model

The School of BEEH received output from five empirically downscaled GCMs from the Climate Systems Analysis Group (CSAG) at the University of Cape Town. Of these models only the output of the ECHAM5/MPI-OM GCM had gone through all the complex configuration procedures for hydrological applications with the *ACRU* model (Lumsden *et al*., 2009) by the end of 2008, and it was thus the only GCM output of which was available for this research. The limitations of using output from a single GCM for impact studies are well documented (e.g. Hewitson *et al*., 2005; Schulze *et al*., 2007; IPPC, 2007) and are well appreciated by the author. However, this dissertation has its focus on the *development of techniques* rather than the certainty or uncertainty of the results. The ECHAM5/MPI-OM model, hereafter and on maps referred to in its abbreviated form of simply ECHAM5, was selected because of the five GCMs received it represents a "middle-of-the-road" future climate with some GCMs displaying drier and others wetter future rainfall conditions (Kunz, 2008). ECHAM5 was developed by the Max Planck Institute for Meteorology (MPI) in Germany. The first results obtained from ECHAM5 were published in 2005 and it was used in the IPPC (2007) Fourth Assessment Report.

It should be noted that **Sections 6.72** – **6.7.4** are a summary of Chapter 8 (Lumsden *et al*., 2009) of WRC Report 1562/01/09 (Tadross and Schulze, 2009), and that I am a co-author of that chapter.

6.7.2 Description of point scale climate change scenarios

The point scale climate change scenarios developed by CSAG for application in this research project were derived from global scenarios produced by the ECHAM5 GCM. The climate scenarios for the ECHAM5 GCM were downscaled by CSAG to a climate station point scale, based on the A2 emissions scenario defined by the IPCC SRES (Nakićenović and Swart, 2000).

The points at which scenarios were generated were the locations of the climate stations used in the empirical downscaling process. Scenarios of daily rainfall were produced by CSAG at 2 642 southern African stations (**Figure 6.3**), while daily maximum and minimum temperature scenarios were produced at 440 and 427 stations, respectively (**Figure 6.4**). The lack of climate stations over Lesotho and Swaziland is of concern in climate change studies, but this reflects the reality of the relatively sparse observation networks of high quality, long duration and readily available data in those countries (Lumsden *et al*., 2009). Regional climate change scenarios were developed from the ECHAM5 GCM for "present", "intermediate future" and more "distant future" climates represented by the following time periods:

- present climate: 1971 - 1990
- intermediate future climate: 2046 - 2065 (defined by the IPCC)
- distant future climate: 2081 - 2100 (defined by the IPCC).

The ECHAM5 downscaled scenarios included a daily time series of rainfall and temperature for each of these climate periods. For this research only 20 years of the available 40 years of ECHAM5 "present" climate data were used in comparative studies with the intermediate and distant future climates in order to consider an equal number of years in all three periods. The 20 year period from 1971-1990 was selected for this purpose, with the period 1961-1980 not considered as the time interval between the present climate and the intermediate future climate would then be very long (85 years) relative to the interval between the intermediate future climate and the distant future climate (35 years). The period from 1981-2000 was not considered as this period may already have experienced a strong climate change signal, making it less suitable as a baseline period (Lumsden *et al*., 2009).

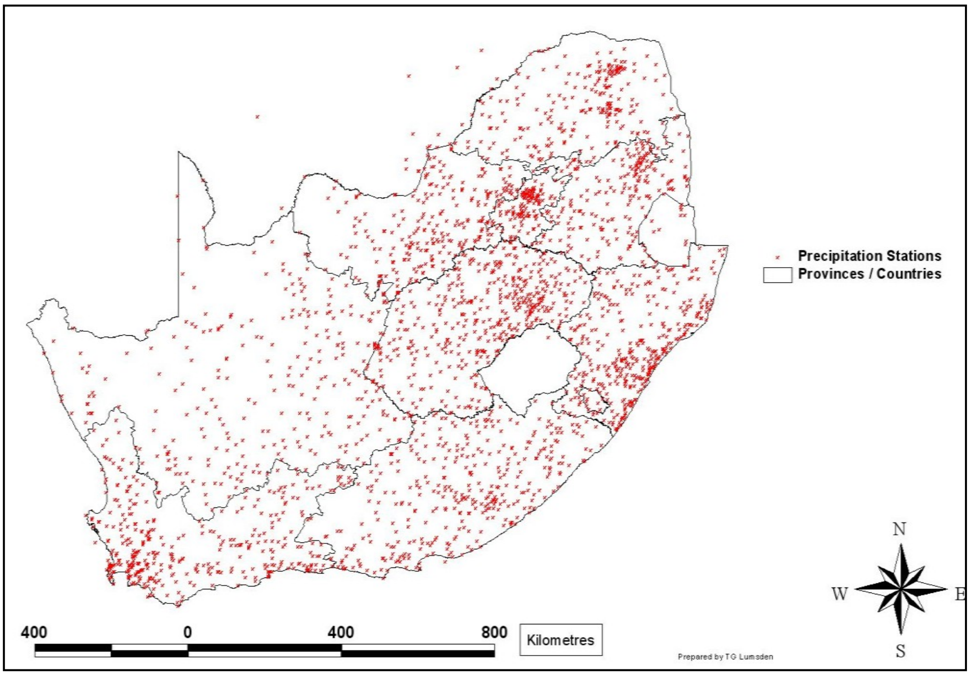

Figure 6.3 Climate stations for which point scale climate change scenarios for daily rainfall were developed (Source: CSAG, 2008)

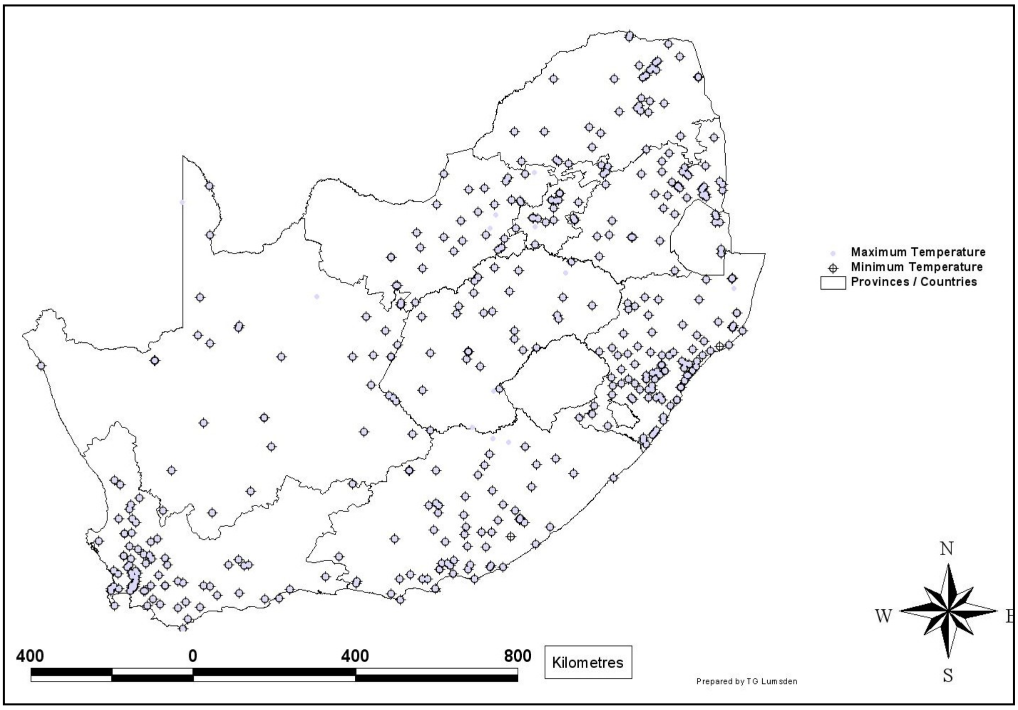

Figure 6.4 Climate stations for which point scale climate change scenarios for daily temperature were developed (Source: CSAG, 2008)

6.7.3 Methods to represent point scale scenarios of rainfall at the scale of Quinary Catchments

The representation of the point scale scenarios of rainfall at the scale of Quinary Catchments was achieved using the same "driver" station approach adopted for baseline historical conditions (cf. **Section 6.2.1**). The number of driver stations previously selected for baseline conditions and for which data on future rainfall scenarios were also available, was determined to be 1 023 (from the set of 2 642 possible stations). It must be noted that these driver stations were assumed to represent future climatic conditions in their associated Quinary Catchments, which numbered 4 863. For the remaining 975 Quinary Catchments (out of the total of 5 838 covering southern Africa), alternative driver stations for which future rainfall scenarios were available, needed to be selected. The criteria used to re-select these driver stations were:

- Distance from the catchment's centroid,
- Mean annual precipitation compared with that of observed data,
- Altitude difference between station and catchment,
- Length of the observed record, and
- Reliability of the observed record (Lumsden *et al*., 2009).

Of the above 975 Quinaries, 687 were assigned to stations that already acted as driver stations for other catchments. The number of driver stations concerned numbered 134. The remaining 288 Quinaries were assigned to stations that had not previously been used as driver stations. This resulted in 38 new driver stations being selected. The total number of all rainfall driver stations used in assessing future rainfall impacts therefore numbered 1 061 (Lumsden *et al*., 2009).

As was the case for the baseline historical climate (cf. **Section 6.2.1**), and alluded to in **Section 6.2.2**, the daily rainfall values for the above 1 061 driver stations were adjusted to better represent the rainfall of each Quinary Catchment, resulting in the development of a unique representative rainfall record for each Quinary. This was done on the assumption that the monthly adjustment factors calculated for the baseline historical climate (cf. **Section 6.2.1**) would also be applicable under the GCM derived climates considered (present, intermediate future and distant future). This assumption was made in the absence of *fine resolution* (e.g. one arc minute) national grids of median monthly rainfall for these new climate periods which would ideally have been required if adjustment factors specific to the periods were to have been calculated. In the calculation of the adjustment factors for the baseline historical climate, limits were placed on the magnitude of the adjustment factors to prevent unrealistic adjustments being made to the driver station data. These limits ensured that adjustment factors fell between 0.5 and 2.0. These limits were relaxed relative to those set in previous studies (e.g. Schulze *et al*., 2005b; Schulze *et al*., 2007) where the factors were constrained to be between 0.7 and 1.3. The relaxed adjustments were deemed necessary because of the finer scale of modelling performed in this study (Quinary Catchments) relative to previous studies (Quaternary Catchments). Quaternary Catchment driver stations are now assumed to drive their component Quinary Catchments, which are often distinctly different from one another in their topographic characteristics (Lumsden *et al*., 2009).

6.7.4 Methods to represent point scale scenarios of temperature at the scale of Quinary Catchments

An examination of the climate stations for which scenarios of temperature change were obtained from CSAG revealed that there were 425 stations common to having both maximum and minimum temperature data sets. Of these 425 stations, 21 had immediately adjacent ‘twin’ stations with identical geographical coordinates (i.e. the same station, but reporting to two different data agencies). Since only one station at a particular location could be considered for application in hydrological modelling, the quality of the historical (observed) records of the 42 (21 x 2) implicated stations were analysed to identify the 'better' station at each location. This therefore resulted in 404 unique stations being identified for representation of maximum and minimum temperatures in the 5 838 Quinary Catchments across South Africa, Lesotho and Swaziland (Lumsden *et al*., 2009).

The methods adopted to represent maximum and minimum temperatures at Quinary Catchment scale involved selecting the two most representative stations for each Quinary Catchment, and obtaining a daily weighted average of their data. Adjustments were simultaneously applied to each of the two stations' data to account for differences between the stations' altitudes and that of the respective Quinary. This was done using the adiabatic temperature lapse rates (i.e. the rate of change of temperature with altitude) which had been determined for each month of the year, and separately for maximum and minimum temperatures, by Schulze and Maharaj (2004) for 12 defined lapse rate regions in southern Africa (Schulze, 1997). Only temperature stations falling within the specific lapse rate region relevant to a particular Quinary Catchment were considered for representation of temperature in that catchment. In certain lapse rate regions, some stations were excluded from consideration based on altitude related criteria (Lumsden *et al*., 2009).

The algorithm to select the two most representative stations for a Quinary Catchment represented a modification of the algorithm developed in Schulze and Maharaj (2004) for selecting target stations for infilling of missing data at representative control stations (control stations were used in the generation of the 1 arc minute resolution daily maximum and minimum temperature grid for South Africa, Lesotho and Swaziland). The modified algorithm involved performing a preliminary suitability ranking of all stations considered in order to determine the five most suitable stations. This suitability ranking was sensitive to the distance of a station from the centroid of a catchment, together with the difference in altitude of the station relative to the catchment's mean altitude. The suitability ranking was determined by the following series of equations (Lumsden *et al*., 2009):

$$DF = (1 - DIST/350)*0.9 + 0.1$$

where DF = distance factor, and

$DIST$ = distance between station and Quinary Catchment centroid (minutes of a degree), constrained to a maximum value of 350 minutes

and $$AF = (1 - DALT/1500)*0.9 + 0.1$$

where AF = altitude factor, and

$DALT$ = altitude difference between station and Quinary Catchment mean altitude (m), constrained to a maximum value of 1500 m

with $$RF = (DF*10) + (AF*1)$$

where RF = ranking factor.

DF was formulated in such a way that it would range between 0.1 (worst case where the station is 350 degree minutes or more away) to 1 (best case where the station coincides with the catchment's centroid). *AF* was formulated in such a way that it would range between 0.1 (worst case where the station has an altitude difference of 1500 m or more relative to the catchment's mean altitude) to 1 (best case where the station has the same altitude as that calculated for the catchment). The five stations with the highest *RF* values would therefore be selected according to the preliminary suitability ranking. The 350 minute and 1500 m thresholds were introduced to *DF* and *AF*, respectively, to ensure that stations met *minimum* criteria for *both* distance and altitude. Otherwise a station could rank well based on only one variable, while in reality it may have been unsuitable in terms of the other variable (e.g. small altitude difference combined with a large distance from the centroid). In the calculation of *RF*, *DF* was assigned a higher weighting than *AF* owing to its relative importance (Lumsden *et al*., 2009).

A final suitability ranking of the five stations identified above was then performed to determine the *'best'* two stations in terms of *both* distance and altitude. To achieve this, the range in distances (relative to the catchment centroid) and altitude differences (relative to the mean altitude of the catchment) among the five stations was introduced into the calculation of *DF* and *AF*, as follows:

$$DF = (1 - (DIST - MIND)/(MAXD - MIND))*0.9 + 0.1$$

where $MIND$ = distance (m) between closest station and Quinary Catchment centroid, and

$MAXD$ = distance between most distant station and Quinary Catchment centroid (m)

and $$AF = (1 - (DALT - MINA)/(MAXA - MINA))*0.9 + 0.1$$

where $MINA$ = difference in altitude between the station most similar in altitude to the Quinary Catchment mean altitude and the Quinary Catchment mean altitude (m), and

$MAXA$ = difference in altitude between the station least similar in altitude to the Quinary Catchment mean altitude and the Quinary Catchment mean altitude (m).

DF becomes 1.0 (best) for the station closest to the Quinary's centroid. All other stations are ranked relative to this closest station as they are compared to the range in distance (*MAXD* - *MIND*). Similarly, *AF* approaches 1.0 (best) for stations at altitudes similar to that of the Quinary's mean altitude. Again, all other stations are ranked relative to this station (*MAXA* - *MINA*). This 'relative' ranking technique is superior to others because it compares each station to the 'best'. Hence, the distance and altitude thresholds used will vary from Quinary to Quinary and are not fixed, as in the preliminary station suitability ranking (Lumsden *et al.*, 2009).

In the calculation of *RF*, more weighting was given to *AF* than previously, as it was assumed that the preliminary ranking would exclude stations that were unsuitable from a distance perspective. Hence:

$RF = (DF*10) + (AF*3)$.

Having identified the two 'best' temperature stations to represent a Quinary Catchment, the data from these stations were then averaged in order to obtain the final temperature record for the catchment. This averaging was weighted according to the *RF* factor calculated for each station. As mentioned previously, adiabatic temperature lapse rates were also simultaneously applied to each station's data (Lumsden *et al*., 2009).

Checks identical to the ones done on historical data by Schulze and Maharaj (2004) were performed on the daily maximum (T_{mxd}) and minimum (T_{mnd}) temperature values from the GCMs to ensure that they would comply with certain logical requirements and those of the *ACRU* hydrological model. These checks were performed both before and after any adjustments (i.e. lapse rate adjustments and weighted averaging) were applied to the downscaled GCM data and they included the following:

- $T_{mxd} \leq T_{mnd}$
- T_{mxd} - T_{mnd} < 1.5°C.

Although not a requirement of *ACRU*, an additional check was performed to highlight potentially unrealistic data in a southern African context, *viz*.

- T_{mxd} < 0°C.

Where instances of the former two checks were found in the raw downscaled GCM values, the relevant days' temperature data were altered to comply with the requirements of *ACRU*, as detailed in Schulze and Maharaj (2004). The data were again checked after lapse rate adjustments and weighted averaging had been completed and, if necessary, altered again to ensure compliance with the *ACRU* model input requirements. Where instances of the last mentioned check were found, no alteration to the maximum temperature values were made (before or after lapse rate adjustments and weighted averaging). These instances were, however, flagged for future reference. Detailed examples of the data checks *before* and *after* lapse rate adjustments and weighted averaging are given in Lumsden *et al*. (2009).

6.8 Deriving Flow Indicators

The need to assess impacts of climatic change on aquatic ecosystems was reviewed in **Chapter 3**. Recent ecological research has developed methods of identifying, monitoring and managing the ecological integrity of aquatic environments through the use of ecological indicators (Fanelli, 2006; cf. **Chapter 4**). Ecological indicators are suitable for use in impact studies where one needs to determine how certain ecological components respond to a change in environmental conditions over an extended period of time. The remainder of this section summarises the methods and techniques used to assess the projected impacts of climate change on selected ecologically related flow indictors over southern Africa.

6.8.1 Final indicator selection

A major problem with using ecological indicators for is that there is no universal set of indicators that is equally applicable in all cases (Manoliadis, 2002). **Sections 4.1 – 4.3** of **Chapter 4** contain detailed descriptions of ecological flow indicators, indicator selection and of the so-called "indicators of hydrological alteration", or IHA. The final set of flow indicators selected for use in this project is a subset of the 67 indices used to more fully describe hydrological regimes. This subset, which focuses solely on the magnitude and duration of flows, was selected for its ease of measurability and lack of data regarding more complex indicators. **Table 6.1** summarises the flow indicators used in this research project.

Table 6.1 Hydrological indicators used in this study, their derivation and source of reference, with the Olden and Poff (2003) symbol notation for indicators (after Taylor, 2006)

Symbol	Unit	Definition	Reference
Magnitude of flow events			
Average flow conditions			
M_A1	$m^3.s^{-1}$	Mean monthly flow for October	
M_A2	$m^3.s^{-1}$	Mean monthly flow for November	
M_A3	$m^3.s^{-1}$	Mean monthly flow for December	
M_A4	$m^3.s^{-1}$	Mean monthly flow for January	
M_A5	$m^3.s^{-1}$	Mean monthly flow for February	
M_A6	$m^3.s^{-1}$	Mean monthly flow for March	
M_A7	$m^3.s^{-1}$	Mean monthly flow for April	
M_A8	$m^3.s^{-1}$	Mean monthly flow for May	
M_A9	$m^3.s^{-1}$	Mean monthly flow for June	
M_A10	$m^3.s^{-1}$	Mean monthly flow for July	
M_A11	$m^3.s^{-1}$	Mean monthly flow for August	
M_A12	$m^3.s^{-1}$	Mean monthly flow for September	

M_A13	-	Mean annual flow	Richter *et al.* (1996; 1997)
M_A14	-	Coefficient of Dispersion of M_A1,	
M_A15	-	Coefficient of Dispersion of M_A2	
M_A16	-	Coefficient of Dispersion of M_A3	
M_A17	-	Coefficient of Dispersion of M_A4	
M_A18	-	Coefficient of Dispersion of M_A5	
M_A19	-	Coefficient of Dispersion of M_A6	
M_A20	-	Coefficient of Dispersion of M_A7	
M_A21	-	Coefficient of Dispersion of M_A8	
M_A22	-	Coefficient of Dispersion of M_A9	
M_A23	-	Coefficient of Dispersion of M_A10	
M_A24	-	Coefficient of Dispersion of M_A11	
M_A25	-	Coefficient of Dispersion of M_A12	
M_A26	-	Coefficient of Dispersion of M_A13	
Low flow conditions			
M_L1	-	Ratio of baseflow volume to total volume (Alt-BFI)	Hughes *et al.* (2003)
Duration of flow events			
Low flow conditions			
D_L1	$m^3.s^{-1}$	Annual minimum 1 day average flow	Richter *et al.* (1996; 1997)
D_L2	$m^3.s^{-1}$	Annual minimum 3 day average flow	
D_L3	$m^3.s^{-1}$	Annual minimum 7 day average flow	
D_L4	$m^3.s^{-1}$	Annual minimum 30 day average flow	
D_L5	$m^3.s^{-1}$	Annual minimum 90 day average flow	
D_L6	-	Coefficient of Dispersion in D_L1	
D_L7	-	Coefficient of Dispersion in D_L2	
D_L8	-	Coefficient of Dispersion in D_L3	
D_L9	-	Coefficient of Dispersion in D_L4	
D_L10	-	Coefficient of Dispersion in D_L5	
High flow conditions			
D_H1	$m^3.s^{-1}$	Annual maximum 1 day average flow	Richter *et al.* (1996; 1997)
D_H2	$m^3.s^{-1}$	Annual maximum 3 day average flow	
D_H3	$m^3.s^{-1}$	Annual maximum 7 day average flow	
D_H4	$m^3.s^{-1}$	Annual maximum 30 day average flow	
D_H5	$m^3.s^{-1}$	Annual maximum 90 day average flow	
D_H6	-	Coefficient of Dispersion in D_H1	
D_H7	-	Coefficient of Dispersion in D_H2	
D_H8	-	Coefficient of Dispersion in D_H3	
D_H9	-	Coefficient of Dispersion in D_H4	
D_H10	-	Coefficient of Dispersion in D_H5	

6.8.2 Magnitude of flows

In order to spatially analyse how the indicators which measure the magnitude of flow may change under conditions of projected climate change, a number of methods and datasets were used. First the *ACRU* model was used to simulate the eco-hydrological responses for the 5 838 hydrologically interlinked and cascading Quinary Catchments, which constitute the defined southern African study region. The *ACRU* model was run with 20 years of daily climate records for a:

- Baseline (i.e. historically observed) Climate (1971 – 1990),
- Present Climate from the ECHAM5 GCM (1971 – 1990), an
- Intermediate Future Climate (2046 – 2065) from ECHAM5, and a more
- Distant Future Climate (2081 – 2100) from ECHAM5.

The above climate scenarios and the datasets described in **Sections 6.1 - 6.5** were used as an input into the *ACRU* model. The 20 year baseline scenario (1971-1990), using historically recorded climate variables, was used in order to gain an insight into how well ECHAM5 was simulating the "present" climate scenario. After running the model using this climatic input, both individual subcatchment runoff and accumulated streamflows were extracted from the model's output in order to describe the spatial patterns across southern Africa of those indicators which are expressions of the magnitude of flow. Simulated runoff from individual subcatchments (*ACRU* variable name = SIMSQ) is an output from the *ACRU* model and is defined as the sum of stormflows and baseflows from only the subcatchment in question, excluding any contributions from upstream catchments (Schulze, 1995). The *ACRU* model outputs this variable in millimetre (mm) equivalent and it is subsequently converted to cubic metres (m^3) using the subcatchment area. Accumulated streamflow (*ACRU* variable name = CELRUN) is also an output from the *ACRU* model and is defined as the total summed streamflow from a (sub)catchment, but also including any contributions from upstream catchments (Schulze, 1995). The *ACRU* model outputs this variable in millimetre (mm) equivalents and, similarly to individual subcatchment runoff, it is converted to cubic metres (m^3) using the (sub) catchment area.

The monthly and annual means were extracted for both individual catchment runoff and accumulated streamflows for the 5 838 Quinary Catchments (Indices M_A1 **-** M_A13 in **Table**

6.1). The runoff and streamflow output from *ACRU* was then subjected to a statistical analysis to determine the 25th, 75th and median values for all Quinary Catchments. Using the result of this analysis the Coefficient of Dispersion (CoD), an indicator of inter-annual flow variability, was calculated using the equation (6.1) given below:

$$\text{CoD} = \frac{\text{75th Percentile – 25th Percentile Value}}{\text{Median of Values Across all Years of Record}} \qquad [6.8.1]$$

The CoD uses the median value across all years of record within a climate scenario, rather than the mean, as the mean value is often skewed by extreme events in the "highly variable" river systems which are found in South Africa (Taylor, 2006). Streamflow is naturally variable and information is also needed about the variation within data samples, and thus the CoD was calculated to determine how the variability regarding the magnitude of flow is likely to change under projected conditions of climate change. The CoD of subcatchment runoff and accumulated streamflow was determined for indices M_A1 **-** M_A13 (**Table 6.1**). The results for this analysis are given in **Chapter 7**.

6.8.3 Duration of flow events

As was the case in **Section 6.8.2**, the *ACRU* model was used to simulate the eco-hydrological responses for the 5 838 Quinary Catchments which constitute the southern Africa, using the same climate scenarios and time periods. However, unlike magnitudes of flow events, only the accumulated streamflow output from *ACRU* was then used to calculate the annual minimum (D_L1 **-** D_L5 in **Table 6.1**) and maximum (D_H1 **-** D_H5 in **Table 6.1**) 1, 3, 7, 30 and 90 day average accumulated streamflow values. The duration of flow events is the period of time associated with a specific water condition (Richter *et al*., 1996). The durations used in the research are based on the recommended durations from the developers of the IHA and attempt to represent natural cycles. They consist of the 1 day, 3 day, 7 day (weekly), 30 day (monthly) and 90 day (seasonal) extremes (The Nature Conservancy, 2005). The 1 day events are the maximum and minimum daily streamflow values that occur in any given year and the multi-day events are the highest and lowest multi-day means of flow occurring in any given year (Taylor, 2006).

Similarly to the magnitude of flow events, the intedr-annual CoD was also calculated for the annual minimum and maximum 1, 3, 7, 30 and 90 day average accumulated streamflow values flow values using the method outlined in **Section 6.8.2**. The results for this analysis are presented in **Chapter 7**.

6.9 Simulating Water Temperature

Water temperature in streams and rivers has previously been (**Section 4.5.1**) identified as an important attribute of water quality and it controls the overall health of freshwater ecosystems (Morrill *et al*., 2005). Unlike the flow indicator analyses which are analysed at the southern Africa scale (**Section 6.8**), the water temperature analyses were computationally very intensive and thus the water temperature results were spatially analysed in this dissertation at the scale of one Water Management Area in South Africa only, *viz*. the Thukela Catchment. In addition to the spatial analysis, a temporal investigation, by means of time series analyses, was performed on the important water temperature related parameters and the methods and techniques used in these analyses are outlined **Sections 6.9.2 - 6.9.7**. Before that, however, detailed background information regarding the Thukela Catchment is provided in the next section.

6.9.1 The study area: The Thukela Catchment

The Thukela Catchment in the province of KwaZulu-Natal in South Africa was selected as the study area for the simulation of water temperature related parameters under conditions of climate change. The Thukela catchment has been selected as a case study area because of its diversity - in altitude, rainfall, soils and ecological regions, as well as in its population geography and levels of education and employment. This diversity presents a challenge to studies of impacts of projected climate change (Schulze *et al*., 2009a), including its potential impacts on water temperatures.

The Thukela Catchment, which extends latitudinally from 27°25'S to 29°24'S and longitudinally from 28°58’E to 31°26’E (**Figure 6.5**), covers an area of approximately 29 061 km^2 (Dlamini, 2005). The Thukela, one of the designated Water Management Areas of South Africa, is the principal river in KwaZulu-Natal and flows for 502 km from its source at over 3 000 m altitude at Mont-aux-Sources in the Drakensberg mountain range in the west (**Figure 6.6**) to its mouth into the Indian Ocean in the east (Wilson, 2001).

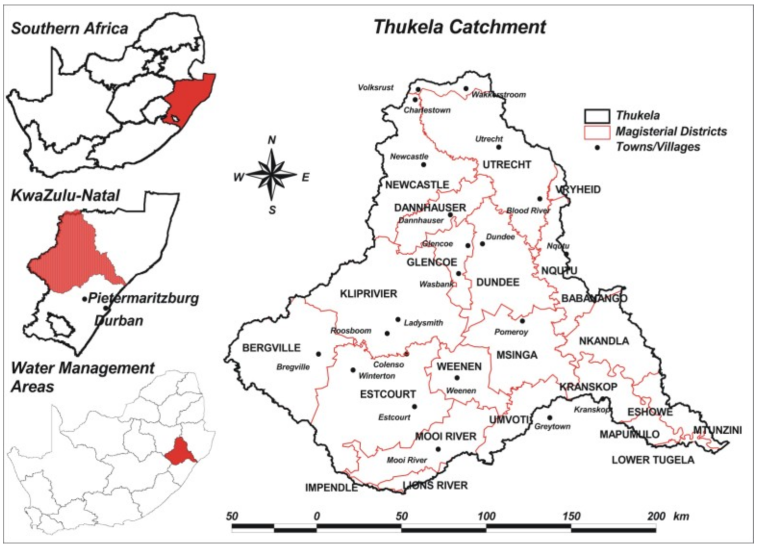

Figure 6.5 Location of the Thukela Catchment in relation to KwaZulu-Natal province, the designated Water Management Areas in South Africa, magisterial districts and major towns within the catchment (Dlamini, 2005)

The mainstem Thukela's major tributaries are the Little Thukela, Mooi and Bushman's Rivers which join from the southwest, and the Klip, Sundays and Buffalo Rivers flowing in from the north. Ecologically the Thukela Catchment has been sub-delineated into seven regions, *viz*. the Mountain Region, the Highlands Region, the Midlands Mistbelt Region, the Interior Basin Region, the Valley Region, the Coast Region, the Coast Hinterland Region and the Coast Lowland Region.

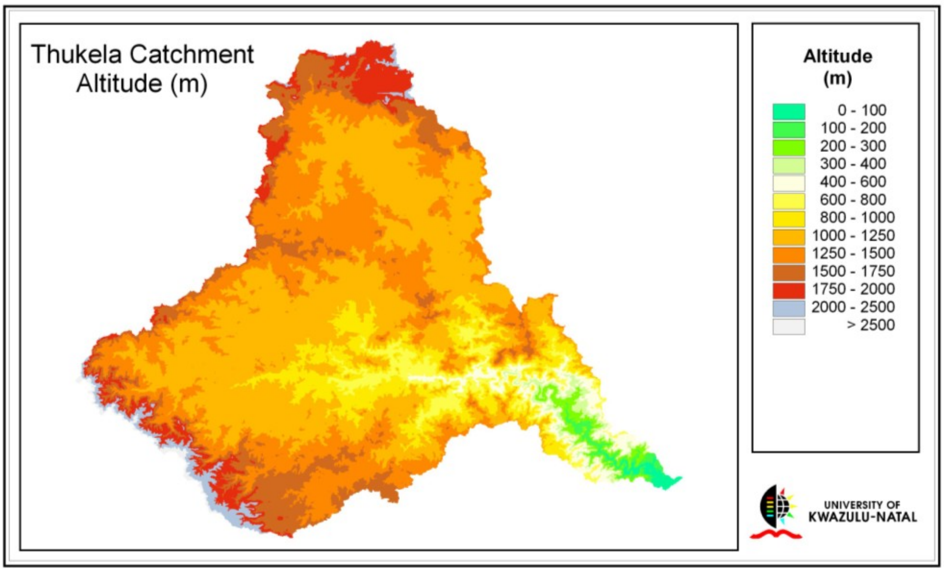

Figure 6.6 Altitude of the Thukela Catchment (after Schulze *et al*., 2005a)

(a) Climate

In regard to climatic variables the Thukela Catchment displays significant spatial heterogeneity. Mean annual temperature (MAT) varies from 13°C in the west (Drakensberg) to 21°C in the east adjacent to the coast. In the Drakensberg mountains the lowest monthly means of daily minimum temperatures are recorded, with sub-zero monthly means of daily minima not uncommon in winter months (Schulze *et al*., 2009a). Mid-summer (January) monthly means of daily maximum temperatures generally range from about 24°C to 28°C (**Table 6.2)**, with the highest values occurring in the Valley Region, while in the high Drakensberg mountains they seldom exceed 20°C (Schulze, 1997). The Drakensberg mountains also record the lowest monthly means of daily minimum temperatures, with sub-zero means of minima not uncommon in July (Schulze, 1997). Unlike the cold Mountain Region, the coastal areas are fairly mild during mid-winter with means of daily minimum temperatures averaging about 10°C in July (Schulze *et al*., 2009a).

Table 6.2 Monthly means of daily maximum and minimum air temperatures (°C) for selected subcatchments representing major ecological regions of the Thukela Catchment (Source: Schulze, 1997)

Region	Variable	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Mountain Region	Min	11.8	11.6	10.2	7.1	3.8	0.8	0.9	2.8	5.6	7.6	9.3	10.8
	Max	24.3	23.5	22.5	20.3	17.7	15.6	15.8	17.6	20.7	21.4	22.1	23.9
Highlands	Min	12.6	12.5	10.9	7.8	4.1	0.7	0.9	3.2	6.2	8.2	9.9	11.7
	Max	24.7	23.9	23.3	21.1	18.6	16.6	16.8	18.6	21.2	21.5	22.2	24.1
Midland Mistbelt	Min	15.1	15.0	14.0	11.2	7.9	4.8	4.9	6.9	9.3	11.0	12.6	14.2
	Max	26.0	26.0	25.2	23.4	21.3	19.1	19.4	20.9	22.6	23.4	24.0	25.9
Interior Basins	Min	14.0	13.7	12.4	9.4	5.7	2.5	2.5	4.8	8.0	10.0	11.6	13.2
	Max	26.1	25.7	25.1	23.1	21.1	18.7	19.0	20.9	23.1	23.7	24.4	25.9
Valley	Min	15.5	15.4	14.1	10.7	6.6	3.2	3.2	5.6	8.9	11.2	13.0	14.6
	Max	28.3	28.0	27.1	24.9	22.7	20.3	20.7	22.5	24.5	25.4	26.5	28.1
Coast Hinterland	Min	18.3	18.4	17.5	15.1	12.0	9.0	8.9	10.6	12.9	14.3	15.8	17.4
	Max	27.3	27.4	26.8	25.3	23.8	21.9	21.9	22.7	23.5	24.2	25.0	26.8
Coast Lowlands	Min	19.7	19.7	18.8	16.2	13.1	10.2	10.0	11.7	14.0	15.6	17.0	18.7
	Max	27.9	27.9	27.4	25.9	24.5	22.9	22.6	23.0	23.9	24.6	25.4	27.2

Mean annual precipitation (MAP) in the Thukela is strongly seasonal, with approximately 80% falling in the summer months October to March. Rainfall in the Thukela catchment displays considerable spatial variation with MAP varying from over 1500 mm in the west, to below 600 mm in the central valleys (**Figure 6.7**), and increasing again to approximately 1000 mm along the coast in the east (Wilson, 2001).

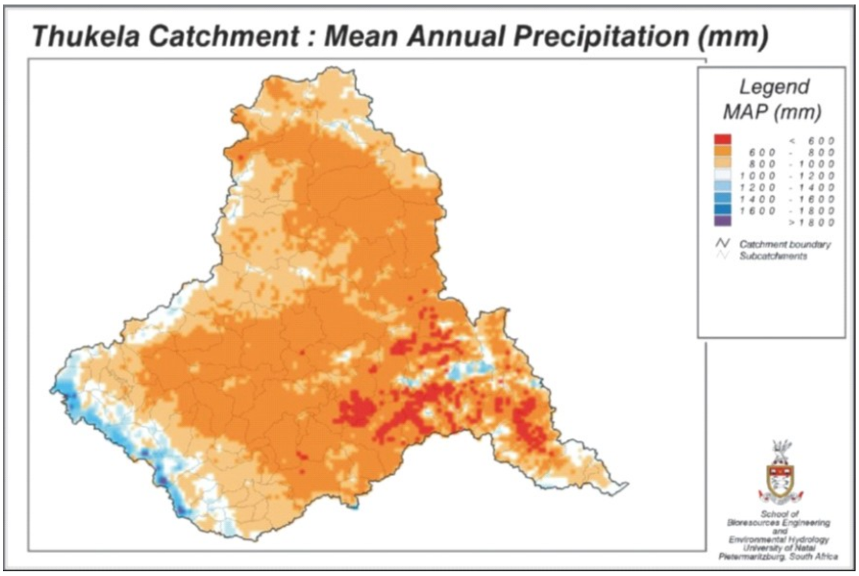

Figure 6.7 Mean annual precipitation (mm) of the Thukela Catchment (after Dent *et al.*, 1989)

(b) Soil and land cover

The Thukela Catchment has been used as a study catchment in a number of research projects undertaken by the School of BEEH (e.g. Dlamini, 2005; Schulze *et al.*, 2005a). In order to meet those projects' objectives, they required detailed soils and land cover information. This project uses the information gathered by those projects. The remainder of section is summarised from Schulze *et al.* (2009a) and summarises the soil and land cover information of the Thukela Catchment.

Soils are a major regulator of hydrological responses in that through/across the soil infiltration, drainage, evapotranspiration and runoff processes occur. In South Africa soils are mapped by so-called "land types", with a marked degree of a uniformity with respect to broad soil patterns, terrain form and climate (Land Type Survey Staff, 1986). Of the nine broad categories of soil land types identified in South Africa, seven are found in the Thukela Catchment, these being predominantly deep and freely drained apedal soils (23.1%) and skeletal, often poorly drained soils mainly of the Glenrosa and/or Mispah soil forms (37.4%). The spatial distributions of selected hydrologically relevant characteristics of the soils found in the Thukela are shown in **Figure 6.8** (Schulze and Horan, 2007). Soil depths vary from < 0.3 m to > 1.0 m, while plant available water, which varies by texture, ranges < 0.04 m/m to over 1.00 m/m and the soils' erodibility factors are from as low as 0.13 to being > 0.70 (Schulze *et al.*, 2009a)

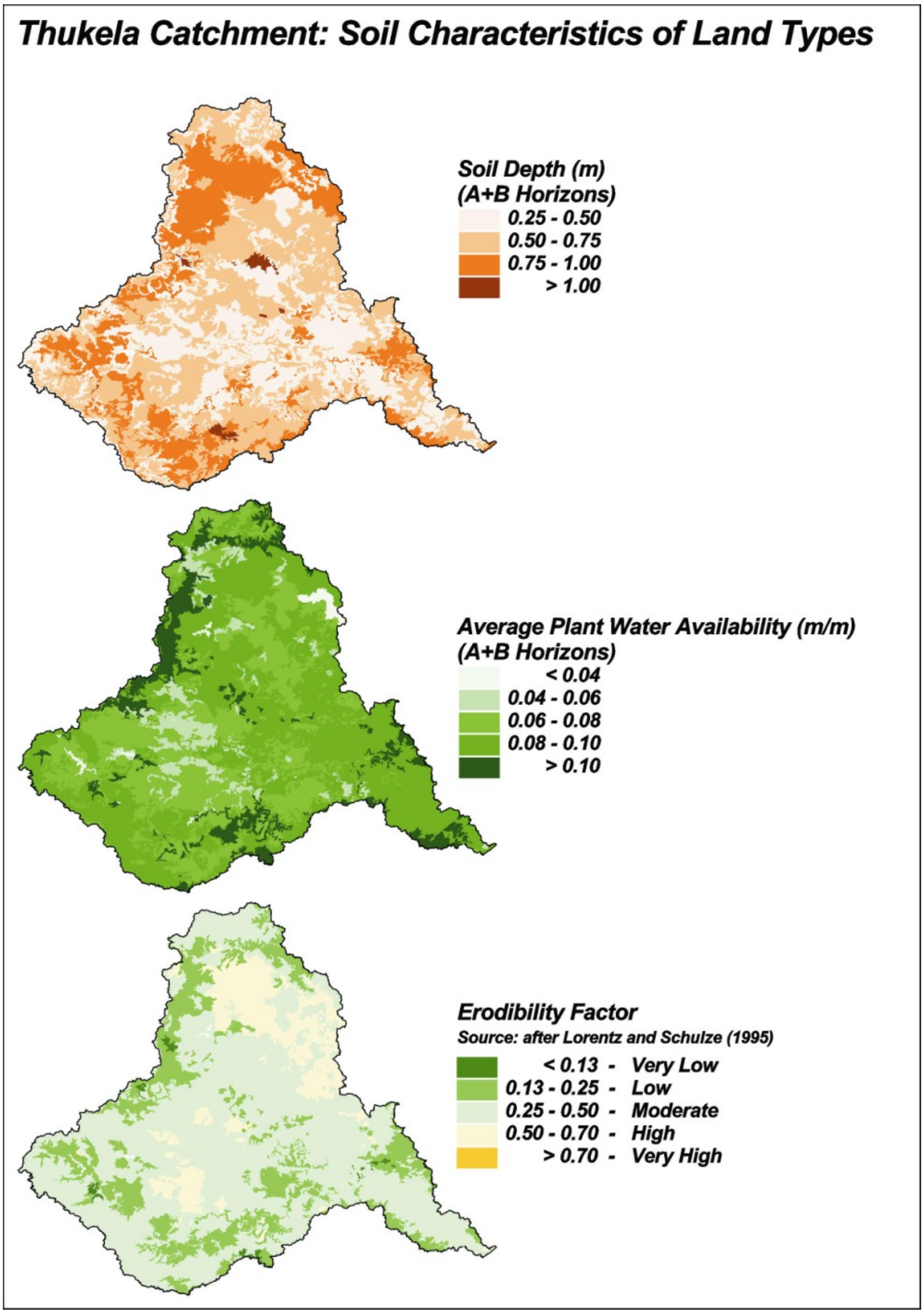

Figure 6.8 Distribution of selected soil characteristics in the Thukela catchment (after Schulze and Horan, 2007)

Land cover affects soil moisture and hence runoff processes, as well as sediment yield production through above-ground biomass, surface litter/mulch and below-ground rooting characteristics. In this study on water temperature (which is dependent, *inter alia*, on runoff), all indices are computed assuming a baseline natural vegetation, and not present land uses. The vegetation classification most commonly used in South African hydrology as an indicator of baseline land cover is that by Acocks (1988), who delineated South Africa, Lesotho and Swaziland into 70 so-called "Veld Types". **Figure 6.9** shows the spatial distribution of the 14

Veld Types found within the Thukela Catchment. The Catchment is dominated by Valley Bushveld, Southern Tall Grassveld, Natal Sourveld and the Highveld Sourveld and Döhne Sourveld. Other important Veld Types are the Ngongoni Veld and the Coastal Forest and Thornveld found in the lower coastal end of the Catchment (Schulze *et al*., 2008).

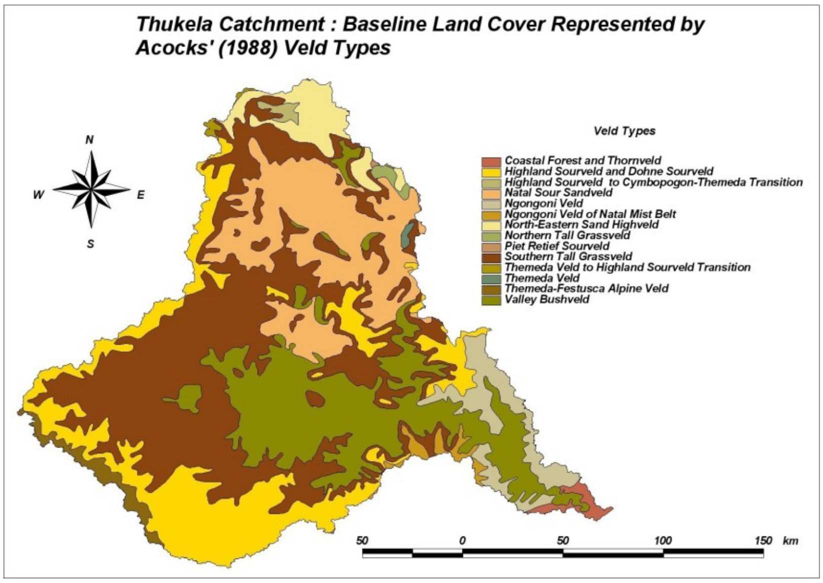

Figure 6.9 Baseline land cover in the Thukela Catchment as represented by Acocks' (1988) Veld Types

(c) Hydrology

Mean annual runoff of the Thukela Catchment ranges from approximately 3 850 to 4 400 million cubic metres, which equates to approximately 17% of the Catchment's mean annual precipitation (Wilson, 2001). For this project, the Thukela Catchment was sub-delineated into 258 Quinary level subcatchments (cf. **Section 5.5**). For the period 1971 - 1990 the mean annual baseline runoff (made up of stormflows and baseflows) per individual subcatchment varies from < 1000 m^3 to > 250 000 m^3 (i.e. < 25 mm equivalent runoff per annum in the drier valley areas to > 250 mm in the high rainfall areas of the west; **Figure 6.10** top). Accumulated streamflows show a far more even flow distribution and the dominance of the mainstem Thukela and its major tributaries is very much in evidence (**Figure 6.10** bottom). The coefficient of variation of annual streamflows ranges from < 40% to around 200% (Schulze *et al*., 2005a), with the variability of accumulated streamflows displaying much more muted patterns than those of individual subcatchments (Schulze *et al*., 2005a).

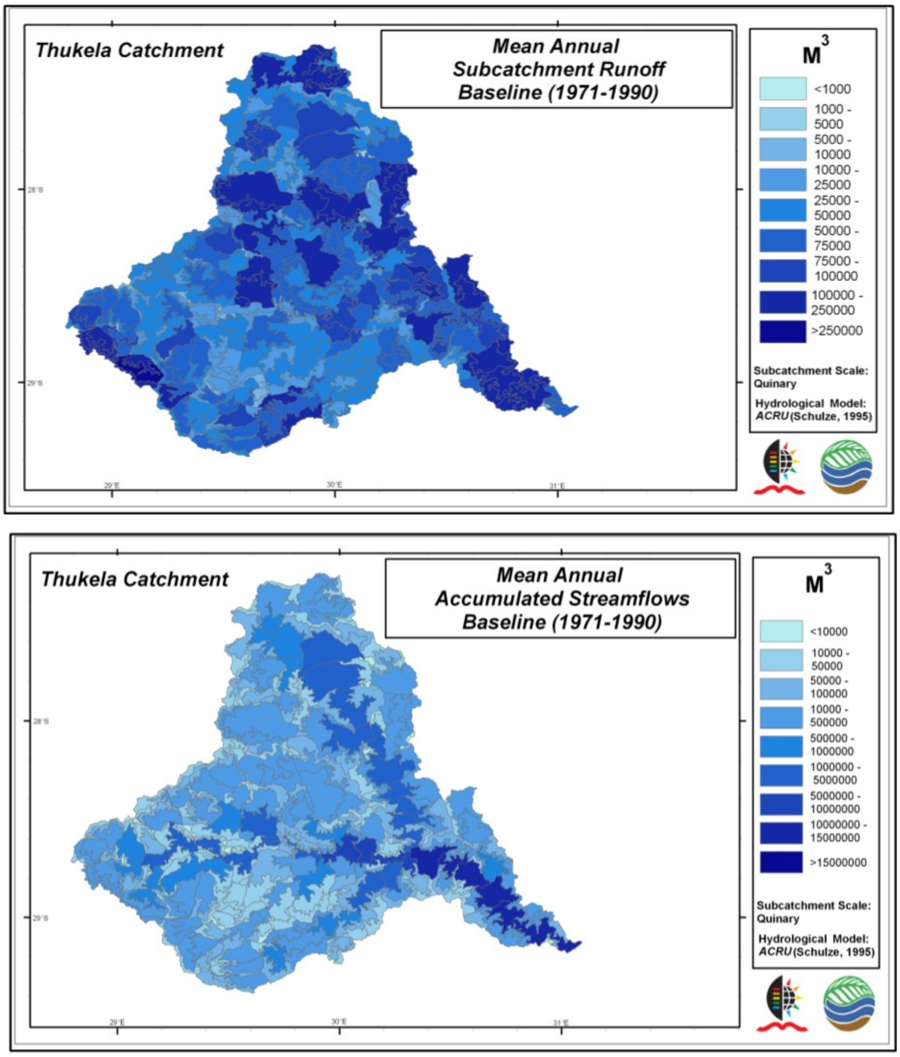

Figure 6.10 Distributions of (top) mean annual runoff for individual sub catchments and (bottom) for mean annual accumulated streamflows

6.9.2 Datasets required

To investigate the possible impacts of climate change on water temperature related parameters, the *ACRU* model was run with the input datasets described in **Sections 6.1 – 6.5** and 20 years of daily climate records for a:

- Baseline (i.e. historically observed) Climate (1971 – 1990),
- Present Climate from the ECHAM5 GCM (1971 – 1990), an
- Intermediate Future Climate (2046 – 2065) from ECHAM5, and a more
- Distant Future Climate (2081 – 2100) from ECHAM5.

After running the model for the above time periods, both daily individual subcatchment runoff and accumulated streamflows for the 258 Quinaries, which constitute the Thukela Catchment, were extracted from the *ACRU* output file. The values of both daily individual subcatchment runoff and accumulated streamflows were subsequently converted from mm equilivalents to m^3 using (sub)catchment area.

6.9.3 Modelling daily maximum water temperature

For this project a stochastic approach was selected in order to model water temperature for each of the 258 Thukela Quinaries because data constraints would have ruled out deterministic approaches (cf. **Section 4.5.5**). For each of the 258 Quinaries daily minimum and maximum daily air temperatures were extracted for the baseline, present, intermediate future and the more distant future climate scenarios and daily means of temperature were subsequently calculated. A linear regression model developed by Rivers-Moore *et al*. (2005) from South African data (**Section 4.5.7**) was then applied to daily means of temperatures for the four climate scenarios in order to calculate daily maximum water temperature using **Equation 4.5.3**.

6.9.4 Cascading water temperature down the catchment

As water cascades down the catchment from its headwaters to the ocean, or from the upper through the middle to the lower Quinary, it warms and thus variation in water temperature occurs longitudinally down a river system, with headwaters typically at lower temperatures than lowland areas (Dallas, 2008). Water temperature is dynamic since water is always mixing within the river channel as well with water from incoming tributaries, and this complicates water temperature modelling. In order to mimic this mixing, maximum water temperature is therefore calculated for each individual Quinary Catchment as well as at the exit point of two or more Quinaries. Furthermore, at an exit point or a confluence the tributary with the greater volume will have more influence on the combined downstream water temperature than the tributary with the smaller volume of water. This weighted cascading therefore continues longitudinally down a river system. Consequently the Quinary flowing into the sea, or out of South Africa into a country downstream of South Africa, or into a river which forms an international border with South Africa, is influenced by streamflows and water temperatures of all the upstream catchments. It is for this reason why a Water Temperature Index is calculated

6.9.5 The Water Temperature Index

The Water Temperature Index (WTI) of a (sub) catchment is the product of daily maximum water temperature (°C) and the simulated flow (m^3) for that day. The WTI was developed in combination with the cascading of water temperature in order to create a weighting system at the exit of of two Quinaries in order to give the larger flow more influence on the combined WTI (**Figure 6.11**). For simplicity it is assumed that perfect mixing occurs at these exits and/ or confluences.

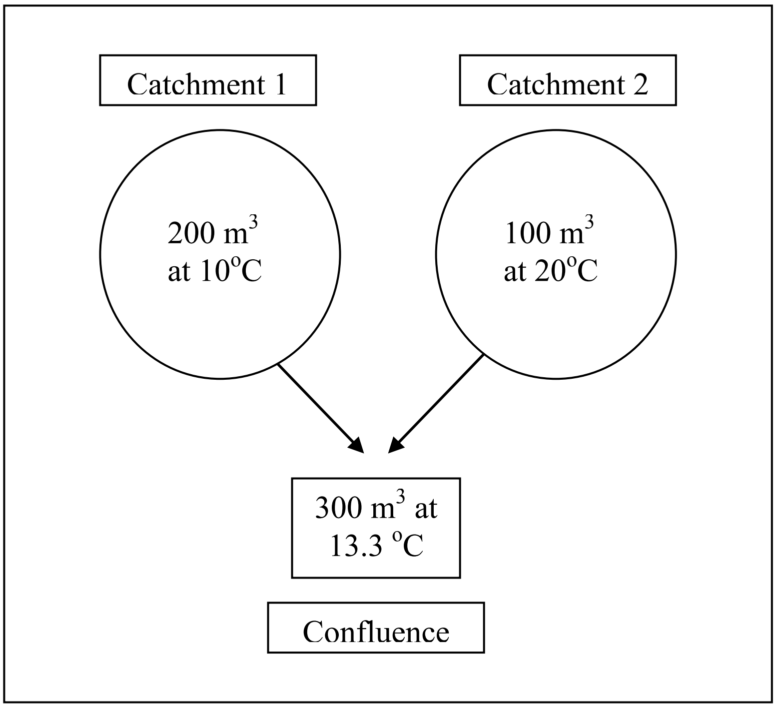

Figure 6.11 An example of cascading streamflow and water temperature at the confluence of two rivers

6.9.6 Calculating maximum mixed daily water temperature

The maximum mixed water temperature is calculated by using a particular Quinary's WTI and subsequently dividing this value by the accumulated streamflows for the same Quinary. Maximum mixed water temperature is an important ecological attribute and can be applied in climate change studies to determine the differences in maximum mixed water temperature between different GCM time periods as a ratio or as a °C difference in water temperature.

The results of the spatial modelling for the water temperature related parameters are given and interpreted in **Chapter 8**.

6.9.7 Time series analyses

Time series analyses were performed on water temperature related parameters (as described in **Sections 6.9.3 - 6.9.6**) at 15 selected Quinary Catchments located in the Thukela Catchment. This time series uses the same datasets and climate scenarios outlined in **Sections 6.9.2 - 6.9.6**.

The time series analysis uses two methods to describe how each water temperature related parameter may vary over time, *viz*.

- How does the parameter vary for a single Quinary catchment by comparing the three ECHAM5 climate scenarios (i.e. a temporal analysis), with the hypothesis being that in future climates temperatures are increasing and streamflows are changing; and
- How does the parameter vary between the three Quinaries making up a Quaternary Catchment for a single climate scenario (i.e. a spatial analysis), with the hypothesis being that Quinaries within a Quaternary are altitude dependent and should therefore influence temperature, rainfall, runoff and thus water temperature patterns.

More detailed background and the results of the time series analysis for the Thukela Catchment are provided in **Chapter 9**.

*****

In this chapter the relevant databases, models and techniques used in this project to assess the projected impacts of climate change on ecological flow and water temperature related parameters were introduced and discussed. This included outlining the Quinary Catchments Database and its relevant rainfall, temperature, soil and land cover datasets which were used as input into the *ACRU* agrohydrological modelling system. The ECHAM5 climate model and climate change scenarios used in this project were subsequently examined. Finally, the methods and techniques used to model the flow and water temperature parameters were described. The following chapter contains the results of the flow indicator study which was performed and which uses the databases, models and techniques described in this chapter.

7. RESULTS 1: ECOLOGICAL FLOW INDICATORS OVER SOUTHERN AFRICA UNDER REGIMES OF PROJECTED CLIMATE CHANGE USING THE ECHAM5/MPI-OM GENERAL CIRCULATION MODEL

7.1 Setting the Scene

The *ACRU* model was used to simulate the eco-hydrological responses for the 5 838 hydrologically interlinked and cascading Quinary Catchments which constitute the southern Africa study region. The *ACRU* model was run with 20 years of daily climate records for:

- Baseline (i.e. historically observed) Climate (1971 – 1990),
- Present Climate from the ECHAM5 GCM (1971 – 1990), an
- Intermediate Future Climate (2046 – 2065) from ECHAM5, and a more
- Distant Future Climate (2081 – 2100) from ECHAM5.

For all eco-hydrological analyses presented in the remainder of this chapter the computer programmes were written by Mr R.P. Kunz of the School of BEEH at the University of KwaZulu-Natal. His contribution is gratefully acknowledged. Furthermore, on all maps which follow in this chapter the term "Intermediate" refers to the intermediate future climate scenario (2046 – 2065) while "Future" refers to the more distant future climate scenario (2081 – 2100).

7.2 Magnitude of Flow Events

Both individual subcatchment runoff and accumulated streamflows were used to describe the magnitudes of flows. Maps for southern Africa were generated from the output of the *ACRU* model using the climate scenarios listed above. To keep the array of maps to a manageable number, only the annual values and those of the four cardinal months representative of the four seasons were spatially analysed in this chapter.

As already alluded to the analyses were performed at two temporal scales, *viz*. for annual flows and for those of selected cardinal months (January = summer, April = autumn, July = winter and October = spring). The annual results can be utilised to reveal overall trends for each scenario while the monthly time scale provides a more focussed representation in order to determine intra-annual (seasonal) differences. The spatial analyses for the magnitudes of flow events comprises a ratio comparison, at a mean annual and at a mean monthly level, between the three ECHAM5 climate scenarios, specifically ratios of the Intermediate Future to Present and those of Distant Future to Present climate scenarios, in order to determine how a particular indicator is projected to be changing from one scenario to the next in the future. A map for each selected indicator was also generated for historical baseline conditions as a point of departure. A spatial analysis of the inter-annual variability of the magnitude indicators was performed for both individual catchment runoff and accumulated streamflows using the Coefficient of Dispersion (CoD, described in **Section 6.8**). This was done to gain information on how the magnitude of flows may vary from year to year and also change under projected future climatic conditions.

7.2.1 Average annual flow projections for subcatchment runoff

Simulated runoff from individual subcatchments is an output from the *ACRU* model and is defined as the sum of stormflows and baseflows from only the subcatchment in question, excluding any contributions from upstream catchments (Schulze, 1995). The *ACRU* model outputs this variable in millimetre (mm) equivalents per day and it is subsequently converted to a flow rate ($m^3.s^{-1}$) using the Quinary Catchment's area. An analysis of individual subcatchment runoff is important because adding accumulated streamflows from upstream can mask the runoff characteristics of the individual subcatchment in question.

Figure 7.1 displays the mean annual runoff from individual subcatchments for southern Africa, the CoD of subcatchment runoff as well as the ratio comparisons for the three ECHAM5 climate scenarios for both these indicators. The historical baseline map for subcatchment runoff (**Figure 7.1** top left) shows a general decrease in runoff in an east to west direction. The Quinary Catchments in the Northern Cape Province display unusually high runoff for such a semi-arid part of southern Africa. The cause of this apparent anomaly is that the unit used to measure flow magnitude, *viz*. $m^3.s^{-1}$, is a function of catchment area and the areas of these Quinaries are among the largest in the study region and hence the relatively large magnitudes of flow there.

The CoD of subcatchment runoff, for the historical baseline scenario, (**Figure 7.1** top right) indicates the wetter eastern regions of southern Africa could experience less inter-annual variability of subcatchment runoff than the drier Northern Cape, which typically displays high CoD values of between 2 and 5 as a result of experiencing erratic year to year rainfall. The ratio map for mean annual runoff derived from intermediate future to present projected climates (**Figure 7.1** middle left) indicates that a large majority of the Quinary Catchments in the eastern parts in southern Africa are likely to experience an increase in runoff according to the ECHAM5 GCM. A band of Quinaries running roughly from the Limpopo Province through to the Eastern Cape Province indicates a decrease in subcatchment runoff in the intermediate future. This trend of increasing runoff in the eastern parts of southern Africa continues and intensifies when comparing the runoff ratio from the distant future to present ECHAM5 climate scenarios (**Figure 7.1** bottom left), while the band of Quinaries which is projected to experience a decrease in subcatchment runoff shifts westwards to now cover the southwestern parts of the Western Cape Province. The ratio maps for the CoD of subcatchment runoff under projected future climates (**Figure 7.1** middle right and bottom right) do not display clear overall trends; however, most Quinaries do seem to indicate a decrease in CoD for both the intermediate and more distant future climate scenarios.

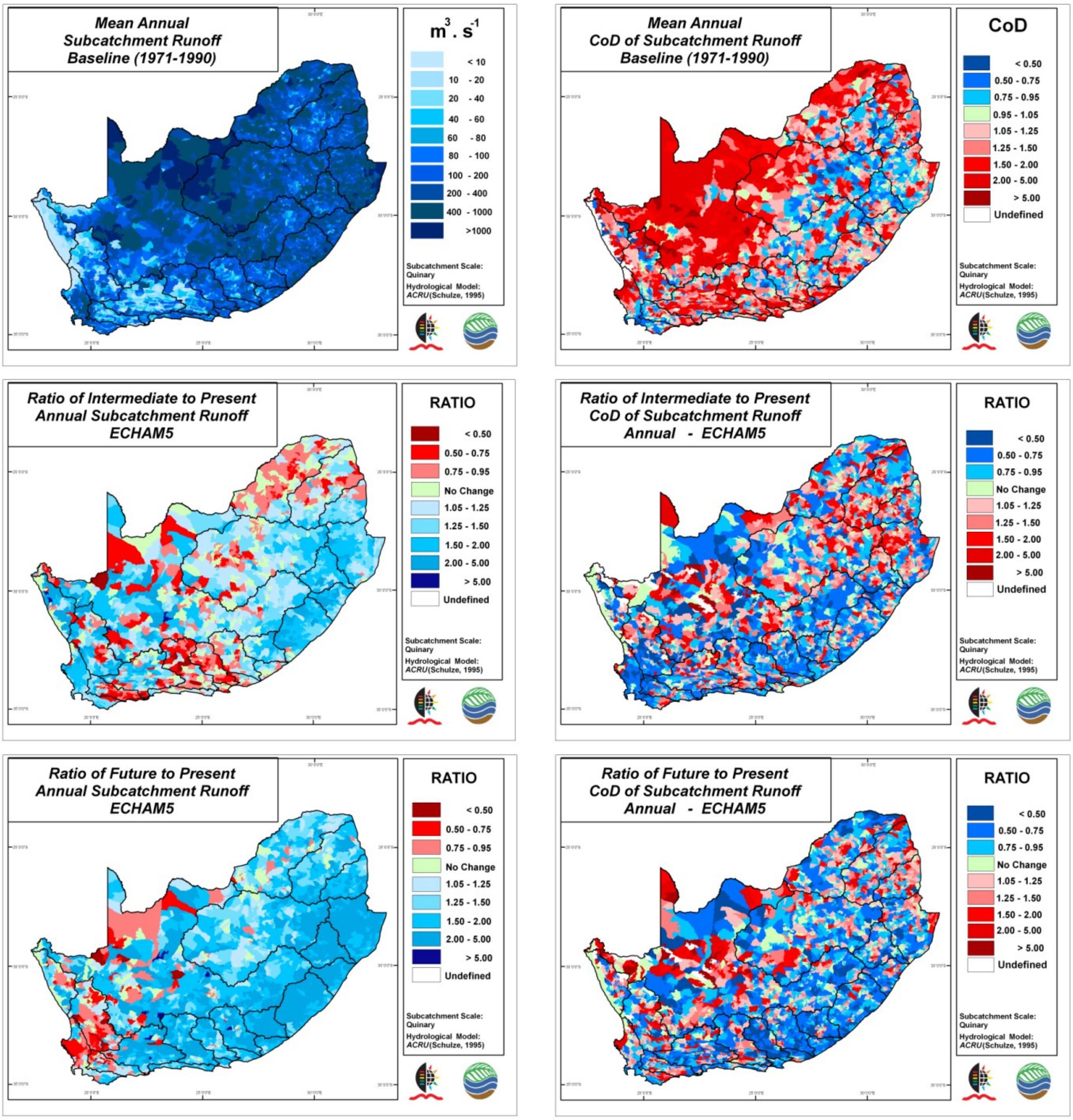

Figure 7.1 Mean annual individual subcatchment runoff ($m^3.s^{-1}$) under baseline climatic conditions, as well as ratios of the intermediate future to present and distant future to present subcatchment runoff derived with the *ACRU* model from ECHAM5 climate input (left hand maps), together with their respective Coefficients of Dispersion (right hand maps)

7.2.2 Average annual flow projections for accumulated streamflows

Accumulated streamflow is an output from the *ACRU* model which is defined as the total summed streamflow from a (sub)catchment, but which also includes any contributions from upstream catchments (Schulze, 1995). The *ACRU* model outputs this variable in millimetre (mm) equivalents and it is subsequently converted to cubic metres (m^3) using the total (sub) catchment area. **Figure 7.2** displays the mean annual accumulated streamflows per Quinary Catchment in southern Africa, for the climate scenarios described in **Section 6.9**. The historical baseline map (**Figure 7.2** top left) clearly shows streamflow accumulation in the major river systems (e.g. the Orange, Vaal and Thukela), indicated by the darker blue colour. The CoD of accumulated streamflow for the historical baseline scenario (**Figure 7.2** top right) indicates that the eastern regions of southern Africa are likely to experience less flow variability compared to the Quinaries located in the drier Northern Cape Province which, as in the case of subcatchment runoff (**Section 7.2.1**), typically display a CoD of between 2 and 5.

Figure 7.2 (middle left and bottom left) also displays the ratio comparisons of mean annual accumulated streamflows between the ECHAM 5 climate scenarios. Both maps indicate an increase in accumulated streamflows in eastern parts of southern Africa under projected future climate conditions. The ratio map of distant future to present ECHAM5 climates (**Figure 7.2** bottom left) displays the greatest change in accumulated streamflows, with most Quinaries on the east coast showing an increase by a factor of between 2 and 5 compared to that simulated from the present ECHAM5 climate scenario. As in the case of subcatchment runoff, there is a band of Quinaries running roughly from Limpopo through to the Eastern Cape Province which indicates a decrease in accumulated streamflows (**Figure 7.2** middle left). This trend of increasing streamflow continues when assessing ratios generated from the distant future to present ECHAM5 climate scenarios (**Figure 7.2** bottom right), and again the band of Quinaries which experiences a decrease in accumulated streamflows shifts westwards and now covers the southwestern parts of the Western Cape. The ratio maps for the CoD of accumulated streamflows under projected future climates (**Figure 7.2** middle right and bottom right) do not display distinctive trends. However, most Quinaries do seem to indicate a decrease in CoD in both the intermediate and more distant future scenarios, particularly on the Eastern Cape and KwaZulu-Natal coasts.

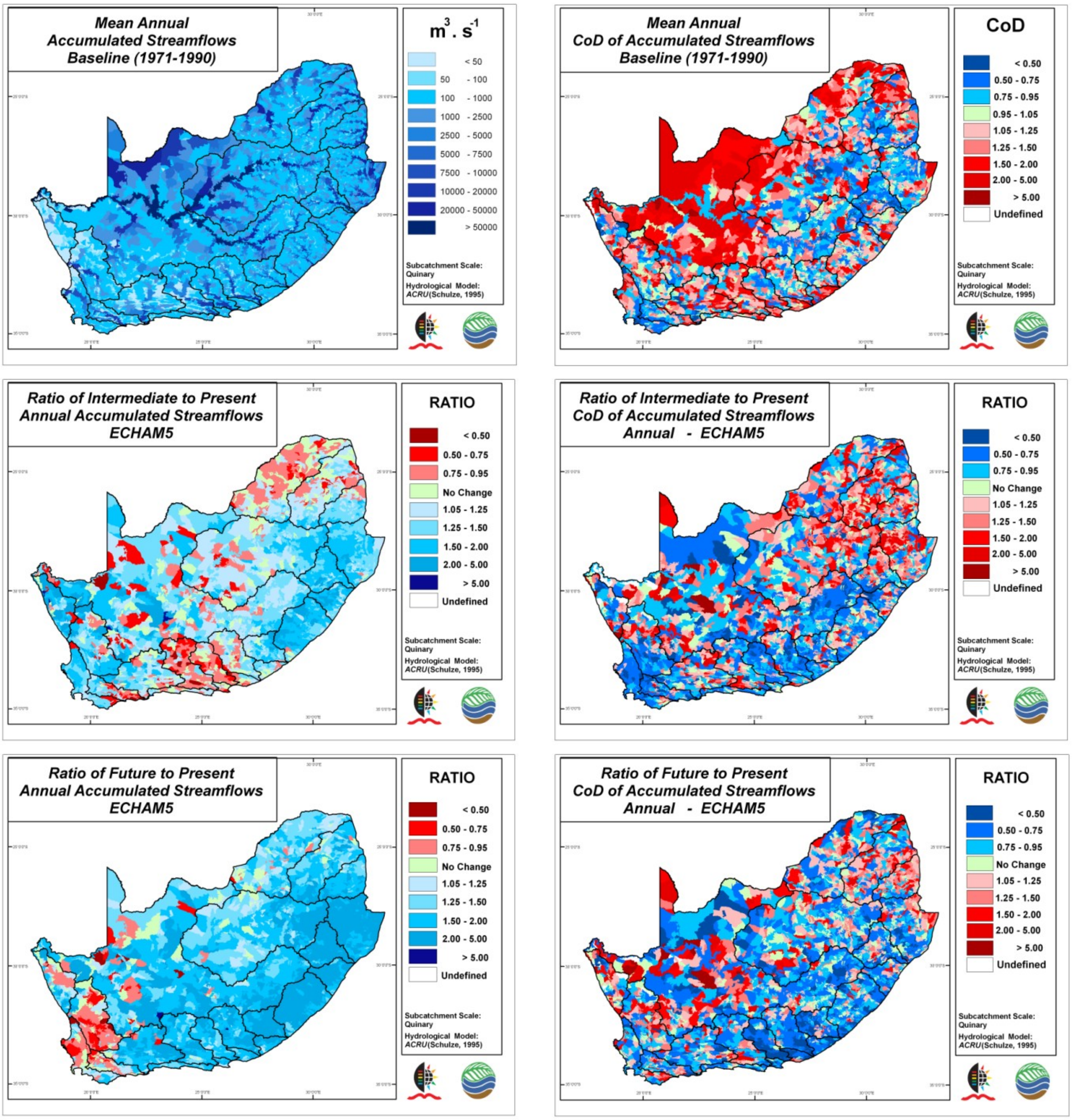

Figure 7.2 Mean annual accumulated streamflows ($m^3.s^{-1}$) under baseline climatic conditions, as well as ratios of the intermediate future to present and distant future to present accumulated streamflows derived with the *ACRU* model from ECHAM5 climate input (left hand maps), together with their respective Coefficients of Dispersion (right hand maps)

7.2.3 Average flow projections in selected months for individual subcatchment runoff

An analysis of subcatchment runoff projections for the four cardinal months selected was performed at Quinary Catchment scale for southern Africa (**Figures 7.3 - 7.5**). Spatial analyses of subcatchment runoff for present baseline climate (1971 - 1990) and ratio comparisons between the three ECHAM5 climate scenarios was performed for the months of January, April, July and October. A CoD analysis of subcatchment runoff was also performed, however only for the representative summer and winter months, *viz*. January and July.

A comparison of the historical baseline maps for the four cardinal months reveals certain trends which are not shown in the annual analysis of subcatchment runoff (cf. **Section 7.2.1**). The January baseline map for subcatchment runoff (**Figure 7.3** top left) displays the greatest amount of runoff, especially in the eastern parts of the study region which has a summer rainfall regime. Conversely, the Western Cape displays virtually no runoff for the month of January. This regional trend reverses for the month of July, when the Western Cape receives its winter rainfall (**Figure 7.4** top left) and thus has more runoff then the eastern parts of southern Africa. The historical baseline climate maps for the months of April and October (**Figure 7.5** top left and right) show similar trends with respect to subcatchment runoff, with April experiencing more runoff in the Free State province. The high values for subcatchment runoff recorded from the large Quinary Catchments in the Northern Cape for January and April is the result of using $m^3.s^{-1}$ as the unit of flow (cf. **Section 7.2**).

A ratio analysis of individual subcatchment runoff generated from the three ECHAM5 scenarios was also performed for the four cardinal months. The ratio analysis for January illustrates a distinct band of decreasing subcatchment runoff trending from the northeastern tip of South Africa to the Eastern Cape province for the intermediate future to present ratio (**Figure 7.3** middle left), with most Quinaries in this band experiencing a decrease in subcatchment runoff of between 5% and 50%. This band then moves westward for the distant future to present ratio analysis (**Figure 7.3** bottom left). The eastern seaboard of southern Africa is projected to experience an increase in subcatchment runoff in both the intermediate and more distant future climate scenarios generated by the ECHAM5 GCM. The ratio analysis for July indicates that most of the region can expect an increase in subcatchment runoff in the intermediate future (**Figure 7.4** middle left). This wetting trend is projected to get stronger under the more distant future climatic conditions (**Figure 7.4** bottom left). April and October, the transitional months, show similar results for both ratio analyses (**Figure 7.5** middle and bottom), with October showing a stronger wetting signal. For both months a general wetting is projected along the east coast of southern Africa for both scenarios, but especially for the future to present analysis, which show most Quinaries in this region likely to experience an increase in runoff by a factor of between 2 and 5 based on the ECHAM5 GCM. Both these months also project a decrease in runoff in the Western Cape in the more distant future compared to the simulated present climate scenario simulated by ECHAM5.

A monthly analysis for the CoD of subcatchment runoff was performed for the months of January and July to determine if there were any differences in spatial patterns of inter-annual runoff. Both January and July exhibit a high CoD for much of the region under present baseline climatic conditions (**Figures 7.3** and **7.4** top left), especially in the Northern Cape province, implying that year to year runoff values are highly variable for these months. January displays lower CoD values, of between 0.50 and 0.75 for the Western Cape then in its dry season, while July shows lower CoDs for eastern parts of southern Africa when that region is in its dry season. The January ratio analysis for the CoD of subcatchment runoff does not reveal any clear regional trends, except that there seems to be an overall decrease in CoD particularly for the distant future to present ratio analysis (**Figure 7.3** bottom right). Like January, July does not exhibit any clear trends in changes of CoD, except that the semi-arid western regions are projected not to experience any significant change in the inter-annual variability of subcatchment runoff under future climatic conditions owing to the lack of runoff in the dry season.

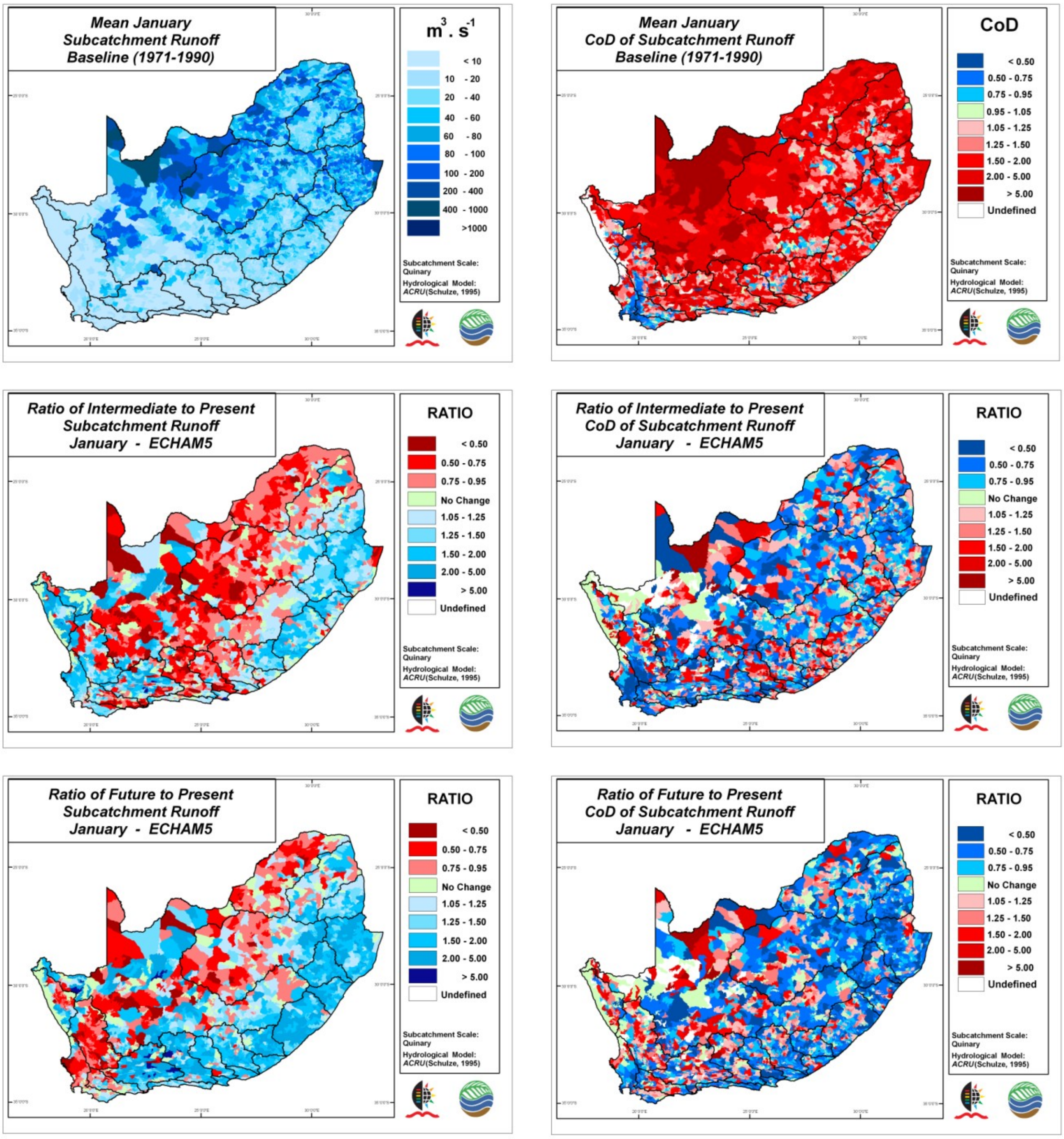

Figure 7.3 Mean January individual subcatchment runoff ($m^3.s^{-1}$) under baseline climatic conditions, as well as ratios of the intermediate future to present and distant future to present subcatchment runoff derived with the *ACRU* model from ECHAM5 climate input (left hand maps), together with their respective Coefficients of Dispersion (right hand maps)

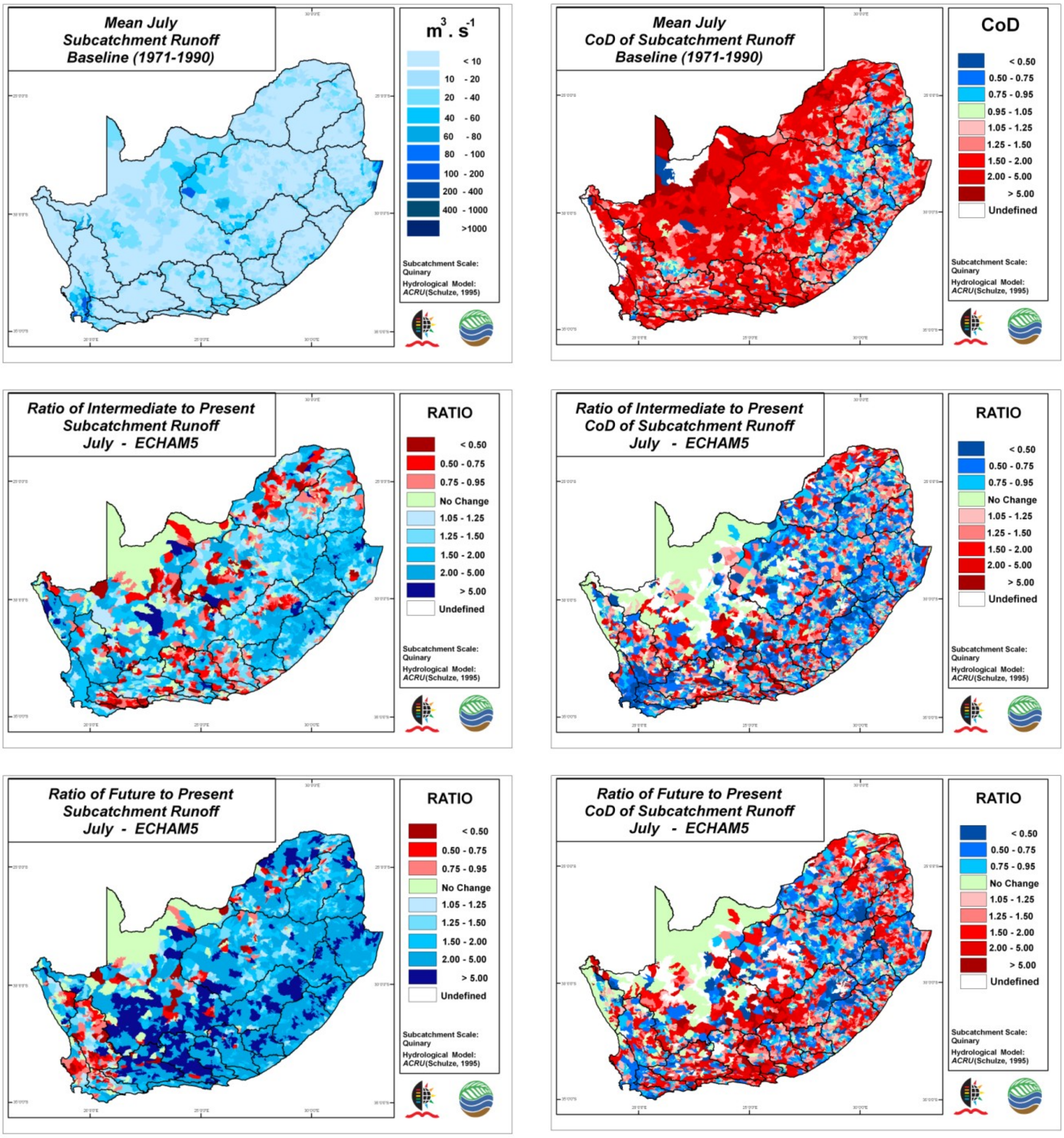

Figure 7.4 Mean July individual subcatchment runoff ($m^3.s^{-1}$) under baseline climatic conditions, as well as ratios of the intermediate future to present and distant future to present subcatchment runoff derived with the *ACRU* model from ECHAM5 climate input (left hand maps), together with their respective Coefficients of Dispersion (right hand maps)

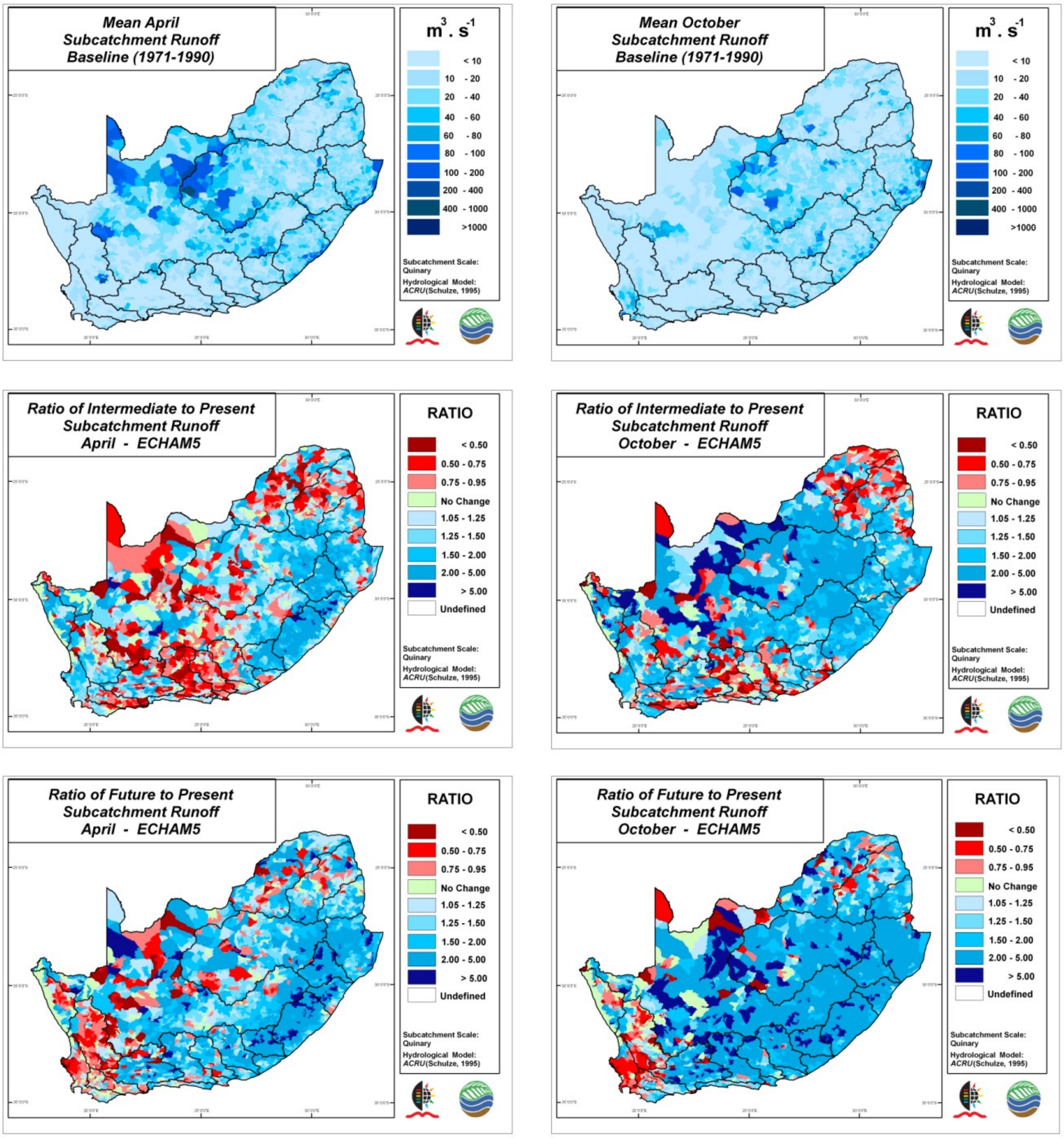

Figure 7.5 Mean April and October individual subcatchment runoff ($m^3.s^{-1}$) under baseline climatic conditions (top maps), as well as ratios of the intermediate future to present (middle row) and distant future to present subcatchment runoff (bottom row) derived with the *ACRU* model from ECHAM5 climate input

7.2.4 Average flow projections for accumulated streamflows in selected months

An analysis of seasonal (intra-annual) changes in accumulated streamflow projections for selected cardinal months (**Figures 7.6 – 7.8**) reveals that present and future accumulated streamflows fluctuate quite considerably throughout the year. A spatial analysis of accumulated streamflows for present baseline climate (1971 - 1990) and a ratio comparison between the three ECHAM5 climate scenarios was performed for the months of January, April, July and October. As with subcatchment runoff (cf. **Section 7.2.3**) a CoD analysis of projected accumulated streamflows was performed for January and July.

Similar to the annual analyses (**Section 7.2.2**), the monthly baseline maps for accumulated streamflows (**Figures 7.6 - 7.8**) clearly illustrate streamflow accumulation in the major river systems (e.g. the Orange, Vaal and Thukela), indicated by the darker shades of blue. The January baseline map for accumulated streamflows (**Figure 7.6** top left) shows the highest magnitudes of streamflows of the four months, especially in the eastern side of the region, as a result of the summer rainfall regime. The July baseline map (**Figure 7.7** top left) shows low streamflow volumes in the tributaries, but greater flows in the mainstems of the larger river systems. The historical baseline climate maps for the months of April and October (**Figure 7.8** top left and right) display similar patterns of accumulated streamflows, but with one difference being that April indicates more streamflow to occur in the Northern Cape Province.

A ratio analysis of accumulated streamflows generated from the three ECHAM5 climate scenarios was performed for the four cardinal months and illustrates similar results to those found in the analyses of subcatchment runoff (cf. **Section 7.2.3**). The ratio analysis for January illustrates a distinct band of decreasing accumulated streamflows from the northeastern tip of South Africa to the Eastern Cape province for the intermediate to present ratio analysis (**Figure 7.6** middle left), with most Quinaries in this band experiencing a decrease in subcatchment runoff of between 5 and 50 %. This band is projected to shift westward to cover the southwestern parts of the Western Cape for the future to present scenario (**Figure 7.6** bottom left). The eastern seaboard of southern Africa is projected to experience an increase in accumulated flows in both the intermediate and more distant future scenario. The ratio analysis for July indicates that most of the region can expect an increase in streamflows in the intermediate future (**Figure 7.7** middle left), with the band of decreasing streamflows becoming far less apparent. This wetting trend is projected to become stronger under the more distant future climate projected by the ECHAM5 GCM (**Figure 7.7** bottom left). April and October, the transitional months, show very similar results for both ratio analyses (**Figure 7.8** middle and bottom), with a decrease in streamflows projected for the Northern Cape and Eastern Cape provinces. Both months also project a decrease in runoff in the Western Cape in the more distant future, compared to the present climate simulated by ECHAM5. For the month of April projections indicate a general wetting on the east coast of southern Africa for both scenarios, but especially for the future to present analysis, where most Quinaries in this region are likely to experience an increase in streamflow by a factor of between 2 and 5 (**Figure 7.8** middle and bottom left). Compared to April, October indicates an even stronger wetting signal for both ratio analyses, except in the southwestern parts of the Western Cape.

A monthly analysis for the CoD of accumulated streamflow was performed for the months of January and July to determine whether any seasonal (intra-annual) differences or spatial patterns were evident at present and with future climate scenarios. Both January and July exhibit a high CoD for much of the region under present baseline climatic conditions (**Figures 7.6** and **7.7** top left), especially in the Northern Cape province, signifying that runoff values between one year and the next are highly variable for these months. Similarly to the analysis for the CoD of monthly subcatchment runoff (**Section 7.2.3**), January shows lower CoD values, of between 0.5 and 0.75, for the Western Cape in its non-rainy rainfall season, while July shows lower CoD for the eastern parts of southern Africa when they are in their dry season. The January ratio analysis of the CoD of accumulated streamflows does not reveal any clear regional trends, except that there seems to be an overall decrease in CoD, particularly for the distant future to present ratio analysis (**Figure 7.6** bottom right), over much of South Africa. July also does not exhibit any clear changes in inter-annual streamflows with climate change projected with the ECHAM5 GCM, except that the arid regions are projected to experience no change in accumulated streamflows under future climatic conditions owing to the general absence of streamflow in non-rainy season.

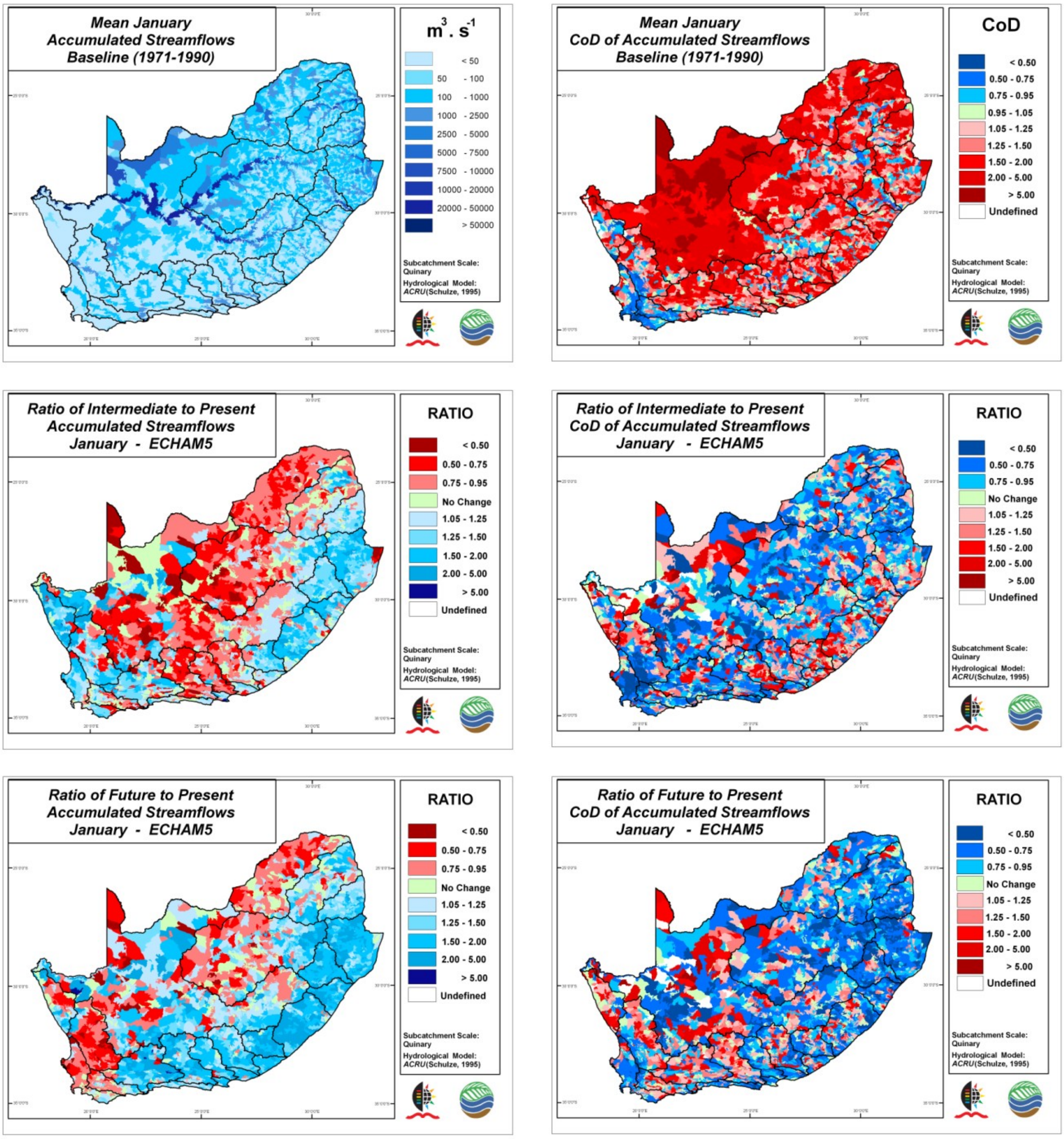

Figure 7.6 Mean January accumulated streamflows ($m^3.s^{-1}$) under baseline climatic conditions, as well as ratios of the intermediate future to present and distant future to present accumulated streamflows derived with the *ACRU* model from ECHAM5 climate input (left hand maps), together with their respective Coefficients of Dispersion (right hand maps)

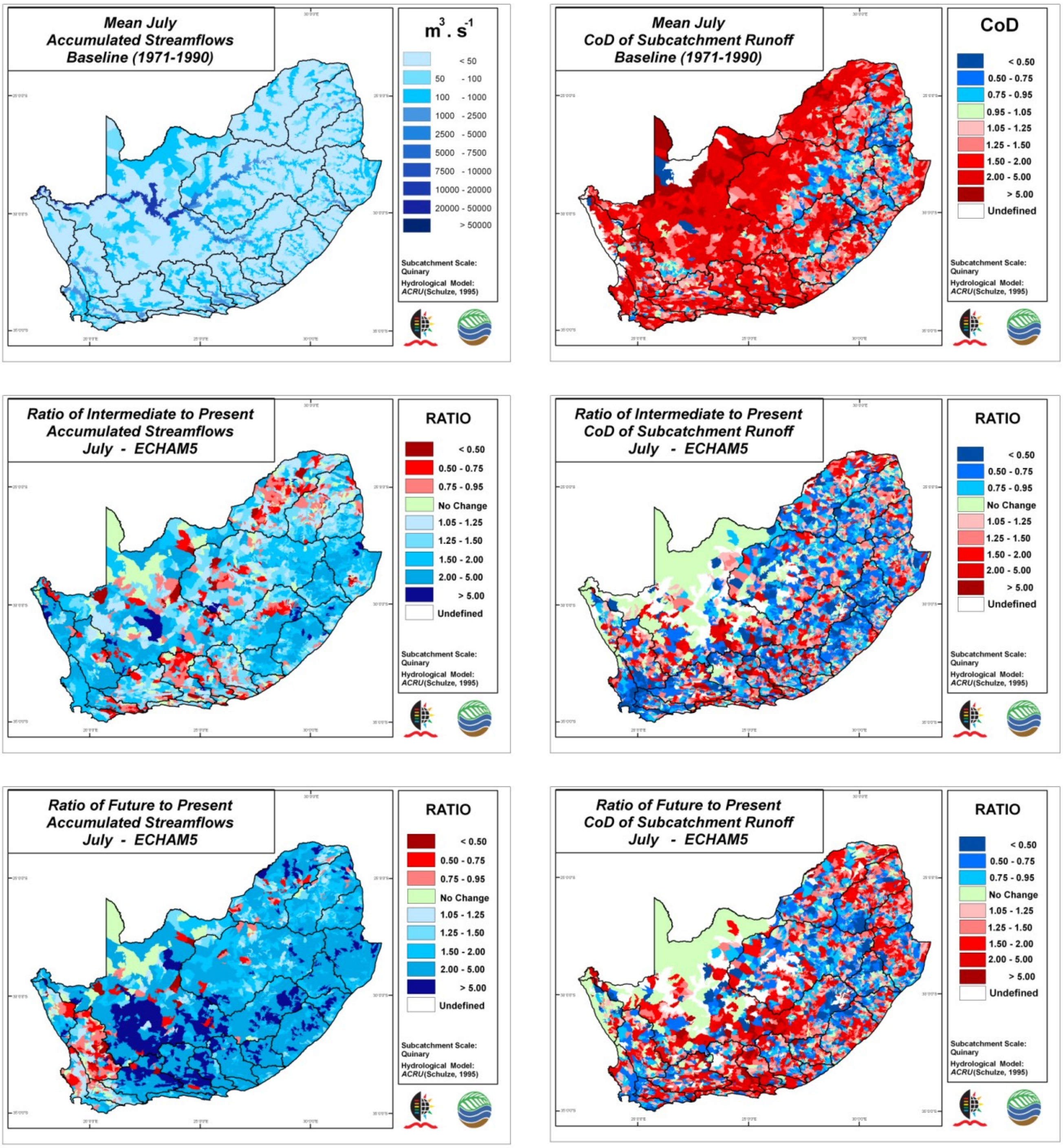

Figure 7.7 Mean July accumulated streamflows ($m^3.s^{-1}$) under baseline climatic conditions, as well as ratios of the intermediate future to present and distant future to present accumulated streamflows derived with the *ACRU* model from ECHAM5 climate input (left hand maps), together with their respective Coefficients of Dispersion (right hand maps)

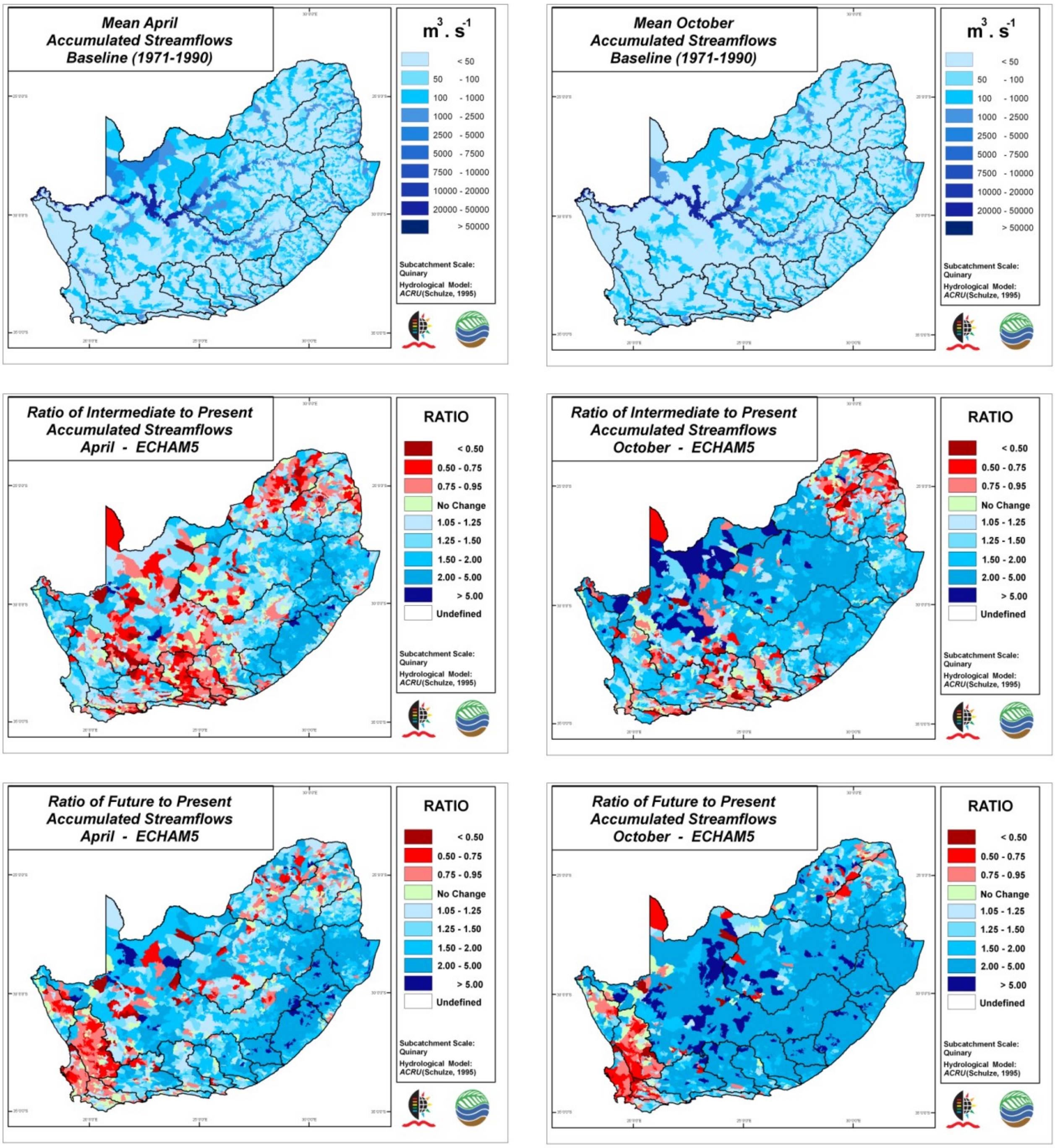

Figure 7.8 Mean April and October accumulated streamflows ($m^3.s^{-1}$) under baseline climatic conditions (top maps), as well as ratios of the intermediate future to present (middle row) and distant future to present accumulated streamflows (bottom row) derived with the *ACRU* model from ECHAM5 climate input

7.2.5 Ratios of baseflow volume to total subcatchment runoff (Alt-BFI)

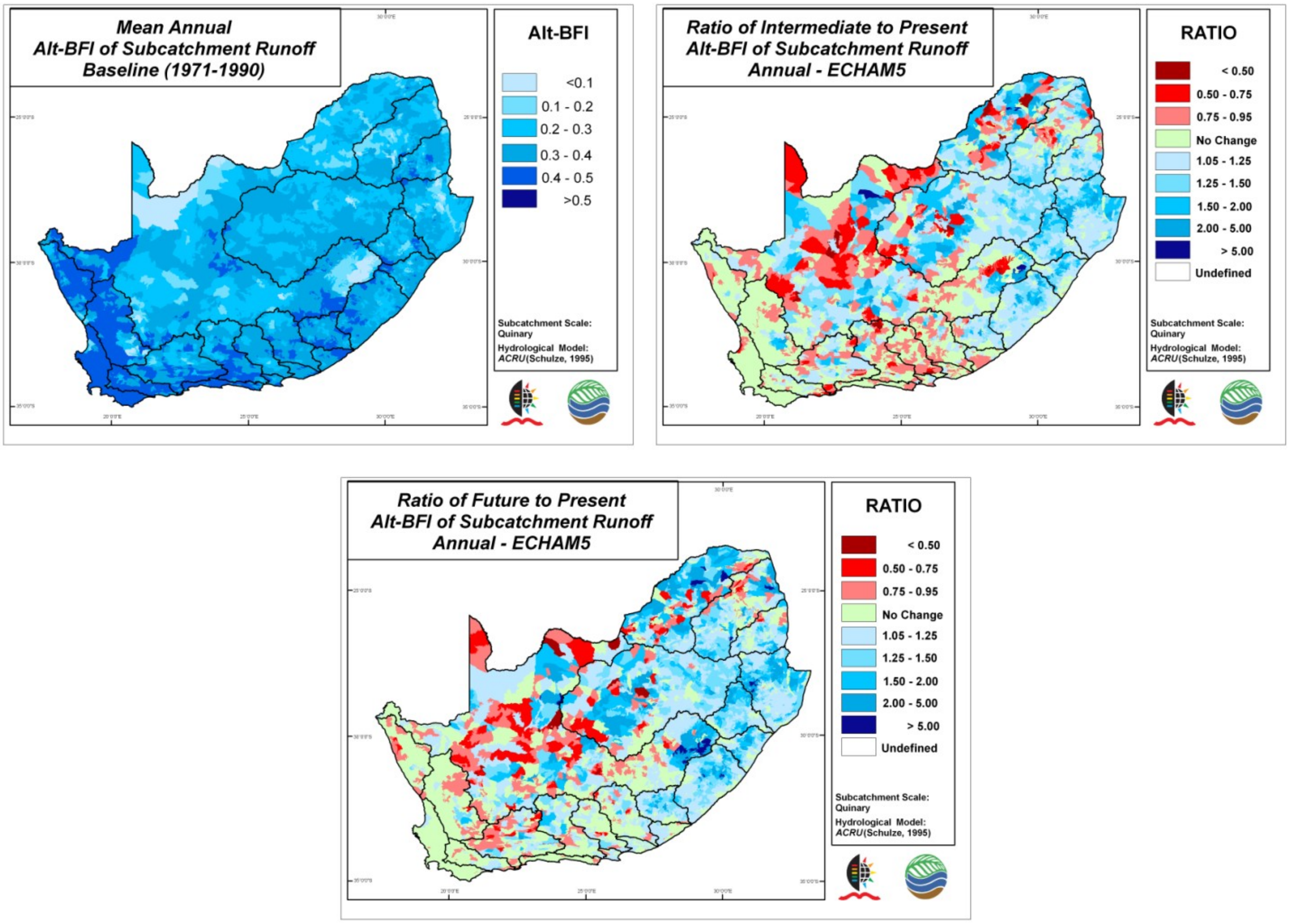

Figure 7.9 Ratios of mean annual subcatchment baseflow to total flow (Alt-BFl) under baseline climatic conditions (top left) and ratio changes of this relationship between intermediate future and present (top right) and distant future and present climates, derived with the *ACRU* model from ECHAM5 climate input

The higher the ratio of baseflow to total subcatchment runoff (termed the "Alt-BFI" indicator of hydrological alteration), the more dependent the area is on groundwater contributing to sustaining streamflows. The baseline climate map of the Alt-BFI indicator shows significant regional trends (**Figure 7.9** top left). In the Western Cape Province and western coastline, the average Alt-BFI values are between 0.4 - 0.5 (i.e. approximately 45%) and are significantly higher than the Alt-BFI values found in the remainder of the region under study. Both climate ratio maps of Alt-BFI project similar magnitudes of change for this indicator. The eastern half of the region is likely to experience a general increase in Alt-BFI, while the western areas show that some Quinaries could experience a slight decrease in the ratio of baseflow to total subcatchment runoff. The Quinaries located in Western Cape province and the western coastline, which showed high Alt-BFI values for the present baseline climate, are projected not to experience any major changes in the intermediate and more distant future climates when runoff components are computed from the *ACRU* model using ECHAM5 climate input.

7.3 Duration of Flow Events

As was the case in the previous section, the *ACRU* model (Schulze, 1995 and updates) was used to simulate the duration of flow event responses from the 5 838 Quinary Catchments which constitute southern Africa when using the climate scenarios outlined in **Section 6.9**.

The duration of flow events is the period of time associated with a specific water condition (Richter *et al*., 1996). The durations used in this research are based on the recommended durations from the developers of the IHA in attempting to represent natural cycles and they consist of the 1 day, 3 day, 7 day (weekly), 30 day (monthly) and 90 day (seasonal) extremes (The Nature Conservancy, 2005). The 1 day events are the maximum and minimum daily streamflow values that occur in any given year and the multi-day events are the highest and lowest multi-day means of flows occurring in any given year (Taylor, 2006). The durations of flows are split into low and high flow conditions and both are analysed in this section. Both the means of the time series of annual minimum and maximum 1, 3, 7, 30 and 90 day average flows are mapped for southern Africa, as are the CoDs for these durations using the historical baseline climate data (1970-1990). In order to project likely changes over time in low and high flows for the selected durations under conditions of climate change, daily climate values from the ECHAM5 GCM's present, intermediate future and more distant future were input into ACRU and flow durations were calculated using the accumulated streamflow output.

7.3.1 Means of annual low flow conditions of different durations

Low flow conditions in South African rivers are a natural seasonal phenomenon, especially in areas with a distinct dry and wet season. Low flow conditions are an important component of a river's flow regime and can enable the recruitment of certain floodplain plants as well as purging invasive (i.e. introduced) species from aquatic and riparian communities. Low flows can also concentrate prey into limited areas to benefit predators, as well as providing migration and spawning cues for fish (The River Center, 2008).

Figures 7.10 - 7.14 display the annual minimum 1, 3, 7, 30 and 90 day averages of accumulated low flows across southern Africa, the CoDs of these flows, as well as the ratio comparisons from the three ECHAM5 climate scenarios for all the aforementioned durations of low flows. A comparison of each of the five durations of low flows reveals that they all exhibit similar overall trends. The historical baseline maps for the minimum 1, 3, 7, 30 and 90 day averages of accumulated streamflows (**Figures 7.10 - 7.14** top left) show that most tributaries located away from the mainstem of major river systems have low flows of less than 1 $m^3.s^{-1}$. The mainstems of the major river systems show the highest low flows, as would be expected for accumulated flows, especially in the Orange River Catchment. It can be noted that the amount of flow rate steadily increases as the duration increases (i.e. from 1 day to 90 day), which again is to be expected.

The ratio maps of intermediate to present ECHAM5 climates for the minimum 1, 3, 7, 30 and 90 day average of accumulated streamflows (**Figures 7.10 - 7.14** middle left) indicates there could be an overall increase in minimum flows for all flow durations, especially on the eastern side of South Africa. However the Eastern Cape and Northern Provinces do contain pockets of Quinaries indicating a projected decrease in flow in the intermediate future.

The ratio maps of future to present ECHAM5 climates (**Figures 7.10 - 7.14** bottom left) show that virtually all Quinary Catchments are projected to experience an increase in minimum accumulated streamflows for all flow durations. The Western Cape is the major exception and this ratio analysis indicates a distinct projected decrease in flows with the ECHAM5 GCM of between 5 and 25% for all flow durations for this region. KwaZulu-Natal and the Eastern Cape show a strong wetting signal with flows derived from ECHAM5, with minimum accumulated streamflows projected to increase by a factor of between 2 and 5 for all flow durations.

The CoDs for the minimum 1, 3, 7, 30 and 90 day averages of accumulated streamflows using the historical baseline climate scenario (**Figures 7.10 - 7.14** top right) depicts the eastern and the coastal regions of southern Africa to experience less inter-annual variability in minimum accumulated streamflows compared to those of the Northern Cape. The Northern Cape experiences erratic rainfalls from one year to the next and this translates into the high CoD for all minimum flow durations there. The ECHAM5 CoD ratio maps for the minimum 1, 3, 7, 30 and 90 day average of annual accumulated streamflows (**Figures 7.10 - 7.14** middle and bottom right) do not display clear overall trends or spatial patterns.

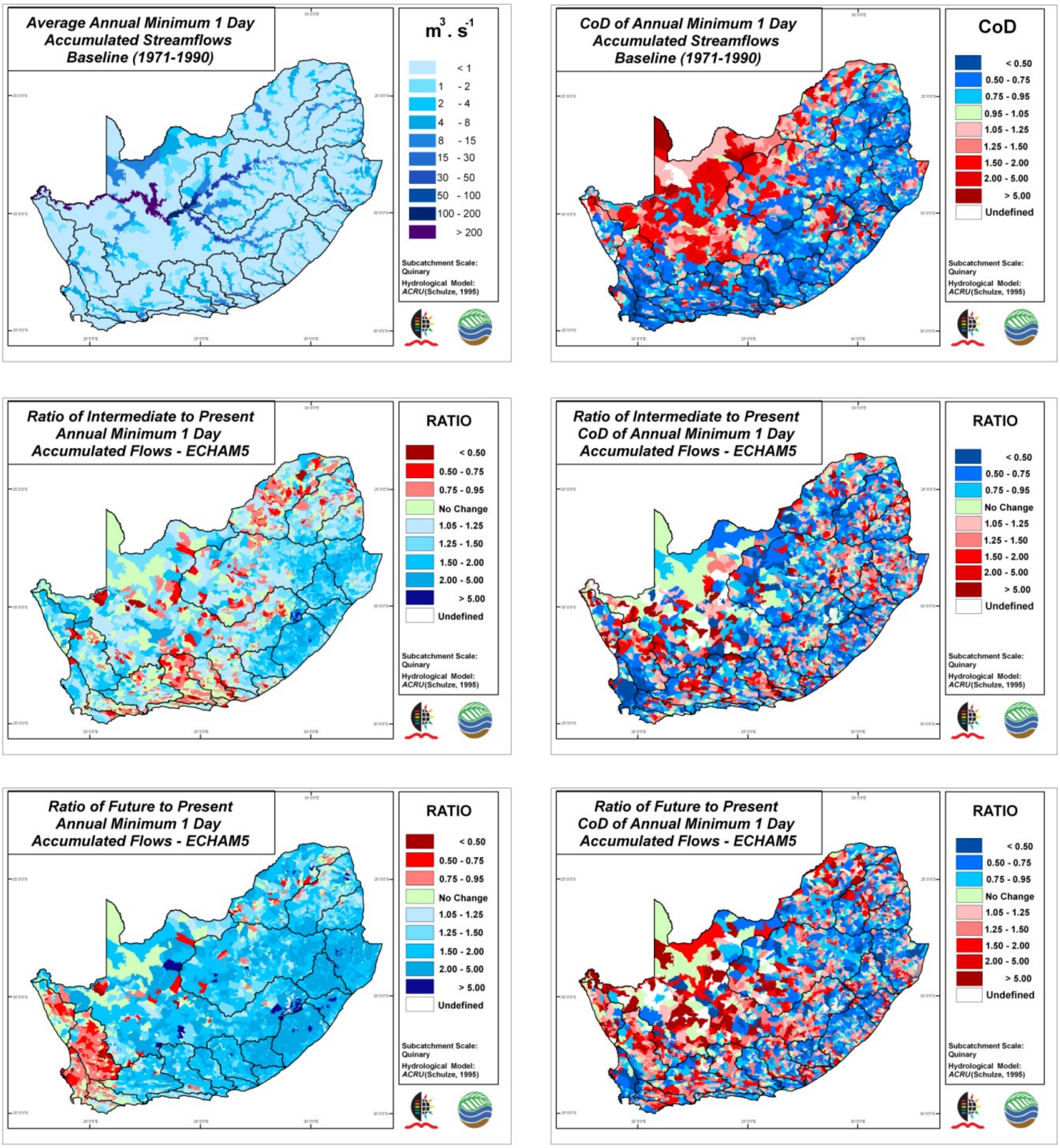

Figure 7.10 Average annual minimum 1 day accumulated streamflows ($m^3.s^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and distant future to present of this indicator, derived with the *ACRU* model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

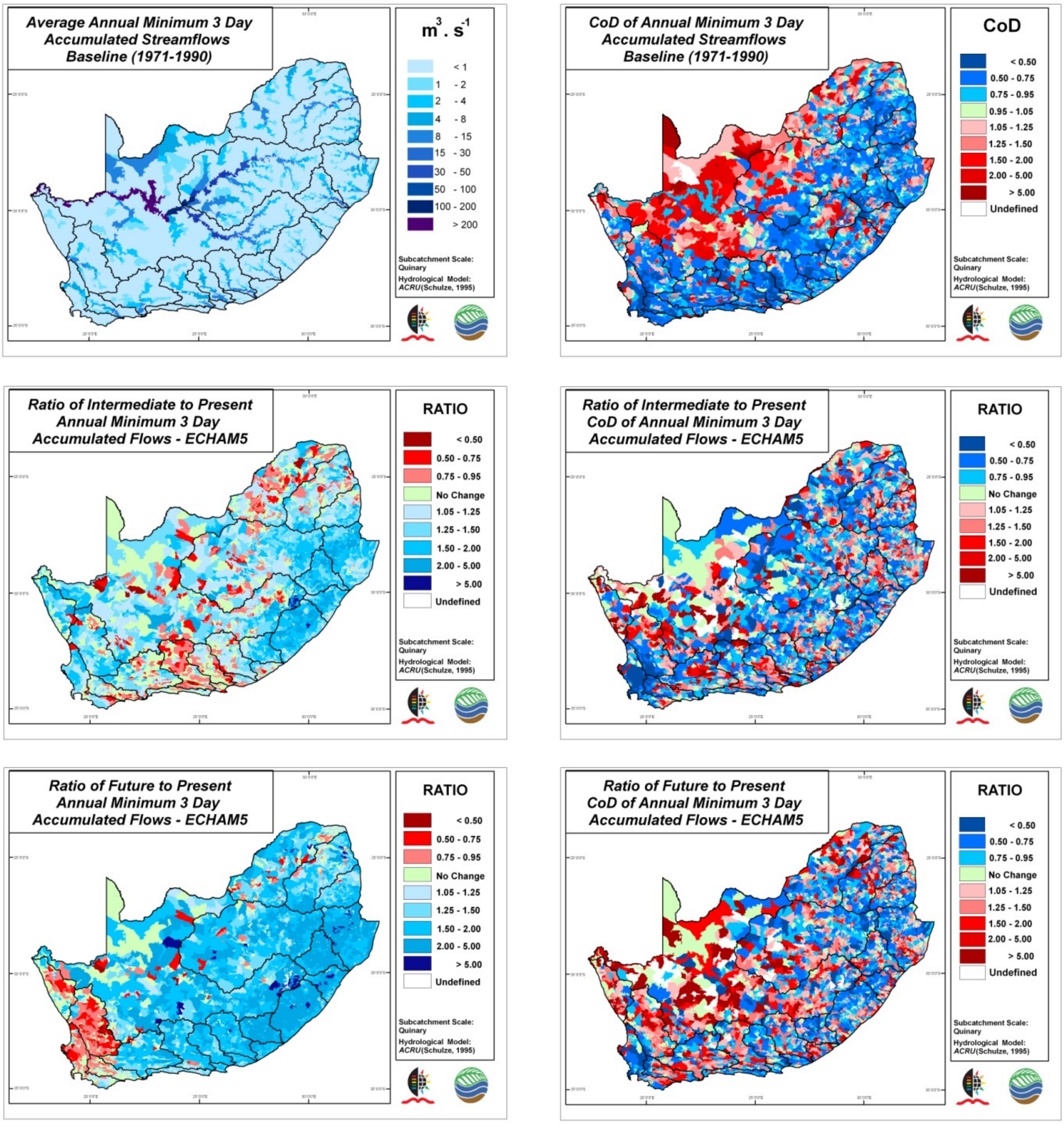

Figure 7.11 Average annual minimum 3 day accumulated streamflows (m^3.s^{-1}) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and distant future to present of this indicator, derived with the *ACRU* model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

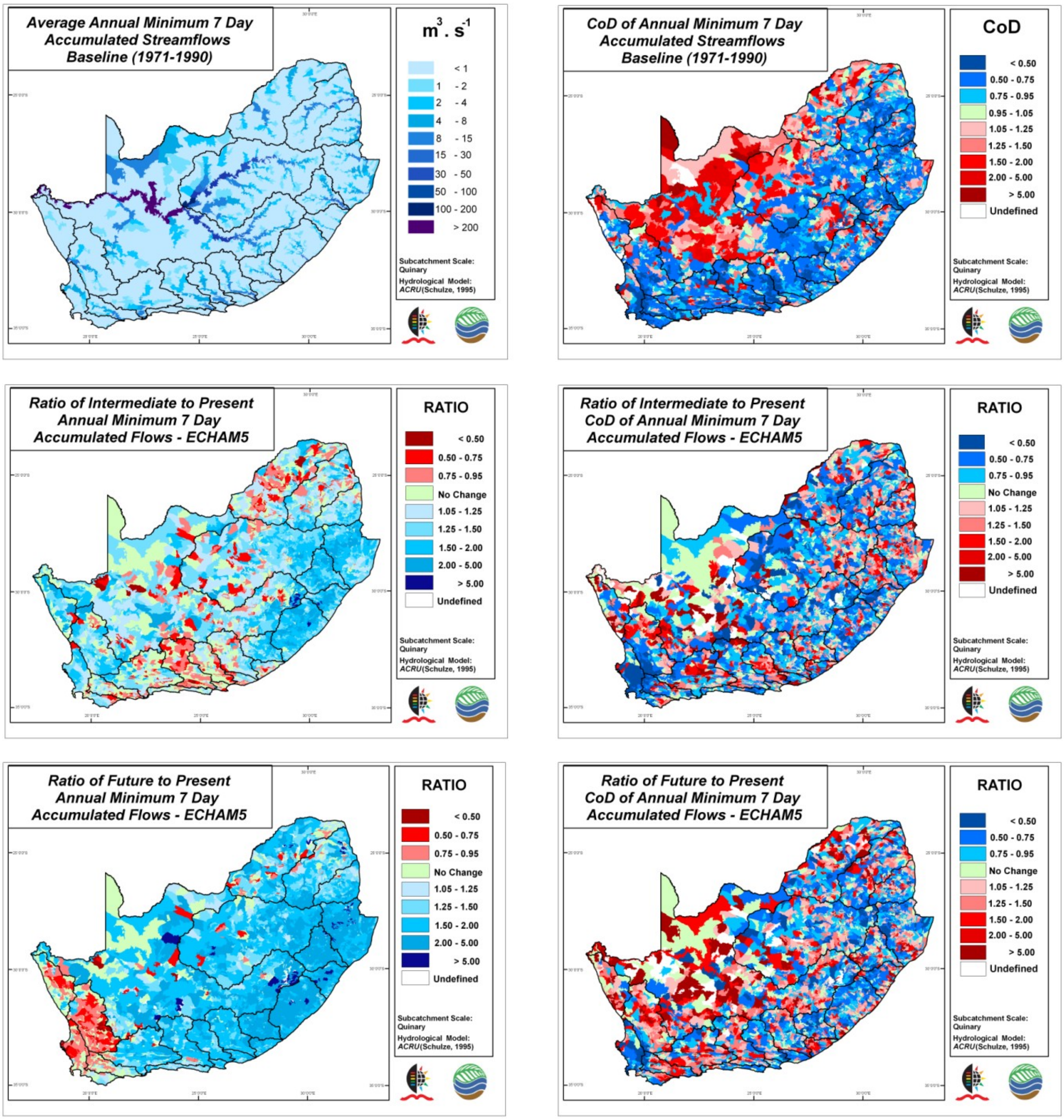

Figure 7.12 Average annual minimum 7 day accumulated streamflows ($m^3.s^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and distant future to present of this indicator, derived with the *ACRU* model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

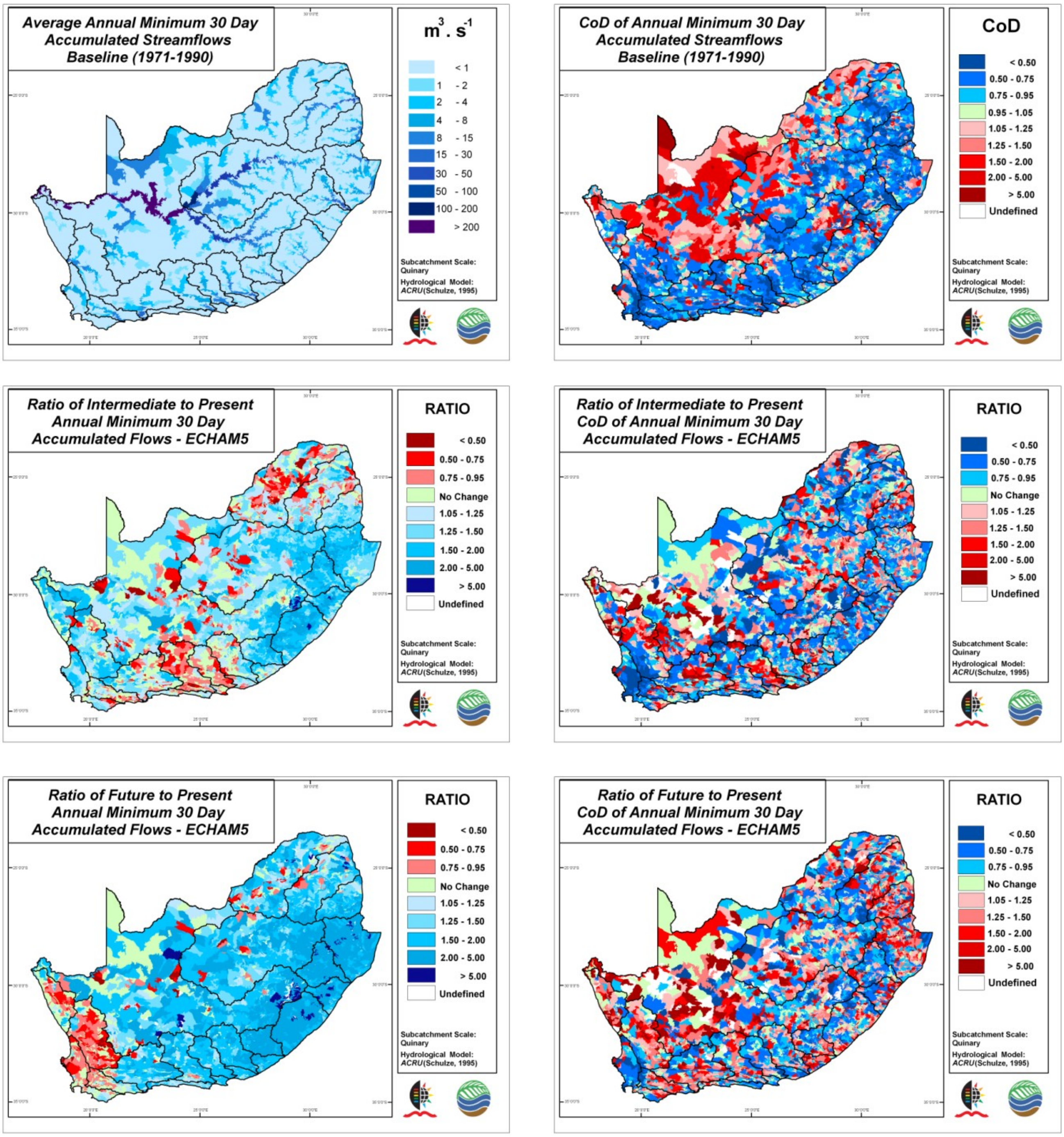

Figure 7.13 Average annual minimum 30 day accumulated streamflows ($m^3.s^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and distant future to present of this indicator, derived with the *ACRU* model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

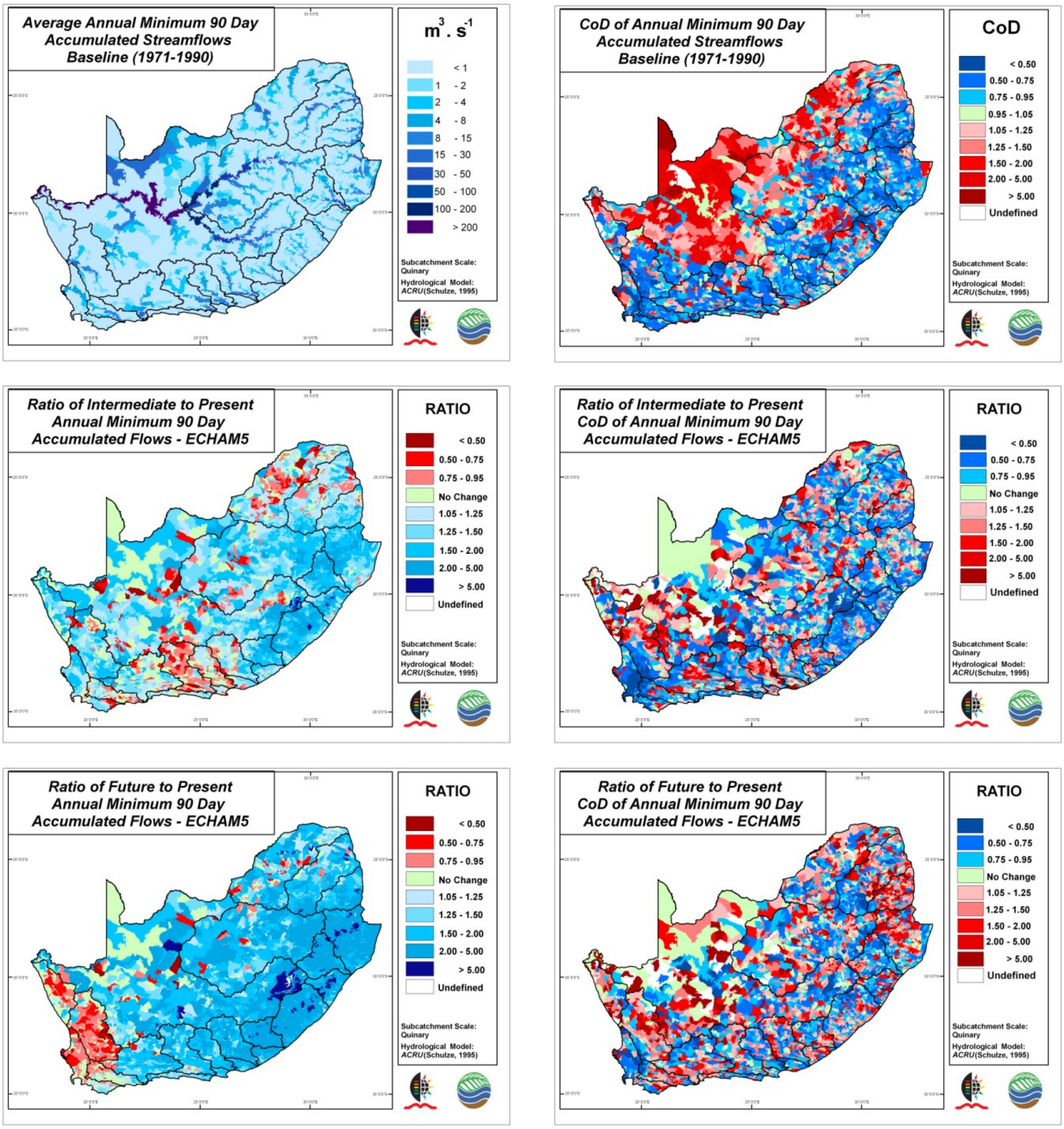

Figure 7.14 Average annual minimum 90 day accumulated streamflows ($m^3.s^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and distant future to present of this indicator, derived with the *ACRU* model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

7.3.2 Means of annual high flow conditions of different durations

As in the case of low flows, high flows and high flow pulses are a critical component of the natural flow regimes of South African rivers. High flows are a major determining factor in the physical characteristics of the river channels and pools, as well as size and combination of streambed substrates such as sand, gravel and cobble. High flows are also required to restore water quality to more normal conditions after prolonged low flows by flushing out waste products and pollutants. This flushing can also transport food and habitat structure into the channel as well as preventing riparian vegetation from encroaching into the channel. High flows are also very important for organisms inhabitating a lotic system as they can provide migration and spawning cues and trigger a new phase in a species life cycle (The River Center, 2008).

Figures 7.15 - **7.19** display the annual maximum 1, 3, 7, 30 and 90 day averages of annual accumulated streamflows for southern Africa, the CoD of these flow as well as the ratio comparisons for the three ECHAM5 climate scenarios for all the aforementioned flow durations. A comparison of each of the five maximum flow durations and the ratio maps reveals that all flow durations exhibit similar trends, which are discussed below.

The historical baseline maps for the maximum 1, 3, 7, 30 and 90 day averages of annual accumulated streamflows (**Figures 7.15 - 7.19** top left) display distinctly wetter patterns than the low flow duration maps presented in **Section 7.2.1**. The mainstems of the primary river systems show the greatest amount of flow, but some streamflow accumulation is also discernible in smaller tributaries, especially for the 1 and 3 day duration maps (**Figures 7.15** and **7.16**). A comparison of the baseline maps of maximum flows shows that the averaged magnitudes of flow rates decreases steadily as the duration of maximum flows increases from the 1 day to the 90 day period, which is to be expected.

The ratio maps of intermediate future to present ECHAM5 climate derived maximum 1, 3, 7, 30 and 90 day annually averaged accumulated streamflows (**Figures 7.15 - 7.19** middle left) indicate there could be an increase in maximum flow in KwaZulu-Natal and along the west coast of South Africa for all durations. These ratio maps of intermediate to present climates also indicate a band of Quinaries, stretching from the northeastern tip of South Africa through to Port Elizabeth for which a decrease in maximum flows for all flow durations is projected from ECHAM5. This band of Quinaries is more apparent and contiguous for the shorter durations of 1 and 3 days.

The ratio maps from the distant future to present ECHAM5 climates (**Figures 7.15 - 7.19** bottom left) show that virtually all Quinary Catchments are projected to experience an increase in their maximum annual accumulated streamflows for all flow durations. The Western Cape is again the major exception and, as in the case of the minimum flow ratio analysis, displays a distinct decrease in maximum averaged annual flows of between 5 and 25% for all flow durations. Across the remainder of the country a wetting signal is indicated, with maximum accumulated streamflows expected to increase by a factor of between 1.05 and 2.0.

The CoDs for the average of the maximum annual 1, 3, 7, 30 and 90 day accumulated streamflows in as year using the historical baseline climate scenario (**Figures 7.15 - 7.19** top right) indicates the eastern side southern Africa to experiences less inter-annual variability of the maximum accumulated streamflows compared to the western half of the region. The western half shows a high CoD of between 2 and 5 for all maximum flow durations from 1 to 90 days. This large CoD implies that high flows for the various durations for this region are highly variable from year to year and this makes it difficult to manage river systems in this area. The ratio maps derived from intermediate future to present ECHAM5 climates for the CoDs for the maximum 1, 3, 7, 30 and 90 day averages of accumulated streamflows (**Figures 7.10 - 7.19** middle right) do not show definitive spatial patterns. However, the CoD ratio maps of distant future to present ECHAM5 climates (**Figures 7.10 - 7.19** bottom right) suggest a decrease in the CoD for most Quinaries, particularly along the eastern coastline of South Africa.

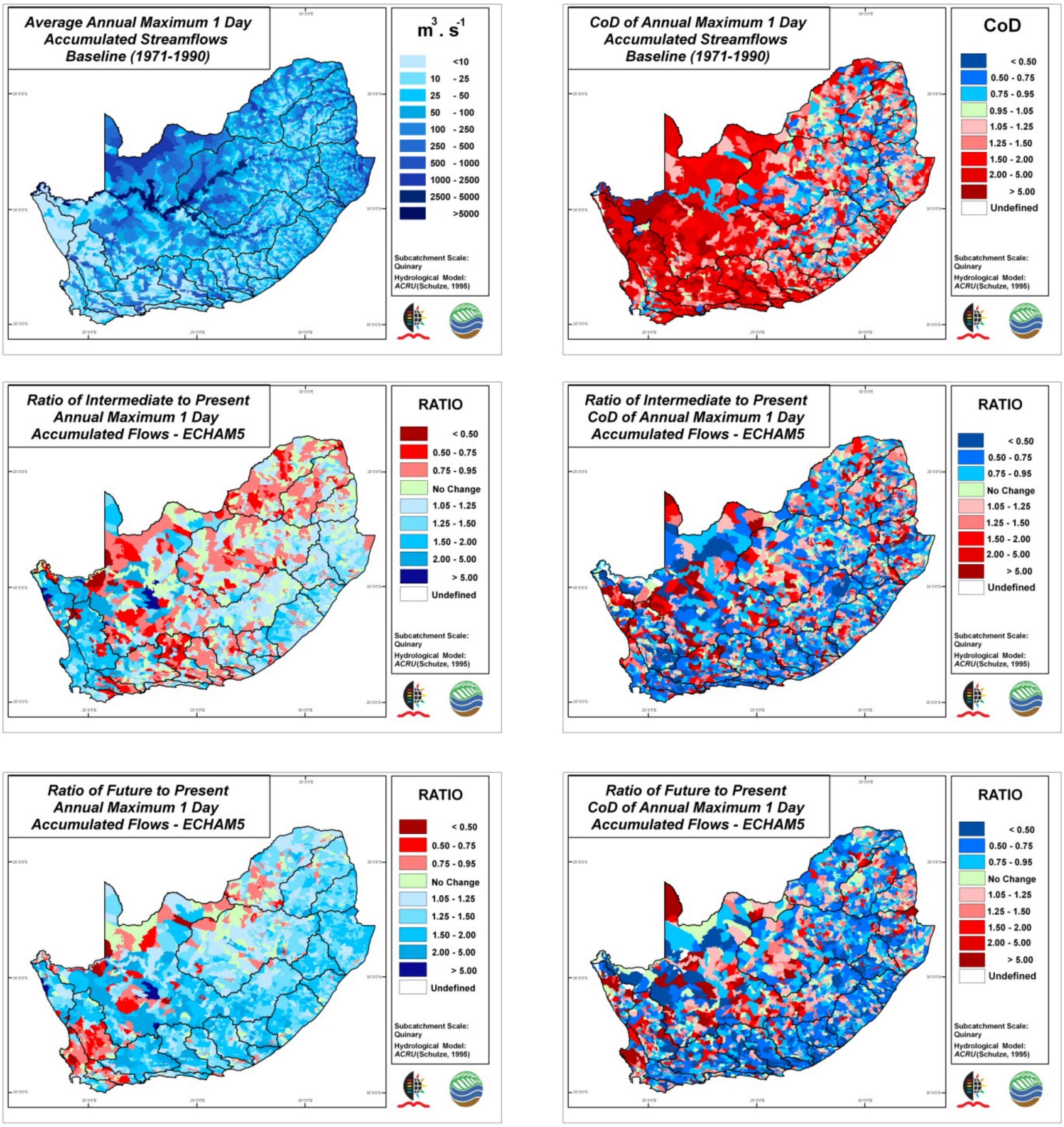

Figure 7.15 Average annual maximum 1 day accumulated streamflows ($m^3.s^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and distant future to present of this indicator, derived with the *ACRU* model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

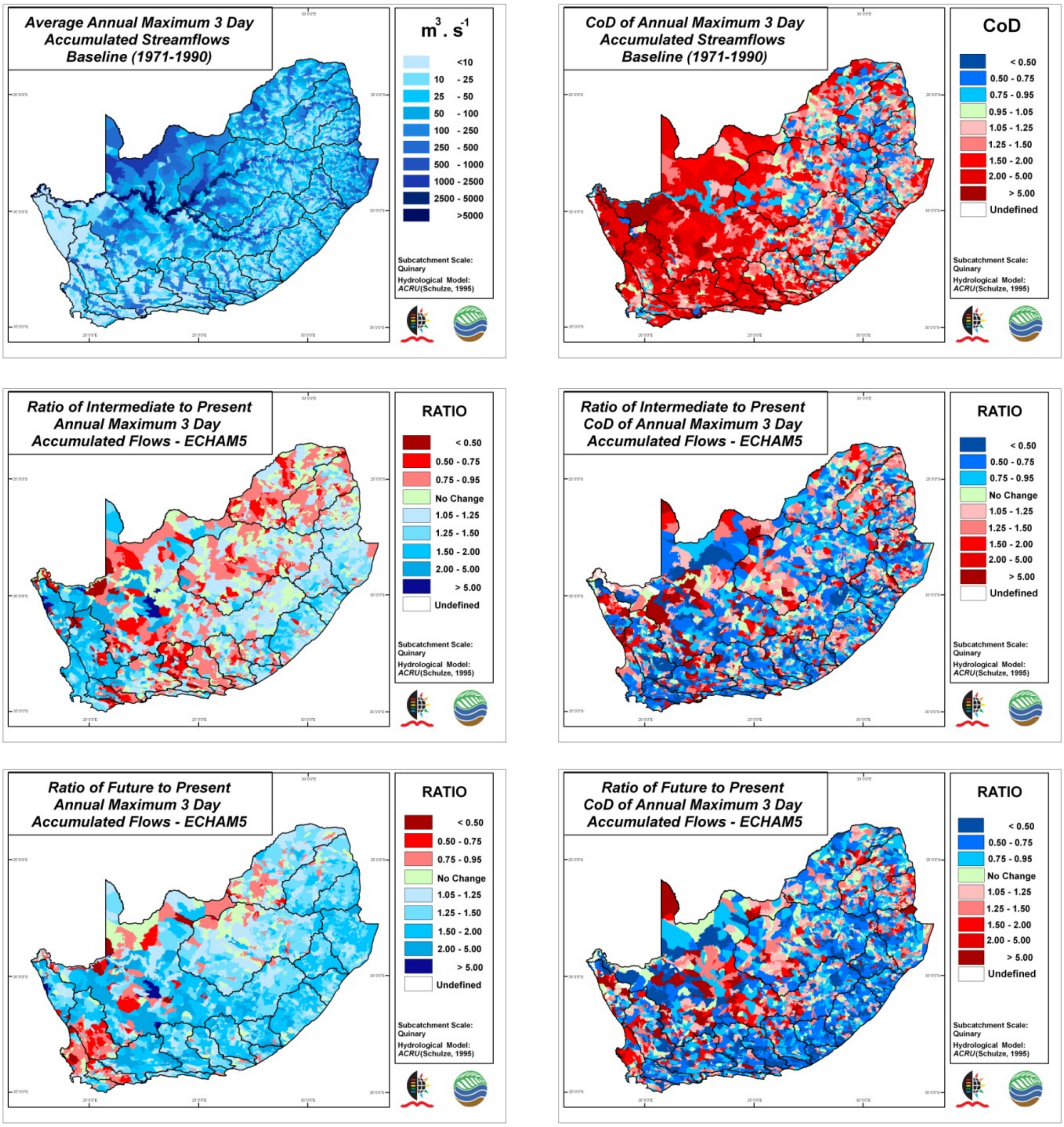

Figure 7.16 Average annual maximum 3 day accumulated streamflows ($m^3.s^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and distant future to present of this indicator, derived with the *ACRU* model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

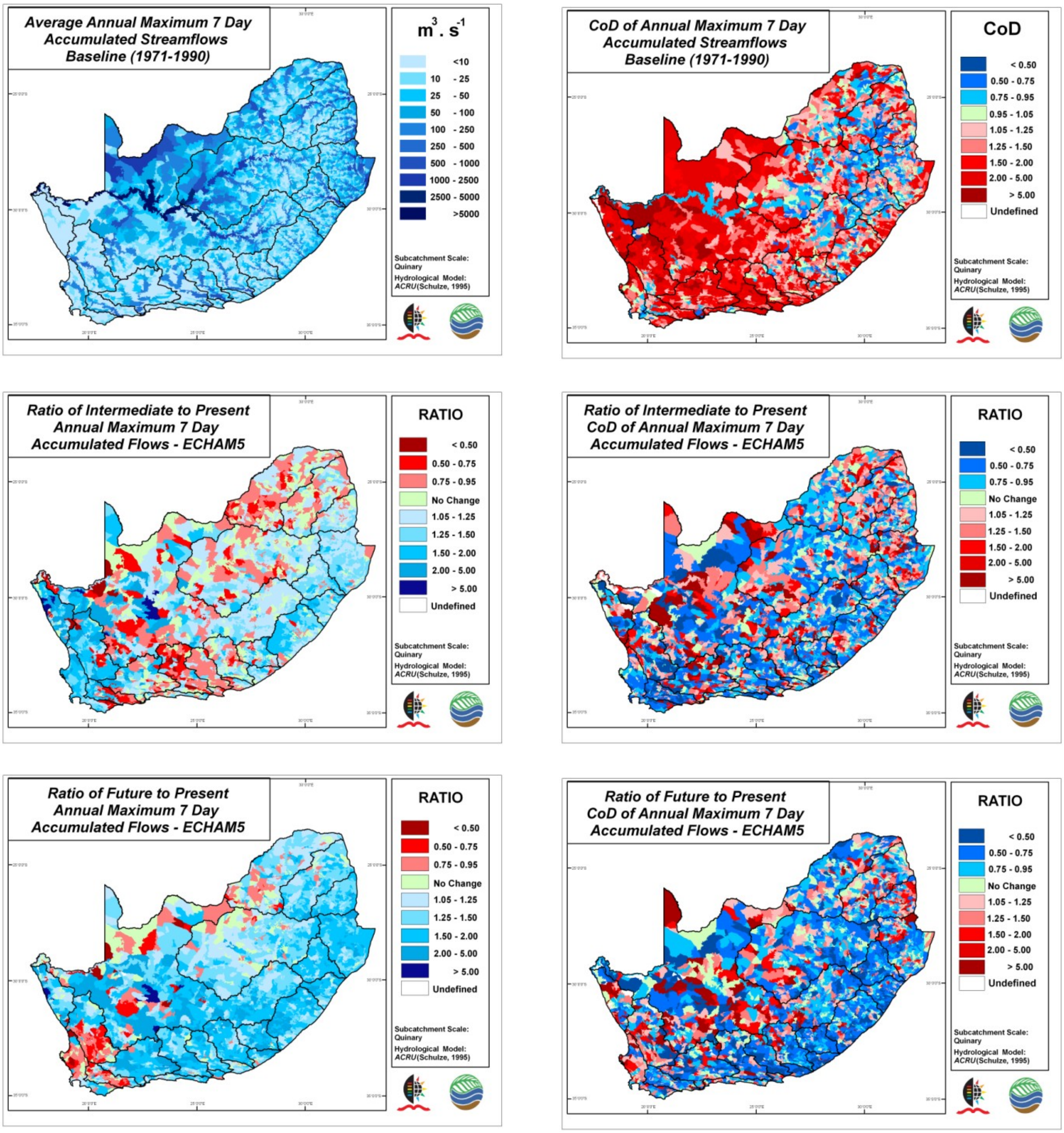

Figure 7.17 Average annual maximum 7 day accumulated streamflows ($m^3.s^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and distant future to present of this indicator, derived with the *ACRU* model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

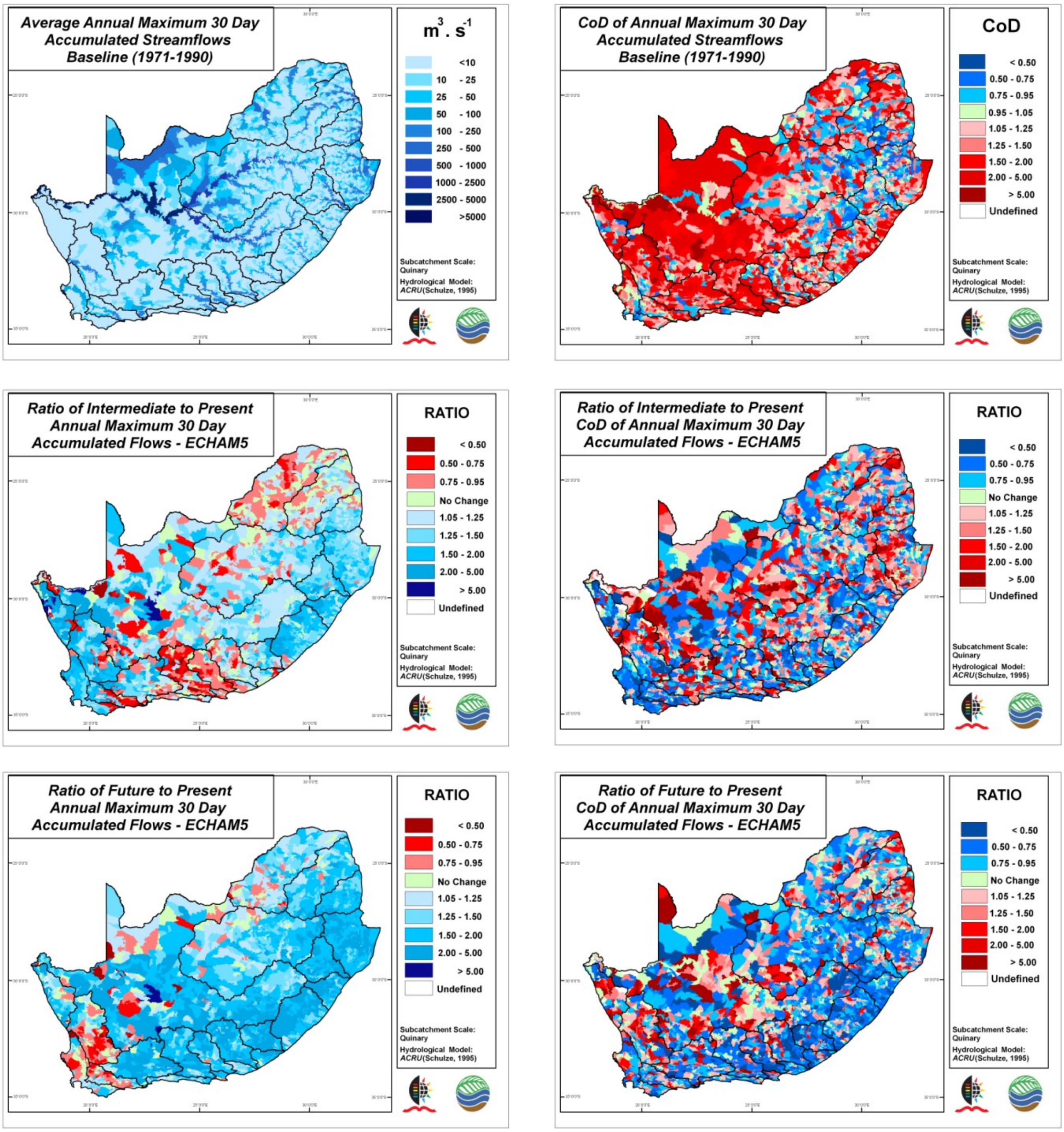

Figure 7.18 Average annual maximum 30 day accumulated streamflows ($m^3.s^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and distant future to present of this indicator, derived with the *ACRU* model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

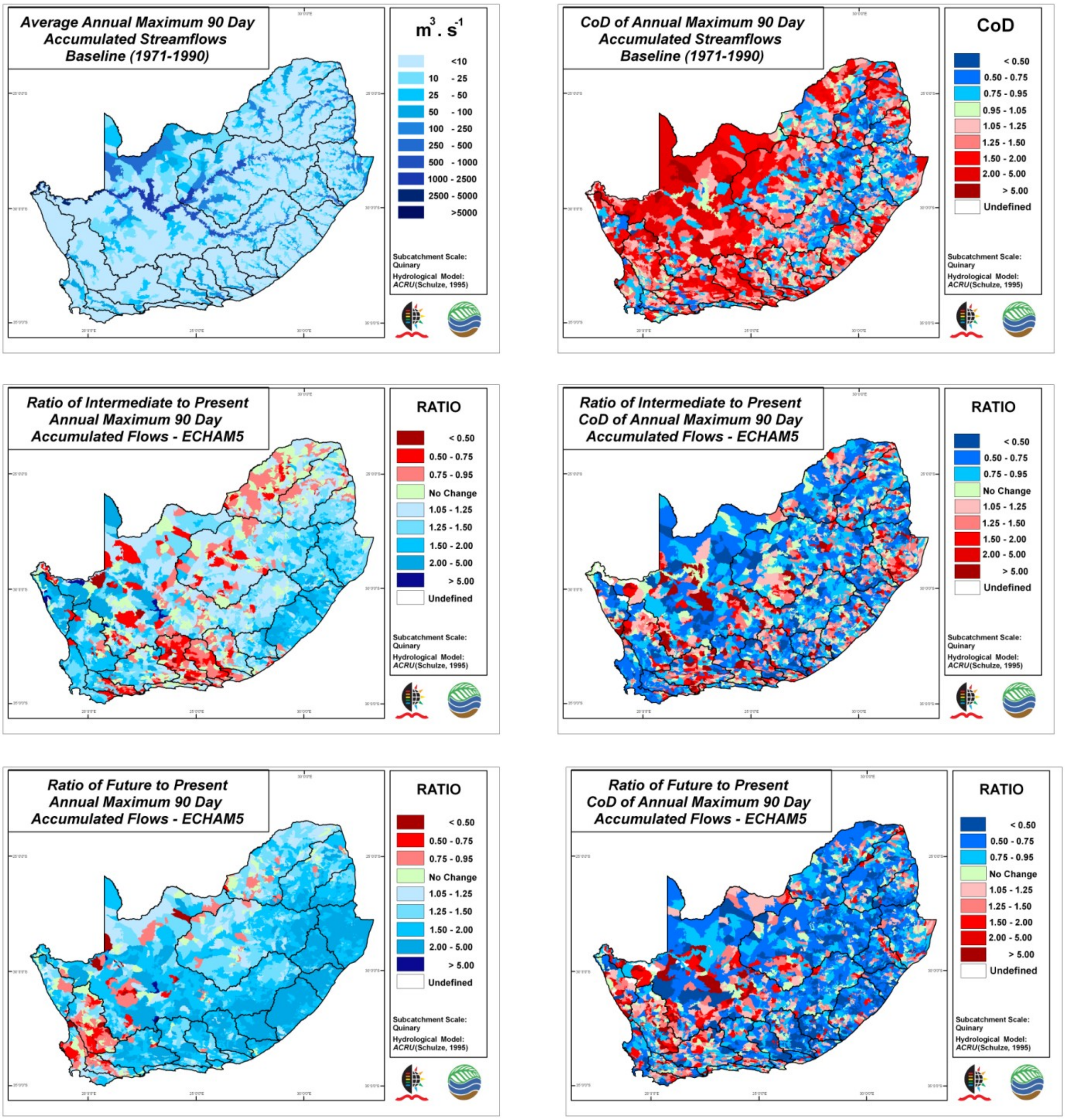

Figure 7.19 Average annual maximum 90 day accumulated streamflows ($m^3.s^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and distant future to present of this indicator, derived with the *ACRU* model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

*****

In **Chapter 7**, the first of three chapters on results, the potential impacts of climate change on the magnitude and duration of flow were assessed using the baseline climate conditions and the ECHAM5 climate scenarios. This spatial assessment was a performed for the 5 838 hydrologically interlinked and cascading Quinary Catchments, which constitute the southern Africa study region. **Section 7.2** focussed on the magnitude of flow events and was performed for both individual catchment runoff and accumulated streamflows and the main findings are summarised in the table and paragraph below:

Table 7.1 Summary of results for the ecological flow indicators

Ecological Flow Indicator		Intermediate: Present	Future: Present
Magnitude of Flow Events	Annual Subcatchment Runoff	Moderate increase projected in the eastern half of southern Africa. Moderate decrease projected for a band of Quinaires running from Limpopo to the Eastern Cape.	A significant increase by a factor of between 2 and 5 is projected throughout southern Africa but excludes the Western Cape, which could experience a decrease by 25-50%.
	Annual Accumulated Streamflows	Moderate increase projected in the eastern half of southern Africa. Moderate decrease projected for a band of Quinaires running from Limpopo to the Eastern Cape.	A significant increase by a factor of between 2 and 5 is projected throughout southern Africa excluding the Western Cape, which could experience a decrease by 25-50%.
	CoD of Annual Subcatchment Runoff	Results do not display clear overall trends but most Quinaries throughout southern Africa could experience a decrease in CoD.	Results do not display clear overall trends but most Quinaries throughout southern Africa could experience a decrease in CoD.
	CoD of Annual Accumulated Streamflows	Results do not display clear overall trends but most Quinaries throughout southern Africa could experience a decrease in CoD.	Results indicate most Quinaries throughout southern Africa could experience a decrease in CoD.

	Annual Alt-BFI	Eastern half of the country could experience an increase while the no significant change is projected for the Western and Eastern Cape.	Eastern half of the country could experience an increase while the no significant change is projected for the Western and Eastern Cape.
Duration of Flow Events	Annual Low Flow Conditions	Moderate increase projected in the eastern half of southern Africa by approximately 50% for all flow durations. Moderate decrease projected for a large band of Quinaires running from Limpopo to the Eastern Cape for all flow durations.	A significant increase by a factor of between 2 and 5 is projected throughout southern Africa but excludes the Western Cape, which could experience a decrease in flows by 25-50% for all flow durations.
	Annual High Flow Conditions	Moderate increase projected in the eastern half of southern Africa by aproximatley 50% for all flow durations. Moderate decrease projected for a large band of Quinaires running from Limpopo to the Eastern Cape for all flow durations.	A significant increase by a factor of between 2 and 5 is projected throughout southern Africa but excludes the Western Cape, which could experience a decrease in flows by 25-50% for all flow durations.
	CoD of Annual Low Flow Conditions	Results do not display clear overall trends but most Quinaries throughout southern Africa could experience a decrease in CoD for all flow durations.	Results indicate most Quinaries throughout southern Africa could experience a decrease in CoD for all flow durations.
	CoD of Annual High Flow Conditions	Results do not display clear overall trends but most Quinaries throughout southern Africa could experience a decrease in CoD for all flow durations.	Results indicate most Quinaries throughout southern Africa could experience a decrease in CoD for all flow durations.

The ECHAM5 GCM projects the magnitude of both annual subcatchment runoff and accumulated streamflows to increase in the eastern parts of southern Africa for the intermediate future climate scenario with this wetting signal strengthening in the distant future climate scenario. A band of Quinaries running roughly from the Limpopo Province through to the Eastern Cape Province indicated a decrease in both subcatchment runoff and accumulated streamflows in the intermediate future while this band of Quinaries is projected to shift westwards to cover the southwestern parts of the Western Cape Province in the distant future climate scenario. The ratio maps for the CoD of both annual subcatchment runoff and accumulated streamflows under projected future climates does not display clear spatial trends. Surprisingly the Quinary Catchments in the Northern Cape Province displayed unusually high runoff for such a semi-arid part of southern Africa. The cause of this apparent anomaly is that the unit used to measure flow magnitude, *viz.* $m^3.s^{-1}$, is a function of catchment area and the areas of these Quinaries are among the largest in the study region and hence the relatively large magnitudes of flow there.

Section 7.3 investigated the duration of flow events using accumulated streamflow only for the 1, 3, 7, 30 and 90 day flow durations for both low and high flows and the main findings are summarised below:

In terms of flow duration the ECHAM5 GCM projects an overall increase in minimum flows for all flow durations, especially on the eastern side of South Africa. The Western Cape is the major exception and this ratio analysis indicated a distinct decrease in flows with the ECHAM5 GCM of between 5 and 25% for all minimum flow durations for this region. The ratio maps from the distant future to present ECHAM5 climates shows that virtually all Quinary Catchments are projected to experience an increase in their maximum annual accumulated streamflows for all flow durations. The Western Cape is again the major exception and, as in the case of the minimum flow ratio analysis, displayed a distinct decrease in maximum averaged annual flows of between 5 and 25% for all flow durations. The ECHAM5 CoD ratio analyses for the minimum and maximum 1, 3, 7, 30 and 90 day average of annual accumulated streamflows does not display clear overall trends or definitive spatial patterns.

In **Chapter 8**, which follows, the second set of results are presented by an assessment of the potential impacts of climate change on water temperature related indicators in the Thukela Catchment, again using the climate scenarios derived from the ECHAM5 GCM.

8. RESULTS 2: WATER TEMPERATURE IN THE THUKELA CATCHMENT UNDER REGIMES OF PROJECTED CLIMATE CHANGE USING THE ECHAM5/MPI-OM GENERAL CIRCULATION MODEL

8.1 Setting the Scene

This chapter focuses on the results from the water temperature related parameters which, because they are computationally intensive, were only analysed spatially at the scale of the Thukela Catchment, unlike the flow related parameters (**Chapter 7**) which were assessed for the entire southern African study region.

Spatial analyses were performed on the following parameters:

- Mean Daily Air Temperature,
- Daily Individual Subcatchment Runoff,
- Accumulated Daily Streamflows,
- Individual Subcatchment Runoff Water Temperature,
- a Water Temperature Index, and
- Mixed Water Temperature.

Each parameter was analysed separately, with a brief description of the parameter being provided at the beginning of each sub-section. The spatial analysis was performed for the following scenarios (cf. **Chapter 6.7** for full description):

- Baseline (i.e. historical observed) Climate (1971 - 1990),
- Present Climate from the ECHAM5 GCM (1971 - 1990), an
- Intermediate Future Climate (2046 - 2065), and a more
- Distant Future Climate (2081 - 2100).

Each analysis was performed for mean annual responses and for those of four selected cardinal months, with January representing mid-summer conditions, April considered typical of autumn, July of mid-winter and October of spring. The annual results show overall trends for each scenario while the monthly time scale focuses on intra-annual differences. A comparison between the baseline historical scenario and the present climate generated by the GCM illustrates how well ECHAM5 is simulating the historically observed climate.

For all water temperature related analyses presented in the remainder of this chapter the computer programmes were written by Mr R.P. Kunz of the School of BEEH at the University of KwaZulu-Natal. His contribution is gratefully acknowledged. Furthermore, on all maps which follow in this Chapter the term "Intermediate" refers to the intermediate future climate scenario (2046 - 2065) while "Future" refers to the more distant future climate scenario (2081 - 2100).

The spatial analysis for all water temperature related parameters comprises a ratio comparison, at mean annual level, between the three ECHAM5 climate scenarios, more specifically the ratios of intermediate future to present, distant future to present and future to intermediate future climates, in order to determine how a particular parameter is projected to be changing from one scenario to the next. The monthly analysis similarly consists of comparisons between the baseline and present GCM scenarios for purposes of validation, as well as ratio comparisons between the intermediate to present and the future to present climate scenarios to assess spatial trends and projected rates of changes of the water temperature related parameters.

8.2 Mean Air Temperature

Mean daily air temperature (°C) is calculated by averaging the daily maximum and minimum air temperatures. Mean air temperature is an important factor for a number of hydrological and ecological processes such as evaporation and growth rates (cf. Schulze, 2007).

8.2.1 Mean annual air temperature

Figure 8.1 displays the mean annual air temperature (MAT) for the 258 Quinary Catchments making up the Thukela Catchment, for the four scenarios described in **Chapter 6**. When comparing MAT from present baseline climate (**Figure 8.1** top left) with that from the present

ECHAM5 climate (**Figure 8.1** top right) the results indicate that the ECHAM5 GCM is performing well, with a slight under-simulation of MAT in the western parts of the catchment.

Overall, however, there is a close correspondence between the MAT from historical air temperature data and that simulated from the GCM. Both the historical baseline and ECHAM5 present scenarios indicate that the high altitude Drakensberg areas in the west experience the lowest MATs (+/- 11 °C) and that air temperatures increase towards the coast (+/- 21 °C), which is expected. A comparison between the ECHAM5 scenarios indicates a strong warming trend over time, particularly in the central parts of the Thukela catchment, with the ECHAM5 distant future climate scenario showing the greatest deviation from that of the present climate.

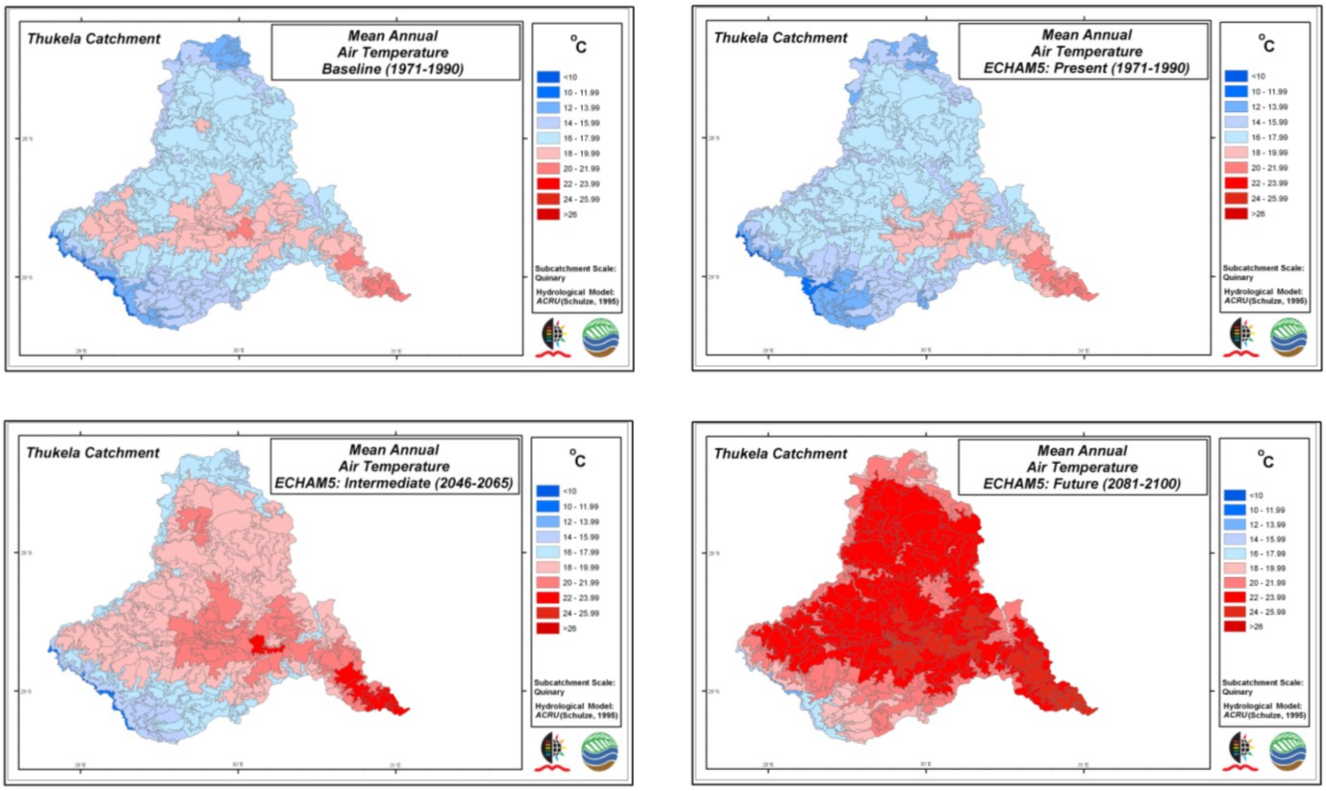

Figure 8.1 Mean annual air temperature per Quinary Catchment in the Thukela for (top left) present baseline climate, (top right) the present ECHAM5 climate scenario, (bottom left) the intermediate future ECHAM5 and (bottom right) the distant future ECHAM5 climate scenarios

8.2.2 Projected changes in future mean annual air temperatures

Figure 8.2 displays differences in MATs between the three ECHAM 5 climate scenarios for the Thukela catchment. All three maps indicate that there will be increases in MAT under projected future climatic conditions. The difference between intermediate and present climates is presented in the top left map in **Figure 8.2** and indicates that all Quinaries will experience virtually uniform increases in MAT of approximately 2 - 3 °C over this time 75 year time period (2046-65 vs 1971-90). The map of future minus present MAT (**Figure 8.2** top right) displays the greatest increase in MAT, with the maximum change occurring in northwestern region of the Catchment, where an increase of around 7 °C is projected. This increase could have a dramatic effect on the sensitive mountain ecosystems located in this region. The central parts of the catchment are projected to experience a temperature increase in the region of 5 - 6 °C while the lower parts of the catchment show less change, with a projected increase of 4 - 5 °C. These major increases in MAT are explained by the map of distant future minus intermediate future ECHAM5 climate scenarios (**Figure 8.2** bottom), with projected increases in MAT for all Quinaries in the Thukela, but with the central areas increasing by 3 - 4 °C over this 35 year period (2081 - 2100 vs 2046 - 65), while the lower reaches show less of a temperature increase, echoing the statement above that the more coastal area appear sensitive to projected climate change.

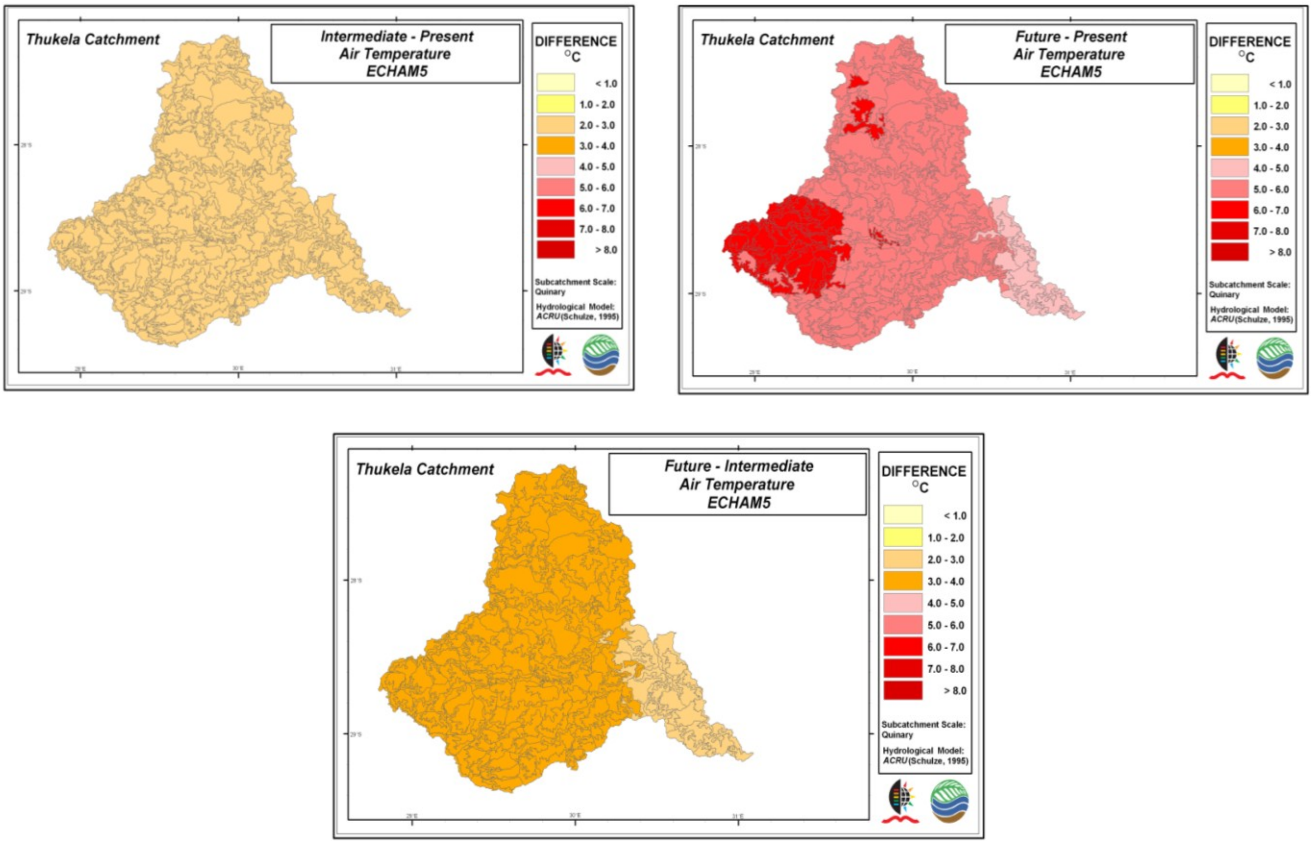

Figure 8.2 Differences in mean annual air temperatures per Quinary Catchment in the Thukela between (top left) intermediate future and present, (top right) distant future and present and (bottom) distant future and intermediate future climate scenarios from the ECHAM5 GCM

8.2.3 Projected changes in future means of air temperature for selected months

Figures 8.3 through **8.6** display the results of an analysis of mean air temperature for four cardinal months in the Thukela Catchment performed at Quinary Catchment scale. The top left map in each of these figures displays the historical mean air temperatures for that particular month, the top right map always displays the temperatures from the present ECHAM5 climate scenario for that particular cardinal month, while the bottom maps in each figure display the differences between future ECHAM5 scenarios for mean air temperature for that particular cardinal month, with the intermediate future minus present temperatures displayed in the bottom left map and the distant future minus present temperatures displayed in the bottom right map. This monthly analysis reveals that January (mid-summer; **Figure 8.3**) is the warmest of the four months selected while July (mid-winter) is the coldest, with April (autumn) and October (spring) experiencing mean air temperatures which are similar to one another and which fall between the two more extremes months.

A comparison between present baseline climate (**Figures 8.3 - 8.6** top left) and present ECHAM5 climate (**Figure 8.3 - 8.6** top right) indicates that the ECHAM5 GCM is under-simulating mean air temperatures in January (**Figure 8.3**) and October (**Figure 8.6**) by between 0.1 and 3.9 ^{o}C, particularly evident in the central and western parts of the Thukela Catchment. Conversely, the comparison between present baseline and present ECHAM5 climates for the month of July indicates that the GCM is, in fact, over-simulating air temperatures for large portions of the catchment while April mean air temperatures (**Figure 8.4**) actually reveal a close correlation between the present historical climate and the present ECHAM5 climate. These results suggest that there are significant intra-annual differences between the historical climate data and the simulated ECHAM5 present climate, and that a simple annual analysis (**Section 8.2.1**) can mask many of these differences.

The bottom left map in **Figures 8.3 - 8.6** displays the differences between the intermediate future and present ECHAM5 climate scenarios for the four cardinal months. All months project that all the Quinaries in the Thukela Catchment will experience an increase in air temperature over this 75 year time period. The months of April, July and October all project increases of between 2 and 4 °C in mean air temperature. Furthermore, these months reveal that the lower (eastern) reaches of the Thukela are less prone to projected temperature increases than the central and upper (more western) parts. It is projected that January (**Figure 8.3** bottom left) will experience less of an increase compared to that of the other three selected months, with most of the catchment only experiencing a 1 to 2 °C increase in air temperature. The bottom right map in **Figures 8.3** - **8.6** illustrates the differences between the more distant future and present ECHAM5 climate scenarios for the four cardinal months. As expected, these maps show far greater changes in mean air temperature over the 110-year period (2081 - 2100 vs 1971 - 1990). This set of maps does, however, follow the same trends as those of the intermediate future minus present analysis, with all Quinaries experiencing significant increases in air temperature. Again, air temperature for the month of January shows less of an increase compared to that of the other three selected months. The western Drakensberg appears to be particularly sensitive to a projected change in air temperature, with this region likely to experience increases of up to 8 °C for the months of April, July and October according to ECHAM5 climate projections.

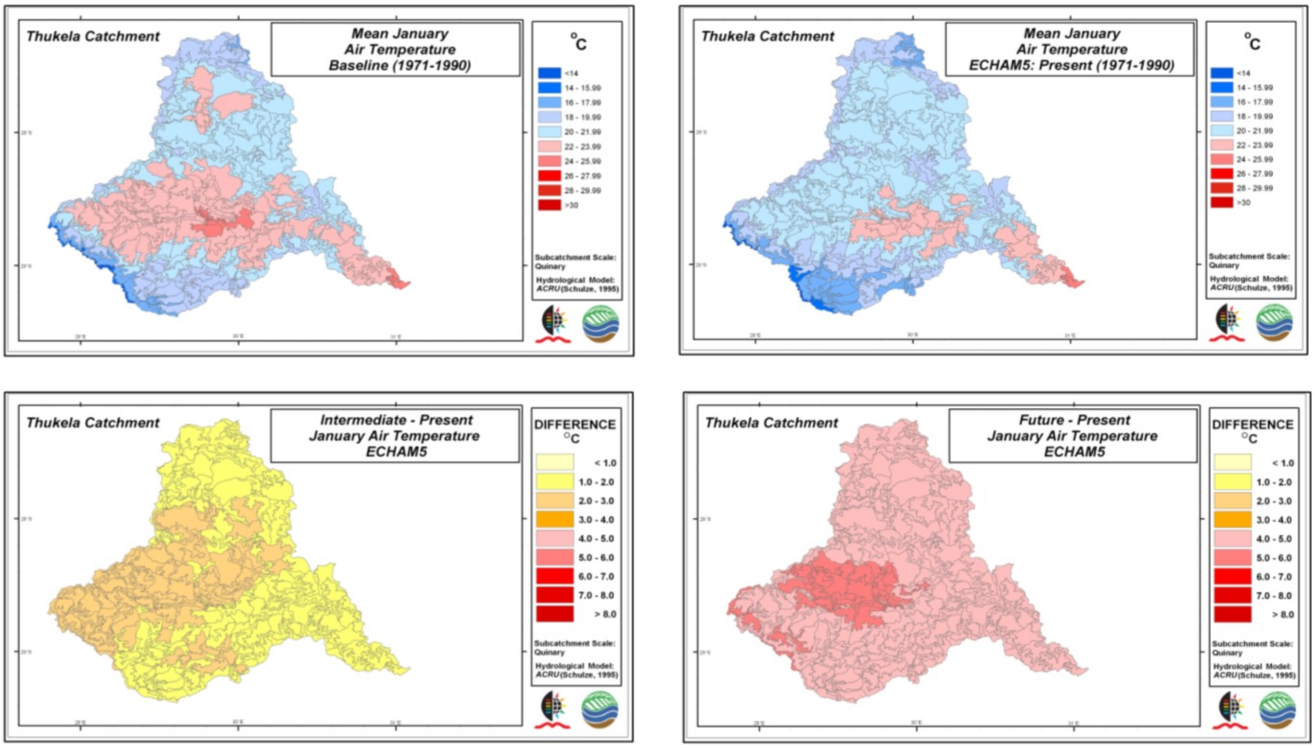

Figure 8.3 Mean January air temperatures in the Thukela Catchment for (top left) present baseline climate vs (top right) present ECHAM5 climate, and differences between projected January intermediate future and present (bottom left), and distant future and present (bottom right) air temperatures

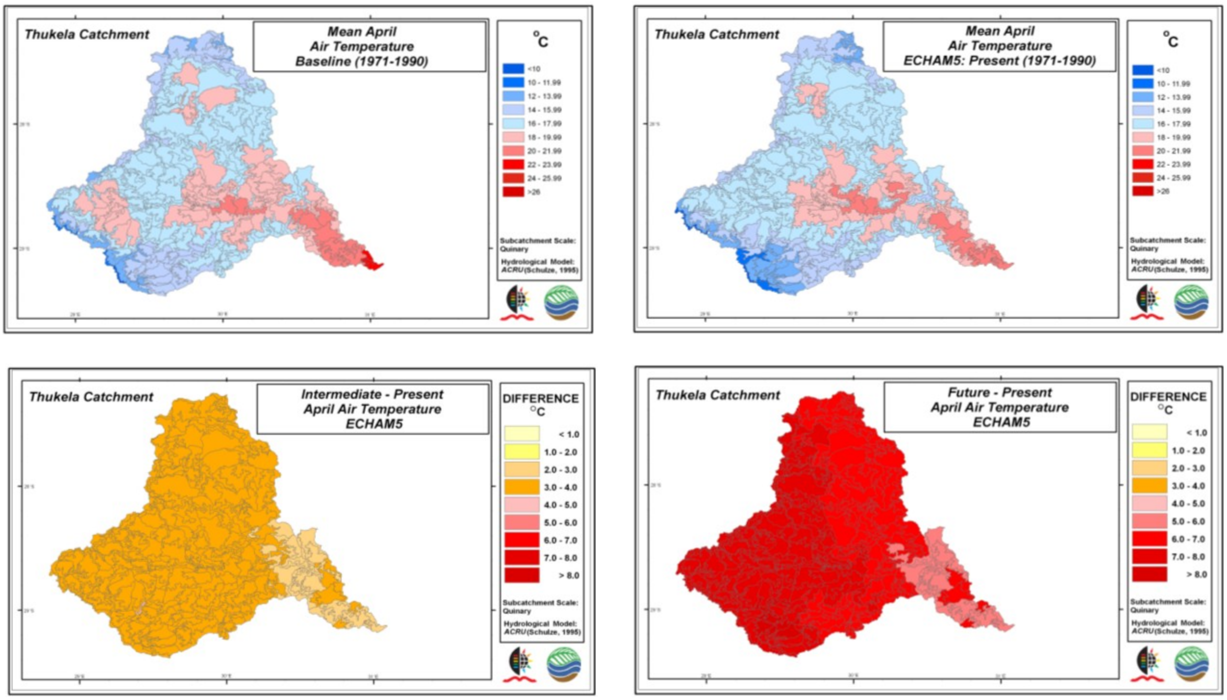

Figure 8.4 Mean April air temperatures in the Thukela Catchment for (top left) present baseline climate vs (top right) present ECHAM5 climate, and differences between projected April intermediate future and present (bottom left), and distant future and present (bottom right) air temperatures

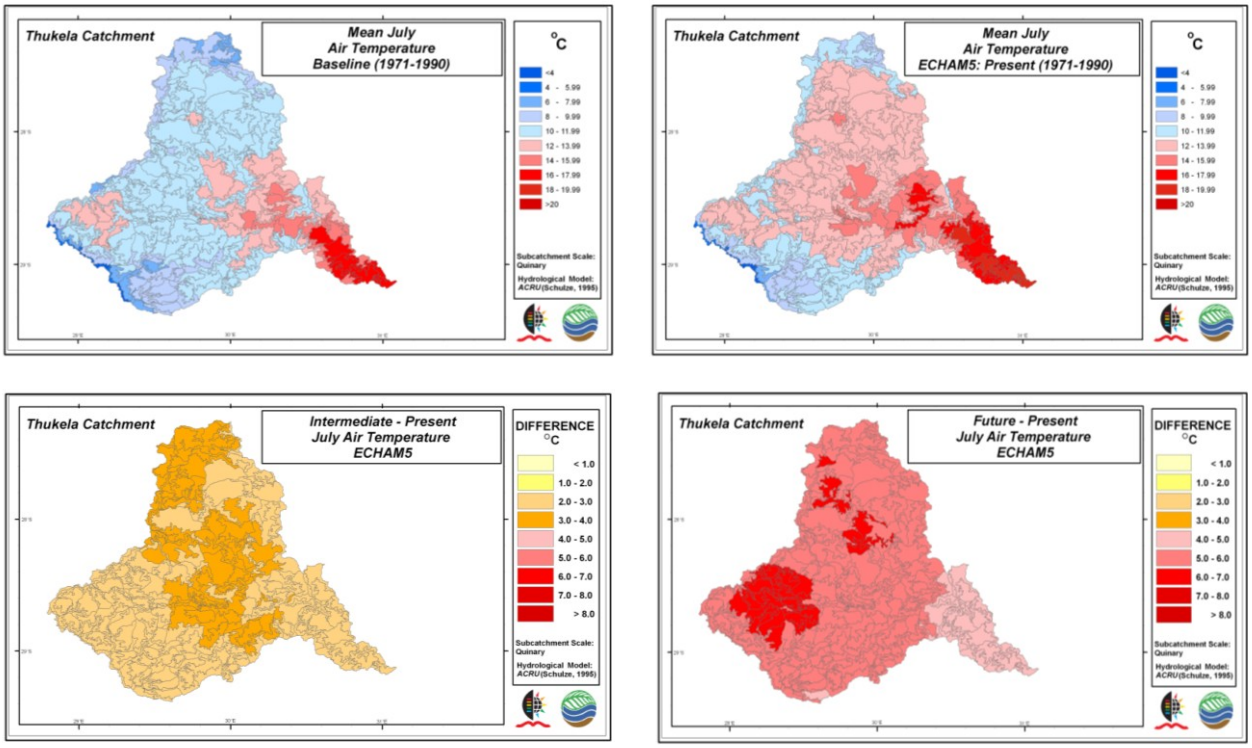

Figure 8.5 Mean July air temperatures in the Thukela Catchment for (top left) present baseline climate vs (top right) present ECHAM5 climate, and differences between projected July intermediate future and present (bottom left), and distant future and present (bottom right) air temperatures

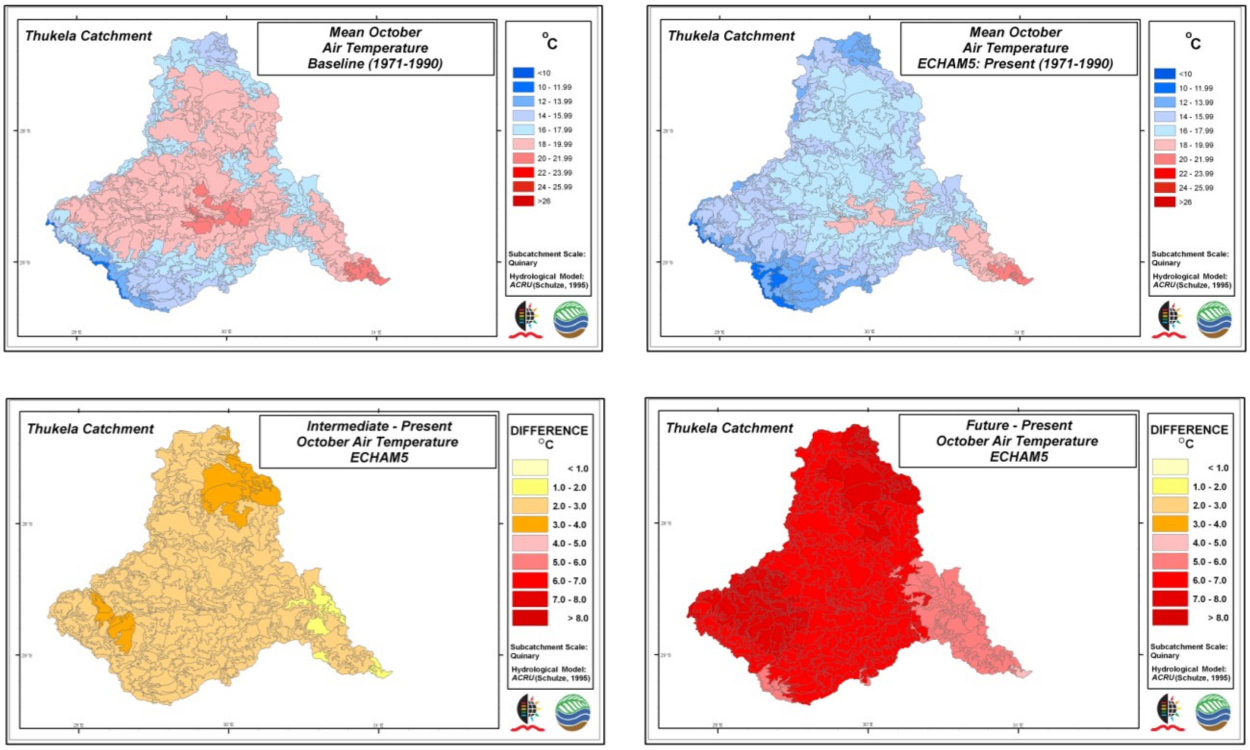

Figure 8.6 Mean October air temperatures in the Thukela Catchment for (top left) present baseline climate vs (top right) present ECHAM5 climate, and differences between projected October intermediate future and present (bottom left), and distant future and present (bottom right) air temperatures

8.3 Runoff from Individual Subcatchments

Simulated runoff from individual subcatchments is an output from the ACRU model and is defined as the sum of stormflows and baseflows, from only the subcatchment in question, excluding any contributions from upstream catchments (Schulze, 1995). The ACRU model outputs this variable in millimetre (mm) equivalents and it is subsequently converted to cubic metres (m^3) using the subcatchment area. An analysis of individual subcatchment runoff is important because adding accumulated streamflows from upstream can mask the runoff characteristics of the individual subcatchment in question. Furthermore, it is vital in aquatic ecological studies to have an idea of how the individual subcatchment's flows are likely to respond to projected climate change.

The analysis was performed at two temporal scales, *viz*. for annual flows and for those of selected cardinal months (January = summer, April = autumn, July = winter and October = spring). The annual results can be utilised to reveal overall trends for each scenario while the monthly time scale provides a more focussed representation in order to determine intra-annual (seasonal) differences. A comparison between the baseline historical scenario and the present scenario is required to judge how well the selected GCM is simulating the present observed climate and, hence, runoff. The analysis of individual subcatchment runoff also includes ratio comparisons between the three ECHAM5 scenarios, *viz*. Intermediate Future to Present, Distant Future to Present and Distant Future to Intermediate Future climate scenarios, in order to determine how individual subcatchment runoff is changing from one scenario to the next.

8.3.1 Mean annual runoff from individual subcatchments

Figure 8.7 displays the mean annual runoff from individual subcatchments within the Thukela Catchment for the four scenarios described in **Chapter 6**. When comparing results from present baseline climate (top left) and present ECHAM5 climate (top right), these indicate that ECHAM5 tends to under-simulate annual individual subcatchment runoff, especially in the central and northern areas of the Thukela Catchment. When comparing the ECHAM5 scenarios, results indicate that there will be a marked increase in projected annual subcatchment runoff, with the distant future scenario (bottom right) showing the greatest change compared to that of the present ECHAM5 climate (top right).

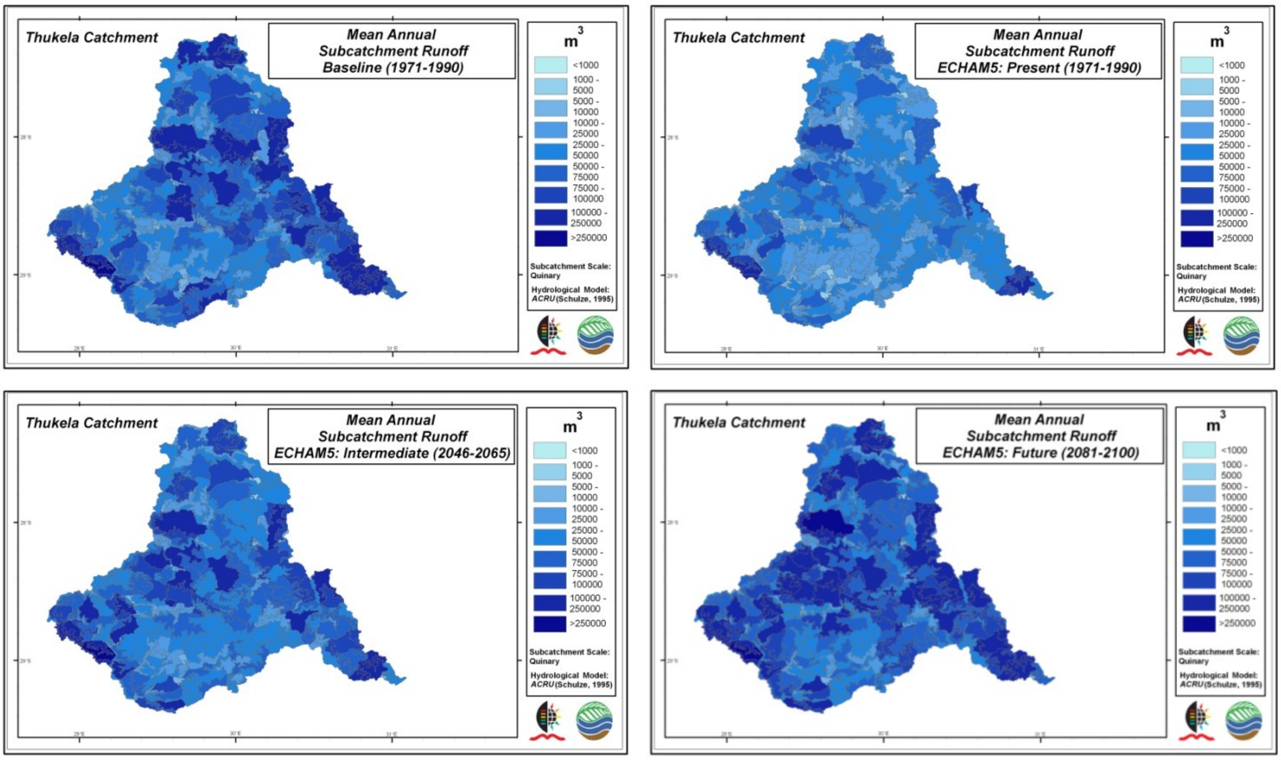

Figure 8.7 Simulated mean annual subcatchment runoff for (top left) present baseline climate, (top right) present ECHAM5 climate, (bottom left) intermediate future ECHAM5 climate and (bottom right) distant future ECHAM5 climate

8.3.2 Projected changes in future annual runoff from individual subcatchments

Figure 8.8 displays the ratios between the three ECHAM 5 scenarios for mean annual runoff from the individual subcatchments making up the Thukela Catchment. All maps indicate that there will be an increase in simulated individual subcatchment runoff under projected future conditions. The ratio map of distant future to present ECHAM5 climates (top right) illustrates the greatest change in individual subcatchment runoff, with most Quinaries showing an increase of between 2 and 3 times compared to that of the simulated runoff from the present ECHAM5 climate. The other two ratio comparisons between intermediate future and present (top left) and the distant and intermediate future climates (bottom) also indicate increases in individual catchment runoff, but to a lesser degree, with average increases by a factor of 1.2 and 1.6. The reason for the distant future to present ratio map (top left) showing the greatest change is that the present climate scenario time period (1971 - 1990) and the future climate scenario time period (2081 - 2100) are 110 years apart, from the commencement of their respective simulation periods - this compared with the difference between the intermediate and future climate scenarios only being 35 years from the start of their respective simulation periods.

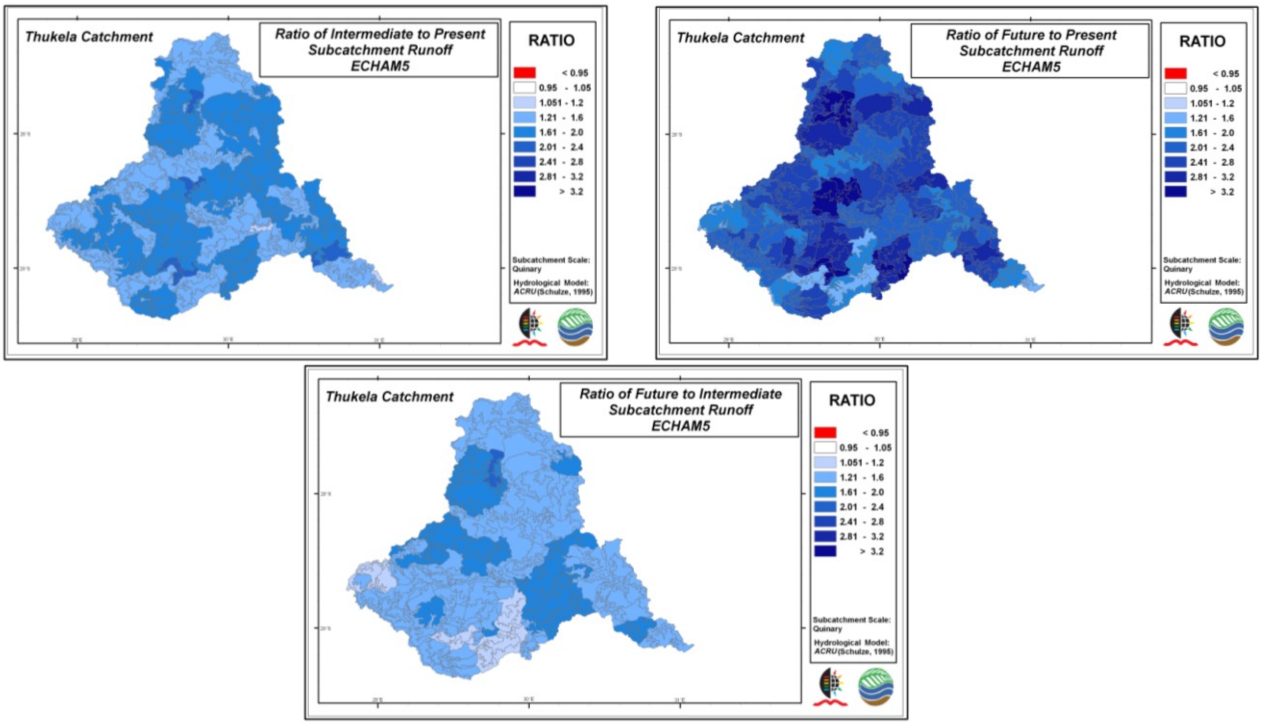

Figure 8.8 Ratios of annual runoff from individual subcatchments for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

8.3.3 Projected changes in future means of runoff from individual subcatchments for selected months

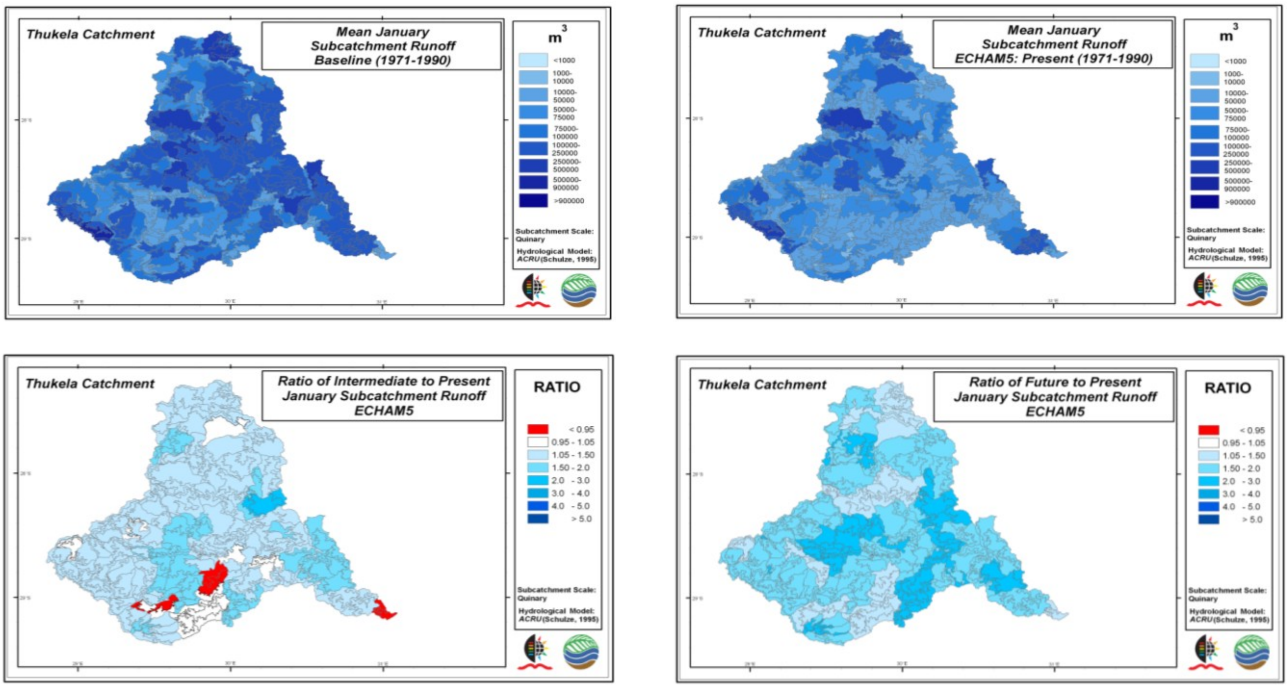

Figure 8.9 Simulated mean January subcatchment runoff for (top left) present baseline climate vs (top right) present ECHAM5 climates, and ratios of January runoff from individual subcatchments for (bottom left) intermediate future to present and (bottom right) distant future to present climate scenarios

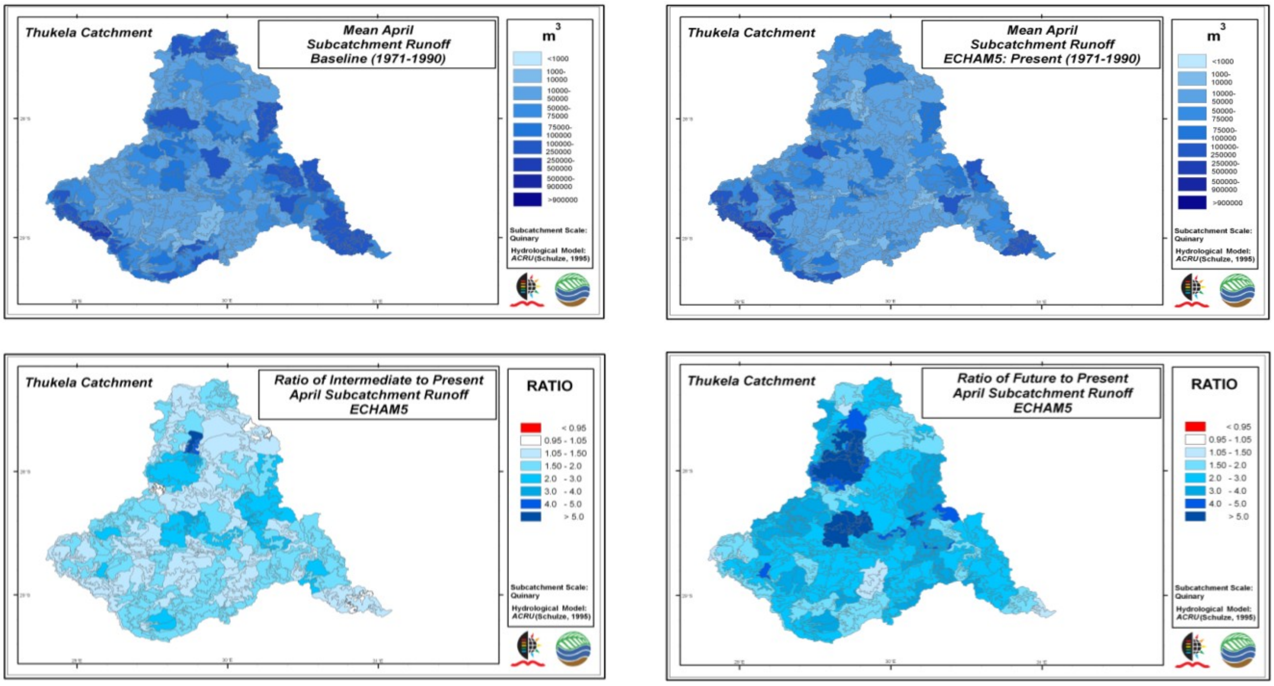

Figure 8.10 Simulated mean April subcatchment runoff for (top left) present baseline climate vs (top right) present ECHAM5 climates, and ratios of April runoff from individual subcatchments for (bottom left) future intermediate to present and (bottom right) distant future to present climate scenarios

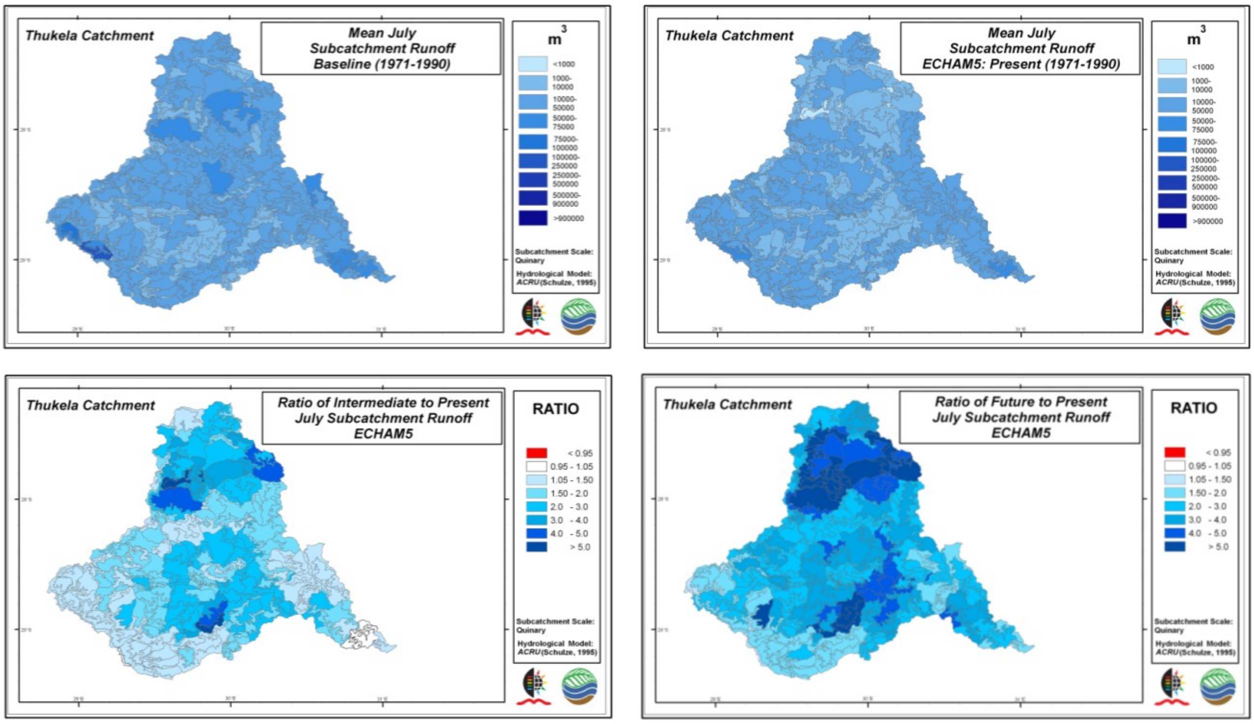

Figure 8.11 Simulated mean July subcatchment runoff for (top left) present baseline climate vs (top right) present ECHAM5 climate and ratios of July runoff from individual subcatchments for (bottom left) intermediate future to present and (bottom right) distant future to present climate scenarios

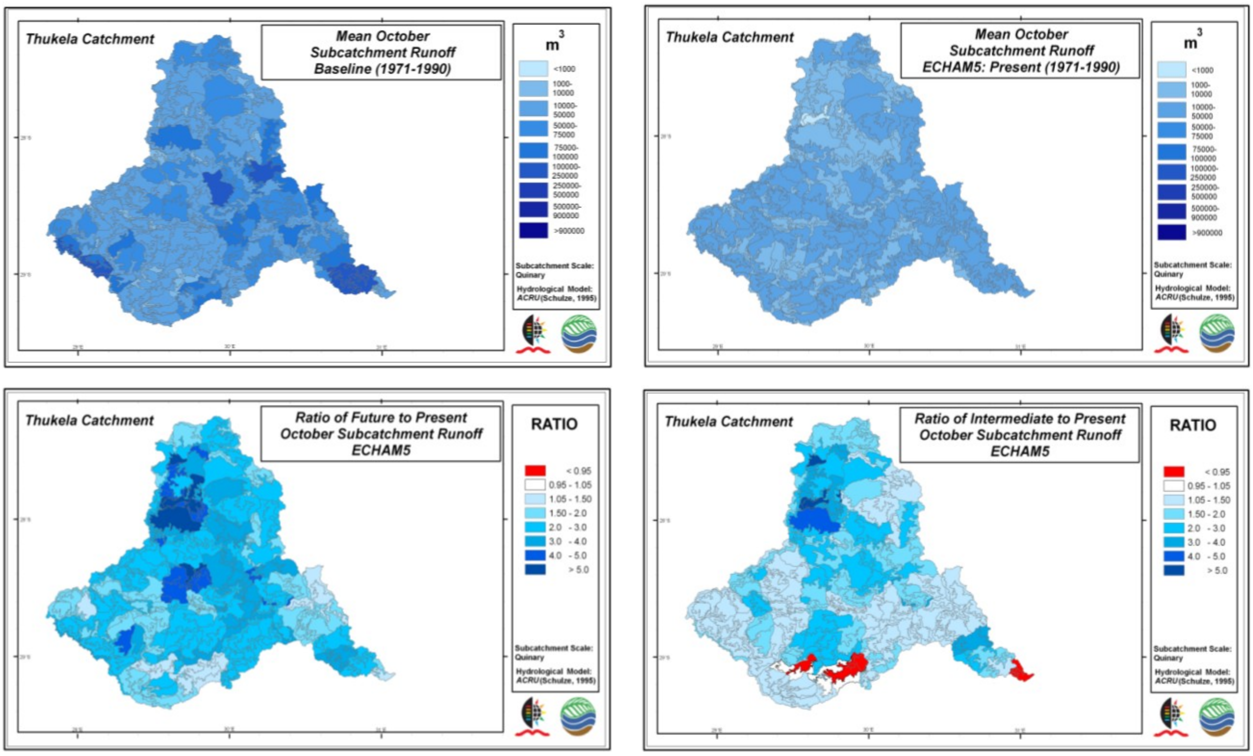

Figure 8.12 Simulated mean October subcatchment runoff for (top left) present baseline climate vs (top right) present ECHAM5 climate and ratios of October runoff from individual subcatchments for (bottom left) intermediate future to present and (bottom right) distant future to present climate scenarios

When comparing simulated mean January individual subcatchment runoff from present ECHAM5 climate (**Figure 8.9** top right) with that from the present baseline climate (**Figure 8.9** top left) it may be seen that the ECHAM5 GCM is under-simulating runoff by a large amount. This under-simulation is particularly noticeable in the central and northeasterly parts of the Thukela Catchment. Scrutiny of daily rainfall files from the ECHAM5 GCM indicates that this GCM appears to be under-simulating large flood producing events, often probably in the form of more local convective storms, which are common in mid-summer in this region of southern Africa. The January ratio map for runoff from intermediate future to present projected climates (**Figure 8.9** bottom left) indicates that a large majority of the Quinary subcatchments in the Thukela Catchment will experience an increase in runoff. A small number of Quinaries nevertheless display no change or even a slight decrease in individual catchment runoff. However, the overall trend seems to indicate an increase in runoff for January of between 1.05 and 1.50 times. This trend continues when comparing the runoff generated from distant future to present ECHAM5 January climate scenarios (**Figure 8.9** bottom right), where all Quinaries in the Thukela show a definite increase in individual subcatchment runoff of between 1.50 and 2.00 times.

When comparing simulated mean April individual subcatchment runoff for present ECHAM5 climate (**Figure 8.10** top right) with that from the present baseline climate (**Figure 8.10** top left), it may be seen that runoff generated by this GCM shows a close correlation with that generated from the historical climate. This strong correlation indicates that the GCM simulation appears to be performing better for this time of the year compared to that of the January analysis (**Section 8.2.3**). This may either signify that the GCM is able to simulate smaller (often frontal) and more general rainfall events more accurately than in mid-summer, and thus performs better in the drier months of the year, or that runoff more likely takes the form of baseflow rather than convective event driven stormflow. The April ratio maps for the projected future climates (**Figure 8.10** bottom left and right) both show an overall increase in individual catchment runoff, with the distant future to present comparison illustrating the greatest changes with some Quinaries showing a 5-fold increase in runoff.

The comparison between simulated mean July individual catchment runoff for present ECHAM5 climate (**Figure 8.11** top right) and the present baseline climate (**Figure 8.11** top left) indicates that the GCM has an almost perfect correspondence with the historical climate, again echoing the point that ECHAM5 performs well in the drier parts of the year. The intermediate future to present ratio map for July (**Figure 8.11** bottom left) shows that almost all Quinaries in the Thukela will experience an increase in individual catchment runoff in the intermediate future, with the central parts of the catchment showing an increase of between 200 and 300%. The distant future to present ratio map (**Figure 8.11** bottom right) also has a wetting trend, but to a far greater degree, with a number of Quinaries in the northern reaches of the Buffalo experiencing a 5-fold increase.

When comparing the mean October present baseline climate (**Figure 8.12** top left) with the mean October present ECHAM5 climate (**Figure 8.12** top right) the results indicate that ECHAM5 is tending to under-simulate rainfall events which is leading to an under-simulation in the individual subcatchment runoff. Like January, October is a month when rainfall is relatively high in the Thukela and this causes a decrease in correlation between the historical climate and the simulated present climate from the GCM. The intermediate future to present ratio map for October (**Figure 8.12** bottom left) points towards an overall increase in individual catchment runoff, with the majority Quinaries in the Thukela experiencing an increase of between 105 and 150%. The distant future to present ratio map for October (**Figure 8.12** bottom right) also reveals a strong wetting pattern in the distant future, with the Buffalo subcatchment being particularly sensitive to projected climate change.

8.4 Accumulated Catchment Streamflows

Accumulated streamflow is an output from the *ACRU* model and is defined as the total summed streamflow from a (sub)catchment which also includes any contributions from upstream catchments (Schulze, 1995). The *ACRU* model outputs this variable in millimetre (mm) equivalents and it is subsequently converted to cubic metres (m^3) using the (sub) catchment area. An analysis of accumulated catchment streamflow is important in water temperature studies not only because it is the integral of all flows which were generated upstream of the point of interest, but also because it is used in the determination of the volume related water temperature of the entire catchment.

8.4.1 Mean annual accumulated catchment streamflows

Figure 8.13 displays the mean annual accumulated streamflows per Quinary Catchment for the entire Thukela Catchment, for the four climate scenarios described in **Chapter 6**. When comparing accumulated streamflows generated from present baseline climate (**Figure 8.1** top left) and the present ECHAM5 climate (**Figure 8.1** top right), the results indicate that the simulations are generally closely correlated, with both these scenarios clearly showing the accumulations of streamflows in the major tributaries in Thukela Catchment with the same/similar darker blue colours on the respective maps. There is, however, a slight under-simulation of generated streamflows in the central parts of the Thukela when using the present ECHAM5 GCM climate as input. Although the wide range within the class intervals makes interpretations difficult, a comparison between the accumulated streamflows derived from the intermediate and more distant future ECHAM5 climate scenarios indicates a wetting trend over time, particularly in the central parts of the Thukela Catchment.

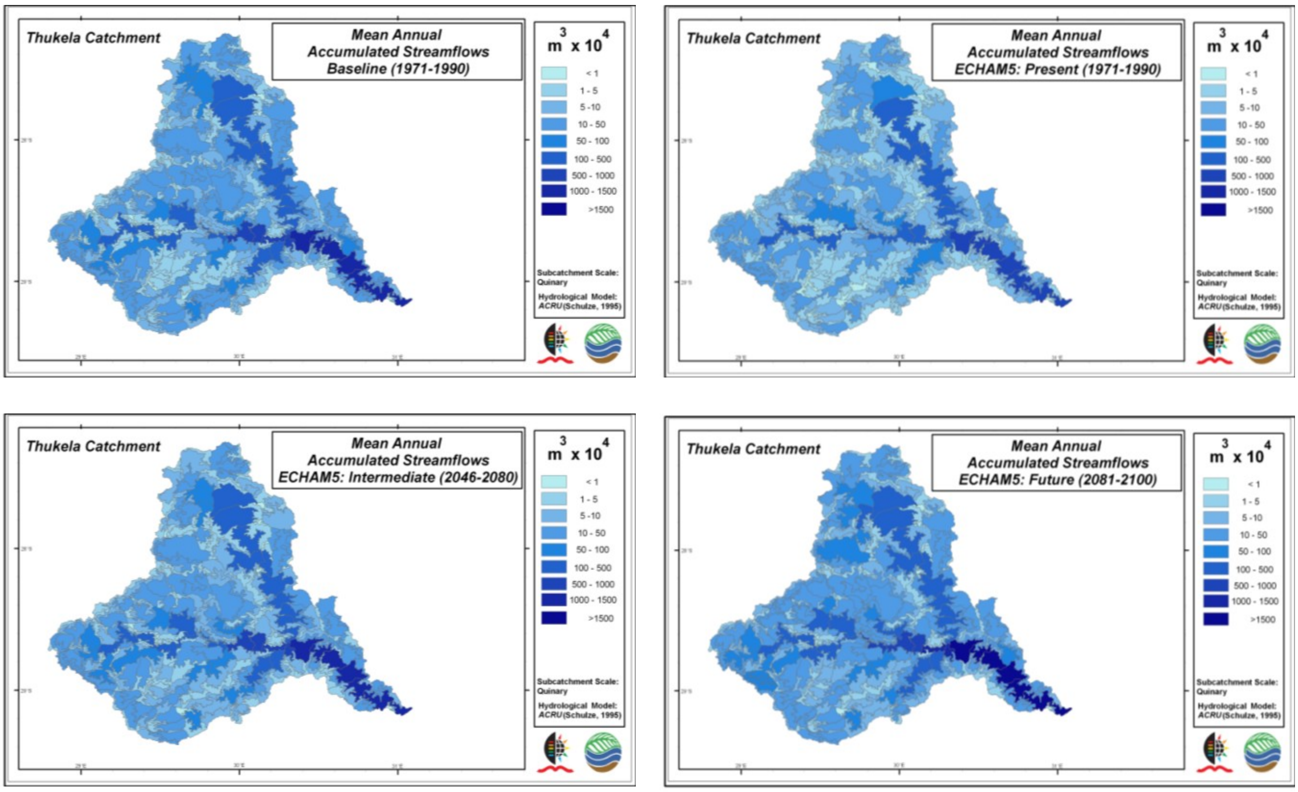

Figure 8.13 Simulated mean annual accumulated streamflows for (top left) present baseline climate, (top right) present ECHAM5 climate, (bottom left) intermediate future ECHAM5 climate and (bottom right) distant future ECHAM5 climate

8.4.2 Projected changes in future annual accumulated catchment streamflows

Figure 8.14 displays the ratio comparisons for the Thukela catchment of mean annual accumulated streamflows between the three ECHAM 5 climate scenarios. All maps indicate that there will be increases in accumulated streamflows under projected future climate conditions.

The ratio map of (distant) future to present ECHAM5 climates (top left) displays the greatest change in accumulated streamflows, with most Quinaries showing a doubling and even tripling compared to that simulated from the present ECHAM5 climate scenario. The other two ratio comparisons between the intermediate future and present (top left), and the more distant and intermediate futures (bottom), also point to increases in accumulated streamflows, but to a lesser degree, with average increases by a factor of 1.2 to 1.6.

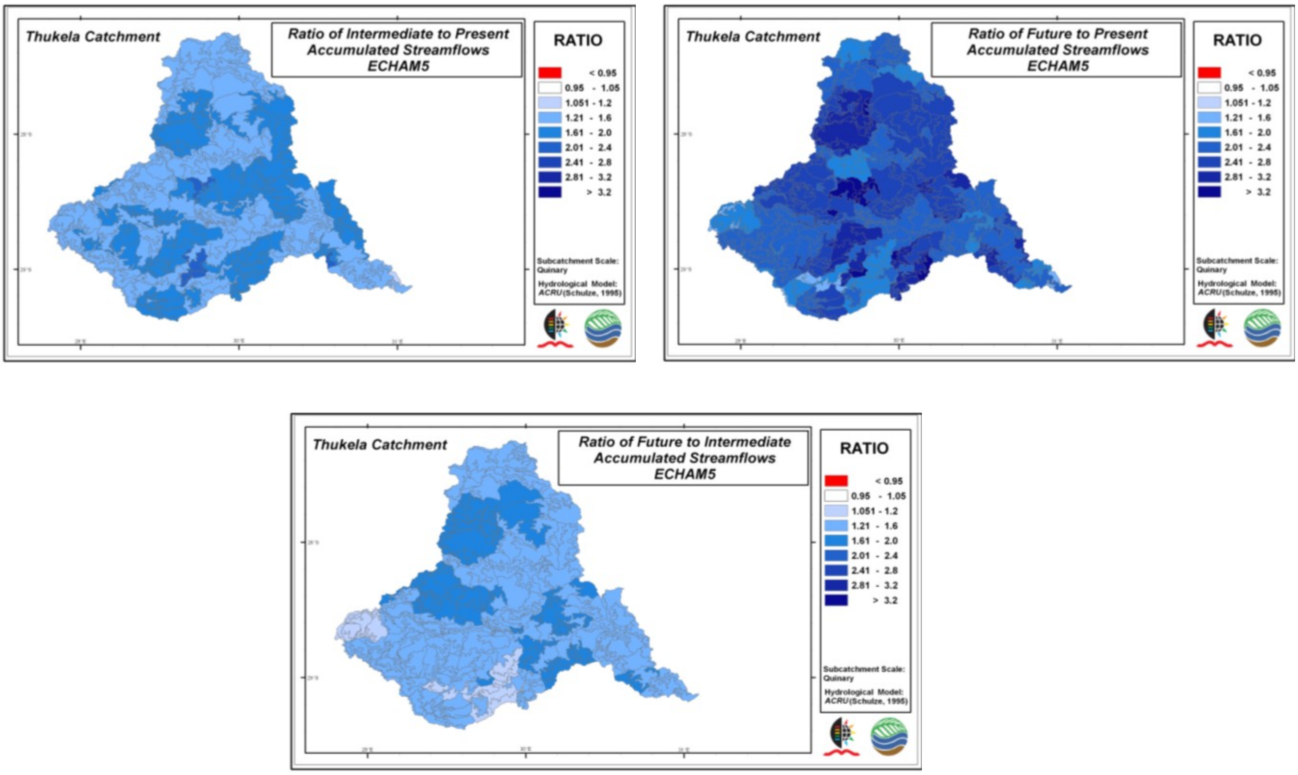

Figure 8.14 Ratios of mean annual accumulated streamflows for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

8.4.3 Projected Changes in future means of annual accumulated catchment streamflows for selected months

An analysis of the four selected cardinal months shows that, as expected in a summer rainfall region, January displays the highest accumulated streamflows, July experiences the lowest streamflows while April and October shows similar spatial patterns of streamflows typical of transitional seasons. An evaluation of monthly accumulated streamflows generated from the baseline present climate and the ECHAM5 present climate (**Figures 8.15 - 8.18**) indicates that there is generally a good correlation between these two scenarios, however, with the present ECHAM5 climate tending to under-simulate accumulated streamflows in all four selected months, most noticeably in October.

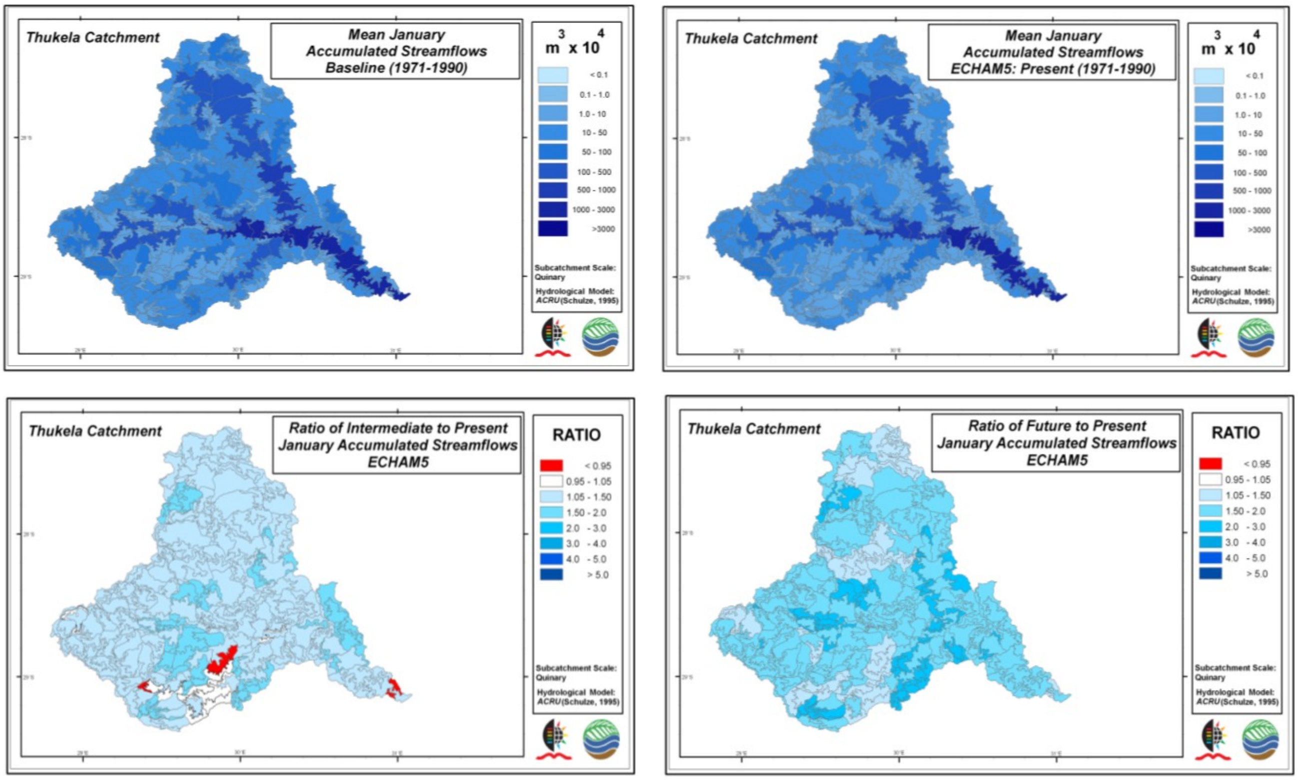

Figure 8.15 Simulated January means of accumulated streamflows generated from (top left) present baseline climate vs (top right) present ECHAM5 climate, and ratios of January accumulated streamflows for (bottom left) intermediate future to present and (bottom right) distant future to present climate scenario

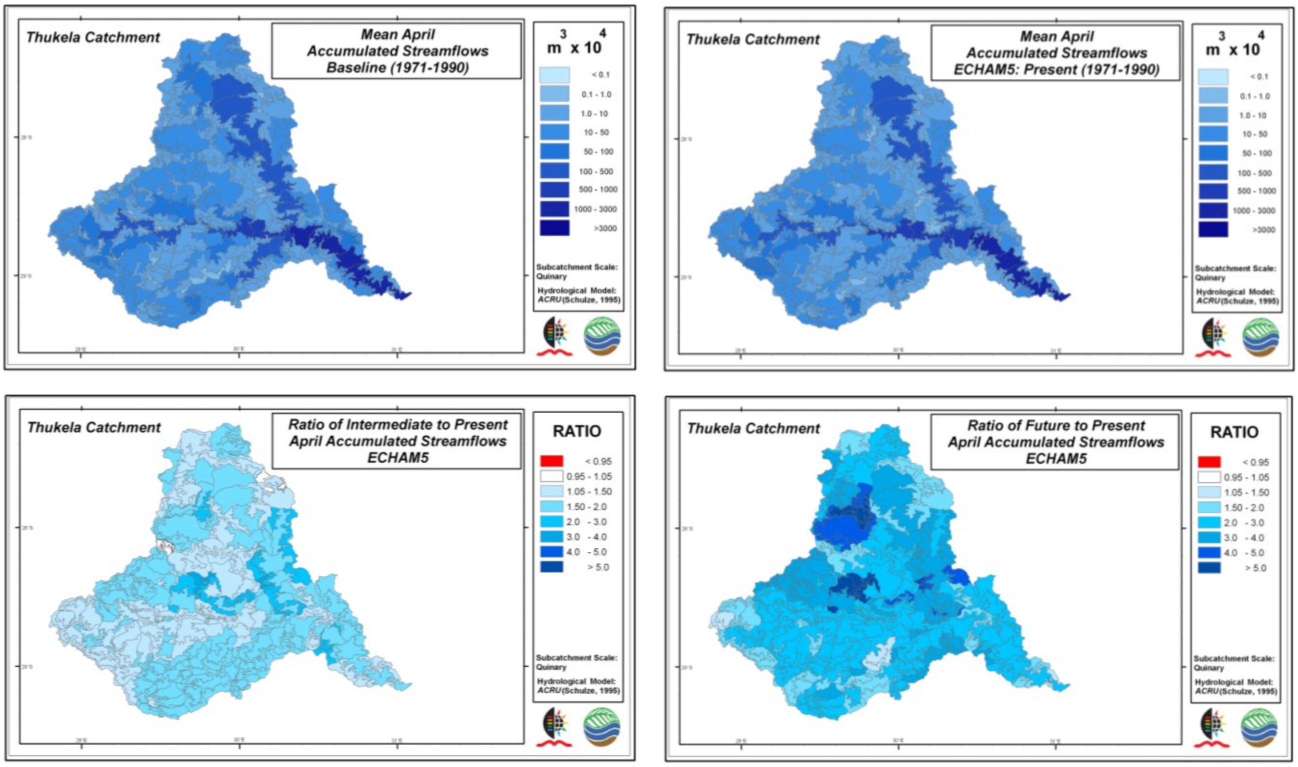

Figure 8.16 Simulated April means of accumulated streamflows generated from (top left) present baseline climate vs (top right) present ECHAM5 climate, and ratios of April accumulated streamflows for (bottom left) intermediate future to present and (bottom right) distant future to present climate scenarios

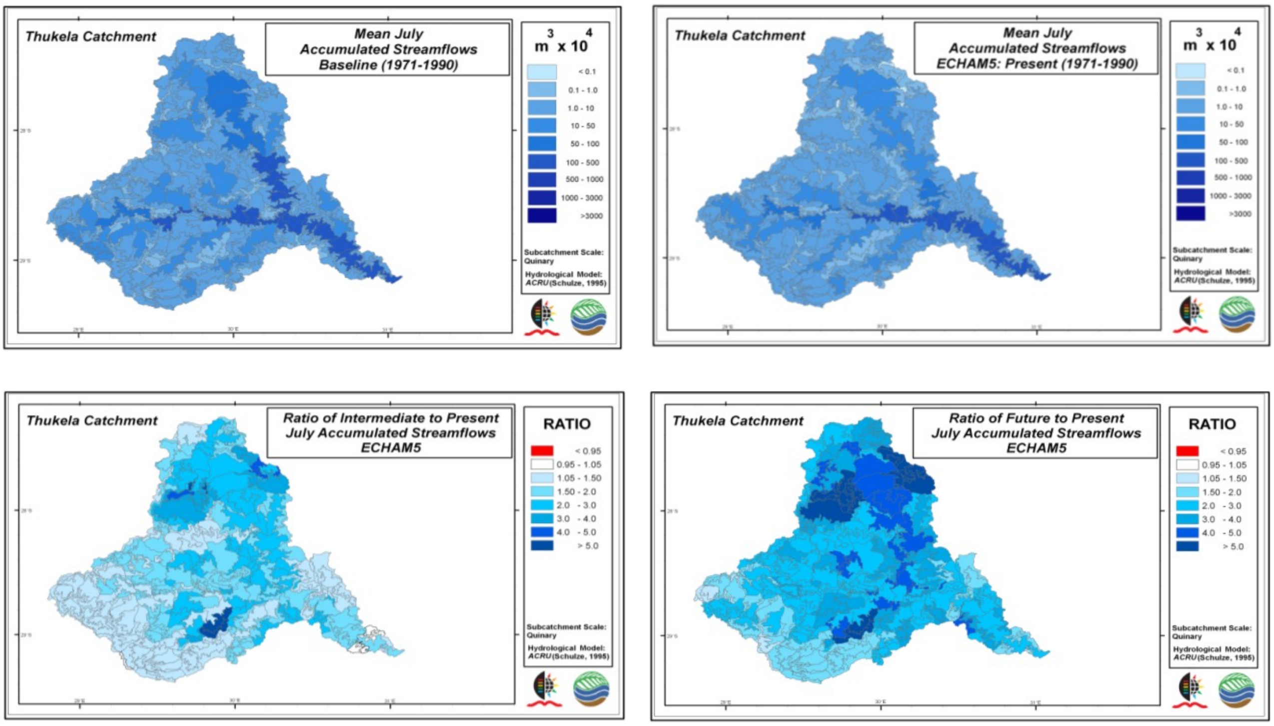

Figure 8.17 Simulated July means of accumulated streamflows generated from (top left) present baseline climate vs (top right) present ECHAM5 climate, and ratios of July accumulated streamflows for (bottom left) intermediate future to present and (bottom right) distant future to present climate scenarios

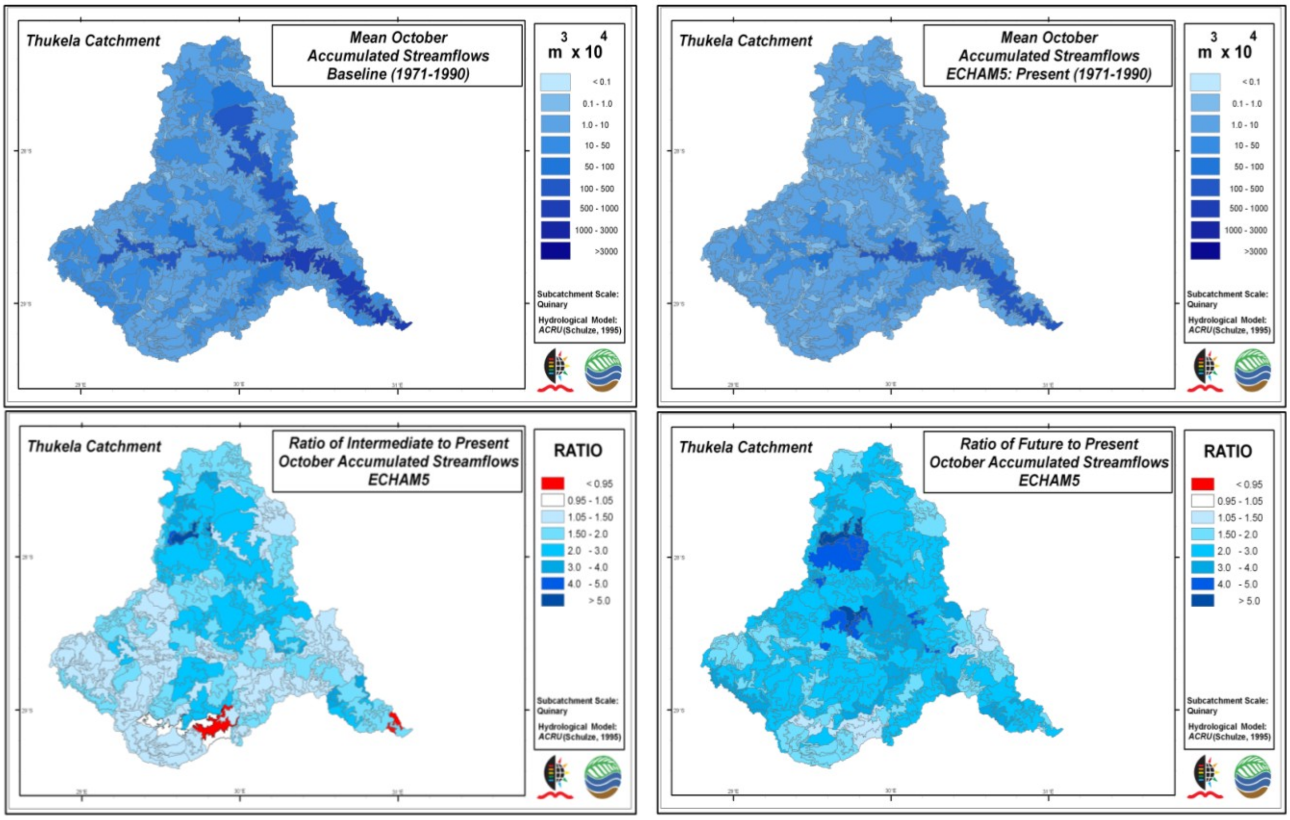

Figure 8.18 Simulated October means of accumulated streamflows generated from (top left) present baseline climate vs (top right) present ECHAM5 climate, and ratios of October accumulated streamflows for (bottom left) intermediate future to present and (bottom right) distant future to present climate scenarios

A ratio analysis between the three ECHAM5 climate scenarios for each of the four cardinal months was also performed for the accumulated streamflows (**Figures 8.15 - 8.18** bottom left and right). An overall examination of each of the cardinal months reveals an increase in accumulated streamflows over time for all future climate scenarios. However, a few Quinaries in the southwestern corner of the Thukela experience no significant changes in volumes, or even in a decrease in accumulated streamflows for the months of January and October, but this going against the overall trend of streamflow increases. The intermediate future to present ratio map for January (**Figure 8.15** bottom left) suggests that the mid-summer season is less sensitive to changes in accumulated streamflows under conditions of projected climate change compared to the three months representing the other seasons. The ratio change in accumulated streamflows for most Quinaries is generally between 1.05 and 1.50 for January, while the other three cardinal months in the non-rainy season project somewhat higher ratios of between 1.50 and 2.00, indicative of higher contributions from baseflows.

The bottom right maps in **Figures 8.15 - 8.18** illustrate the differences between the more distant future and present ECHAM5 climate scenarios for the four cardinal months. As expected, these maps show far greater ratio changes in accumulated streamflows than the intermediate future to present maps. Again January (**Figure 8.15** bottom right) seems to be less sensitive to projected climate change while July (**Figure 8.17** bottom right) shows a large ratio change, with the upper Buffalo tributary of the Thukela Catchment seeming to be particularly sensitive, with some Quinaries experiencing flow increases of between 4 and 5 times compared to present accumulated streamflow volumes. April and October (**Figure 8.16** and **8.18** bottom right) project similar ratio increases of between 2 and 3 times the present accumulated streamflow volumes. As already explained before, these large relative increases are most likely due to enhanced baseflows in the non-rainy seasons which result from significant recharge to the groundwater zone in the rainy season.

8.5 Water Temperature Index for Individual Subcatchments

The Water Temperature Index (WTI) for individual subcatchments is equal to the product of the daily maximum water temperature in °C (cf. **Section 6.9.5**) and the simulated daily runoff (m^3) for a particular subcatchment. The analysis of individual subcatchment WTIs is restricted to a ratio comparison between the three ECHAM5 scenarios because the actual WTI value is relatively meaningless. The individual subcatchment WTI reveals how the combination of water temperature and runoff are likely to respond to projected climate change, at the level of a single subcatchment. An analysis of individual subcatchment WTI is important because accumulating WTIs from upstream can mask the runoff and water temperature characteristics of the individual subcatchment in question.

8.5.1 Projected changes in future annual Water Temperature Indexes for individual subcatchments

Figure 8.19 displays the ratios between the three ECHAM5 scenarios for mean annual individual subcatchment WTIs. All maps indicate that there will be an increase in the simulated individual subcatchment WTI under projected future climate conditions. The ratio comparisons between intermediate future and present (**Figure 8.19** top left) and distant and intermediate future (**Figure 8.19** bottom) climates show similar results and indicate increases in individual catchment WTIs, with average increases by a factor of 1.5 and 2. The ratio map of distant future to present ECHAM5 climates (**Figure 8.19** top right) illustrates the greatest change in individual subcatchment WTIs, as expected, with some Quinaries showing an increase by a factor of 4 and more compared to that of the simulated WTI from the present ECHAM5 climate.

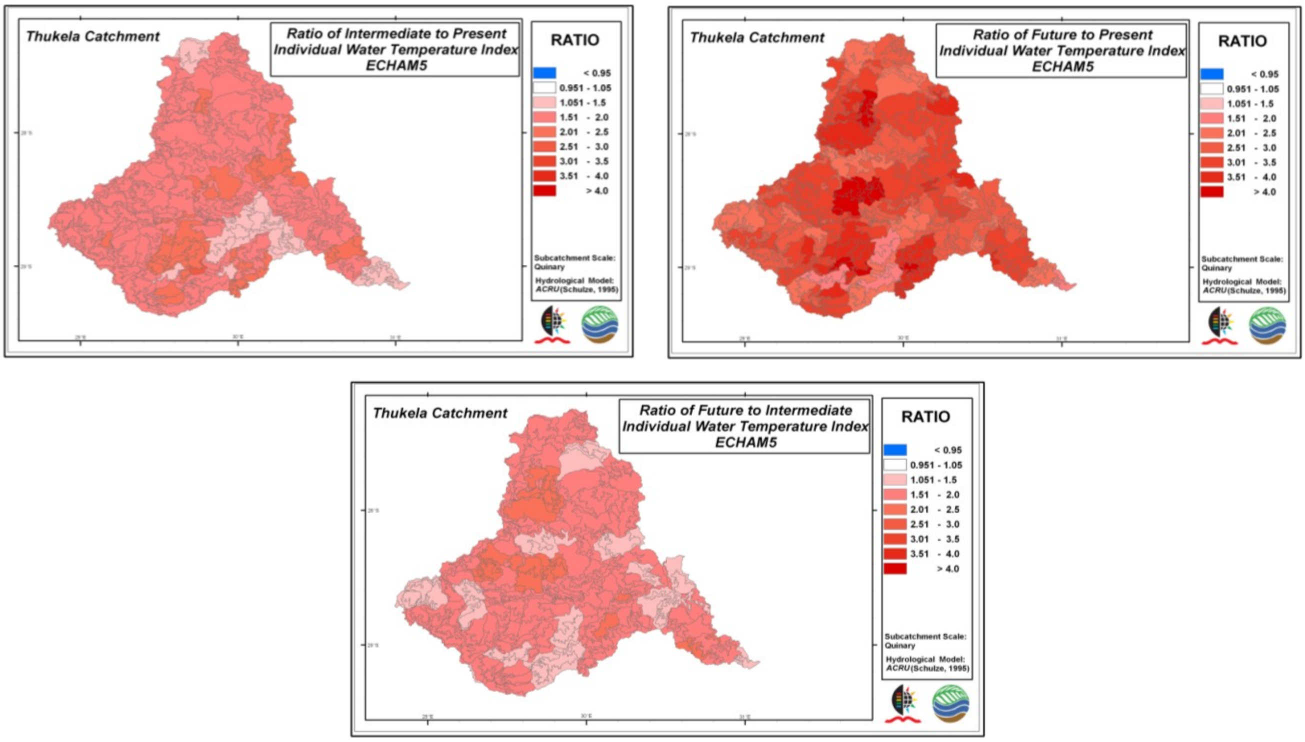

Figure 8.19 Ratios of future annual Water Temperature Indexes from individual subcatchments for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

8.5.2 Projected changes in future means of the Water Temperature Index for individual subcatchments for selected months

A ratio analysis between the three ECHAM5 scenarios was performed for individual subcatchment WTIs for the four cardinal months. All months show an overall increase in individual catchment WTI over time, with the distant future to present scenario experiencing the greatest increase. This overall increase over time is expected owing to the fact that individual catchment WTI is, ultimately, based on air temperature (**Section 8.1**) and individual subcatchment runoff (**Section 8.3**) and in the Thukela Catchment both of these parameters are predicted to increase with projected climate change. The month of January, for all ratio comparisons, tends to be relatively less sensitive to projected climate change compared to the other three cardinal months. The intermediate future to present maps (**Figures 8.20 – 8.23** top left) all project an increase in individual catchment WTIs, but reveal some intra-annual differences.

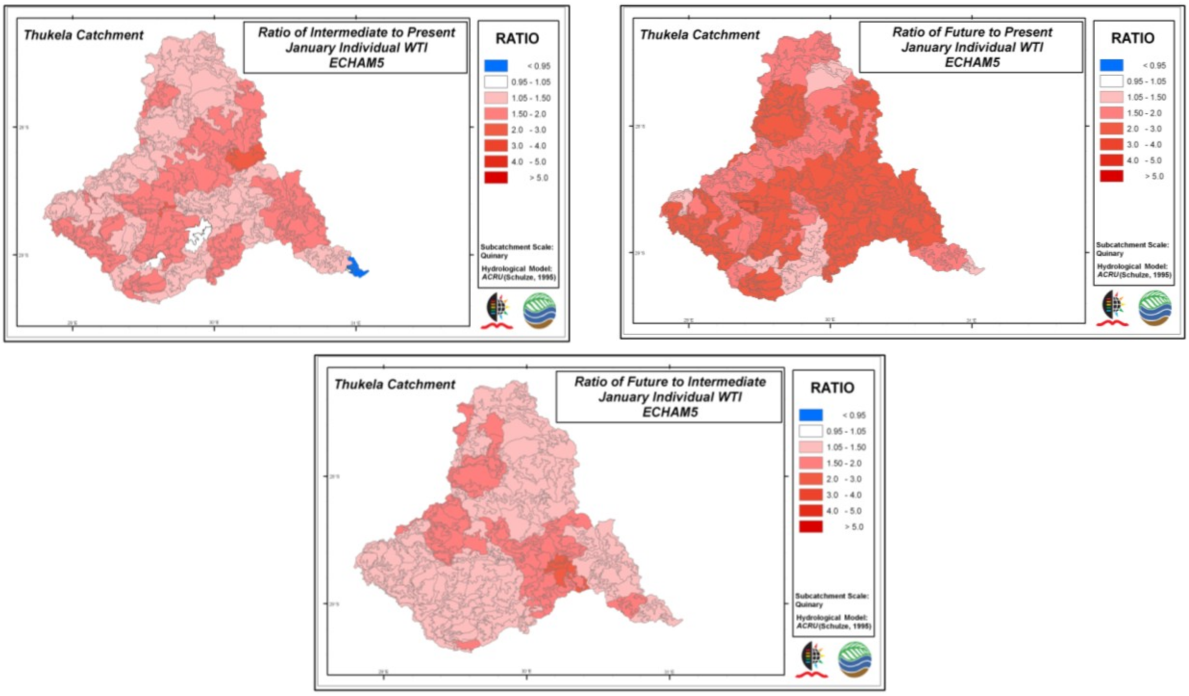

Figure 8.20 Ratios of future January Water Temperature Indexes from individual subcatchments for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

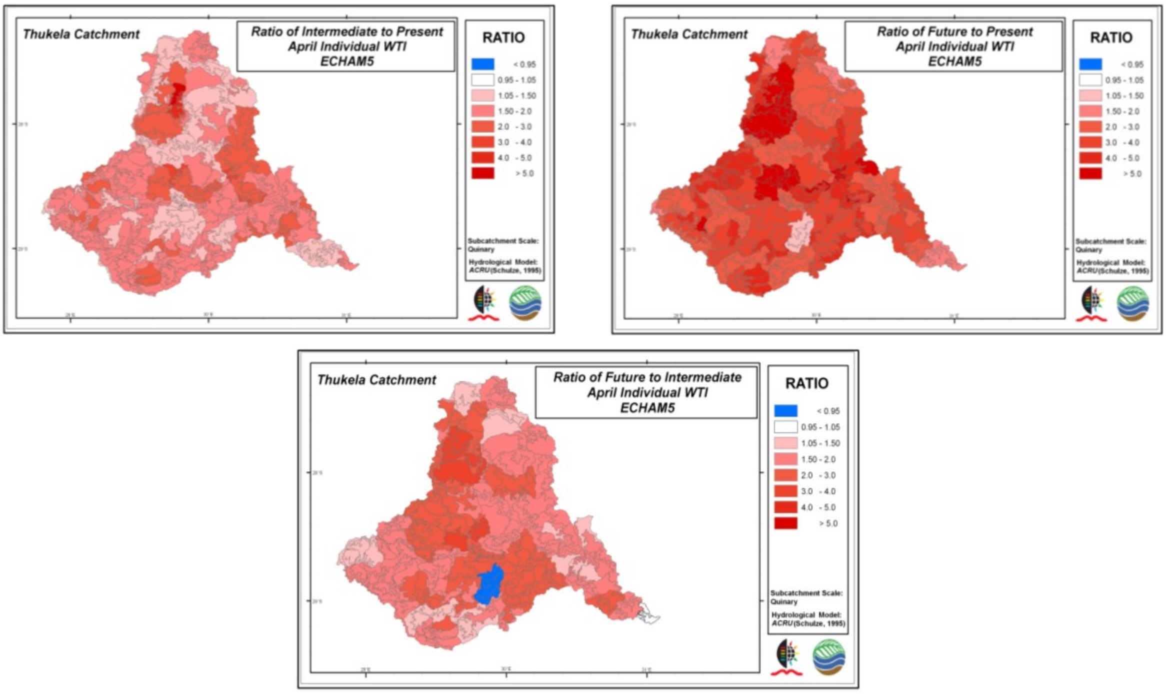

Figure 8.21 Ratios of future April Water Temperature Indexes from individual subcatchments for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

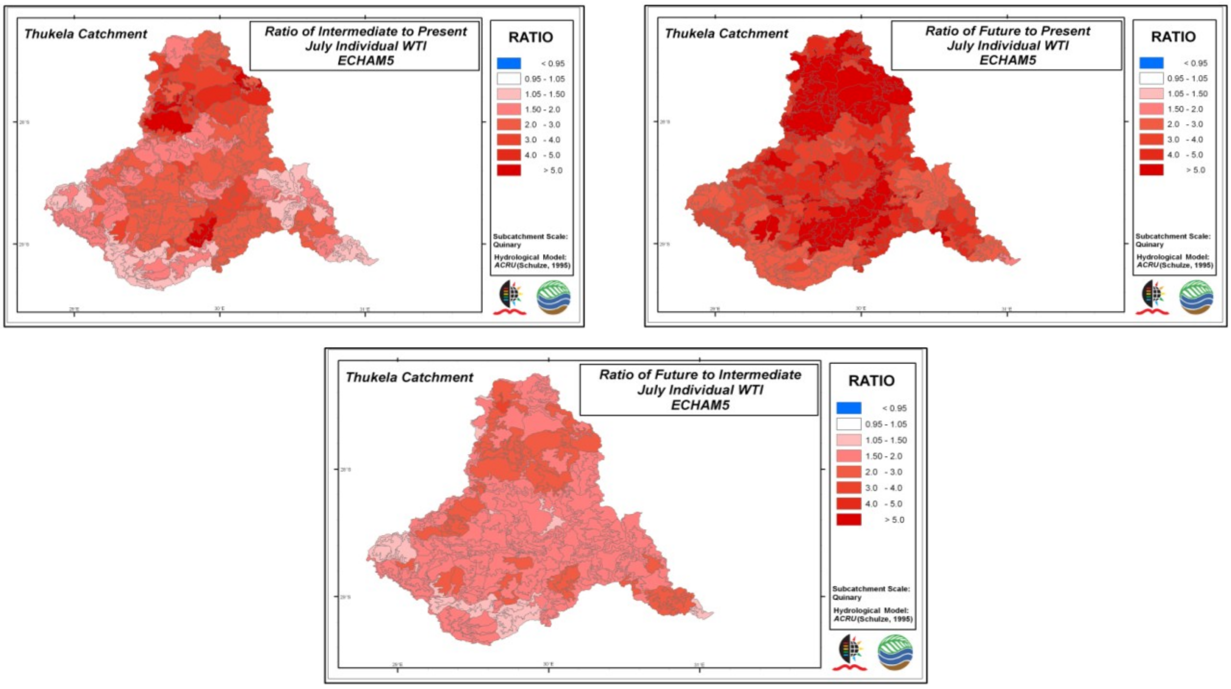

Figure 8.22 Ratios of future July Water Temperature Indexes from individual subcatchments for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

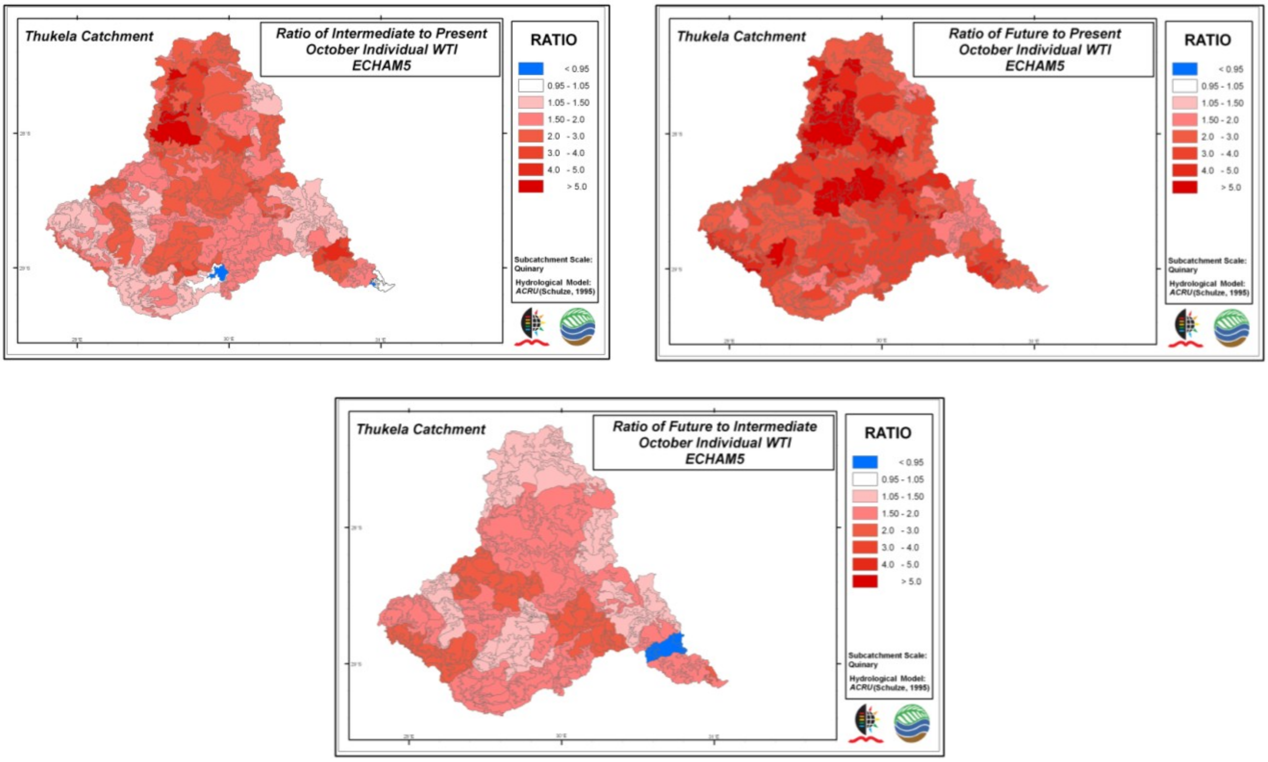

Figure 8.23 Ratios of future October Water Temperature Indexes from individual subcatchments for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

The January intermediate future to present map (**Figure 8.20** top left) shows a virtually uniform increase in individual subcatchment WTIs by a factor of between 1.05 and 1.5. The increases are projected to be higher for April (**Figure 8.21** top left), with most Quinaries experiencing increases of between 1.5 and 2.0. July and October show similar results for the intermediate future to present analysis (**Figures 8.22** and **8.23** top left), with both these months revealing a strong increase in individual subcatchment WTIs, particularly in the Buffalo tributary catchment where Quinaries are projected to experience an increase by a factor of between 3 to 4 compared to that of the ECHAM5 simulated present climate.

The distant future to present maps (**Figures 8.20 - 8.23** top right) also project an increase in individual catchment WTIs for all months, but by an even greater magnitude compared to the other ratio maps. Again January (**Figure 8.20** top right) tends to be less sensitive to projected climate change in relative terms, with individual subcatchment WTIs for the middle Quinaries increasing by a factor of between 2 and 3 for the distant future to present ratio analysis. April, July and October maps (**Figures 8.21 - 8.23** top right) show similar results to each other with these months experiencing large increases in individual subcatchment WTIs by factors of up to 5 in certain Quinaries.

The distant to intermediate future ratio maps (**Figures 8.20 - 8.23** bottom) show similar results to the intermediate future to present analysis in regard to the magnitude of change for individual subcatchment WTIs. January and July (**Figures 8.20** and **8.22** bottom) show an almost uniform increase in individual subcatchment WTIs between the future and intermediate scenarios. Individual catchment WTIs for January are projected to increase by a factor of between 1.05 and 1.50 for the distant future to intermediate future analysis. The ratio changes for April (**Figure 8.21** bottom) between the distant and intermediate future climate scenarios tend to be highly variable, with some Quinaries projected to even decrease while others are projected to increase their WTI by a factor of between 3.0 and 4.0. Finally, October (**Figure 8.23** bottom) shows an overall increase in individual catchment WTI, with the middle Quinaries expected to increase by a factor between 1.50 and 2.0 and the western Drakensberg Quinaries increasing by approximately 2.5 times over this time period.

8.6 Water Temperature Index of Accumulated Flows

Water temperature is dynamic as water is always mixing within the river channel as well with water from incoming tributaries. This, however, complicates water temperature modelling. In order to account for this mixing, the accumulated water temperature index (WTI) was developed. The accumulated WTI uses individual subcatchment WTIs (**Section 8.5**), but accumulates these down the catchment in a similar way that accumulated streamflow is calculated (**Section 8.4**). The accumulated WTI, or simply WTI, creates a weighting system at the exit of two Quinaries or a confluence of rivers in order to give the larger flow more influence on the combined WTI. This accumulation continues longitudinally down a river system, and consequently the water of the Quinary entering the ocean will have been influenced by all the upstream catchments. The analysis of accumulated WTIs is restricted to a ratio comparison between the three ECHAM5 scenarios since the actual WTI value *per se* is a relatively meaningless one.

8.6.1 Projected changes in future annual accumulated Water Temperature Index

An annual ratio analysis between the three ECHAM5 scenarios was performed for the accumulated WTIs. All maps indicate an increase in the accumulated WTI over time (**Figure 8.24**). The intermediate future to present climate ratio map (**Figure 8.24** top left) and that of the distant to intermediate future climates (**Figure 8.24** bottom) both show similar results, with most Quinaries experiencing an increase by a factor of 1.5 to 2.0. The map showing the ratios between the distant future and present ECHAM5 climates (**Figure 8.24** top right) contains the greatest increase in accumulated WTIs, as expected, with most of the Quinaries' WTIs increasing between 2.5 and 3.5 times compared to those of the accumulated WTIs from the present ECHAM5 climate.

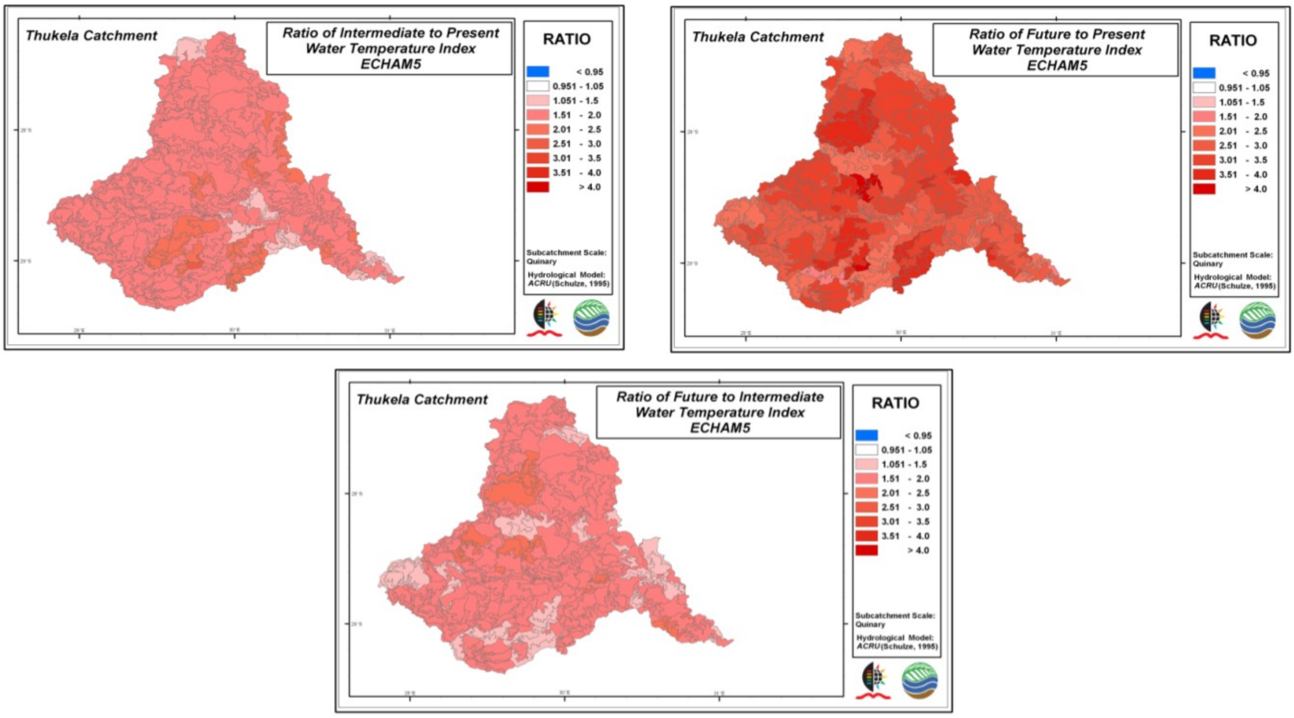

Figure 8.24 Ratios of future annual accumulated Water Temperature Indexes for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

8.6.2 Projected changes in future means of the accumulated Water Temperature Index for Selected Months

A ratio analysis of the four cardinal months was performed for the accumulated WTI using the three ECHAM5 scenarios (**Figures 8.25 - 8.28**). An overall assessment shows an increase in accumulated WTI over time for all scenarios and in all four months. Like individual subcatchment WTIs, the increase in accumulated WTIs is to be expected since accumulated WTIs are ultimately based on air temperature (**Section 8.2**) and accumulated streamflows (**Section 8.4**), both of which are projected to increase in the Thukela Catchment with future climates. A small number of Quinaries do, however, display a zero change in volume or even in a decrease in accumulated streamflows for the months of January, April and October in the southwestern corner and near the mouth of the Thukela, but this goes against the overall trend.

The intermediate future to present ratio map for January (**Figure 8.25** top left) suggests that January is less sensitive to changes in accumulated WTI under conditions of projected climate change compared to the other cardinal months. The ratio change in accumulated WTI, for most Quinaries, is around 1.05 – 1.50 for January while the other three cardinal months project a more mixed and variable increase in magnitude. The month of July (**Figure 8.27** top left) seems to be more sensitive to projected climate change over this time period, especially in the upper regions of the Buffalo Catchment, where accumulated WTI is projected to increase by a factor of between 2.0 and 3.0.

The top right map for **Figures 8.25 - 8.28** illustrates the ratio changes between the distant future and present ECHAM5 climate scenarios for the four cardinal months. As expected, this map shows a far greater change in accumulated WTI compared to the intermediate future to present and distant to intermediate future ratio maps. Again the month of January (**Figure 8.25** top right) seems to be less sensitive to projected climate change, with most Quinaries experiencing an increase in accumulated WTI by a factor of between 1.50 and 3.0. The months of April, July and October (**Figures 8.26** - **8.28** top right) all show a strong increasing trend for accumulated WTI over this time period. The month of July seems to be particularly sensitive, with some Quinaries in the upper Buffalo Catchment experiencing an increase by a factor of between 4 and 5 compared to present accumulated WTI. April and October (**Figure 8.26** and **8.28** bottom right) project similar ratio increases of between 2 and 3 times the present accumulated WTI over the remaining parts of the Thukela catchment.

The bottom map for Figures **8.25 - 8.28** illustrates the ratio changes between the distant and intermediate future ECHAM5 climate scenarios for the four cardinal months. January (**Figure 8.25**) has an almost uniform increase in accumulated WTI with a ratio of between 1.05 and 1.50 for all the Thukela Quinaries. July (**Figure 8.27**) also projects a virtually uniform increase in accumulated WTI, but at a greater magnitude of change for this ratio analysis, with most Quinaries experiencing a doubling in accumulated WTI over this time period. April and October (**Figures 8.26** and **8.28**) reveal a large amount of variability in the magnitude of increase for accumulated WTI, but overall the WTI is projected to increase from the intermediate to more distant future ECHAM5 climate scenarios, as temperatures continue to rise and rainfall, hence streamflow, is projected to continue increasing.

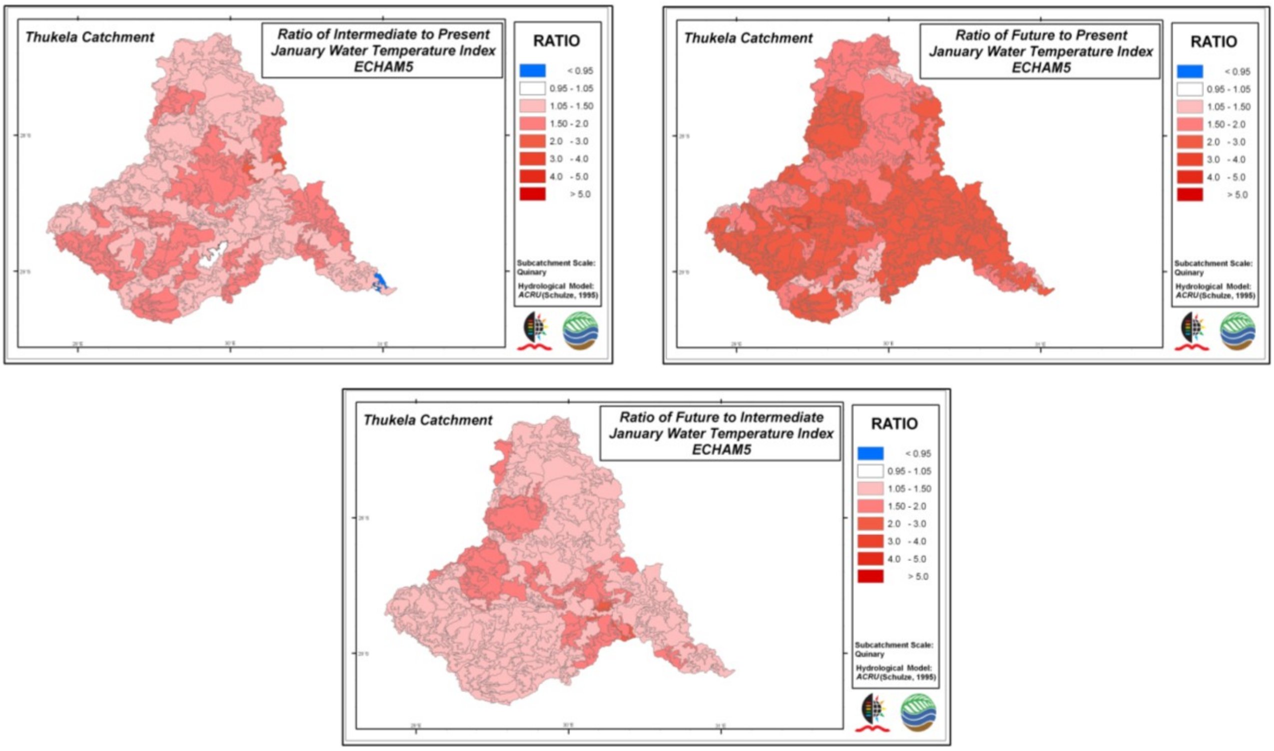

Figure 8.25 Ratios of the January accumulated Water Temperature Index for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

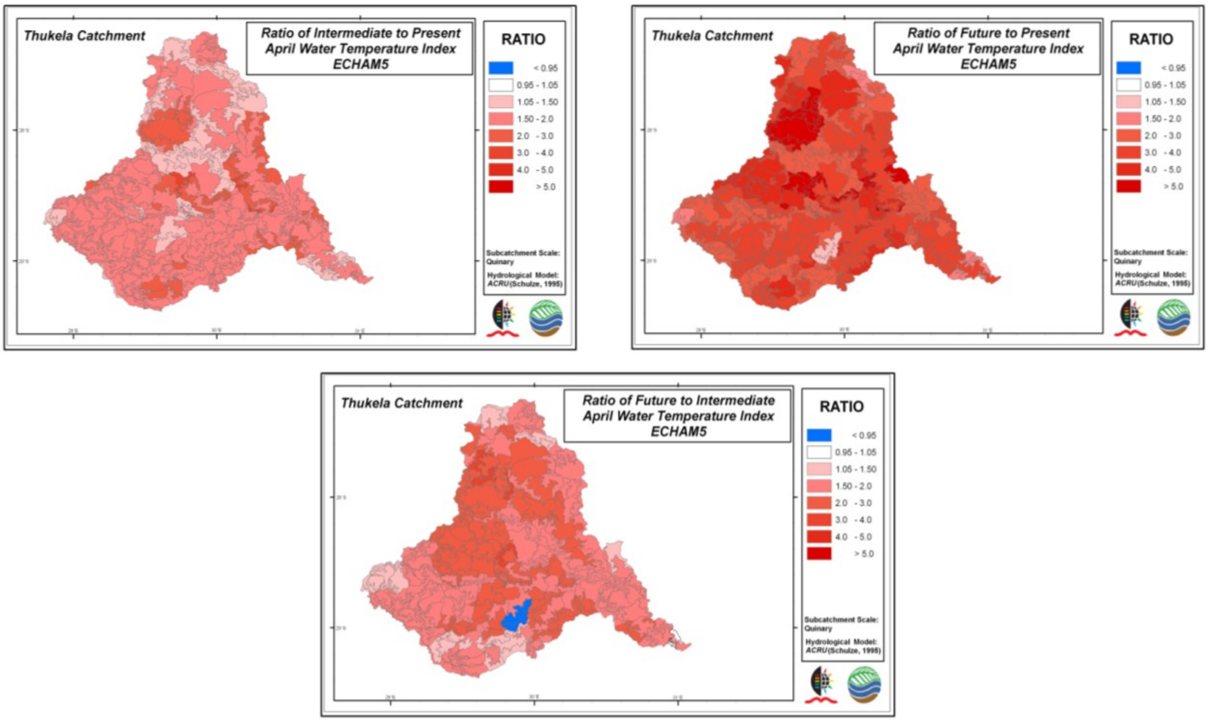

Figure 8.26 Ratios of the April accumulated Water Temperature Index for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

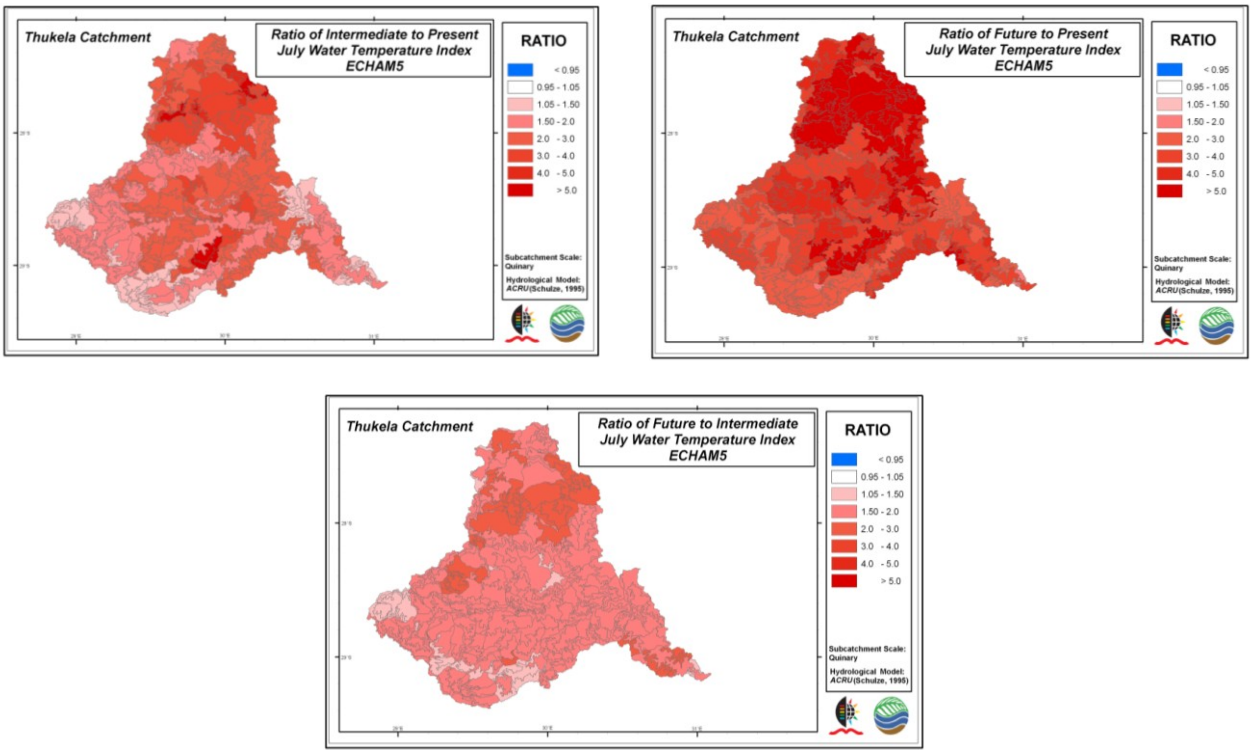

Figure 8.27 Ratios of the July accumulated Water Temperature Index for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

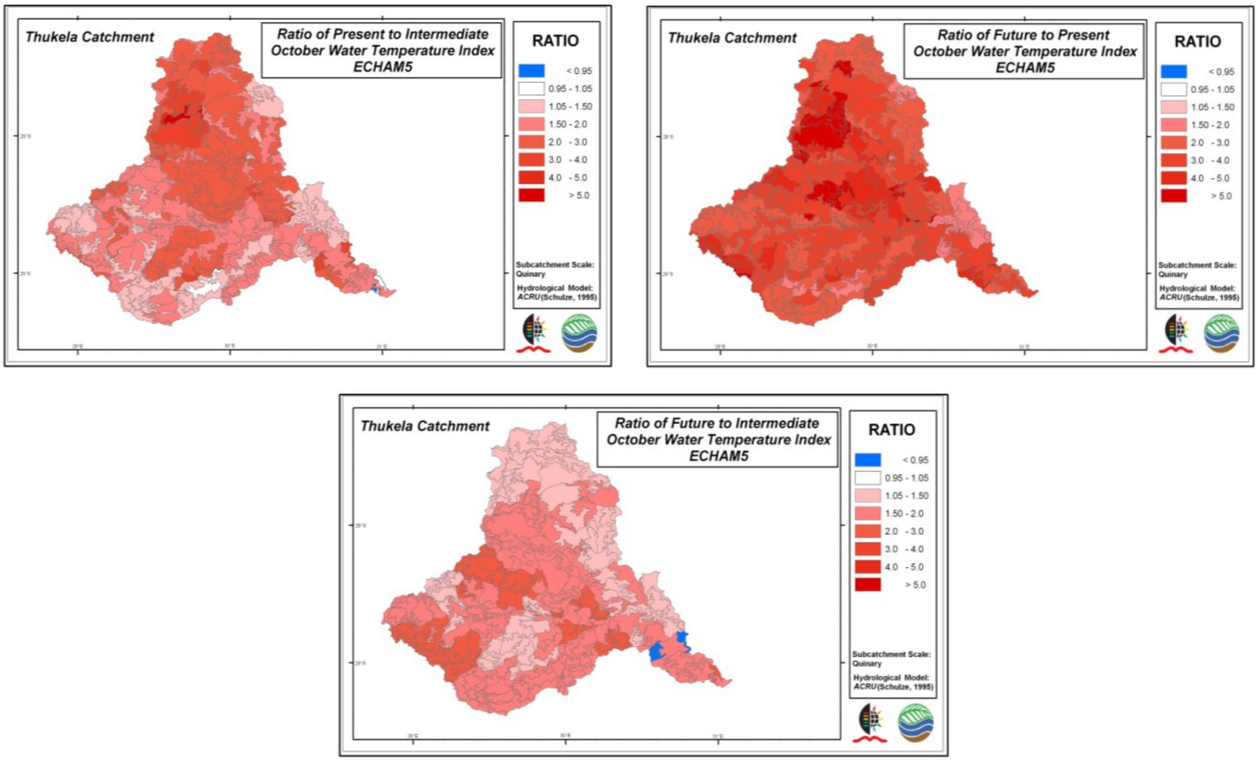

Figure 8.28 Ratios of the October accumulated Water Temperature Index for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

8.7 Mixed Maximum Water Temperature

The mixed maximum water temperature (MMWT) is calculated by dividing the accumulated Water Temperature Index (WTI) on a specific day by the accumulated streamflow of that day for a particular Quinary Catchment (**Section 8.6**). MMWT is therefore essentially a weighted value, expressed in degree Celsius, based on maximum water temperature (**Section 6.9.6**). The MMWT is an important indicator for aquatic ecosystems and is in a workable and understandable unit.

8.7.1 Mean annual mixed maximum water temperature

An evaluation of mean annual MMWTs derived from the baseline present climate and that computed from the ECHAM5 present climate scenario indicates that both are showing the same overall trends (**Figure 8.29** top left and right). The mean annual water temperature is relatively low at +/- 11 °C in the high lying areas, especially in the western Drakensberg region and, as the water cascades down the catchment, it warms to approximately 19°C in the central regions. The present ECHAM5 climate tends to be under-simulating MMWT in the centre of the Thukela Catchment and along the mainstem of the Thukela River. These results follow similar trends found in the air temperature (**Section 8.2**) and accumulated streamflow (**Section 8.3**) analyses. A comparison between the MMWT simulations from the three ECHAM5 climate scenarios reveals a definite increase in MMWT under conditions of projected climate change. For the intermediate future ECHAM5 scenario (**Figure 8.28** bottom left) the Quinaries in the middle of the catchment experience a mean annual maximum water temperature of approximately 21 °C and this value increases to 25 °C for the more distant projected future climate (**Figure 8.29** bottom right).

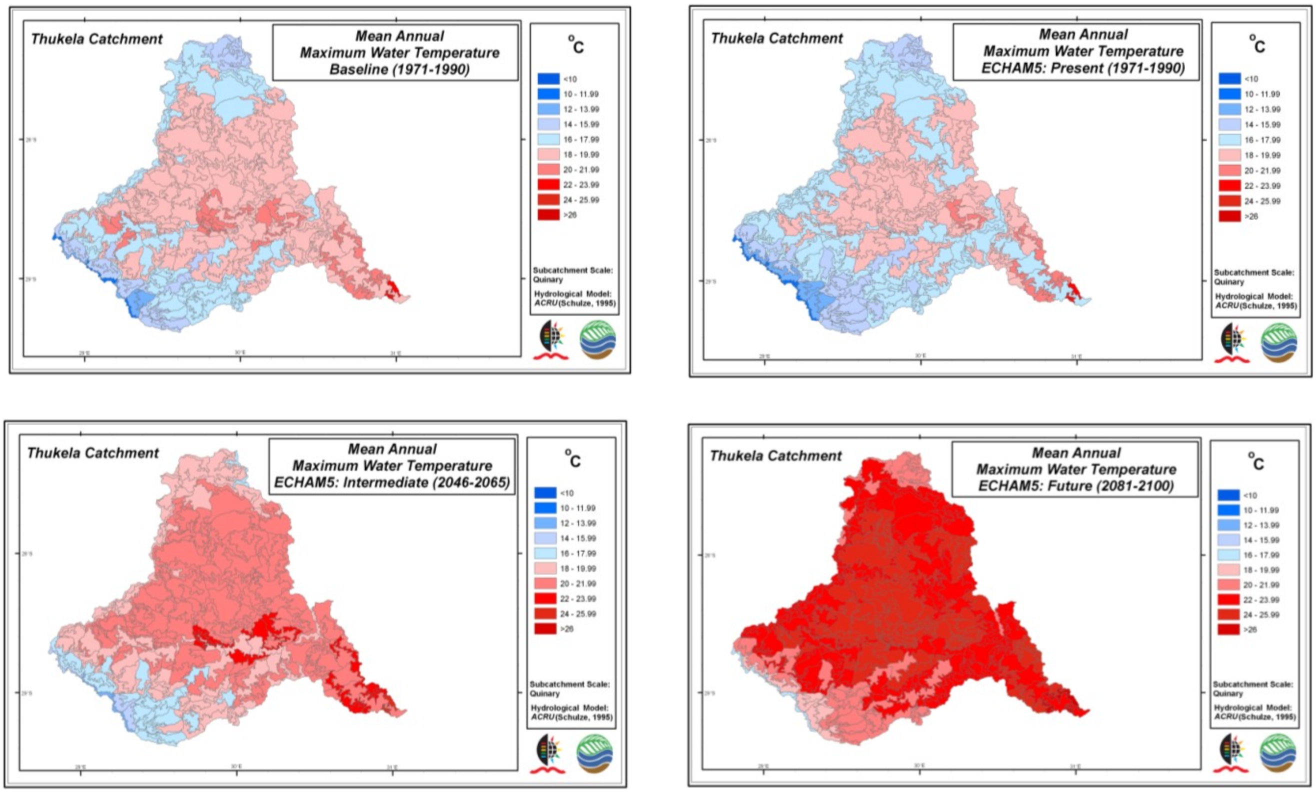

Figure 8.29 Simulated mean annual mixed maximum water temperature generated from (top left) present baseline climate and (top right) the present ECHAM5 climate scenario, as well as (bottom left) from the intermediate future and (bottom right) more distant future ECHAM5 climate scenarios

8.7.2 Projected changes in future mean annual mixed maximum water temperatures

A mean annual difference analysis in MMWTs simulated from the three ECHAM5 climate scenarios was performed. The intermediate future minus present map (**Figure 8.30** top left) shows a warming in mean annual MMWTs, especially along the major tributaries and the mainstem of the Thukela. These Quinaries are projected to experience an increase of between 2.5 and 3 °C, while the remaining Quinaries experience a smaller projected increase of between 2.0 and 2.5 °C. The map showing the difference between the more distant future and present ECHAM5 climates (**Figure 8.30** top right) contains the greatest increase in maximum water temperatures, with most of the Quinaries showing increases of around 5 °C, but with the higher lying subcatchments tending to be more sensitive to projected climate change. **Figure 8.30** (bottom) also shows a warming trend in maximum water temperature, with a majority of the Quinaries experiencing a rise around 2.5 – 3 °C for the distant minus intermediate future analysis.

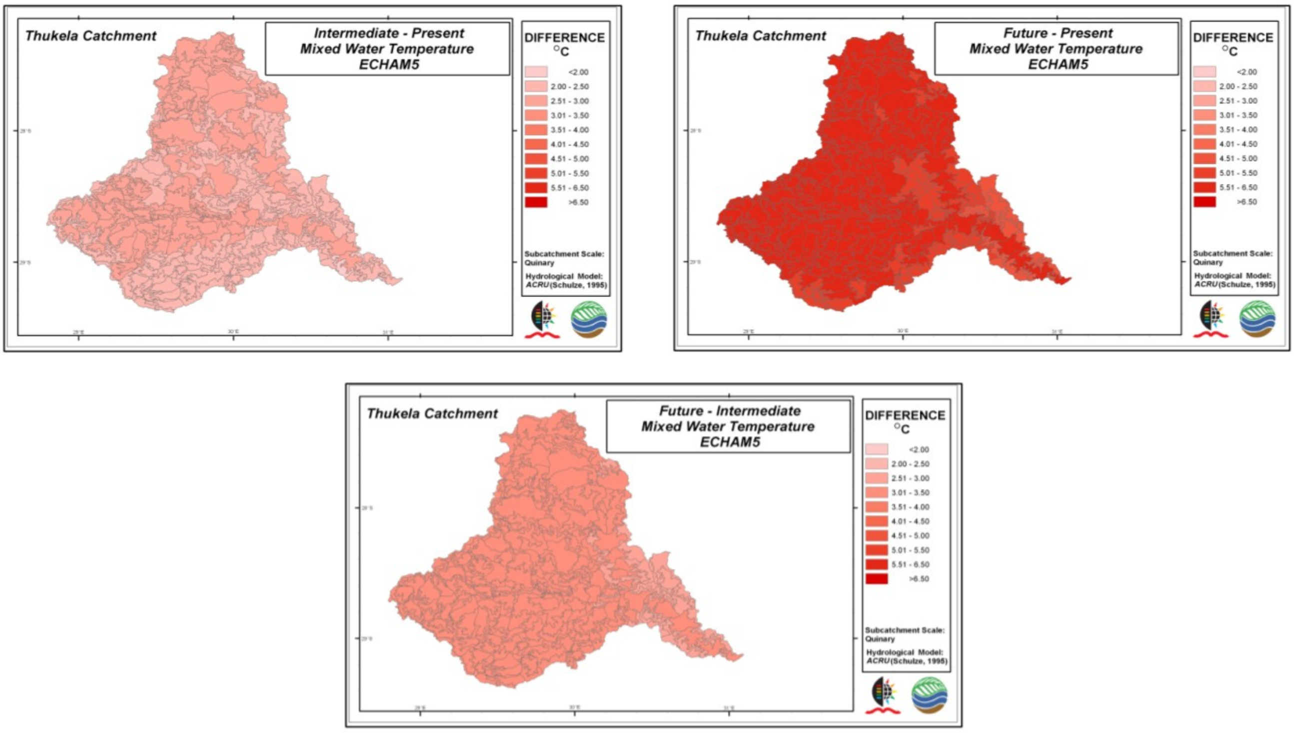

Figure 8.30 Differences in mean annual mixed maximum water temperatures for (top left) intermediate future and present, (top right) more distant future and present and (bottom) distant and intermediate future ECHAM5 climate scenarios

8.7.3 Projected changes in future means of monthly maximum mixed water temperatures for selected months

An analysis of intra-annual differences in MMWTs for selected cardinal months (**Figures 8.31 - 8.34**) reveals that mixed maximum water temperature changes fluctuate quite considerably throughout the year. In regard to MMWTs, January displays the highest and July the lowest values, while April and October MMWTs tend to fit between these two extremes. Mean mixed maximum water temperatures for the western Drakensberg are ~ 18 °C for January and this value decreases to 13 °C for April and October and falls to 10 °C for July. This natural fluctuation is important in terms of aquatic organism as these changes act as cues for the initiation of certain lifecycle stages.

A comparison of MMWTs derived from the baseline present climate (top left in **Figures 8.31 - 8.34**) and the ECHAM5 present climate (top right in **Figures 8.31 - 8.34**) for the four cardinal months, indicates that this GCM is performing well in certain months and less so in others. The January analysis shows that the GCM is under-simulating MMWTs, particularly in the southwestern regions of the Thukela Catchment. April and July both show close correlations between the baseline and the simulated ECHAM5 present climates. On the other hand, October MMWTs do not show a close relationship to those from the GCM simulated climate, with under-simulations of mixed maximum water temperatures by over 3 °C in the central parts of the Thukela. This probably stems from a noticeable under-simulation of accumulated streamflows for the present ECHAM5 scenario (**Section 8.4.2**).

A difference analysis in MMWTs generated from the three ECHAM5 scenarios was also performed for the four cardinal months. All months project an increase in MMWTs over time, with the difference between the distant future and present climate scenarios experiencing the greatest increase. January shows the least change in MMWTs, but still demonstrates noticeable downstream warming along the major tributaries and the mainstem of the Thukela. The intermediate future minus present MMWTs (**Figure 8.31** bottom left) project increases of between 2 and 3 °C down these main stems and this difference increases to between 4 and 5 °C down these main river valleys for the distant future minus present analysis (**Figure 8.31** bottom right). April also shows noticeable warming down the primary tributaries of approximately 3.5 °C between the intermediate future and present climate scenarios, and this value increases to over 7 °C for the distant future minus present climate scenarios of the ECHAM5 GCM (**Figure 8.32**). This trend of warmer mainstems and cooler adjacent Quinaries is important and could imply that these adjacent Quinaries could be used as refugia for species that prefer cooler waters. July and October (**Figures 8.33** and **8.34**) both show similar trends to one another in terms of a projected increase in mixed maximum water temperature for the intermediate future minus present scenarios, with differences of between 2 and 3 °C in the central parts of the catchment.

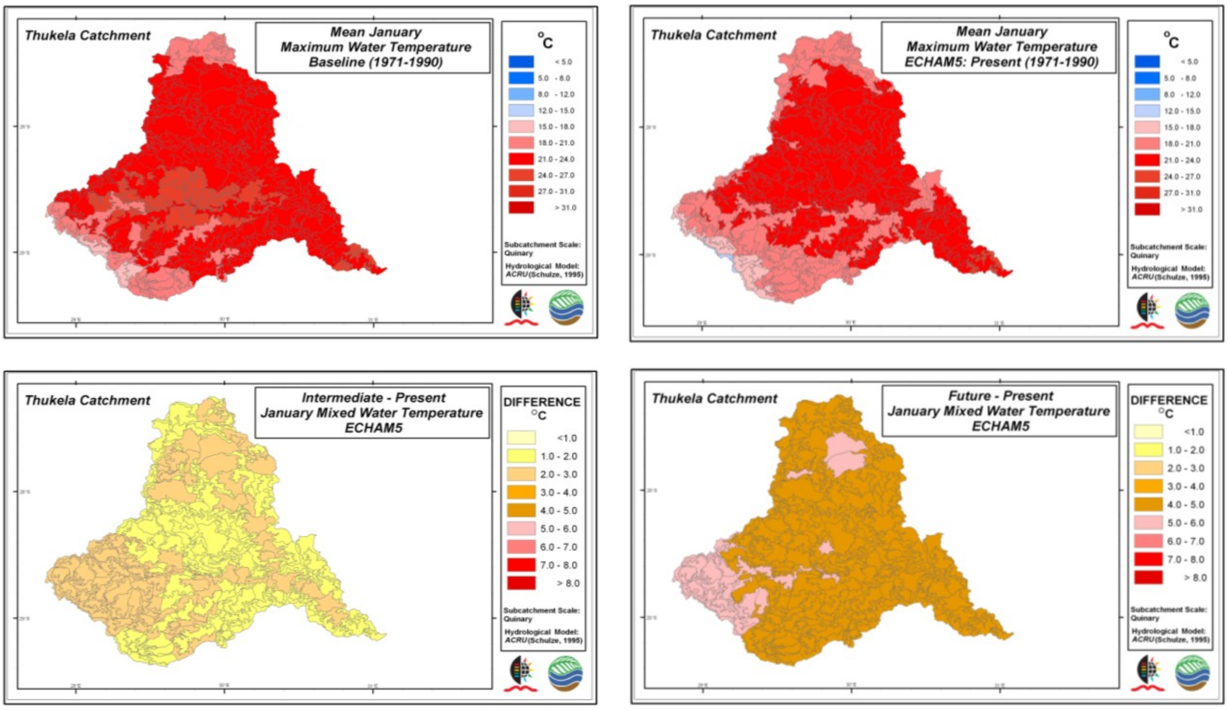

Figure 8.31 Mean January mixed maximum water temperatures in the Thukela Catchment simulated from (top left) present baseline climate vs (top right) the present ECHAM5 climate scenario, and differences between projected future January intermediate future and present (bottom left), and distant future and present (bottom right) mixed maximum water temperatures

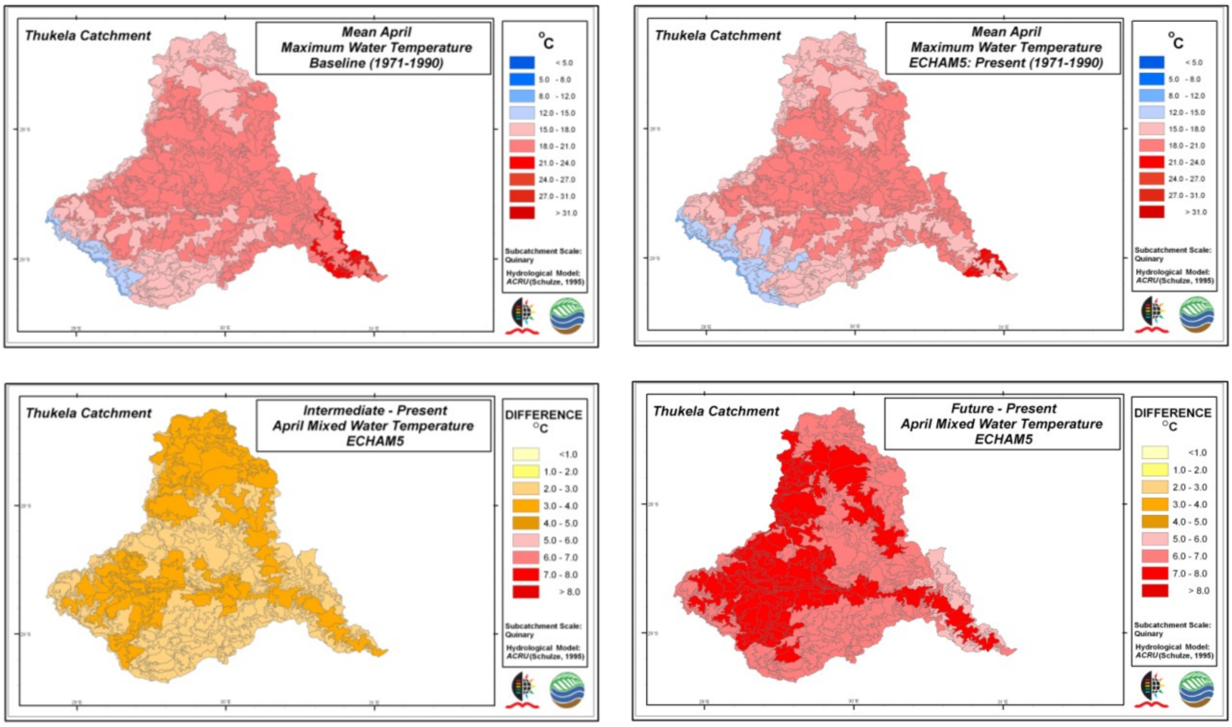

Figure 8.32 Mean April mixed maximum water temperatures in the Thukela Catchment simulated from (top left) present baseline climate vs (top right) the present ECHAM5 climate scenario, and differences between projected future April intermediate future and present (bottom left), and distant future and present (bottom right) mixed maximum water temperatures

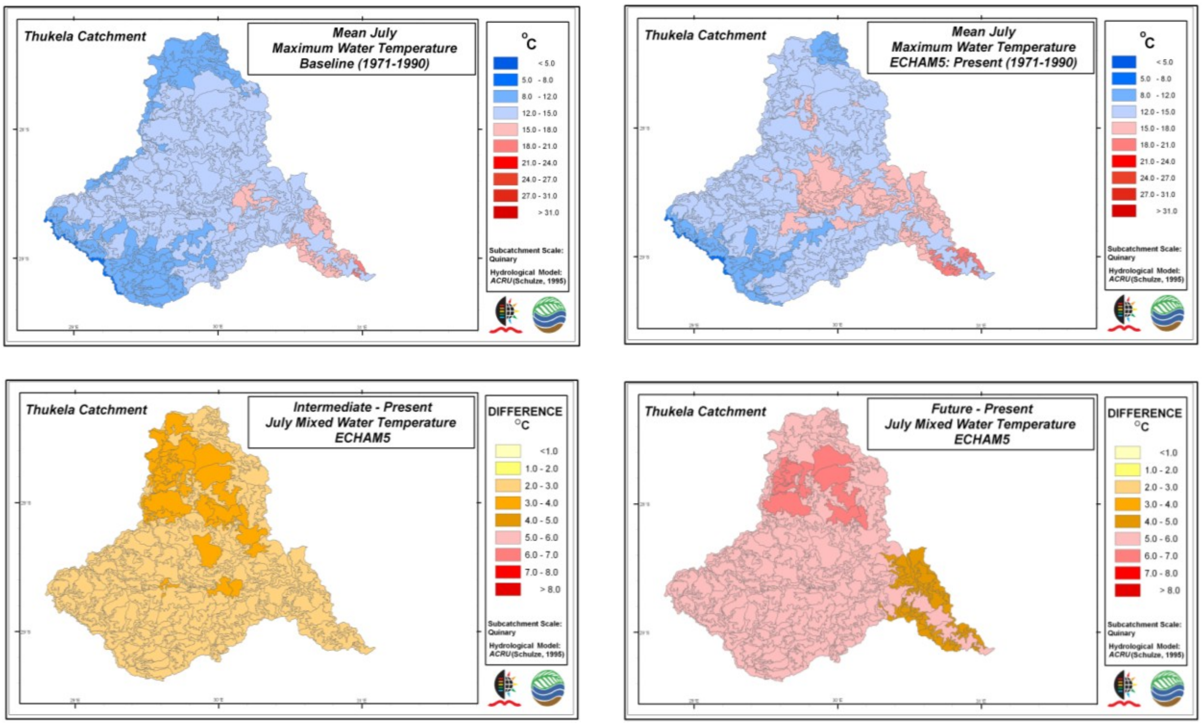

Figure 8.33 Mean July mixed maximum water temperatures in the Thukela Catchment simulated from (top left) present baseline climate vs (top right) the present ECHAM5 climate scenario, and differences between projected future July intermediate future and present (bottom left), and distant future and present (bottom right) mixed maximum water temperatures

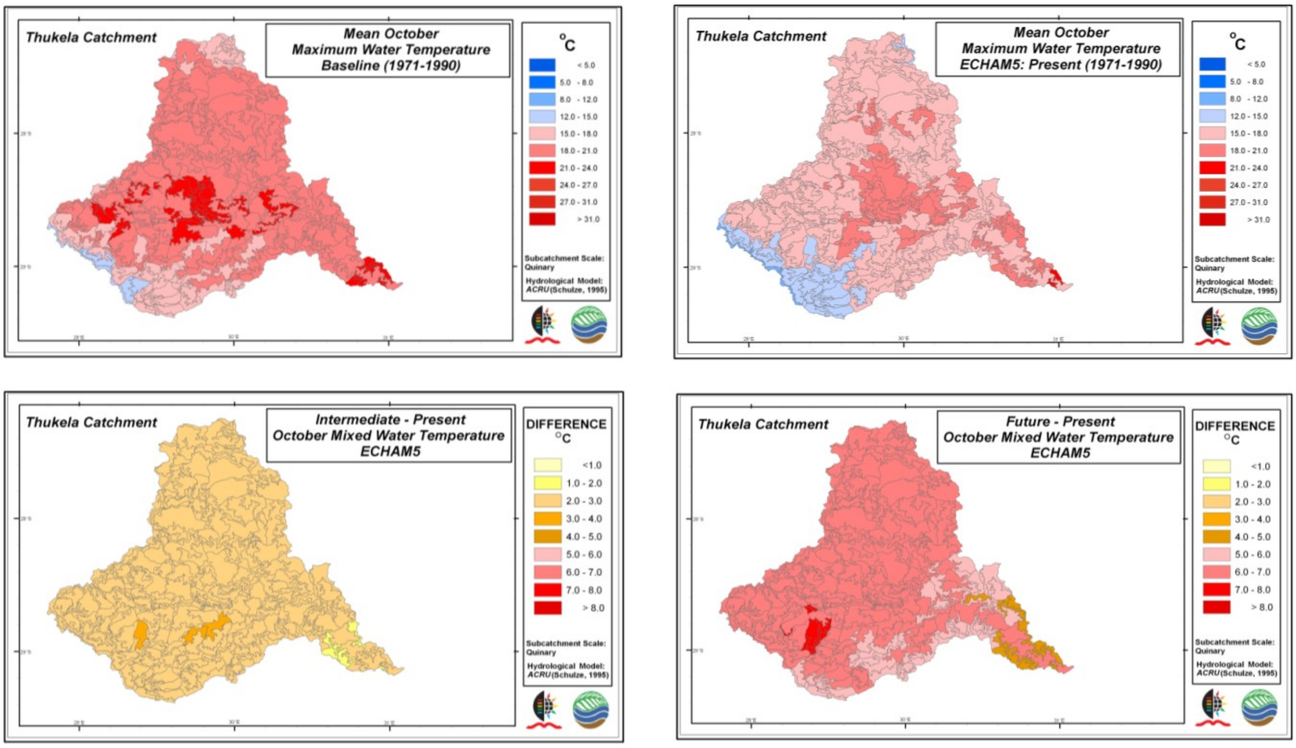

Figure 8.34 Mean October mixed maximum water temperatures in the Thukela Catchment simulated from (top left) present baseline climate vs (top right) the present ECHAM5 climate scenario, and differences between projected future October intermediate future and present (bottom left), and distant future and present (bottom right) mixed maximum water temperature

*****

In **Chapter 8**, the second of three result chapters, an assessment is made of the potential impacts of climate change on the water temperature related parameters using the baseline climate conditions and the ECHAM5 climate scenarios. This spatial assessment is performed for the 258 hydrologically interlinked and cascading Quinary Catchments which constitute the Thukela Catchment. In this chapter a series of maps were used to spatially analyse air temperature, individual catchment runoff, accumulated streamflows, mixed maximum water temperature and two water temperature indices. A summary of the main findings are provided below.

In regard to mean air temperature the spatial analysis shows that there is a close correspondence between the MAT from historical air temperature data and that simulated from the ECHAM 5 GCM. A comparison between the ECHAM5 scenarios indicates a strong warming trend over time, particularly in the central parts of the Thukela catchment, with the ECHAM5 distant future climate scenario showing the greatest deviation from that of the present climate. The reason for the distant future to present ratio map showing the greatest change is that the present climate scenario time period (1971 - 1990) and the future climate scenario time period (2081 - 2100) are 110 years apart, from the commencement of their respective simulation periods - this compared with the difference between the intermediate and future climate scenarios only being 35 years from the start of their respective simulation periods and this trend was found to be consistent for all water temperature related parameters.

The spatial analysis of runoff from individual subcatchment indicates that there could be a marked increase in projected annual subcatchment runoff, with the distant future scenario showing the greatest change compared to that of the present ECHAM5 climate, with most Quinaries showing an increase of between 2 and 3 times compared to that of the simulated runoff from the present ECHAM5 climate.

When comparing accumulated streamflows generated from present baseline climate and the present ECHAM5 climate the results indicate that the simulations are generally closely correlated, with both these scenarios clearly showing the accumulations of streamflows in the major tributaries in Thukela Catchment. As with subcatchment runoff, all ECHAM5 scenarios indicate that there will be substantial increase in accumulated streamflows under projected future climate conditions.

With reference to mixed maximum water temperature, these results follow similar trends to those found in the air temperature and accumulated streamflow analyses. A comparison between the MMWT simulations from the three ECHAM5 climate scenarios reveals a definite increase in MMWT under conditions of projected climate change. The difference between distant future and present ECHAM5 climates contain the greatest increase in MMWT, with most of the Quinaries showing increases of around 5 °C, but with the higher lying subcatchments tending to be more sensitive to projected climate change.

Chapter 9, which follows, is the third and final results chapter and there a time series analysis is employed in order to temporally assess the potential impacts of climate change on water temperature related parameters in the Thukela Catchment.

9. RESULTS 3: TIME SERIES ANALYSES OF WATER TEMPERATURES IN THE THUKELA CATCHMENT

9.1 Setting the Scene

In the Engineering Statistics Handbook (2006) a time series is defined as an ordered sequence of values of a variable at uniformly spaced time intervals. For a number of years researchers have applied time series analyses in order to interpret the temporal characteristics and trends of hydrological processes (Duffy and Gelhar, 1986). According to the Australian Bureau of Statistics (2008), three components constitute a time series, *viz*.

- the *trend* (long term direction),
- the *seasonal* (i.e. systematic) *variation* based on calendar related movements and
- the *irregular* (i.e. unsystematic) *variation* and short term fluctuations.

The purpose of the time series analyses described in this chapter is to observe and describe these three components based on the water temperature related parameters identified in **Chapter 8** for climate change conditions in 15 selected Quinary Catchments located in the Thukela Catchment. Time series analyses were performed on the following parameters:

- Mean Daily Air Temperature,
- Individual Subcatchment Runoff,
- Accumulated Streamflows, and
- Mixed Water Temperature.

The time series analyses were performed on the three ECHAM5 GCM scenarios (cf. **Section 6.7** for a more detailed description), *viz*

- Present Climate from the ECHAM5 GCM (1971 - 1990), an
- Intermediate Future Climate (2046 - 2065), and a more
- Distant Future Climate (2081 - 2100).

Results from the present baseline climate scenario are not compared against those of the present ECHAM5 climate scenario as they are not temporally conditioned, i.e. aligned, and hence do not have a temporal correlation. The time series used is at an annual time step for each of the aforementioned parameters for the entire respective 20 years of record. The time series analyses use two methods to describe how each water temperature related indicator varies over time, *viz*.

- How does an indicator vary for a single Quinary catchment by comparing the three ECHAM5 climate scenarios (i.e. a temporal analysis), with the hypothesis being that in future climates temperatures are increasing and streamflows are changing; and
- How does an indicator vary between the three Quinaries making up a Quaternary Catchment for a single climate scenario (i.e. a spatial analysis), with the hypothesis being that Quinaries within a Quaternary are altitude determined and therefore have influences on temperature, rainfall, hence on runoff and thus also on water temperature patterns.

9.2 Catchment Selection

In total 15 Quinary Catchments, which make up five Quaternaries, were selected in the Thukela to undergo time series analyses. The location of these 15 Quinaries is given in **Figure 9.1**. From **Figure 9.1** it may be seen that the selected catchments are in different hydroclimatic regions within the Thukela Catchment in order to determine how different areas might respond to projected climate change. **Table 9.1** summarises the characteristics of the 15 selected subcatchments.

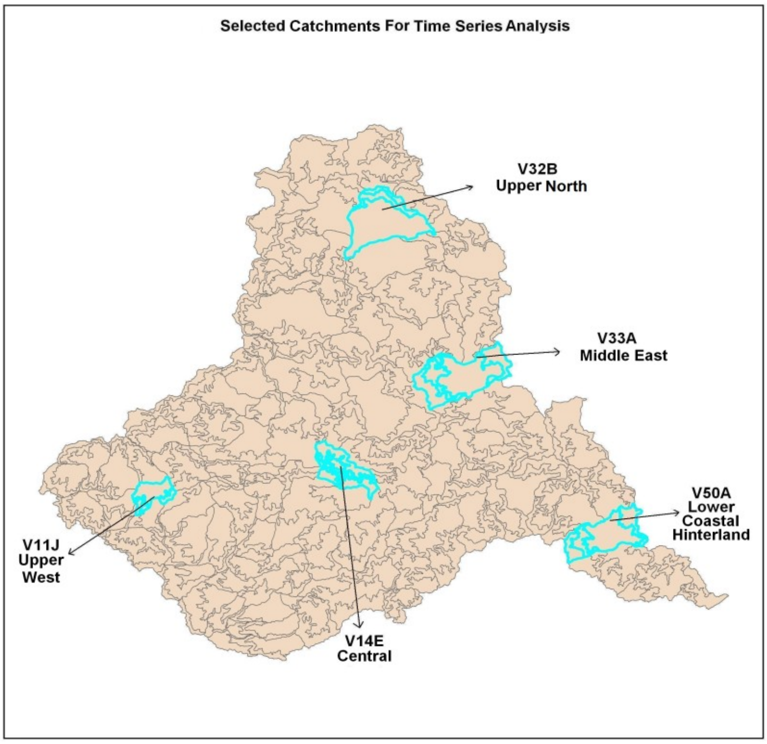

Figure 9.1 Locations of the selected Quinary Catchments in the Thukela for time series analyses

Table 9.1 Characteristics of the 15 selected Quinary Catchments

Quaternary Catchment Number	BEEH Quinary Catchment Number	Mean Catchment Altitude (m)	Relative Location of Catchment	Catchment Area (km^2)	River System
V11J	4846	1465	Upper West	15.50	Upper Thukela
	4847	1266		33.34	
	4848	1175		95.93	
V14E	4906	1021	Central	143.54	Upper Thukela
	4907	897		76.68	
	4908	780		68.48	
V32B	5020	1835	Upper North	34.00	Buffalo
	5021	1472		70.52	
	5022	1245		456.28	
V33A	5041	1460	Middle East	105.77	Buffalo
	5042	1295		188.09	
	5043	1140		290.31	
V50A	5068	975	Lower Coastal Hinterland	53.85	Lower Thukela
	5069	535		78.02	
	5070	286		57.31	

9.3 Time Series Analysis of Air Temperature

9.3.1 Projected changes in air temperature in a single Quinary Catchment with climate change

The values produced by the time series analysis all indicate that air temperature is likely to increase under the projected conditions of climate change for all the selected Quinaries. This is illustrated in **Figures 9.2 - 9.4** by way of time series graphs from selected Quinaries. **Figure 9.2** shows a time series of air temperature for Quinary 4848, located in the high altitude upper western part of the Thukela Catchment. Air temperature is shown to remain relatively constant over the 20 years of a climate scenario, but there are significant differences between the three ECHAM5 scenarios. The air temperature for the present ECHAM5 climate scenario for Quinary 4848 (**Figure 9.2**) is approximately 17^{o}C, this value increases to approximately 20^{o}C for the intermediate future ECHAM5 climate and increases further to around 23^{o}C for the more distant future ECHAM5 climate. Essentially air temperature is thus projected to increase significantly over time, with the present ECHAM5 climate being the coolest, the future ECHAM5 climate being the warmest and the intermediate ECHAM5 being somewhere between these two extremes. This increasing trend between ECHAM5 scenarios was found in all 15 selected Quinaries evaluated.

By comparing **Figures 9.2 - 9.4** one can determine how spatial location can influence the temporal characteristics of air temperature. **Figure 9.2** represents Quinary 4848 located in the upper Thukela, **Figure 9.3** represents Quinary 4908 located in the central parts of the Thukela Catchment and **Figure 9.4** represents Quinary 5070 located in the lower altitude Coastal Hinterland. By comparing the average air temperatures of each ECHAM5 climate scenario it can be concluded that air temperatures increase as one moves from higher altitudes towards the lower altitude coastal zones, in accordance with lapse rate decreases in air temperature with altitude and the moderating influence of the warm Indian Ocean. For all three ECHAM5 scenarios Quinary 4848, located in the upper west Thukela, is approximately 2^{o}C cooler than Quinary 4908, located in the centre of the Thukela Catchment and is around 3^{o}C cooler than Quinary 5070, which is located near the coast.

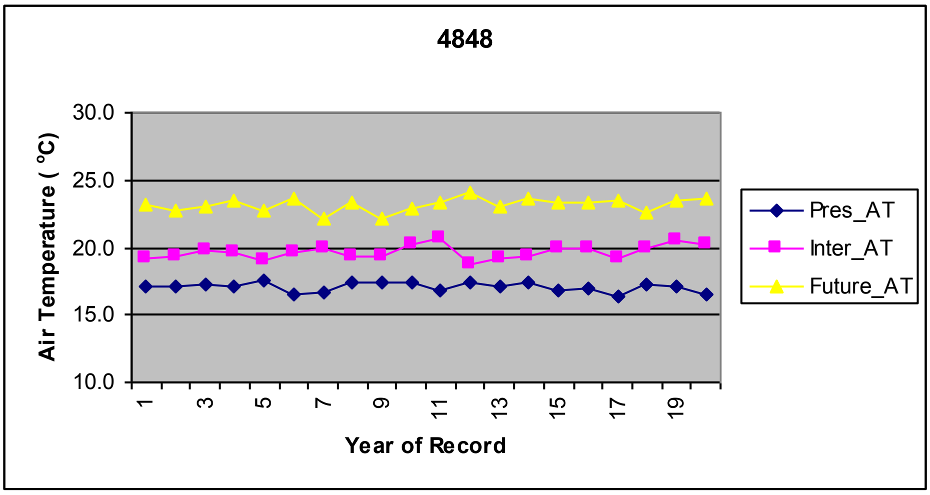

Figure 9.2 Time series of mean annual air temperature (°C) for Quinary 4848 for present, intermediate future and distant future ECHAM5 climate scenarios

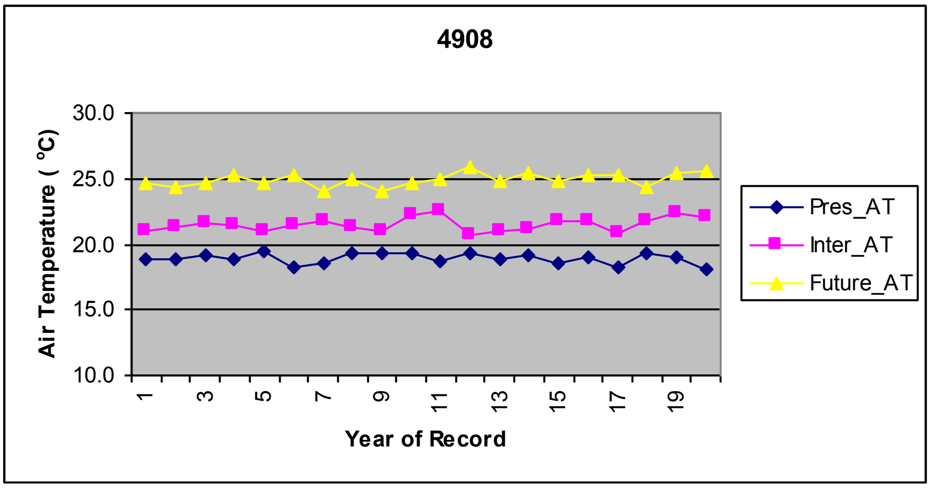

Figure 9.3 Time series of mean annual air temperature (°C) for Quinary 4908 for present, intermediate future and distant future ECHAM5 climate scenarios

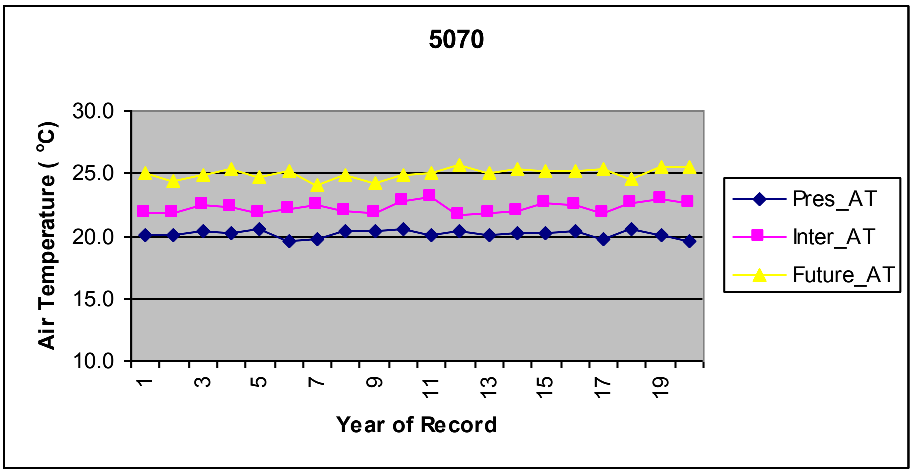

Figure 9.4 Time series of mean annual air temperature (°C) for Quinary 5070 for present, intermediate future and distant future ECHAM5 climate scenarios

Closer scrutiny of the times series indicates a rising air temperature trend within the 20 years of values in both the intermediate and distant future climates, which is not visible in the present climate scenario. This increasing trend can be clearly observed when a linear trend line is placed over the individual times series (**Figures 9.5 – 9.7**). This is an important result as it indicates that air temperature is likely to increase steadily even over a relatively short 20 period of time.

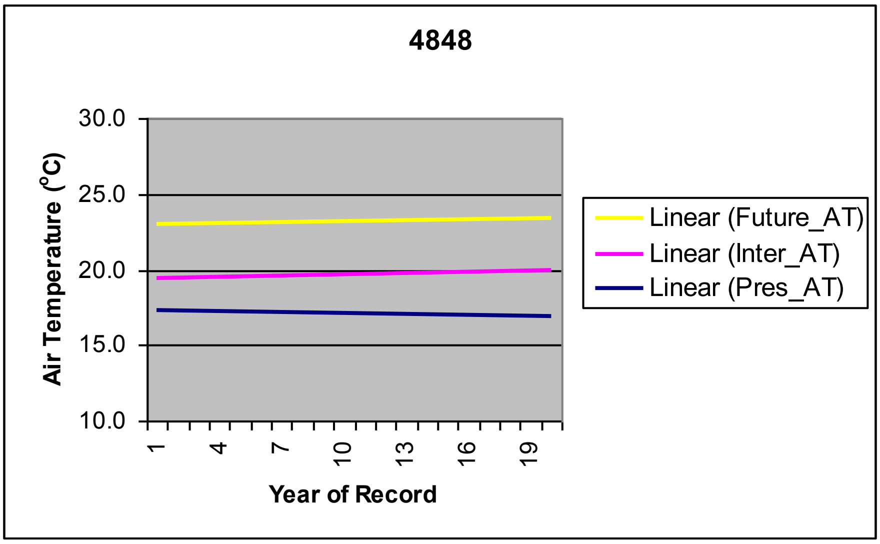

Figure 9.5 Linear trends of mean air temperature (^{o}C) for Quinary 4848 for present, intermediate future and distant future ECHAM5 climate scenarios

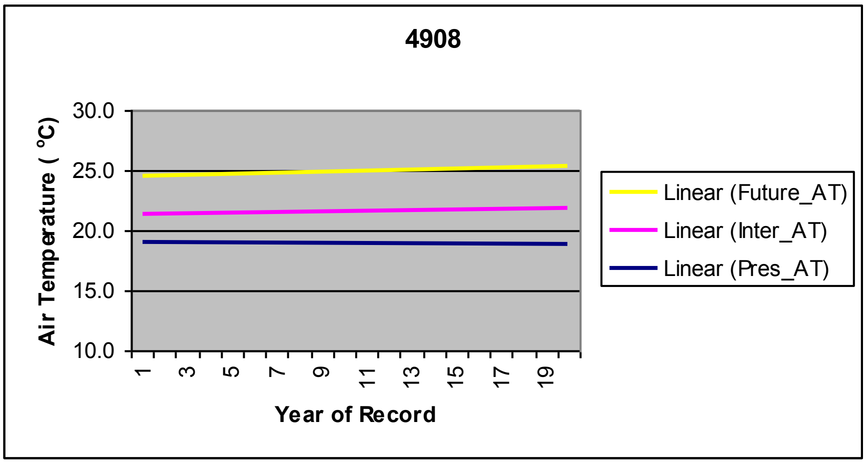

Figure 9.6 Linear trends of mean air temperature (^{o}C) for Quinary 4908 for present, intermediate future and distant future ECHAM5 climate scenarios

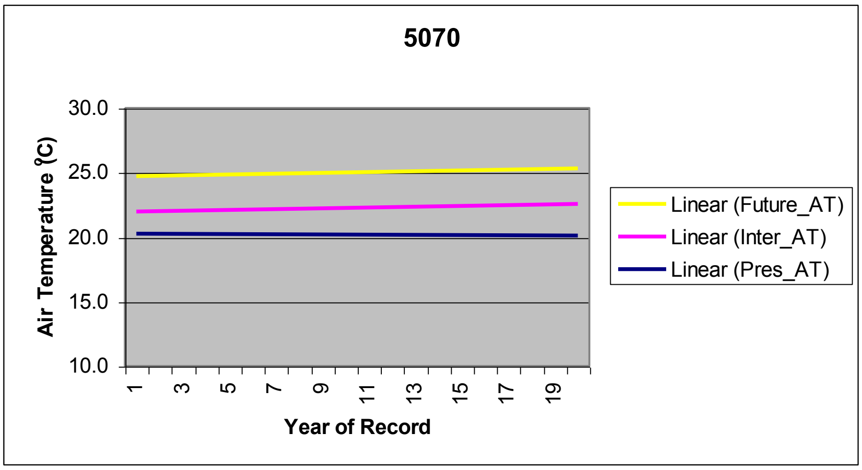

Figure 9.7 Linear trends of mean air temperature (^{o}C) for Quinary 5070 for present, intermediate future and distant future ECHAM5 climate scenarios

9.3.2 Variations in air temperature between the Quinaries making up a Quaternary Catchment for a single climate scenario

The second method describing how air temperature may vary over time explores how it fluctuates between the three altitudinally defined Quinaries (upper, middle and lower; cf. **Section 5.5**) of a Quaternary Catchment, for a single ECHAM5 climate scenario. **Figure 9.8** displays a typical time series using this method of analysis and all 15 selected catchments follow the same overall trend. **Figure 9.8** shows that the higher lying upper Quinary catchment (5020; altitude 1835 m) of Quaternary V32B has the lowest annual means of air temperature compared to those of the middle (5021; altitude 1472 m) and lower Quinaries (5022; altitude 1245 m), with the latter experiencing the highest air temperatures. By comparing the differences in air temperature between each Quinary one is able to infer the significance of the altitude differences between the three Quinaries within a single Quaternary and the value of simulating at Quinary Catchment scale.

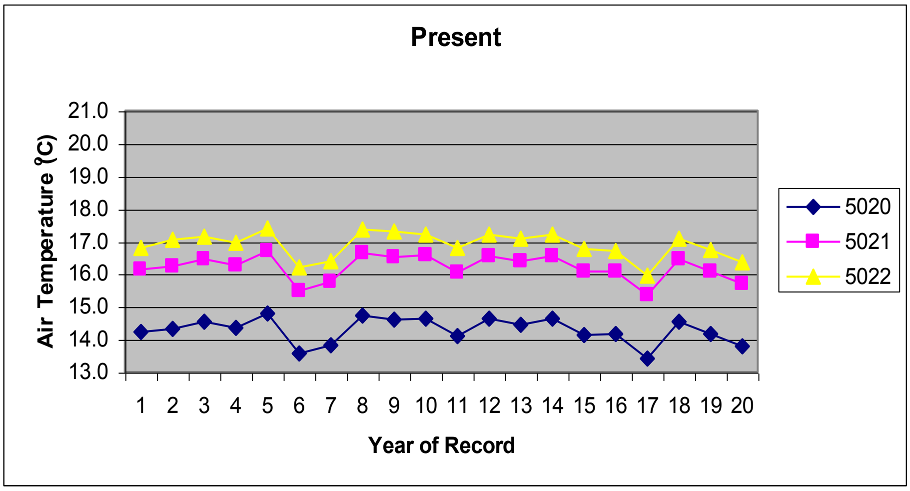

Figure 9.8 Time series of annual means of air temperature (°C) for Quinaries 5020, 5021 and 5022 for the present ECHAM5 climate scenario

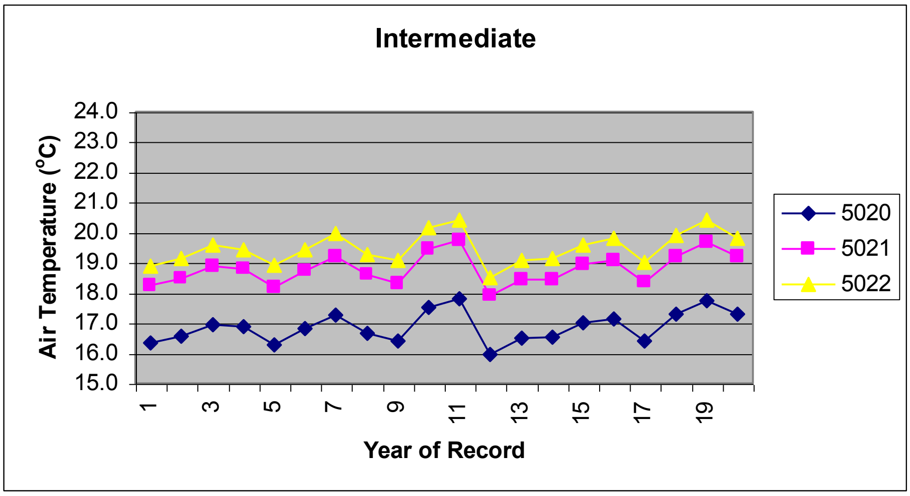

Figure 9.9 Time series of annual means of air temperature (°C) for Quinaries 5020, 5021 and 5022 for the intermediate future ECHAM5 climate scenario

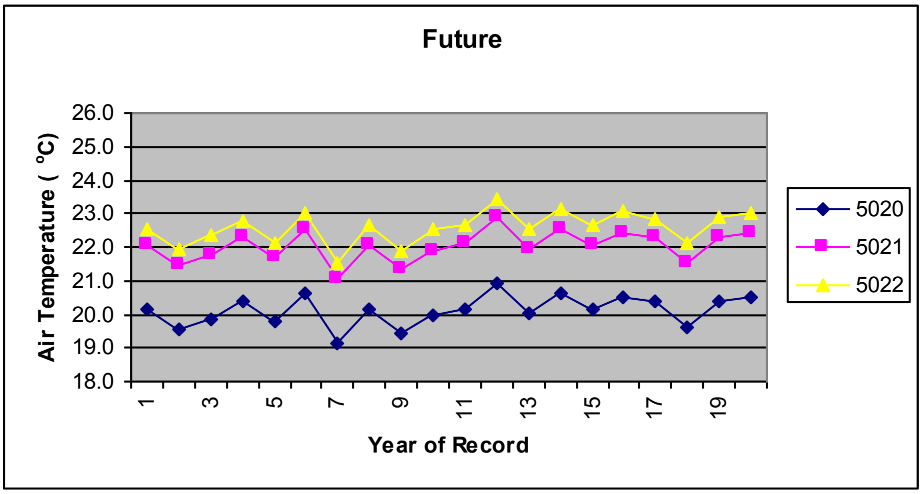

Figure 9.10 Time series of annual means of air temperature (°C) for Quinaries 5020, 5021 and 5022 for the distant future ECHAM5 climate scenario

Table 9.2 A summary of standard deviations of annual means of air temperature for the 15 selected Quinary Catchments for 20 years of present (P), intermediate (I) future (F) and distant future climate scenarios from the ECHAM5 GCM

Quinary Number	Standard Deviation (°C) Present	Standard Deviation (°C) Intermediate	Standard Deviation (°C) Future	I: P	F: P	F: I
4846	0.35	0.49	0.48	1.42	1.39	0.98
4847	0.36	0.50	0.47	1.41	1.31	0.93
4848	0.35	0.50	0.47	1.42	1.33	0.94
4906	0.41	0.51	0.51	1.25	1.24	0.99
4907	0.41	0.52	0.51	1.26	1.24	0.99
4908	0.41	0.52	0.50	1.29	1.22	0.95
5020	0.39	0.51	0.46	1.31	1.18	0.89
5021	0.39	0.51	0.46	1.32	1.18	0.90
5022	0.40	0.53	0.47	1.30	1.17	0.90
5041	0.37	0.53	0.47	1.43	1.26	0.88
5042	0.35	0.52	0.46	1.46	1.30	0.90
5043	0.37	0.53	0.47	1.43	1.26	0.88
5068	0.32	0.49	0.48	1.53	1.52	0.99
5069	0.31	0.45	0.42	1.45	1.37	0.94
5070	0.30	0.44	0.42	1.47	1.39	0.94

Visual comparison of results in **Figures 9.8 - 9.10** indicates an increased variability in annual means of air temperature from one climate scenario to the next into the future. For example, the annual means of air temperature for the present ECHAM5 climate scenario **(Figure 9.8)** appear reasonably stable, with a few spikes over the 20 year record, compared with those of the intermediate and distant future ECHAM5 climate scenarios (**Figures 9.9 and 9.10**), which project a higher variation in air temperature from one year to the next over their 20 years of record. An increase in the variability of future air temperature, important to water temperatures, can be quantified by calculating the standard deviations of the annual means of air temperature for three ECHAM5 climate scenarios (**Table 9.2**). Standard deviation is a measure of dispersal around the mean and is a commonly used measure of variability of a temperature time series (e.g. Schulze, 2007). The results from this test support the visual conclusions from the graphical analysis that air temperature variability is, indeed, increasing in the intermediate and distant futures. From **Table 9.2** it is seen that standard deviations for the intermediate and future ECHAM5 climate scenarios are increasing by an average of 38 and 30% respectively, compared to those of the present ECHAM5 scenario. Furthermore, there does not seem to be a regional trend in the magnitudes of standard deviations. Ultimately, therefore, annual air temperature is projected to fluctuate more in the intermediate and distant futures, which could very well have serious implications for aquatic ecosystems and the species that inhabit them.

9.3.3 Conclusions on air temperature

In conclusion, both methods used to describe how air temperature varies over time indicate that annual means of air temperature and their variability, derived from the ECHAM5 GCM, are likely to increase in the intermediate (2046 - 2065) and more distant (2081 - 2100) futures. Furthermore, there is a noticeable difference in air temperature between the three Quinaries within a single Quaternary Catchment due to altitudinal variation. For both cases the hypotheses set out in **Section 9.1** have been confirmed.

9.4 Time Series Analysis of Runoff from Individual Subcatchments

9.4.1 Projected changes in runoff from a single Quinary Catchment with climate change

The result from the time series analysis for annual runoff from individual subcatchments does not show a distinct pattern of change in runoff over the three ECHAM5 scenarios (**Figures 9.11 - 9.13**). **Figures 9.11 - 9.13** are time series graphs from three Quinaries from different regions of the Thukela and share the same y-axis scale for ease of comparison. All the aforementioned figures indicate a similar overall trend in that annul runoff, in the intermediate and distant futures, could experience more inter-annual variations with larger spikes in annual runoff volumes being evident. For example, closer scrutiny of results from Quinary 5042 (**Figure 9.13**), which is located in the middle to east of the Thukela Catchment, shows that the distant future climate scenario typically generates larger annual runoff volumes than those from intermediate future and present ECHMAM5 scenarios, indicating that larger runoff events are projected to occur under future climatic conditions.

The issue of how the runoff variability from individual subcatchments is likely to change in the future was deemed important for a water temperature study and was therefore quantified by calculating both the standard deviation and the coefficient of variation for all 15 selected Quinaries for the three ECHAM5 climate scenarios.

Standard deviation is an absolute measure of dispersal around the mean while the coefficient of variation is a normalised, i.e. relative, measure of dispersion and is defined as the ratio of the standard deviation to the mean, expressed as a percentage (**Equation 9.1**), i.e.

$$\text{Coefficient of Variation } (C_v) = \frac{\text{Standard Deviation}}{\text{Mean}} * 100 \qquad [9.1]$$

In **Table 9.3** the results of a standard deviation test for the 15 selected catchments for individual subcatchment runoff is presented. The results indicate that standard deviations for individual subcatchment runoff are likely to increase in the intermediate and more distant futures. From **Table 9.3** standard deviations of runoff derived from the intermediate and future ECHAM5 climate scenarios are increasing by an average factor of 1.74 and 2.10 respectively, compared to those of the present ECHAM5 scenario. This is a significant increase in inter-annual variability, particularly for the distant future scenario, where a doubling in standard deviations for individual subcatchment runoff is projected. In **Table 9.4**, on the other hand**,** the results of inter-annual coefficients of variation (C_v) for the 15 selected catchments are summarised for individual subcatchment runoff. This test shows an entirely different set of results to the standard deviation results.

From **Table 9.4** the C_v of annual runoff derived from the intermediate ECHAM5 climate scenario remains relatively constant (a ratio close to unity) compared to the C_v values calculated for the present ECHAM5 scenario. The ratio comparison actually shows a slight decrease in C_v for the future to present and future to intermediate ECHAM5 climate scenarios. It can be concluded that the standard deviation of individual subcatchment runoff is increasing markedly while its C_v is remaining relatively constant or actually decreasing in the intermediate and more distant futures, implying that the means are increasing at a similar rate to the absolute variability. The standard deviation ratio analysis for individual subcatchment runoff also displays a regional trend, indicating an increase in values over time as one moves from the upper (higher altitude) to the lower altitude regions of the Thukela Catchment.

A comparison of Quinaries 5021, 5042 and 5069 (**Figures 9.11 - 9.13**) allows one to determine what effects catchment area and location within the Thukela have on individual catchment runoff. Quinary 5021 is located in the upper north region of the Thukela and has a catchment area of 70.5 km^2. Quinary 5069 has a similar catchment area of 78.0 km^2, but is located in the coastal hinterland region and the difference in location has a large influence on individual catchment runoff volume. The coastal Quinary (5069) experiences far more runoff for all three ECHAM5 climate scenarios than the drier Quinary 5021. Quinary 5042 is located middle east region of the Thukela, which also generally has lower runoff than the coastal hinterland, but shows similar runoff volumes to the coastal catchment (Quinary 5069). This similarity in terms of runoff volume may be attributed to Quinary 5042 being more than double the catchment size at 188.7 km^2, thus giving this drier catchment a similar runoff volume to that of the coastal Quinary. A volumetric comparison of runoff can thus be misleading and the impact of catchment area therefore needs to be taken into account.

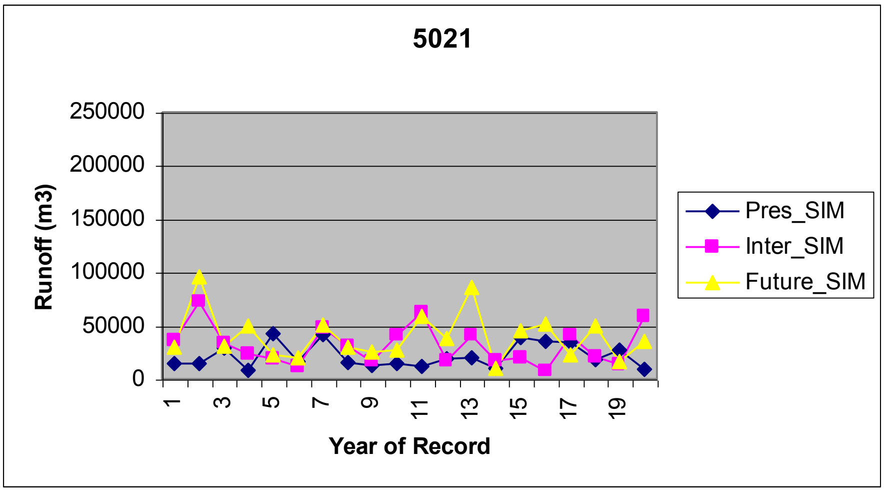

Figure 9.11 Time series of individual subcatchment runoff (m^3) for Quinary 5021 for present, intermediate future and distant future ECHAM5 climate scenarios

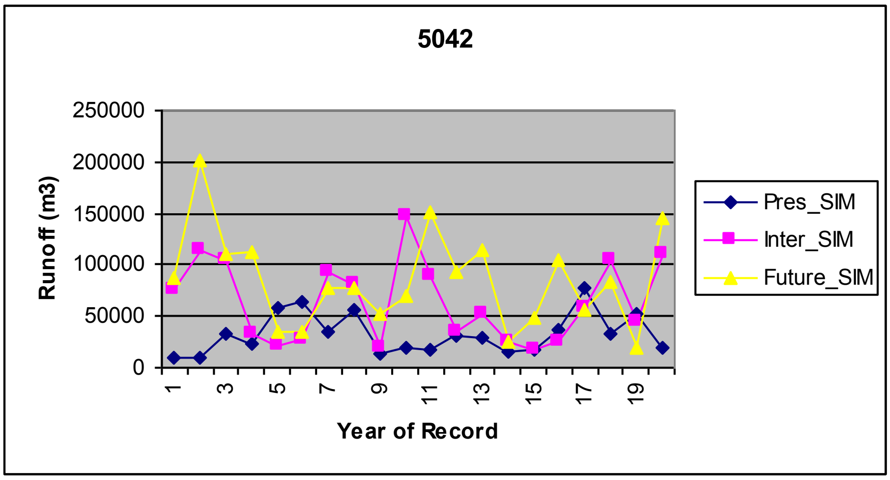

Figure 9.12 Time series of individual subcatchment runoff (m^3) for Quinary 5042 for present, intermediate future and distant future ECHAM5 climate scenarios

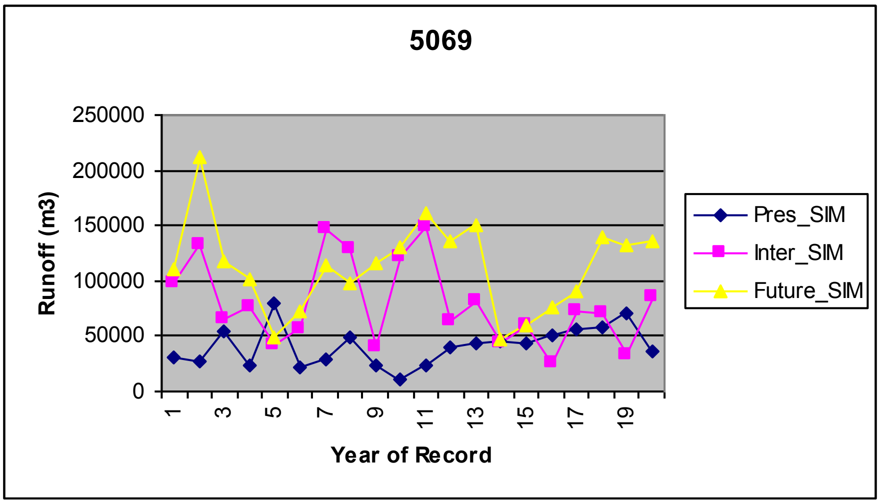

Figure 9.13 Time series of individual subcatchment runoff (m^3) for Quinary 5069 for present, intermediate future and distant future ECHAM5 climate scenarios

Table 9.3 A summary of standard deviations (m^3) of individual subcatchment annual runoff for the 15 selected Quinary Catchments derived from present (P), intermediate (I) future and distant future (F) ECHAM5 climate scenarios

Quinary Number	Standard Deviation (m^3) Present	Standard Deviation (m^3) Intermediate	Standard Deviation (m^3) Future	I: P	F: P	F: I
4846	5065	5562	6865	1.10	1.36	1.23
4847	8158	8957	12152	1.10	1.49	1.36
4848	19118	21274	29426	1.11	1.54	1.38
4906	22993	34258	43446	1.49	1.89	1.27
4907	10915	16390	21553	1.50	1.97	1.32
4908	8471	13404	18329	1.58	2.16	1.37
5020	5840	9624	11384	1.65	1.95	1.18
5021	11375	18214	21935	1.60	1.93	1.20
5022	43993	71542	96027	1.63	2.18	1.34
5041	8960	20878	25035	2.33	2.79	1.20
5042	19566	39363	46531	2.01	2.38	1.18
5043	27736	59047	72229	2.13	2.60	1.22
5068	5659	13931	14862	2.46	2.63	1.07
5069	17664	38096	40433	2.16	2.29	1.06
5070	19650	44401	46912	2.26	2.39	1.06

Table 9.4 A summary of inter-annual coefficients of variation (%) of individual catchment runoff for the 15 selected Quinary Catchments derived from present (P), intermediate future (I) and distant future(F) ECHAM5 climate scenarios

Quinary Number	Coefficient of Variation (%) Present	Coefficient of Variation (%) Intermediate	Coefficient of Variation (%) Future	I: P	F: P	F: I
4846	43.83	31.27	28.42	0.71	0.65	0.91
4847	50.42	35.14	34.63	0.70	0.69	0.99
4848	55.86	38.52	38.14	0.69	0.68	0.99
4906	45.49	45.51	41.16	1.00	0.90	0.90
4907	48.62	48.18	44.20	0.99	0.91	0.92
4908	50.15	51.35	46.61	1.02	0.93	0.91
5020	49.22	56.26	52.37	1.14	1.06	0.93
5021	52.58	57.88	55.12	1.10	1.05	0.95
5022	70.29	73.20	73.62	1.04	1.05	1.01
5041	48.31	58.36	53.42	1.21	1.11	0.92
5042	60.00	61.35	54.77	1.02	0.91	0.89
5043	58.18	63.08	56.99	1.08	0.98	0.90
5068	42.32	50.05	37.62	1.18	0.89	0.75
5069	43.44	47.88	35.98	1.10	0.83	0.75
5070	52.30	56.64	41.76	1.08	0.80	0.74

9.4.2 Variations in individual subcatchment runoff between the Quinaries making up a Quaternary Catchment for a single climate scenario

This analysis describes how annual runoff from individual subcatchments varies over time and explores how runoff fluctuates between the three altitudinally defined Quinaries (upper, middle and lower; cf. **Section 5.5**) of a Quaternary Catchment, for a single ECHAM5 climate scenario. **Figures 9.14 - 9.16** show time series for Quaternary V14E located in the central region of the Thukela and these results are typical of the time series from this method of analysis, with all 15 selected catchments following the same overall trend. The results indicate that catchment area has a large influence on runoff volume. For example, Quinary 4906 is the largest of the three at 143 km^2 and thus its runoff is always greater than that from the other two smaller Quinaries, which are similar in terms of area (+/- 70 km^2). However, due to these three Quinaries being in the same Quaternary, they all experience the same fluctuations with respect to their annual runoff. Therefore, if there is a wet year all three Quinaries will show an increase in runoff for that year. When comparing results from **Figures 9.14 - 9.16** it is noted that there is a definite increase in runoff volume from one scenario to the next for all Quinaries, with the distant future climate scenario (**Figure 9.16**) exhibiting the largest magnitude of flow.

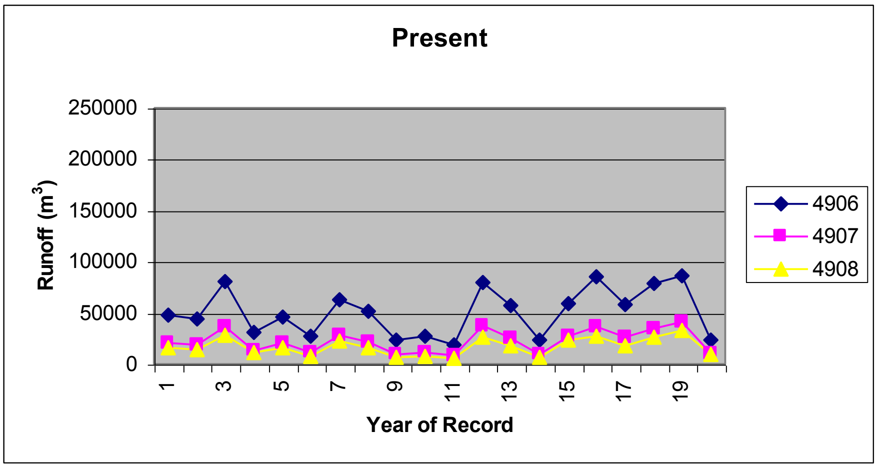

Figure 9.14 A time series of individual subcatchment annual runoff (m^3) for Quinaries 4906, 4907 and 4908 within Quaternary Catchment V14E derived from the present ECHAM5 climate scenario

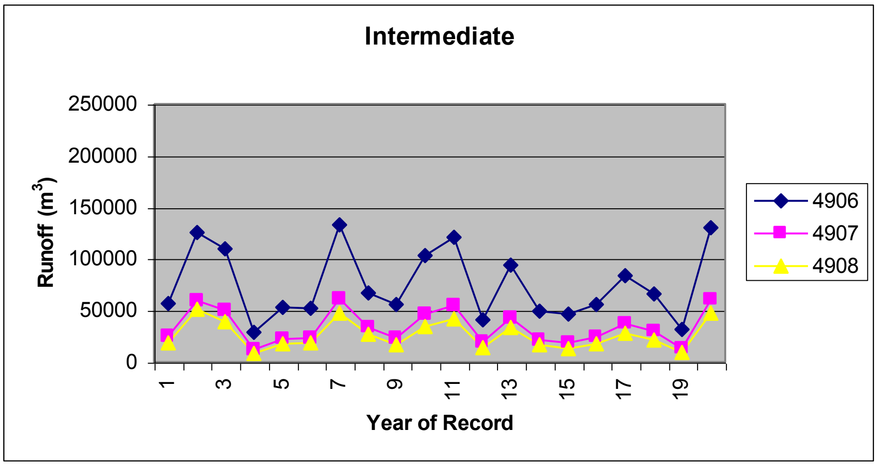

Figure 9.15 A time series of individual subcatchment annual runoff (m^3) for Quinaries 4906, 4907 and 4908 within Quaternary Catchment V14E derived from the intermediate future ECHAM5 climate scenario

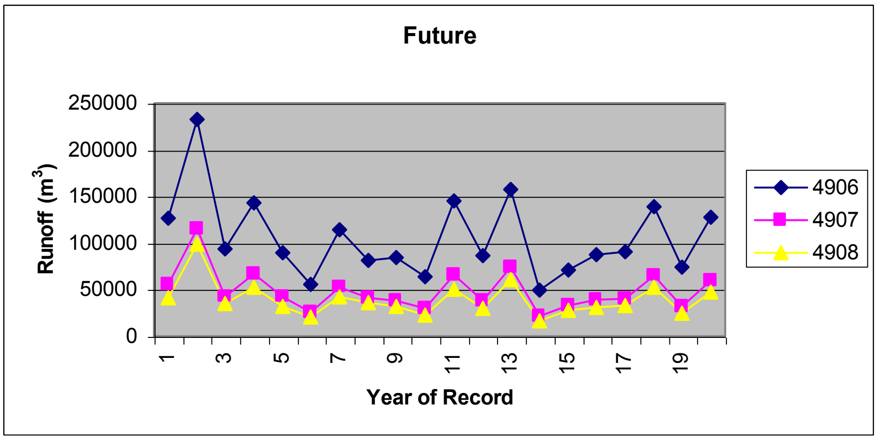

Figure 9.16 A time series of individual subcatchment annual runoff (m^3) for Quinaries 4906, 4907 and 4908 within Quaternary Catchment V14E derived from the distant future ECHAM5 climate scenario

9.4.3 Conclusions on individual subcatchment runoff

In conclusion, both methods used to describe how individual subcatchment runoff varies over time indicate that runoff, derived with the *ACRU* model using output from the ECHAM5 GCM, and its absolute variability (i.e. standard deviation) are likely to increase in the intermediate (2046 - 2065) and more distant (2081 - 2100) futures, while the relative variability (i.e. C_V) is likely to remain much the same or even decrease slightly over these time periods. Furthermore, there is a noticeable difference in individual subcatchment runoff within a single Quaternary Catchment due to altitudinal and area variations. For both cases the hypotheses set out in **Section 9.1** have been confirmed.

9.5 Time Series Analysis of Accumulated Catchment Streamflows

9.5.1 Projected changes in accumulated catchment streamflows from a single Quinary Catchment with climate change

Similar to the results from individual subcatchment runoff, the results produced from the time series analysis for annual accumulated streamflows do not show a distinct pattern of change over the three ECHAM5 scenarios (**Figures 9.17 - 9.19)**. **Figures 9.17 - 9.19** show time series from three lower Quinaries from different regions of the Thukela Catchment and it must be noted that these figures do not share the same y-axis scale owing to the large differences in streamflow magnitude between these Quinaries. Essentially Quinary 5070, which is located in the coastal hinterland, will have more accumulated streamflow then Quinary 4848 which is located in the upper west of the Thukela, as more flows are routed through this lower coastal Quinary.

Figures 9.17 - 9.19 indicate a similar overall trend in that annul accumulated streamflows are increasing and the intermediate and distant futures could be experiencing a higher inter-annual variation and larger spikes in annual accumulated streamflow volumes. All three aforementioned figures show that the distant future climate scenario typically generates larger accumulated streamflow volumes than the intermediate future and present ECHMAM5 climate scenarios. The results indicate that larger streamflow events are projected to be generated under future climatic conditions.

As in **Sections 9.3** and **9.4**, the issue of variability needs to be considered. Variability of accumulated annual streamflows was quantified by calculating the standard deviation (**Table 9.5**) and the inter-annual C_V (**Table 9.6**) from all 15 selected Quinaries with flows derived from the three ECHAM5 climate scenarios.

Table 9.5 summarises the results of a standard deviation test for the 15 selected catchments for accumulated streamflows. The results indicate that standard deviations for accumulated annual streamflows are likely to increase in the intermediate and more distant futures. The ratios of distant future to present standard deviations of accumulated flows derived from ECHAM5 climate scenarios display the greatest change, with an average increase by a factor of around 2.2. The other two ratio comparisons between the intermediate future and present, and the more distant and intermediate futures, also point to increases in standard deviation for accumulated streamflows, but to a lesser degree. The position of the Quinary within the larger Quaternary Catchment also appears to influence standard deviations of accumulated streamflows, with the lower Quinaries, the flows of which are modulated by accumulated flows from upstream, tending to have a lower standard deviation then the upper and middle Quinaries.

Table 9.6 summarises the results of the inter-annual coefficients of variation (C_v) for the 15 selected subcatchments for accumulated streamflows. The table shows an entirely different set of results to those of the standard deviations. From **Table 9.6** the C_v for the intermediate ECHAM5 climate scenario remains relatively constant (a ratio of close to unity) compared to C_v values calculated for the present ECHAM5 scenario. The ratio comparison actually shows a slight decrease in C_v for the distant future to present and distant future to intermediate ECHAM5 climate scenarios. It can thus be concluded that the absolute variability, expressed through the standard deviation, is increasing markedly for accumulated streamflows while the relative variability, expressed through the C_v and dependent also on changes of the mean, is remaining relatively constant or even decreasing in the intermediate and more distant future. The standard deviation ratio analysis for accumulated annual streamflows also displays a regional trend, which indicates an increase in standard deviation values over time as one moves from the higher rainfall western to the lower rainfall central and eastern regions of the Thukela Catchment.

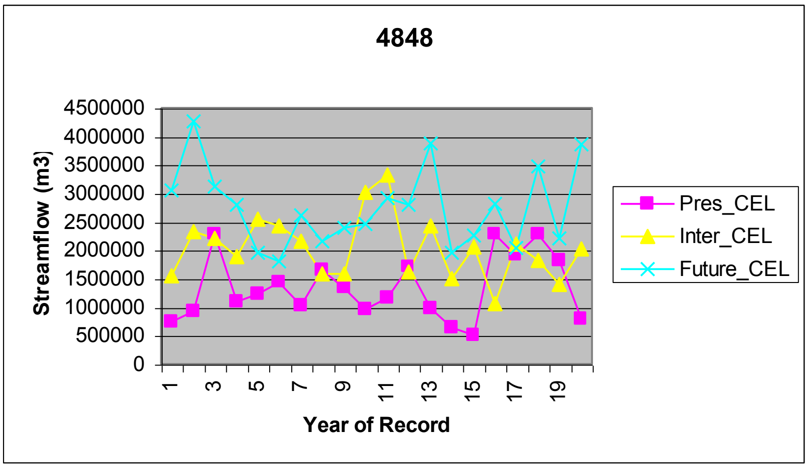

Figure 9.17 A time series of accumulated annual streamflows (m^3) for Quinary 4848 of Quaternary Catchment V11J derived from present, intermediate future and distant future ECHAM5 climate scenarios

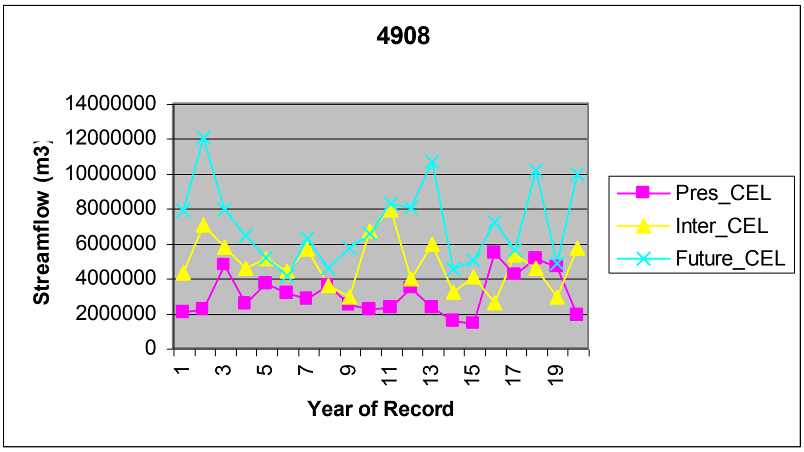

Figure 9.18 A time series of accumulated annual streamflows (m^3) for Quinary 4908 of Quaternary Catchment V14E derived from present, intermediate future and distant future ECHAM5 climate scenarios

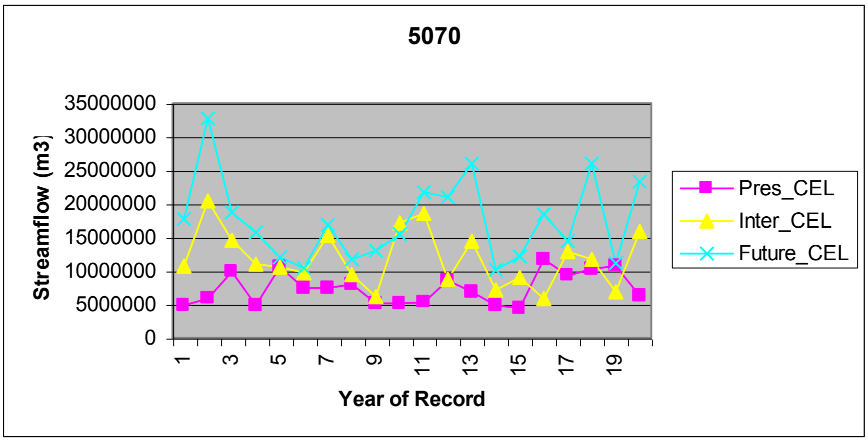

Figure 9.19 A time series of accumulated annual streamflows (m^3) for Quinary 5070 of Quaternary Catchment V50A derived from present, intermediate future and distant future ECHAM5 climate scenarios

Table 9.5 A summary of standard deviations of accumulated annual streamflows for the 15 selected Quinary Catchments derived from present, intermediate future and distant future ECHAM5 climate scenarios

Quinary Number	Standard Deviation (m^3) Present	Standard Deviation (m^3) Intermediate	Standard Deviation (m^3) Future	I: P	F: P	F: I
4846	5065	5562	6866	1.10	1.36	1.23
4847	13187	14441	18939	1.10	1.44	1.31
4848	556968	555275	701160	1.00	1.26	1.26
4906	22994	34258	43446	1.49	1.89	1.27
4907	33887	50618	64942	1.49	1.92	1.28
4908	1218130	1455606	2277062	1.19	1.87	1.56
5020	5840	9624	11384	1.65	1.95	1.18
5021	17211	27833	33306	1.62	1.94	1.20
5022	299336	673227	1088828	2.25	3.64	1.62
5041	8961	20878	25036	2.33	2.79	1.20
5042	28318	60000	71345	2.12	2.52	1.19
5043	481763	1101827	1637450	2.29	3.40	1.49
5068	5660	13932	14863	2.46	2.63	1.07
5069	23253	51975	55216	2.24	2.37	1.06
5070	2374342	4212677	6146886	1.77	2.59	1.46

Table 9.6 A summary of coefficients of variation of accumulated annual streamflows for the 15 selected Quinary Catchments derived from present, intermediate future and distant future ECHAM5 climate scenarios

Quinary Number	Coefficient of Deviation (%) Present	Coefficient of Deviation (%) Intermediate	Coefficient of Deviation (%) Future	I: P	F: P	F: I
4846	43.83	31.27	28.42	0.71	0.65	0.91
4847	47.54	33.37	31.96	0.70	0.67	0.96
4848	41.62	27.33	25.59	0.66	0.61	0.94
4906	45.49	45.51	41.16	1.00	0.90	0.90
4907	46.42	46.32	42.08	1.00	0.91	0.91
4908	39.67	30.24	32.41	0.76	0.82	1.07
5020	49.22	56.26	52.37	1.14	1.06	0.93
5021	51.38	57.30	54.13	1.12	1.05	0.94
5022	30.96	44.26	44.07	1.43	1.42	1.00
5041	48.31	58.36	53.42	1.21	1.11	0.92
5042	55.35	60.04	54.12	1.08	0.98	0.90
5043	32.96	46.03	43.87	1.40	1.33	0.95
5068	42.32	50.05	37.62	1.18	0.89	0.75
5069	43.03	48.39	36.35	1.12	0.84	0.75
5070	32.15	35.71	35.30	1.11	1.10	0.99

9.5.2 Variations in accumulated catchment streamflows between the Quinaries making up a Quaternary Catchment for a single climate scenario

The second method used to describe how accumulated catchment streamflows vary over time explores the flow fluctuations between the three altitudinally defined Quinaries (upper, middle and lower; cf. **Section 5.5**) of a Quaternary Catchment, for a single ECHAM5 climate scenario. **Figures 9.20 - 9.22** display time series for Quaternary V11JE located in the upper west region of the Thukela Catchment, and they are typical of time series from this method of analysis, with all 15 selected catchments following the same overall trend. **Figures 9.20 - 9.22** immediately show an inherent problem with this method of time series analysis for accumulated streamflows, with the flows from lower Quinary (in this case 4848) always significantly larger in terms of streamflow magnitude because its streamflow volume equals the total summed streamflows from itself and from contributions of upstream subcatchments, in this case Quinaries 4846 and 4847. This accumulation results in a scaling problem, results in the graph to only be able to display the streamflow variation of the lower Quinary catchment. A comparison of **Figures 9.20 - 9.22** does, however, reveal that accumulated streamflows will increase significantly for both the intermediate and distant future ECHAM5 climate scenarios for the lower Quinary (4848).

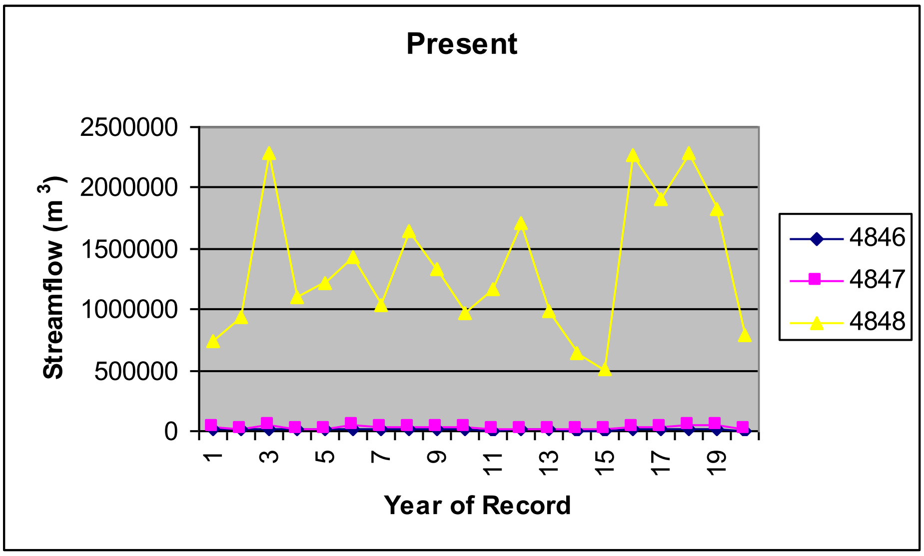

Figure 9.20 A time series of accumulated annual streamflows (m^3) for Quinaries 4846, 4847 and 4848 of Quaternary Catchment V11J derived from the present ECHAM5 climate scenario

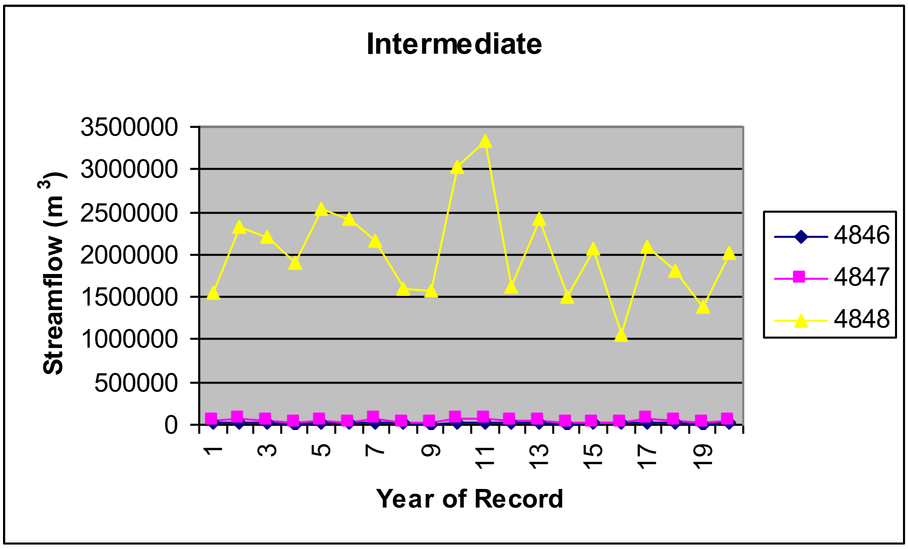

Figure 9.21 A time series of accumulated annual streamflows (m^3) for Quinaries 4846, 4847 and 4848 of Quaternary Catchment V11J derived from the intermediate future ECHAM5 climate scenario

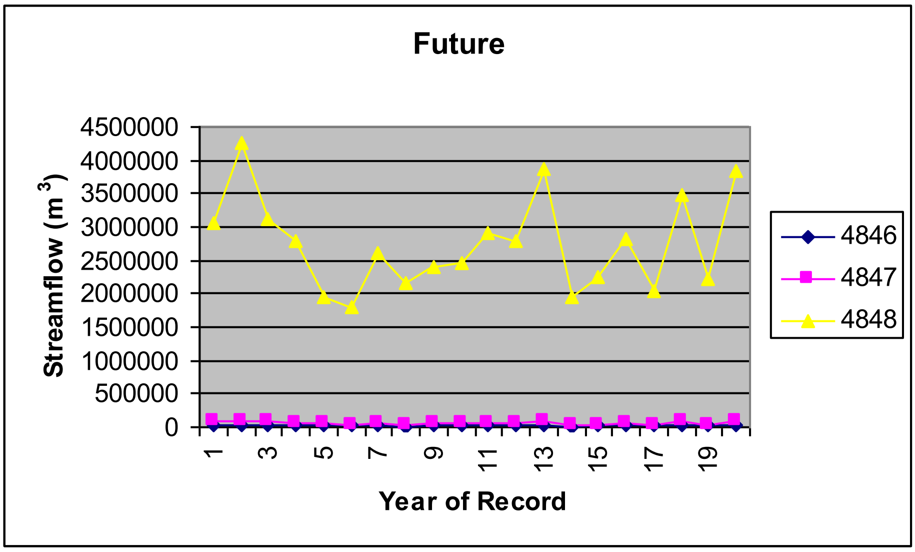

Figure 9.22 A time series of accumulated annual streamflows (m^3) for Quinaries 4846, 4847 and 4848 of Quaternary Catchment V11J derived from the distant future ECHAM5 climate scenario

9.5.3 Conclusions on accumulated catchment streamflows

In conclusion, the method used to assess projected changes in accumulated annual streamflows from a single Quinary Catchment with climate change indicates that streamflow and its standard deviation are likely to increase in the intermediate (2046 - 2065) and more distant (2081 - 2100) futures while the C_V is likely to remain the same or even decrease slightly over these time periods. The method used to project variations in accumulated catchment streamflows between the Quinaries making up a Quaternary Catchment for a single climate scenario is not ideal for accumulated streamflows owing to accumulation and scaling issues, but it nevertheless displays significant flow increases for future climate scenarios from the ECHAM5 GCM which are likely to have important implications in water temperature simulations with future climate scenarios.

9.6 Time Series Analysis of Mixed Maximum Water Temperature

9.6.1 Projected changes in mixed maximum water temperature from a single Quinary Catchment with climate change

The results produced by the time series analysis in the previous sections all indicate that there is likely to be a significant increase in mixed maximum water temperature (MMWT) under the projected future climate change scenarios for all the selected Quinaries. These results are expected as MMWT is based on a combination air temperature (**Section 9.3**) and streamflow (**Section 9.5**) and both these indicated likely increases under projected future climatic conditions. This projected increase in MMWT is illustrated in **Figures 9.23** - **9.27** by way of time series plots from selected Quinaries, with these plots sharing the same y-axis scale for ease of comparison. Each of the five plots in **Figures 9.23** - **9.27** represents the upper Quinary from each of the different regions within the Thukela Catchment. By comparing results from **Figures 9.23** - **9.27** one can determine how spatial location can influence the temporal characteristics of MMWT. By comparing MMWT for each ECHAM5 climate scenario it can be concluded that MMWT increases as water cascades from the cooler higher altitudes towards the warmer coastal catchments. The MMWTs of the two Quinaries located in the higher altitudes (4847 and 5021) are in the order of 2 °C lower than those of the Quinary located near the coast (5069) for all three ECHAM5 climate scenarios.

Figure 9.23 shows a time series of MMWT for Quinary 4847, located in the high altitude upper western part of the Thukela. MMWT is shown to remain relatively constant over the 20 years of a climate scenario, but there are significant differences between the three ECHAM5 scenarios. However, as in the case of air temperature a closer look at the time series indicates a rising MMWT trend over the 20 year period of record in both the intermediate and distant futures, which is not visible in the present climate scenario. The MMWT derived from the present ECHAM5 climate scenario for Quinary 4848 (**Figure 9.2**) is approximately 18 °C, with this value increasing to approximately 21 °C for the intermediate future ECHAM5 climate and finally to around 24 °C when derived from the more distant future ECHAM5 climate scenario. Essentially MMWT is thus projected to increase significantly over time, with water temperatures from the present ECHAM5 climate being the lowest, the future ECHAM5 climate being the highest and the intermediate ECHAM5 being somewhere between these two extremes. This increasing trend and magnitude of change in MMWT between the three ECHAM5 scenarios was found in all 15 selected Quinaries evaluated and can be observed in the remaining four time series plots for this section (**Figures 9.24 - 9.27**).

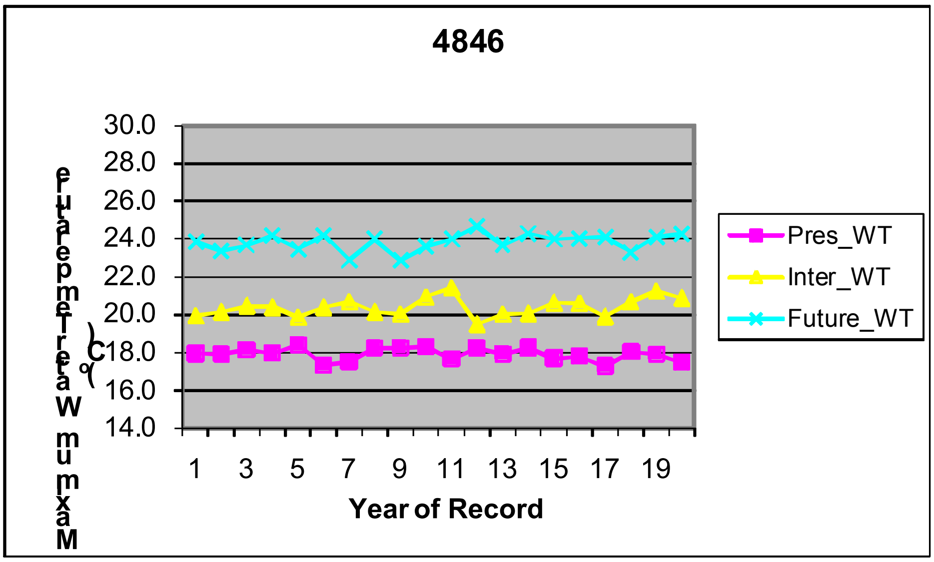

Figure 9.23 A time series of mixed maximum water temperature (°C) for Quinary 4846 of Quaternary Catchment V11J derived from present, intermediate future and distant future ECHAM5 climate scenarios

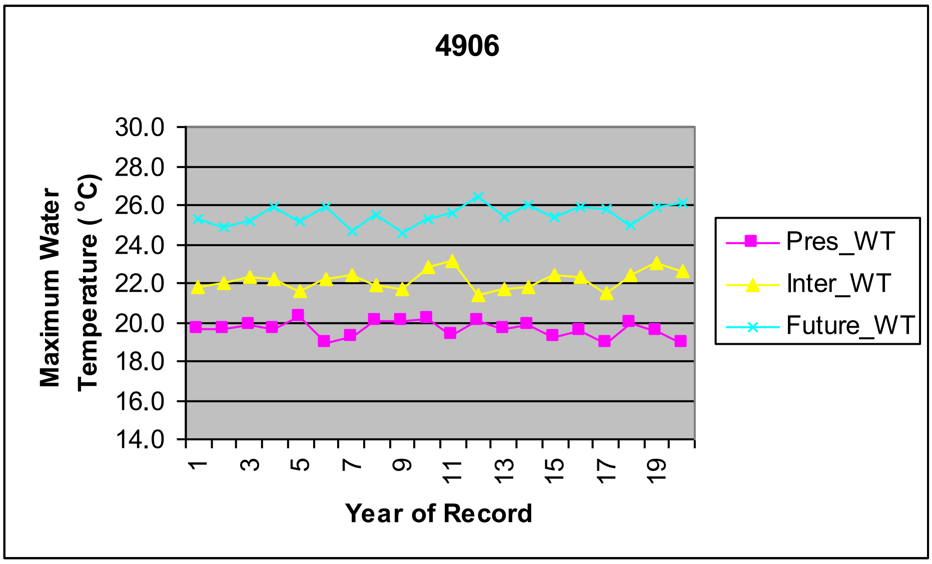

Figure 9.24 A time series of mixed maximum water temperature (°C) for Quinary 4906 of Quaternary Catchment V14E derived from present, intermediate future and distant future ECHAM5 climate scenarios

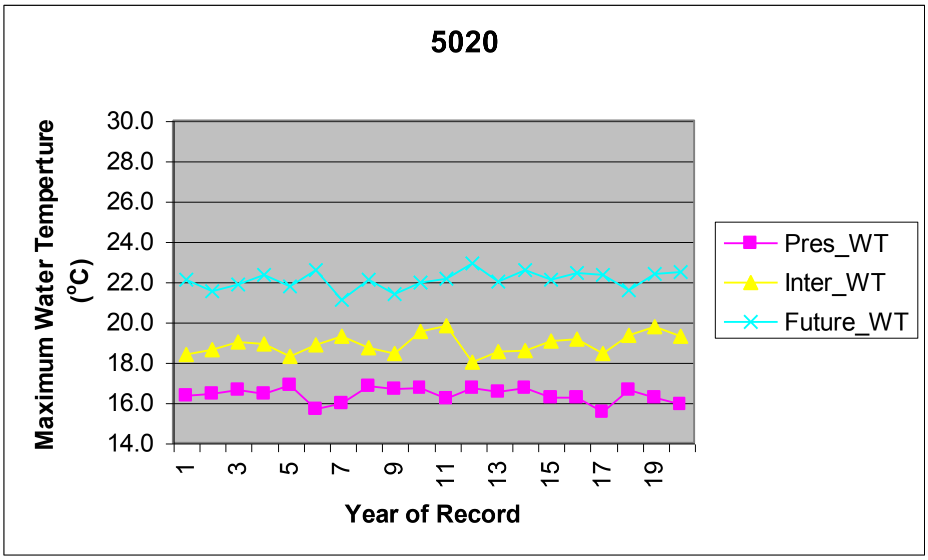

Figure 9.25 A time series of mixed maximum water temperature (°C) for Quinary 5020 of Quaternary Catchment V32B derived from present, intermediate future and distant future ECHAM5 climate scenarios

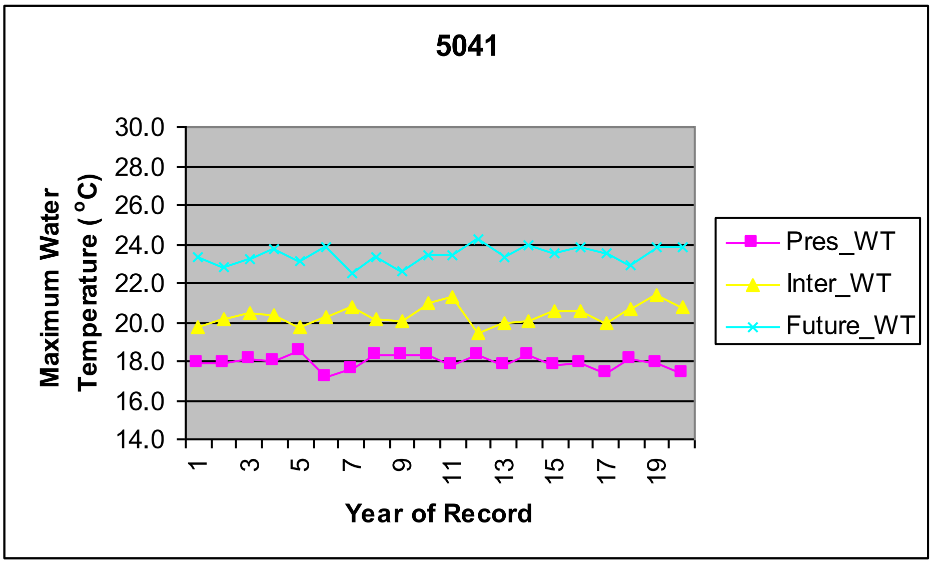

Figure 9.26 A time series of mixed maximum water temperature (°C) for Quinary 5041 of Quaternary Catchment V33A derived from present, intermediate future and distant future ECHAM5 climate scenarios

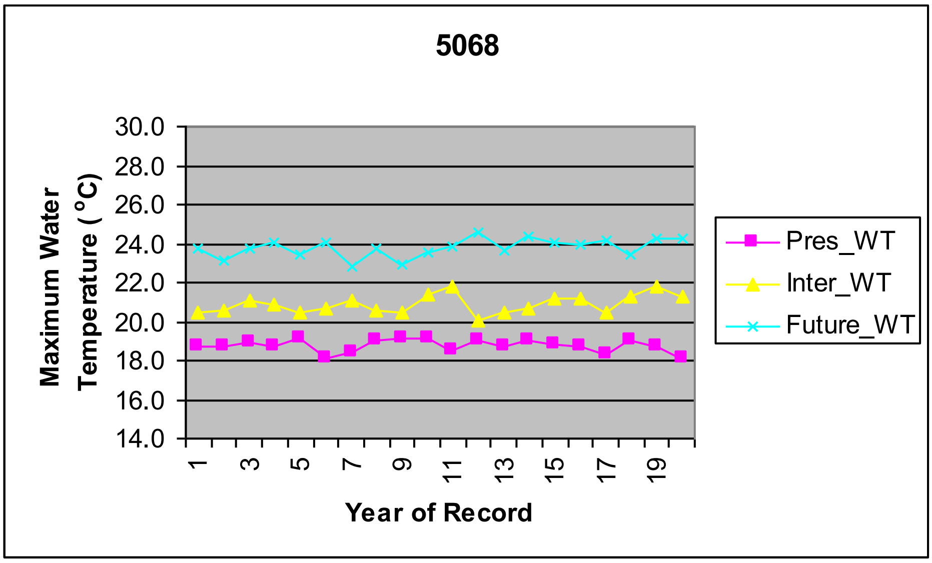

Figure 9.27 A time series of mixed maximum water temperature (°C) for Quinary 5068 of Quaternary Catchment V50A derived from present, intermediate future and distant future ECHAM5 climate scenarios

9.6.2 Variations in mixed maximum water temperature between the Quinaries making up a Quaternary Catchment for a single climate scenario

The second method used to describe how MMWT varies explores how water temperature fluctuates between the three altitudinally defined Quinaries (upper, middle and lower; cf. **Section 5.5**) of a Quaternary Catchment, for a single ECHAM5 climate scenario. **Figure 9.28** shows typical time series from this method of analysis, and all 15 selected catchments which underwent this analysis illustrated the same overall trends. **Figure 9.28** shows that the upper Quinary catchment (4906) of Quaternary V14E has the lowest MMWT compared to those of the middle (4907) and lower altitude Quinary (4908), with the latter experiencing the highest MMWT. In terms of flow routing, water from Quinary 4906 flows into Quinary 4907, the water of which in turn flows into the bottom Quinary 4908. As the water flows downstream to lower altitudes it warms and this is illustrated in the respective times series. This analysis also indicates that all three hydrologically linked Quinaries are situated in the same region as they all experience the same year-to-year fluctuations of MMWT. If there is therefore a warm year all three Quinaries will show a corresponding increase in MMWT. If one compares **Figures 9.28 - 9.30** it is noted that there is a definite increase in MMWT from one scenario to the next for all Quinary Catchments.

By comparing results in **Figures 9.28 - 9.30** there appears to be an increased inter-annual variation in MMWT from one climate scenario to the next into the future. For example, the present ECHAM5 climate scenario's MMWT **(Figure 9.28)** is reasonably stable with some inter-annual variation over the 20 year record, compared with MMWTs of the intermediate and distant future ECHAM5 climate scenarios (**Figures 9.29** and **9.30**) which project higher variations and many more spikes in MMWT from one year to the next. As already alluded to in pervious sections, an increase in the inter-annual variabilities of future MMWTs is an important ecological issue and can be quantified by calculating the standard deviation of the annual MMWTs for the three ECHAM5 climate scenarios (**Table 9.7**). These results support the visual conclusions from the graphical analysis that, like air temperature and streamflow, the variability of MMWT is increasing in the intermediate and distant futures. From **Table 9.7** standard deviations for the intermediate and future ECHAM5 climate scenarios are increasing by an average of 39 and 29% respectively when compared to those of the present ECHAM5 scenario – a result which is similar to that of the standard deviation of air temperature (**Table 9.2**). Furthermore, as in the case of air temperature, there does not seem to be a regional trend, which governs the magnitude of standard deviation. Ultimately annual MMWT is projected to fluctuate far more in the intermediate and distant future than under present climatic conditions, which could very well have serious implications for aquatic species and the management of these ecosystems.

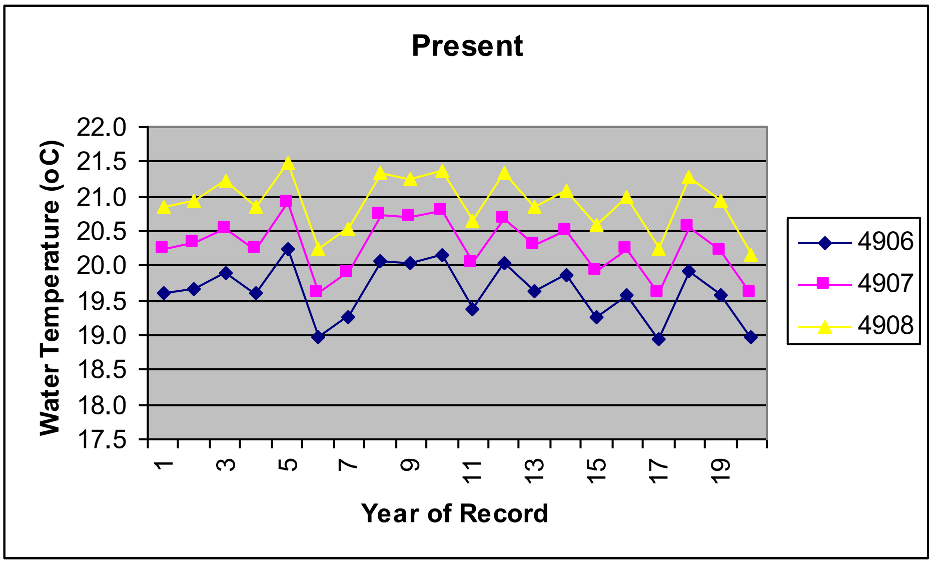

Figure 9.28 A time series of mixed maximum water temperature (°C) derived from the present ECHAM5 climate scenario for Quinaries 4906 (upper), 4907 (middle) and 4908 (lower) of Quaternary Catchment V14E

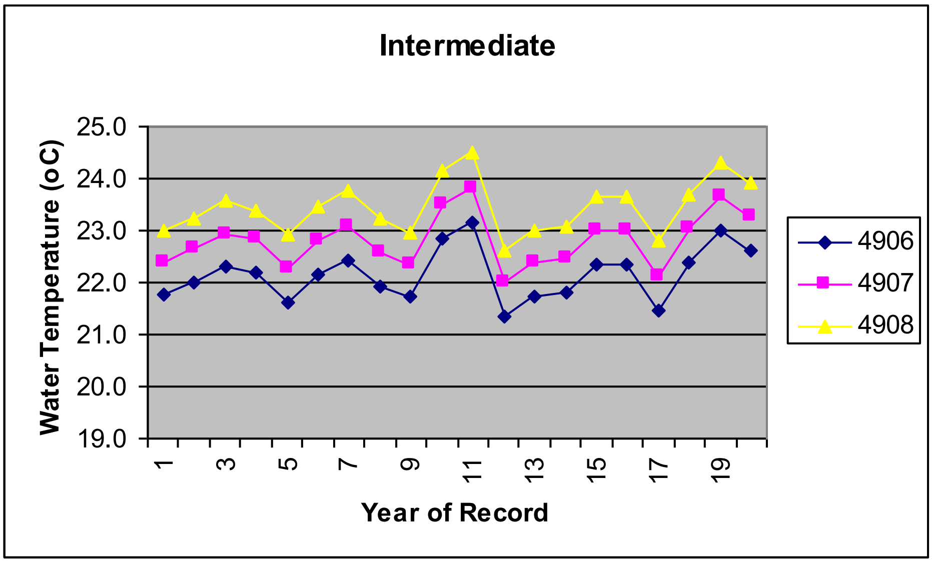

Figure 9.29 A time series of mixed maximum water temperature (°C) derived from the present ECHAM5 climate scenario for Quinaries 4906 (upper), 4907 (middle) and 4908 (lower) of Quaternary Catchment V14E

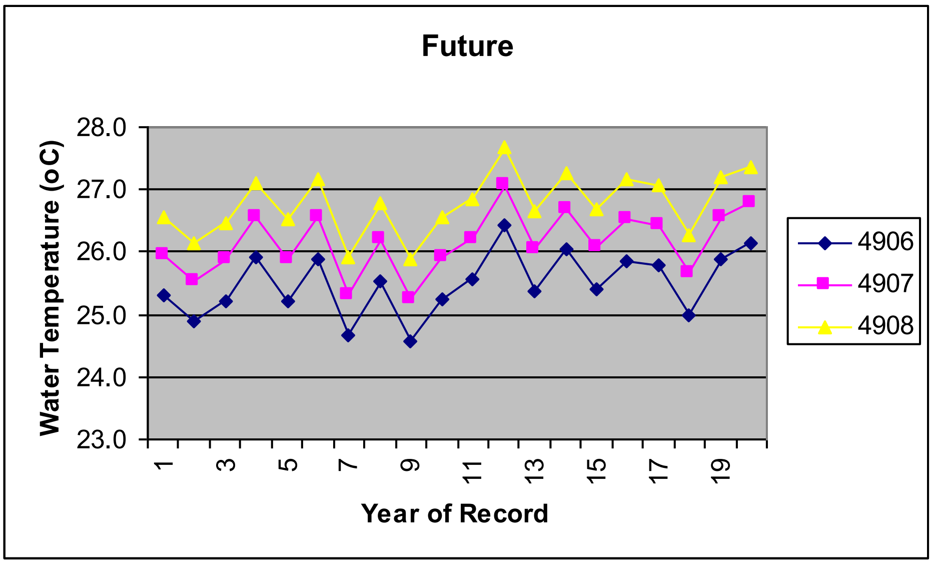

Figure 9.30 A time series of mixed maximum water temperature (°C) derived from the present ECHAM5 climate scenario for Quinaries 4906 (upper), 4907 (middle) and 4908 (lower) of Quaternary Catchment V14E

Table 9.7 A summary of standard deviations of annual mixed maximum water temperatures for the 15 selected Quinary Catchments derived from present, intermediate future and distant future ECHAM5 climate scenarios

Quinary Number	Standard Deviation (°C) Present	Standard Deviation (°C) Intermediate	Standard Deviation (°C) Future	I: P	F: P	F: I
4846	0.34	0.48	0.47	1.42	1.39	0.98
4847	0.35	0.49	0.46	1.42	1.32	0.93
4848	0.35	0.49	0.46	1.42	1.34	0.94
4906	0.40	0.51	0.50	1.26	1.24	0.98
4907	0.40	0.51	0.50	1.26	1.24	0.98
4908	0.40	0.51	0.49	1.29	1.22	0.95
5020	0.38	0.50	0.45	1.32	1.18	0.89
5021	0.38	0.50	0.45	1.32	1.18	0.89
5022	0.39	0.52	0.46	1.31	1.17	0.90
5041	0.36	0.52	0.46	1.44	1.27	0.88
5042	0.35	0.50	0.45	1.46	1.31	0.90
5043	0.36	0.52	0.46	1.43	1.26	0.88
5068	0.31	0.48	0.47	1.54	1.52	0.99
5069	0.30	0.44	0.41	1.46	1.37	0.94
5070	0.29	0.44	0.41	1.48	1.39	0.94

9.6.3 Conclusions on mixed maximum water temperature

In conclusion, both methods used to describe how MMWT varies over time and space indicate that mean annual MMWT and its variability are likely to increase in the intermediate (2046 - 2065) and more distant (2081 - 2100) futures when derived from the ECHAM5 GCM. Furthermore, there is a noticeable difference in the MMWT within a single Quaternary Catchment due to hydrological flow routing, with an increase in water temperatures as the water cascades downstream from higher altitude upper Quinaries to lower Quinaries at lower altitudes. In both cases the hypotheses set out in **Section 9.1** have thus been confirmed.

*****

In **Chapter 9**, the third and final chapter on results, times series analyses are employed in order to temporally assess the potential impacts of climate change on water temperature related parameters in the Thukela Catchment. In total 15 Quinary Catchments, which make up five Quaternaries, were selected in the Thukela to undergo time series analyses. The main outcomes of this chapter are summarised below:

Time series analyses were performed on the following parameters:

- Mean Air Temperature,
- Individual Subcatchment Runoff,
- Accumulated Streamflows, and
- Mixed Water Temperature.

The time series analyses uses two methods to describe how each water temperature related parameter varies over time, *viz*.

- How an parameter varies for a single Quinary Catchment by comparing the three ECHAM5 climate scenarios (i.e. a temporal analysis), with the hypothesis being that in future climates temperatures are increasing and streamflows are changing; and
- How an parameter varies between the three Quinaries making up a Quaternary Catchment for a single climate scenario (i.e. a spatial analysis), with the hypothesis being that Quinaries within a Quaternary are altitude determined and therefore have influences on temperature, rainfall, hence on runoff and thus also on water temperature patterns.

With regard to air temperature, results from time series analyses indicate that annual means of air temperature and their variability, derived from the ECHAM5 GCM, are likely to increase in future. Furthermore, there is a noticeable difference in air temperature between the three Quinaries within a single Quaternary Catchment due to their altitudinal differences. Closer scrutiny of the time series indicates a rising air temperature trend within the 20 years of values in both the intermediate and distant future climates, which is not visible in the present climate scenario.

With reference to individual subcatchment runoff and accumulated catchment streamflows, their absolute variability (i.e. standard deviation) is likely to increase in the intermediate (2046 - 2065) and more distant (2081 - 2100) futures, while the relative variability (i.e. C_V) is likely to remain much the same or even decrease slightly over these time periods. There is a noticeable difference in individual subcatchment runoff within a single Quaternary Catchment due to altitudinal and area variations, but this analyses technique is not ideal when applied to accumulated catchment streamflows owing to accumulation and scaling issues.

With respect to MMWT, results from time series analyses indicate that mean annual MMWT and its variability are likely to increase in the intermediate (2046 - 2065) and more distant (2081 - 2100) futures when derived from the ECHAM5 GCM. Furthermore, there is a noticeable difference in the MMWT within a single Quaternary Catchment due to hydrological flow routing, with an increase in water temperatures as the water cascades downstream from higher altitude upper Quinaries to lower Quinaries at lower altitudes.

10. DISCUSSION AND CONCLUSIONS

Anthropogenic emissions of greenhouse gases have already produced a discernible human footprint on the world's climate, as shown by the historical climate record (**Figure 2.1**). This change in climate, which has also been observed in South Africa, is both long term and is accelerating and, as a result, identified the need to determine the possible effects of climate change on aquatic ecosystems. Freshwater environments are just one type of ecosystem which may be affected detrimentally by rising temperatures, changing precipitation patterns and increasing carbon dioxide levels associated with anthropogenically driven climate change. Over recent years there has been a large increase in amount of literature and studies which have focussed on the potential impacts of climate change on aquatic ecosystems. In this chapter, the aims and objectives stated in **Chapter 1** will be revisited and thereafter conclusions are drawn as to whether it is believed that the aims and objectives were met. Finally recommendations for future research will be made.

10.1 Aims and Objectives Revisited

The aims of this project were to:

- conceptualise the higher order impacts of projected climate change on environmentally related streamflow and water temperature indicators in southern Africa,
- utilise a finer spatial scale of investigation and apply output from more advanced climate models than employed in previous climate change impact studies in southern Africa, as input into an appropriate hydrological model, and
- simulate and map the magnitude and direction (positive or negative) of changes of these indicators at a high spatial resolution over southern Africa.

In order to conceptualise the higher order impacts of projected climate change on environmentally related streamflows and relevant water temperature parameters in southern Africa, a review of the relevant literature was conducted. This review focussed on how to model the impacts of climate change (**Chapter 2**), on conceptualising aquatic ecosystems within the context of climate change (**Chapter 3**), on employing eco-hydrological indicators to assess the impacts of climate change (**Chapter 4)** and on the scale issues surrounding the mapping of ecological indicators under the regimes of climate change (**Chapter 5**).

A scale dilemma was identified in **Chapter 5.4**, and problems associated with modelling climate change impacts at the scale of Quaternary Catchments were outlined. In order to address this dilemma it was concluded that there was a need to sub-delineate Quaternary Catchments into smaller, more detailed and hydrologically homogeneous response zones (cf. **Section 5.5**). A new method delineates a Quaternary Catchment into three altitudinally defined Quinary Catchments was developed by Schulze and Horan (2009). The RSA, Lesotho and Swaziland have now been delineated into 5 838 hydrologically interlinked and cascading Quinaries (**Figure 5.5**). This finer scale of investigation was employed in this research project to provide greater spatial detail of hydrological responses than in previous climate change impact studies in southern Africa. The ECHAM5/MPI-OM GCM (abbreviated to ECHAM5) was selected to simulate present and future projected climatic conditions for this research (**Section 6.7**) and was one of the models used in the IPPC's (2007) Fourth Assessment Report. The ECHAM5 GCM is a relatively new climate model with the first results obtained from this GCM having been published in 2005. The ECHAM5 GCM was selected because it projects future climate changes over southern Africa near the middle of the range of "wetter" and "drier" GCMs and by 2008 when model runs for this project were undertaken, was the only downscaled GCM configured hydrologically at the level of detail required by this project. Even though this project utilised one of the latest GCMs international literature still concludes that there are still major uncertainties regarding GCM output and its regional significance. As such the results from this research should be viewed in the light of being within a range of possible outcomes.

A small subset of the 67 so-called Indicators of Hydrological Alteration was selected for simulations using the individual subcatchment runoff and accumulated streamflow outputs from the *ACRU* agrohydrological modelling system, driven by downscaled daily climate variables from the ECHAM5 GCM for present, intermediate future and more distant future climate scenarios. This subset of indicators focussed on the magnitudes and durations of flows and a spatial assessment of how these indicators are projected to change was performed (**Chapter 7**). However in order to fully describe a South African river's flow regime, climate change responses from all 67 indices should be modelled. The final indicator selection was based on the ease of calculation and availability of data. The main findings of **Chapter 7** are summarised below:

The spatial assessment is a performed for the 5 838 hydrologically interlinked and cascading Quinary Catchments which constitute the southern Africa study region. The first half of **Chapter 7** focuses on the magnitude of flows and the ECHAM5 GCM projects the magnitude of both annual subcatchment runoff and accumulated streamflows to increase in the eastern parts of southern Africa for the intermediate future climate scenario, with this wetting signal strengthening in the distant future climate scenario. A band of Quinaries running roughly from the Limpopo Province through to the Eastern Cape Province indicate a decrease in both subcatchment runoff and accumulated streamflows in the intermediate future while this band of Quinaries is projected to shift westwards to cover the southwestern parts of the Western Cape Province in the distant future climate scenario. The ratio maps for the CoD of both annual subcatchment runoff and accumulated streamflows under projected future climates do not display clear spatial trends. Surprisingly the Quinary Catchments in the Northern Cape Province display unusually high runoff for such a semi-arid part of southern Africa. The cause of this apparent anomaly is that the unit used to measure flow magnitude, *viz.* $m^3.s^{-1}$, is a function of catchment area and the areas of these Quinaries are among the largest in the study region and hence the relatively large magnitudes of flow there. These results build on previous climate change studies and provide additional scientific techniques and workable scientific results which could aid decision makers involved in ecological and water management planning.

The second half of **Chapter 7** focuses on the duration of flow events by exclusively using accumulated streamflow for the 1, 3, 7, 30 and 90 day flow durations for both low and high flows, and in terms of flow duration the ECHAM5 GCM projected an overall increase in minimum flows for all flow durations, especially on the eastern side of South Africa. The Western Cape is the major exception and this ratio analysis indicates a distinct decrease in flows with the ECHAM5 GCM of between 5 and 25% for all minimum flow durations for this region. The ratio maps from the distant future to present ECHAM5 climates show that virtually all Quinary Catchments are projected to experience an increase in their maximum annual accumulated streamflows for all flow durations. The Western Cape is again the major exception and, as in the case of the minimum flow ratio analysis, displays a distinct decrease in maximum averaged annual flows of between 5 and 25% for all flow durations. The

ECHAM5 CoD ratio analyses for the minimum and maximum 1, 3, 7, 30 and 90 day average of annual accumulated streamflows does not display clear overall trends or definitive spatial patterns.

Water temperature related parameters are analysed both spatially and temporally at the scale of the Thukela Catchment (**Chapter 8** and **9**). In **Chapter 8** a spatial assessment was made of the potential impacts of climate change on the water temperature related parameters using the baseline climate conditions and the ECHAM5 climate scenarios. This spatial assessment was performed for the 258 hydrologically interlinked and cascading Quinary Catchments, which constitute the Thukela Catchment. In this chapter a series of maps is used to spatially analyse air temperature, individual catchment runoff, accumulated streamflows, mixed maximum water temperature and two water temperature indices. The results and techniques developed in this dissertation culminate in the first real attempt to map potential changes in water temperature variables under conditions of climate change. The techniques developed to assess the impact of projected climate change on the water temperature parameters produced workable results and thus it is recommended that a study covering southern Africa be performed. A summary of the main findings from **Chapter 8** is provided below.

With respect to mean air temperature the spatial analysis shows that there is a close correlation between the MAT from historical air temperature data and that simulated from the ECHAM 5 GCM. A comparison between the ECHAM5 scenarios indicates a strong warming trend over time, particularly in the central parts of the Thukela catchment, with the ECHAM5 distant future climate scenario showing the greatest deviation from that of the present climate. The reason for the distant future to present ratio map showing the greatest change is that the present climate scenario time period (1971 - 1990) and the future climate scenario time period (2081 - 2100) are 110 years apart, from the commencement of their respective simulation periods - this compared with the difference between the intermediate and future climate scenarios only being 35 years from the start of their respective simulation periods, and this trend was found to be consistent for all water temperature related parameters.

The spatial analysis of runoff from individual subcatchment indicates that there could be a marked increase in projected annual subcatchment runoff, with the distant future scenario showing the greatest change compared to that of the present ECHAM5 climate, with most

Quinaries showing an increase of between 2 and 3 times compared to that of the simulated runoff from the present ECHAM5 climate.

When comparing accumulated streamflows generated from present baseline climate and the present ECHAM5 climate the results indicate that the simulations are generally closely correlated, with both these scenarios clearly showing the accumulations of streamflows in the major tributaries in Thukela Catchment. As with subcatchment runoff, all ECHAM5 scenarios indicate that there will be substantial increase in accumulated streamflows under projected future climate conditions.

In regard to mixed maximum water temperature, these results follow similar trends to those found in the air temperature and accumulated streamflow analyses. A comparison between the MMWT simulations from the three ECHAM5 climate scenarios reveals a definite increase in MMWT under conditions of projected climate change. The difference between distant future and present ECHAM5 climates contains the greatest increase in MMWT, with most of the Quinaries showing increases of around 5 °C, but with the higher lying subcatchments tending to be more sensitive to projected climate change.

In **Chapter 9** times series analyses are employed in order to temporally assess the potential impacts of climate change on water temperature related parameters in the Thukela Catchment. In total 15 Quinary Catchments, which make up five Quaternaries, were selected in the Thukela to undergo time series analyses. The main outcomes of Chapter 9 are summarised below.

Time series analyses were performed on the following parameters:

- Mean Air Temperature,
- Individual Subcatchment Runoff,
- Accumulated Streamflows, and
- Mixed Water Temperature.

The time series analyses uses two methods to describe how each water temperature related indicator varies over time, *viz*.

- How does an indicator vary for a single Quinary catchment by comparing the three ECHAM5 climate scenarios (i.e. a temporal analysis), with the hypothesis being that in future climates temperatures are increasing and streamflows are changing; and
- How does an indicator vary between the three Quinaries making up a Quaternary Catchment for a single climate scenario (i.e. a spatial analysis), with the hypothesis being that Quinaries within a Quaternary are altitude determined and therefore have influences on temperature, rainfall, hence on runoff and thus also on water temperature patterns.

For air temperature, results from time series analyses indicate that annual means of air temperature and their variability, derived from the ECHAM5 GCM, are likely to increase in future. Furthermore, there is a noticeable difference in air temperature between the three Quinaries within a single Quaternary Catchment due to altitudinal variation. Closer scrutiny of the times series indicates a rising air temperature trend within the 20 years of values in both the intermediate and distant future climates, which is not visible in the present climate scenario.

In regard to individual subcatchment runoff and accumulated catchment streamflows, their absolute variability (i.e. standard deviation) from the ECHAM5 GCM is projected to increase in the intermediate (2046 - 2065) and more distant (2081 - 2100) futures, while the relative variability (i.e. C_V) is likely to remain much the same or even decrease slightly over these time periods. There is a noticeable difference in individual subcatchment runoff within a single Quaternary Catchment due to altitudinal and area variations. However, this analysis technique is not ideal when applied to accumulated catchment streamflows owing to accumulation and scaling issues.

For MMWT, results from time series analyses indicate that mean annual MMWT and its variability are likely to increase in the intermediate (2046 - 2065) and more distant (2081 - 2100) futures when derived from the ECHAM5 GCM. Furthermore, there is a noticeable difference in the MMWT within a single Quaternary Catchment due to hydrological flow routing, with an increase in water temperatures as the water cascades downstream from higher altitude upper Quinaries to lower Quinaries at lower altitudes.

It may be concluded from the above summaries and analyses of results that the objectives stated in **Chapter 1** were met.

10.2 Recommendations for Future Research

During the course of this research project, which focuses on conceptualising and developing techniques to assess projected climate change, numerous issues have arisen, which are suggested as foci of future research. The issues that were identified are summarised below:

(i) The ECHAM5 GCM was employed as the climate model in this research in order to project likely future climate conditions (cf. **Section 6.7**). The aim of this project was to *develop techniques* to assess eco-hydrologically related impacts on climate change, and thus only one GCM was used. However, projecting into the future is always linked to uncertainties, especially with models as complex as those simulating future climate systems. In order to reduce this uncertainty and assign levels of confidence to results, output from a series of GCMs should be used in order to obtain a probability distribution of, and a level of confidence on, the climate impacts being modelled.

(ii) All *ACRU* model simulations in this research were performed using baseline land cover information, with the reference vegetation being Acocks' (1988) Veld Types (cf. **Section 6.5**). The incorporation of detailed actual land use information and of the water engineered system (e.g. dams, irrigation and return flows) would significantly enhance the usefulness from the *ACRU* model on catchments where crucial real-world decision may need to be made.

(iii) In this research project only a subset of all the available flow indicators was applied with the three climate scenarios (**Section 6.8.1**). In order to fully describe a South African river's flow regime, climate change responses from all 67 indices should be modelled. Therefore, in future projects investigating the likely impacts of climate change on flow regimes it is recommended that methods and techniques be developed to assess all 67 indices.

(iv) The equation used to estimate maximum water temperature (Rivers-Moore, 2007) was developed in the Sabie River Catchment, but has been shown to be acceptably robust for other regions in South Africa (**Section 4.5.7**). However, a regionally co-correlated equation could provide more regionally relevant results. Furthermore, a more complex equation could be employed to estimate maximum water temperature, as the equation in its current form is fully reliant on the accuracy of the mean air temperature data.

(v) The Thukela Catchment was used as the test catchment for the water temperature related analysis in this research project (**Chapters 8** and **9**). The techniques developed to assess the impact of projected climate change on the water temperature parameters produced workable results and thus it is recommended that a study covering southern Africa be performed.

11. REFERENCES

Acocks, J.P.H. 1988. Veld Types of Southern Africa. Botanical Research Institute, Pretoria, RSA. *Botanical Survey of South Africa Memoirs*, 57. pp 146.,

Andreasen, J.K., O'Neill, R.V., Noss, R. and Slosser, N.C. 2001. Considerations for the development of a terrestrial index of ecological integrity. *Ecological Indicators,* 1, 21-35.

Arnell, N. 1996. *Global Warming, River Flows and Water Resources*. Water Science Series. John Wiley and Sons, Chichester, UK.

Australian Bureau of Statistics, 2008. *Time Series Analysis: The Basics*. Source: http://www.abs.gov.au. Accessed 12/09/2008.

Avila, A., Neal, C. and Terradas, J. 1996. Climate change implications for streamflow and streamwater chemistry in a Mediterranean catchment. *Journal of Hydrology*, 177, 99-116.

Baron, J.S., Poff, N.L., Angermeier, P.L., Dahm, C.N., Gleick, P.H., Hairston, N.G., Jackson, R.B., Johnston, C.A., Richter, B.D. and Steinman, A.D. 2003. Sustaining healthy freshwater ecosystems. *Issues in Ecology,* 10, Winter 2003.

Bartholow, J.M. 1989. Stream temperature investigations: Field and analytic methods. Instream flow information. Publication 13. US Fish and Wildlife Service, Fort Collins, CO, USA. *Biological Report*, 89.

Beisner, B.E., McCauley, E. and Wrona, F.J. 1997. The influence of temperature and food chain length on plankton predator-prey dynamics. *Canadian Journal of Fisheries and Aquatic Science,* 54, 586-595.

Beschta, R.L., Bilby, R.E., Brown, G.W., Holtby, L.B. and Hofstra, T.D. 1987. Stream temperature and aquatic habitat: Fisheries and forestry interactions. In: Salo, E.O. and Cundy, T.W. (Eds) *Streamside Management: Forestry and Fishery Interactions*. University of Washington Institute of Forest Resources, Contribution No. 57, 191-232.

Beven, KJ. 1995. Linking parameters across scales: Subgrid parameterisations and scale dependent hydrological models. In: *Advances in Hydrological Processes, Scale Issues in Hydrological Modelling.* Kalma, J.D. and Sivapalan, M. (Ed). Wiley, UK.

Bhattacharya, S. 2006. 2005 was the Warmest Year on Record. *Source:* www.newscientist.com. *(*Accessed 26/01/2006*)*.

Biggs, B.J.F., Smith, R.A. and Duncan, M.J. 1999. Velocity and sediment disturbance of periphyton in headwater streams: Biomass and metabolism. *Journal of North American Benthological Society,* 18, 222–241.

Bogan, T., Othmer, J., Mohseni, O. and Stefan, H.G. 2006. Estimating extreme stream temperatures by the standard deviate method. *Journal of Hydrology*, 317, 173-189.

Boon, P.J. 1992. Essential Elements in the Case for River Conservation. *In*: Boon, P.J., Calow, P. and Petts, G.E. (Eds). *River Conservation and Management*. pp 11-34.

Cafferata, P. 1990. Temperature Regimes of Small Streams Along the Mendocino Coast. *Jackson Demonstration State Forest Newsletter*. Number 39.

Caissie, D., El-Jabi, N. and Satish, G. 2001. Modelling of maximum daily water temperatures in a small stream using air temperatures. *Journal of Hydrology*, 251, 14-28.

Cao, Y. and Hawkins, C.P. 2005. Simulating biological impairment to evaluate the accuracy of ecological Indicators. *Journal of Applied Ecology*, 42, 954–965.

Chu, C., Mandrak, N.E. and Minns, C.K. 2005. Potential impacts of climate change on the distributions of several common and rare freshwater fishes in Canada. *Diversity and Distributions*, 11, 299-310.

Clausen, B, Jowett, I.G., Biggs, B.J.F. and Moeslund, B. 2004. Stream ecology and management. Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater. In: *Developments in Water Science*. Tallaksen, L.M. and Van Lanen, H.A.J. (Eds). (48) pp 411-455.

Cotgreave, P. and Forseth, I. 2002. *Introductory Ecology*. Blackwell Science Ltd., Oxford, UK.

Coulson, D. and Joyce, L. 2005. Indexing variability: A case study with Climate Change Impacts on Ecosystems. *Ecological Indicators,* 6, 749–769.

CSAG, 2008. Climate Systems Analysis Group. *Source*: http://www.csag.uct.ac.za. (Accessed 25/11/2008)

Dahm, C.N. and Molles, M.C. (Jr). 1992. Streams in semiarid regions as sensitive indicators of global climate change. *Global Climate Change and Freshwater Ecosystems. Firth, P. and Fisher*. S.G. (Eds.). Springer-Verlag, New York. pp 211-233.

Dale, V.H. and Beyeler, S.C. 2001. Challenges in the development and use of ecological indicators. *Ecological Indicators*, 1, 3-10.

Dallas, H.F. 2008. Water temperature and riverine ecosystems: An overview of knowledge and approaches for assessing biotic responses, with special reference to South Africa. *Water SA,* 34, 393-404.

Dallas, H.F. and Day, J.A. 2004. The Effect of Water Quality Variables on Aquatic Ecosystems: A Review. Water Research Commission, Pretoria, RSA, *WRC Report No*. TT 224/04.

DeBusk, W., Graham, W., Jacobs, J., Ogram, A., Miller, D., Prenger, J., Roa, S., Reddy, R. and Tanner, G. 2001. Determination of indicators of ecological change. SEMP Project CS-1114A-99 University of Florida, Purdue University, IL, USA. https://www.denix.osd.mil/denix/Public/Library/SEMP/Research/ResearchProjects/RPFY99/Debusk_ar_fy01/debusk_ar_fy01.html. (Accessed 20/06/2006).

Dent, M.C., Lynch, S.D. and Schulze, R.E. 1989. *Mapping Mean Annual and Other Rainfall Statistics over Southern Africa*. Water Research Commission, Pretoria, RSA, *WRC Report* 109/1/89. pp 198 plus Appendices.

Dlamini, D.J.M. 2005. *Testing and Applying the Water Poverty Index for the Assessment of Water Wellbeing at Meso-Catchment Scale in the Thukela Basin, South Africa*. PhD Thesis. School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu Natal, Pietermaritzburg, South Africa.

Dolph, J., Marks, D. and King, G.A. 1992. Sensitivity of the regional water balance in the Columbia River Basin to climate variability: Application of a spatially distributed water balance model. In*: Naiman, R.J. (Ed)* Watershed Management: Balancing Sustainability and Environmental Change*. Springer-Varlag, New York, USA.*

Dooge, J.C.I. 1982. The parameterization of hydrologic processes. In: *Land Surface Processes in Atmospheric General Circulation Models.* Eagleson, PS. (Ed). Cambridge University Press, New York, pp. 243–288.

Dooge, J.C.I. 1986. *Scale Problems in Hydrology*. University of Arizona, Tucson.

Dooge, J.C.I. 1992. Hydrological models and climate change. *Journal of Geophysical Research*, 97(D3) 2677–2686.

Downes, B.J., Barmuta, L.A., Fairweather, P.G., Faith, D.P., Keough, M.J., Lake, P.S., Mapstone, B.D. and Quinn, G.P. 2002. *Monitoring Ecological Impacts: Concepts and Practice in Flowing Water*. Cambridge University Press, New York, NY, USA.

Duffy, C. J. and Gelhar, L.W. 1985. A frequency domain approach to water quality modeling in groundwater: Theory. *Water Resource Research*, 21, 1175-1184.

EEA, 2007. *Climate Change and Water Adaptation Issues*. European Environmental Agency, Brussels, Belgium. Technical Report, 2/2007.

Elliot, J.M. and Hurley, A. 1997. Functional model for maximum growth of Atlantic salmon parr, *Salmo salar*, from two populations in northwest England. *Functional Ecology*, 11, 592-603.

Engelbrecht, F. 2005. Simulations of Climate and Climate Change over Southern and Tropical Africa with the Conformal-Cubic Atmospheric Model. *In*: Schulze RE (ed) *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation*. Water Research Commission, Pretoria, RSA. WRC Report 1430/1/05. Chapter 4, 57 - 74.

Engineering Statistics Handbook, 2006. *Introduction to Time Series Analysis*. Source: http://www.itl.nist.gov/div898/handbook. (Accessed 10/09/2008).

EPA. 2006. Aquatic Indicators. Source : http://www.epa.gov/nhrlsup1/arm/indicators/indicators.htm. (Accessed 15/06/2006).

Erickson, T.R., Stefan, H.G. and Members of the ASCE, 2000. Linear air/water temperature correlation for streams during open water periods. *Journal of Hydrologic Engineering*, 5(3), 317-321.

Fanelli, G., Tescarollo, P. and Testi, A. 2006. Ecological indicators applied to urban and suburban floras. *Ecological Indicators*, 6, 444–457.

Franklin, J.F. 1992. Scientific basis for new perspectives in forests and streams. *In*: Naiman, R.J. (Ed). *Watershed Management: Balancing Sustainability and Environmental Change*. pp 25-72. Springer-Verlag, New York.

Gan, K.C. and McMahon, T.A. 1990. *Comparison of Two Computer Models for Assessing Environmental Flow Requirements*. Report to Dept. of Water Resources, Victoria, Australia.

Giller, P.S. and Malmqvist, B. 1998. *The Biology of Streams and Rivers*. Oxford University Press, Oxford, UK.

Global Atmospheric Research Programme, 1972. *Parameterization of Sub-Grid Scale Processes*. Report of Study Group Conference, Leningrad, October 1972, Publication No. 8.

Gras, R. 1969. Simulation du comportement thermique d'une rivière à partir des données fournies par un réseau classique d'observations météorologiques. *Proceedings of the 13th Congress of the International Association for Hydraulic Research (Tokyo, Japan)*, 1, 491 - 502.

Gray, R.P. 2005. *Possible Effects of Climate Change on Water Resources*. Unpublished MSc Seminar. School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu Natal, Pietermaritzburg, South Africa.

Grimm, N.B., Chacon, A, Dahm, C.N., Hostetler, S.W., Lind, O.T., Starkweather, P.L. and Wurtsbaugh W.W. 1997. Sensitivity of aquatic ecosystems to climatic and anthropogenic changes: The basin and range, American Southwest and Mexico. *Hydrology Processes* 11 1023-1041.

Hadley Centre. 2006. Hadley Centre for Climate Prediction and Research. Source: http://www.metoffice.gov.uk/research/hadleycentre/models/modeltypes.html (Accessed 18/05/2006).

Handcock, R.N., Gillespie, A.R., Cherkauer, K.A., Kay, J.E., Burges, S.J. and Kampf, S.K. 2006. Accuracy and uncertainty of thermal-infrared remote sensing of stream temperatures at multiple spatial scales. *Remote Sensing of Environment*, 100, 427-440.

Hansen, J.E. 2006. Global Climate Modelling: General Circulation Models. Source: http://www.giss.nasa.gov/research/modeling/gcms.html. (Accessed 18/05/2006).

Hardy, J.T. 2003. *Climate Change: Causes, Effects and Solutions*. John Wiley and Sons, Chichester, UK.

Hay, L.E. and Clark, M.P. 2003. Use of statistically and dynamically downscaled atmospheric model output for hydrologic simulations in Three Mountainous Basins in the Western United States. *Journal of Hydrology.* 282 56–75.

Hellawell, J.M. 1986. *Biological Indicators of Freshwater Pollution and Environmental Management*. Elsevier Applied Science, London, UK. pp 546.

Hem, J.D. 1985. Study and Interpretation of the Chemical Characteristics of Natural Water. United States Geological Survey, Reston, VA, USA. Water Supply Paper 2254.

Hewitson, B.C., Tadross, M. and Jack, C. 2005. Climate Change Scenarios: Conceptual Foundations, Large Scale Forcing, Uncertainty and the Climate Context. *In*: Schulze, R.E. (ed) *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation*. Water Research Commission, Pretoria, RSA. WRC Report 1430/1/05. Chapter 2, 21-38.

Hostetler, S.W. 1991. Analysis and modelling of long term stream temperatures on the Steamboat Creek Basin, Oregon: Implications for landuse and fish habitat. *Water Resources Bulletin*, 27, 637-647.

Hughes, DA. 2006. Problems of estimating hydrological characteristics for small catchments based on information from the South African national surface water resource database. Source: http://www.ru.ac.za/institutes/iwr/software/reserve/hydro_resdss/sub_quat.htm (Accessed 22/05/2006).

Hughes, D.A., Hannart, P. and Watkins, D. (2003). Continuous baseflow separation from time series of daily and monthly streamflow data. *Water SA* 29 (1): 43 – 48.

Huguet, F., Parey, S., Dacunha-Castelle, D. and Malek, F. 2008. Is there a trend in extremely high water temperature for the next decades? A case study in France. *Natural Hazards Earth System Science,* 8, 67-79.

Hull, P. J. 2008. *Agroclimatic Response mapping for sugarcane production in Southern Africa.* Unpublished MSc Dissertation. School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu Natal, Pietermaritzburg, South Africa.

IPCC 1990. *Climate Change: The IPCC Scientific Assessment*. Houghton, J.T., Jenkins, G.J. and Ephraums, J. J. (Eds). Cambridge University Press.

IPCC, 2001. *Summary for Policy Makers: Climate Change 2001: The Scientific Basis. In:* Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van de Linden, P.J., Dai, X., Mashell, K. and Johnson, C.A. (Eds) *Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY, USA. pp 1-20.

IPCC, 2007. Climate Change 2007: The Physical Science Basis; Summary for Policymakers. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Noguer, M., van den Linden, P.J., Dai, X., Mashell, K. and Johnson, C.A. (Eds). Cambridge University Press.

Jewitt, G.P.W, Heritage, G.L., Weeks, D.C., Mackenzie, J.A., van Niekerk, A., Gorgens, A.H.M, O'Keeffe, J., Rogers, K. and Horn, M. 1998. *Modelling Abiotic-Biotic Links in the Sabie River*. Water Research Commission Report, Pretoria, RSA. WRC Report No. 777/1/98.

Jones, P. and Palutikof, J. 2006. The Global Temperature Record. Source: http://www.cru.uea.ac.uk/cru/info/warming/. (Accessed 28/06/2006).

Kabat, P, Schulze, R.E., Hellmuth, M.E. and Veraart, J.A. 2003. *Coping with impacts of climate variability and climate change in water management: A scoping paper*. DWC-

Report no. DWCSSO-01 International Secretariat of the Dialogue on Water and Climate, Wageningen, Netherlands. pp 6-10.

Karr, J.R. 1991. Biological integrity: A long neglected aspect of water resource management. *Ecological Applications*, 1, 66-84.

King, J.M. and Tharme, R.E. 1993. *Assessment of the Instream Flow Incremental Methodology and Initial Development of Alternative Instream Flow Mythologies for South Africa.* Water Research Commission Report, Pretoria, RSA. WRC Report No. 295/1/94.

Kershner, J.L. and Snider, W.M. 1992. Importance of a habitat-level classification system to design instream flow studies. *River Conservation and Management*. Boon, P.J, Calow, P. and Petts, G.E. (Eds). John Wiley and Sons, England.

Kunz, R. P. 1993. *Techniques to Assess Possible Impacts of Climate Change in Southern Africa.* Unpublished MSc dissertation, Department of Agricultural Engineering, University of Natal, Pietermaritzburg, RSA.

Kunz, R.P. 2004. Daily Rainfall Data Extraction Utility User Manual Version 1.4. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

Kunz, R. P. 2007. Personal Communication. School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu Natal, Pietermaritzburg, South Africa.

Land Type Survey Staff, 1986. Memoirs, Agricultural Natural Resources. Department of Agriculture and Water Supply, Pretoria, RSA.

Lau, K.-M., Kim, J.H. and Sud, Y. 1996. Comparison of hydrologic processes in AMIP GCMs. *Bulletin of the American Meteorological Society,* 77, 2209-2227.

Levin, J.S. 1992. Global climate change. *Global Climate Change and Freshwater Ecosystems*. Firth, P. and Fisher S.G. (Eds.). Springer-Verlag, New York. pp 1-25.

Lowe, K.L. 1997. *Agrohydrological Sensitivity Analysis with Regard to Projected Climate Change in Southern Africa*. Unpublished MSc dissertation, Department of Agricultural Engineering, University of Natal, Pietermaritzburg, RSA.

Lumsden, T.G., Kunz, R.P., Schulze, R.E., Knoesen, D.M. and Barichievy, K.R. 2009. Methods 4: Representation of Grid and Point Scale Regional Climate Change Scenarios for National and Catchment Level Hydrological Impacts Assessments. In: Tadross, M and Schulze, R.E. (Eds) Regional Aspects of Climate Change and Their Secondary Impacts on Water Resources. Draft Water Research Commission Report, Pretoria, RSA, WRC. *WRC Report* 1562/01/09 Chapter 4.

Lynch, S.D. 2004. *Development of a Raster Database of Annual, Monthly and Daily Rainfall for Southern Africa*. Water Research Commission, Pretoria, RSA, *WRC Report* 1156/1/04. pp 78.

Manoliadis, O. 2001. Analysis of irrigation systems using sustainability-related criteria. *Journal of Environmental Quality*, 30, 1150-1153.

Manoliadis, O. 2002. Development of ecological indicators - A methodological framework using compromise programming. *Ecological Indicators*, 2, 169-176.

McGinn, N.A. 2002. Fisheries in a changing climate. *American Fisheries Society, Symposium 32*, Bethesda, Washington DC,USA.

Melack, J.M. 1992. Reciprocal interactions among lakes, large rivers and climate. *Global Climate Change and Freshwater Ecosystems*. Firth, P. and Fisher S.G. (Eds.). Springer-Verlag, New York, USA. pp 68-87.

Methratta, E.T. and Link, J.S. 2006. Evaluation of quantitative indicators for marine fish communities. *Ecological Indicators*, 6, 575-588.

Meyer, J.L., Sale, M.J., Mulholland, P.J. and Poff, N.L. 1999. Impacts of climate change on aquatic ecosystem functioning and health. *Journal of the American Water Resources Association*, 35, 1373-1386.

Midgley, D.C, Pitman, W.V. and Middleton, B.J. 1994. *Surface water resources of South Africa 1990. Vols. I – V*I. Water Research Commission Pretoria, RSA. *WRC Report* No. 298/1.1/94 to 198/6.1/94.

Mohseni, O., Erickson, T. R., and Stefan, H. G. 1998. Sensitivity of stream temperature in the United States to air temperature projected under a global warming scenario. *Water Resources Research*, 35, 3723–3733.

Mohseni, O., Erickson, T.R. and Stefan, H.G. 2002. Upper bounds for stream temperatures in the contiguous United States. *Journal of Environmental Engineering*, 128, 4-11.

Mohseni, O. and Stefan, H.G. 1999. Stream temperature/air temperature relationship: A physical interpretation. *Journal of Hydrology*, 218, 128-141.

Morrill, J.C., Bales, R.C., Members of the ASCE and Conklin, M.H. 2005. Estimating stream temperature from air temperature: Implications for future water quality. *Journal of Environmental Engineering*, 139-149.

Naiman, R.J., Beechie, T.J., Benda, L.E., Berg, D.R., Bisson, P.A., MacDonald, L.H., O'Conner, M.D., Olson, P.L. Steel, E.A. and Risser, P.G. 1992. Fundamental elements of ecologically healthy watersheds in the Pacific Northwest Coastal Region

In: Naiman, R.J. (Ed). *Watershed Management: Balancing Sustainability and Environmental Change*. pp 127-188. Springer-Verlag, New York.

Nakićenović N. and Swart R. (eds) 2000. *Special Report on Emissions Scenarios*. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA. pp 599.

Neumann, D.W., Rajagopalan, B. and Zagona, E.A. 2003. Regression model for daily maximum stream temperature. *Journal of Environmental Engineering,* 129, 667-674.

Noon, B.R., Spies, T.A. and Raphael, M.G. 1999. Conceptual basis for designing an effectiveness monitoring program. In: Mulder, B.S., Noon, B.R., Spies, T.A., Raphael, M.G., Palmer, C.J., Olsen, A.R., Reeves, G.H. and Welsh, H.H. Jr. (Eds) *The Strategy and Designing of the Effectiveness Program for the Northwest Forest Plan*. USDA Forest Services General Technical Report, PNW-GTR-437, Pacific Northwest Station, Portland, OR, USA. pp 21-48.

Olden, J.D. and Poff, N.L. 2003. Redundancy and the choice of hydrological indices for characterizing streamflow regimes. *River Research and Applications*, 19, 101-121.

Panagouliaa, D. and Dimoub, G. 1997. Linking space–time scale in hydrological modelling with respect to global climate change. Part 1. Models, model properties, and experimental design. *Journal of Hydrology*, 194, 15–37.

Perks, L.A. 2001. *Refinement of Modelling Tools to Assess Potential Agrohydrological Impacts of Climate Change in Southern Africa*. Unpublished PhD thesis, Department of Agricultural Engineering, University of Natal, Pietermaritzburg, South Africa.

Pilgrim, J.M., Fang, X. and Stefan, H.G., 1998. Stream temperature correlations with air temperatures in Minnesota: implications for climate warming. *Journal of the American Water Resources Association,* 34, 1109-1121.

Pike, A. and Schulze, R.E. 1995. AUTOSOIL Version 3: A Soils Decision Support System for South African soils. Department of Agricultural Engineering, University of Natal, Pietermaritzburg.

Poff, N.L. 2002. Ecological response to and management of increased flooding caused by climate change. *Philosophical Transactions of the Royal Society*, London, 360, 1497-1510.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E. and Stromberg, J.C. 1997. The natural flow regime: A paradigm for river conservation and restoration. *Bioscience*, 47, 769-784.

Poff, N.L., Brinson, M.M. and Day, J.W. 2002. Potential Impacts on Inland Freshwater and Coastal Wetland Ecosystems in the United States Aquatic Ecosystems and Global Climate Change.Pew Center on Global Climate Change. Source: http://www.pewclimate.org/docUploads/aquatic.pdf. (Accessed 05/09/2008).

Poole, G. and Berman C. 2001. An ecological perspective on instream temperature: Natural heat dynamics and mechanisms of human-caused thermal degradation. *Environmental Management,* 27, 787-802.

Quattrochi, D.A. and Goodchild, M.F. 1997. *Scale in Remote Sensing and GIS*. Lewis Publishers, New York, pp 1-13.

Richter, B.D., Baumgartner, J.V., Powell, J. and Braun, D.P. 1996. A method for assessing hydrologic alteration within ecosystems. *Conservation Biology*, 10, 1163-1174.

Richter, B.D., Baumgartner, J.V., Wiginton, R. and Braun, D.P. 1997. How much water does a river need? *Freshwater Biology*, 37, 231-249.

Risser, P.G. 1992. Impacts on Ecosystems of Global Environmental Changes in Pacific Northwest Watersheds. In: Naiman, R.J. (Ed). *Watershed Management: Balancing Sustainability and Environmental Change.* pp 12-24.

Rivers-Moore, N.A. 2003. *Water Temperature and Fish Distribution in the Sabie River System: Towards the Development of an Adaptive Management Tool*. PhD Thesis. School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu Natal, Pietermaritzburg, South Africa.

Rivers-Moore, N.A., Bezuidenhout, C.N. and Jewitt, G.P.W. 2005. Modelling highly variable maximum water temperatures in a perennial South African river system. *African Journal of Aquatic Science*, 30, 55-63.

Rivers-Moore, N.A., Hughes, D.A. and de Moor, F.C. 2007. A model to predict outbreak periods of the pest blackfly *Simulium chutteri* Lewis (Simuliidae, Diptera) in the Great Fish River, Eastern Cape province, South Africa. National Research Foundation of South Africa.

Schulze, R.E. 1989. Hydrological response to long term climatic change. *In*: Walker, B.H. and Dickson, R.G. (Eds) *Southern Hemisphere Perspectives of Global Change: Scientific Issues, Research Needs and Proposed Activities*. International Geosphere-Biosphere Programme - Global Change, Report No. 9, 41-44.

Schulze, R.E. 1990. Climate change and hydrological response in southern Africa: Heading towards the future. *South African Journal of Science*, 86, 373-381.

Schulze, R.E. 1991a. Perspectives on the "Greenhouse Effect" and global warming on agriculture in southern Africa. *Agricultural Engineering in South Africa*, 23, 408-419.

Schulze, R.E. 1991b. Global Climate Change and Hydrological Response : A Southern African Perspective (invited keynote address). *Proceedings, 5th South African National Hydrology Symposium*, Stellenbosch, RSA, 1-1 to 1-17.

Schulze, R.E. 1995. *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*. Water Research Commission, Pretoria, RSA, *WRC Report* TT 69/9/95. pp 552.

Schulze, R.E. 1997. *South African Atlas of Agrohydrology and Climatology*. Water Research Commission, Pretoria, RSA, *WRC Report* TT 82/96. pp 276.

Schulze, R.E. 2000. Transcending scales of space and time in impact studies of climate and climate change on agrohydrological responses. In: *Agriculture, Ecosystems and Environment*. 82 (2000) 185-212.

Schulze, R.E. 2003. The Thukela Dialogue: Managing water related issues on climate variability and climate change in South Africa. Proceedings of the DWC Thukela Dialogue Workshop, University of Natal, Pietermaritzburg, RSA, School of Bioresources Engineering and Environmental Hydrology, *ACRUcons* Report, 44.pp 134.

Schulze, R.E. 2004. Determination of Baseline Land Cover Variables for Applications in Assessing Land Use Impacts on Hydrological Responses in South Africa. *In*: Schulze, R.E. and Pike, A. *Development and Evaluation of an Installed Hydrological Modelling System*. Water Research Commission, Pretoria, RSA, *WRC Report* 1155/1/04. Chapter 2, 37-50.

Schulze, R.E. 2005. *Hydrological Modelling: Concepts and Practice*. UNESCO-IHE, Delft, The Netherlands. pp 134.

Schulze, R.E. 2006. Personal Communication. School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, RSA.

Schulze, R.E. (Ed) 2007. *South African Atlas of Climatology and Agrohydrology*. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/07. pp 535 (On interactive DVD).

Schulze, R.E., Dlamini, D.J.M. and Horan, M.J.C. 2005a. The Thukela Catchment : Physical and Socio-Economic Background . *In*: Schulze, R.E. (Ed) *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and*

Adaptation. Water Research Commission, Pretoria, RSA, *WRC Report* 1430/1/05. Chapter 10, 191 - 209.

Schulze, R.E., Dlamini, D.J.M and Horan, M.J.C. 2009. The Thukela Catchment: Description of the Case Study Area for the Assessment of Climate Change on Water Temperature. In: Tadross, M and Schulze, R.E. (Eds) Regional Aspects of Climate Change and Their Secondary Impacts on Water Resources. Draft Water Research Commission Report, Pretoria, RSA, WRC. *WRC Report* 1562/01/09 Chapter 4.

Schulze, R.E., Hallowes, L.A., Horan, M.J.C., Lumsden, T.G., Pike, A., Thornton-Dibb, S. and Warburton, M.L. 2007. South African Quaternary Catchments Database. *In:* Schulze, R.E. (Ed). South African Atlas of Climatology and Agrohydrology. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/06, Section 2.3.

Schulze, R.E. and Horan, M.J.C. 2007. Soils: Hydrological Attributes. *In:* Schulze, R.E. (Ed). 2007. *South African Atlas of Climatology and Agrohydrology*. Water Research Commission, Pretoria, RSA, *WRC Report* 1489/1/07, Section 4.2.

Schulze, R.E. and Horan, M.J.C. 2009. Methods 1: Delineation of South Africa, Lesotho and Swaziland into Quinary Catchments. In: Tadross, M and Schulze, R.E. (Eds) Regional Aspects of Climate Change and Their Secondary Impacts on Water Resources. Draft Water Research Commission Report, Pretoria, RSA, WRC. *WRC Report* 1562/01/09 Chapter 5.

Schulze, R.E., Horan, M.J.C., Kunz, R.P., Lumsden, T.G. and Knoesen, D.M. 2009b. Methods 2: Development of the Southern African Quinary Catchments Database. In: Tadross, M and Schulze, R.E. (Eds) Regional Aspects of Climate Change and Their Secondary Impacts on Water Resources. Draft Water Research Commission Report, Pretoria, RSA, WRC. *WRC Report* 1562/01/09 Chapter 6.

Schulze, R.E., Lumsden, T.G., Horan, M.J.C., Warburton, M. and Maharaj, M. 2005b. An Assessment of Impacts of Climate Change on Agrohydrological Responses Over Southern Africa. *In*: Schulze, R.E. (ed) *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation*. Water Research Commission, Pretoria, RSA, *WRC Report* 1430/1/05. Chapter 9, 141-189.

Schulze, R.E. and Maharaj, M. 2004. *Development of a Database of Gridded Daily Temperatures for Southern Africa*. Water Research Commission, Pretoria, RSA, *WRC Report* 1156/2/04. pp 82

Schulze, R.E. and Perks, L.A. 2000. Assessment of the impact of climate change on hydrology and water resources in South Africa. University of Natal, Pietermaritzburg, School of Bioresources Engineering and Environmental Hydrology Report to South African Country Studies for Climate Change Programme. *ACRUcons Report*, 33, pp 118.

Schulze, R.E. and Smithers, J.C. 2004. The *ACRU* Modelling System as of 2002: Background, Concepts, Structure, Output, Typical Applications and Operations. *In*: Schulze, R.E. (Ed) *Modelling as a Tool in Integrated Water Resources* Management*: Conceptual Issues and Case Study Applications*. Water Research Commission, Pretoria, RSA, *WRC Report* 749/1/02. Chapter 3, 47-83.

SIRI, 1987. Land Type Series. Department of Agriculture and Water Supply, Pretoria, RSA, Soil and Irrigation Research Institute. *Memoirs on the Agricultural Natural Resources of South Africa*.

Smagorinsky, J. 1974. Global atmospheric modelling and the numerical simulation of climate. *Weather and Climate Modification*. W.M. Hess (Ed). Wiley, New York, USA. pp. 633–686.

Stanford, J.A. and Ward, J.V. 1992. Management of Aquatic Resources in Large Catchments: Recognizing Interactions between Ecosystem Connectivity and Environmental Disturbance. *In*: Naiman, R.J. (Ed) *Watershed Management: Balancing Sustainability and Environmental Change*. pp 91-124. Springer-Verlag, New York, USA.

Stumm, W. and Morgan, J.J. 1996. *Aquatic Chemistry*. Wiley, New York.

Tadross M. and Schulze, R.E. 2009. Regional Aspects of Climate Change and Their Secondary Impacts on Water Resources. Water Research Commission, Pretoria, RSA, *WRC Report* 1562/1/09.

Taylor, V. 2006. *The Hydrological Basis for the Protection of Water Resources to Meet Environmental and Societal Requirements*. Unpublished PhD Thesis. School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, RSA.

The Nature Conservancy, 2005. Indicators of Hydrologic Alteration. Version 7. User's Manual. The Nature Conservancy with Smythe Scientific Software and Totten Software Design. Charlottesville, VI, USA.

The River Center. 2008. Ecosystem Flow Prescriptions. Source: http://www.rivercenter.uga.edu/. (Accessed 30/07/2008)

Tomasion, M. and Dalla Valle, F. 2000. Natural climatic changes and solar cycles: An analysis of hydrological time series. In*: Hydrological Sciences Journal*. 45 (3): 477-490.

Tyson, P.D. and Preston-Whyte, R.A. 2000. *The Weather and Climate of Southern Africa.* (2nd Ed.) Oxford University Press, Cape Town.

UNFCC 2002. United Nations Framework Convention on Climate Change. Source: http://unfcc.int /resource. (Accessed 1/02/2006).

Vannote, R. and Sweeney, B. 1980. Geographic analysis of thermal equilibria: A conceptual model for evaluating the effect of natural and modified thermal regimes on aquatic insect communities. *American Naturalist,* 115, 667-695.

Warburton, M.L. and Schulze, R.E. 2005. On the Southern African Rainfall Station Network and its Data for Climate Change Detection and Other Hydrological Studies. *In*: Schulze, R.E. (ed) *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation*. Water Research Commission, Pretoria, RSA, *WRC Report* 1430/1/05. Chapter 20, 339-348.

Ward, J. 1985. Thermal characteristics of running waters. *Hydrobiology,* 125, 31-46.

Waugh, D. 1995. *Geography: An Integrated Approach*. Nelson International, England.

Webb, B. W. 1987. The relationship between air and water temperatures for a Devon River: Report. *Transactions of the Devon Association for the Advancement of Science*, Exeter, UK, 119, 197-222.

Webb, B.W. and Nobilis, F. 1997. Long-term perspective on the nature of the air-water temperature relationship: a case study. *Hydrological Processes,* 11, 137-147.

Wilby, R.L, Hay, L.E. and Leavesley, GH. 1999. A comparison of downscaled and raw GCM output: implications for climate change scenarios in the San Juan River basin, Colorado. *Journal of Hydrology.* 225 (1999) 67–91.

Williams, M. 1991. Understanding wetlands. *In:* Williams, M. (Ed.) *Wetlands: A Threatened Landscape*. Basil Blackwell Limited, Oxford, UK.

Wilson, A. J. 2001. Thukela Water Management Area: Draft Situational Assessment. Department of Water Affairs and Forestry, KwaZulu Natal Regional Office, Durban, RSA.

World Bank, 1999. *Environmental Performance Indicators*. A Second Edition Note. The Word Bank, Washington, DC, USA.