INTEGRATING HYDRO-CLIMATIC HAZARDS AND CLIMATE CHANGE AS A TOOL FOR ADAPTIVE WATER RESOURCES MANAGEMENT IN THE ORANGE RIVER CATCHMENT

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This thesis is dedicated to my son,

James

ABSTRACT

The world's freshwater resources are being placed under increasing pressure owing to growth in population, economic development, improved standards of living, agricultural intensification (linked mainly to irrigation), pollution and mismanagement of available freshwater resources. Already, in many parts of the Orange River Catchment, water availability has reached a critical stage.

It has become increasingly evident that water related problems can no longer be resolved by water managers alone, owing to the problems becoming more interconnected with other development related issues, as well as with social, economic, environmental, legal and political factors. With the advent of climate change and the likelihood of increases in extreme events, water managers' awareness of uncertainties and critical reflections on the adequacy of current management approaches is increasing.

In order to manage water resources effectively a more holistic approach is required than has hitherto been the case, in which technological, social and economic development are linked with the protection of natural ecosystems and with dependable projections of future climatic conditions. To assess the climate risk connected with rural and urban water management, and to develop adaptive strategies that can respond to an increasingly variable climate that is projected into the future and help to reduce adverse impacts, it is necessary to make connections between climate related hazards, climate forecasts as well as climate change, and the planning, design, operation, maintenance, and rehabilitation of water related infrastructure. Therefore, adaptive water resources management (AWRM), which in essence is "learning by doing", is believed to be a timely extension of the integrated water resources management (IWRM) approach as it acknowledges uncertainty and is flexible in that it allows for the adjustment of actions based on information learned about the system. Furthermore, it is suggested that climate risk management be imbedded within the AWRM framework.

The objective of the research presented in this thesis is to develop techniques to integrate state-of-the-art climate projection scenarios – which forms part of the first step of the adaptive management cycle – downscaled to the regional/local scale, with hydro-climatic hazard determination – which forms part of the first step in the risk management process – in order to simulate projected impacts of climate change on hydro-climatic hazards in the Orange River Catchment (defined in this study as those areas of the catchment that exist within South Africa and Lesotho). The techniques developed and the results presented in this study can be used by decision-makers in the water sector in order to make informed *proactive* decisions as a response to projected future impacts of hydro-climatic hazards – all within a framework of AWRM.

Steps towards fulfilling the above-mentioned objective begins by way of a comprehensive literature review; firstly of the study area, where it is identified that the Orange River Catchment is, in hydro-climatic terms, already a high risk environment; and secondly, of the relevant concepts involved which are, for this specific study, those pertaining to climate change, and the associated potential hydro-climatic impacts. These include risk management and its components, in order identify how hazard identification fits into the broader concept of risk management; and water resources management practices, in order to place the issues identified above within the context of AWRM.

This study uses future projections of climate from five General Circulation Models, all using the SRES A2 emission scenario. By and large, however, where techniques developed in this study are demonstrated, this is done using the projections from the ECHAM5/MPI-OM GCM which, relative to the other four available GCMs, is considered to provide “middle of the road” projections of future climates over southern Africa. These climate projections are used in conjunction with the locally developed and widely verified *ACRU* hydrological model, as well as a newly developed hydro-climatic database at a finer spatial resolution than was available before, to make projections regarding the likelihood and severity of hydro-climatic hazards that may occur in the Orange River Catchment. The impacts of climate change on hydro-climatic hazards, *viz*. design rainfalls, design floods, droughts and sediment yields are investigated, with the results including a quantitative uncertainty analysis, by way of an index of concurrence from multiple GCM projections, for each of the respective analyses.

A new methodology for the calculation of short duration (< 24 hour) design rainfalls from daily GCM rainfall projections is developed in this study. The methodology utilises an index storm approach and is based on L-moments, allowing for short duration design rainfalls to be estimated at any location in South Africa for which daily GCM rainfall projections exist.

The results from the five GCMs used in this study indicate the following possible impacts of climate change on hydro-climatic hazards in the Orange River Catchment:

- Design rainfalls of both short and long duration are, by and large, projected to increase by the intermediate future period represented by 2046 - 2065, and even more so by the more distant future period 2081 - 2100.
- Design floods are, by and large, projected to increase into the intermediate future, and even more into the more distant future; with these increases being larger than those projected for design rainfalls.
- Both meteorological and hydrological droughts are projected to decrease, both in terms of magnitude and frequency, by the period 2046 - 2065, with further decreases projected for the period 2081 - 2100. Where increases in meteorological and hydrological droughts are projected to occur, these are most likely to be in the western, drier regions of the catchment.
- Annual sediment yields, as well as their year-to-year variability, are projected to increase by the period 2046 - 2065, and even more so by the period 2081 - 2100. These increases are most likely to occur in the higher rainfall, and especially in the steeper, regions in the east of the catchment.

Additionally, with respect to the above-mentioned hydro-climatic hazards, it was found that:

- The statistic chosen to describe inter-annual variability of hydro-climatic variables may create different perceptions of the projected future hydro-climatic environment and, hence, whether or not the water manager would decide whether adaptive action is necessary to manage future variability.

- There is greater uncertainty amongst the GCMs used in this study when estimating design events (rainfall and streamflow) for shorter durations and longer return periods, indicating that GCMs may still be failing to simulate individual extreme events.
- The spatial distribution of projected changes in meteorological and hydrological droughts are different, owing to the complexities introduced by the hydrological system
- Many areas may be exposed to increases in hydrological hazards (i.e. hydrological drought, floods and/or sediment yields) because, where one extreme is projected to decrease, one of the others is often projected to increase.

The thesis is concluded with recommendations for future research in the climate change and hydrological fields, based on the experiences gained in undertaking this study.

DECLARATION

The work described in this thesis was carried out in the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, from April 2006 to October 2009, under the supervision of Professor Roland 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: ……………

D.M. Knoesen (Author)

Signed: …………………………… Date: ……………

Professor R.E. Schulze (Supervisor)

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TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

1. INTRODUCTION

The need for water is a universal one and is inextricably linked with food security, human health and environmental protection (Appleton *et al.*, 2003; Biswas, 2004). The world's freshwater resources are being placed under increasing pressure owing to growth in population, economic development, improved standards of living, agricultural intensification (linked mainly to irrigation), pollution and mismanagement of available freshwater resources (Ashton, 1996; GWP, 2000; Frost, 2001). In the Orange River Catchment, water availability has already reached a critical stage (Diederichs *et al.*, 2005). Natural climate variability and human induced climate change exacerbate this situation, particularly in catchments such as the Orange, which forms part of a generally lesser-developed region, where the impacts are potentially greater than in more developed regions and the capacity to cope with climate variability and change is often relatively weak (Appleton *et al.*, 2003).

It has become increasingly evident that water related problems can no longer be resolved by water managers alone, owing to the problems becoming ever more interconnected with other development related issues, as well as with social, economic, environmental, legal and political factors (Biswas, 2004). With the advent of climate change and a likelihood of increases in extreme events, water managers' awareness of uncertainties, as well as critical reflections on the adequacy of current management approaches, has started to increase (Pahl-Wostl *et al.*, 2005b).

In order to manage water resources effectively a more holistic approach is required, in which technological, social and economic developments are linked with the protection of natural ecosystems and with dependable projections of future climatic conditions (FP6, 2004). To assess the climate risk connected with rural and urban water management, and to develop adaptive strategies that can respond to an increasingly variable climate and help to reduce adverse impacts, there is a need to mobilise expertise across several disciplines to provide the knowledge and methods necessary (FP6, 2004). This process involves making connections between climate related hazards, climate forecasts as well as climate change, and the planning, design, operation, maintenance, and rehabilitation of water related infrastructure (FP6, 2004).

1.1 Background to the Project

This study has been undertaken as part of the European Union funded NeWater Project, which is aimed at developing new approaches to water management under uncertain conditions (Pahl-Wostl *et al.*, 2005b). The NeWater Project recognised that fundamental changes are needed in the way in which water is managed, as current management strategies are clearly not always successfully protecting the water resource and are thus threatening our future access to this resource (Knoesen *et al.*, 2009). The NeWater Project has promoted Adaptive Water Resources Management, AWRM, (as a reality and not merely as an intention) as a potential way forward. AWRM is essentially “learning by doing”, but needs to be informed if to be successful (Knoesen *et al.*, 2009).

It has been suggested that climate risk management should be imbedded within AWRM (Aerts and Droogers, 2009). With the first step of the risk management process being identification and hazard determination (cf. Chapter 3), and the first step of an adaptive management cycle including scenario development (cf. Chapter 4), the integration of hydro-climatic hazards and climate change scenarios is believed to provide an important first step in the risk/adaptive management process. Furthermore, modelled impacts studies of climate change on hydro-climatic hazards have received little attention in previous climate change studies in South Africa (cf. Chapter 2). It is the intention of this study to address that gap in South African climate change research, while also aiming at developing techniques to provide water managers with information on which they can base decisions going into the future.

In the NeWater Project seven case study catchments were selected, *viz.* the Amudarya, Elbe, Guadiana, Nile, Orange, Rhine and Tisza, the locations of which are shown in Figure 1.1.The content of this thesis fits into the NeWater Project as a contribution to Work Block 3 (*Case Studies in River Basins)*, and, in particular, to

Work Package 3.8 – *The Orange Basin*. The following section provides some background to the Orange River Catchment.

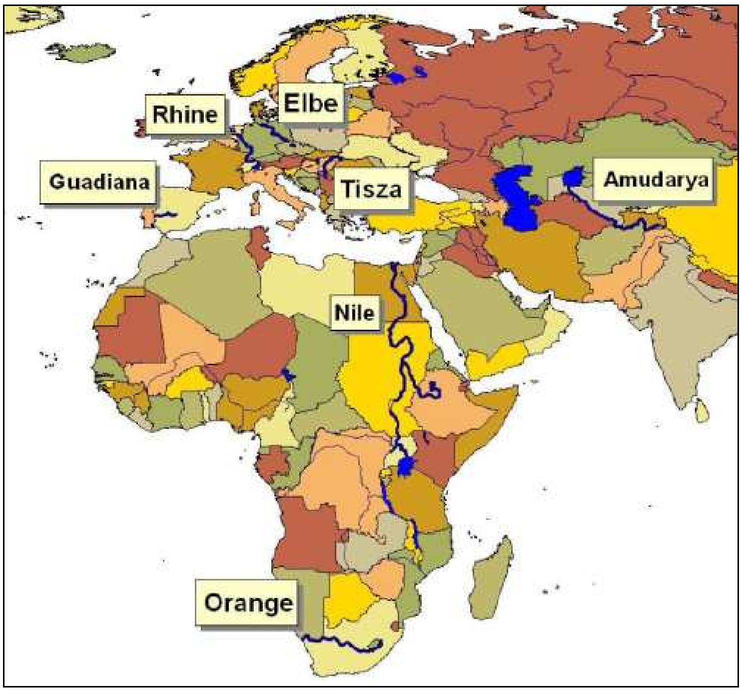


Figure 1.1 Locations of the seven case study catchments in the NeWater Project (FP6, 2004)

1.2 Background to the Orange River Catchment

The Orange River Catchment, shown in Figure 1.2, is one of the larger river basins in the world, spanning an area of almost 900 000 km^2 and covering 43% of South Africa, the whole of Lesotho, and significant portions of Botswana and Namibia. It is also the most developed transboundary catchment in southern Africa and supplies water to municipalities, industries and farms located inside and outside the catchment (Earle *et al.*, 2005).

The headwaters of the Orange River rise in the Maluti Mountain range in Lesotho at elevations nearing 3 500 m above sea level. In Lesotho the Orange River is known as the Senqu River and is only referred to as the Orange River within South Africa's borders, occasionally leading to the river being referred to as the Orange-Senqu River (Earle *et al.*, 2005). The river flows westwards across South Africa for some

2 200 km, forming the border between South Africa and Namibia for approximately 550 km, before discharging into the Atlantic Ocean (DWAF, 2004d; DWAF, 2007c).

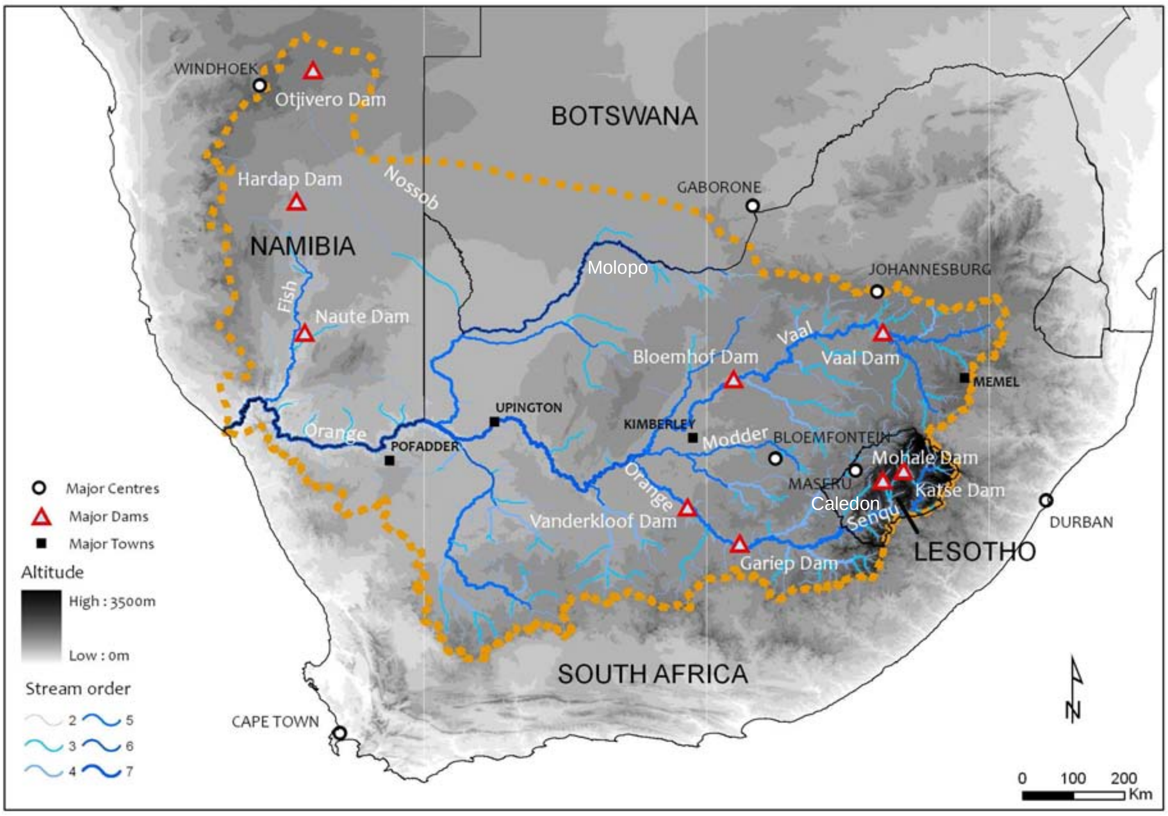


Figure 1.2 Location of the Orange River Catchment (after INR, 2009)

Several major tributaries such as the Vaal, Harts, Fish, Caledon, Molopo, Nossob and Modder rivers support the livelihoods of millions of people across the region. The Vaal River in South Africa is the largest of these and is considered to be the most important, but certainly the most over-utilised, river system in South Africa, supporting approximately 50% of the country’s economic activity (Basson *et al.*, 1997; DWAF, 2007d). It originates on the plateau west of the Drakensberg escarpment in Mpumalanga province, flowing towards the southwest until it converges with the Orange River, draining much of the central Highveld of South Africa (DWAF, 2007a). The Caledon River is the largest tributary of the Orange-Senqu River in Lesotho and forms, for most of its length, the border between Lesotho and South Africa (DWAF, 2004d; DWAF, 2007a). The Molopo River and its tributary, the Nossob River, form the boundary between South Africa and Botswana while the Fish River drains a large portion of the Orange River Catchment within Namibia (DWAF, 2007c).

1.2.1 Hydro-climatic indicators

The Orange River Catchment is classified as being generally arid, with over 50% classified as hyper-arid to semi-arid (UNEP, 2005), not only owing to its relatively low mean annual precipitation (MAP), but also because it experiences high atmospheric demand (cf. Figures 1.3 and 1.4), thereby rendering it a generally high risk and water limiting natural environment (Schulze, 2008d). With a MAP of ~ 330 mm (Earle *et al.*, 2005), which is less than 40% of the world average of 860 mm per annum, the Orange River Catchment's water resources are, in global terms, scarce and limited in extent (DWAF, 2004g; Schulze, 2008d). The rainfall in the Orange River Catchment is not only relatively low, but is also spatially unevenly distributed (Figure 1.3), with the rainfall station MAPs ranging from < 50 mm to > 1 800 mm (Lynch, 2004), and with increasing aridity to the west (Schulze, 2008d).

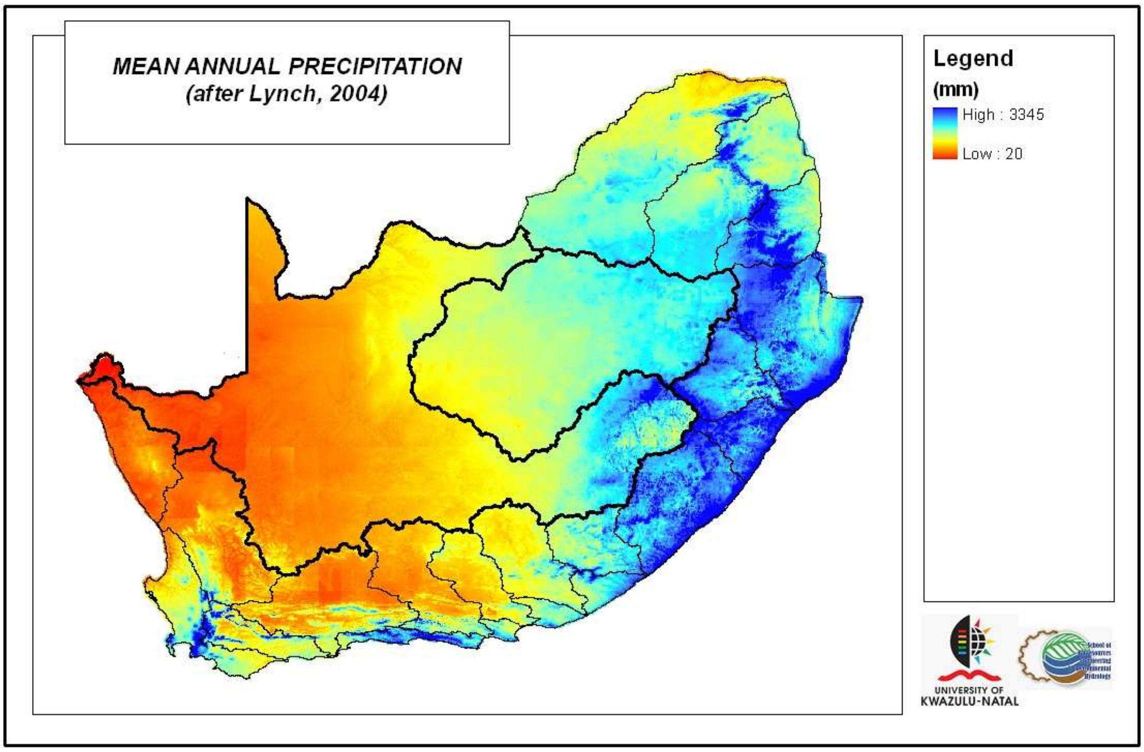


Figure 1.3 Mean annual precipitation across the Orange River Catchment (after Lynch, 2004)

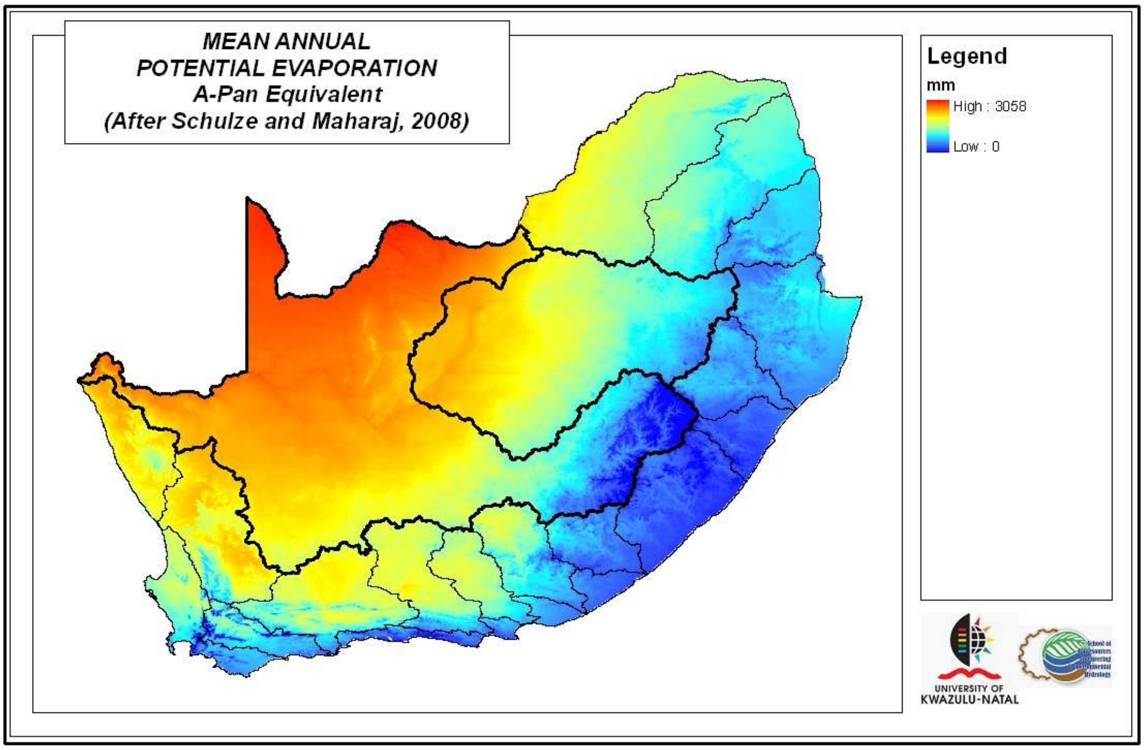


Figure 1.4 Mean annual potential evaporation across the Orange River Catchment (after Schulze and Maharaj, 2008)

The total natural runoff from the Orange River Catchment is currently estimated at approximately 11 800 million $m^3.a^{-1}$, comprised of 4 000 million $m^3.a^{-1}$ from the Senqu River and its tributaries in Lesotho, 2 700 million $m^3.a^{-1}$ from the Upper Orange and Caledon Rivers and their tributaries, 3 900 million m^3 a^{-1} from the subcatchments and tributaries of the Vaal River, and 1 200 million $m^3.a^{-1}$ from the main Orange River and its tributaries downstream of the Orange/Vaal confluence (DWAF, 2007c).

The annual runoff from the Orange River Catchment equates to less than 10% of the annual rainfall, approaching 1% in the west (Earle *et al.*, 2005), i.e. 1% of an already very low MAP. This compares poorly with the world average runoff to rainfall ratio of 35% (Schulze, 2005e).

High evapotranspiration rates, as shown in Figure 1.4, are a major contributor to the low conversion rate of rainfall to runoff, with over 90% of South Africa’s rainfall being lost through various evaporative processes (Schulze, 2003c). Of particular relevance is the high variability of rainfall as well as the highly seasonal occurrence of rainfall over virtually all of South Africa (Basson *et al.*, 1997), adding further to the complexity of the hydro-climatic environment with its strongly defined winter and summer rainfall regions (Schulze, 2005e). The main body of the Orange River Catchment lies in the summer rainfall region and about 75% of the annual runoff occurs in the summer months (Diederichs *et al.*, 2005). The strength of this seasonality becomes more pronounced owing to already seasonal rainfall being concentrated into only a few months (Schulze, 2005e). To highlight this point, approximately 85% of the rainfall in Lesotho is received during the period from October to April, while as much as 15% of the MAP may occur in a 24 hour period in some areas (Diederichs *et al.*, 2005).

It is the inter- and intra-annual variability, rather than the average amounts *per se*, that result in complexities and uncertainties in water resources management and which frequently result in water stresses (Schulze, 2005e). This statement is particularly concerning, especially considering that South Africa, along with Australia, has been found to have the highest regional variability of rainfall and runoff in the world (Haines *et al.*, 1988; Schulze, 2005e). This is due to already high levels of climate variability being amplified by the hydrological cycle (Kabat *et al.*, 2003). This amplification in variability results from spatial and temporal variations in rainfall, evaporation, topography, soils and land use (Schulze, 2003a). Additionally, different rates of process responses (e.g. surface runoff vs groundwater movement) introduce a high degree of non-linearity to the system (Schulze, 2003a). The effects of the above-mentioned factors become intensified when the natural environment is impacted upon by humans, e.g. the construction of dams, draining of fields or changes in land uses such as agricultural intensification or urbanisation (Schulze, 2003a). The result is a year-to-year runoff in the Orange River Catchment that is, in places, up to seven times more variable than that of rainfall (Schulze, 2005e). Consequently, the natural availability of water across the catchment is uneven and is already at a critical stage (DWAF, 2004g; Diederichs *et al.*, 2005).

1.2.2 Geology, soils and land cover

The geology of the Orange River Catchment is complex. The majority of the catchment is dominated by sedimentary rocks of the Karoo Supergroup, with intrusions of dolerite, extensive dolomite exposures and Kalahari sands (LHDA, 2002; DWAF, 2003a; DWAF, 2003b; DWAF, 2004b; DWAF, 2004c; DWAF, 2004f).

The highlands of Lesotho consist mainly of extrusive volcanic rock (basalt) with sedimentary rocks of shale, sandstone and mudstone in the lowlands (LHDA, 2002; DWAF, 2007b). Owing to the hard geological formation underlying most of the catchment only the dolomites, Kalahari sands and alluvial deposits associated with rivers and coastal plains contain water in primary aquifers (DWAF, 2004a; DWAF, 2004b; DWAF, 2004c; DWAF, 2004f). Although groundwater is a relatively small component of the total water resource in the Orange River Catchment, groundwater constitutes a highly valuable source of water, particularly in the western regions where approximately 60 - 70% of the water used in the tributary catchments is from groundwater sources (DWAF, 2004d).

The soils in the Lesotho highlands region of the Orange River Catchment are dominated by shallow Mountain Black Clays derived from basalt, while the soils derived from the sedimentary rocks in the lowlands are deeper, sandier soils (LHDA, 2002; DWAF, 2007b; UNDP-GEF, 2008). Most of the remainder of the Orange River Catchment is covered either by shallow, rocky soils, poorly structured sandy soils or soils showing weak to moderate development (DWAF, 2003a; DWAF, 2003b; DWAF, 2004b; DWAF, 2004c; DWAF, 2004f; DWAF, 2007b; UNDP-GEF, 2008). With the exception of the Kalahari sands the soils of the Orange River Catchment have a moderate to high erosivity index, which coupled with poor land management practices – such as overgrazing, uncontrolled burning, cultivation on steep slopes and alluvial diamond mining – has resulted in high erosion rates and sediment loading (DWAF, 2004e; DWAF, 2007b; Schulze and Horan, 2008; UNDP-GEF, 2008).

Owing to its size and its wide range of altitudinal and climatic zones, the Orange River Catchment displays a diverse set of ecological systems, and contains all seven of South Africa's biomes (Diederichs *et al.*, 2005). The National Land Cover Database developed by Fairbanks *et al.* (2000), shown in Figure 1.5, indicates that the Orange River Catchment is largely covered by natural vegetation. The eastern parts of the catchments are dominated by natural grasslands while the shrubland and low fynbos dominate in the west. Other dominant land cover types include thicket and bushland, woodland and cultivated areas. The harsh conditions of the lower Orange

River Catchment are highlighted by agriculture being largely limited to the floodplains of the Orange River.

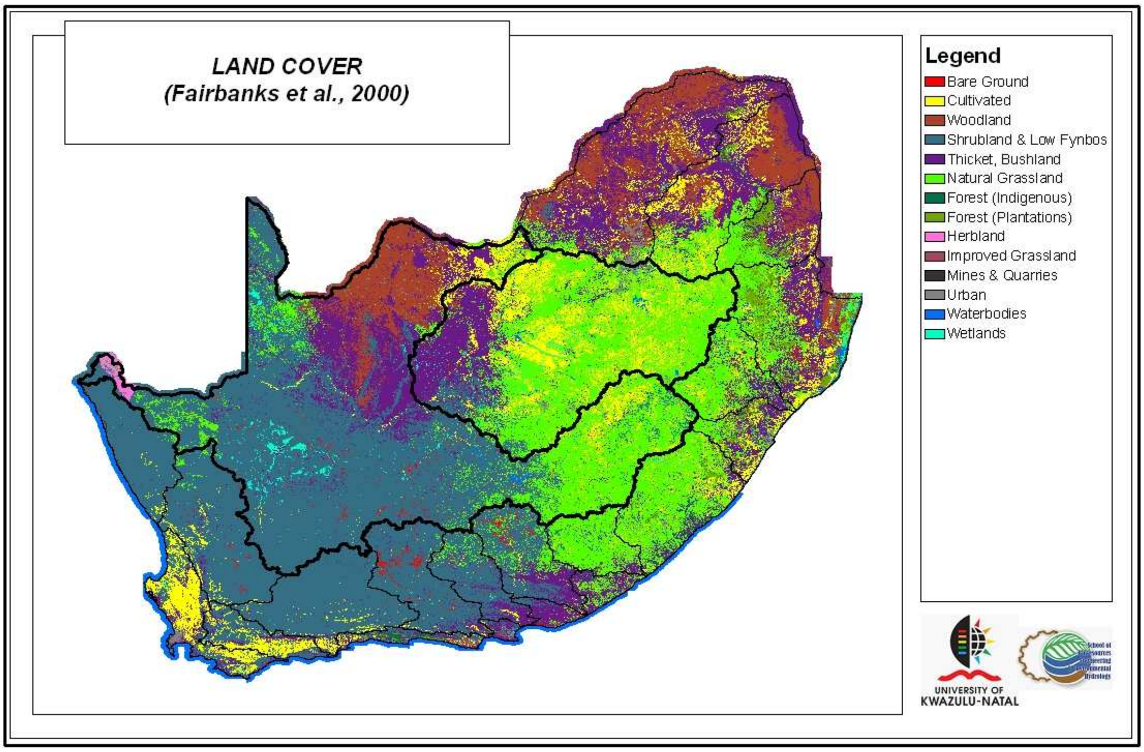


Figure 1.5 Primary land cover classes within the Orange River Catchment (after Fairbanks *et al.*, 2000)

1.2.3 Water resources

Although the Orange is viewed as a perennial river, the year-to-year runoff is highly variable, with annual flows ranging from 40 000 million $m^3.a^{-1}$ to nearly zero (Diederichs *et al.*, 2005). Under average conditions many of the rivers are dry for several months of the year, with even the higher order rivers having dried up periodically before the inception of major dams (Diederichs *et al.*, 2005), such as those indicated, together with their full supply capacities, in Table 1.1.

Table 1.1 Major dams, with gross storage greater than 500 x 10^6 m^3, in the Orange River Catchment and their storages at full supply level (DWAF, 2007a)

Dam	Storage at Full Supply Level (10^6 m^3)
Gariep	5 348
Van der Kloof	3 189
Sterkfontein	2 617
Vaal	2 610
Katse	1 950
Bloemhof	1 241
Mohale	947

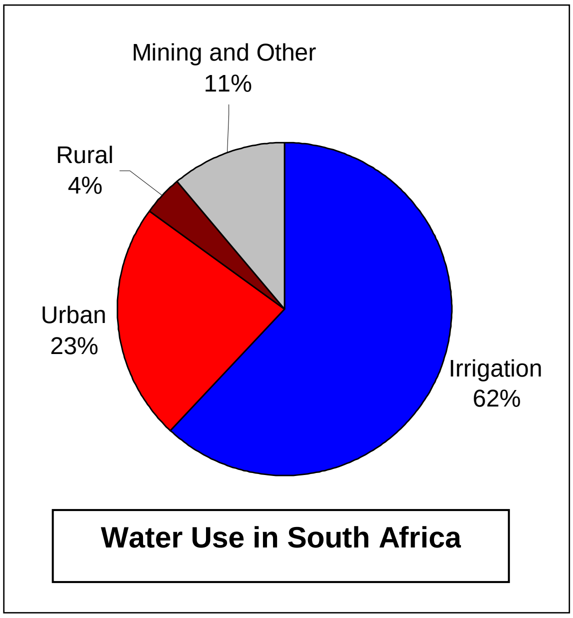
The average water availability per capita in the Orange River Catchment is less than 1 000 $m^3.a^{-1}$, indicating a situation of overall water scarcity. This, however, does vary spatially across the catchment depending on the levels of development and servicing (Diederichs *et al.*, 2005). The situation regarding availability of water is further exacerbated by the following factors:

- The high variability of rainfall has implications for water related disasters such as floods and droughts (DWAF, 2004g).
- Water quality issues exist owing to landscape degradation and the intensification of water use (Taylor *et al.*, 1999; Diederichs *et al.*, 2005; Schulze, 2005e).
- Most urban and industrial developments have been established in locations away from large watercourses. Consequently, the requirements for water already far exceed the natural availability of water in many of those catchments, and therefore large scale transfers of water across catchments have been implemented, e.g. the Orange River Project and the Lesotho Highlands Water Project (DWAF, 2004g; Diederichs *et al.*, 2005).
- Many rural communities are settled near lower order streams/tributaries, which display more variable flow patterns with less assured supply of water than main-stem rivers (Schulze, 2005e). One consequence of the low assurance of supply associated with surface water in the tributary catchments is that, as mentioned in Section 1.2.2, approximately two thirds of the water used in the tributary catchments comes from groundwater (Diederichs *et al.*, 2005).

- Only 20% of groundwater in South Africa exists in aquifers that can be utilised on a large scale, owing to various geological constraints (DWAF, 2004g).

1.2.4 Water use

The water resources in South Africa are used for various purposes, with irrigated agriculture and domestic consumption being the main user sectors. The water requirements of different sectors of the economy are depicted in Figure 1.6 for both South Africa and the Orange River Catchment. The total water requirements for South Africa in 2000 amounted to 12 871 million $m^3.a^{-1}$, of which irrigated agriculture was the largest user, requiring 62% of the available yield (DWAF, 2004g). Substantial volumes of water from urban and industrial developments are returned to streams and are available for re-use, provided that the quality of the return flows satisfies the relevant user requirements. The total usable water from return flows is close to double the current yield from groundwater (DWAF, 2004g).



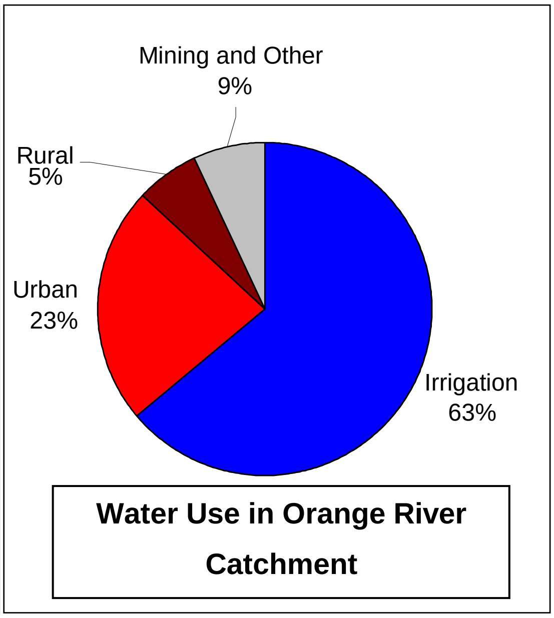


Figure 1.6 Water use per sector for 2000 (left) in South Africa, and (right) in the Orange River Catchment (DWAF, 2004a; DWAF, 2004b; DWAF, 2004c; DWAF, 2004e; DWAF, 2004f; DWAF, 2004g)

In the Orange River Catchment the total water requirements amount to approximately 6 500 million $m^3.a^{-1}$, and when compared with the whole of South Africa, displays a similar distribution per sector (Figure 1.6). However, the distribution of water use per sector differs between each water management area (WMA) within the South African portion of the Orange River Catchment. Water uses within Upper Orange, Lower Orange and Lower Vaal WMAs are dominated by irrigation (> 85%), while the remainder of the water used in these WMAs is predominantly for urban and rural purposes (DWAF, 2004a; DWAF, 2004b; DWAF, 2004e).

In the Middle Vaal WMA the distribution of water use shifts away from being completely dominated by irrigation (with little or no use from other sectors). Although irrigation remains the dominant water user in the Middle Vaal WMA (approximately 40%), around 30% of the water is used for urban and industrial purposes and about 20% is used for mining (DWAF, 2004c).

The water use of the Upper Vaal WMA is dominated by the urban, industrial and mining sectors (77% of the WMA's total water use), reflecting the region's industrialised environment (DWAF, 2004f). Furthermore, large quantities of water, destined for urban, industrial and mining use, are transferred to neighbouring WMAs (DWAF, 2004f).

A large proportion of water used in the urban and industrial sectors throughout the Orange River Catchment consists of non-consumptive use and is discharged back into the rivers after appropriate treatment (DWAF, 2004a; DWAF, 2004b; DWAF, 2004e; DWAF, 2004f).

1.2.5 Projected future of water supply and demand

When considering future water requirements, population and economic growth are regarded as the primary determinants. Although changes in population have a relatively small direct impact on water demand *per se*, they do, however, present significant indirect consequences in the economic sectors (Mukheibir and Sparks, 2003). Rural-urban migration and the negative impacts of HIV/AIDS are also key considerations when making future projections on water requirements in southern Africa (Mukheibir and Sparks, 2003). Furthermore, the deterioration of water quality as a consequence of intensification of water use is considered to be a major threat to future water supplies. These conditions will place pressure on the already stressed water systems, leading to a reduction in water availability – a situation likely to result in an increase in conflicts over water allocation (Otieno and Ochieng, 2004).

The Orange River system is reaching hydrological ‘closure’, a state where obtaining more water becomes increasingly expensive and produces diminishing returns (Hatfield Consultants, 2009). Water requirements in the Orange River Catchment are increasing (Earle *et al.*, 2005), and it is expected that the current system will be fully utilised by 2020 (Diederichs *et al.*, 2005). The largest increase in water requirements is expected in the upper reaches of the Vaal River Catchment, subcatchment of the Orange River Catchment, where the demand is expected to increase by approximately 25% between 2000 and 2025. However, as the resources within this area are essentially fully developed, future growth in the requirements for water will have to be met by increased water transfers from other areas (DWAF, 2004g).

1.3 Objective and Structure of Thesis

The primary objective of this thesis is to use the recent climate projection scenarios from the Intergovernmental Panel on Climate Change (IPCC), downscaled to the regional/local scale, to simulate projected impacts of climate change on hydro-climatic hazards in the Orange River Catchment. The techniques developed in this research, i.e. the development of a framework for integrating hydro-climatic hazards and climate change, as well as the techniques developed for mapping and interpretation of the results may be used by water resources managers and other decision-makers to make informed decisions within a framework of AWRM.

In order to achieve this objective several steps need to be undertaken. These include, *inter alia*:

- A review of the study area (cf. Section 1.2);
- A review of relevant concepts involved, which, for this specific study, are those pertaining to climate change and the associated potential hydro-climatic impacts; risk management and its components, in order to identify how hazard identification fits into the broader concept of risk management; and water

resources management practices, in order to place the issues identified above within the context of AWRM;

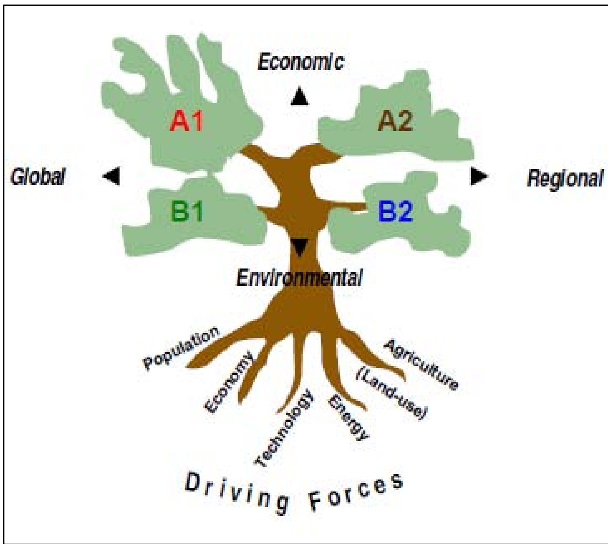
- The development of an input database, with significant contributions by the author of this thesis, to facilitate hydrological modelling for a baseline historical climate, as well as future climate scenarios; and
- Writing a suite of computer programs (cf. Appendix) for the post-processing of hydrological simulation output, in order to analyse the potential impacts of climate change on hydro-climatic hazards, *viz*. design rainfalls, design floods, meteorological and hydrological droughts, and sediment yields.

In the chapter which follows (Chapter 2) an overview is provided of *climate change* with particular reference to the *Orange River Catchment*, as are approaches to *modelling impacts* of climate change. The concept of *risk*, alluded to in Section 1.3 and Chapter 2, is discussed in detail in Chapter 3 as *hazard identification* and *hazard determination* form part of the *risk management* process. Furthermore, the *uncertainties* in risk management, within a context of climate change, are highlighted. In Chapter 4 current approaches to *water resources management* in South Africa are addressed, with particular focus on Integrated Water Resources Management (IWRM). In Chapter 4 an overview of the concept of *Adaptive Water Resources Management* (AWRM), alluded to in Section 1.1, is also provided. Chapters 1 through 4 provide the bulk of the literature review conducted in this study.

In Chapter 5 the methodologies used to model the impacts of climate change on streamflows in the Orange River Catchment are described, including sections on the selection of an appropriate hydrological model, the development of an input database, as well as the representation of regional climate change scenarios for catchment level hydrological impacts assessments. In Chapter 6 a selection of the more general results from the study is given, based on output from one General Circulation Model (GCM), *viz*. ECHAM5/MPI-OM, which is considered to provide "middle of the road" climate projections for southern Africa. These results set the scene for the results presented in Chapter 7, which form the heart of this thesis. In Chapter 7, the impacts of climate change on hydro-climatic hazards, *viz*. design rainfalls, design floods, meteorological and hydrological droughts, as well as sediment yields are investigated. Although certain results and subsequent interpretations are largely from one GCM a quantitative uncertainty analysis, by way of an index of concurrence, from multiple GCM projections is conducted for each of the respective analyses. The methodologies used to obtain these “higher order” impacts are described in the respective sections. The final chapter (Chapter 8) contains a discussion of, and conclusions drawn from, this research, while also highlighting the scientific contributions made through this research. The final section of Chapter 8 makes recommendations for future research in this field.

2. CONCEPTS 1: A BRIEF OVERVIEW OF CLIMATE CHANGE AND THE POTENTIAL IMPACTS ON WATER RESOURCES IN SOUTH AFRICA AND THE ORANGE RIVER CATCHMENT

Irrespective of what climate scenarios of the future (e.g. those by the IPCC; Figure 2.1) are foreseen few, if any, countries and their societies, economies and environments are likely to escape the impacts of global climate change (Schulze, 2005c). Some countries, sectors of society and environments will, however, be more at risk than others, either through being subjected to more hazardous degrees of climate change or through being more vulnerable to possible impacts of climate change (Schulze, 2005c). The Orange River Catchment (cf. Chapter 1) is located among the most water scarce regions in Africa and the countries within the catchment are facing increasing water resources problems and water scarcity (Diederichs *et al.*, 2005). Owing to this, and its already high climatic variability (cf. Chapter 1), the Orange River Catchment may be seen to be more at risk than many other regions of the world.



A1:	A world of rapid economic growth and rapid introductions of new and more efficient technologies
A2:	A very heterogeneous world with an emphasis on family values and local traditions
B1:	A world of dematerialisation and introduction of clean technologies
B2	A world of emphasis on local solutions to economic and environmental sustainability

Figure 2.1 SRES scenario storylines considered by the IPCC (after Nakićenović *et al.*, 2000; graphic from IPCC-TGICA, 2007)

This chapter sets out to give a brief overview of climate change, and potential impacts thereof, from a hydrological perspective and within a South African context, with particular reference to the Orange River Catchment. Furthermore, a short description and critique of the climate models used in climate change impacts assessments is provided in the chapter.

2.1 What is Climate Change?

The Earth's atmosphere protects and sustains life on Earth. The atmosphere is continuously in motion and is driven by the Sun's radiation, differences in the heating of the Earth's surface between the poles and the Equator, and the rotation of the Earth itself. The state of the atmosphere, i.e. its temperature, moisture content, pressure and airflow, is generally described in terms of weather and climate (Parry and Carter, 1998).

Weather refers to the prevailing atmospheric variables at a given place and it ranges from minutes to days, arising from instabilities in the atmosphere, which are termed weather systems (Parry and Carter, 1998; Kabat *et al.*, 2003). *Climate* may be defined as the average of the weather over periods longer than a month, e.g. a season, a year, a decade, etc. (Appleton *et al.*, 2003). Typically, weather observations such as temperature, precipitation and wind speed, are averaged over a period of time, conventionally 30 years, in order to produce the statistics that describe the climate (Parry and Carter, 1998; Kabat *et al.*, 2003).

Like the weather, climate is also variable. Schulze (2003a) defines *climate variability* as variations in the mean state, and in regard to other statistics, of the climate on all temporal and spatial scales beyond that of individual weather events. Climate variability may be a naturally inherent process within the climate system that is reversible and non-permanent, or may be the result of variations in natural or anthropogenic external forcing. The time scales of climate variability range from diurnal (within the course of a day, e.g. time of occurrence of convective thunderstorms), through to decadal, e.g. persistent sequences of wet years or dry years (Schulze, 2003a).

Climate may also change over longer time scales, ranging from decades to centuries. Within a human lifetime, this change in climate is essentially irreversible and permanent (Schulze, 2003a). *Climate change* may be defined as a statistically significant change in either the mean state of the climate, or in its variability, and in the context of this study is considered to be attributed directly or indirectly to anthropogenic influences that alter the composition of the global atmosphere and persists for an extended period (Appleton *et al.*, 2003; Schulze, 2003a).

Although the global climate has changed greatly over geological time, it is the unprecedented rapid global warming trend in the past few decades, depicted in Figure 2.2, which is of immediate concern (Pittock, 2005). The average rate of warming calculated over the past 50 years (0.13℃ ± 0.03℃ per decade) is nearly twice that for the past 100 years (IPCC, 2007b). Up until 2006, the years 2005 and 1998 had been the warmest two years in the instrumental global surface air temperature record since 1850. Surface temperatures in 1998 were enhanced by the major 1997 - 1998 El Niño but no such strong anomaly was present in 2005 (IPCC, 2007b). Thirteen of the 14 warmest years have now occurred in the 14 years from 1995 - 2008 (Brohan *et al.*, 2006; Jones, 2009).

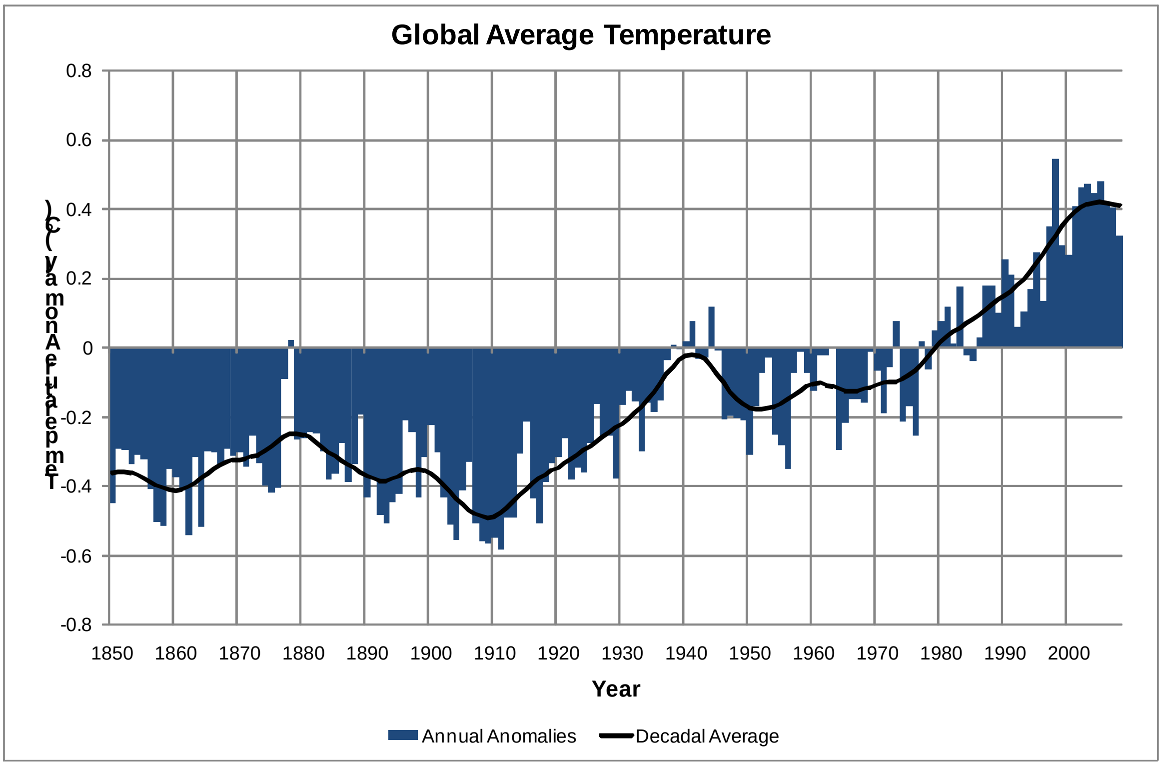


Figure 2.2 Time series showing the annual average temperature record from 1850 to 2008 (after Jones, 2009). This time series is continually being updated and improved, the key reference for which is Brohan *et al.* (2006)

It is widely acknowledged that increases in concentrations of atmospheric greenhouse gases are mainly responsible for this global warming. Raupach *et al.* (2007) estimate the growth rate of atmospheric CO_2 concentration to be > 2 parts per million (ppm) from the year 2000 to 2005. Extrapolating from the atmospheric CO_2 concentration of 379 ppm in 2005 (IPCC, 2007b), the 2009 atmospheric CO_2 concentration would be at least 387 parts per million, > 38% above the pre-industrial concentration of about 280 ppm in 1750.

However, these increases in atmospheric CO_2 concentration, and other greenhouse gases, cannot be explained by natural processes alone. Figure 2.3 shows that simulations that account for anthropogenic forcings (including increasing greenhouse gas concentrations and the effects of aerosols, also incorporating natural external forcings) provide a consistent explanation of the observed temperature record, whereas simulations that include only natural forcings fail to simulate the warming observed over the past 30 years (IPCC, 2007b). That climate models are only able to simulate observed global mean temperature changes over the 20th century when they include anthropogenic forcings is evidence of the influence of humans on global climate (IPCC, 2007b).

2.2 Impacts of Climate Change on the Hydrological Cycle

Spatial and temporal changes in hydrological responses are determined by changes in temperature, evaporation and precipitation; the latter considered to be the most important as it is precipitation that generally induces the critical changes in catchment responses (Chiew, 2007). Increasing global temperatures will have profound effects on evaporation, which in turn affects atmospheric water storage and hence magnitudes, frequencies and intensities of rainfall events as well as the seasonal and geographic distribution of rainfall and its inter-annual variability (Kabat *et al.*, 2003). Some of these climate change impacts on hydrological processes may have already been observed (IPCC, 2007a). Figure 2.4 shows that, although the number of disasters reported that are associated with geophysical events, such as earthquakes and volcanic eruptions, have remained remarkably constant, those associated with hydro-meteorological events, particularly storms and floods, have increased significantly.

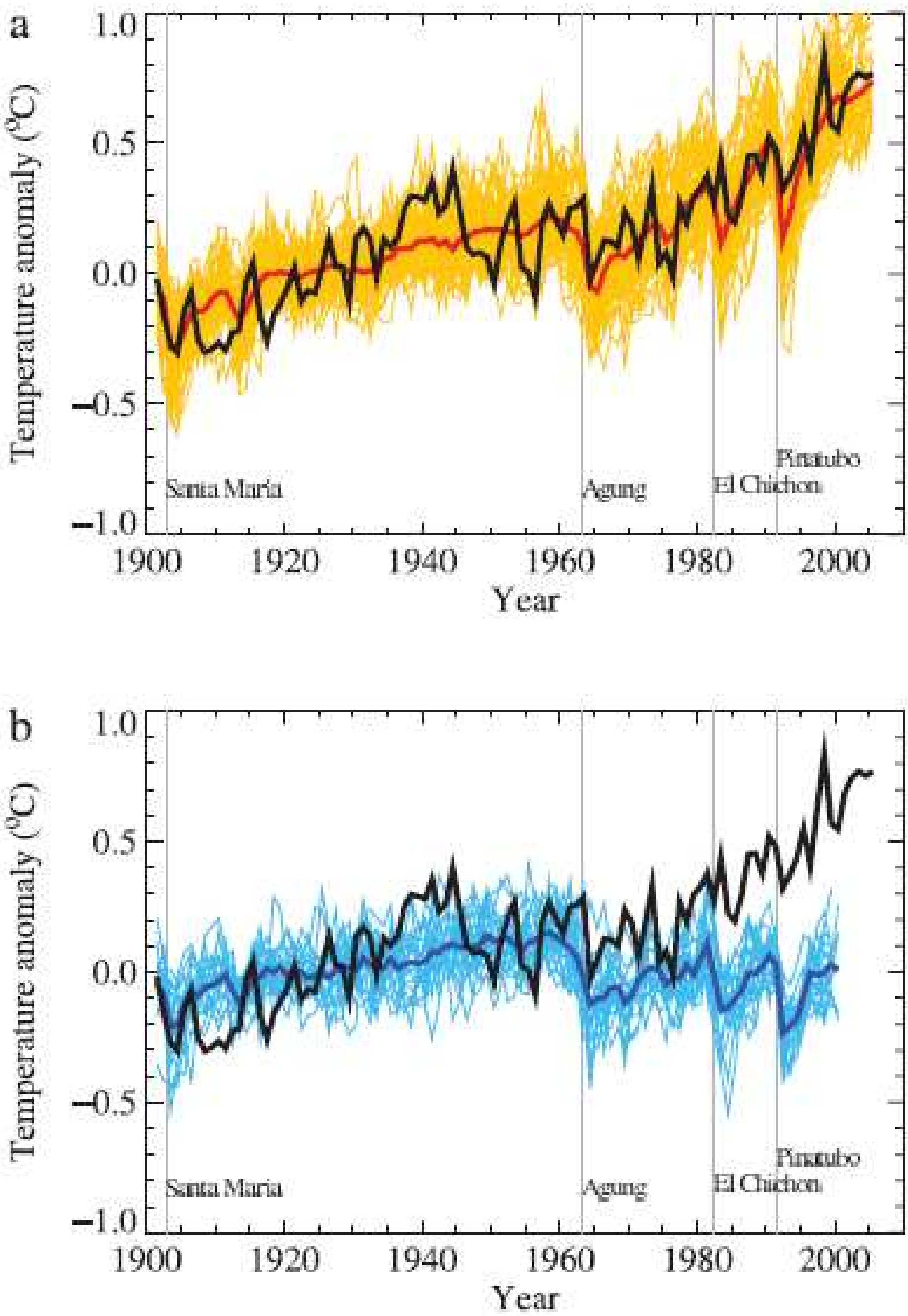


Figure 2.3 Comparison between global mean surface temperature anomalies (℃) from observations (black) and GCM simulations forced with (a) both anthropogenic and natural forcings, with the multi-model ensemble mean shown as a thick red curve and individual simulations shown as thin yellow curves; and (b) natural forcings only, with the multi-model ensemble mean shown as a thick blue curve and individual simulations shown as thin blue curves. Vertical grey lines indicate the timing of major volcanic events (IPCC, 2007b)

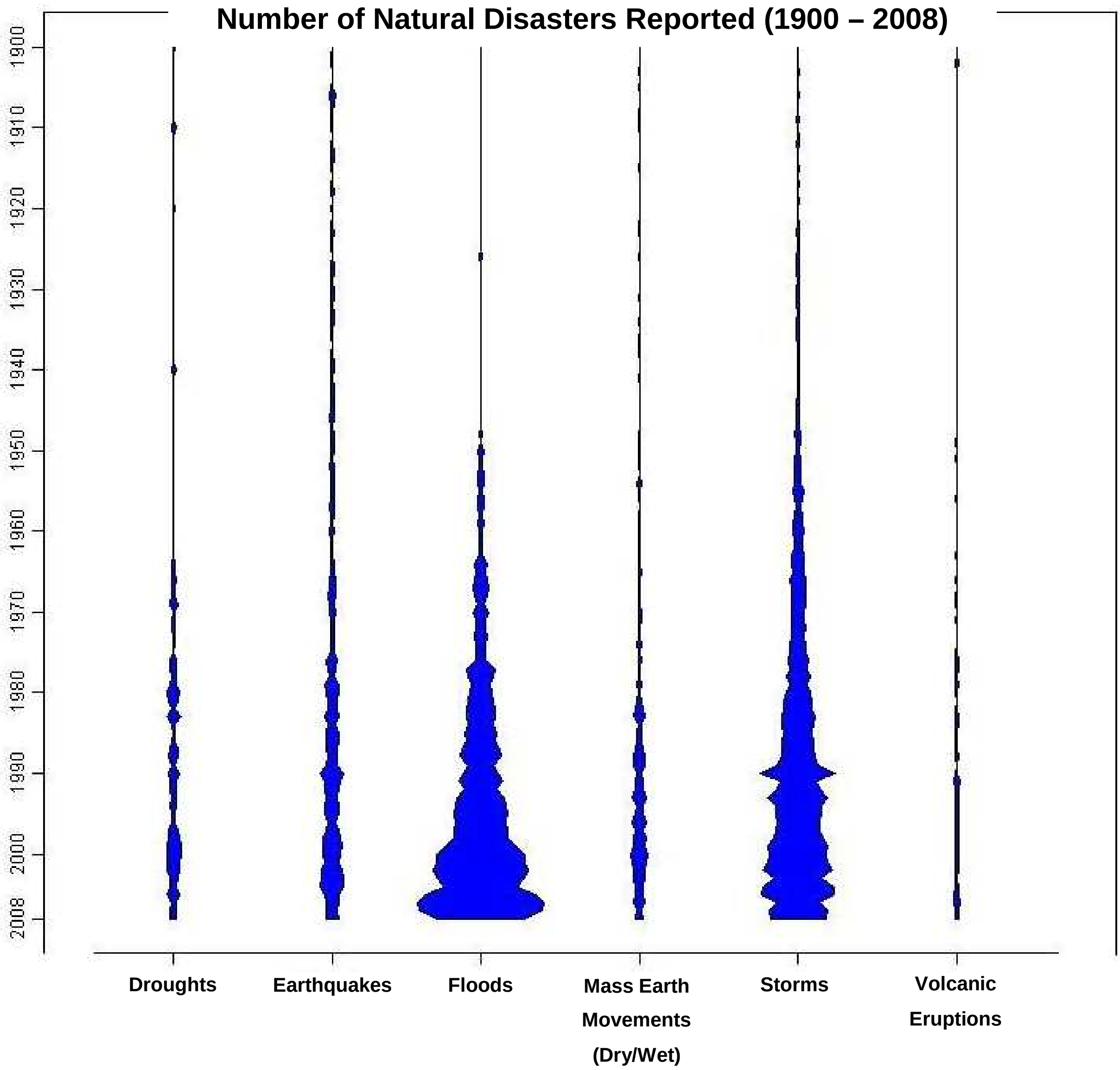


Figure 2.4 A schematic of globally reported hydro-meteorological and geophysical disasters from 1900 - 2008 (EM-DAT, 2009)

Climate change impacts may also have already been observed at a more local scale. Some examples are given below:

- Mason *et al.* (1999) identified significant increases in the intensity of extreme rainfall between 1931 - 1960 and 1961 - 1990 over approximately 70% of South Africa. The intensity of the highest rainfall in 10 years has increased by over 10% over vast areas of the country, except in parts of the northeast, northwest and in the winter rainfall region of the southwest of South Africa (Mason *et al.*, 1999). Percentage increases in the intensity of high rainfall events were found to be largest for the most extreme events (Mason *et al.*, 1999).

- In agreement with the above findings, New *et al.* (2006) analysed climate data from 14 south and west African countries over the period 1961 - 2000 and found strong trends in the regional climate, most notably with respect to changes in secondary attributes of rainfall such as intensity and frequency, but also with respect to dry spell duration.
- Furthermore, an analysis of historical precipitation trends by Hewitson *et al.* (2005c), which used robust regression with an interpolated 0.1° gridded precipitation data set that draws on over 3 000 station records across South Africa, identified the following broad regional characteristics:
    - Increases in the late summer dry spell duration for much of the summer rainfall region.
    - Arid zones, in general, receiving more days on which rain fell.
    - Contrasting changes in the winter rainfall region, with mountainous regions receiving more rain days per month and increased totals, while the neighbouring coastal plain regions displayed the reverse.
- On the hemispheric scale Hewitson and Crane (2006) note that there are also indications that the El Niño-Southern Oscillation teleconnection to southern Africa may be weakening (Landman and Mason, 1999; Sewell and Landman, 2001). Since this teleconnection may not exist in future climates its use for climate prediction should be avoided (Hewitson and Crane, 2006).

Although climate change is expected to affect many of the natural and man-made sectors of the environment (Ringius *et al.*, 1996), change in water availability is considered to be one of the most critical factors associated with climate change impacts (MacIver, 1998; Hardy, 2003). There is a sensitive, non-linear relationship between rainfall and runoff, where a small change in rainfall causes considerable effects in runoff (IPCC, 2001b; Schulze, 2003a). Arid and semi-arid regions, such as the Orange River Catchment, are particularly sensitive to changes in rainfall owing to the small fraction of water that runs off or percolates to the groundwater (Schulze, 1997a).

Potential impacts of climate change on surface water supply include (Schulze, 2003a):

- Changes in the seasonality of streamflows, which might affect supply and demand for various sectors, e.g. irrigation or domestic, with knock-on effects on water pricing/licensing and effects on water resources infrastructure, including sizing of reservoirs, curtailment rules, or reservoir maintenance.
- Changes in streamflow variability at inter- and intra-annual time scales, including effects on vegetation dynamics and resultant hydrological responses, the regional amplification of variability and persistent sequences of flows above or below selected thresholds.
- Changes in magnitudes and frequencies of extreme events related to both floods and droughts.
- Effects of land use on water availability, mainly through alterations in the partitioning of rainfall into stormflow and baseflow.

Potential impacts of climate change on higher order hydrological responses, such as changes in water quality, also need to be considered (Schulze, 2003a). Water quality changes that might be expected are alterations in the physical, chemical and biological status of the water systems (Ashton, 1996). All soil erosion studies have suggested that increased rainfall intensities and flooding will result in greater rates of erosion (IPCC, 2007b) and, therefore, higher sediment yields. Erosion rates are expected to change primarily due to changes in rainfall and streamflow erosivity, but also due to the knock-on effects of the impacts of climate change on land cover and land use (Tucker and Slingerland, 1997; IPCC, 2007b). Increases in sediment yields may have repercussions for water quality (Gleick, 2000; Dennis *et al.*, 2003; DWAF, 2004e; UNDP-GEF, 2008) as sediments have the capacity to bind with nutrient chemicals (e.g. phosphates) and industrial toxins (Newson, 2009). Furthermore, increases in sediment yields may increase the rate of sedimentation of river channels and reservoirs (Takeuchi, 2002; Newson, 2009), leading not only to a reduction in water storage capacity, and hence water supply, but also to increased flood risks.

Climate perturbations through the hydrological system may result in potential changes in transboundary water interests and conflicts, where rivers form international boundaries, or especially where rivers discharge downstream from one country to another (Schulze, 2003a), as is the situation in the Orange River Catchment (cf. Chapter 1). Furthermore, there may also be changes in water issues to the poor, who often live either on floodplains, which may become more prone to flooding in the future, or alternatively live along watersheds, where presently ephemeral streams may become even more so in future (Schulze, 2003a).

In order to project future climate trends, or to validate various assumptions on the potential impacts of climate change, such as those presented above, scientists employ the use of complex atmospheric models. The following section, therefore, provides an overview of modelling the impacts of climate change.

2.3 Modelling the Impacts of Climate Change

Of the numerous ways by which climate change scenarios can be constructed, the use of output from General Circulation Models (GCMs) is the most widely applied method (Perks, 2001). GCMs are able to simulate the most important features of the global climate reliably at a large scale, but owing to the low horizontal resolution and limited description of sub-grid processes, they fail to characterise the impacts at a regional/local scale (Bergant *et al.*, 2006). However, water managers require information to be at the regional/local scale in order to assess local vulnerabilities to potential climate change and explore local adaptation options. Therefore, climate change impacts studies rely on outputs from GCMs that, through linking to regional climate characteristics, are downscaled to an appropriate finer scale spatial resolution (Hewitson *et al.*, 2005a; Bergant *et al.*, 2006; Giorgi *et al.*, 2008). This section continues with a brief description of GCMs and the approaches taken to generate regional/local scale climate change scenarios.

2.3.1 General Circulation Models

The interactions between the many processes that govern the Earth's climate are so complex and extensive that quantitative predictions of the impacts of increasing concentrations of greenhouse gases on climate cannot be made through simple intuitive reasoning (Shaka, 2008). For this reason, computer models, i.e. GCMs, have been developed, which are mathematical representations of the Earth's system, in which physical and biogeochemical processes are described numerically to simulate the climate system as realistically as possible (Jacob and van den Hurk, 2009).

GCMs are founded on assumptions on the evolution of drivers of climate change, for example, the distributions of aerosols and greenhouse gases, and their respective concentrations, in the atmosphere (Jacob and van den Hurk, 2009). These depend directly upon natural and anthropogenic emissions, which are estimated through emission scenarios – developed using so-called "story lines" (Nakićenović *et al.*, 2000) which describe possible developments in global population growth and other aspects of the socio-economic system (Cox and Stephenson, 2007; Jacob and van den Hurk, 2009). These emission scenarios are used to drive atmospheric chemistry and carbon cycle models that simulate changes in the concentration of greenhouse gases and aerosols (Cox and Stephenson, 2007). The resulting concentration scenarios are then input into GCMs, which generate climate change scenarios that, in turn, drive models of the impacts on human and natural systems (Cox and Stephenson, 2007).

Uncertainties inherent in GCMs have been well documented (e.g. UKCIP, 2003; Cox and Stephenson, 2007; Giorgi *et al.*, 2008; Jacob and van den Hurk, 2009; Schulze, 2009a). In addition to the limitations resulting from uncertainties, GCMs are less capable of simulating second order atmospheric processes, such as precipitation, compared to those related to first order atmospheric processes, such as surface heat and vapour fluxes (Hardy, 2003). These limitations include:

- Failure to simulate individual convective rainfall events, owing to the coarse spatial resolutions of GCMs, and the smaller spatial and temporal nature of convective rainfall (Barichievy, 2009). This is problematic as in many parts of the world, including most of southern Africa, where convective rainfall is a dominant form of precipitation.
- GCMs fail to simulate the intensity, frequency and distribution of extreme rainfall (IPCC, 2007b).
- GCMs have also been shown to simulate too many light rainfall events (<10 $mm.day^{-1}$) and too few heavy rainfall events (>10 $mm.day^{-1}$), whilst maintaining a fairly realistic mean precipitation (IPCC, 2007b).

- Major drivers of climate variability, such as the El Niño-Southern Oscillation, which is associated with a broad band of variability throughout southern Africa (Tyson, 1996), are also represented poorly (Hulme *et al.*, 2001).
- Climatological variables representing other atmospheric conditions that lead to high magnitude precipitation and flood-producing events cannot generally be obtained from GCMs.

These factors reduce the accuracy of precipitation output from GCMs. Additionally, global mean temperatures are quite unrepresentative at the regional/local scale (Jacob and van den Hurk, 2009), and hence any subsequent estimations of potential evaporation. Therefore, there are questions surrounding the usability of GCM output in hydrological studies, where precipitation, temperature and potential evaporation at the local scale are primary inputs into hydrological models.

Even so, output from GCMs forms the basis for climate change impacts assessments. However, as has already been alluded to, a significant discontinuity exists between the output from GCMs (spatial scales of 10^4 - 10^5 km^2) and the catchment scale (10^1 - 10^2 km^2) at which local decisions are sought (Schulze, 2009a). It is due to this discontinuity that GCM output needs to be translated from the coarse to more regional/local scales by the process of regional climate downscaling (Hewitson *et al.*, 2005a; Giorgi *et al.*, 2008; Schulze, 2009a).

2.3.2 Approaches to regional climate downscaling

Downscaling refers to techniques that enable the results from GCMs to be made relevant to local decision-makers and impacts assessments (UKCIP, 2003). Two approaches are commonly used to bridge the gap between large scale and local scale climate change scenarios, *viz. dynamical downscaling* and *empirical downscaling* (Hewitson *et al.*, 2005a; Bergant *et al.*, 2006; Giorgi *et al.*, 2008).

2.3.2.1 Dynamical downscaling

Dynamical downscaling involves the use of high-resolution regional climate models (RCMs), which are nested within GCMs (UKCIP, 2003; Jacob and van den Hurk, 2009). The GCMs are used to define the boundary conditions for the RCMs, but additional detail is provided regarding complex topographical features and land cover heterogeneity in a physically-based manner, thereby allowing smaller scale features of the atmosphere, such as orographic enhancement of rainfall, to be modelled better than is possible within the GCMs (UKCIP, 2003; Jacob and van den Hurk, 2009). Two major disadvantages of RCMs are that they propagate the uncertainties of the GCMs and that they are computationally intensive (UKCIP, 2003; Jacob and van den Hurk, 2009). Despite these, and several other limitations listed by Hewitson *et al*. (2005b), their use is growing in popularity.

2.3.2.2 Empirical downscaling

Empirical, i.e. statistical, downscaling represents an empirical equivalent of RCMs. Whereas RCMs use the GCM fields to provide input to numerical representation of the physics of the climate system dynamics, empirical downscaling seeks to do the same using empirical formulations derived from observational data (Hewitson *et al.*, 2005b). Empirical downscaling involves developing a quantitative relationship between local scale variables and large scale atmospheric variables, which is subsequently applied to the GCM output to obtain local and regional climate change signals (Jacob and van den Hurk, 2009). An advantage of this technique is that GCM output can be downscaled to a point, which is useful for obtaining projections – e.g. rainfall – at a particular site, which can then be input into a hydrological model. Furthermore, this technique is computationally far less demanding than the RCM approach (UKCIP, 2003). A major disadvantage of this approach is the implicit assumption that these statistical relationships will remain stationary under a future climate (UKCIP, 2003; Jacob and van den Hurk, 2009).

2.3.3 Modelling impacts of climate change on hydrological responses over South Africa and more specifically the Orange River Catchment – A review of research up to 2005

The majority of research in South Africa on impacts of projected changes in hydrological responses due to climate change in the period 1996 – 2005 was summarised in reports on the South African Country Study on climate change

(Schulze and Perks, 2000), a PhD thesis by Perks (2001), in the 20 papers making up the so-called “Thukela Dialogue” edited by Schulze (2003b) and in a major report on scenarios, impacts, vulnerabilities and adaptation to the Water Research Commission by a multi-institutional team, also edited by Schulze (2005a).

According to C-CAM regional climate scenarios (Engelbrecht, 2005), MAP for South Africa was projected to decrease between 5 and 10% of the present, with reductions of up to 25% in the already water stressed areas of the lower Orange River Catchment. Furthermore, the number of dry days was projected to increase over most of the Orange River Catchment, while the number of days producing heavy rainfall, i.e. ≥ 25 mm, was projected to increase in the upper reaches of the catchment; amplifying the risk of increases in sediment yields – and the indirect consequences for water quality (Gleick, 2000; Dennis *et al.*, 2003; DWAF, 2004e; UNDP-GEF, 2008) – as well as posing heightened flood risks (cf. Section 2.2). This was surmised to be exacerbated by an expected increase in an already high inter-annual variability over most of South Africa (Schulze *et al.*, 2005a).

Changes in the above-mentioned rainfall parameters were modelled to change soil moisture storage, runoff processes and groundwater recharge which, in turn, was expected to affect the amount of water available to the various water-using sectors, *viz*. domestic, environment, industry, agriculture and recreation (Schulze *et al.*, 2005a).

Generally, changing patterns in runoff were consistent with those identified for precipitation (IPCC, 2001b). This was consistent with the results of Schulze and Perks (2000) who found that the mean accumulated streamflows over most of the Orange River Catchment would decrease in a future climate, with the worst effects felt in the lower reaches of the catchment (Figure 2.5). However, more recent results published by Schulze (2005c) indicated that the situation was not necessarily going to be so dire, with some areas in the lower Orange River Catchment projected to experience an increase in mean annual accumulated streamflows of up to 4 times the present amount. Furthermore, mean annual stormflow – the water that contributes to streamflows, which is generated from a specific rainfall event, either at or near the surface, i.e. does not include baseflow – was projected to increase in many parts of the Orange River Catchment. This was considered important, as it is largely from stormflow events that reservoirs are filled (Schulze, 2005c).

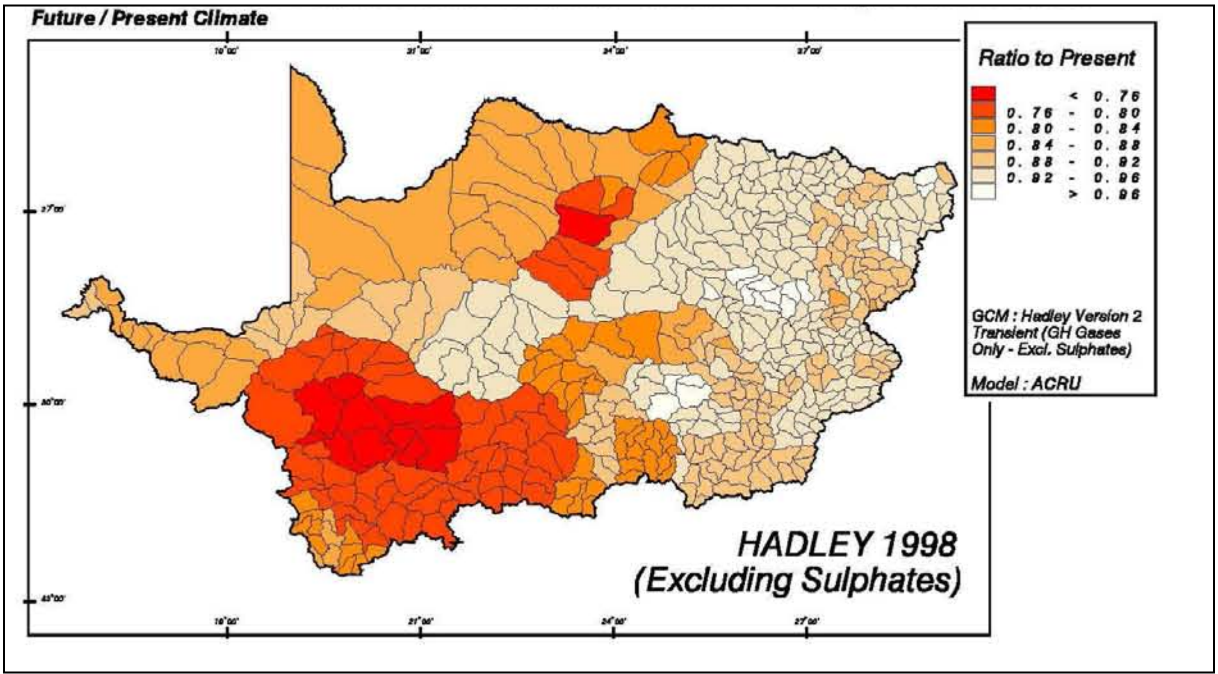


Figure 2.5 Simulated relative changes in mean annual accumulated streamflows in the Orange River Catchment, using an older GCM (Schulze and Perks, 2000)

Future projections of the global climate indicated that precipitation patterns were changing, thus leaving the future probability of deep percolation to recharge aquifers an area of marked concern for some of the country (Cavé *et al.*, 2003). Shallow, unconfined aquifers along floodplains in semi-arid and arid regions are recharged by seasonal streamflows and can be depleted directly by evaporation (Appleton *et al.*, 2003). Projected increases in evaporation and potential increases in the concentration of streamflow in many of the rivers in the Orange River Catchment (Schulze *et al.*, 2005a) could thus lead to reduced groundwater recharge. This is particularly concerning for the lower Orange River Catchment where a large proportion of the domestic and agricultural water supply is derived from groundwater (cf. Section 1.2.2).

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This chapter has provided an overview of climate change by describing the concept of climate change and by alerting the reader to the projected impacts thereof. Furthermore, approaches adopted for climate change impacts studies have been discussed, with particular reference to results from such approaches that have been conducted in South Africa and the Orange River Catchment.

What is clear from the assessment of potential climate change impacts studies on hydrological responses in South Africa is that most climate change research in South Africa has been focussed on water resources and agriculture, with very little reference to hydro-climatic risk management, particularly with regard to modelled studies of floods and droughts. Where reference has been made to changes in design rainfall, for example WRC Report 1430/1/05 (Schulze, 2005a), very little was said about the projections. Furthermore, in that same study, references to changes in design floods were based on shifts in climate zones rather than simulated floods. This study, which focuses on modelling the impacts of climate change on hydro-climatic hazards, therefore fills an important knowledge gap.

3. CONCEPTS 2: RISK MANAGEMENT – HAZARD, VULNERABILITY, RISK AND UNCERTAINTY

The Orange River Catchment has been shown already to display characteristics such as low rainfall in places, high evaporative demand, and overall high climatic variability, which render it a high risk environment (cf. Section 1.2). Furthermore, it has been indicated in Chapter 2 that this situation may be exacerbated by climate change. This section provides an overview of the concepts of risk and risk management, as well as their respective components.

A plethora of definitions of *risk* may be found in the literature, and a selection is shown in Box 3.1. Imbedded within many of the definitions of risk are the terms *hazard* and *vulnerability*. Cardona's (2003) definition of risk introduces the mathematical concept of convolution, which, in this case, refers to the concomitance and mutual conditioning of hazard and vulnerability. If there is no hazard it is not feasible to be vulnerable, when seen from the perspective of the potential damage or loss due to the occurrence of an event. In the same way, there is no situation of hazard for an element, or system, if it is not exposed, or vulnerable, to the potential event (Cardona, 2003). In order to understand the concept of risk it is necessary to understand the components of risk. Therefore, the terms hazard and vulnerability are described next, before returning to broader issues surrounding risk and risk management.

3.1 Hazard

A hazard may be defined as a potentially damaging physical event, phenomenon or human activity that may cause injury or the loss of life, property damage, social and economic disruption or environmental degradation (Few *et al.*, 2006).

For a physical event to be hazardous, by the above definition, there has to be a subject to experience the physical event or the threat. For example, people, infrastructure and economic activities have to be located in an area where the event, often an extreme one, occurs (UNDP, 2004).

Box 3.1 Selected definitions of risk

Risk may be expressed as:

- The actual exposure of something of human value to a hazard and is often regarded as the combination of probability and loss (Smith and Petley, 2009).
- The potential loss to the exposed subject or system, resulting from the convolution of hazard and vulnerability (Cardona, 2003).
- A quantitative measure of a defined hazard, which combines the probability or frequency of occurrence of the damaging event (i.e. the hazard) and the magnitude of the consequences (i.e. expected losses) of the occurrence (Kabat *et al.*, 2003).
- The probability of harmful consequences, or expected loss of lives, people injured, property, livelihoods, economic activity disrupted (or environment damaged) resulting from interactions between natural or human induced hazards and vulnerable conditions (UNDP, 2004).
- The propensity of an exposed element to suffer damage from a given hazard with consideration of the element's vulnerability (Douglas, 2007).

From all of the above, risk may be expressed as follows:

Risk = Hazard x Vulnerability

This very notion of a hazard remits to socially induced transformation of physical elements and resources into dangerous, or potentially dangerous, phenomena (UNDP, 2002), thus distinguishing extreme events from hazards. The magnitude of a hazard is determined by the extent to which a physical event disrupts the human environment (Schulze, 2003d). Therefore, a hazard may be expresses as follows:

Hazard = Physical Event x Exposure

The physical exposure is a function of the elements at risk, *viz*. people, buildings, economic activities, public services, infrastructure, the environment, etc., located in areas where the hazardous events occur, combined with the characteristics associated with the magnitude of the hazard (Schulze, 2003d; UNDP, 2004). An everyday natural process only becomes a hazard when it produces an event that exceeds the critical limits that the environment can normally tolerate before impacting negatively on the exposed subject or system (Cardona, 2003). For example, too much rainfall produces a flood hazard, while too little rainfall produces a drought hazard. In Figure 3.1, the shaded area represents the tolerance limits of the variation about the average, within which a resource such as water can be used beneficially for social and economic activities within the human environment (Schulze, 2003d). The magnitude by which an event exceeds a given threshold is proportional to the damage-causing potential of such an event. The magnitude of a hazard is determined by the following factors:

- *Duration* (the length of time the threshold is exceeded, as shown by the horizontal scale in Figure 3.1).
- *Intensity* (the peak deviation beyond the threshold, as shown by the vertical scale in Figure 3.1).
- *Speed of onset* (time between the initiation of the event and its peak).
- *Spatial distribution* (where the impacts occur).
- *Areal extent* (total area impacted by the event).

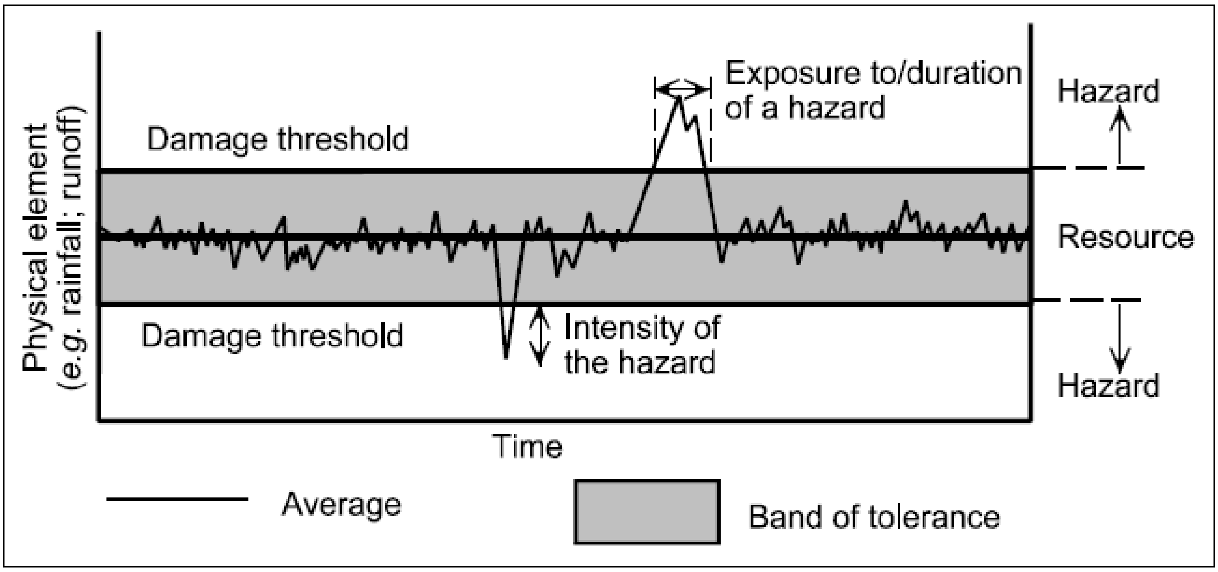

Figure 3.1 The magnitude of environmental hazards expressed as a function of the variability of a physical element within the limits of tolerance (Schulze, 2003d)

It should be noted, however, that Figure 3.1 only accounts for physical exposure in terms of the magnitude of the event itself, and not in terms of the exposed elements at risk. An increase in the elements at risk, or an increase in the frequency of occurrence of the hazard, would increase the physical exposure and, hence, the damage-causing potential (UNDP, 2004).

Physical exposure is a condition necessary for risk to exist. However, it is insufficient to explain risk on its own. Countries with similar levels of physical exposure to a given hazard experience widely differing levels of risk (UNDP, 2004). This is due to the other factor in the risk equation, *viz*. vulnerability.

3.2 Vulnerability

Vulnerability is a condition or process resulting from physical, social, economic and/or environmental factors, which determines the probability and magnitude of damage from the impact of a given hazard (UNDP, 2004). This concept has been a powerful analytical tool for describing states of susceptibility to harm, and for guiding actions taken for risk reduction (Adger, 2006).

Vulnerability may be defined as the degree to which a person, or group, or component of a natural system is susceptible to harm due to exposure to a perturbation or stress, and the ability (or lack thereof) to cope with, resist, recover from, anticipate, or fundamentally adapt to the impacts of that perturbation or stress (adapted from Schulze, 2003d; Pahl-Wostl *et al.*, 2005a).

From this definition, the multi-dimensionality of the concept of vulnerability becomes apparent. Not only does vulnerability encompass social, economic and ecological dimensions (Kumpulainen, 2006; Thywissen, 2006), but, as is observed consistently throughout the literature, it also comprises complex and interconnected parameters such as *sensitivity*, *resilience* and *adaptive capacity*, i.e.

Vulnerability = f(sensitivity, resilience, adaptive capacity)

Sensitivity is the degree to which a system is affected, adversely or beneficially, by a disturbance, or set of disturbances (Gallopín, 2006; IPCC, 2007b). Conceptually, it can be measured as the amount of transformation of the system per unit change in the disturbance (Gallopín, 2006). Smit and Wandel (2006) state that sensitivity is almost inextricably linked with exposure, thus making exposure a necessary condition for vulnerability to exist, a view also held by Cardona (2003). This would imply that a system that is not exposed to a disturbance would be defined as non-vulnerable (Gallopín, 2006). However, according to Thywissen (2006), vulnerability cannot be "switched on and off with the coming and going of events" and is thus an intrinsic property of the system. Therefore, exposure is externalised, making it a relational property of the system (Gallopín, 2006).

The next feature of vulnerability is *resilience*, which may be defined as the magnitude of disturbance a system can undergo whilst retaining the same controls on function and structure, the degree to which a system is capable of self-organisation and the capacity for adaptation to emerging circumstances (Holling, 1973; Adger, 2006). Therefore, resilience is not only concerned with persistence when experiencing disturbance, but also about the possible opportunities created in terms of recombination of evolved structures and processes, renewal of the system and emergence of new trajectories (Folke, 2006). Resilience therefore implies that there are thresholds of vulnerability (Schulze, 2003d), which can be increased by increasing the *adaptive capacity* of the system.

The capacity to adapt is a critical element of the process of adaptation, but this varies depending on various factors, which include scale (e.g. global, national and local scales), context and time (Reid and Vogel, 2006; Smit and Wandel, 2006), highlighting the dynamic nature of adaptive capacity. Adaptive capacity is defined by Pahl-Wostl *et al*. (2005a) as "the potential or capability of a system to adjust, via changes in its characteristics or behaviour, so as to cope better with existing and future stresses".

Smit and Wandel (2006) cite Vogel (1998) who applies adaptive capacity to more long term sustainable adjustments and uses coping ability to describe shorter term survival strategies. Similarly, Gallopín (2006) views adaptive capacity as a concept comprising a “coping” component as well as a more sustainable component that includes the capacity to improve its condition even if the environment does not change, or by extending the range of environments to which it is adapted. The resulting adaptations are thus manifestations of adaptive capacity (Smit and Wandel, 2006).

The measurement of vulnerability is difficult as the above-mentioned parameters that make up vulnerability are often more difficult to conceptualise due to their intangible nature (Thywissen, 2006). This, together with the dynamic nature of the components involved, makes it difficult to reduce the concept of vulnerability to a single metric and, in many ways, attempts to do so reduce its impact and hide its complexity (Adger, 2006).

3.3 Risk

To summarise what has been presented above, risk is a function of hazard and vulnerability and, consequently, all those parameters that constitute hazard and vulnerability, as shown in Figure 3.2. Risk, therefore, embraces an *external dimension*, *viz*. the relationship between the perturbation and the system, and an *internal dimension*, *viz*. the intrinsic properties of the system itself, which affect the ability of the system to withstand or respond to an external disturbance (Schulze, 2003d; Gallopín, 2006).

While the product of hazard and vulnerability, as presented in Box 3.1, is insufficient to fully describe risk, it does provide a means for the comparison of risks and making resources decisions (Helm, 1996). Hazard parameters for different types of threats cannot be readily compared as they often measure different physical quantities (Douglas, 2007). However, Sayers *et al*. (2002), cited by Kelman (2003), warn that although it may be assumed that similar values of risk have similar significance, high probability, low consequence events are treated very differently to those events occurring less frequently but yielding more severe repercussions. Therefore, it can be gleaned that the dynamic interplay between hazard and vulnerability gives rise to several possibilities of risk, which can change over time. An example of these is illustrated in Figure 3.3, where Cases A to C were initially presented by Smith (1996), and Case D was later added by Schulze (2003d).

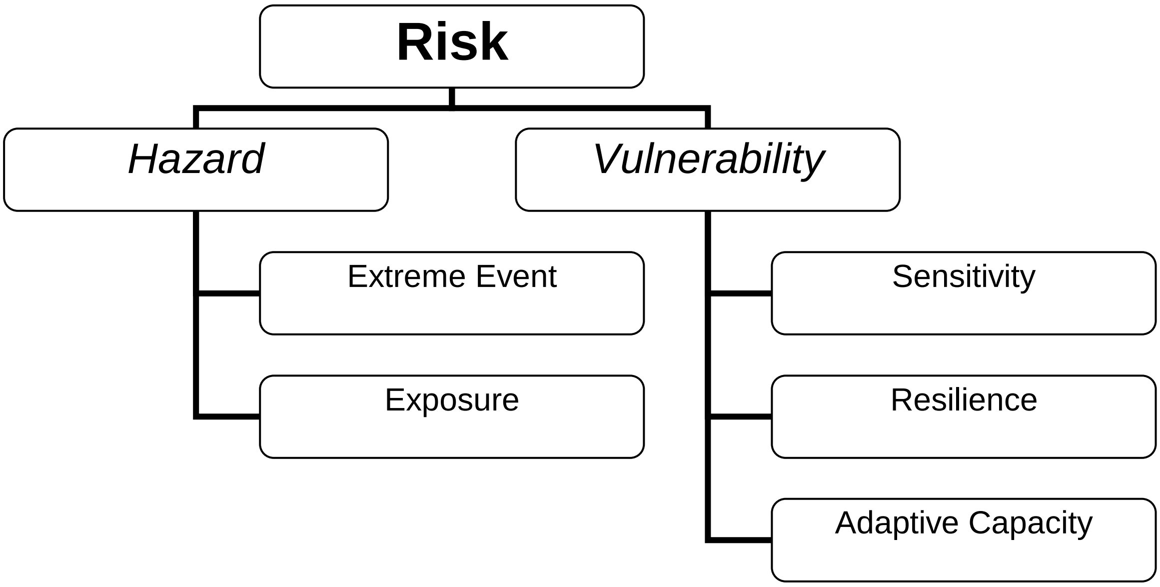

Figure 3.2 Components of risk

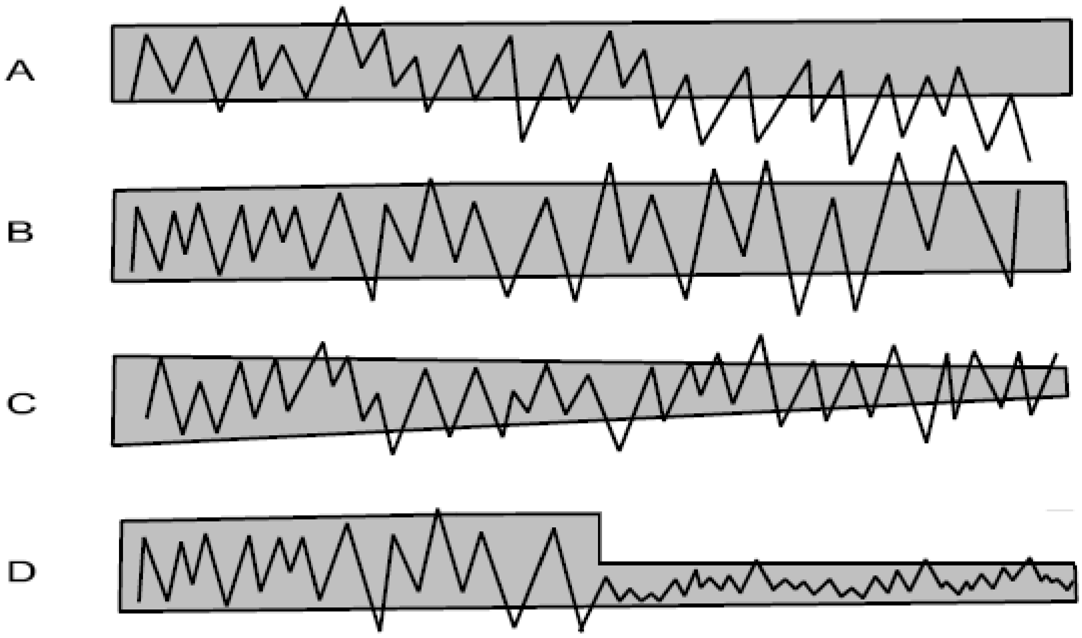

Figure 3.3 A schematic illustration of how risk is influenced over time by external and internal dimensions, represented by the black zigzagged line and grey shaded areas, respectively (Smith, 1996; Schulze, 2003d)

Case A illustrates a scenario where the tolerance and the variability remain constant, but there is a change in the mean (e.g. reduction in streamflow following upstream afforestation). Here the frequency of extreme events (i.e. perturbations beyond the tolerance thresholds) at one end of the scale is shown to increase over time (more occurrences of critical low flows). Case B represents a scenario in which both the mean and the tolerance remain constant, but the variability increases (e.g. change in variability associated with climate change). Here the frequency of extreme events increases at both ends of the scale over time. In Case C, the physical variable remains constant, but there is a reduction in tolerance (e.g. a subsistence farmer increasing the area of maize production at the expense of other more drought resistant cultivars). This reduction in diversity increases the vulnerability to the natural climate variability (Hallowes, 2002). Here the frequency of extreme events increases at both ends of the scale over time. Case D represents a sudden change in both the variability and the tolerance of a system (e.g. downstream impact following construction of a major dam, with controlled releases changing downstream flow characteristics). In this scenario, Schulze (2003d) states that risk may increase or decrease over time. However, this may also demonstrate an example of *risk homeostasis*, whereby a constant level of risk is maintained irrespective of external influences (Kelman, 2003).

That risks are societal constructs implies that they can be influenced by policy-makers (Tol *et al.*, 1994). Risk management is a process that attempts to reduce risks by enabling decision-makers and stakeholders to choose the best course of action under a given range of situations (Schulze, 2003d).

3.4 Risk Management

Risk management is the means by which a rational level of acceptable, or tolerable, risk is sought (McColl *et al.*, 2000). It is a comprehensive, formalised framework that assists decision-makers and stakeholders in identifying, analysing, evaluating and mitigating risks (Fairman *et al.*, 1998; Plate, 2002b). It is a technical, social and economic process based on balancing costs and benefits both in monetary and social terms, in order to choose appropriate risk reduction measures (Fairman *et al.*, 1998; McColl *et al.*, 2000; Plate, 2002b). The objective of risk management is to ensure that significant risks, and therefore their components, *viz*. hazards and vulnerabilities, are identified and that appropriate action is taken in an attempt to control these risks to the extent that is reasonably achievable (McColl *et al.*, 2000).

There are many models of risk management (e.g. Levitt, 1997; McColl *et al.*, 2000; Schulze, 2003d) in which the process of risk can be conceptualised as a sequence of actions (Plate, 2002b), an example being shown in Figure 3.4. The various components of this framework are used in an attempt to find the answers to the following questions posed by Grigg (2000):

- What is the threat? (*Hazard identification*)
- What are the chances of it occurring? (*Statistical hazard determination*)
- How severe could the impacts be? (*Vulnerability determination*)
- Are the effects acceptable or tolerable? (*Risk evaluation*)
- What can be done to minimise the effects? (*Risk mitigation and control*)

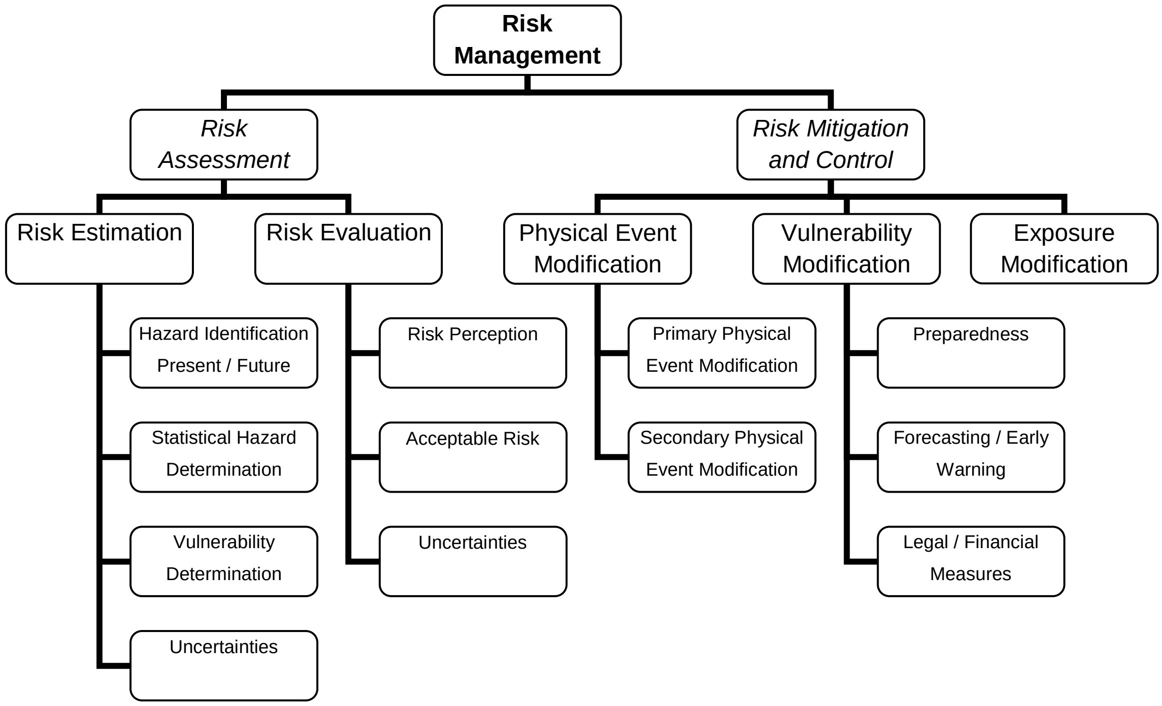

Figure 3.4 A risk management framework from a hydrological perspective (adapted from Schulze, 2003d)

3.4.1 Risk assessment

Schulze (2003d) defines risk assessment as "*the process of assigning magnitudes and probabilities to the adverse effects of natural catastrophes or human activities using rigorous, formal and consistent forms of measurement and testing; alternatively, of deterministic or statistical models, to quantify the relationship between the initiating event (e.g. rainfall) and the responding effects (e.g. a flood and its associated damage) and, while acknowledging the inherent uncertainties involved, providing a quantitative basis for prioritising and comparing hazards and risks in accordance with what the people at risk perceive and judge as being acceptable or tolerable to them by their value systems*."

A risk assessment therefore comprises the processes of estimating and evaluating risks.

3.4.1.1 Risk estimation

Risk estimation makes use of science-based risk information and analytical methods to characterise the nature and extent of risks to the system (McColl *et al.*, 2000). It involves identifying the threat, calculating its probability of occurrence, and estimating the likely consequences.

The inherent complexities of a water resources system imply that risks can emanate from different sources – e.g. physical/environmental, technological and socio-economic – and affect different components (Paoli and Bass, 1994). In the first step of risk estimation, *viz*. hazard identification, those hazards that are a threat to the safety, performance or the failure of a system are identified (Schulze, 2003d). From a hydrological perspective, this may include the potential for flooding or droughts.

Although a detailed understanding of what events have occurred in the past (as well as their effects) have usually provided scientists with the basis for understanding of what could or will happen in the future, it is also important to identify new potential hazards, or how existing hazards may change. Climate change, with possible changes in rainfall magnitude, variability and intensity, as well as the potential for human induced catchment influences, could result in changes to the magnitudes of extreme events, or result in higher order impacts such as changes to sediment yields (Plate, 2002b; Schulze, 2003d). Therefore, it is important to base risk assessment on the most recent information available, such as new data, new theoretical developments, or new boundary conditions (Plate, 2002a).

The next step of the risk assessment is the statistical hazard determination, which usually takes the form of a probability analysis, calculated using extreme value distributions, and then presented in a useful form, e.g. hazard maps, which shows the extreme event as a function of location for a given exceedance probability (Plate, 2002b). In hydrology, where long duration, high quality observed data are frequently lacking, this step often employs a modelling approach, e.g. downscaled GCM temperature and rainfall values may be used in a hydrological model to simulate streamflow in order to calculate projected future flood and drought probabilities.

Vulnerability determination is then required in order to determine the propensity of the exposed elements in the system to suffer damage. There exists a range of different approaches to measure vulnerability (Kumpulainen, 2006), yet it is often not considered at all and only the hazard is determined (Douglas, 2007). This may be due to, *inter alia* (Douglas, 2007):

- Differing causes of human losses.
- Temporal and geographical scale issues.
- The complexity of modelling the effects of the hazard on the exposed element.
- The difficulty of reducing the intangible components of vulnerability to a single metric (Adger, 2006), as mentioned in Section 3.2.

Modelling assumptions and techniques used in the process of risk estimation inject further uncertainty into the risk assessment (Paoli and Bass, 1994). This is discussed further in Section 3.5.

3.4.1.2 Risk evaluation

Risk evaluation, the second major component of risk assessment, is often separated from the more ‘scientific’ determination of a hazard as it is becoming increasingly acknowledged that subjective judgement and values form an integral part of any risk assessment (Fairman *et al.*, 1998). Risk evaluation is the consideration of the economic, social, political and legal factors that influence a decision to adopt a particular course of action to reduce risks (McColl *et al.*, 2000).

Risk evaluation is concerned with the labelling of the estimated risk as acceptable (or at least tolerable) or unacceptable, which is central to the process of risk prioritisation (Paoli and Bass, 1994; Granger, 2000). Acceptable risk is influenced by the perceptions of risk – comprehensively described by Schulze (2003d) – held by the exposed population level, as well as their level of vulnerability (Plate, 2002a; Plate, 2002b). Many of the consequences elicited in the risk estimation are not readily expressible in common units, and there are no universally accepted means for carrying out this conversion. Furthermore, many other intangible factors enter the assessment in this phase, such as equitable distribution of risk and assignment of responsibility for the risk (Paoli and Bass, 1994).

Therefore, more uncertainty is injected into the risk assessment. This is compounded by the subjectivity of decision-makers, who carry their own inherent biases related to their professional training, past experiences and personal views (McColl *et al.*, 2000).

3.4.2 Risk mitigation and control

Risk mitigation and control constitute the second major component of risk management (Figure 3.4). “Risk mitigation considers setting up alternative measures to reduce the impacts of a hazard by minimising its destructive and disruptive effects, thereby lessening the scale of the disaster. It attempts to find practical and workable strategies and solutions for minimising risk at scales ranging from international to national to local (Schulze, 2003d).”

Risk may be reduced by decreasing the extent of any one or more of the contributing variables. From the equations relating to risk and hazard in Box 3.1 and Section 3.1, respectively, the risk equation can be expanded so that

Risk = Physical Event x Exposure x Vulnerability

This can be illustrated by assuming the 'dimension' of each of the three variables represents the side of a triangle, with risk represented by the area of the triangle (Granger, 2000). In Figure 3.5, the larger (yellow) triangle portrays each of the variables as being equal, whilst in the smaller (green hatched) triangle the risk has been mitigated by the reduction of both exposure and vulnerability. The reduction of any one of the three factors to zero would consequently eliminate the risk (Granger, 2000).

It follows that the main mitigation strategies would involve *physical event modification*, i.e. modifying the physical processes that create or constitute the hazard, involving some degree of direct confrontation; as well as *vulnerability modification*, i.e. reducing the impact of the event by rendering the human environment less vulnerable to, and more prepared for the event; and *exposure modification*, which is usually achieved as a result of the first two mitigation strategies.

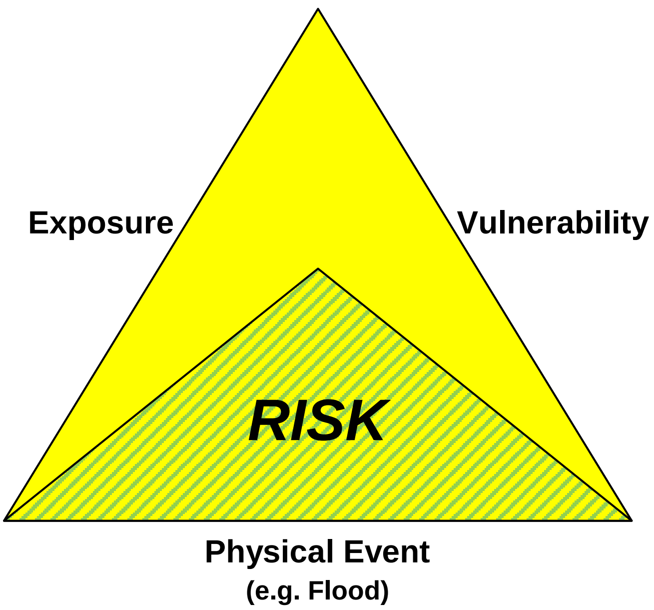

Figure 3.5 A schematic illustration of risk mitigation through modification of the components of risk (adapted from Granger, 2000)

3.4.2.1 Physical event modification

The objective of physical event modification is to reduce the damage potential associated with a particular event by means of some extent of physical control over the primary processes of the event involved (Schulze, 2003d), e.g. the stimulation of cumulus clouds to reduce rainfall intensity and increase rainfall duration. However, owing to technological deficiencies and the uncertainty involved, the suppression of natural events such as those causing large scale flood events is not yet possible (Schulze, 2003d).

A more common approach to event modification is via manipulation of the secondary processes that cause a hazard (Schulze, 2003d). In the case of floods, for example, instead of attempting to manipulate the rainfall event, the runoff generation processes could be manipulated through the restoration and rehabilitation of wetlands, or by increasing the efficiency and capacity by which floodwaters are conveyed through channel improvements (Smith and Ward, 1998). Hazard resistance is another form of event modification, this involving the construction of defensive engineering structures such as levees for flood proofing or dams to contain floodwaters (Smith and Ward, 1998; Alexander, 2001; Schulze, 2003d).

3.4.2.2 Vulnerability modification

Vulnerability modification is a more complicated process that involves the interaction of several different interrelated factors, and is concerned with human reactions toward a potential hazard (Schulze, 2003d). Risk mitigation through vulnerability modification may be achieved through the implementation of several different measures, which include community preparedness programmes, forecasting and warning systems, and legal and financial measures such as insurance, which ideally should be linked into one interrelated programme (Schulze, 2003d).

Preparedness reflects the extent to which a community is provided with the necessary decision support system for the case where the above-mentioned physical event modification has failed (Smith and Petley, 2009). No technical solution is absolutely safe; therefore there is always a residual risk (Plate, 2002a). It is the purpose of preparedness to reduce the residual risk through widespread and ongoing community awareness programmes based on risk history, effective risk communication, evacuation strategies, the provision of medical and food aid as well as shelter for evacuees (Granger, 2000; Schulze, 2003d).

An important step in improving an existing flood protection system is the provision of better warning systems. An effective forecasting and warning system, combined with a high level of community awareness and risk appreciation, is one of the most potent mechanisms by which to achieve risk reduction (Granger, 2000). The basis for a warning system has to be an effective forecasting system, which permits the early identification and quantification of an imminent hazard (Plate, 2002a). Although typically taken to mean short term warnings, longer term estimates of the ‘hazardousness’ of a region can also be generated (Granger, 2000), for example those resulting from climate change scenario analyses. For these longer term estimates, however, it is important to note that warnings are based on predictions (e.g. design flood probability) or projections (e.g. scenarios of climate change), rather than forecasts (Schulze, 2003d).

A governing factor in the decision process for risk mitigation and control measures is the availability of legal and financial resources (Plate, 2002a). Legal and financial measures are designed to either avoid the settlement of individuals or communities into areas of high risk, or to provide aid that is able to accelerate the recovery of affected communities (Schulze, 2003d). However, it is important to note that financial resources for risk mitigation are often sourced from public funds and are in competition with other needs of society (Plate, 2002a).

3.4.3 Decision-making

An important component of risk mitigation is the process by which decisions are made in risk management. The choice of implementing one or more of the risk reduction options that have been proposed and evaluated is a decision that may require broad stakeholder involvement (McColl *et al.*, 2000). Furthermore, risk reduction and the potential financial costs involved may not be the sole determinants of the applicability of a proposed method (McColl *et al.*, 2000). Therefore, the decision-making process will be based not only on technical criteria, but also on intuition and social and political priorities (Plate, 2002b).

The risk management process relies on major operating principles to aid with decision-making under uncertainty. These principles include, *inter alia* (McColl *et al.*, 2000):

- The Precautionary Principle – which drives decision-makers towards taking action in situations where a hazard is believed to exist as a possibility, although the exact probability is imperfectly understood.
- Sound Science – which seeks to restrain decision-makers from attempting premature or erroneous judgements about hazards that may not constitute meaningful threats, and which requires that the decision to act should be based on a reasonable probability of harm.

Increasingly, risk management is being guided by the ALARP (As Low as Reasonably Practicable) Principle – in which the mutually opposed principles mentioned above are brought together, thereby conceivably ensuring an acceptable risk by adopting reasonably achievable control measures that balance risks and benefits (McColl *et al.*, 2000; Smith and Petley, 2009). In the UK, this approach is embedded in law as a result of a legal ruling in the European Court of Justice in 2007 (Smith and Petley, 2009).

However, in order to use these principles in the decision-making process, the characterisation of the uncertainties involved is crucial (Giorgi *et al.*, 2008). Under-appreciation of these uncertainties results in higher risk (Koutsoyiannis *et al.*, 2009).

3.5 Uncertainty

Risk decisions are typically characterised by high levels of uncertainty, which need to be appreciated by those involved in the risk management process (Suter, 1993). In water resources, for example, the existence of various uncertainties is a major contributor to potential project, or system, failure (Yen, 2002). These uncertainties, in the exactness of the values produced and in the decisions taken, exist despite the statistical rigour with which risk estimation may have been carried out (Suter, 1993).

Uncertainty may be defined as "*the situation in which no unique and complete understanding of the system to be managed exists"* (Brugnach *et al.*, 2009). Disregarding the uncertainties inherent in a system is one of the most critical errors in any type of risk management (McColl *et al.*, 2000). Uncertainties can arise from various sources, which are not only technical or scientific in nature, but may also result from different perceptions and conflicting views about a particular issue (Brugnach *et al.*, 2009).

Conceptually, the typologies of uncertainty in risk management identified by Suter (1993), McColl *et al*. (2000), Schulze (2003d) and Brugnach *et al*. (2009), can be characterised into four types (Figure 3.6), *viz*. *natural variability*, *incomplete knowledge*, *decision-rule* uncertainty and the *human element*.

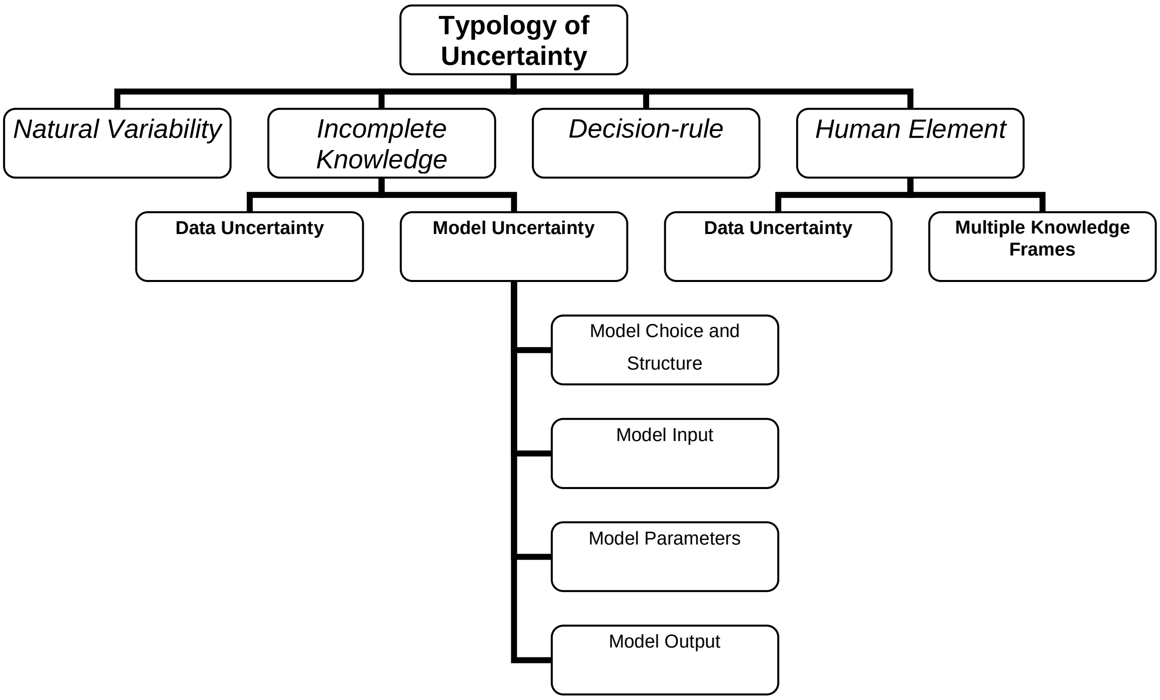

Figure 3.6 Typology of uncertainty, developed from multiple sources (Suter, 1993; McColl *et al.*, 2000; Schulze, 2003d; Brugnach *et al.*, 2009)

Natural variability arises from many inherently random factors that must be considered in a risk assessment (McColl *et al.*, 2000). This type of uncertainty refers to the inherently unpredictable aspects of a system that are due to inherent natural variability or complex system behaviour (Brugnach *et al.*, 2009). From a hydro-climatic hazard perspective this may include occurrences of episodic events, such as intense rainfall, which may become further complicated by demographic factors in the exposed population, such as the distributions of age and gender. In regard to this type of uncertainty, the unpredictability of the system is accepted as something that will not change in the foreseeable future (Brugnach *et al.*, 2009), and while it can be described, no amount of additional data collection or analysis can reduce the degree of variability, nor the resulting uncertainty, found in natural processes (Suter, 1993; McColl *et al.*, 2000; Schulze, 2003d).

The second type of uncertainty shown in Figure 3.6, *incomplete knowledge*, refers to situations where the available theoretical and empirical knowledge is unable to provide sufficient understanding of things that are potentially knowable (Suter, 1993). This can be due to several factors, including lack of, or inadequate representativeness of, data due to practical constraints (Yen, 2002), to the unreliability of the available data, to incomplete theoretical understanding of system dynamics, or to ignorance (Brugnach *et al.*, 2009). Furthermore, incomplete knowledge includes uncertainty about the future, for example, on socio-economic development and consequent emissions of greenhouse gases, or the effectiveness of policies to mitigate these emissions (UKCIP, 2003).

A subset of incomplete knowledge is that of model uncertainty. Owing to models being simplifications of reality, their predictive accuracy is limited (McColl *et al.*, 2000). Model uncertainties may arise from numerous factors:

- Model choice and structure – This reflects the inability of the simulation model to accurately represent the complexities of the system's true physical behaviour (McColl *et al.*, 2000; Yen, 2002). Furthermore, different models may give different results for the same problem, as a result of differences in their detailed structures, even though they are based on the same fundamental physics. An example is GCMs producing different responses to the same greenhouse gas forcing (UKCIP, 2003; Giorgi *et al.*, 2008). Therefore, the choice as to which model to use introduces more uncertainty through the subjective human element. However, using several models to create an ensemble of projections may improve confidence (Giorgi *et al.*, 2008), or at least give a better understanding of the uncertainties involved.

- Model parameters – This reflects an inability to accurately quantify the model parameters, e.g. the behaviour of clouds and/or the strength of atmospheric convection in GCMs (Cox and Stephenson, 2007). This inability may be attributed to statistical uncertainties or to flawed experimental design (McColl *et al.*, 2000; Yen, 2002).
- Model input and output – Uncertainties in model input often result from one or many of the sources of incomplete knowledge stated above, e.g. those regarding future greenhouse gas emissions, which form the basis for developing the parameters with which to force a GCM simulation (Hewitson *et al.*, 2005b). These uncertainties are then propagated through the model, together with model structure and parameter uncertainties, to result in uncertain output. Furthermore, these uncertain outputs often become inputs into other models (e.g. uncertain GCM output is input into downscaling algorithms, and this output becomes input into hydrological models), further increasing the uncertainties associated with final resulting output (UKCIP, 2003; Cox and Stephenson, 2007; Giorgi *et al.*, 2008).

Decision-rule uncertainty takes the form of vague or unsuitable operational definitions for desired outcome criteria, value parameters, and decision variables (McColl *et al.*, 2000). These include the selection of particular types of summary statistics for outcome measures, (e.g. lifetime mortality risk versus annual mortality risk), and the choice of variables that express subjective value judgments in the form of utility functions, for example, the monetary value attributed to loss of life (McColl *et al.*, 2000).

The last type of uncertainty shown in Figure 3.6 is that associated with what makes us human in regard to imperfections and subjectivity. Imperfections refer to human errors, which include mistakes made in the execution of risk assessment, mainly through poor quality assurance, (e.g. data recording errors, data handling and transcription errors), model input errors and any other human factors that are not accounted for in the modelling or design procedure (Suter, 1993; Yen, 2002).

The basic philosophy of risk assessment has several inherent contradictions that seriously compromise its claim to scientific consistency and objectivity (McColl *et al.*, 2000). Subjectivity, referred to by Brugnach *et al*. (2009) as *multiple knowledge frames,* refers to different, sometimes conflicting, views about the best way to understand the system (Brugnach *et al.*, 2009). Those involved in the risk management process carry their own inherent biases related to their professional training and are often unaware of their personal biases, nor do they fully realise the extent to which this can influence professional judgement (McColl *et al.*, 2000). This kind of uncertainty can be called ambiguity and can originate from differences in, *inter alia*, professional backgrounds, scientific disciplines, value systems and societal positions (Brugnach *et al.*, 2009).

Other than uncertainties associated with natural variability, uncertainties in the risk management process are, in principle, reducible given either more time, more data or improved quality assurance (McColl *et al.*, 2000; Brugnach *et al.*, 2009). It is important to note that many, if not all, of these types of uncertainty are present simultaneously in each stage of the risk management process.

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Following on the above review on hazards, vulnerabilities, risk and uncertainty, it needs to be reiterated that while this thesis focuses on techniques for identifying changes in hydro-climatic hazards related to impacts of projected climate change (i.e. the initial stages of the risk management process – cf. Section 3.4), it is ubiquitously stated in the literature that the most effective way of reducing risk is to address the vulnerability side of the risk equation. This, however, can only be achieved if one can answer the question of “vulnerable to what?”, as the hazard and the potential vulnerability it exposes are inextricably linked within the context of risk.

Without adequate feedback and learning, risk management is unlikely to be effective (Smith and Petley, 2009). The uncertainties mentioned above, and hence those associated with climate change, provide justification for developing water management institutions that are more flexible and responsive to changing conditions (Frederick, 1998). Users of water resources may be protected from the impacts of climate change through the application of effective water management strategies, which would require adopting appropriate policies (Pittock, 2005). Therefore, the incorporation of risk management strategies within adaptive water resources management is a key element to hydro-climatic risk mitigation (Aerts and Droogers, 2009). The following chapter addresses water resources management in South Africa, with particular reference to integrated and adaptive water resources management.

4. CONCEPTS 3: WATER RESOURCES MANAGEMENT

Worldwide, water is recognised as the most fundamental and indispensable of all natural resources and is a key factor for the sustainability of social and economic development, as well as environmental diversity (Ashton and Seetal, 2002). However, the world's, and more specifically the Orange River Catchment's, freshwater resources are under increasing pressure (cf. Chapter 1), leading to increased competition for, and conflicts over, the limited available freshwater resource (GWP, 2000), a situation exacerbated by natural climate variability and human-induced climate change. This problem is further aggravated by the shortcomings in the management of water resources.

Up until recently the conventional approaches to water resources management were characterised by clearly defined problems that society needed to solve (Pahl-Wostl *et al.*, 2005b). These include (Schulze, 2003e):

- Building dams and levees for flood control rather than floodplain relocation.
- Dam building and/or inter-catchment transfers to manage adequate supplies of water for society's and agriculture's needs.
- Solving water quality problems by chemical treatment downstream of waste production rather than upstream at the source.

Conventionally these problems were confined to sectoral management approaches while potential long term consequences were not taken into consideration (Pahl-Wostl *et al.*, 2005b). Sectoral approaches to water resources management have dominated in the past, which has led to fragmented and uncoordinated development and management of the resource (GWP, 2000).

There has been a growing awareness over the past three decades that water resources management requires an integrated, holistic approach (Rahaman and Varis, 2005). This approach, termed Integrated Water Resources Management (IWRM), has been the focus at numerous international conferences, e.g. the International Conference on Water and Environment (1992), the Second World Water Forum (2000), the International Conference on Freshwater (2001), the World Summit on Sustainable Development (2002) and the Third World Water Forum (2003), from where several fundamental principles underpinning IWRM have been developed. These principles recognise the following:

- Freshwater is a finite and vulnerable resource, essential to sustaining life, development and the environment.
- Water development and management should be based on a participatory approach.
- Women play a central part in the provision, management and safeguarding of water, particularly in lesser-developed countries.
- Water has an economic value and should be recognised as an economic good. These first four principles are also known as the Dublin Principles (GWP, 2000).
- Water is a tool for community development, peace building and preventative diplomacy (Rahaman and Varis, 2005).
- Water is the common symbol for humanity, social equity and justice. It is also viewed as a compelling link with the sacred, with nature and with our cultural heritage (Rahaman and Varis, 2005).
- Water is best managed at the level for which decisions and responsibilities are routinely exercised (Kabat *et al.*, 2003).
- The privatisation of selected water resources management functions should be promoted to the extent possible in the developed sectors. However, Kabat *et al.* (2003) warn that this can hinder, rather than promote, the development and well being of the poorer segments of society.

Efforts such as those emanating from the above-mentioned conferences and the acknowledgment of the resulting management principles have collectively led to breakthroughs that thrust IWRM onto the political agenda (Rahaman and Varis, 2005). This is evident in South Africa, where the government introduced revised legislation, *viz.* the National Water Act (NWA, 1998), in which the preamble recognises that:

- *The ultimate aim of water resource management is to achieve the sustainable use of water for the benefit of all users.*

- *The protection of the quality of water resources is necessary to ensure sustainability of the nation's water resources in the interests of all water users.*
- *There is a need for the integrated management of all aspects of water resources and, where appropriate, the management functions should be delegated to a regional or catchment level so as to enable everyone to participate.*

4.1 Integrated Water Resources Management

In a South African context, IWRM has been defined as (DWAF, 1998):

"*a philosophy, process and implementation strategy to achieve sustainable use of resources by all stakeholders at catchment, regional, national and international levels, while maintaining the characteristics and integrity of water resources at the catchment scale within agreed limits*".

An international definition given by the Global Water Partnership (GWP, 2000) views IWRM as:

"*a process which promotes the coordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems*".

However, as the above definitions illustrate, IWRM is not only about managing biophysical resources. It is also about reforming human systems to enable people to reap sustainable benefit from those resources (GWP, 2004). Therefore, the resource is considered in relation to its social and economic activities and functions (van Beek, 2009).

In order to achieve the major objectives of IWRM, the harmonisation of policies, institutions, regulatory frameworks, planning, operations, maintenance and design standards of numerous agencies and departments responsible for one or more aspects of water and related natural resources management is required (Kabat *et al.*, 2003). This approach should encompass various levels of integration (Burton, 2003; Kabat *et al.*, 2003; Schulze, 2003e; GWP, 2004), *viz*.:

- *Vertical integration*, which takes place across a range of political, legislative and management sectors, e.g. from the lowest water user to the top policy-makers.
- *Horizontal integration*, which implies collaboration and coordination among users and/or institutions at the same hierarchical level, e.g. cooperation for international rivers.
- *Interdisciplinary integration*, which involves all relevant disciplines, including socio-economic, engineering, hydrological, economic and ecological.
- *Functional integration*, which includes planning, regulation, design, operations, maintenance and monitoring.
- *Stakeholder integration*, which recognises the importance of the involvement of individuals, landowners and government agencies, in all aspects of water management and decision-making.

The complexities involved in the coordination of the above-mentioned integration are best managed by the trained staff of Catchment Management Agencies (CMAs) (Kabat *et al.*, 2003), In South Africa the National Water Act provides for the establishment of CMAs. The National Water Act delineates South Africa into 19 Water Management Areas (WMAs), each of which will, in time, be managed by a single CMA, representing the interests of different water users at the catchment level.

There are few countries in the world that have developed comprehensive national water management plans and strategies. In the absence of these, fragmented approaches by government agencies and other stakeholders make the implementation of IWRM difficult (Kabat *et al.*, 2003). Although the principles of IWRM are widely agreed upon among water resources managers, the ideology of IWRM is rarely accomplished (Kabat *et al.*, 2003; Biswas, 2004; Pahl-Wostl *et al.*, 2005b).

Identification of problems is a prerequisite to identification of solutions (Kabat *et al.*, 2003). Factors inhibiting the success of IWRM have been well documented (e.g.

Frost, 2001; Kabat *et al.*, 2003; Schulze, 2003e; Biswas, 2004; Pahl-Wostl *et al.*, 2005b). These include, *inter alia*:

- Sectoralism within and between the government departments and the fragmented nature of institutional structures (Frost, 2001; Schulze, 2003e; Newson, 2009).
- Water being a source of potential conflict not only between sectors, but also within a sector, and in particular with respect to upstream vs. downstream users and uses (Frost, 2001; Schulze, 2003e).
- Lack of audit and post-audit procedures, which embrace, *inter alia*, who is going to enforce and control progress in coping strategies, as well as who will critically evaluate the performance of actions during and after an extreme event (Schulze, 2003e).
- Vagueness of the concept of IWRM, of which Biswas (2004) gives a comprehensive critique.
- Uncertainty in management processes, system understanding and modelling knowledge (Pahl-Wostl *et al.*, 2005b).
- Lack of indicators or criteria for indicating implementation success (Walmsley *et al.*, 2001; Pahl-Wostl *et al.*, 2005b).
- Lack of evidence of successful implementation of IWRM (Schulze, 2003e; Biswas, 2004; Lankford and Cour, 2005; Pahl-Wostl *et al.*, 2005b).

All these factors limit the success of implementing the IWRM approach. In order to address the above-mentioned barriers, political institutions need to rethink fundamental assumptions and paradigms underpinning current management approaches. The challenges for IWRM can be summarised as follows (Pahl-Wostl, 2002):

- Expand traditional methods of IWRM in order to integrate the human dimension.
- Adopt more adaptive and flexible management policies which can account for change and uncertainty, particularly in light of climate change.
- Bridge the science-policy gap by defining a new role for science as an active participant in polycentric policy processes.

- Develop new concepts and methods for public and stakeholder participation in multi-scale integrated assessment processes and modelling.

To deal with these challenges, IWRM must be able to respond to changes in the natural and social environment and to anticipate the uncertainties associated with these changes. Pahl-Wostl *et al.* (2005a) advocate *adaptive* water resources management (AWRM) as an essential and timely extension of the IWRM approach.

4.2 Adaptive Water Resources Management

Adaptive management is not a new concept. To the contrary, it is as old as evolution. Over the ages, species that did not adapt to changing circumstances eventually became extinct (Thomas, 2006). Formally, the idea of adaptive management was introduced into natural resources management during the late 1970s, and has existed for quite some time (Holling, 1978; Walters, 1986). The concept of adaptive management has been designed primarily to deal with uncertainties, recognising that the ability to predict future key drivers and issues, as well as system behaviour and responses to these drivers and issues, is inherently limited (Pahl-Wostl *et al.*, 2005a). Consequently, the management of natural resources should be based on incremental, experiential learning and decision-making, supported by active monitoring of, and feedback from, the effects of outcomes and decisions (Holling, 1978; Walters, 1986; MacKay *et al.*, 2003).

Nyberg (1998) defines adaptive management as a systematic process for continually improving management policies and practices by learning from the outcomes of operational programmes. In its most effective form, adaptive management employs management programmes that are designed to experimentally compare selected policies or practices, by evaluating alternative hypotheses about the system being managed (Nyberg, 1998), e.g. evaluation of climate change impacts scenarios.

This inherently ordered process of learning and adapting can be applied to guide those responsible for the protection, control, management and allocation of natural resources, such as water (MacKay *et al.*, 2003), with the goal being to increase the adaptive capacity (cf. Section 3.2) of the water system (Pahl-Wostl, 2004). The process is considered as "learning-by-doing" and provides a way of ensuring proactivity even in the face of uncertainty (MacKay *et al.*, 2003). Therefore, adaptive management could be seen as a process that is both anticipatory as well as adaptive.

4.2.1 Elements of an adaptive management approach

Various models have been proposed for adaptive management, ranging from simple to relatively elaborate (e.g. Nyberg, 1998; MacKay *et al.*, 2003; Levine, 2004; Pahl-Wostl *et al.*, 2005b; Tracy, 2006). Each of these describes adaptive management as a continually repeated cycle of an organised sequence of activities. Simplified, an adaptive management framework can be described as being a six-step process (Nyberg, 1998), as depicted in Figure 4.1.

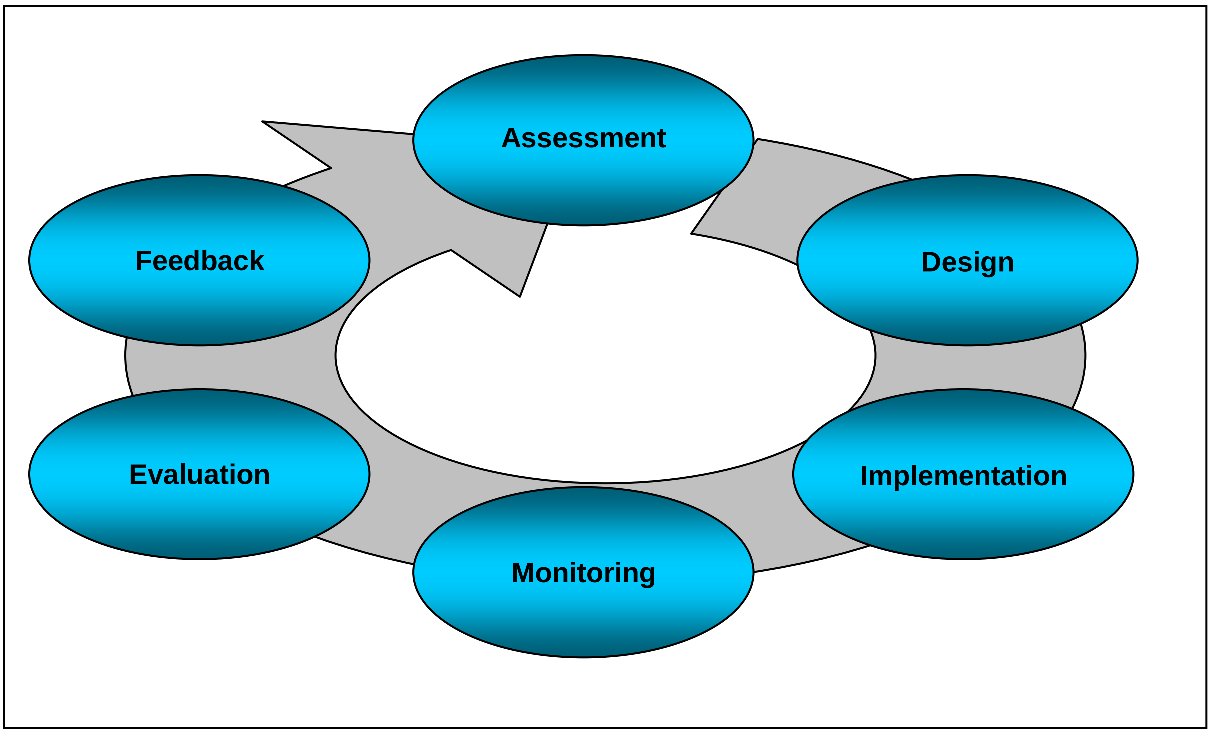

Figure 4.1 Simplified adaptive management framework (adapted from Nyberg, 1998)

Many researchers have emphasised the importance of stakeholder involvement throughout the process for improving the quality and perception of decisions made at each step (e.g. Holling, 1995; Lescuyer, 2002; Pahl-Wostl *et al.*, 2005a; Möllenkamp and Kastens, 2009). This is particularly important in Step 1 (problem assessment), where relevant stakeholders, including water users, managers and scientists, define the scope of the management problem (Murray and Marmorek, 2003). Making use of the best available information about the system, management objectives can be defined and key indicators for each objective determined (Murray and Marmorek, 2003; Tracy, 2006). Thereafter comes the building of scenarios to represent or illustrate potential outcomes of alternative management actions (MacKay *et al.*, 2003; Murray and Marmorek, 2003).

The second step (design) involves designing a management plan and monitoring programme that will provide reliable feedback about the effectiveness of the chosen actions (Murray and Marmorek, 2003). In South Africa, the National Water Act provides for the development of catchment management strategies, which will specify the timeframes for achieving objectives, actions to be taken and responsibilities of the various parties, including water management institutions as well as water users and stakeholders (MacKay *et al.*, 2003).

The third step comprises implementation of the restoration plan. It is critically important that implementers understand the logic of the experimental design. All aspects of the plan must be adhered to, including prescribed locations and timing of restoration actions. Deviations from the plan may occur for unavoidable operational reasons. If so, these deviations, and their rationale, must be clearly documented (Murray and Marmorek, 2003).

Indicators are the ideal means by which progress towards a goal can be monitored (Walmsley *et al.*, 2001). In Step 4, indicators are monitored to determine how effective actions are in meeting management objectives (Murray and Marmorek, 2003). Furthermore, monitoring prolongs community interest/involvement and keeps information flowing across the centre of the stakeholder platform (Newson, 2009). Through monitoring and evaluation (Step 5, where the actual outcomes are compared to the outcomes predicted in Step 1 and the reasons underlying any differences are interpreted), knowledge is gained about the resources being managed and how these resources respond to various actions, to identify if the strategy needs to be adapted in order to achieve the predefined objectives (MacKay *et al.*, 2003; Murray and Marmorek, 2003).

The feedback step is the final step before the next iteration in the adaptive management process, the purpose of which is to use the acquired knowledge on the behaviour of the system to guide the next cycle of the adaptive management process (Tracy, 2006). Therefore, one begins the cycle with deeper knowledge and understanding than before and, hence, with an ability to make better decisions, design better and more detailed action plans, and institute better monitoring programmes (MacKay *et al.*, 2003). However, in order to fully reap the benefits of an adaptive management process, the feedback step must go beyond merely providing an argument for changing management actions; it must actually force changes in management actions when justified by the results of the evaluation step (Tracy, 2006).

4.2.2 Barriers to adaptive management

Despite the appeal of adaptive management, as with IWRM, several barriers to its successful implementation have been identified. Reflecting on many years of experience in attempting to apply adaptive management, Walters (1997) identified the following to be the most common barriers:

- Protracted modelling exercises, based on the presumption that detailed modelling can be substituted for field experimentation.
- Effective experiments in adaptive management often seen as being too costly or risky.
- Strong opposition to experimental policies by stakeholders protecting various self-interests.
- Fundamental conflicts in values among diverse stakeholders.

Other barriers to implementation include, *inter alia*:

- Lack of “buy-in” from politicians and bureaucrats, who are sceptical owing to the considerable time required and costly nature of adaptive management (Jiggins and Röling, 2002; Levine, 2004; Möllenkamp and Kastens, 2009).

- Monitoring, which is essential to well founded adaptive management, is seldom funded at the required level (Thomas, 2006).
- Lack of leadership and coordination (Levine, 2004).
- The term “adaptive management” is unclear owing to various interpretations and misinterpretations of its meaning (Nyberg, 1998).

4.2.3 Need for an adaptive management approach

There would be little need to develop new policies or methods if managers were dealing with stable and predictable ecological and social systems (Nyberg, 1998). However, most natural systems exhibit uncertainties in that they are variable, non-linear, complex, and inherently possess the potential for irreversible change (Lescuyer, 2002). Water managers, when planning for the future, somehow need to account for these various uncertainties, including:

- Inter- and intra-annual climate variability and its repercussions for water resources management (Kabat *et al.*, 2003 - cf. Chapter 1).
- Human impacts on the environment through global climate change, new technology, and a growing population (Nyberg, 1998 - cf. Chapter 2).
- Lack of knowledge about many aspects of the systems being managed, not only because trends occur over time, but also because the system elements and their interactions that generate those trends are not well understood (Pahl-Wostl *et al.*, 2005b - cf. Chapter 3).

Uncertainty is what drives adaptive management (Walters, 1986). Where high uncertainty and risk coexist, adaptive management can provide an effective path forward (Boesch *et al.*, 2006) by not allowing uncertainties to thwart socially timely action (Lee, 1993; cited by Newson, 2009). However, adaptive management will only be effective to the degree to which identified barriers are effectively overcome (Boesch *et al.*, 2006).

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This chapter has provided an overview of the current status of water resources management in South Africa and has introduced the concept of AWRM as a timely extension to current water resources management approaches, as suggested by the NeWater Project. By developing techniques for assessing projected impacts of climate change on hydro-climatic hazards, this study aims at facilitating AWRM by providing decision-makers with a tool with which to convert GCM climate scenarios into hydro-climatic hazard scenarios, the analyses of which can subsequently be used to make decisions and establish proactive policies to reduce future risks posed by a changing climate – by influencing either the hazard or vulnerability side of the risk equation (cf. Chapter 3). The following chapter describes the approaches adopted in this study to model the impacts of climate change on the Orange River Catchment's hydrological system.

5. METHODS: MODELLING IMPACTS OF CLIMATE CHANGE ON THE ORANGE RIVER CATCHMENT'S HYDROLOGICAL SYSTEM

Hydrological models are becoming increasingly important tools in addressing the consequences of climate change. However, as alluded to in Chapter 3, an issue and major source of uncertainty remains as to what renders a hydrological model appropriate for selection, in terms of its attributes, process representations and the manner by which the major state variables and outputs that are relevant to simulating responses to projected future climates are computed (Schulze, 2005d; Schulze, 2009b).

Schulze (2005d; 2009b) lists the following model requirements for effective climate change impacts studies on the hydrological system:

- The need to be able to model the dynamics of different streamflow generation mechanisms explicitly.
- The need to distinguish clearly between landscape-based and channel-based processes.
- The ability to model hillslope processes.
- The ability to model the different processes that may dominate in different climatic regimes.
- The ability to model different intensities of land management practices.
- The need for a daily time step, physical-conceptual, process-based and non-linear dynamic response model.

The major advantage of such models is that, due to their high level of process representation and physically-based boundary conditions, they may be applied confidently in extrapolations involving "what-if" scenarios associated with climate change and which are essential ingredients of AWRM (Schulze, 2009b).

The *ACRU* agrohydrological modelling system (Schulze, 1995; Schulze and Smithers, 2004 and updates), which has been, and is currently being, used extensively in IWRM and climate change impacts studies in southern Africa, was selected as the preferred simulation tool for this study.

5.1 Selection of the *ACRU* Modelling System

The *ACRU* agrohydrological modelling system was developed within the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal (formerly the Department of Agricultural Engineering at the University of Natal) in Pietermaritzburg. The theoretical background, concepts and capabilities of the *ACRU* model are detailed in *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System* by Schulze (1995). A summary of the concepts of the *ACRU* model and its water budget is presented below.

5.1.1 Concepts on which the model is based

The *ACRU* modelling system (Schulze, 1995) has been designed according to the modelling philosophies represented in Figures 5.1 and 5.2. It is a *daily time step, physical-conceptual* model, where variables (rather than optimised parameter values) are estimated from physically based characteristics of the catchment. *ACRU* is a *multi-purpose* model which integrates the various water budgeting and runoff generation components of the terrestrial hydrological system (Figure 5.1). Revolving around daily *multi-layer soil water budgeting*, the model has been developed essentially into a versatile total evaporation model (Figure 5.2), structured to be sensitive to dynamic climate and land cover factors – both of which are necessities for climate change impacts assessments (Schulze, 1995).

Importantly, *ACRU* can operate at multiple scales from being a point model or as a lumped small-catchments model, to large catchments or at national scale. When applying the model over large catchments or at national scale, where heterogeneous climates, land uses and soils render the lumped modelling approach less appropriate, *ACRU* operates as a distributed cell-type model. In distributed mode, individual subcatchments are identified, discretised and flows can take place from “exterior” through “interior” cells (subcatchments) according to a predetermined

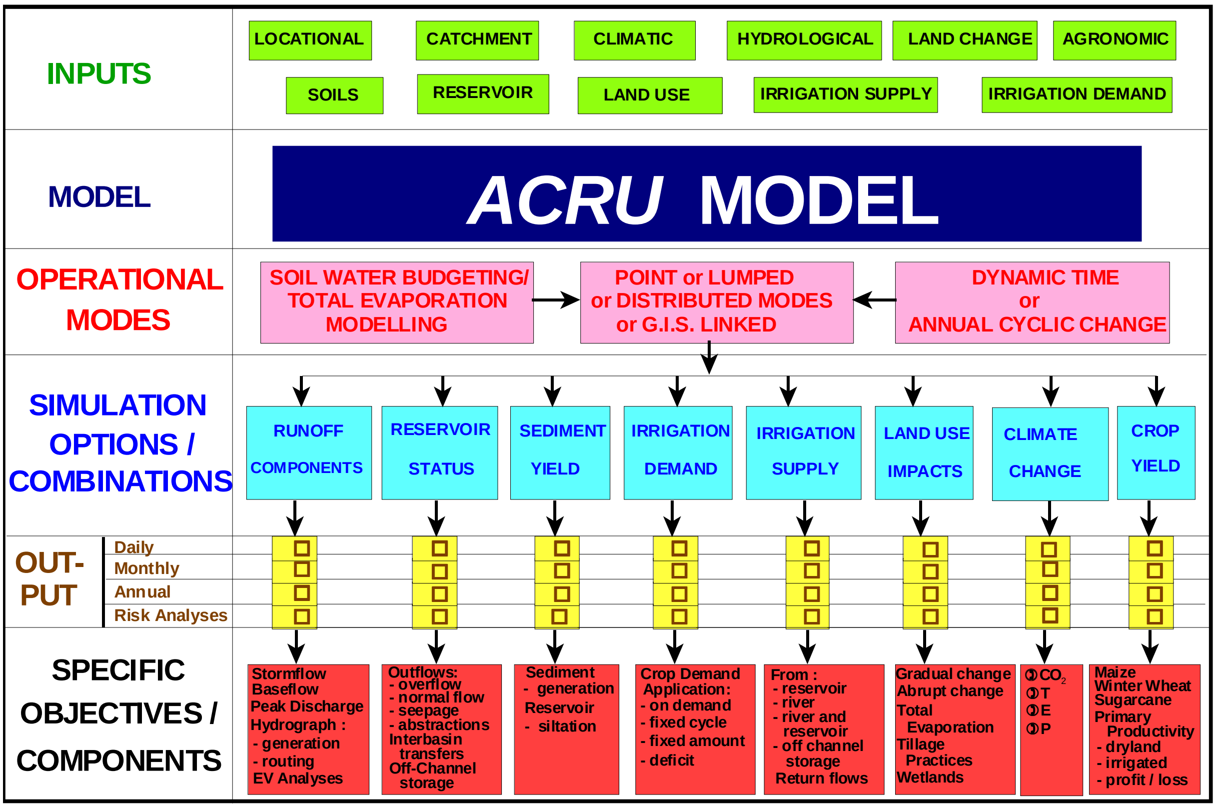

Figure 5.1 The *ACRU* agrohydrological modelling system: Concepts and linkages (after Schulze, 1995)

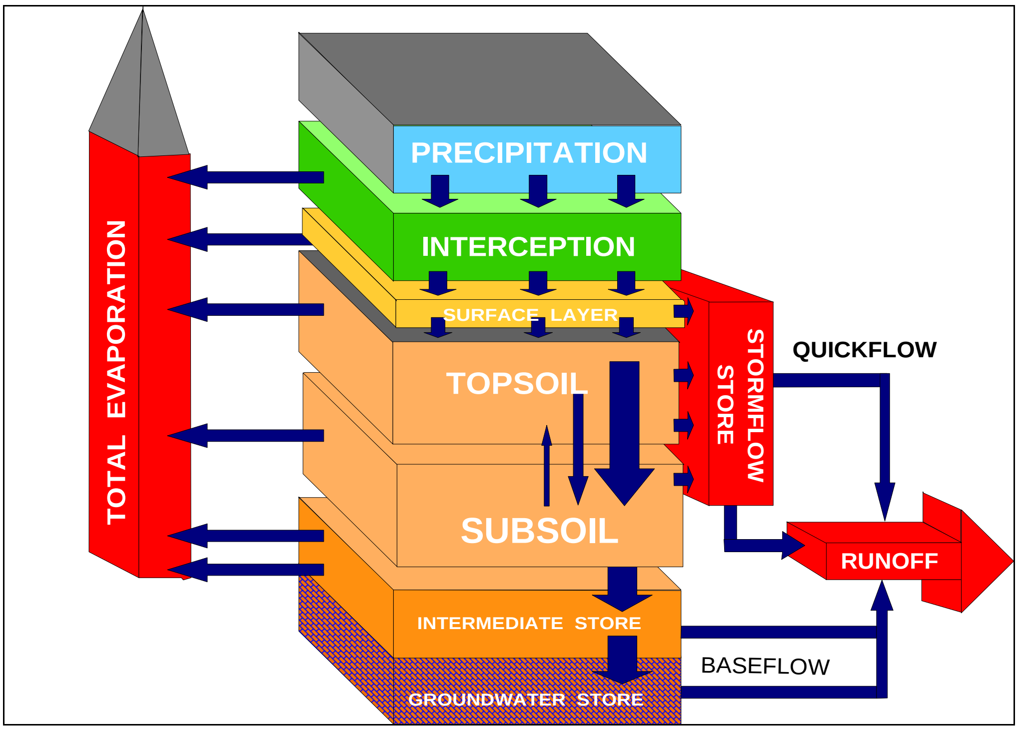

Figure 5.2 The *ACRU* agrohydrological modelling system: Schematic of its general structure (after Schulze, 1995)

configuration, with each subcatchment able to generate individually requested outputs, which may be different to those of other subcatchments or with different levels of input/information (Schulze, 1995).

Furthermore, the model includes a *dynamic input* option to facilitate modelling hydrological responses to climate or land use or management changes in a time series. A dynamic input file is then accessed each year of the simulation, with the new variable inputs to be used from that year onwards (Schulze, 1995).

The *ACRU* model has been linked to the Southern African National Quaternary and Quinary Catchments Databases (QCD and QnCD, respectively) for applications at a range of scales in South Africa, Lesotho and Swaziland for studies involving, *inter alia*, water resources assessments, design flood estimation, the calculation of low flows and/or the impacts of climate change.

5.1.2 Synopsis of the general structure of the *ACRU* model for water budgeting

The streamflow generation water balance of the effective rainfall, i.e. rainfall that is not abstracted as plant interception, comprises (Schulze, 1995; van Zyl and Lorentz, 2003):

- Rapid, event-based runoff (stormflow).
- Evapotranspiration losses from the soil.
- Slower baseflow from a groundwater store.

Stormflow is controlled by the magnitude of the effective rainfall and the antecedent soil water content to a specified depth in the soil profile. The stormflow depth generated by an event is estimated using an equation developed by the Soil Conservation Service (SCS) of the United States Department of Agriculture (USDA) that has been adapted South African conditions. Not all the stormflow generated from a rainfall event reaches the catchment outlet on the same day. Rather, stormflow is divided into quickflow (i.e. same day response) and delayed stormflow (cf. Figure 5.2), and is controlled by a release rate parameter (Schulze, 1995; van Zyl and Lorentz, 2003; Schulze, 2009b).

Rainfall that is not abstracted as plant interception or removed as stormflow, enters through the surface layers of the soil, where the water is moved up and down between the top- and subsoil horizons. These processes are based on the soil water retention at critical thresholds (e.g. field capacity), on soil texture and/or impeding layers, and the volumetric water content between horizons. Slow, unsaturated up- and downward soil water redistribution is also accounted for. The process of evapotranspiration occurs simultaneously from various soil horizons, and is driven by a reference potential evaporation, representing the atmospheric demand, which may be estimated by a number of methods. Furthermore, evapotranspiration is controlled by various vegetation parameters, soil water content and atmospheric demand (Schulze, 1995; van Zyl and Lorentz, 2003; Schulze, 2009b).

Baseflow is generated from excess water percolating through the bottom of the active root zone, into the intermediate (vadose) zone, and then into the groundwater stores. Baseflow is released from this store to the catchment outlet on a daily basis at an exponential rate of decay, dependant on the volume in storage and a decay rate constant (Schulze, 1995; van Zyl and Lorentz, 2003; Schulze, 2009b).

For more details on the above processes, including all equations, the reader is referred to Schulze (1995). More detailed explanations of the methodologies utilised for the calculation of the various hydro-climatic hazards assessed in this study are presented in the relevant sections of Chapter 7.

5.1.3 Suitability of the *ACRU* model as a tool for climate change impacts studies on hydrological processes and water resources in the Orange River Catchment

Not only does the *ACRU* modelling system meet many of the criteria/requirements outlined in the introduction to this chapter, but the generation of streamflow with the *ACRU* model has been verified against observed outputs from 44 catchments worldwide in 31 independent studies. Of the 44 catchments, 10 were international catchments in the USA, Germany, Swaziland, Zimbabwe and Eritrea, and with those verifications undertaken in nine of the 31 separate studies. The remainder of the verifications were performed on South African catchments. Specific design hydrology verifications have been undertaken in four separate studies at seven hydro-climatically diverse sets of catchments in the USA, and in five South African studies at three diverse hydro-climatic locations (Schulze, 2008b).

In addition to these verification studies, the *ACRU* model has been used extensively in decision-making in southern Africa and internationally, in water resources related research and applications in all four countries in which the Orange River Catchment exists, *viz*. Botswana, Lesotho, Namibia and South Africa; as well as in Mozambique, Swaziland, Canada, Chile, Germany and the USA (Schulze and Smithers, 2004).

For the reasons presented above, and despite several shortcomings (Schulze, 2005d), *ACRU* is believed to be a modelling system highly suitable for evaluating impacts of climate change on the hydrology and water resources of southern Africa and, hence, the Orange River Catchment.

5.2 Model Input

The erstwhile South African Department of Water Affairs and Forestry (DWAF; now DWA – the Department of Water Affairs, within the Ministry of Water and Environmental Affairs) has delineated South Africa, together with Swaziland and Lesotho, into 22 Primary Catchments, which are further disaggregated into Secondary, then Tertiary and finally, into 1 946 interlinked and hydrologically cascading Quaternary Catchments (QCs), as shown in Figure 5.3. This "fourth level" discretisation has, to date, constituted the most detailed level of operational catchment in the DWA for general planning purposes (Midgley *et al.*, 1994). As already alluded to in Section 5.1.1, the *ACRU* model is linked to the Southern African National Quaternary Catchments Database (QCD), which provides extensive and valuable input (in the form of rainfall, temperature-based reference evaporation, and soils attributes) into the model at the level of the QC.

5.2.1 The concept of Quinary Catchments

Schulze and Horan (2009) have shown that many fourth level Quaternary Catchments in southern Africa are physiographically too diverse for hydrological responses from them to be considered homogeneous. By applying Jenks' optimisation procedures available within the ArcGIS software, Schulze and Horan (2009) carried out a three-fold sub-delineation of Quaternaries into fifth level Quinary Catchments (the upper, middle and lower Quinaries of a QC), based on breaks in altitude (Figure 5.4). These Quinary Catchments were then reconfigured within the predetermined QC configuration, such that the outflow of the upper Quinary enters the middle Quinary, which in turn flows into the lower Quinary (Schulze and Horan, 2009). However, the outflow from the lower Quinary of a QC does not enter the upper Quinary of the next downstream QC, because that upper Quinary may be at a higher altitude than the lower Quinary of the immediate upstream QC (Schulze and Horan, 2009). Therefore, the outflow of the lower Quinary has been configured to rather enter the downstream QC at its exit (Schulze and Horan, 2009). A schematic of the flowpath configuration between Quinaries and Quaternaries is demonstrated in Figure 5.5.

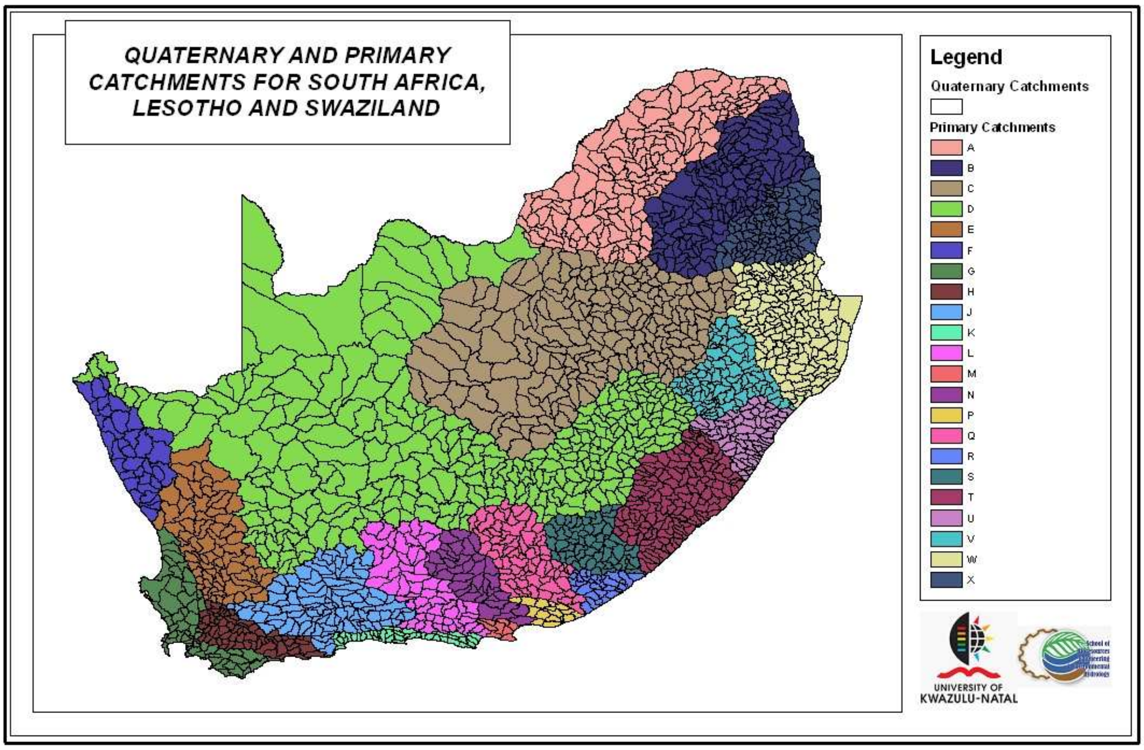

Figure 5.3 Quaternary and Primary Catchments covering South Africa, Lesotho and Swaziland, as delineated by the erstwhile Department of Water Affairs and Forestry (after Midgley *et al.*, 1994)

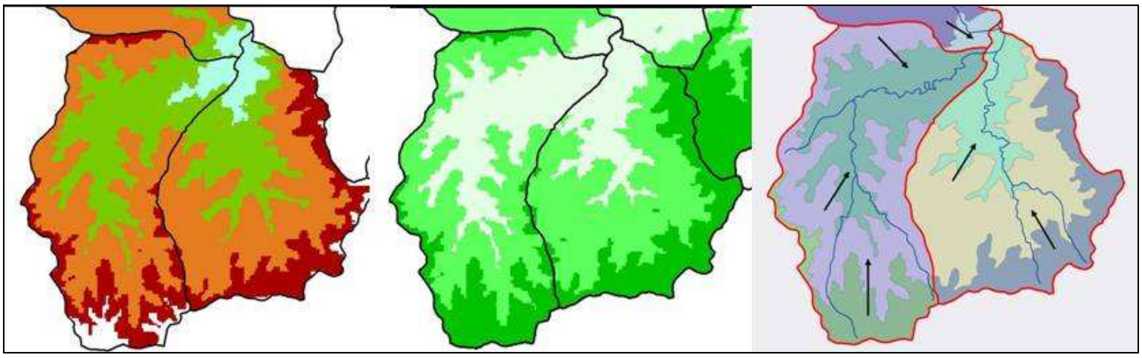

Figure 5.4 Sub-delineation of Quaternary Catchments (left) into three Quinary Catchments by natural breaks in altitude (middle), with flowpaths of water (right) (Schulze and Horan, 2009)

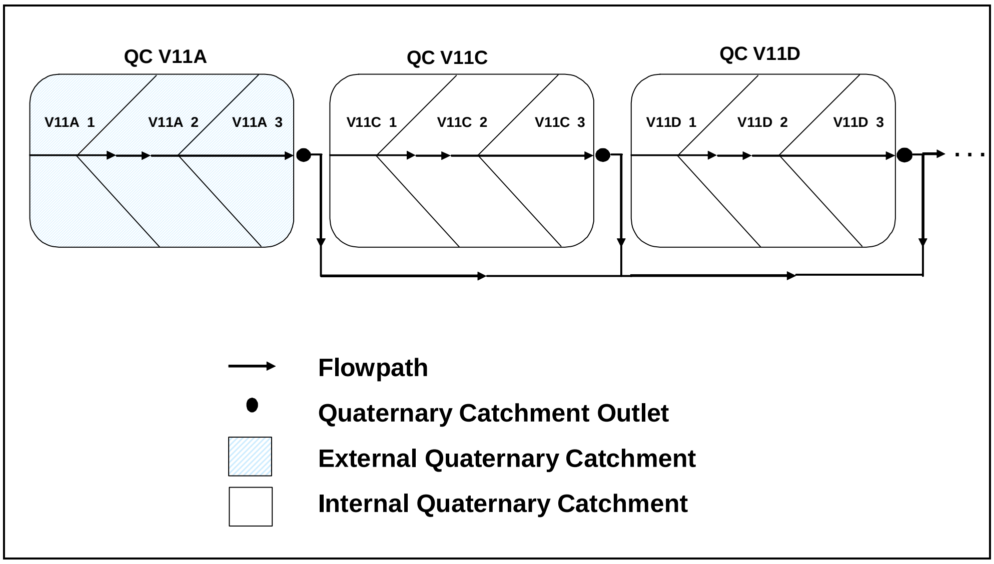

Figure 5.5 Example of flowpaths between Quinary and Quaternary Catchments in the Upper Thukela Catchment (Schulze and Horan, 2007)

The sub-delineation of Quaternary into Quinary Catchments has resulted in 5 838 hydrologically interlinked and cascading Quinary Catchments (Figure 5.6), which have been demonstrated to be considerably more homogeneous than the Quaternary Catchments (Schulze and Horan, 2009) and on a national and smaller scale are considered to be relatively homogeneous *hydrological response zones*, and have been shown to be so by Schulze and Horan (2007; 2009).

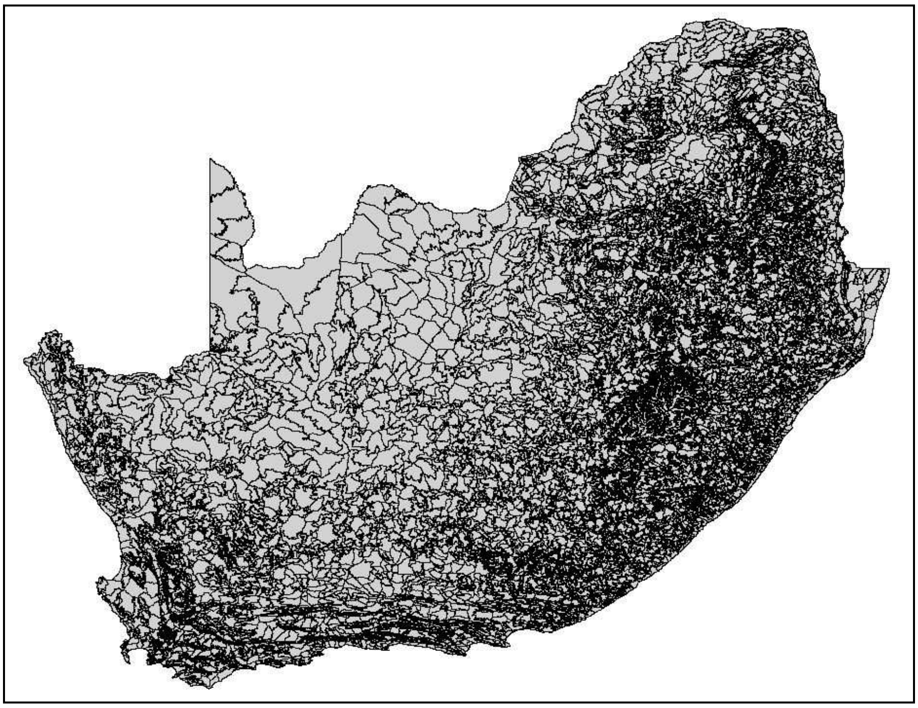

Figure 5.6 Delineation of South Africa, Lesotho and Swaziland into 5 838 hydrologically interlinked and cascading Quinary Catchments (Schulze and Horan, 2009)

5.2.2 From a Quaternary to Quinary Catchments Database

Following the delineation of the southern African countries of South Africa, Lesotho and Swaziland into hydrologically interlinked Quinary Catchments, the QCD needed to be expanded to form a new database, *viz*. the Southern African Quinary Catchments Database, QnCD (Schulze *et al.*, 2009a). The expansion of the QCD to the newly formed QnCD was achieved in collaboration with researchers from another climate change impacts study (Schulze *et al.*, 2009c), *viz*. Water Research Commission (WRC) Report No. 1562/1/09, as the QnCD was a vital component of that project as well. The remainder of this Section (5.2.2) is a summary of the above-mentioned WRC report's Chapter 6 (Schulze *et al.*, 2009a). The author of this thesis contributed to the development of the QnCD by:

- Disaggregating the QCD and reconfiguring the flowpaths for all 1 946 Quaternary Catchments (cf. Section 5.2.1) according to the rules determined by Schulze and Horan (2009);

- Calculating rainfall adjustment factors for the representative rainfall station of each Quinary Catchment for baseline and future scenarios (cf. Section 5.2.2.1 and Section 5.3.2); and
- Populating the QnCD with all climatic and catchment input parameters required by the *ACRU* model.

The following subsections are a description of the key climatic and catchment input into the QnCD, and the link to the *ACRU* model. The focus of the climatic input is primarily on baseline historical conditions, with only a brief description of the future climate input. More detail surrounding the preparation of climate inputs derived from climate change scenarios is provided in Section 5.3.

5.2.2.1 Daily rainfall input per Quinary Catchment

Rainfall is generally considered to be the most important input into any hydrological model. Methods of estimations of daily rainfall values for simulations under baseline and future climatic conditions are described below.

I: Estimation of daily rainfall values for simulations under baseline historical climatic conditions

As reported in Schulze *et al.* (2009a), a comprehensive rainfall database consisting of rainfall values from 12 153 daily rainfall stations in southern Africa has been compiled by Lynch (2004). From this database, a rainfall station had to be selected to represent the daily rainfall for each of the 5 838 Quinary Catchments (Schulze *et al.*, 2009a).

A similar exercise was carried out by Schulze *et al.* (2005b) at the scale of Quaternary Catchments, where Kunz's (2004) Daily Rainfall Extraction Utility was used in the selection of "driver" stations (representative rainfall stations) for each Quaternary Catchment (Schulze *et al.*, 2009a). The 1 244 driver stations identified in that study were assumed to represent the respective Quinary Catchments derived from each of the 1 946 Quaternary Catchments (Schulze *et al.*, 2009a). Owing to rainfall record reliability concerns in the highlands of Lesotho, the Western Cape fold mountains region and along the remote northeastern border of South Africa with Mozambique, one rainfall station often had to "drive" the hydrology of numerous Quaternary Catchments (Schulze *et al.*, 2009a).

Schulze *et al.* (2009a) subsequently changed the driver stations for 11 Quaternary Catchments in order to improve the representation of rainfall in those catchments, which reduced the total number of unique driver stations from 1 244 to 1 240. Based on the assumption made above, these 1 240 stations were then used to generate 50 years (1950 - 1999) of daily rainfall for each of the 5 838 Quinary Catchments (Schulze *et al.*, 2009a).

In order to render each Quinary's driver station's daily rainfall to be more representative of the respective Quinary Catchment's rainfall, adjustments to the driver station's records were required (Schulze *et al.*, 2009a). Monthly adjustment factors were derived by calculating the ratios of the spatial averages of median rainfall for each month within a Quinary Catchment – derived from Lynch's (2004) one arc minute grid of median monthly rainfalls for southern Africa – to the median monthly rainfall of the respective driver station (Schulze *et al.*, 2009a). These 12 multiplicative, monthly adjustment factors were then applied within the *ACRU* model to generate a unique, 50 year, daily rainfall record for each of the 5 838 Quinary Catchments (Schulze *et al.*, 2009a).

II: Estimations of daily rainfall values for simulations with GCM-derived present and future climate scenarios

The Climate Systems Analysis Group (CSAG) at the University of Cape Town empirically downscaled output from five General Circulation Models (GCMs) to rainfall station level for 2 642 stations (Schulze *et al.*, 2009a). The downscaled data for each station consisted of daily rainfall values for a "present" climate scenario (1971 - 1990), as well as daily values for an "intermediate future" climate (2046 - 2065) and a more "distant future" climate (2081 - 2100) (Schulze *et al.*, 2009a).

The downscaling was trained using observed daily rainfall data from the above-mentioned 2 642 stations using so-called Self-Organising Maps (SOMs) (Hewitson and Crane, 2006). SOMs are used to characterise the state of the atmosphere on a localised domain surrounding each of the above-mentioned rainfall stations on the basis of NCEP 6-hourly reanalysis data (Hewitson and Crane, 2006). A probability density function (PDF) of observed rainfall is derived for each typical large-scale daily atmospheric circulation (Hewitson and Crane, 2006). For each day in the respective GCM's time-series, the data are mapped to the NCEP SOMs for the respective rainfall station, allowing for a daily rainfall value to be selected at random from the associated precipitation PDF (Hewitson and Crane, 2006).

Schulze *et al.* (2009a) adopted a similar approach for the climate change scenarios as for the baseline scenarios whereby suitable rainfall driver stations were identified from the above-mentioned 2 642 stations for which future climate scenarios were available. Following stringent quality controls, Schulze *et al.* (2009a) identified a total of 1 061 driver stations, which – as was the case for the baseline historical climate – were adjusted according to the one arc minute rainfall grids, prepared by Lynch (2004). This adjustment allowed for better representation of the rainfall of each Quinary Catchment, and resulted in the development of a unique representative rainfall record from the GCMs for each Quinary (Schulze *et al.*, 2009a).

5.2.2.2 Daily temperature input per Quinary Catchment

Hydrological models such as *ACRU* utilise, *inter alia*, inputs of rainfall and evaporation data in order to calculate runoff. Algorithms have been developed for southern Africa that use daily maximum and minimum temperature values in order to estimate solar radiation, vapour pressure deficit and, in turn, potential evaporation (Schulze *et al.*, 2009a). A summary of the estimations of daily maximum and minimum temperature values, as performed by Schulze *et al.* (2009a), for simulations under baseline historical, and GCM-derived present and future climatic conditions, is provided below.

I: Estimation of daily values of maximum and minimum temperatures for simulations under baseline historical climatic conditions

Schulze and Maharaj (2004) developed a one arc minute gridded database of daily maximum and minimum temperatures covering South Africa, Lesotho and Swaziland, enabling the generation of a 50 year historical time series (1950-1999) of daily maximum and minimum temperatures for any of the 429 700 grid points covering the region (Schulze *et al.*, 2009a). Using this gridded temperature database Schulze *at al.* (2009a) selected representative grid points for each of the 5 838 Quinary Catchments covering the study area using a selection algorithm based on the distance between the grid points and the Quinary centroids, together with the difference in the altitudes of the grid points relative to the mean catchment altitude (Schulze *et al.*, 2009a).

With the use of temperature-based algorithms developed by Schulze and Chapman (2008a; 2008b), Schulze *et al.* (2009a) used the resulting 50 year series of daily maximum and minimum temperatures for each Quinary Catchment to generate daily estimates of solar radiation and vapour pressure deficit, details of which are described in Schulze *et al.* (2009a). From these, daily values of reference potential evaporation as well as reference crop evaporation could be computed (Schulze *et al.*, 2009a), as described in Section 5.2.2.3.

II: Estimation of daily values of maximum and minimum temperatures for simulations with GCM-derived present and future climate scenarios

The CSAG empirically downscaled output from the five GCMs used in this study to temperature station level for 404 unique locations (Schulze *et al.*, 2009a). The downscaled values for each station location consisted of daily maximum and minimum temperature values for a “present” climate scenario (1971 - 1990), an “intermediate future” climate (2046 - 2065) and a more “distant future” climate (2081 - 2100) (Schulze *et al.*, 2009a). Based on the methodology developed by Schulze and Maharaj (2004), Schulze *et al.* (2009a) selected two temperature stations to represent daily maximum and minimum temperatures in each of the Quinary Catchments using a similar selection algorithm to that developed for selecting representative grid points for the baseline scenarios. After adjusting each of the selected station's records to account for differences in altitude (relative to the mean catchment altitude) a weighted average of the adjusted temperatures from the two stations was then calculated to represent temperatures in each of the 5 838 Quinary Catchments (Schulze *et al.*, 2009a).

5.2.2.3 Estimation of daily values of reference crop evaporation per Quinary Catchment

Methods of estimating potential evapotranspiration (E_p) range from complex physically-based equations to relatively simple surrogates based on single variables such as temperature (Schulze *et al.*, 2009a). The physically-based FAO (1992) version of the Penman-Monteith equation (Penman, 1948; Monteith, 1981) has now become the *de facto* international standard of what is termed reference crop evaporation, against which other methods must be adjusted appropriately (Schulze *et al.*, 2009a).

I: Estimation of daily values of reference crop evaporation for simulations under baseline historical climatic conditions

As reported in more detail by Schulze *et al.* (2009a), the estimates of the Penman-Monteith equation used in the QnCD are based on daily maximum and minimum temperatures. As a result, Schulze *et al.* (2009a) utilised 50 years of one arc minute, gridded, daily temperatures over southern Africa, based on research by Schulze and Maharaj (2004), in order to generate daily values of solar radiation, saturated vapour pressures and vapour pressure deficits, all of which are components of the Penman-Monteith equation.

The original form of the Penman-Monteith equation (Monteith, 1981) may be written as follows (Schulze *et al.*, 2009a):

$$\lambda ET_o = \frac{\Delta(R_n - G) + \rho c_p (e_a - e_d)/r_a}{\Delta + \gamma(1 + r_c / r_a)} \qquad (5.1)$$

where

λET_o = latent heat influx of evaporation ($kJ.m^{-2}.s^{-1}$),
R_n = net radiation flux at surface ($kJ.m^{-2}.s^{-1}$),
G = soil heat flux ($kJ.m^{-2}.s^{-1}$),
ρ = atmospheric density ($kg.m^{-3}$),
c_p = specific heat moist air ($kJ.kg^{-1}.°C^{-1}$),
$(e_a - e_d)$ = vapour pressure deficit (kPa),
r_c = crop canopy resistance ($s.m^{-1}$),
r_a = aerodynamic resistance ($s.m^{-1}$),
Δ = slope of the vapour pressure curve ($kPa.°C^{-1}$),
γ = psychrometric constant ($kPa.°C^{-1}$), and
λ = latent heat of vaporisation ($MJ.kg^{-1}$).

Adapting the above equation according to derivations and formulae given in FAO (1992), the above equation may be simplified to the following formula (Schulze *et al.*, 2009a):

$$E_{rpm} = \frac{0.408\Delta.R_n + \gamma \frac{900}{T_{xd} + 273} u_2 (e_a - e_d)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (5.2)$$

where

E_{rpm} = reference crop evaporation ($mm.day^{-1}$),
R_n = net radiation at the crop surface ($MJ.m^{-2}.day^{-1}$),
T_{xd} = average daily air temperature (°C) at screen hei ght, and
u_2 = daily mean wind-speed at 2 m height ($m.s^{-1}$), defaulted (in the absence of measurements) to 1.6 $m.s^{-1}$,

with the other variables defined as above.

A combination of the simplifications of FAO (1992) derived equations and empirical expressions developed specifically from southern African research is then used to formulate T_{xd}, Δ, γ, R_n,, e_d and e_a (Schulze et al., 2009a). Thus:

T_{xd} = $(T_{mxd} + T_{mnd}) / 2$, is the mean daily air temperature (°C), with (5.3)

T_{mxd} = daily maximum temperature (°C), derived by Schulze and Maharaj (2004),

T_{mnd} = daily minimum temperature (°C), from Schulze and Maharaj (2004),

e_a = saturated vapour pressure (kPa), which according to Tetens (1930), is

= $0.6108 \exp[(17.27 \cdot T_{xd})/(T_{xd} + 237.3)]$, (5.4)

e_d = actual vapour pressure (kPa), derived for South Africa by techniques developed by Schulze and Chapman (2008b),

Δ = delta, i.e. slope of vapour pressure curve (kPa.°C^{-1})

= $4098[0.6108 \exp\{(17.27 \cdot T_{xd})/(T_{xd} + 237.3)\}]/(T_{xd} + 237.3)^2$, (5.5)

γ = psychrometric "constant" (kPa.°C^{-1})

= $0.665 / (10^3 P_a)$, with (5.6)

P_a = atmospheric pressure (kPa), determined from altitude, *viz*.

= $101.3[(293 - 0.065z) / 293]^{5.26}$, with (5.7)

z = altitude (m) above mean sea level,

R_n = $R_{sn} - R_{lw}$, with (5.8)

R_{sn} = net shortwave (solar) radiation (MJ.m^{-2}.day^{-1}), with albedo of short grass assumed to be 0.23,

= $(1 - 0.23) R_s$, and (5.9)

R_{lw} = net longwave (solar) radiation (MJ.m^{-2}.day^{-1})

= $0.5(4.903/10^9)[(T_{mxd} + 273.16)^4 + (T_{mnd} + 273.16)^4]$
$(0.34 – 0.14e_d^{0.5})[1.35R_s/(R_a (0.75 + (2z/10^5)))]$, and (5.10)

R_s = $0.75 R_a(1 - 1/T_{ra}^{2.5})[1 - \exp(- bT_{ra}^c)]$, based on research by Schulze and Chapman (2008a), with (5.11)

R_a = extraterrestrial solar radiation, from standard formulations (Schulze and Chapman, 2008a),

T_{ra} = $T_{mxd} - T_{mnd}$, is the diurnal temperature range (°C), and (5.12)

b, c = empirically derived constants, derived by Schulze and Chapman (2008a), which govern the depletion of the solar beam due to cloudiness and rainfall.

The 50 year daily maximum and minimum temperature series generated at each of the representative points that were selected for daily temperature estimates within each Quinary Catchment (cf. Section 5.2.2.2) were then input into the above equations (Schulze *et al.*, 2009a). This enabled the estimation of 50 years of daily reference crop evaporation by the Penman-Monteith technique for each Quinary Catchment (Schulze *et al.*, 2009a).

II: Estimations of daily values of reference crop evaporation for simulations with GCM-derived present and future climate scenarios

As described in more detail in Section 5.3, Schulze *et al.* (2009a) generated a 20 year representative series of daily maximum and minimum temperatures for each Quinary Catchment and for 15 scenarios (three climate scenarios for each of the five GCMs). Each of these data series then served as input into the temperature-based equations and approaches described above to produce equivalent 20 year series of daily reference crop evaporation for each Quinary Catchment (Schulze *et al.*, 2009a).

5.2.2.4 Soils information

As mentioned in Section 5.1.1, the *ACRU* model (Schulze, 1995 and updates) revolves around multi-layer soil water budgeting and therefore requires soils information as input. Being a threshold-based model, *ACRU* needs input values on the following soils variables (Schulze *et al.*, 2009a):

- Thicknesses (m) of the topsoil and subsoil.
- Soil water contents ($m.m^{-1}$) at (1) saturation (porosity), (2) drained upper limit (also commonly referred to as field capacity), and (3) 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.
- Erodibility of the soil (Schulze *et al.*, 2009a).

Values of the above variables have been derived by Schulze and Horan (2008) who interrogated the soils database from the Institute for Soil, Climate and Water (SIRI, 1987 and updates) by applying the AUTOSOILS decision support tool (Pike and

Schulze, 1995 and updates) to each of the soil mapping units (Land Types) that cover South Africa (Schulze *et al.*, 2009a). By intersecting the Land Type map with the Quinary Catchment boundaries, representative Quinary Catchment values for each of the hydrological soil parameters required by the *ACRU* model were determined by area-weighting (Schulze *et al.*, 2009a).

5.2.2.5 Baseline land cover information

It is reported in Schulze *et al.* (2009a) that in order to assess impacts of land use – or of climate change – on hydrological responses, a baseline land cover is required as a reference against which to evaluate the impacts. Acocks (1988) delineated 70 Veld Types covering South Africa, Lesotho and Swaziland, which have become the recognised baseline land cover for application in hydrological impacts studies (Schulze *et al.*, 2009a).

Monthly values of hydrological attributes, given in Schulze (2004; 2008a), were assigned to each of the 70 Acocks Veld Types and were incorporated into the QnCD (Schulze *et al.*, 2009a). These attributes are (Schulze *et al.*, 2009a):

- Water use coefficient (K_{cm}).
- Interception loss per rain day (I_l).
- Fraction of roots in the topsoil (R_A).
- Coefficient of infiltrability (*c*) – dependent on rainfall intensity estimates.
- Soil surface cover by litter ($C_{s\%}$) – an index of suppression of soil water evaporation by a litter/mulch layer.

The spatially most dominant Veld Type within each Quinary Catchment was then selected as the representative baseline land cover for that respective catchment (Schulze *et al.*, 2009a).

5.3 Representation of Regional Climate Change Scenarios for Catchment Level Hydrological Impacts Assessments

The future representations of daily climate were obtained from the Climate Systems Analysis Group (CSAG) at the University of Cape Town (Lumsden *et al.*, 2009). These values, i.e. daily rainfall, as well as daily minimum and maximum temperatures, were provided at various point locations throughout southern Africa (Lumsden *et al.*, 2009). This section describes the techniques developed in order to apply the point scale climate scenarios in catchment scale hydrological assessments. As was the case for the development of the QnCD (Section 5.2), the representation of the regional climate change scenarios was achieved in collaboration with researchers of WRC Report No. 1562/1/09 (Schulze *et al.*, 2009c), because these scenarios also formed a significant component of that project. Sections 5.3.1 to 5.3.3, therefore, represent a summary of the above-mentioned WRC report's Chapter 8 by Lumsden *et al.* (2009), with the methodology used to represent point scale scenarios of rainfall at the scale of Quinary Catchments (Section 5.3.2) having been contributed directly by the author of this thesis.

5.3.1 Description of climate change scenarios

The climate change scenarios used in this study were produced by five GCMs that were applied in the IPCC's (2007b) Fourth Assessment Report (Lumsden *et al.*, 2009), details of which are provided in Table 5.1. All of the future global climate scenarios were based on the assumption that efforts to reduce global greenhouse gas emissions during this century would be relatively ineffective (Lumsden *et al.*, 2009), i.e. the A2 emissions scenario defined by the IPCC SRES (Nakićenović *et al.*, 2000).

CSAG applied empirical downscaling (cf. Section 2.3.2) to the GCM simulation output using relationships developed between observed large-scale and local-scale climate data (Hewitson and Crane, 2006; Lumsden *et al.*, 2009). This enabled the generation of point-scale climate change scenarios at the locations of the climate stations used in the empirical downscaling process (Lumsden *et al.*, 2009). Scenarios of daily rainfall were produced at 2 642 southern African stations (Figure 5.7), while daily maximum and minimum temperature scenarios were produced at 440 and 427 stations, respectively (Lumsden *et al.*, 2009), which are depicted in Figure 5.8. Evident in Figures 5.7 and 5.8 is the relative paucity of climate stations over Lesotho and Swaziland. Although this is of concern in climate change studies it reflects the reality of poor data availability in those countries (Lumsden *et al.*, 2009).

Table 5.1 Information on GCMs, the global climate change scenarios of which were empirically downscaled by CSAG to point scale for application in this project (Lumsden *et al.*, 2009)

Institute	GCM
Canadian Center for Climate Modelling and Analysis (CCCma), Canada	**Name:** CGCM3.1(T47) **First published:** 2005 **Website:** http://www.cccma.bc.ec.gc.ca/models/cgcm3.shtml
Meteo-France / Centre National de Recherches Meteorologiques (CNRM), France	**Name:** CNRM-CM3 **First published:** 2004 **Website:** http://www.cnrm.meteo.fr/scenario2004/indexenglish.html
Max Planck Institute for Meteorology (MPI-M), Germany	**Name:** ECHAM5/MPI-OM **First published:** 2005 **Website:** http://www.mpimet.mpg.de/en/wissenschaft/modelle.html
NASA / Goddard Institute for Space Studies (GISS), USA	**Name:** GISS-ER **First published:** 2004 **Website:** http://www.giss.nasa.gov/tools/modelE
Institut Pierre Simon Laplace (IPSL), France	**Name:** IPSL-CM4 **First published:** 2005 **Website:** http://mc2.ipsl.jussieu.fr/simules.html

As reported by Lumsden *et al.* (2009), regional climate change scenarios were developed for a "present" climate (1961 - 2000), an "intermediate future" climate (2046 - 2065) and a more "distant future" climate (2081 - 2100), of which the latter two time periods were defined by the IPCC.

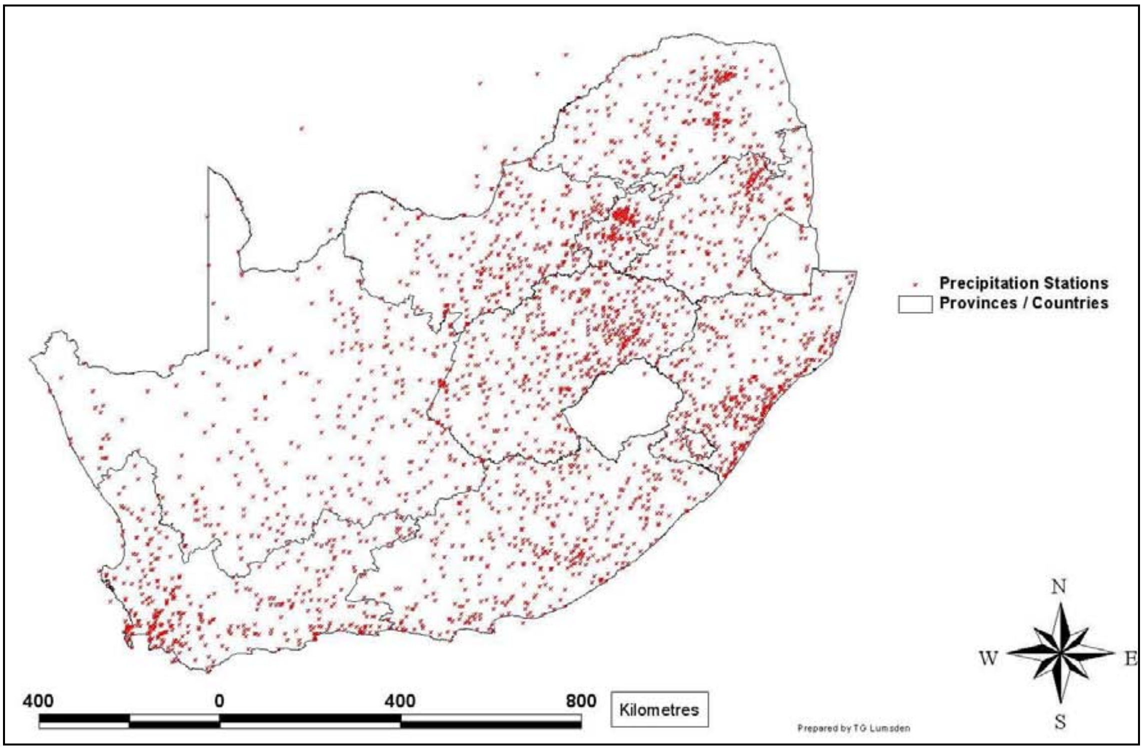

Figure 5.7 Climate stations for which point scale climate change scenarios for daily rainfall were developed (Lumsden *et al.*, 2009)

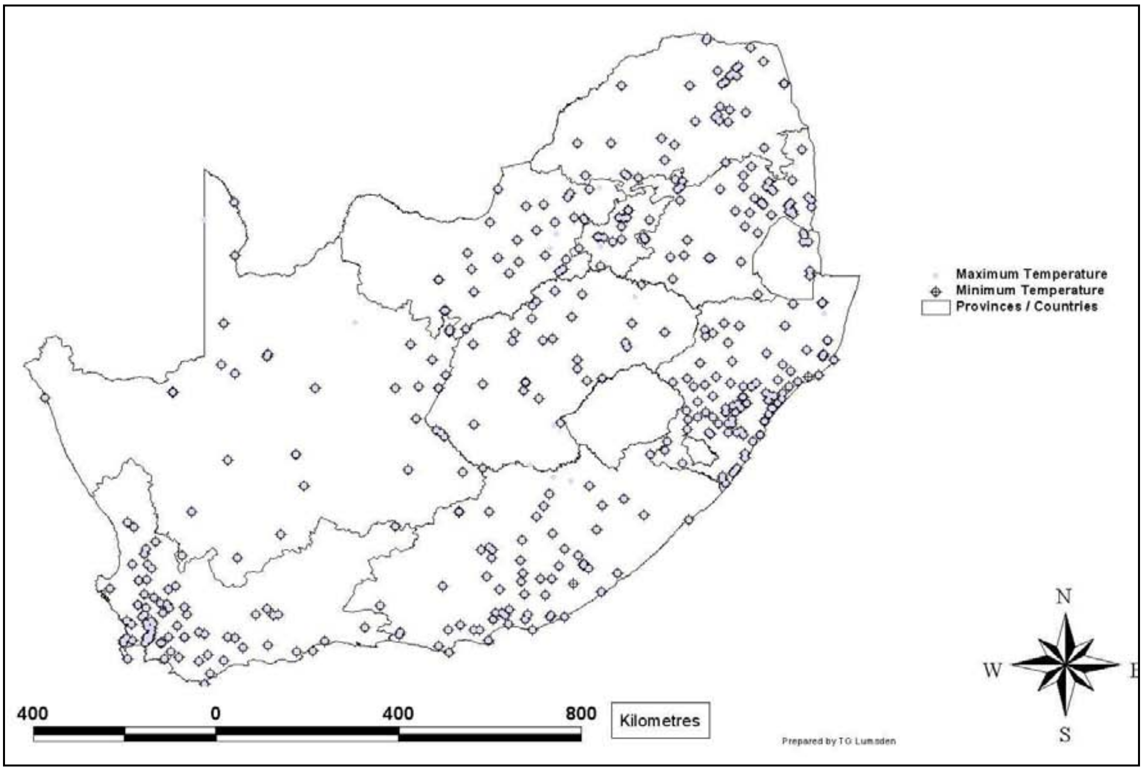

Figure 5.8 Climate stations for which point scale climate change scenarios for daily temperatures were developed (Lumsden *et al.*, 2009)

In order to facilitate comparisons between present and future climate scenarios only 20 of the 40 available years for the present climate scenario were used in order to be consistent with the 20 year periods available for the intermediate future and more distant future climate scenarios (Lumsden *et al.*, 2009). The period 1971 - 1990 was selected to represent the present climate, with the period 1961 - 1980 not considered due to the long time interval (85 years) between the present climate and intermediate climate, relative to the shorter interval (35 years) between the intermediate future climate and the distant future climate (Lumsden *et al.*, 2009). 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). The periods considered in comparative analyses in this study were therefore (Lumsden *et al.*, 2009):

- Present climate: **1971-1990**
- Intermediate future climate: **2046-2065**
- Distant future climate: **2081-2100**

5.3.2 Methodology used 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 by the author of this thesis using the same “driver” station approach adopted for baseline historical conditions (cf. Section 5.2.2.1) (Lumsden *et al.*, 2009). Of the 2 642 rainfall for which downscaled climate scenarios existed 1 023 had previously been selected to represent baseline conditions (Lumsden *et al.*, 2009). These driver stations were used to represent future climatic conditions in 4 863 Quinary Catchments out of the total of 5 838 Quinary Catchments that cover southern Africa (Lumsden *et al.*, 2009). Therefore, alternative driver stations for the remaining 975 Quinary Catchments, and for which future rainfall scenarios were available, needed to be selected, which was achieved by the author of this thesis using the following criteria (Lumsden *et al.*, 2009):

- Distance from the Quinary Catchment’s centroid.
- Mean annual precipitation compared with that of observed data.
- Altitude difference between the station and the Quinary.

- Length of the observed record.
- Reliability of the observed record.

Driver stations that already served as “drivers” for other catchments were assigned by the author to 687 of the above 975 Quinary Catchments – the number of driver stations concerned numbered 134 (Lumsden *et al.*, 2009). To the remaining 288 Quinary Catchments, stations that had not previously been used as driver stations were assigned (Lumsden *et al.*, 2009). This resulted in 38 new driver stations being selected by the author of this thesis, bringing the total number of rainfall driver stations used in assessing future rainfall impacts to 1 061 (Lumsden *et al.*, 2009).

As was the case for the baseline historical climate (cf. Section 5.2.2.1), multiplicative adjustment factors were applied to the daily rainfall values of the above 1 061 driver stations in order to better represent the rainfall of each Quinary Catchment (Lumsden *et al.*, 2009). This resulted in the development of a unique, representative rainfall record for each Quinary Catchment (Lumsden *et al.*, 2009). In the absence of fine resolution national grids of median monthly rainfall for the future climate periods, which would be necessary to calculate adjustment factors specific to these climate periods, it was assumed that the monthly adjustment factors calculated for the baseline historical climate (cf. Section 5.2.2.1) would also be applicable under the GCM-derived climates considered (Lumsden *et al.*, 2009). In order to prevent unrealistic adjustments being made to the driver station, data limits were placed on the adjustment factors, which ranged between 0.5 and 2.0 (Lumsden *et al.*, 2009). These limits were relaxed relative to previous studies (e.g. Schulze *et al.*, 2005a; Schulze, 2008a) where the factors were constrained to be between 0.7 and 1.3, as it was deemed necessary due to the finer scale of modelling at Quinary Catchment scale in this study relative to Quaternary Catchment scale in previous studies (Lumsden *et al.*, 2009). 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). It should be reiterated that the work reported in this Section was undertaken by the author of this thesis.

5.3.3 Methodology used to represent point scale scenarios of temperature at the scale of Quinary Catchments

Out of all the climate stations for which CSAG developed point scale climate change scenarios for daily temperatures, 425 stations had both maximum and minimum temperature data sets, of which 404 stations were selected to represent maximum and minimum temperatures in the 5 838 Quinary Catchments covering southern Africa (Lumsden *et al.*, 2009). The approach to represent maximum and minimum temperatures at Quinary Catchment scale involved obtaining a daily weighted average of the data from the two most representative stations for each Quinary Catchment (Lumsden *et al.*, 2009). Using monthly adiabatic maximum and minimum temperature lapse rates determined by Schulze and Maharaj (2004) for 12 defined lapse rate regions in southern Africa (Schulze, 1997b), the two stations' data were adjusted to account for differences between the stations' altitudes and that of the respective Quinary (Lumsden *et al.*, 2009). Only stations located within the specific lapse rate region relevant to a particular Quinary Catchment were considered, with some of these eventually being discarded based on altitude related criteria (Lumsden *et al.*, 2009).

A modification of the algorithm developed by Schulze and Maharaj (2004) for selecting target stations for infilling of missing data at representative control stations was used to select the two most representative stations for a Quinary Catchment (Lumsden *et al.*, 2009). Using this modified algorithm all stations eligible for consideration were ranked according to their suitability and the five most suitable stations were identified (Lumsden *et al.*, 2009). The suitability ranking of a particular station depended on the distance of that station from the centroid of the catchment, as well as the difference in altitude of the station relative to the catchment's mean altitude; as demonstrated by the following series of equations (Lumsden *et al.*, 2009):

$$DF = 0.9\left(1 - \frac{DIST}{350}\right) + 0.1 \qquad (5.13)$$

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

$$AF = 0.9\left(1 - \frac{DALT}{1500}\right) + 0.1 \tag{5.14}$$

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

$$RF = (DF \times 10) + (AF \times 1) \tag{5.15}$$

where

RF	=	ranking factor.

For each Quinary Catchment the five stations with the highest *RF* values were selected according to the preliminary suitability ranking (Lumsden *et al.*, 2009). A final suitability ranking of the five stations identified was then performed to determine the two most suitable stations in terms of both distance and altitude, which required the range in distances (relative to the catchment centroid) and altitude differences (relative to the mean altitude of the catchment) among the five stations to be introduced into the calculation of *DF* and *AF*, as demonstrated by the following equations (Lumsden *et al.*, 2009):

$$DF = 0.9\left(1 - \frac{DIST - MIND}{MAXD - MIND}\right) + 0.1 \tag{5.16}$$

where

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

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

and

$$AF = 0.9\left(1 - \frac{DALT - MINA}{MAXA - MINA}\right) + 0.1 \qquad (5.17)$$

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).

In the calculation of *RF*, *AF* was weighted higher than it was in Equation 5.15, as it was assumed that the preliminary ranking would have excluded all stations that were unsuitable from a distance perspective (Lumsden *et al.*, 2009). Hence:

$$RF = (DF \times 10) + (AF \times 3) \qquad (5.18)$$

The data from the two most suitable temperature stations to represent each Quinary Catchment (based on *RF*) were then adjusted using adiabatic temperature lapse rates (Lumsden *et al.*, 2009). The two stations' adjusted values were then averaged (weighted according to the *RF* factor) in order to obtain the final maximum and minimum temperature records for the catchment (Lumsden *et al.*, 2009).

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This chapter has focussed on the methodology adopted in this study for modelling the impacts of climate change on the hydrological system. More specifically, the suitability of the *ACRU* model was addressed; an overview of the development of a new input database (based *inter alia* on research carried out by the author of this thesis), which is linked to the *ACRU* model, was given; and details of the approaches adopted for representing point climate change scenarios at catchment scale, also to be input into the *ACRU* model, was provided.

These scenarios are analysed in the following chapters. First, Chapter 6 provides a brief overview of how projected changes by the ECHAM5/MPI-OM GCM affects hydrological drivers such as temperature, reference crop evaporation and rainfall; as well as hydrological responses such as changes in mean annual streamflows. This sets the scene for the crux of the study, which follows in Chapter 7, in which the impacts on hydro-climatic hazards are analysed. These include impacts on short and long duration design rainfalls, design floods, meteorological and hydrological droughts, as well as the potential knock-on effects of these changes on sediment yields.

6. RESULTS 1: ASSESSING IMPACTS OF CLIMATE CHANGE ON KEY HYDROLOGICAL DRIVERS AND RESPONSES IN THE ORANGE RIVER CATCHMENT WITH PROJECTIONS USING OUTPUT FROM THE ECHAM5/MPI-OM GCM

The Orange River Catchment has been shown already to experience a high risk hydro-climate (cf. Section 1.3), with a low rainfall to runoff conversion, high aridity, strong rainfall seasonality, and in many areas a concentration of the rainy season over just a few months, all of which result in water scarcity. Moreover, an already high variability of rainfall is amplified by the natural hydrological system, often by a factor of 2 - 4 (Schulze, 2005e). Consequently, the Orange River Catchment may be seen to be more at risk to climate change than many other regions of the world.

This chapter proceeds with a summary of the methodology adopted in this study, followed by three sections in which results are presented of changes, as projected by the ECHAM5/MPI-OM GCM, in climate related input to the hydrological model that was used in this study, *viz*. temperature, reference crop evaporation and rainfall. This is followed by a brief section on changes to mean annual accumulated streamflows, i.e. a hydrological response to the changes in the above-mentioned hydrological drivers.

6.1 Summary of the Approach Adopted in This Study

As described in more detail in Chapter 5, in this study hydro-climatic output is simulated for each of the 1 443 hydrologically interlinked Quinary Catchments that make up the Orange River Catchment, using information from the Quinary Catchments Database, QnCD (Schulze and Horan, 2009). The QnCD has been populated with 50 years (1950 - 1999) of daily rainfall, temperature and potential evaporation data, as well as with hydrologically relevant soils and land cover information for each Quinary Catchment (Schulze *et al.*, 2009a). The QnCD information is used as input into the daily time step *ACRU* hydrological model (Schulze, 1995 and updates) in order to simulate daily streamflows, both per individual Quinary Catchment and for accumulated streamflows (Schulze *et al.*, 2009a).

In order to simulate streamflows for the intermediate (2046 - 2065) and more distant (2081 - 2100) future climate scenarios, the daily rainfall and temperature values from five GCMs, *viz.* CGCM3.1(T47), CNRM-CM3, ECHAM5/MPI-OM, GISS-ER and IPSL-CM4 (cf. Table 5.1), all of which were based on the A2 emissions scenario and were empirically downscaled to over 2 500 rainfall and > 400 temperature stations in southern Africa, are input into the *ACRU* model, whilst keeping each Quinary's soils and land cover information constant (Lumsden *et al.*, 2009; Schulze *et al.*, 2009a). Maps showing the spatial distributions of the rainfall and temperature stations used in the downscaling are provided in Figures 5.7 and 5.8, respectively.

Ratios of the point scale GCM-derived intermediate or more distant future climate occurrences and statistics to the point scale GCM-derived present climate (1971 - 1990) occurrences and statistics were computed in this study to facilitate the assessment of potential impacts of climate change (Schulze *et al.*, 2009b). Any potential impacts of climate change could then be assessed in relative terms by evaluating whether the ratio of future to present was > 1 or < 1 (Schulze *et al.*, 2009b). Furthermore, these analyses are presented in conjunction with maps of the corresponding baseline condition derived from 50 years of historical daily climate values from the QnCD.

All maps and tables in the results chapters that make reference to the Orange River Catchment, refer only to those areas of the catchment that exist within South Africa and Lesotho, i.e. those areas of the catchment that extend into Botswana and Namibia are excluded from all analyses – owing to a lack of readily available historical data and downscaled values for these respective areas. The maps presented in the results chapters depict the whole of South Africa, with the boundary of the Orange River Catchment highlighted, so as to facilitate the explanation of spatial trends, especially when these trends extend from outside of the Orange River Catchment.

The results presented throughout the remainder of this chapter, and a significant portion of the following chapter, are derived from computations using downscaled daily climate output from a single emission scenario from a single GCM. The use of a single projection, the limitations of which are well appreciated and documented (Hewitson *et al.*, 2005b; IPCC, 2007b; Schulze, 2007), obviously fails to capture the range of possible futures projected by the 23 GCMs and for the various SRES emissions scenarios used in the IPCC's AR4. As a result, a meaningful description of uncertainty cannot be achieved from results in these chapters. Despite this shortcoming, it is believed that these results still provide decision-makers with valuable information that may be incorporated into water resources and risk management strategies. Furthermore, these chapters demonstrate another key objective of this thesis, *viz*. the development of techniques, *i.e.* the development of a modelling framework for integrating hydro-climatic hazards with scenarios of climate change, as well as the development of mapping and analytical techniques, to facilitate the interpretation of the resulting hydro-climatic hazard scenarios.

Of the five GCMs available for this study, the ECHAM5/MPI-OM GCM was selected for use in the development of the above-mentioned techniques, as it is considered by the southern African climate modelling specialists, *viz*. CSAG (2008) to represent a "middle of the road" projection of future climates for this region of Africa. However, in the following chapter (Chapter 7), which addresses hydro-climatic hazard scenarios, analyses using all five GCMs are carried out.

6.2 Projected Changes in Mean Annual Temperature with Climate Change in the Intermediate and More Distant Futures

Increasing temperatures will have profound effects on evaporation, which in turn affects atmospheric water storage and hence magnitudes, frequencies and intensities of rainfall events, as well as the seasonal and geographic distribution of rainfall and its inter-annual variability (Kabat *et al.*, 2003). Furthermore, Schulze *et al*. (2005a) note that increases in temperatures can have a direct, or indirect, bearing on agrohydrologically related processes and phenomena by changes in soil moisture, irrigation water demands, heat wave episodes, or meteorological and hydrological droughts, in regard to their frequencies, severities, durations and spatial extent.

Figure 6.1 shows that in the intermediate future mean annual temperatures (MATs) are projected by the ECHAM5/MPI-OM GCM to be increasing throughout the Orange River Catchment, and the rest of South Africa. The magnitude of the increases in MATs heightens with increasing distance from the sea; a trend detectable in both the intermediate and distant future scenarios. The maximum increase in MATs in the Orange River Catchment is between 3℃ and 3.5℃, wh ile in the distant future this increases to a change that is > 7℃, according to p rojections with the ECHAM5/MPI-OM GCM. Furthermore, Figure 6.1 shows that changes in distant future MATs are generally double those projected for the intermediate future.

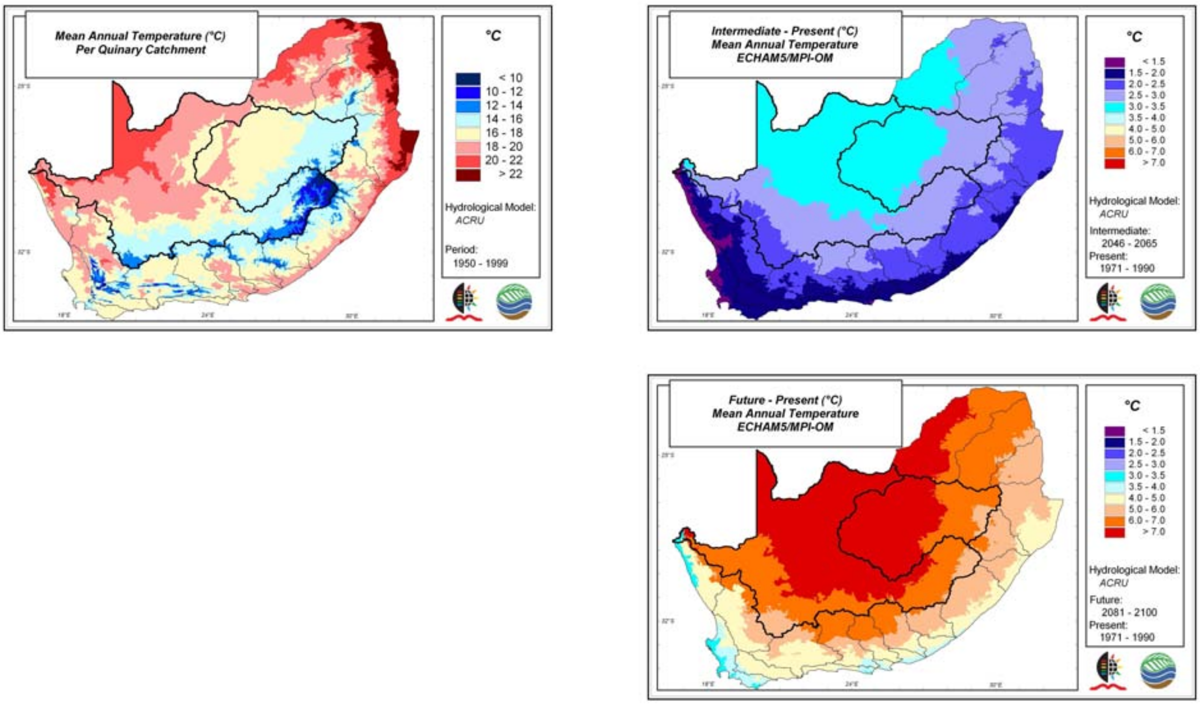


Figure 6.1 Differences between intermediate future and present (top right), and more distant future and present (bottom right), mean annual temperatures, derived from downscaled daily climate output from the ECHAM5/MPI-OM GCM, compared with baseline values derived from historical daily climate data from the QnCD (top left)

Viewing the projected changes in relative terms (Figure 6.2) is useful for identifying areas that are sensitive to temperature increases, and shows different spatial patterns to those shown by the absolute differences in Figure 6.1. The highest ratios, indicating an increase from the present MATs in the order of 20 - 40%, occur over Lesotho, i.e. the source of the Orange River, and the location of one of its main tributaries, *viz*. the Caledon. In the distant future, the eastern two thirds of the Orange River Catchment is projected to experience increases in MATs by 40 - 60%, with the highest ratios, once again, projected to occur in Lesotho. This indicates that Lesotho, and the areas surrounding it, are particularly sensitive to changes in temperature, which may have hydro-ecological implications.

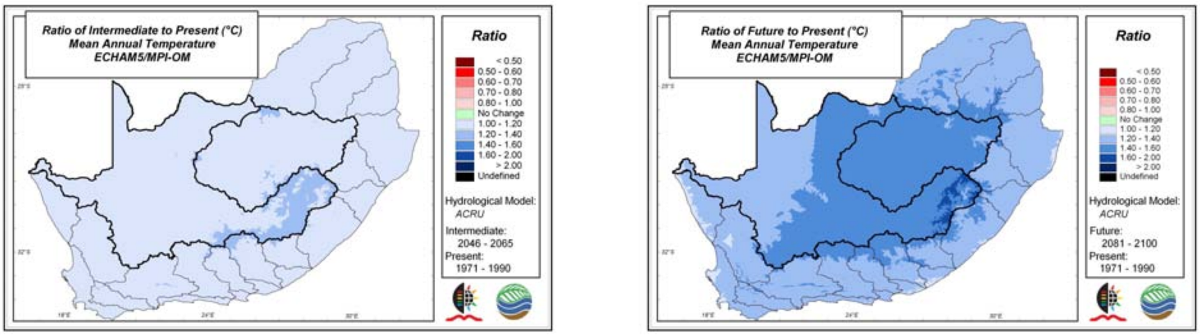


Figure 6.2 Ratios of intermediate future to present (left), and more distant future to present (right), mean annual temperatures, derived from downscaled daily climate output from the ECHAM5/MPI-OM GCM

6.3 Projected Changes in Mean Annual Reference Crop Evaporation with Climate Change in the Intermediate and More Distant Futures

Atmospheric evaporative demand largely dictates rates of evaporation losses (Schulze *et al.*, 2005a). Evaporation may occur from open water bodies, plant intercepted water, from the soil surface or through transpiration – which represents the water lost mainly through the leaves of plants (Schulze, 2008c). Evaporative demand may be estimated from climatic and plant variables using a selected reference technique - hence E_r. A physically-based reference crop evaporation equation is that by Penman-Monteith (Penman, 1948; Monteith, 1981) and its modifications (FAO, 1992), and this has been used here because it can account explicitly for shortwave solar and longwave terrestrial radiation, for vapour pressure deficit and wind effects on evaporation rates, as well as for stomatal and aerodynamic resistances from plants on a day-to-day basis using simple climate input variables (Schulze *et al.*, 2005a). Where these daily E_r values from the modified

Penman-Monteith technique need to be converted to A-pan equivalent reference potential evaporation, this is done with an internationally verified multiplication factor of 1.2.

From Figure 6.3, it can be seen that the mean annual reference crop evaporation is projected by the ECHAM5/MPI-OM GCM to increase over the entire Orange River Catchment with both intermediate and more distant future climates. The greatest increases in the intermediate future, in the order of 10 - 15%, occur over the eastern half of the catchment, while almost the entire catchment is expected to potentially lose 20 - 25% more water through evaporation and transpiration in the distant future – a particularly concerning projection for the already water stressed western regions of the Orange River Catchment.

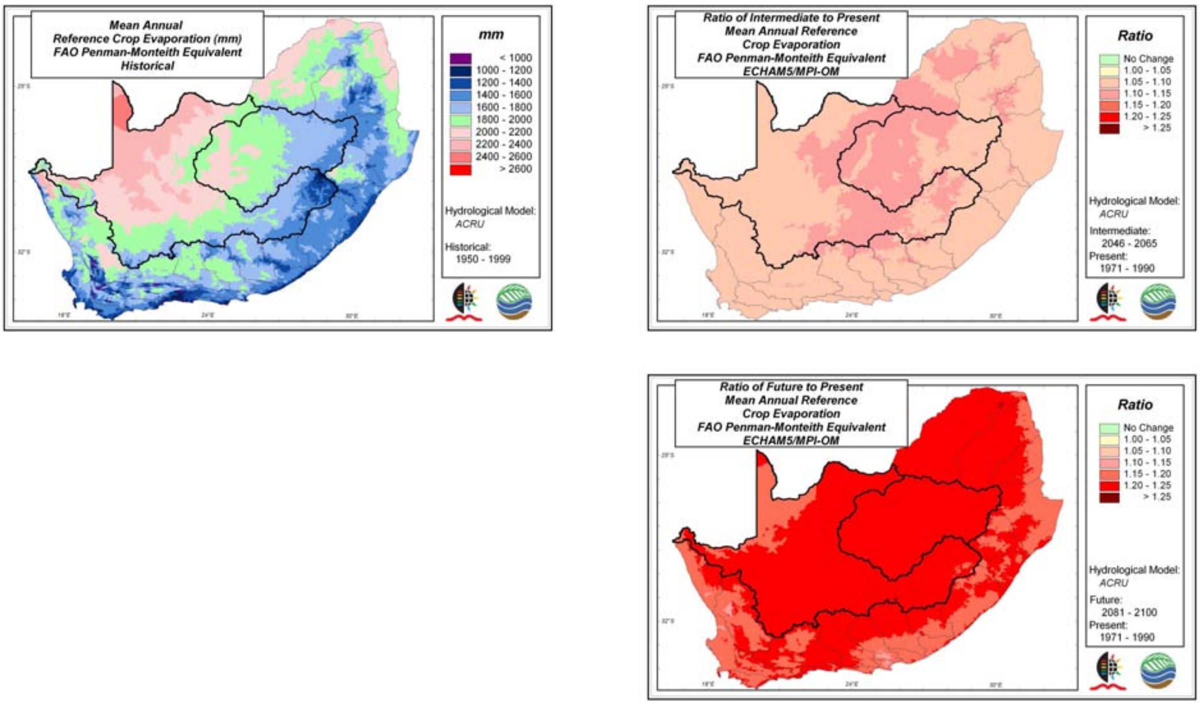


Figure 6.3 Ratios of intermediate future to present (top right), and more distant future to present (bottom right), mean annual reference crop evaporation, using the FAO (1992) modified Penman-Monteith equation, derived from downscaled daily climate output from the ECHAM5/MPI-OM GCM, compared with baseline values derived from historical daily climate data from the QnCD (top left)

The implications of increases in Er of this magnitude could be severe, as reduced soil moisture levels could impact runoff generating mechanisms and dams, as well as channels, could lose considerably more water to the atmosphere than they already do.

6.4 Projected Changes in Mean Annual Precipitation and Its Inter-Annual Variability with Climate Change in the Intermediate and More Distant Futures

Mean annual precipitation, MAP (mm), provides an indication of the long term quantity of water available to a region for hydrological and agricultural purposes. Under non-irrigated conditions it provides an upper limit to a region's sustainable agricultural potential in regard to biomass production if other factors (e.g. solar radiation, temperature, topography, soils) are not limiting (Schulze *et al.*, 2005a). Not only is MAP important as a general statistic in its own right, but it is probably also the best known climatic variable to hydrologists and agriculturists (Schulze *et al.*, 2008b).

According to ECHAM5/MPI-OM GCM scenarios, most of the Orange River Catchment's MAP is set to increase in the intermediate future (Figure 6.4, top centre), with the majority of the area projected to have an MAP up to 20% greater than the present MAP. In the more distant future (Figure 6.4, top right) further increases are expected, with the majority of the area projected to experience an MAP between 20 - 100% greater than the present MAP. The biggest increases in the intermediate future occur in the eastern regions of the Orange River Catchment, i.e. in the higher MAP, runoff-producing areas. A common trend in both the intermediate future and the more distant future MAP projections is the decreasing rate of change from the east to the west of the catchment. In the extreme western regions of the catchment, i.e. the already water stressed regions, the MAP is projected to decrease in the intermediate future. In the more distant future the west coast of South Africa is projected to experience a decrease in MAP. Although this appears to lie immediately outside the Orange River Catchment, the possibility of these projected decreases extending into the Orange River Catchment may be of concern to water managers in the region.

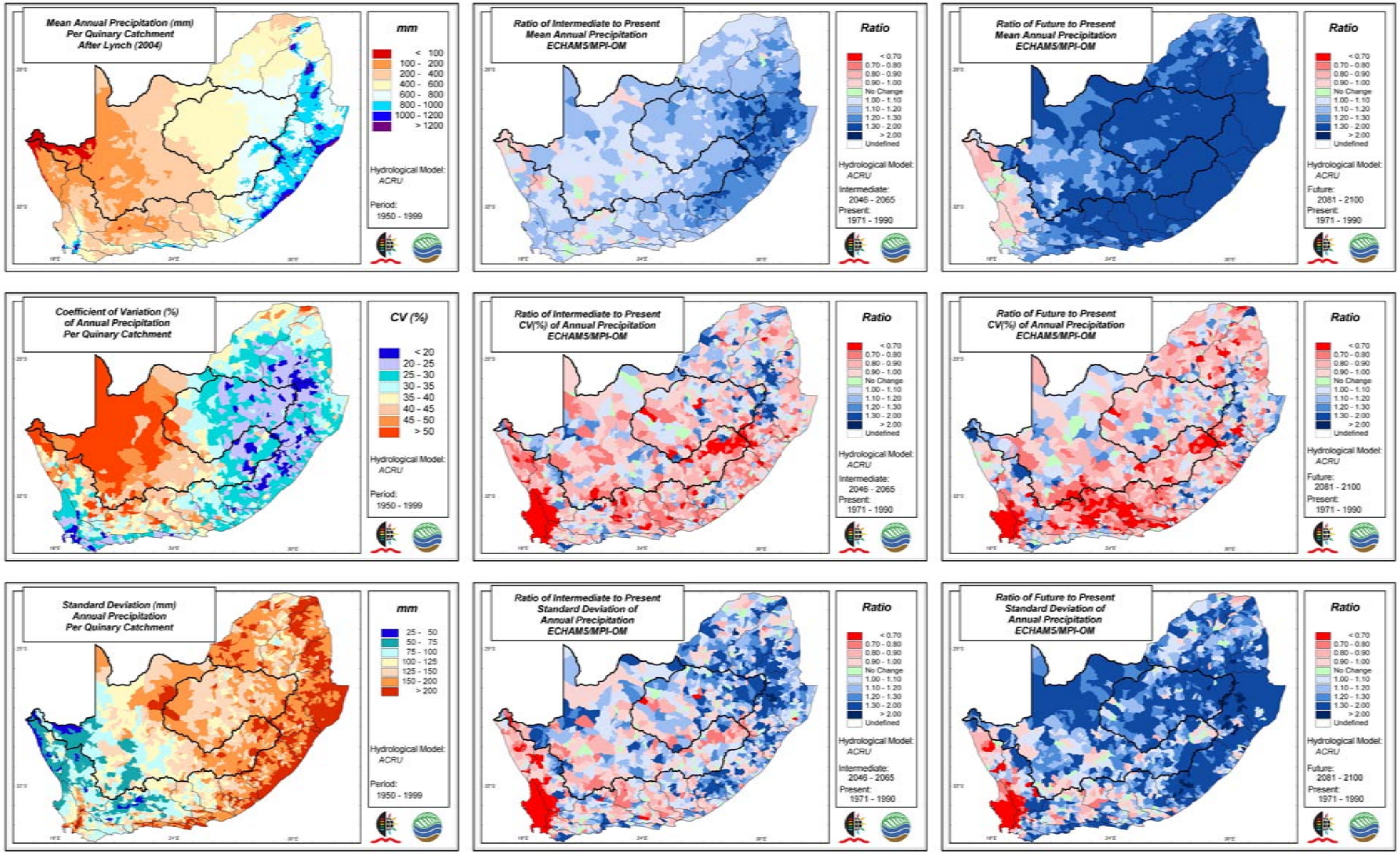


Figure 6.4 Ratios of intermediate future to present (centre), and more distant future to present (right), mean annual precipitation with its inter-annual variability, expressed by both the coefficient of variation and the standard deviation, derived from downscaled daily rainfall output from the ECHAM5/MPI-OM GCM, compared with baseline values derived from

Future year-to-year deviations of annual precipitation from the mean, which may be viewed as an index of climatic risk and therefore also hydrological risk, and which in relative terms may be expressed through the coefficient of variation (CV%) are, by and large, projected to decrease in the intermediate future (Figure 6.4: middle row, centre), as well as in the more distant future (Figure 6.4: middle row, right). Although these vast areas of the Orange River Catchment with projected decreases in inter-annual CV% may appear to be a pleasing finding for water managers, this result may be misleading due to the widespread simultaneous increases in MAP. Figure 6.4 (bottom row, centre and right) shows the spatial variation of the standard deviation of annual rainfall, where it can be seen that deviations from the mean, in absolute terms, are actually projected to increase over many parts of the Orange River Catchment. Furthermore, the variability is projected to increase further from the intermediate future to the more distant future. This is concerning as the increase in absolute (as opposed to relative) variability may bring about an increase in the magnitude or frequency, or both, of extreme events such as floods and droughts.

6.5 Projected Changes in Mean Annual Accumulated Streamflow and Its Inter-Annual Variability with Climate Change in the Intermediate and More Distant Futures

The projected changes in mean annual streamflows, by the ECHAM5/MPI-OM GCM, in the intermediate future (Figure 6.5: top row, centre map) shows a band of predominantly decreasing annual streamflows extending from the northeast of South Africa, through the Orange River Catchment, to the south of the country. This area of decreasing annual streamflows in the southern regions of South Africa also extends upwards and westwards, resulting in a vast area in the south of the Orange River Catchment projected to experience decreases in annual streamflows. The runoff-producing areas in the east of the catchment are projected to experience an increase in annual streamflows, in some cases > 30% of the present annual streamflows. These increases, at the source of the Orange River and its main tributaries, appear to sustain a net projected increase over the entire length of the Orange River, even in those areas where a general decrease in annual streamflows is projected.

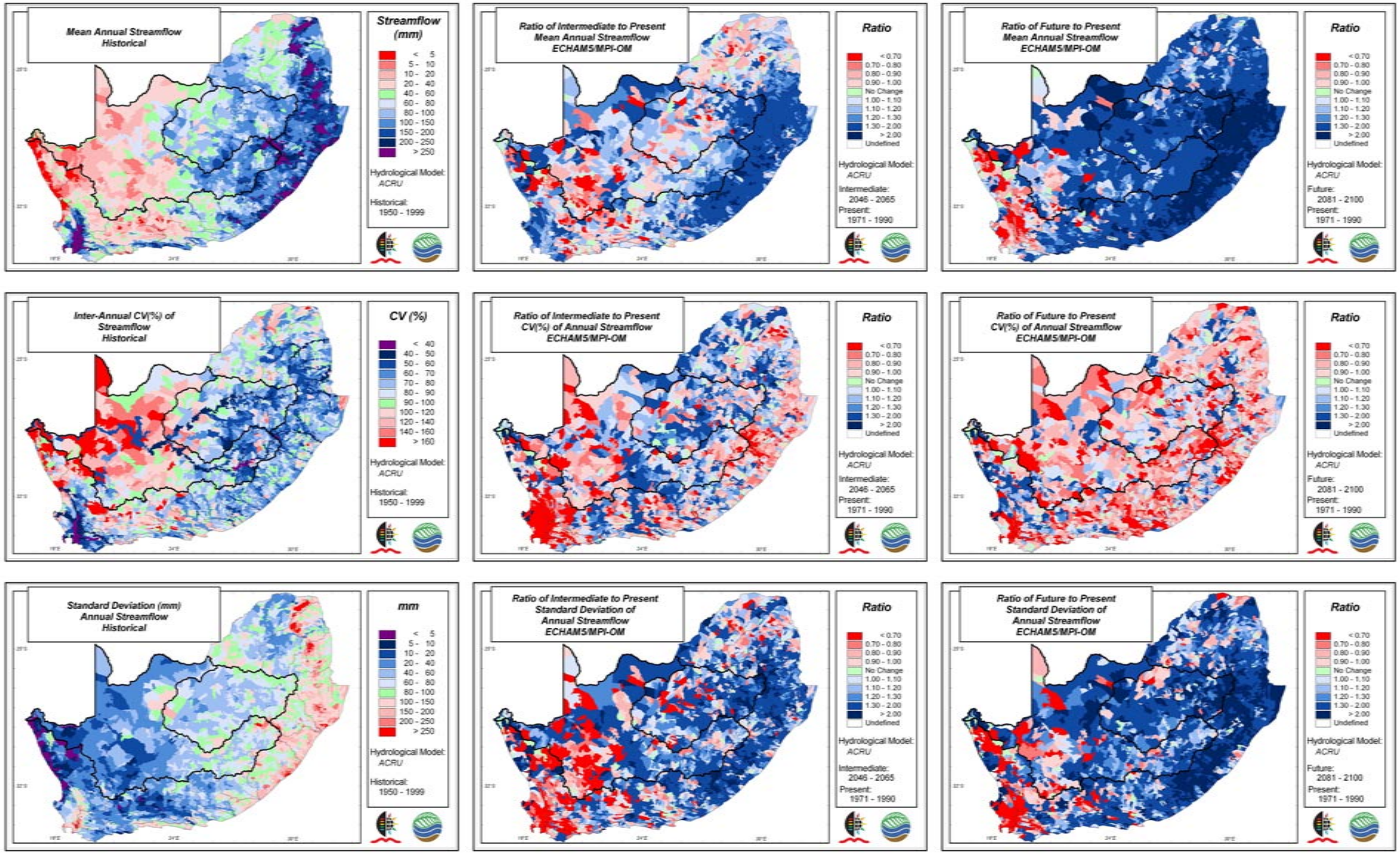


Figure 6.5 Ratios of intermediate future to present (centre), and more distant future to present (right), mean annual accumulated streamflows with their inter-annual variability, expressed by both the coefficient of variation and standard deviation, derived from *ACRU* simulations with downscaled daily climate output from the ECHAM5/MPI-OM GCM, compared with baseline values derived from *ACRU* simulations using historical daily climate data from the QnCD (left)

Comparing the projected changes to MAP with those changes to mean annual streamflows shows different spatial patterns, with decreases in annual streamflows projected in areas where the annual rainfall is increasing. Furthermore, where the annual streamflows are projected to increase in the intermediate future, e.g. in the east of the Orange River Catchment, those increases are greater than those projected for annual rainfall. These findings are indicative of how changes in rainfall may become amplified, in both directions, within a non-linearly responding hydrological system.

In the more distant future (Figure 6.5: top right) the area of the Orange River Catchment that is projected to experience increases in annual streamflows grows in both extent and magnitude. The highest changes, i.e. more than double the present annual streamflows, are projected in the east of the catchment. The ratios decrease westwards across the catchment, with the western areas of the Orange River Catchment projected to experience a decline in annual streamflows. Similar to findings for the intermediate future, however, the entire Orange River is projected to experience increases in its streamflows, even in the western regions of the catchment. It is postulated that this is a result of the upstream contributions, particularly from those regions in the east where the already high annual streamflows are projected to increase by 30 - 100%, and more.

The inter-annual variability of streamflows, expressed in relative terms by the CV%, is shown to be generally decreasing in the west, and increasing in the east, of the Orange River Catchment in the intermediate future (Figure 6.5: middle row, centre map). In the more distant future, however, the inter-annual variability of streamflows appears to be decreasing over most of the catchment. As was found in the analysis of inter-annual rainfall variability, even though the CV% is projected to decrease over vast areas of the Orange River Catchment, the projected year-to-year absolute deviations from the mean, measured by the standard deviation (Figure 6.5: bottom row), are generally shown to be increasing in the intermediate future and, in particular, the more distant future. As noted for the projected increases in inter-annual rainfall variability, this is an area of concern as increases in the inter-annual variability of accumulated streamflows may bring about an increase in the magnitude or frequency, or both, of extreme events such as floods and droughts.

6.6 Summary of Main Findings

- The ECHAM5/MPI-OM GCM is selected and used to develop mapping and analytical techniques for the interpretation of potential impacts of climate change on key hydrological drivers and responses.
- MATs are projected by the ECHAM5/MPI-OM GCM to increase over the entire Orange River Catchment in the intermediate future, and even more so in the more distant future.
- The largest relative increases in MATs, in both the intermediate and in the more distant futures, occur at the source of the Orange River in Lesotho, implying that these are, hydro-ecologically, particularly sensitive areas.
- One effect of increasing MATs can be seen in the analysis of projected changes to E_r, with catchment-wide projected increases in reference crop evaporation in the intermediate and more distant futures.
- MAP is projected to generally increase across the Orange River Catchment in the intermediate future, and then even more so in the distant future.
- Inter-annual variations of rainfall, as expressed by the standard deviation, indicate widespread increases across the Orange River Catchment in the intermediate and more distant futures, with the more distant future shown to be spatially more variable than the intermediate future.
- Changes in mean annual accumulated streamflows, which represent the integrated hydrological response to changes in hydrological drivers, show that annual streamflows are generally projected to increase in the intermediate and more distant futures projected by the ECHAM5/MPI-OM GCM.
- However, notwithstanding the widespread increases in MAP projected for the intermediate future, there are clearly defined areas with projected decreases in annual streamflows.
- Changes in rainfall are shown to become amplified, in both positive and negative directions, in a non-linearly responding hydrological system.
- As was the case for MAP, the standard deviations of accumulated streamflows show that the year-to-year deviations from the mean are projected to increase in future, with increases greater in the more distant than the intermediate future.

7. RESULTS 2: ASSESSING IMPACTS OF CLIMATE CHANGE ON HYDRO-CLIMATIC HAZARDS IN THE ORANGE RIVER CATCHMENT WITH PROJECTIONS USING OUTPUT FROM MULTIPLE GCMs

It has already been discussed, in Chapter 2, that climate change may impact hydro-climatic hazards, such as floods and droughts. Furthermore, in the previous chapter (Chapter 6) projections from the ECHAM5/MPI-OM GCM, and subsequent streamflow simulations using the *ACRU* model, have indicated that the means, as well as the annual variations, of both rainfall and streamflow may increase in future climates; the possible consequences being more frequent, and more severe, floods and droughts. This chapter proceeds by first addressing the high end of the spectrum of extreme rainfall, and then streamflow, i.e. design rainfalls (Section 7.1) and design floods (Section 7.2), respectively. This is followed by the other end of the spectrum, with analyses of meteorological and hydrological droughts (Section 7.3). The chapter then concludes with an analysis of the projected impacts on sediment yields (Section 7.4), which, as already mentioned in Chapter 2, may be affected by increasing rainfall intensities and flooding.

7.1 Design Rainfall

Hydraulic engineering and conservation structures such as dams, bridges, culverts and stormwater systems need to be designed to accommodate peak floods of a certain magnitude in order to function safely at a given level of risk. Climate change, by expected alterations to the temperature and rainfall regimes, as well as increases to rainfall variability, may lead to increases in the intensity and frequency of extreme rainfall events and associated flooding (cf. Chapter 2 and Chapter 6). Consequently, this might have serious repercussions on the design of hydraulic structures. Since the failure of such structures can have potential economic, environmental and societal repercussions, including loss of life, it can be appreciated why flood frequency analysis is of great importance (Smithers and Schulze, 2003).

However, reliable estimates of flood frequencies derived from long time series of good quality observed streamflow data are seldom available at the site of interest because of the lack of such streamflow data (Schulze and Smithers, 2008). Therefore, it is common for rainfall-based methods of flood frequency estimations to be used. This requires a probabilistic approach to analysing rainfall for design purposes (Schulze and Smithers, 2008). The frequently used term “design rainfall” is thus used to describe the following rainfall event characteristics (Smithers and Schulze, 2003):

- *Depth* – i.e. the magnitude, in mm, of rainfall.
- *Duration* – e.g. of short duration, conventionally defined to be < 24 hours and which is important when considering designs on small catchments, in urban areas and for local flooding; or of long duration, such as one to seven days, and which is important when considering designs on larger catchments, for multiple day flooding and for regional damage assessments.
- *Frequency* – i.e. the probability of exceedance (e.g. once in 10 or in 50 years, depending on the size and economic importance of the structure), and is inversely related to the more commonly used term, return period.

An estimate of design rainfall can then be used to generate design flood hydrographs when combined with catchment characteristics such as slope, size, land use and soils (Smithers and Schulze, 2003).

This section on design rainfalls proceeds firstly with long duration design rainfalls, with an initial outline of the methodology followed by an interpretation of historical design rainfalls of selected return periods and durations. A similar sequence is followed for short duration design rainfalls. This is followed by an uncertainty analysis of the projected long duration and short duration design rainfalls.

7.1.1 Methodology: Computation of long duration design rainfalls

In this study, historical estimates of design rainfalls are computed using the 50 year daily rainfall datasets of the Quinary Catchments Database, i.e. QnCD (Schulze and Horan, 2009). The projected intermediate future (2046 - 2065) and more distant future (2081 - 2100) scenarios from each of the General Circulation Models (GCMs) selected have been empirically downscaled to point locations at climate station level, with daily values for the respective 20 year time slices (Lumsden *et al.*, 2009). Hence, the corresponding point locations used for the baseline estimates can be used for the future estimates.

The *annual maximum series* (AMS) of daily rainfall, which uses the largest daily value of each year of record for further statistical analysis with an extreme value distribution (EVD), has been selected for this study. While there is no “most suitable” EVD for use in a region as climatologically diverse as the Orange River Catchment, the widely applicable three parameter Log-Pearson Type III distribution (Kite, 1988) was selected for the analyses which follow. This distribution fits most sets of hydrological data, with no exceptions having been found when applied to South African rainfall and river flow data (Alexander, 2001).

The general form of the equation for the Log-Pearson Type III distribution is:

$$y_T = \bar{y} + s_y K_T \tag{7.1}$$

where

$\bar{y}$	=	the mean of the log-transformed AMS data.
s_y	=	the standard deviation of the log-transformed AMS data, and
K_T	=	the frequency factor.

The first step is to take the logarithms of the individual years’ annual maximum daily rainfall data, x:

$$y = \log x \tag{7.2}$$

$\bar{y}$, s_y and coefficient of skewness C_s are then calculated for the logarithms of the data. The frequency factor K_T depends on the return period T and C_s. When $C_s = 0$, then K_T is equal to the standard normal variate z, which can be approximated to within 0.00045 of the true value by the following equation (Abramowitz and Stegun, 1965), *viz*.

$$z = w - \frac{2.515517 + 0.802853w + 0.010328w^2}{1 + 1432788w + 0.189269w^2 + 0.001308w^3} \qquad (7.3)$$

where

$$w = \left[\ln\left(\frac{1}{p^2}\right)\right]^{\frac{1}{2}} \text{ is an intermediate variable, and} \qquad (7.4)$$

$$p = \frac{1}{T} \text{ is the exceedance probability.} \qquad (7.5)$$

When $C_s \neq 0$, then K_T can be approximated by the following (Kite, 1988)

$$K_T = z + (z^2 - 1)\left(\frac{C_s}{6}\right) + \frac{1}{3}(z^3 - 6z)\left(\frac{C_s}{6}\right)^2 - (z^2 - 1)\left(\frac{C_s}{6}\right)^3 + z\left(\frac{C_s}{6}\right)^4 + \frac{1}{3}\left(\frac{C_s}{6}\right)^5 \qquad (7.6)$$

Values of the 2, 5, 10, 20, 50 and 100 year return period design rainfall magnitudes were computed for the one, two, three and seven day durations. Owing to the relatively short length of record for the two climate change scenarios (20 years), any results from return periods exceeding 20 years should be interpreted and used with caution. Selected results from the design rainfall analysis are presented below.

7.1.2 Results A: Spatial patterns of the one to seven day design rainfall magnitudes for selected return periods, derived from historical observed rainfall data, per Quinary Catchment

Figure 7.1 displays very strong spatial variations of design rainfalls for all three return periods and three durations shown. The distribution of design rainfalls is highly correlated with the distribution of MAP over the Orange River Catchment, with an increasing trend of design rainfall from west to east, regardless of the return period or

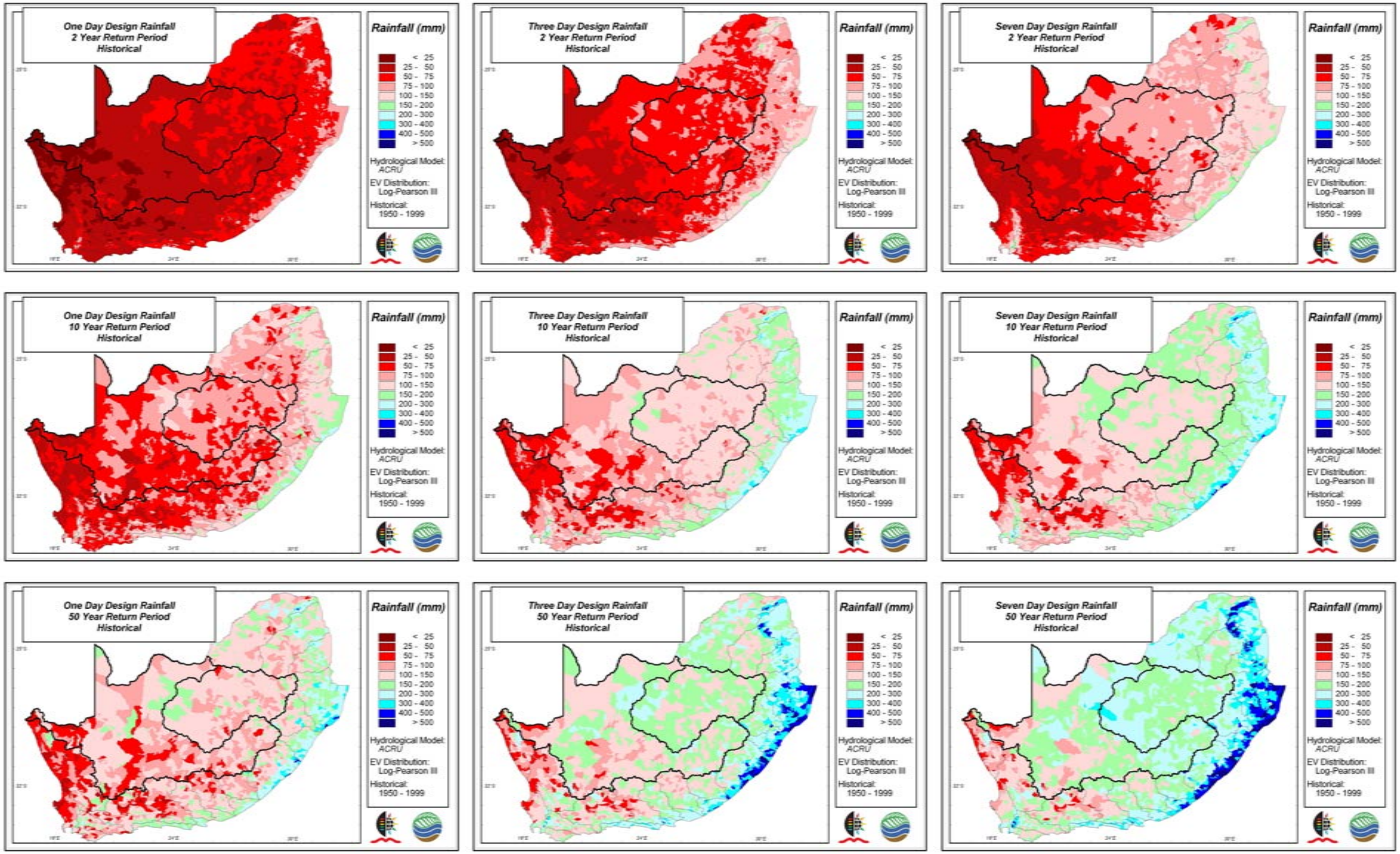


Figure 7.1 Long duration design rainfall depths for selected return periods and durations, derived from historical daily rainfall data from the QnCD

duration. As expected, the design values increase with both return period and duration. However, the rate of change across the Orange River Catchment is not uniform. When increasing the return period from 2 to 10 to 50 years and the duration from one to three to seven days, the increases observed in arid western regions are very small when compared to those in the east, with the 10 year design values in east often exceeding the 50 year values in the west for all durations.

7.1.3 Results B: Projected changes in long duration design rainfalls with climate change in the intermediate and more distant futures

From the five climate models available for this study, the ECHAM5/MPI-OM GCM has been selected to develop techniques for the analysis of projected changes in long duration design rainfall, for intermediate and distant future climate scenarios. The ECHAM5/MPI-OM GCM provides "middle of the road" estimates of future climate projections relative to the other four available GCMs (CSAG, 2008), as already mentioned in Section 6.1. Figures 7.2 and 7.3, respectively, show the projected ratio changes for the intermediate and distant futures in long duration design rainfalls for selected return periods and durations, from the ECHAM5/MPI-OM GCM.

The spatial distribution of the projected changes for the one day, 2 year return period in the intermediate future (Figure 7.2: top left) shows the eastern parts of the Orange River Catchment tending towards a slight increase in design rainfalls. This increase forms part of a band of projected increases that extends down the east coast of South Africa. However, extending from the northeast of South Africa, across a vast area of the Vaal component of the Orange River Catchment (i.e. the northeastern region) and the southern regions of the catchment, to the southwest of South Africa, is a band of predominantly decreasing design rainfalls. West of this band, in the semi-arid parts of the Orange River Catchment, a mixed picture of increasing and decreasing design values is displayed, but with the increases greater in magnitude than the decreases.

Moving from the one to three day duration, i.e. from the top left to the top centre map of Figure 7.2, indicates that the spatial pattern of design rainfalls changes with event

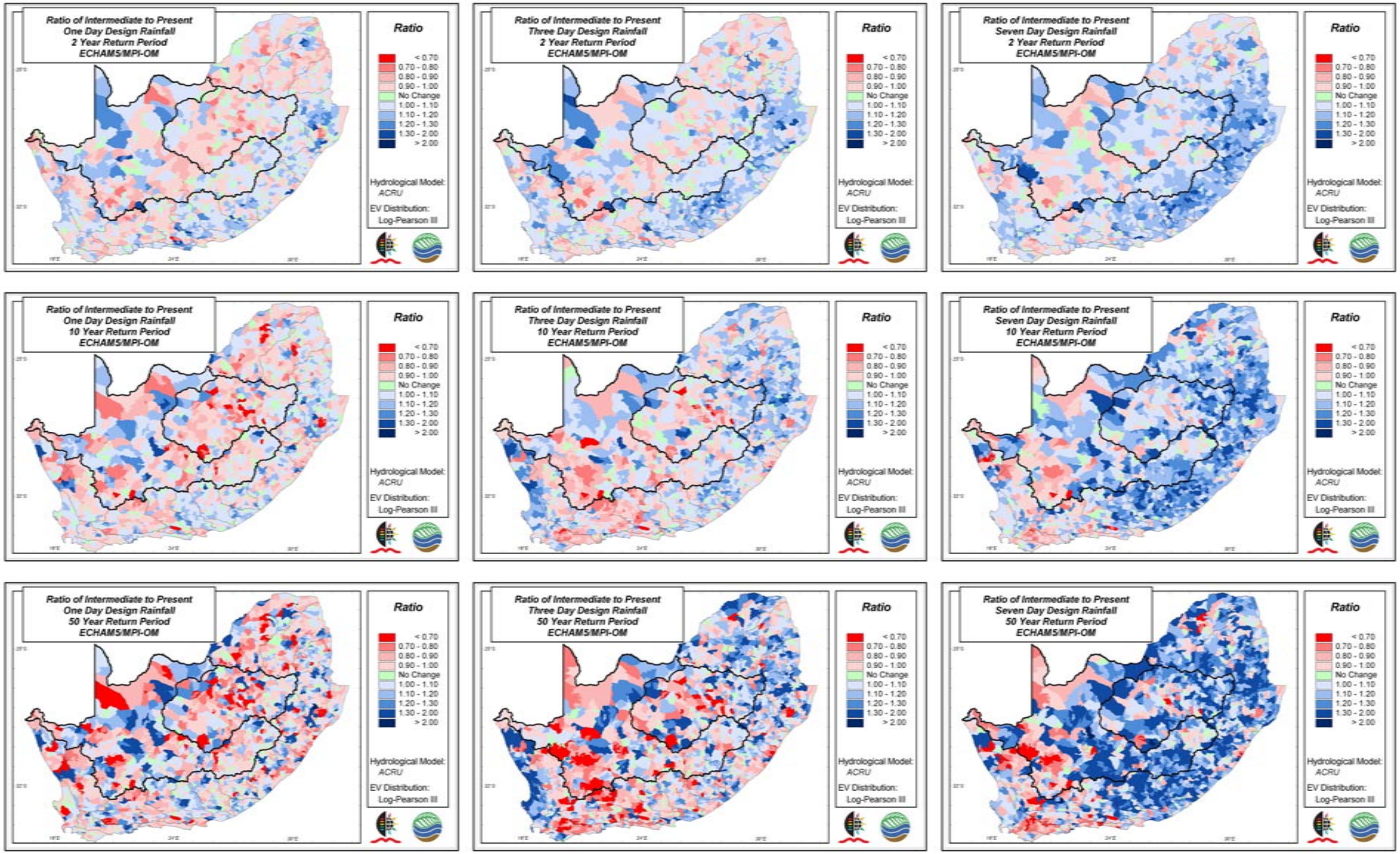


Figure 7.2 Ratios of intermediate future to present design rainfalls for selected return periods and durations, derived from downscaled daily rainfall output from the ECHAM5/MPI-OM GCM

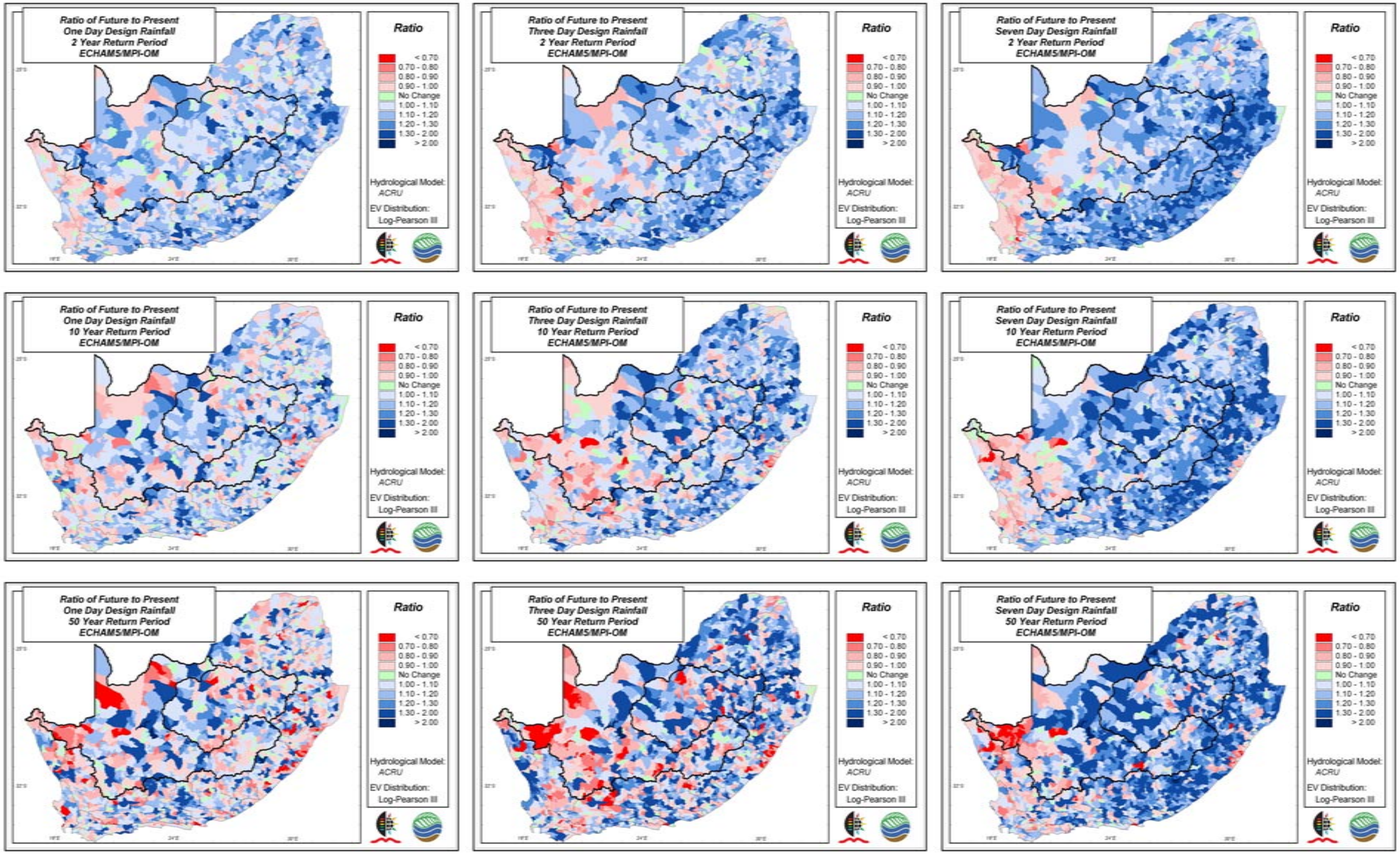


Figure 7.3 Ratios of more distant future to present design rainfalls for selected return periods and durations, derived from downscaled daily rainfall output from the ECHAM5/MPI-OM GCM

duration. The central band of decreasing design rainfalls that was apparent for the one day duration is less distinct, with many of the Quinary Catchments that were showing a decrease now showing no change or even a slight increase in design rainfalls. This is an intensification of an increasing trend projected in the east of South Africa, which seems to be expanding westwards. This trend continues on to the seven day duration, for which most of the catchment shows increasing design rainfalls, however, with a significant portion of the Orange River Catchment west of the Vaal Catchment still showing decreasing design rainfalls. This trend of projected increases in design rainfalls, in terms of magnitude and spatial extent, is present for all return periods.

Moving down the left-hand side of Figure 7.2, i.e. from the 2 to the 10 and 50 year return periods for the one day duration, it can be seen that, while the area that will experience increases in design rainfalls is shrinking, the spatial distribution of design rainfalls becomes increasingly less distinct. Furthermore, the shades of reds and blues are getting darker with increasing return period, indicating that the magnitude of change is increasing, both positively and negatively. Although these trends are apparent for all design durations, they are most prominent for the lower return periods.

Shifting the focus to the more distant future (Figure 7.3), it is immediately noticeable that a greater area of the Orange River Catchment is projected to experience increasing design rainfalls when compared to the intermediate future projection. As was apparent for the intermediate future, the cumulative area projected to experience higher design rainfalls decreases with increasing return period, while the magnitudes of projected changes increase.

One trend that was apparent for the intermediate future (Figure 7.2), but is not as clear for the more distant future scenario (Figure 7.3), is the increase in the area projected to experience higher design rainfalls with increases in the duration of the design event (i.e. one to three to seven day flood producing rainfalls). The ratio change between the one day and three day duration is barely noticeable in Figure 7.3; however, the increase in the area projected to experience greater design rainfalls does become apparent between the three and seven day durations.

These findings drawn from Figures 7.2 and 7.3 are confirmed by results presented in Table 7.1, where it is also shown that, although the area of the Orange River Catchment that is projected to experience greater design rainfall decreases with increasing return period, the area projected to experience changes in design rainfalls in excess of 30% increases.

Table 7.1 Percentage area of the Orange River Catchment projected to experience an increase, decrease, or no change in long duration design rainfalls in the intermediate and more distant futures, derived from computations using downscaled daily rainfall output from the ECHAM5/MPI-OM GCM

Attribute		**Percentage Area of the Orange River Catchment**					
		Intermediate Future			**More Distant Future**		
Return Period	**Direction of Change**	**One Day**	**Three Day**	**Seven Day**	**One Day**	**Three Day**	**Seven Day**
2 Year	**No Change**	11.3	11.1	8.8	6.7	4.0	3.5
	Decrease	42.2	31.0	24.5	16.1	18.0	13.9
	Increase	46.5	57.9	66.7	77.2	78.0	82.6
	Decrease > 30%	0.0	0.0	0.0	0.0	0.0	0.0
	Increase > 30%	0.5	1.6	1.6	3.9	3.9	6.8
10 Year	**No Change**	7.1	7.9	7.1	5.5	7.1	4.6
	Decrease	48.6	42.9	24.3	29.3	32.9	13.9
	Increase	44.3	49.2	68.6	65.2	60.0	81.5
	Decrease > 30%	2.1	1.0	0.3	0.0	1.2	0.4
	Increase > 30%	1.4	1.5	7.7	9.1	9.9	15.0
50 Year	**No Change**	6.8	5.2	4.3	6.6	4.0	3.9
	Decrease	47.4	51.9	29.0	37.1	39.5	20.9
	Increase	45.8	42.9	66.7	56.3	56.5	75.2
	Decrease > 30%	7.9	6.6	2.4	4.1	4.7	2.4
	Increase > 30%	7.6	8.3	26.8	14.7	16.5	29.1

Of the above results, it is the increases that occur in the eastern parts of the Orange River Catchment that are most concerning to water managers in the future as this is where most of the rainfall occurs (cf. Figure 6.4) and where the current design values are already the highest in the catchment (cf. Figure 7.1). Even where there are increases in design rainfalls projected in the west, they are only of the order of 10 - 20%, which when considered with the relatively small design values calculated from the historically observed data, results in small increases in the design values.

7.1.4 Methodology: Computation of short duration design rainfalls

In order to understand how storm intensities might change, short duration design storm magnitudes were calculated. The IPCC (2007b) states that rainfall intensities are projected to increase as a result of global warming. This statement is, however, based on a relatively simplistic assumption that intensity can be calculated by dividing the annual rainfall by the number of rain days per year. A study of trends in daily climate extremes over southern and west Africa indicates that time-averaged measures of rainfall may be inadequate to capture changes in intensity (New *et al.*, 2006). In this study, a more sophisticated approach has been adopted, *viz*. a modification of a complex index storm approach, based on so-called L-moments, developed by Smithers and Schulze (2003). Using this approach, the design rainfall for a given location can be estimated for durations ranging from five minutes to seven days. However, owing to the use of an index storm, ratios for all durations < 24 hours and all return periods will remain constant for intermediate to present, and more distant future to present, climates. Results in this section are therefore an indication of potential changes in short duration design rainfall in general.

As already alluded to above, in order to estimate short duration design rainfall a methodology developed by Smithers and Schulze (2003), utilising an index storm approach based on L-moments, was employed. Using this methodology, design rainfall can be estimated anywhere in South Africa. Growth curves which relate design rainfall, scaled by the mean of the annual maximum series (AMS), to return periods are utilised in conjunction with an estimate of the mean of the AMS at the required location to compute the rainfall depth for the specified duration and return period. Smithers and Schulze (2003) showed that one day growth curves, derived from daily rainfall data, were applicable and could be used for durations ranging from five minutes to seven days.

7.1.4.1 Methodology for the calculation of short duration design rainfalls from historical observed rainfall

The procedure that is followed is to first estimate the mean of the one day AMS for the required location. This is achieved using regression equations developed for each of the seven relatively homogeneous regions identified by Smithers and Schulze (2003) and shown in Figure 7.4. The mean for the 24 hour AMS is estimated, as shown in Equation 7.7, from the one day mean of the AMS and regionalised 24 hour : one day ratios (Smithers and Schulze, 2003).

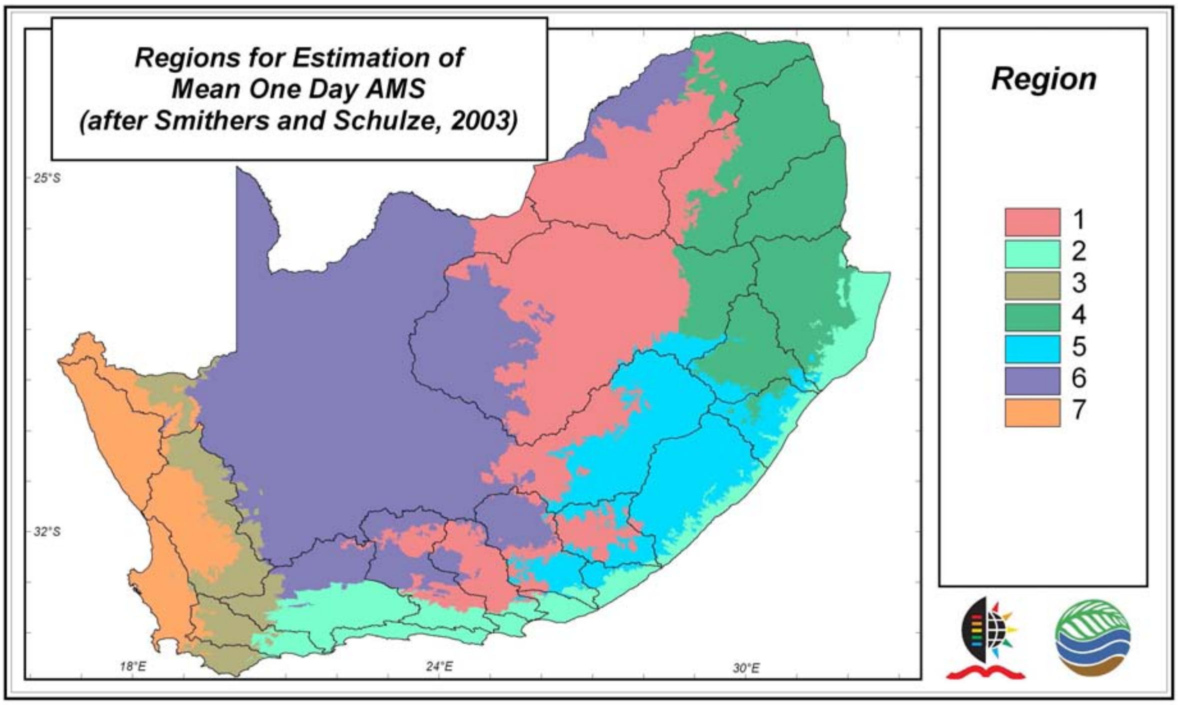


Figure 7.4 Relatively homogenous regions used for the estimation of the mean of the one day AMS for any location in South Africa (after Smithers and Schulze, 2003)

$$L\_1_{24\text{ hour}} = L\_1_{1\text{ day}} \times Ratio_{24\text{ hour : 1 day}} \qquad (7.7)$$

where

$L\_1_{24\text{ hour}}$	=	mean of the 24 hour AMS,
$L\_1_{1\text{ day}}$	=	mean of the one day AMS, and
$Ratio_{24\text{ hour : 1 day}}$	=	ratio to convert the mean of the one day AMS to a 24 hour AMS

The next step is to estimate the mean of the AMS for the required duration, i.e. 5 minutes - 24 hours. In order to do this, the scaling characteristics of the AMS were used, which relate the mean of the AMS for the required duration to the mean of the 24 hour AMS (Smithers and Schulze, 2003). The slope of this relationship is estimated and used to determine the mean of the AMS for the required duration, as shown Figure 7.5 for Regional Cluster 1.

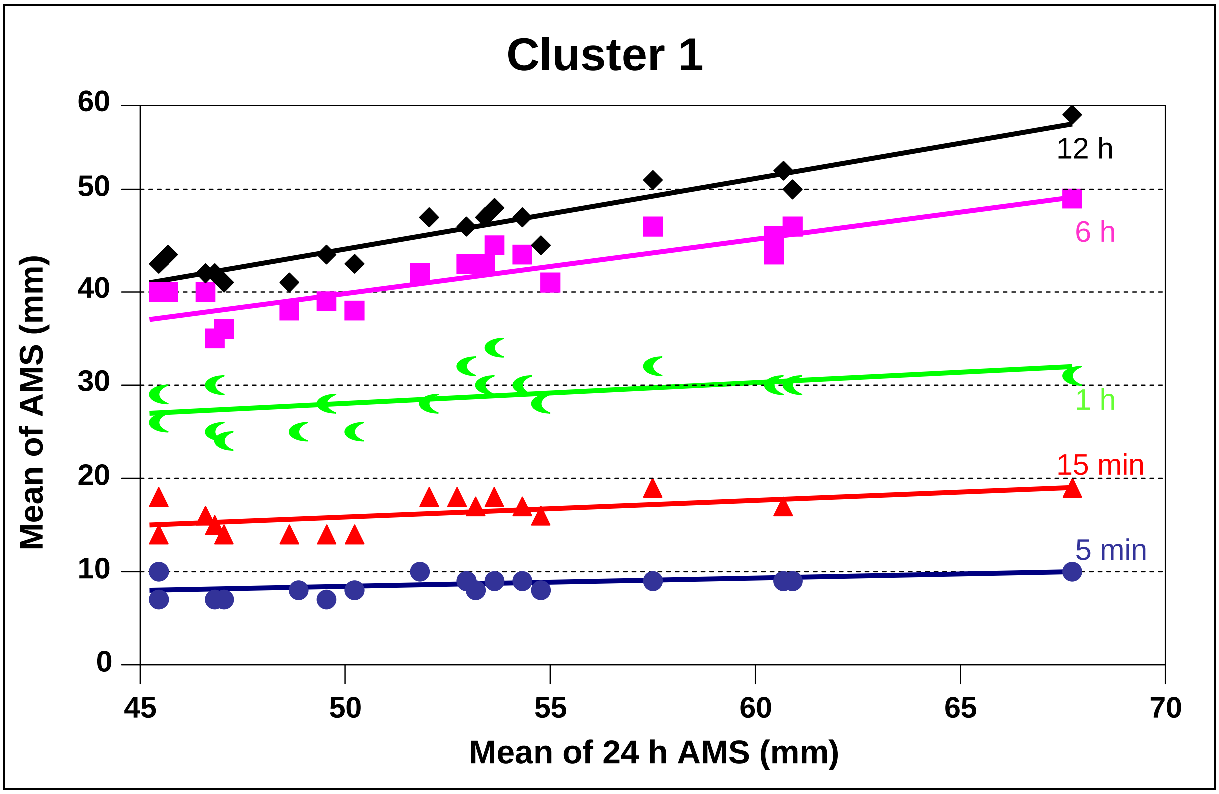


Figure 7.5 Example of the scaling of the AMS for a selected regional cluster (after Smithers and Schulze, 2003)

Thus, knowing the mean of the AMS for the required duration, design rainfall depths are calculated using Equation 7.8.

$$DRE_{i,\,j} = GC_{1\text{ day},\,j} \text{ x } L\_1_i \qquad (7.8)$$

where

$DRE_{i,\,j}$ = design rainfall estimate for duration = i and return period = j

$GC_{1\text{ day},\,j}$ = growth curve for one day duration and return period = j, and

L_1_i = mean of the AMS for duration = i estimated from the above procedures.

Using this approach short duration (5 min - 24 h) design rainfall, for the 2 year to 100 year return periods, could be calculated.

7.1.4.2 Methodology for the calculation of short duration design rainfalls from GCM-derived rainfall

When calculating short duration design rainfall for the five available GCMs, the above-mentioned technique needed to be modified slightly. Instead of using the program developed by Smithers and Schulze (2003) to estimate $L\_1_{1\ \mathrm{day}}$, the GCMs' daily rainfall records were processed and the $L\_1_{1\ \mathrm{day}}$ values were extracted for the defined "present climate" (1971 - 1990) from the GCMs. Using these values and the existing growth curves, the short duration design rainfall for the present climates simulated by the GCMs were then calculated.

Before applying the revised methodology of manually calculating the $L\_1_{1\ \mathrm{day}}$ and using the existing growth curves, it was necessary to verify that the scaling characteristics, such as those shown in Figure 7.5, would still be valid in a future climate. Owing to the lack of short duration climate change rainfall data, which are necessary to redevelop the scaling relationships for the short duration design rainfall estimates, the analysis was focussed on the scaling of the long duration GCM values, i.e. the two to seven day vs. one day, for both the intermediate future and distant future climates. It was postulated that if the long duration scaling relationships were consistent for projected future climates then the short duration relationships (i.e. D hour : 24 hour, for D < 24) would remain the same as those derived from the historical data.

In each of the seven relatively homogeneous regions (Figure 7.4) identified by Smithers and Schulze (2003) and used for the estimation of $L\_1_{1\ \mathrm{day}}$, the scaling relationship between the two day to seven day AMS means and $L\_1_{1\ \mathrm{day}}$ was investigated. This was achieved by plotting the mean of the two day AMS against the mean of the one day AMS for all stations in a particular region. The slope of the data was then calculated. Similarly, the slopes for the three day, four day, five day, six day and seven day AMSs to the one day AMS were calculated for each of the seven regions and for the climate scenarios for each of the five GCMs. By then plotting the slopes of the intermediate and future climates against slopes of the present climate it was possible to determine if the scaling of the long duration data was projected to change or not.

As shown in Figure 7.6, the slopes calculated from the intermediate and future climates are similar to those calculated from the present climate, with only the French GCMs, *viz*. CNRM-CM3 and IPSL-CM4, deviating slightly from the 1:1 slope. Therefore, the growth curves used to scale up from the mean of the one day AMS when estimating long duration design rainfall are postulated to remain relatively constant, and hence the growth curves used to estimate the short duration design rainfall are assumed to remain constant in the intermediate and more distant futures.

7.1.5 Results C: Projected changes in short duration design rainfalls with climate change in the intermediate and more distant futures

The spatial distribution of the projections for changes in short duration design rainfall, shown in Figure 7.7, are very similar to the one day, 2 year return period projections, with the intermediate future displaying a decreasing design rainfall trend in the central to western Vaal Catchment and extending into the southern regions of the Orange River Catchment, while the western and eastern regions of the Orange River Catchment both show projected increases. Table 7.2 shows that most of the projected increases in short duration design rainfalls are only slight, of the order of 1 - 10%, as is the case for the projected decreases.

There is a significant increase in the area projected to experience an increase in short duration design rainfall in the distant future, increasing from approximately 40% in the intermediate future, to over 70% in the distant future. Furthermore, it can be seen in Table 7.2 that the area projected to experience changes of greater magnitude also increases in the distant future. When considering only those ratios > 1, the smaller ratios in the eastern regions might have more devastating consequences than the larger ratios in the central to western regions owing to the historically higher rainfall in the east, where a single event can produce up to half, or more, of the MAP of some areas in the west of the Orange River Catchment.

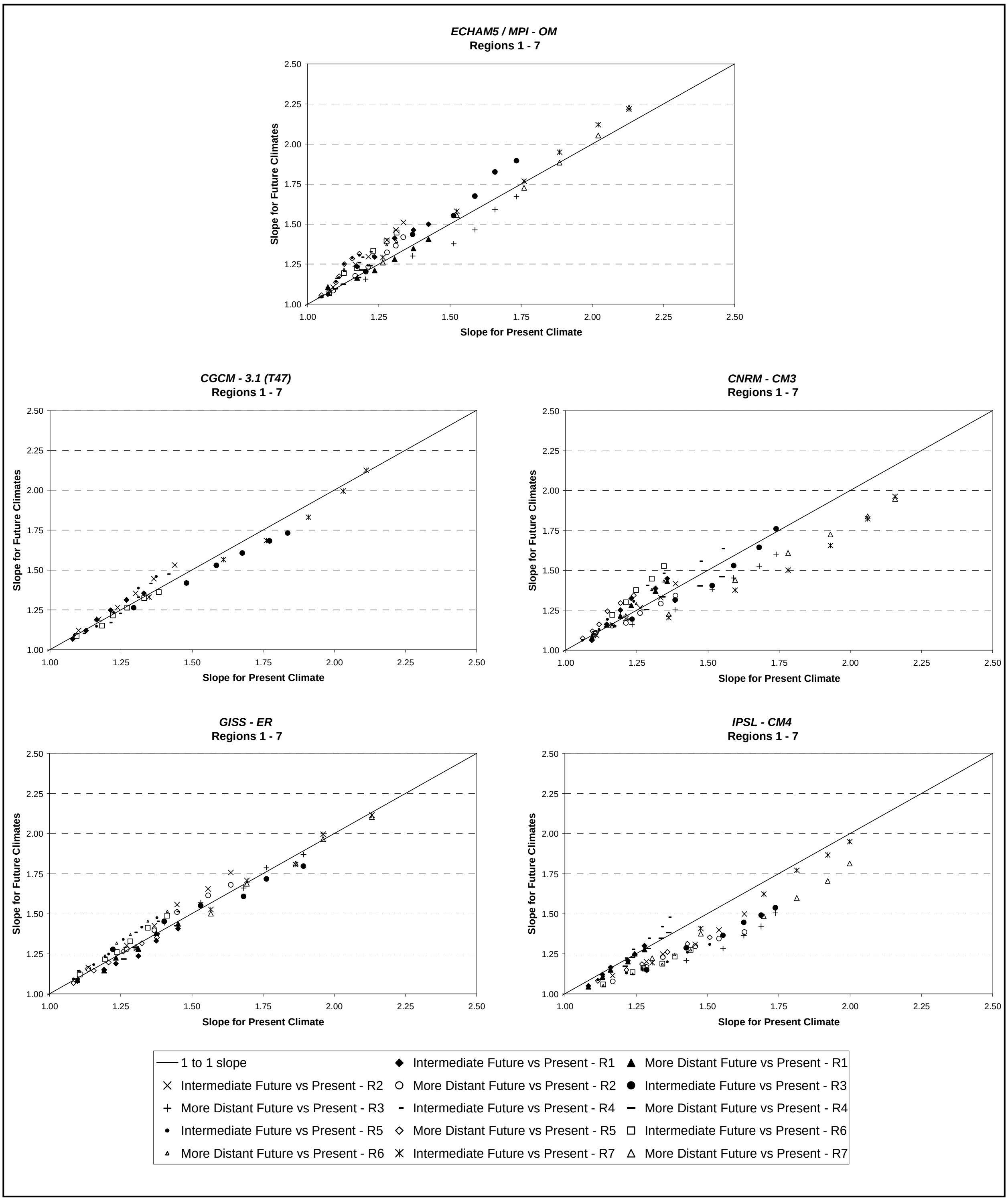


Figure 7.6 Comparison of intermediate future, and more distant future (where applicable), scaling relationships to present climate scaling relationships, for Region 1 (R1) to Region 7 (R7) in South Africa, calculated from GCM-derived rainfall output

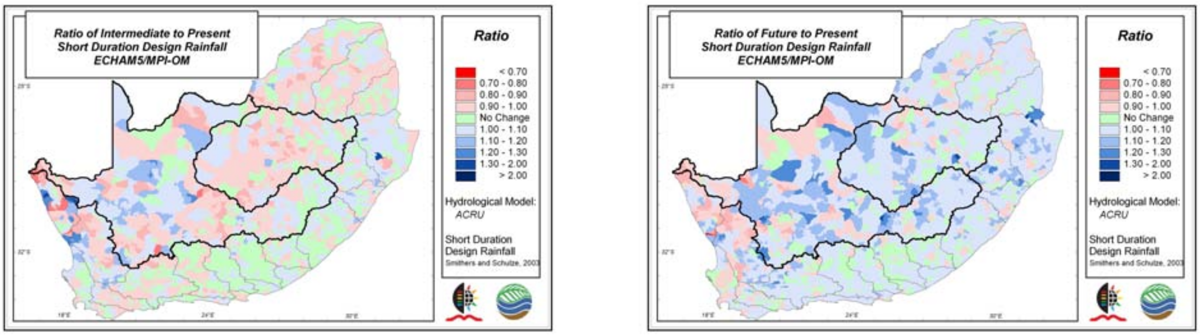


Figure 7.7 Ratios of intermediate future to present (left), and more distant future to present (right), short duration design rainfalls, derived from downscaled daily rainfall output from the ECHAM5/MPI-OM GCM

Table 7.2 Percentage area of the Orange River Catchment projected to experience an increase, decrease, or no change in short duration design rainfalls in the intermediate and more distant futures, derived from computations using downscaled daily rainfall output from the ECHAM5/MPI-OM GCM

Attribute	**Percentage Area of the Orange River Catchment**	
Ratio	**Intermediate Future**	**More Distant Future**
<0.7	0.0	0.0
0.7 - 0.8	0.5	0.0
0.8 - 0.9	6.4	2.0
0.9 - 1.0	31.2	14.4
No Change	21.5	12.2
1.0 - 1.1	31.0	41.4
1.1 - 1.2	8.1	24.7
1.2 - 1.3	1.3	5.1
1.3 - 2.0	0.0	0.2
Decreasing (i.e. < 1)	38.1	16.4
Increasing (i.e. > 1)	40.4	71.4

7.1.6 Methodology: How certain are we of changes in design rainfalls in the Orange River Catchment?

The IPCC has published an uncertainty guidance note (IPCC, 2007b) that defines a framework for the treatment of uncertainties. Where uncertainty is assessed quantitatively, the scale of confidence levels shown in Table 7.3 is used. Of the five GCMs available for this study, *viz*. CGCM3.1(T47), CNRM-CM3, ECHAM5/MPI-OM, GISS-ER and IPSL-CM4 (cf. Table 5.1), the more distant future scenario for the

CGCM3.1(T47) GCM was unavailable. Because downscaled daily outputs from only five (and in the case of the more distant future climates, only four) GCMs were available for this study, an adaptation of Table 7.3 has been developed, and is shown in Table 7.4.

Table 7.3 Scale of confidence levels for quantitative assessment of uncertainty as defined by the IPCC (IPCC, 2007b)

Confidence Terminology	Degree of confidence in being correct
Very high confidence	At least 9 out of 10 chance
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than 1 out of 10 chance

Table 7.4 Scale of confidence levels for quantitative assessment of uncertainty in this study

Confidence Terminology	Degree of confidence when 5 GCMs are used	Degree of confidence when 4 GCMs are used
Very high confidence	5 out of 5 GCMs give same signal	4 out of 4 GCMs give same signal
High confidence	4 out of 5 GCMs give same signal	3 out of 4 GCMs give same signal
Medium high confidence	3 out of 5 GCMs give same signal	N/A
Medium confidence	N/A	2 out of 4 GCMs give same signal
Medium low confidence	2 out of 5 GCMs give same signal	N/A
Low confidence	< 2 out of 5 GCMs give same signal	< 2 out of 4 GCMs give same signal

Owing to the discrepancy in the number GCMs available for the intermediate and more distant future scenarios, i.e. respectively five and four, comparing the results of the uncertainty analyses from the intermediate future with those of the more distant future may be misleading, and is not recommended. However, as this study has its focus on the development of techniques, which includes analytical techniques such as mapping and subsequent interpretations, comparisons between the intermediate and more distant futures have been made. The demonstrated techniques in the remaining sections may then be applied by decision-makers in situations where more GCMs, and more SRES emission scenarios, are available for both the intermediate and more distant futures, so that meaningful results can be obtained on which to base decisions.

7.1.7 Results D: Uncertainty analysis of projected changes in long duration design rainfalls with climate change in the intermediate and more distant futures

The general consensus from the selected GCMs is one of concurrence with the hypothesis that long duration design rainfall will increase in the intermediate and more distant futures, as shown in Figures 7.8 and 7.9, respectively. Furthermore, it appears that there is more confidence in the hypothesis for the more distant future climate scenario than that for the intermediate future. It should be noted, however, that the area displaying medium confidence (shaded blue in the maps) in the distant future may be misleading (cf. Section 7.1.6) as this is the result of only two out of four GCMs in agreement with the hypothesis, compared to the three out of five required for medium high confidence in the intermediate future scenarios.

For the intermediate future, Figure 7.8 shows that there is an increase in confidence, in a westward direction, that one day duration design rainfalls will increase in magnitude. This observation is no longer evident for the three day duration, and appears to reverse for the seven day duration, for which an increase in concurrence in an eastward direction is shown. For the more distant future, although lacking the apparent westwards increase in concurrence at the one day duration, which was evident for the intermediate future, a similar spatial trend seems to follow with an increase in concurrence in an eastward direction as the event duration is increased (Figure 7.9).

Within a particular scenario there are two trends that stand out. Firstly, the area of the Orange River Catchment with medium (or higher than medium) confidence generally increases from the one day duration through to the seven day duration, i.e. the longer the duration of the design rainfalls, the greater the confidence that they will increase. Secondly, the area of the Orange River Catchment with medium (or higher) confidence appears to decrease as the return period increases, i.e. the higher the return period, the lower the levels of confidence that the long duration design rainfall will increase. This is confirmed by the statistics in Table 7.5, where it is also shown that these trends are present for the percentage area with high confidence (or

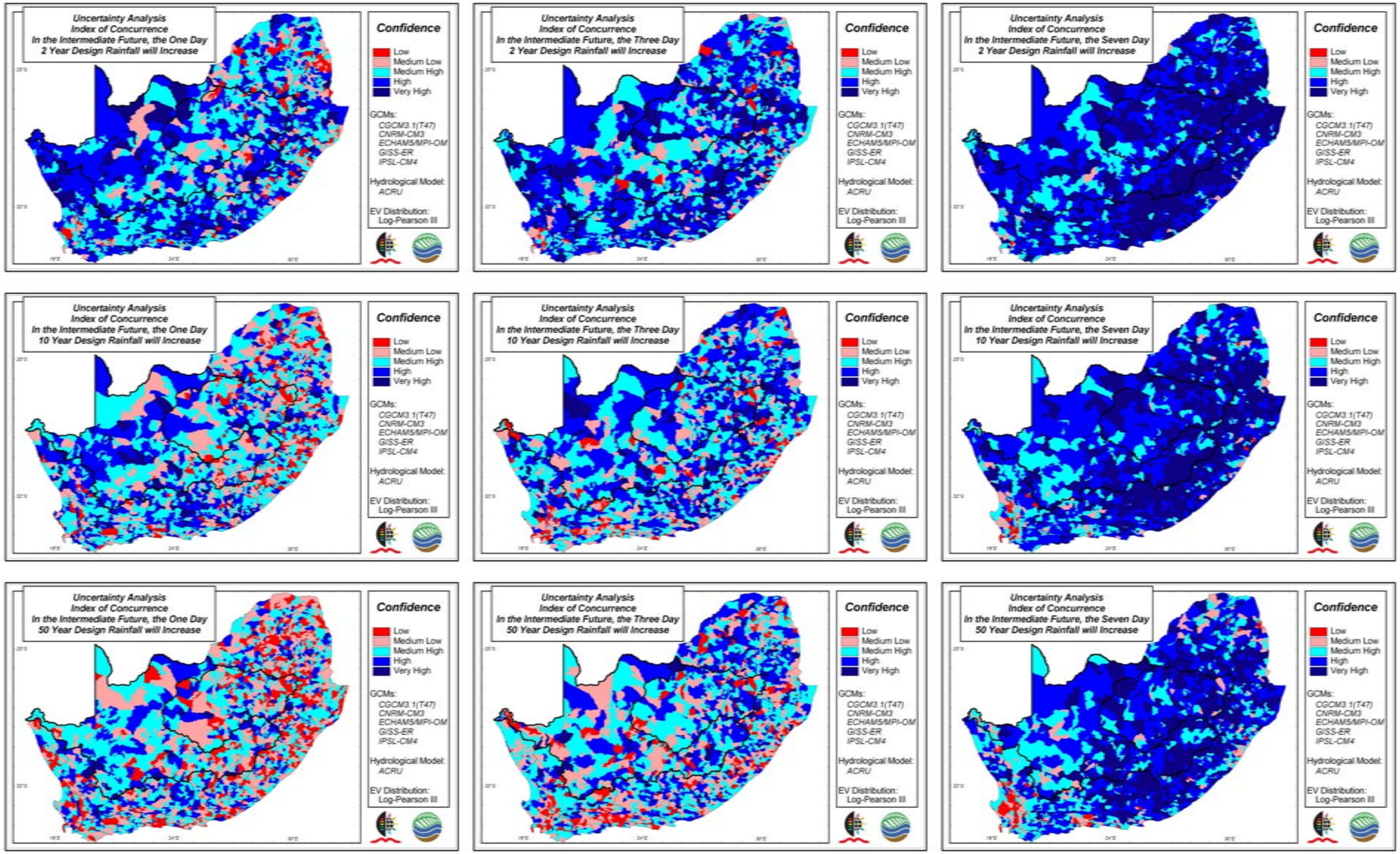


Figure 7.8 Levels of confidence in the hypothesis that long duration design rainfalls of increasing duration (left to right) and increasing return period (top to bottom) will increase in the intermediate future, derived from downscaled daily rainfall output from multiple GCMs

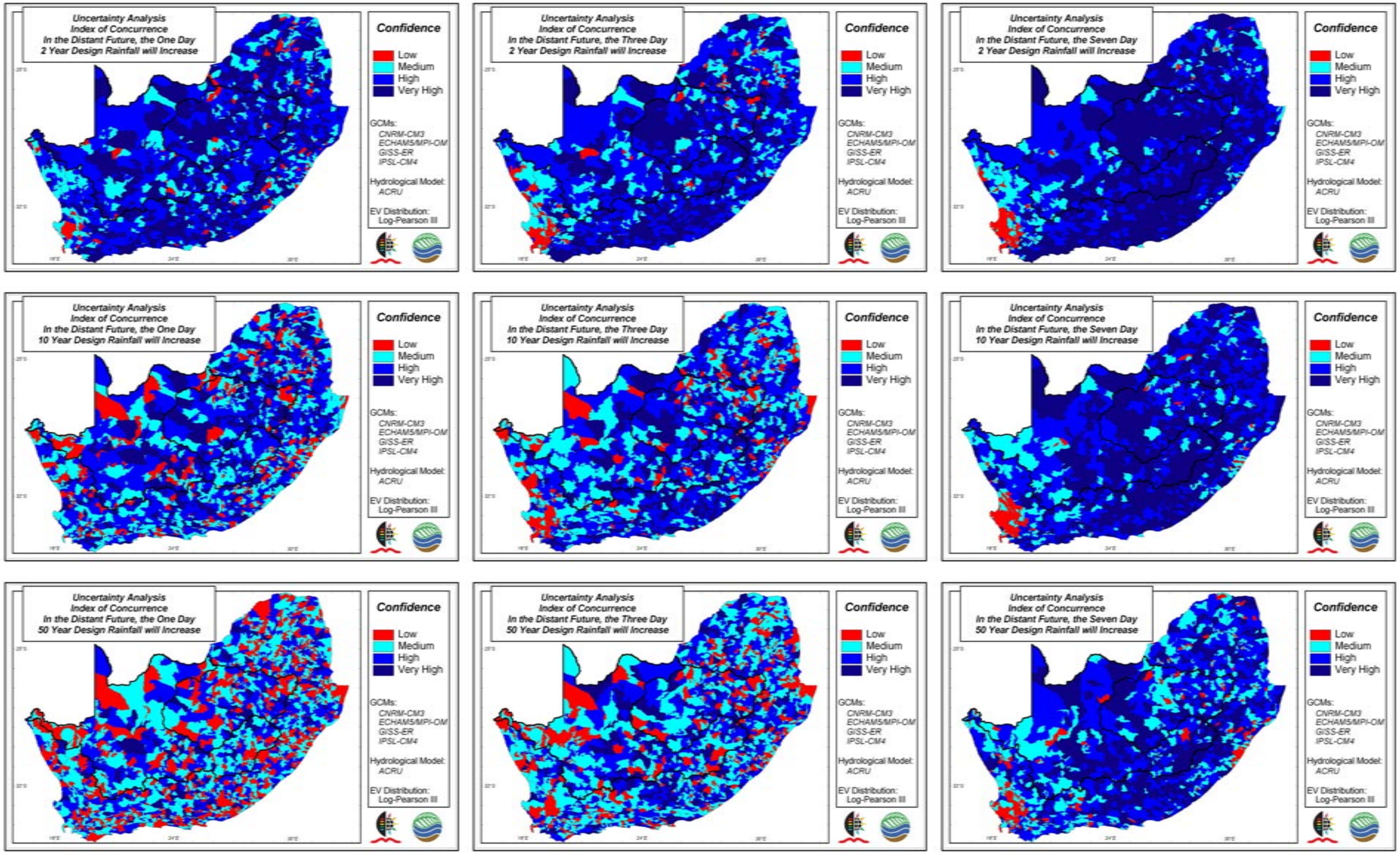


Figure 7.9 Levels of confidence in the hypothesis that long duration design rainfalls of increasing duration (left to right) and increasing return period (top to bottom) will increase in the more distant future, derived from downscaled daily rainfall output from multiple GCMs

greater). An analysis of the results in Table 7.6, which shows the projected direction of change based on the agreement of three or more GCMs, indicates that while confidence in the hypothesis increases with increasing duration and decreasing return period, the opposite occurs for projected decreases in design rainfall, while the area that has no projected changes is little affected.

Table 7.5 Percentage area of the Orange River Catchment with medium (or greater) and high (or greater) confidence in the hypothesis that long duration design rainfalls will increase in the intermediate and more distant futures, derived from computations using downscaled daily rainfall output from the five GCMs used in this study

Attribute		Percentage Area of the Orange River Catchment					
		Intermediate Future			More Distant Future		
Confidence	Return Period	One Day	Three Day	Seven Day	One Day	Three Day	Seven Day
Medium +	**2 Year**	85.8	90.5	99.4	98.3	98.1	99.9
Medium +	**10 Year**	75.0	83.5	99.7	86.4	90.5	99.6
Medium +	**50 Year**	63.4	69.3	95.9	76.7	81.7	97.3
High +	**2 Year**	57.6	57.6	81.0	84.6	85.1	93.3
High +	**10 Year**	38.1	50.0	80.7	63.9	61.1	85.9
High +	**50 Year**	24.2	33.2	74.4	41.2	47.3	77.4

Table 7.6 Percentage area of the Orange River Catchment projected by > 50% of the GCMs used in this study to experience an increase, decrease, or no change in long duration design rainfalls in the intermediate and more distant futures

Attribute		Percentage Area of the Orange River Catchment					
		Intermediate Future			More Distant Future		
Return Period	Direction of Change	One Day	Three Day	Seven Day	One Day	Three Day	Seven Day
2 Year	**Decrease**	4.1	3.0	0.0	1.0	0.7	0.0
	Increase	85.8	90.5	99.4	84.6	85.1	93.3
	Same	0.6	0.3	0.0	0.1	0.1	0.0
	Inconclusive	9.5	6.2	0.6	14.3	14.1	6.7
10 Year	**Decrease**	12.4	10.1	0.1	5.6	2.5	0.1
	Increase	75.0	83.5	99.7	63.9	61.1	85.9
	Same	1.1	0.3	0.0	0.1	0.1	0.0
	Inconclusive	11.5	6.1	0.2	30.4	36.3	14.0
50 Year	**Decrease**	23.6	17.9	1.8	17.2	11.7	1.5
	Increase	63.4	69.3	95.9	41.2	47.3	77.4
	Same	0.4	0.1	0.0	0.1	0.0	0.0
	Inconclusive	12.6	12.7	2.3	41.5	41.0	21.1

Since it was decided that *more* than half of the GCMs – i.e. at least three GCMs for the intermediate and more distant future scenarios – had to agree in order to allocate a direction of change, the limitations of only having four GCMs for the more distant future climate scenario become immediately apparent in Table 7.6, where it appears that more of the Orange River Catchment is projected to experience increases in design rainfalls in the intermediate future than in the more distant future. This is contrary to the findings using output from the ECHAM5/MPI-OM GCM (cf. Figures 7.3 and 7.4). Furthermore, it is evident that the percentage area of the Orange River Catchment for which a direction of change is inconclusive is shown to increase for the more distant future scenario. This is likely to be the result of only having four GCMs for the more distant future analysis.

It was shown above that the level of concurrence with the hypothesis, *viz*. that design rainfalls would increase in the future, decreases with return period. Table 7.7 shows that, regardless of the direction of projected change, there is less agreement between the GCMs when the return period is increased. This can also be seen diagrammatically in Figures 7.8 and 7.9, which show that the spatial variation of confidence becomes increasingly erratic with increasing return period.

Table 7.7 Percentage area of the Orange River Catchment with various levels of GCM agreement on projecting a direction of change in long duration design rainfalls in the intermediate and more distant futures*

Attribute		**Percentage Area of the Orange River Catchment**					
		Intermediate Future			**More Distant Future**		
Return Period	**Agreement of GCMs**	**One Day**	**Three Day**	**Seven Day**	**One Day**	**Three Day**	**Seven Day**
2 Year	**5 GCMs**	15.9	17.0	35.5			
	4 GCMs	41.9	40.8	45.4	40.7	36.9	55.9
	3 GCMs	32.6	36.0	18.5	44.9	49.1	37.4
	High Confidence +	57.8	57.8	81.0	85.6	85.9	93.3
10 Year	**5 GCMs**	5.9	9.3	34.0			
	4 GCMs	33.7	42.6	46.7	23.9	23.5	50.8
	3 GCMs	49.0	42.0	19.1	45.8	40.2	35.2
	High Confidence +	39.6	51.9	80.7	69.6	63.8	86.0
50 Year	**5 GCMs**	3.1	5.0	29.9			
	4 GCMs	27.0	32.2	44.5	9.9	17.1	36.0
	3 GCMs	57.4	50.2	23.3	48.6	41.9	42.9
	High Confidence +	30.1	37.2	74.4	58.5	59.0	78.9

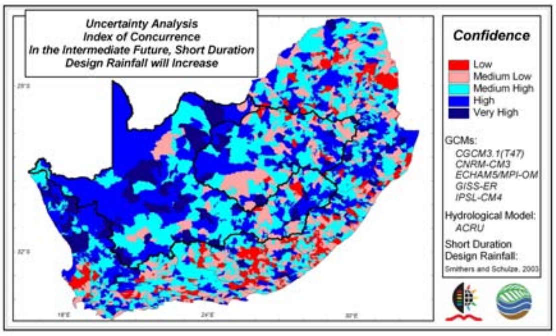
*** Shaded area implies non-applicable case**

These findings may be indicative of the uncertainty surrounding the ability of the GCMs to simulate extreme events. Furthermore, these results indicate that the 20 year simulation period may be too short for design rainfall estimations to display high confidence, particularly when extrapolating to design rainfalls for return periods higher than 20 years.

There is, however, an increase in agreement between the GCMs as the duration of the design rainfalls increase beyond one day. This is hypothesised to be related to the GCMs' reduced ability to simulate daily events, particularly for extremes, a problem which largely self-corrects when rainfalls are accumulated over a number of days.

7.1.8 Results E: Uncertainty analysis of projected changes in short duration design rainfalls with climate change in the intermediate and more distant futures

As was the case for the long duration design rainfall, short duration design rainfall is projected, with medium confidence (or greater), to increase over most of the Orange River Catchment for both intermediate and more distant future climate scenarios (Figure 7.10). Furthermore, the area showing high confidence (or greater) covers more than half of the Orange River Catchment (Table 7.8). Another trend that is present for the short duration design rainfall projections that was noticeable for the longer durations, is that there is an increase in the area projected to experience increases in design rainfall from the intermediate to distant future. It can be seen in Table 7.8, however, that the changes in area are relatively small compared to those projected for the longer durations.



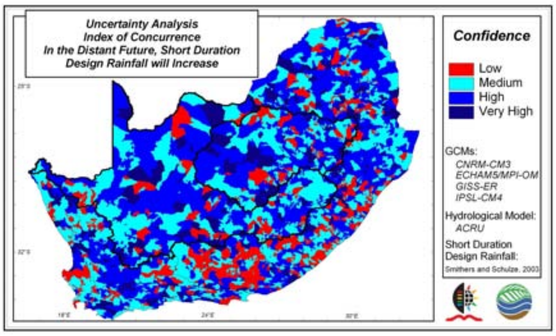


Figure 7.10 Levels of confidence in the hypothesis that short duration design rainfalls will increase in the intermediate future (left) and more distant future (right), derived from downscaled daily rainfall output from multiple GCMs

Table 7.8 Percentage area of the Orange River Catchment with medium (or greater) and high (or greater) confidence in the hypothesis that short duration design rainfalls will increase in the intermediate and more distant futures, derived from computations using downscaled daily rainfall output from the five GCMs used in this study

Attribute	**Percentage Area of the Orange River Catchment**	
Confidence	**Intermediate Future**	**More Distant Future**
Medium +	85.5%	90.1%
High +	54.9%	58.2%

7.1.9 Summary of main findings

- Both short duration and long duration design rainfalls are projected to increase over vast portions of the Orange River Catchment in the intermediate future, and even more so in the more distant future.
- As the duration of long duration design rainfalls is increased from one day to seven days, a greater area of the Orange River Catchment is projected to be affected by increases in design rainfalls.
- As the return period of long duration design rainfalls is increased from 2 years to 50 years, so a smaller area of the Orange River Catchment is projected to be affected by design rainfall increases.
- The GCMs used in this study show greater agreement as the duration of design rainfall is increased from one to three to seven days.

- The GCMs used in this study show less agreement as the return period is increased, from 2 to 10 to 50 years.
- The GCMs used in this study appear to show more agreement in the more distant future than they do in the intermediate future.

7.2 Design Floods

This section on design floods has been divided into two sub-sections, *viz*. the flood volume (Section 7.2.1) and peak discharge (Section 7.2.2). The flood volume, i.e. the total quantity of water flowing past a particular point for a given duration, is an important factor when considering the design and operation of flood protection structures, such as flood control reservoirs (Smith and Ward, 1998). The peak discharge of a flood, on the other hand, is an important indicator of the potential for maximal inundation and greatest damage (Smith and Ward, 1998). From here on the term *design streamflow* will be used when describing design flood volumes (or their equivalent depths in mm) calculated from the accumulated streamflows from all subcatchments upstream of a point of interest, while *design peak discharge* will be used when describing design flood peaks from individual subcatchments.

7.2.1 Design streamflow

This section commences with a short description of the methodology used in the computation of design streamflows, followed by the ensuing results. The section concludes with an uncertainty analysis of the projected design streamflows derived from the five GCMs used in this study.

7.2.1.1 Methodology: Computation of design streamflows

As was the case with design rainfalls, the Log-Pearson Type III extreme value distribution (cf. Section 7.1) was used with the Annual Maximum Series to compute the one, two, three and seven day design streamflow magnitudes for the 2, 5, 10, 20, 50 and 100 year return periods. The design streamflows were simulated with the daily time step *ACRU* agrohydrological model (Schulze, 1995 and updates - cf. Section 6.1) using climate, soils and land cover from the South African QnCD

(Schulze and Horan, 2009; Schulze *et al.*, 2009a). Simulated runoff from individual Quinaries were summed as flows cascaded downstream to then give values of accumulated streamflows. Design streamflows at each Quinary's exit were then calculated, from which selected results are presented below.

7.2.1.2 Results F: Spatial patterns of the one to seven day design streamflow magnitudes for selected return periods, modelled using historical observed climate data, per Quinary Catchment

In Figures 7.11 and 7.12, design streamflows are shown to increase with both return period and duration, as would be expected. Furthermore, it can be seen in Figure 7.11 that the design flood estimates, when expressed in millions of m^3, increase along the length of a river, again as expected. This, together with larger Quinary Catchments in the western regions of the Orange River Catchment compared to those in the east, results in the general impression that the magnitude of flooding for a given probability of recurrence increases from east to west. However, when design floods are expressed in *depth* equivalents, i.e. in mm and therefore negating the influence of catchment area, it is shown that the most severe floods in the Orange River Catchment generally occur in eastern regions and that the relative magnitudes decrease westwards. This spatial pattern is similar to that of design rainfalls (cf. Figure 7.1) and indicates that the larger flood events, per unit of area, generally occur in those areas that experience larger rainfall events.

7.2.1.3 Results G: Projected changes in design streamflows with climate change in the intermediate and more distant futures

In Figures 7.13 and 7.14, the projected ratio changes in design streamflows for selected return periods and durations, and generated from the ECHAM5/MPI-OM GCM climate output, are shown for the intermediate and more distant futures, respectively. The spatial distribution of the projected changes for the one day, 2 year return period in the intermediate future (Figure 7.13: top left) is very similar to that of the one day, 2 year return period design rainfalls (cf. Figure 7.2: top left), i.e. the eastern parts of the Orange River Catchment are tending towards an increase in design streamflows; a band of predominantly decreasing design streamflows extends

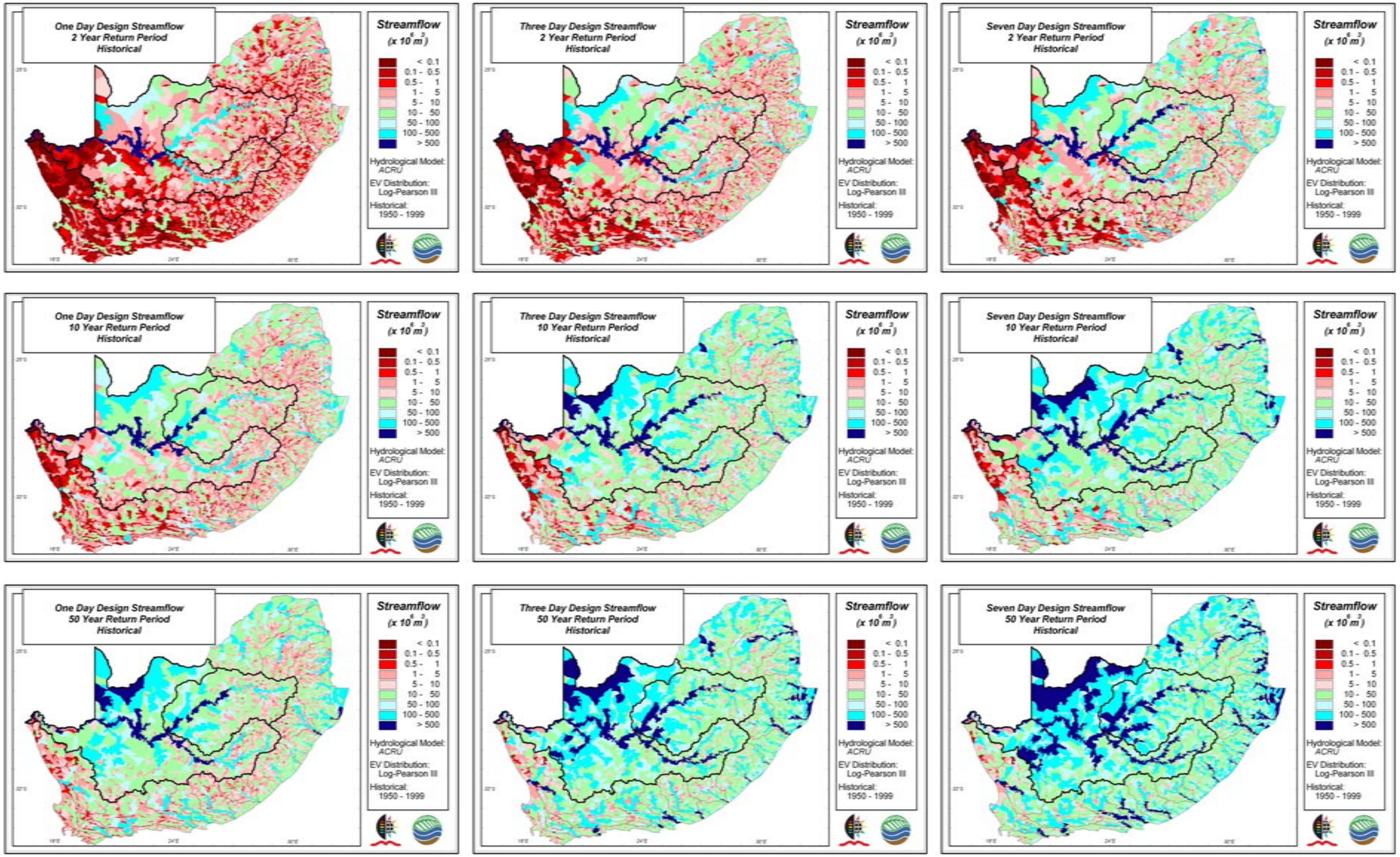


Figure 7.11 Design streamflow volumes (10^6 m^3) for selected return periods and durations, derived from *ACRU* simulations using historical daily climate data from the QnCD

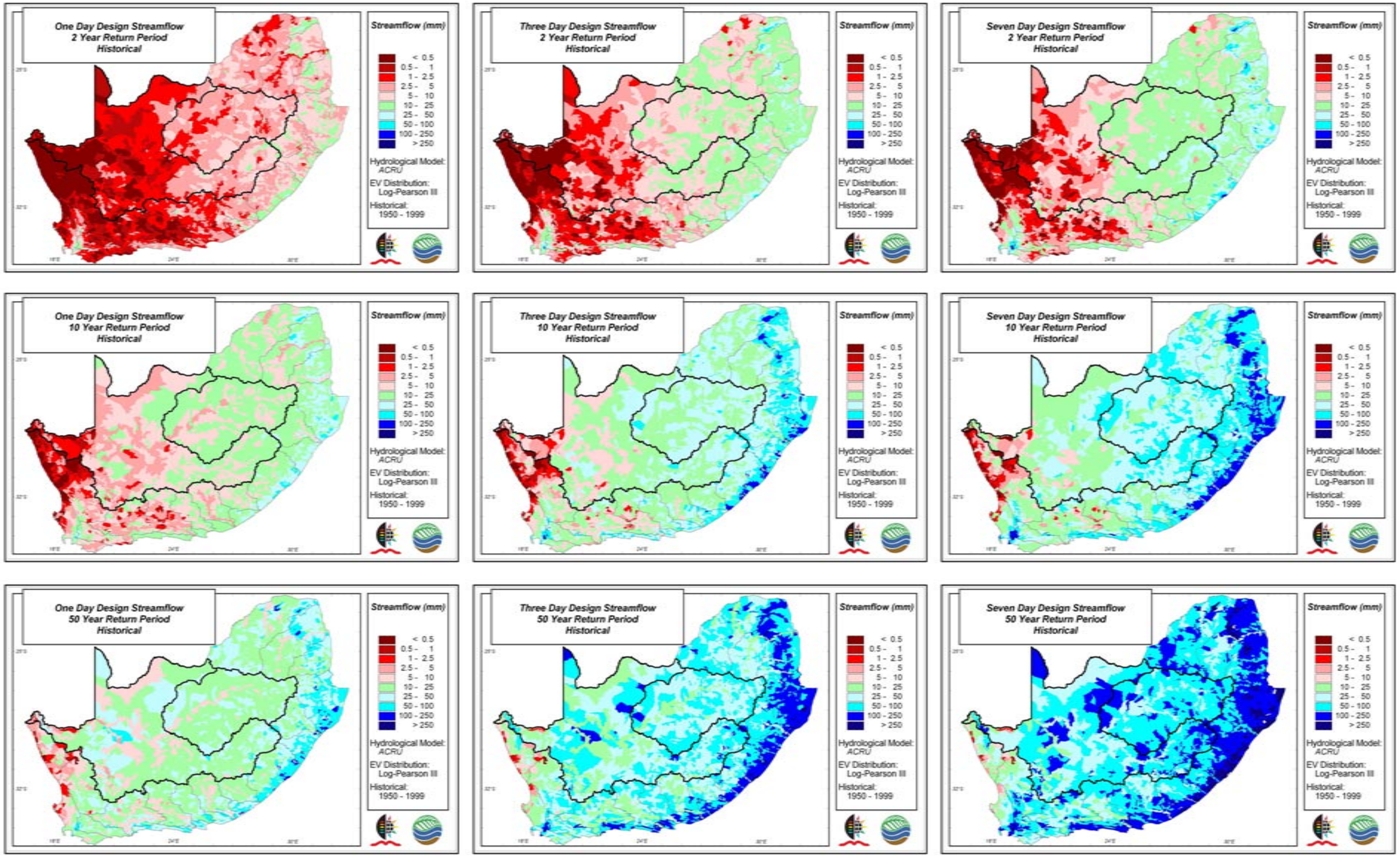


Figure 7.12 Design streamflow depths (mm) for selected return periods and durations, derived from *ACRU* simulations using historical daily climate data from the QnCD

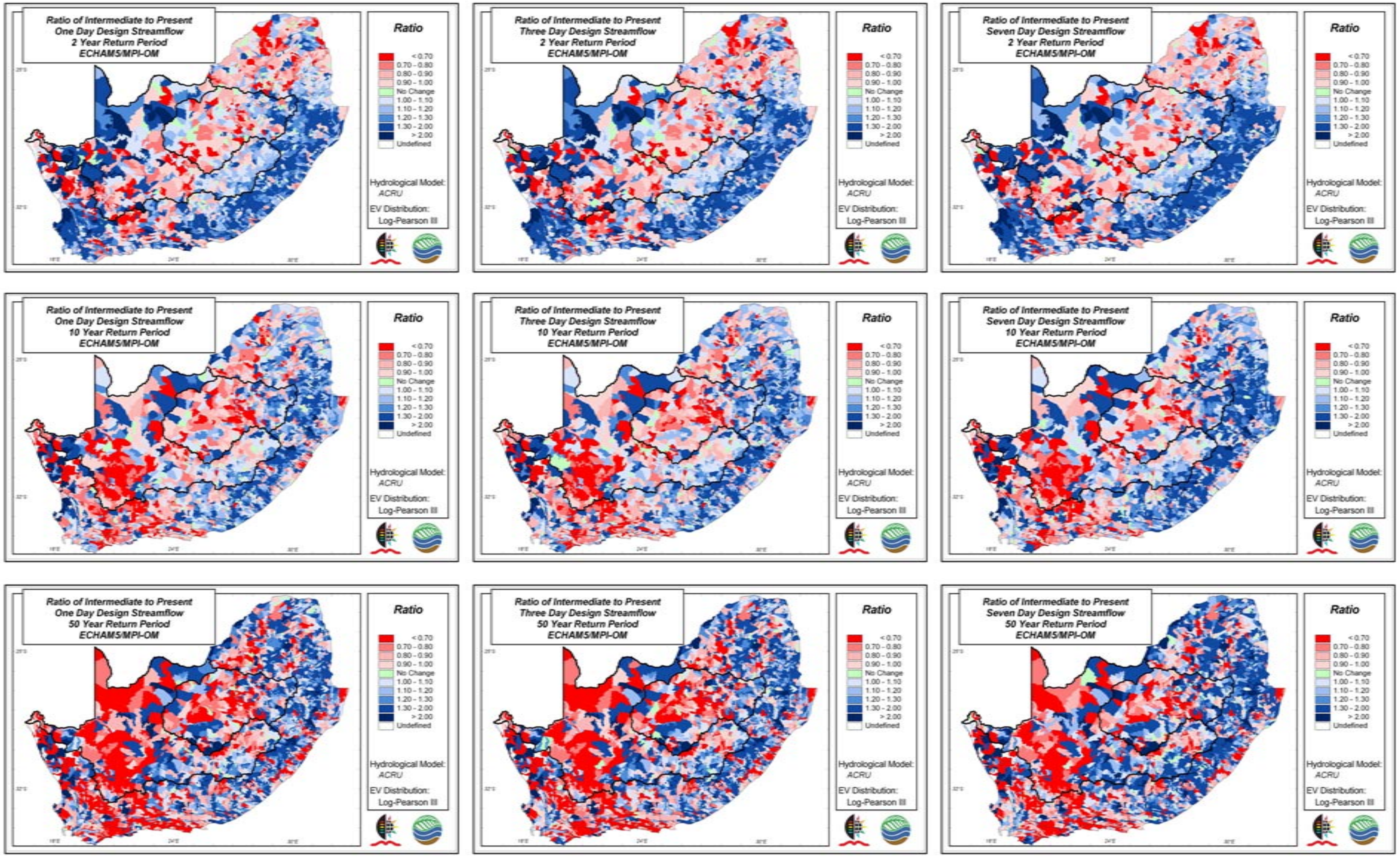


Figure 7.13 Ratios of intermediate future to present design streamflows for selected return periods and durations, derived from *ACRU* simulations using downscaled daily climate output from the ECHAM5/MPI-OM GCM

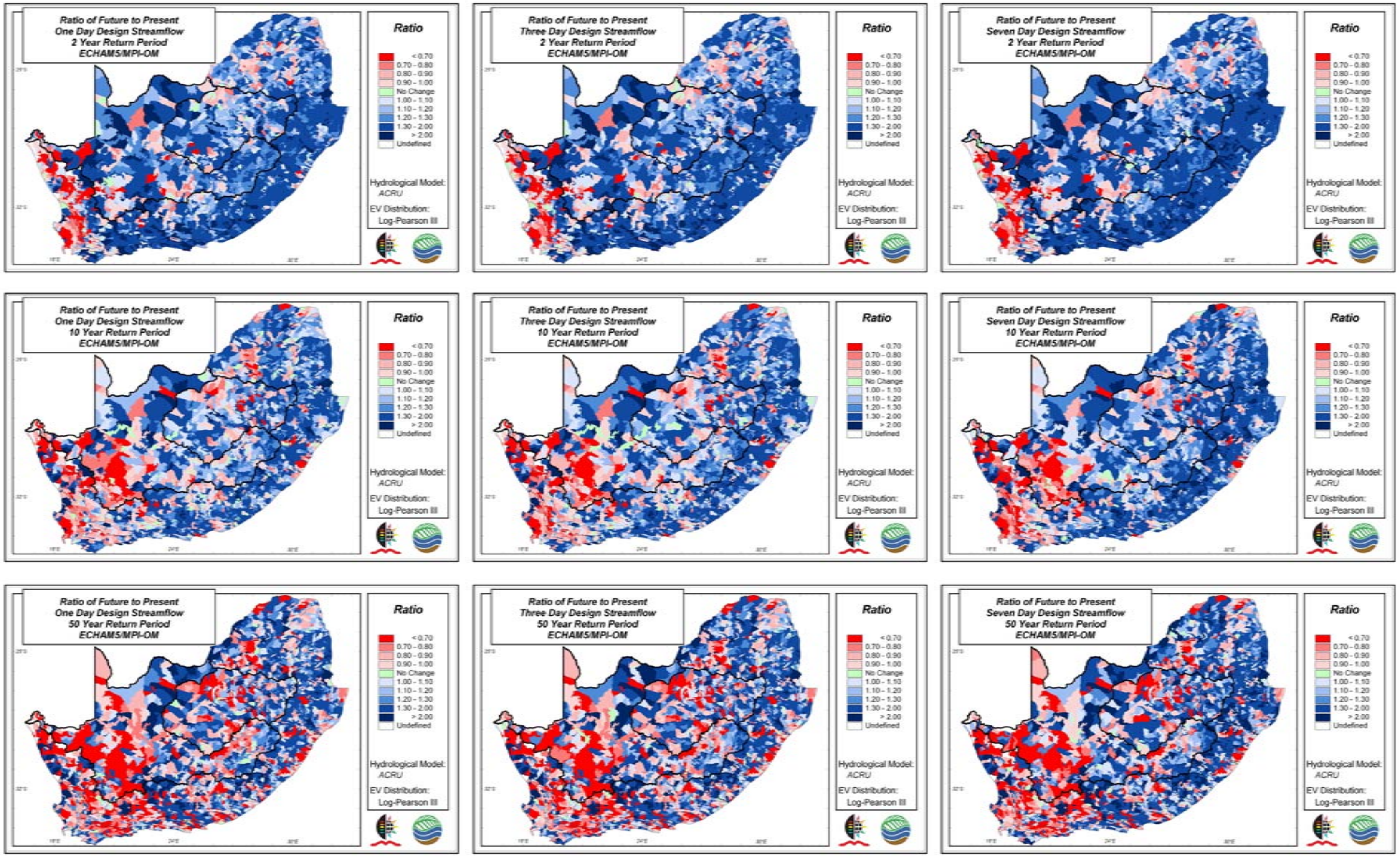


Figure 7.14 Ratios of more distant future to present design streamflows for selected return periods and durations, derived from *ACRU* simulations using downscaled daily climate output from the ECHAM5/MPI-OM GCM

from the northeast of South Africa, across a vast area of the Vaal River Catchment and southern regions of the Orange River Catchment to the southwest of South Africa; and west of this band, in the semi-arid parts of the Orange River Catchment, predominantly increasing design streamflow values are indicated.

Although the spatial distributions of the increases and decreases appear relatively similar for the one day, 2 year design rainfalls and design streamflows, a notable difference is the intensification of the magnitudes of change between design rainfalls, where only 10% of the Orange River Catchment is projected to experience a change in magnitude of greater than 20%, and design streamflows, where approximately 45% of the catchment is projected to experience a change in magnitude in excess of 20%. This is indicative of how changes in rainfall may become amplified by the hydrological system.

Unlike design rainfalls, which shows an intensification of the increasing trend as the duration is increased from one day to seven days, the distribution of projected ratio increases and decreases in design streamflows in the intermediate future remain relatively constant for all durations, from one to seven days, for the 2 year return period, as shown in Table 7.9. Furthermore, it may be seen that the higher return periods, *viz*. those of 10 and 50 years, do show a slight growth of the area projected to experience larger design streamflows in the intermediate future. However, this change is not enough to influence the spatial distribution of projected increases and decreases in design streamflows, which remains relatively constant for all durations for a given recurrence interval, as shown when moving across from the left to the right maps in Figure 7.13.

As was the case for the design rainfalls, when moving from top to bottom of Figure 7.13, from the 2 year to the 10 year and 50 year return periods for a particular duration, it may be seen that the area projected to experience increases in design streamflows is shrinking, while the area projected to experience a decrease in design streamflows is growing. Although the spatial distribution does become somewhat less distinct with increasing return period, the spatial trend is not lost completely, as was the case with the design rainfalls. Instead, as the return period is increased the band of projected decreasing design streamflows that extended from the northeast to the southwest of the Orange River Catchment begins to extend westwards, while also increasing in magnitude, particularly in the western areas. This change in magnitude of the decreases in design streamflows that is noticeable when increasing the return period can also be seen in Table 7.9, where the area projected to experience a decrease in design streamflows by 30%, or more, doubles from the 2 year to 10 year return period, and almost doubles again from the 10 year to 50 year return period.

Table 7.9 Percentage area of the Orange River Catchment projected to experience an increase, decrease, or no change in design streamflows in the intermediate and more distant futures, derived from computations using downscaled daily climate output from the ECHAM5/MPI-OM GCM

Attribute		Percentage Area of the Orange River Catchment					
		Intermediate Future			More Distant Future		
Return Period	**Direction of Change**	**One Day**	**Three Day**	**Seven Day**	**One Day**	**Three Day**	**Seven Day**
2 Year	**No Change**	5.6	5.4	4.9	3.4	2.3	1.3
	Decrease	37.9	38.9	38.4	15.9	16.2	15.7
	Increase	56.5	55.7	56.7	80.7	81.5	83.0
	Decrease > 30%	7.4	7.5	7.2	3.0	3.0	2.8
	Increase > 30%	21.4	21.4	22.0	41.5	44.0	50.2
10 Year	**No Change**	4.9	4.9	4.0	6.0	5.2	2.5
	Decrease	52.6	51.1	46.3	29.3	29.7	25.7
	Increase	42.5	44.0	49.7	64.7	65.1	71.8
	Decrease > 30%	15.2	14.4	13.7	7.6	7.3	6.9
	Increase > 30%	14.5	15.2	19.4	29.3	29.7	35.3
50 Year	**No Change**	2.5	2.7	3.6	2.5	3.1	1.2
	Decrease	59.4	57.7	50.1	47.0	44.9	41.0
	Increase	38.1	39.6	46.3	50.5	52.0	57.8
	Decrease > 30%	26.7	26.1	21.8	17.6	16.2	15.8
	Increase > 30%	20.7	21.0	25.0	26.3	27.4	31.5

Shifting the focus to the Orange River itself, and its primary tributaries, *viz*. the Vaal River within South Africa and the Caledon River bordering with Lesotho (cf. Figure 1.3), it may be seen that at the 2 year return period the whole of the Orange River is projected to experience an increase in design streamflows when using output from the ECHAM5/MPI-OM GCM. This includes the primary tributaries. This increase is even present in those areas that are generally showing a decreasing trend, *viz*. the band of predominantly decreasing design streamflows that extend from the northeast of South Africa to the southwest of South Africa, and is a result of the accumulation of increased flows from the east. As shown for the overall spatial trends (Figure

7.13), design streamflows appear to increase further with increasing duration, and decrease with increasing return period. Furthermore, the ratios of intermediate future to present design streamflows decrease downstream. For the 10 and 50 year return period design streamflows of one day's duration, it is seen that the lower reaches of the Orange River are showing decreases in design streamflow magnitudes, while the upper reaches in the east are still projected to experience an increase in flooding. However, these increases in the east are limited to the main-stem of the Orange River, as the Vaal and Caledon rivers, by and large, indicate decreasing design streamflows for all durations at the 10 year and 50 year return periods.

In the more distant future (Figure 7.14), it is projected from ECHAM5/MPI-OM GCM output that a significantly greater area of the Orange River Catchment is likely to experience increases in design streamflows when compared to those from the intermediate future projection. Furthermore, there is also a growth in the area which is projected to experience increases that are 30% or greater than present design streamflows when moving from the projected climates of the intermediate future to those of the more distant future.

The one day, 2 year return period design streamflows in the more distant future are projected to increase across approximately 80% of the Orange River Catchment, with a band of decreasing design streamflows to the west of the catchment and extending along the west coast of South Africa. As seen for the intermediate future projections, although there is a slight growth in the area projected to experience increases in design streamflows with increasing duration, the spatial distribution is maintained from the one day through to the seven day duration.

Also seen in the intermediate future projections is the trend of a growing area projected to experience a decrease in design streamflows with increasing return period. This is shown when moving from the top to the bottom maps in Figure 7.14, as the band of projected decreases on the west coast of South Africa expands eastwards into, and across, the Orange River Catchment.

The trends projected from ECHAM5/MPI-OM GCM output and simulated with the *ACRU* model for the Orange River and its primary tributaries in the more distant future, are similar to those noted above for the intermediate future. The magnitudes of the projected increases in the more distant future are generally in the order of 10 - 20% greater than those projected for the intermediate future. Another difference between the intermediate and more distant future projections may be seen at the 10 year return period, where the upper reaches of the Orange River, including the main tributaries, are projected to experience increases in design streamflows in the more distant future – an observation that was not present for the intermediate future projections.

7.2.1.4 Methodology: How certain are we of changes in design streamflows in the Orange River Catchment?

As with design rainfalls (cf. Section 7.1.6), a quantitative uncertainty assessment was performed for the intermediate future, and more distant future, design streamflow projections using the scale described in Table 7.4. The intermediate future is assessed using five GCMs, *viz*. CGCM3.1(T47), CNRM-CM3, ECHAM5/MPI-OM, GISS-ER and IPSL-CM4. The distant future is assessed with only four of the above-mentioned GCMs as the distant future scenario for the CGCM3.1(T47) model was unavailable.

7.2.1.5 Results H: Uncertainty analysis of projected changes in design streamflows with climate change in the intermediate and more distant futures

As was the case for the design rainfall projections, the general consensus from the selected GCMs is one of concurrence with the hypothesis that design streamflows will increase with climates of the intermediate and more distant futures, as shown in Figures 7.15 and 7.16, respectively. Furthermore, it appears that the area of the Orange River Catchment displaying medium confidence, or greater, increases from the intermediate to distant future. However, as was noted in the corresponding design rainfall section (Section 7.1.5), the area displaying medium confidence in the distant future may be misleading, as this is the result of only two out of four GCMs being in agreement with the hypothesis, compared to the three out of five required for the intermediate future scenarios.

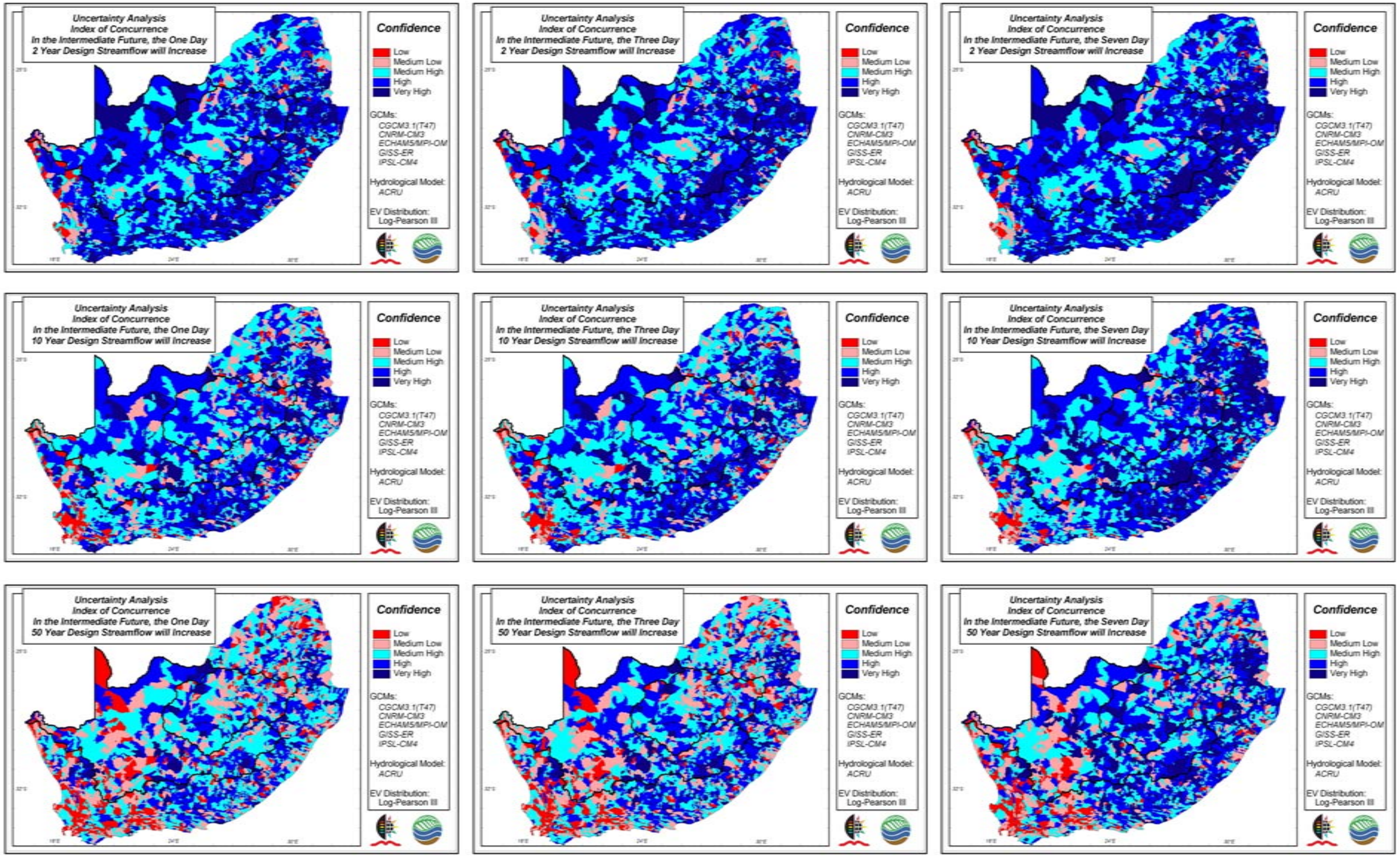


Figure 7.15 Levels of confidence in the hypothesis that long duration design streamflows of increasing duration (left to right) and increasing return period (top to bottom) will increase in the intermediate future, derived from *ACRU* simulations using downscaled daily climate output from multiple GCMs

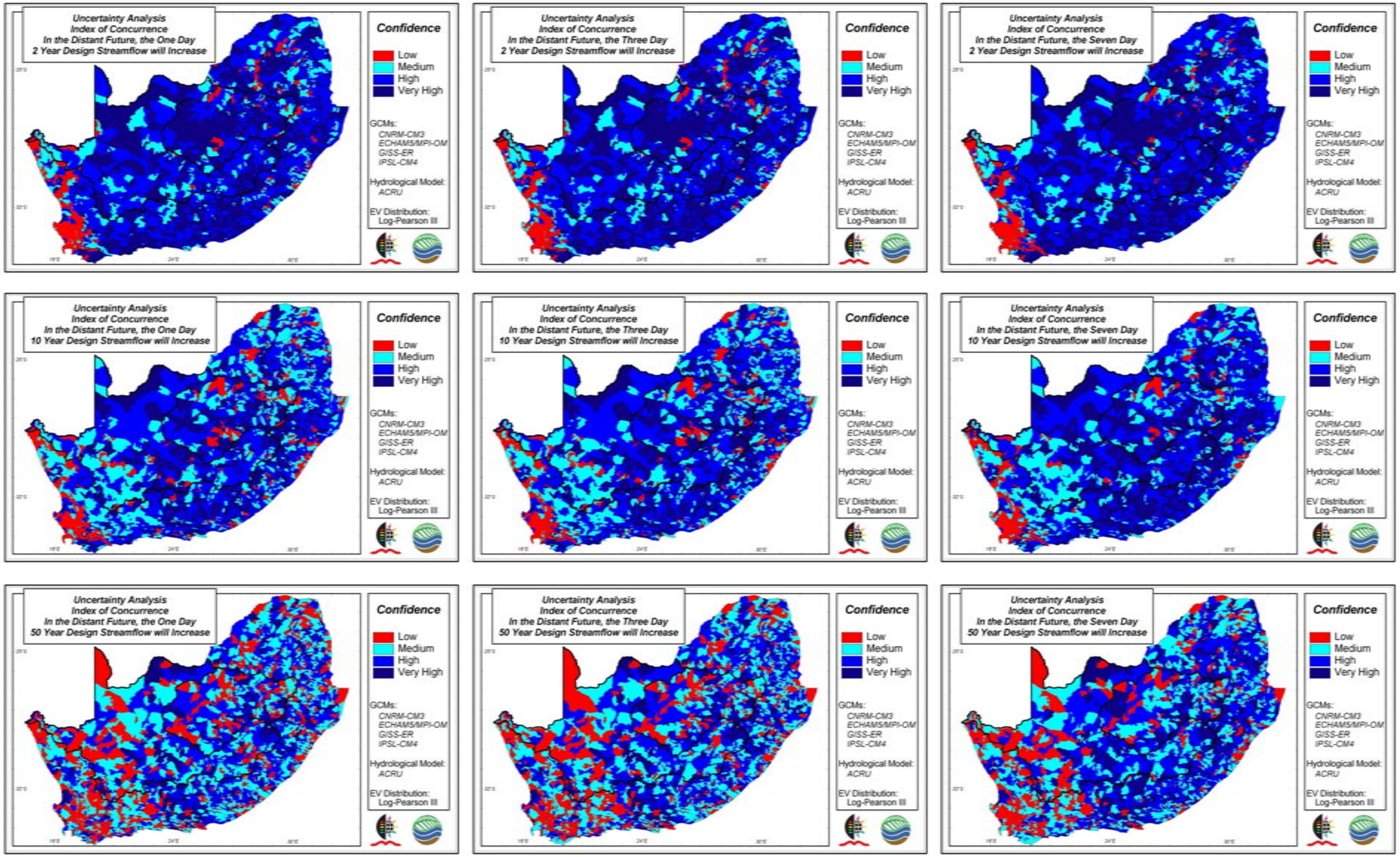


Figure 7.16 Levels of confidence in the hypothesis that long duration design streamflows of increasing duration (left to right) and increasing return period (top to bottom) will increase in the more distant future, derived from *ACRU* simulations using downscaled daily climate output from multiple GCMs

The spatial distribution of confidence in the hypothesis is very similar for both the intermediate future and the more distant future projections. Effectively, the entire Orange River Catchment is projected to experience increases in design streamflows at the 2 year return period. However, as the return period is increased, i.e. shifting to the larger, less frequent events, the area on the west coast of South Africa that displays low confidence in the hypothesis expands into the Orange River Catchment. Simultaneously, more Quinary Catchments, particularly in the eastern regions of the Vaal Catchment, shift to lower levels of confidence in the hypothesis. Therefore, there is a trend of decreasing confidence in the hypothesis as the return period is increased. This is confirmed in Table 7.10, in which it can be seen that, for both the intermediate future and the more distant future projections, the area of the Orange River Catchment that is projected with high confidence to experience increased flooding at the 50 year return period is approximately half that of the 2 year return period.

Table 7.10 Percentage area of the Orange River Catchment with medium (or greater) and high (or greater) confidence in the hypothesis that design streamflows will increase in the intermediate and more distant futures, derived from computations using downscaled daily climate output from the five GCMs used in this study

Attribute		**Percentage Area of the Orange River Catchment**					
		Intermediate Future			**More Distant Future**		
Confidence	**Return Period**	**One Day**	**Three Day**	**Seven Day**	**One Day**	**Three Day**	**Seven Day**
Medium +	**2 Year**	94.2	93.9	95.1	98.0	97.9	98.5
Medium +	**10 Year**	87.6	88.8	92.4	93.4	93.6	96.2
Medium +	**50 Year**	69.0	69.2	75.8	76.3	75.4	80.4
High +	**2 Year**	66.1	66.4	68.5	85.1	85.6	86.6
High +	**10 Year**	55.4	54.8	61.4	70.5	70.8	74.9
High +	**50 Year**	34.3	40.2	49.9	45.4	45.7	52.9

Table 7.11 shows that the above-mentioned decrease in confidence in the hypothesis with increasing return period is not purely the result of an increase in inconclusive results, but partly due to an increase in the area expected to experience a decrease in design streamflows. These findings concur with those found for design rainfall projections. As already described in Section 7.1.5, the relatively high inconclusive results for the more distant future (and the corresponding decrease in

confidence in the hypothesis), shown in Table 7.11, are mainly due to only having four GCMs for use when determining a projected direction of change. Notwithstanding this limitation, significant portions of the Orange River Catchment are still projected to experience increases in design streamflows in the more distant future, with approximately half the catchment projected to experience increases in the 50 year return period events, for all durations.

Table 7.11 Percentage area of the Orange River Catchment projected by > 50% of the GCMs used in this study to experience an increase, decrease, or no change in design streamflows in the intermediate and more distant futures

Attribute		Percentage Area of the Orange River Catchment					
		Intermediate Future			More Distant Future		
Return Period	**Direction of Change**	**One Day**	**Three Day**	**Seven Day**	**One Day**	**Three Day**	**Seven Day**
2 Year	**Decrease**	4.0	4.6	3.8	0.7	0.7	0.8
	Increase	94.2	93.9	95.1	85.1	85.6	86.6
	Same	0.1	0.0	0.0	0.0	0.0	0.0
	Inconclusive	1.7	1.5	1.1	14.2	13.7	12.6
10 Year	**Decrease**	9.4	8.5	5.7	4.5	4.0	3.0
	Increase	87.6	88.8	92.4	70.5	70.8	74.9
	Same	0.0	0.0	0.0	0.0	0.0	0.0
	Inconclusive	3.0	2.7	1.9	25.0	25.2	22.1
50 Year	**Decrease**	26.4	26.1	22.0	20.0	19.8	17.6
	Increase	69.0	69.9	75.8	45.4	45.7	52.9
	Same	0.0	0.0	0.0	0.0	0.0	0.0
	Inconclusive	4.6	4.0	2.2	34.6	34.5	29.5

Unlike the design rainfall projections, however, where it was found that confidence in the hypothesis improved with increasing design event duration, increasing the design event duration has very little effect on the confidence of the projection of design streamflows.

It was shown above that the level of concurrence with the hypothesis, that design floods would increase in the future, decreases with increasing return period. Table 7.12 shows that, regardless of the direction of change, there is less agreement between the GCMs when the return period is increased. The area of the Orange River Catchment where the incidence of concurrence in the future projections is high, drops by approximately 20% when increasing from the 2 year to 50 year return period. This indication of increasing uncertainty with return period can also be seen graphically in Figures 7.15 and 7.16, in which the spatial distribution of confidence becomes increasingly inconsistent with increasing return period. As noted in regard to similar findings for design rainfall (cf. Section 7.1.7), this may be indicative of the uncertainty surrounding the ability of the GCMs to simulate extreme events and also that the 20 year simulation period may be too short for design streamflow estimations with high confidence, particularly when extrapolating to estimate design streamflows with return periods greater than the simulation period.

Table 7.12 Percentage area of the Orange River Catchment with various levels of GCM agreement on projecting a direction of change in design streamflows in the intermediate and more distant futures*

Attribute		**Percentage Area of the Orange River Catchment**					
		Intermediate Future			**More Distant Future**		
Return Period	**Agreement of GCMs**	**One Day**	**Three Day**	**Seven Day**	**One Day**	**Three Day**	**Seven Day**
2 Year	**5 GCMs**	20.9	21.0	24.6			
	4 GCMs	45.6	45.6	44.2	46.8	46.9	48.2
	3 GCMs	31.8	31.9	30.1	39.1	39.5	39.2
	High Confidence +	66.5	66.6	68.8	85.9	86.4	87.4
10 Year	**5 GCMs**	11.1	12.7	19.5			
	4 GCMs	45.7	43.4	42.6	29.5	29.0	34.9
	3 GCMs	40.2	41.2	36.0	45.5	45.8	43.1
	High Confidence +	56.8	56.1	62.1	75.0	74.8	78.0
50 Year	**5 GCMs**	11.2	11.2	16.9			
	4 GCMs	32.0	37.2	38.2	17.9	17.8	21.6
	3 GCMs	52.2	47.7	42.7	47.5	47.8	48.8
	High Confidence +	43.2	48.4	55.1	65.4	65.6	70.4

*** Shaded area implies non-applicable case**

Once again, the reduced effect of increasing the design event duration on the confidence of design streamflow estimation is noticeable, in comparison to the same analysis for design rainfall.

7.2.2 Design peak discharge

This section follows a similar structure to that for design streamflows, with a description of the methodology used in the calculation of peak discharge, followed by the ensuing results.

7.2.2.1 Methodology: Computation of design peak discharges

For these simulations the SCS peak discharge equation (USDA, 1972), modified significantly by Schulze and Schmidt (1995), is used. In its modified version, peak discharge may be estimated by:

$$q_p = \frac{0.2083QA}{1.83L} \tag{7.9}$$

where

q_p = peak discharge ($m^3.s^{-1}$),

Q = stormflow depth (mm) from an individual catchment,

A = catchment area (km^2),

L = catchment lag (response) time (h)

$$= \frac{A^{0.35}MAP^{1.1}}{41.67y^{0.3}\bar{I}_{30}^{\,0.87}} \text{ and} \tag{7.10}$$

1.83 = a multiplier which was computed assuming high intensity rainfall to be associated with annual maximum one day storms over relatively small catchments,

The catchment lag equation (Equation 7.10) was developed by Schmidt and Schulze (1984) using several hundred hydrographs from over 20 research catchments at seven hydro-climatically divergent hydro-climatic regions in the USA and South Africa, and in which :

A = catchment area (km^2),

MAP = mean annual precipitation, MAP (mm),

y = mean catchment slope (%), determined from a 200 m digital elevation model, and

$\bar{I}_{30}$ = magnitude of the 2 year return period 30 minute rainfall intensity ($mm.h^{-1}$).

As is evident from the above equations, Schmidt and Schulze (1984) found that climatic attributes played a major role in determining a catchment's runoff response (or lag) time. For example, they found that a rainfall event's intensity, best represented by the most intense 30 minute period of that event, significantly affects catchment lag time (Schmidt and Schulze, 1984), as did the mean annual precipitation, which was used as a surrogate variable to describe the retardation of stormflow as affected by a catchment's vegetative cover. Therefore, by using Equation 7.10, the potential effects of climate change on catchment lag, and hence peak discharge, can be calculated. MAP for the intermediate future and distant future was calculated as described in Chapter 6, while the methodology developed in Section 7.1.4 was used to calculate the magnitude of the 2 year return period, 30 minute rainfall intensity for each Quinary Catchment.

Once again, the Log-Pearson Type III extreme value distribution (cf. Section 7.1) was used to compute the design peak discharges (in $m^3.s^{-1}$) for the 2, 5, 10, 20, 50 and 100 year return periods. Unlike the calculations for streamflows, the peak discharge of a hydrograph, which is used in the estimation of sediment yield (cf. Section 7.4), has been calculated based on the simulated stormflow, i.e. streamflows excluding contributions from baseflow (cf. Section 5.1.2), generated from each runoff producing event for each individual Quinary, and not the accumulated streamflows. The reason for this is that the hydraulic properties for the 1443 Quinary Catchments in the Orange River Catchment are unknown, and are necessary in order to route the hydrograph downstream. Selected results from the design peak discharge analysis are presented below.

7.2.2.2 Results I: Spatial patterns of design peak discharges for selected return periods, modelled using historical observed climate data, per Quinary Catchment

From the left-hand column of the maps making up Figure 7.17, it can be seen that increases in design peak discharges, simulated with the *ACRU* model using 50 years (1950 - 1999) of historical daily climate input together with soils, land cover and slope information from the QnCD (Schulze *et al.*, 2009a), appear to increase in a westerly direction across the Orange River Catchment, and then to decrease rapidly in the extreme west of the catchment. This spatial distribution is very similar to that of the historical design streamflows by volume (Figure 7.11). However, this spatial pattern is hypothesised to be mainly due to the larger Quinary Catchments in the west of the Orange River Catchment, since catchment area is an important variable in the peak discharge equation (Equation 7.9).

7.2.2.3 Results J: Projected changes in design peak discharge magnitudes with climate change in the intermediate and more distant futures

From the projected ratio changes in design peak discharges, modelled using output from the ECHAM5/MPI-OM GCM, for the intermediate future (Figure 7.17: centre column of maps) and more distant future (Figure 7.17: right-hand column of maps), it becomes immediately evident that, by and large, the Orange River Catchment is projected to experience a decrease in design peak discharges in the future. However, following from the general projected increases in MAP, as well as in design rainfall and design streamflow from the ECHAM5/MPI-OM GCM, it would have been expected that a greater area of the Orange River Catchment would yield increasing future design peak discharges.

These apparently anomalous results instigated further investigation into the methodology used for determining peak discharge, particularly the equation used for estimating catchment lag. It was found that the climatic variables used in the Schmidt and Schulze (1984) lag equation, although seemingly attractive for a climate change study by rendering lag to be a climatically dynamic variable, were the reason for the lower than expected projected design peak discharges. An investigation into the Schmidt and Schulze (1984) lag equation yielded that the MAP variable was not a direct climatic variable *per se* but, as already alluded to in Section 7.2.2.1, rather a surrogate variable to represent soils and above-ground biomass (Schmidt and Schulze, 1984). Thus, an area with a higher MAP would indicate an area with generally deeper, better drained soils and denser vegetation – hence greater infiltration, interception capacity and evaporative losses (thus lower soil water content), which together would retard stormflows and thereby tend to increase catchment lag.

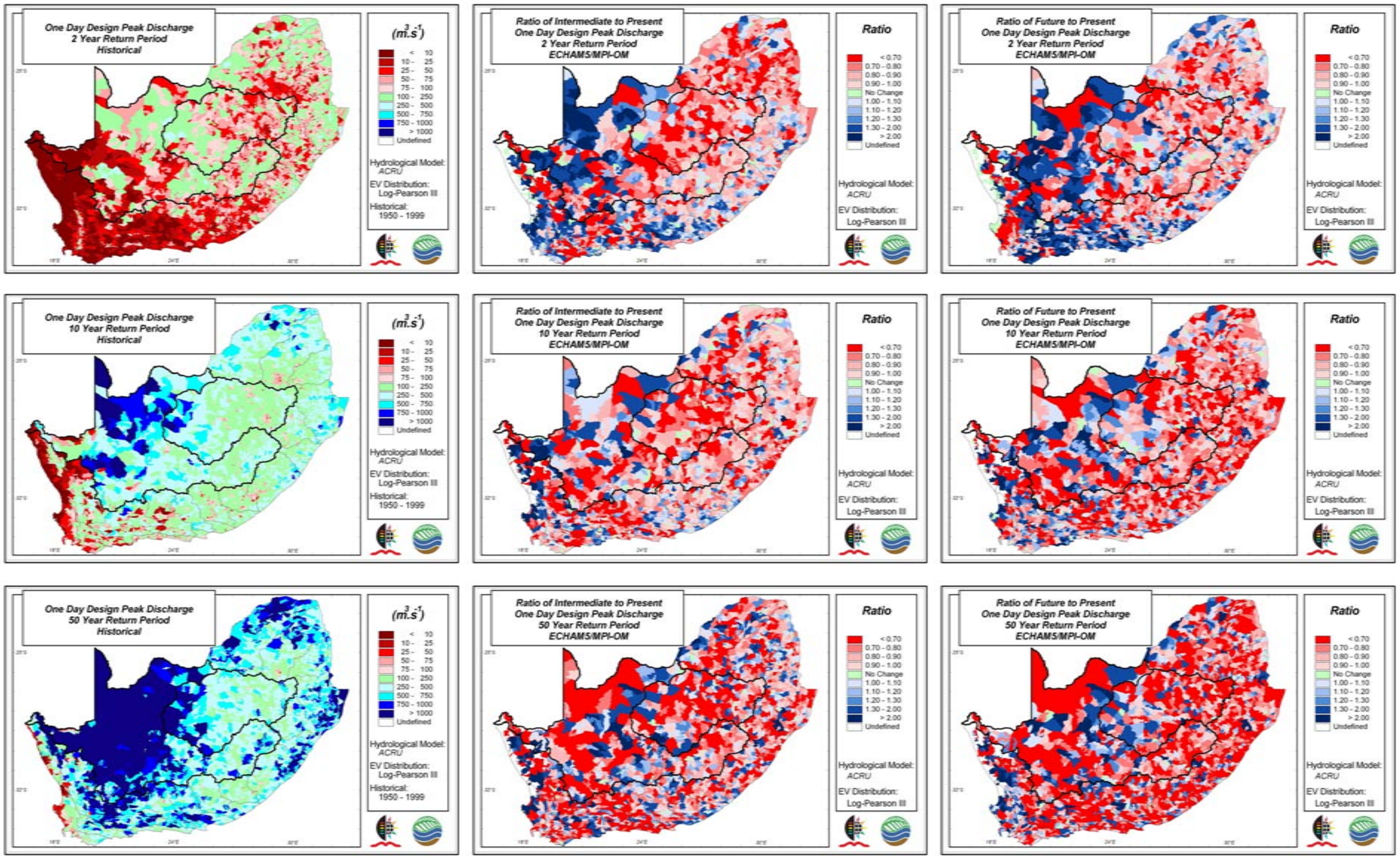


Figure 7.17 Ratios of intermediate future to present (centre), and more distant future to present (right), design peak discharges for selected return periods, derived from *ACRU* simulations using downscaled daily climate output from the ECHAM5/MPI-OM GCM, compared with baseline values derived from *ACRU* simulations using historical daily climate data from the QnCD (left)

Therefore, the generally increasing MAP projected by the ECHAM5/MPI-OM GCM (as well as the other four GCMs used in this study) is, in effect, creating a denser land cover through the lag equation, which is not what was assumed in this study in which only climate variables, and not those of soils and/or land cover, were perturbed for future climate scenarios. Since MAP lies in the numerator of Equation 7.10 and has an exponent > 1, any increases in MAP thus result in increases in catchment lag, thereby resulting in a decreased peak discharge. Owing to this, the results from the design peak discharge analysis are likely to be lower than would have resulted had a less dynamic index of catchment lag, independent of changing MAP, been used.

Despite the use of the Schmidt and Schulze (1984) lag equation and the consequent effects on peak discharges under projected future climatic conditions, a significant area of the Orange River Catchment is, nevertheless, projected by 3 or more of the 5 (or 4, in the case of the more distant future) GCMs used, to experience an increase in design peak discharges for the 2 year return period, as shown in Figure 7.18. This is the case for both the intermediate future, and the more distant future scenarios. The affected area is similar for both future scenarios and covers mainly the western and central regions of the Orange River Catchment, extending slightly into the eastern regions. It is postulated that the use of a different lag equation would have increased the areal extent of medium or greater confidence, as well as the level of confidence, in the hypothesis that design peak discharges will increase with the climates projected for the intermediate and more distant futures.

Moving from the 2 year return period to the 10 year and 50 year return periods, the level of confidence is seen to decrease. This finding of decreasing magnitudes with increasing return periods for design peak discharge is consistent with those for design rainfall, as well as design streamflows.

7.2.3 Summary of main findings

- Design streamflows are modelled to increase over vast portions of the Orange River Catchment in the intermediate future, and even more so in the more distant future.

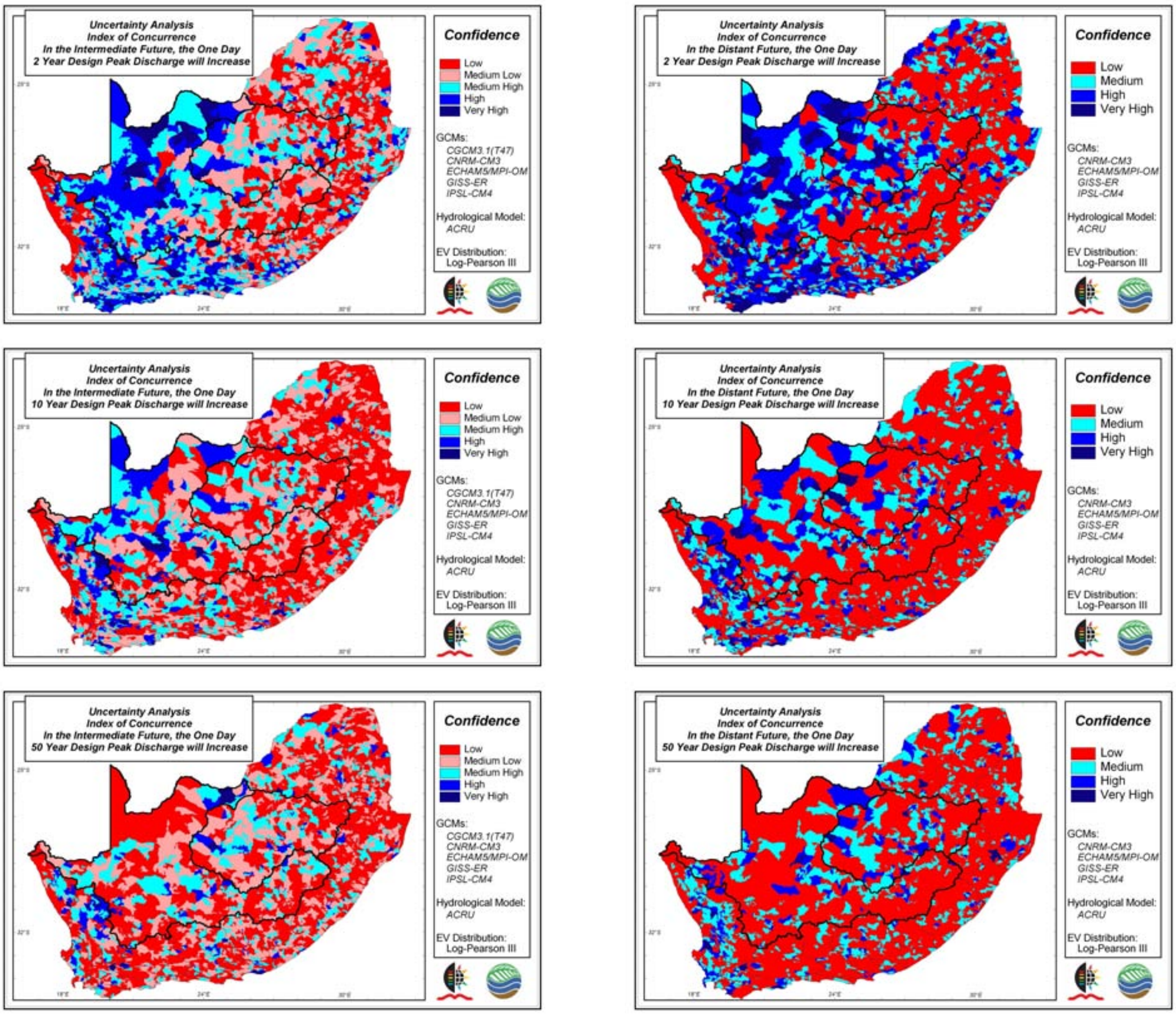


Figure 7.18 Levels of confidence in the hypothesis that design peak discharges will increase in the intermediate future (left), and more distant future (right), derived from *ACRU* simulations using downscaled daily climate output from multiple GCMs

- The magnitudes of the projected changes in design streamflows are greater than those projected for the equivalent design rainfalls.
- Unlike design rainfall, increasing the duration of design streamflows from one day to seven days has little effect on the extent of projected increases and decreases in design streamflows in the future.
- Increases in design streamflows are less extensive for longer return periods.
- The eastern reaches of the Orange River are projected to experience the largest increases in design streamflows, regardless of design event duration or return period.

- Design peak discharges were largely found to be decreasing with the intermediate and more distant future scenarios. However, these results were largely due to the MAP variable in the Schmidt and Schulze (1984) lag equation used in the calculation of peak discharge, which was found to be a surrogate for land cover and soils rather than a climatic variable *per se*.
- Notwithstanding the shortcomings and consequences of using the Schmidt and Schulze (1984) lag equation in the calculation of peak discharge, a large area of the Orange River Catchment is projected by three GCMs or more (out of the 5 used for intermediate future assessments and 4 for the more distant future) to experience increases in the 2 year design peak discharge in the intermediate and more distant future scenarios.

7.3 Droughts

Drought may be described as a creeping, slow-onsetting natural hazard, which can manifest itself either through a lack of precipitation, a lack of available soil moisture for crops, a reduction of streamflows below a critical threshold (or of the amount of water stored in reservoirs), or reduced levels of groundwater (Schulze, 2003b; Schmidt-Thomé, 2006). However, unlike aridity, which is a permanent feature of the climate in low rainfall areas, droughts are a temporary aberration that can occur in low, as well as high, rainfall areas (Ghile, 2008). Droughts have both direct and indirect consequences for human livelihoods. A direct consequence of drought is crop loss which can, in turn, result in starvation among humans if alternative food sources are not available. Indirectly, a water shortage may contribute to the proliferation of diseases when people lack water for basic hygiene (Schulze, 2003b). Owing to the projected increases in temperature, and changes in rainfall amounts and variability, it is anticipated that the frequency as well as the duration and magnitude of droughts will change in future climates, either increasing or decreasing, with potentially severe economic, social and environmental implications. It is therefore necessary to assess how these hazards might change in future climates.

This section on droughts commences with a description of the methodology adopted for the computation of meteorological and hydrological droughts. This is followed by analyses of meteorological droughts using historical data and climate scenarios projected by the ECHAM5/MPI-OM GCM, which is used to develop techniques for the mapping and subsequent interpretation of projected changes in meteorological droughts in future climates. Similar analyses are then performed, using the ECHAM5/MPI-OM GCM, for hydrological droughts. Finally, a quantitative uncertainty analysis, based on the hypothesis that *droughts, both meteorological and hydrological, will increase in future climates* is performed using all five of the GCMs available for this study.

7.3.1 Methodology: Computation of meteorological and hydrological droughts

As already intimated above, there are many concepts, and hence definitions, of drought. Droughts are generally dependent on who, or what, is being affected. In this study meteorological droughts and hydrological droughts were analysed. Meteorological drought occurs with a reduction in rainfall supply over an extended period (from months to years) compared with the long-term average expected conditions (UNDP, 2004; Schmidt-Thomé, 2006). Hydrological drought consists of a substantial reduction in streamflow, i.e. of surface and subsurface water resources, in a specified area, again when compared with long term expected conditions.

In regard to *drought duration*, in previous studies a drought has been defined as a sustained period in which *monthly* precipitation or streamflow at a given location is below the long term average (UNDP, 2004; Lehner *et al.*, 2006). Both of these studies identified the onset of drought when rainfall or runoff dropped below the *median* monthly values, with the UNPD (2004) using fractions of the monthly median to distinguish between droughts of varying severity. A similar approach has been adopted in this study, but with either *single* or *consecutive multiple years* having been analysed.

In regard to *drought severity*, a distinction has been made in this study between mild, moderate and severe droughts. A year experiencing *mild* drought is defined here to have occurred if that year's rainfall or streamflow is less than or equal to the 33rd percentile of the present series of annual rainfalls or streamflows, i.e. if it occurs on average once every three years or less frequently. On the maps this is indicated as "Mild (or More Severe)". Similarly, a *moderate* drought is defined here as occurring on average only once every five years or less frequently (i.e. ≤ 20th percentile), and this is indicated on the maps as "Moderate (or More Severe"), while *severe* droughts occur only once in ten years or less frequently (i.e. ≤ 10th percentile), as calculated from the present rainfall or streamflow record.

In order to calculate whether or not meteorological droughts are projected to occur more, or less, frequently in the intermediate and more distant future climates, the above-mentioned thresholds for mild, moderate and severe droughts were used to determine what magnitude would constitute a drought under present climatic conditions, derived from output from each of the five GCMs available in this study, *viz*. CGCM3.1(T47), CNRM-CM3, ECHAM5/MPI-OM, GISS-ER and IPSL-CM4. In addition to this, the number of occurrences of two and three consecutive drought years for the different severities of drought was computed. Using the same magnitudes that constitute a meteorological drought for a respective location, and from a particular GCM's present climate, the number of drought years, as well as the number of two and three successive drought years, was computed from the intermediate and more distant future rainfall record. The frequencies of meteorological drought occurrences in the intermediate and more distant future projected climates were then compared to the frequencies from the respective present climates.

The hydrological drought analysis was carried out in the same way as mentioned above, except that simulated accumulated streamflow values were used. The streamflow simulations were performed with the *ACRU* hydrological model, using daily temperature and rainfall input projected from the respective GCMs.

7.3.2 Meteorological droughts

As a point of departure to this section a brief overview of historical droughts is provided. This is followed by ratio analyses of droughts derived from the intermediate future to present, and more distant future to present climate scenarios, respectively, in order to determine the projected direction of change in drought occurrences of different durations and severities, using outputs from the ECHAM5/MPI-OM GCM climate scenarios.

7.3.2.1 Results K: Spatial patterns of frequencies of meteorological drought years, derived from historical observed rainfall data, per Quinary Catchment

Figure 7.19 shows the spatial variation of the frequency of two consecutive, and three consecutive, drought years for various thresholds of meteorological drought. Owing to the definitions of drought used in this study (cf. Section 7.3.1), the number of individual drought years has not been mapped, as the number of occurrences in the 50 year historical data set for the mild (or more severe), moderate (or more severe) and severe droughts would be approximately 17, 10 and 5, respectively.

It may be seen in Figure 7.19 that regardless of the severity of the drought, or whether the prolonged dry period lasts two years or three years, the frequency of successive drought years is greater in the eastern, higher rainfall, areas than elsewhere. This puts the entire Orange River Catchment at risk, with the eastern regions experiencing elevated water demands owing to a high population and industrial activity, and the arid western regions being dependent on water (mainly for irrigation) that flows through it from the east.

7.3.2.2 Results L: Projected changes in frequencies of meteorological droughts with climate change in the intermediate and more distant futures

The most noticeable result when scrutinising the intermediate future to present climate ratios of meteorological drought occurrences from the ECHAM5/MPI-OM GCM, shown in Figure 7.20, is the small number of Quinary Catchments with ratios greater than one, indicated by shades of red, which are indicative of those areas projected to experience an increase in drought occurrences. Generally the number of meteorological drought years, regardless of the severity, is projected to decrease, with only a few Quinary Catchments in the west of the Orange River Catchment projected to experience an increase in drought years – these making up less than 10% of the total catchment area (Table 7.13). It is important to note that areas that are “undefined” may be regarded as increases, as they denote areas that do not experience any drought occurrences at present, but do so in projected future climates.

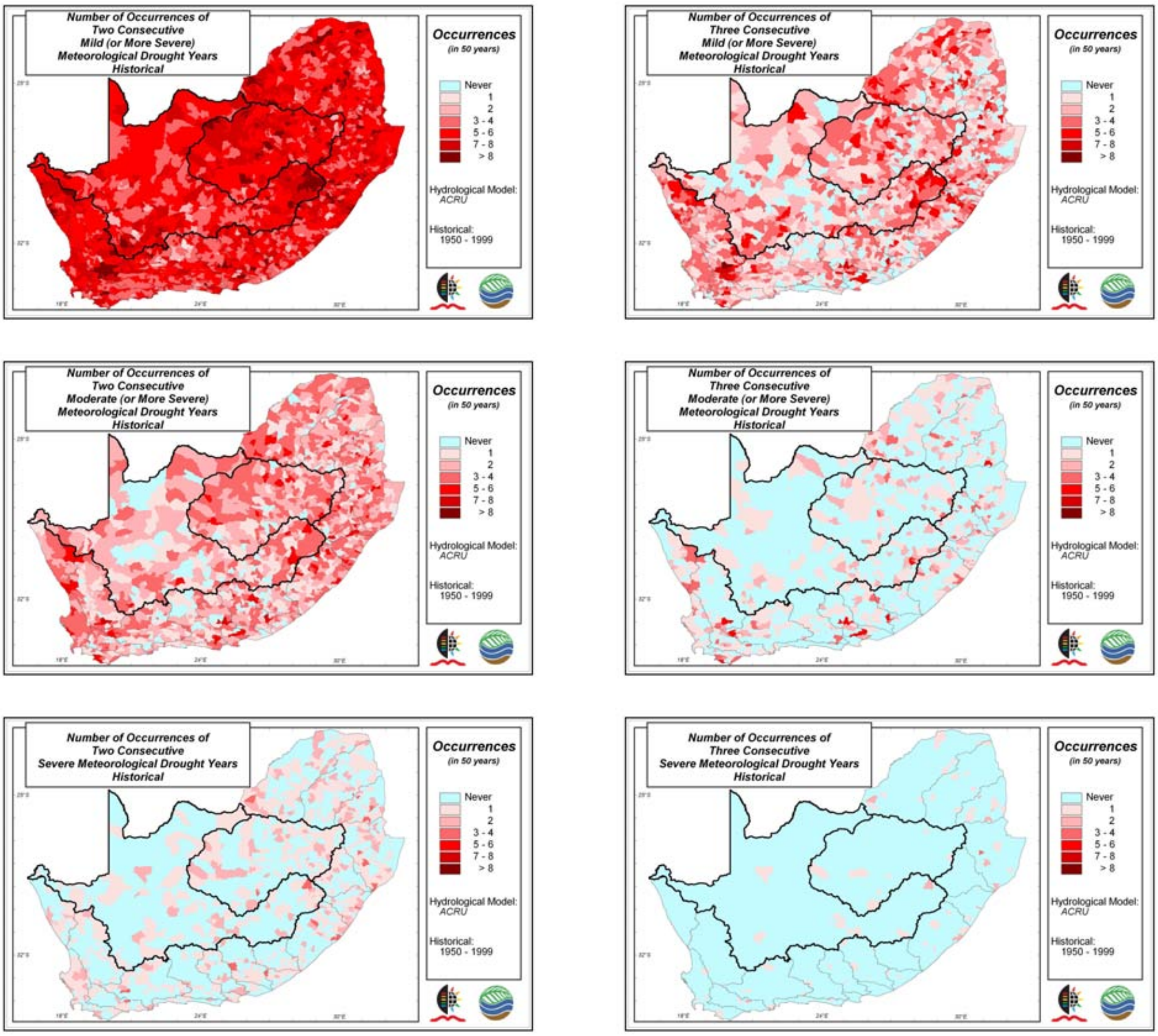


Figure 7.19 Number of occurrences of two and three consecutive years of meteorological droughts of differing severity, in 50 years of historical daily rainfall data from the QnCD

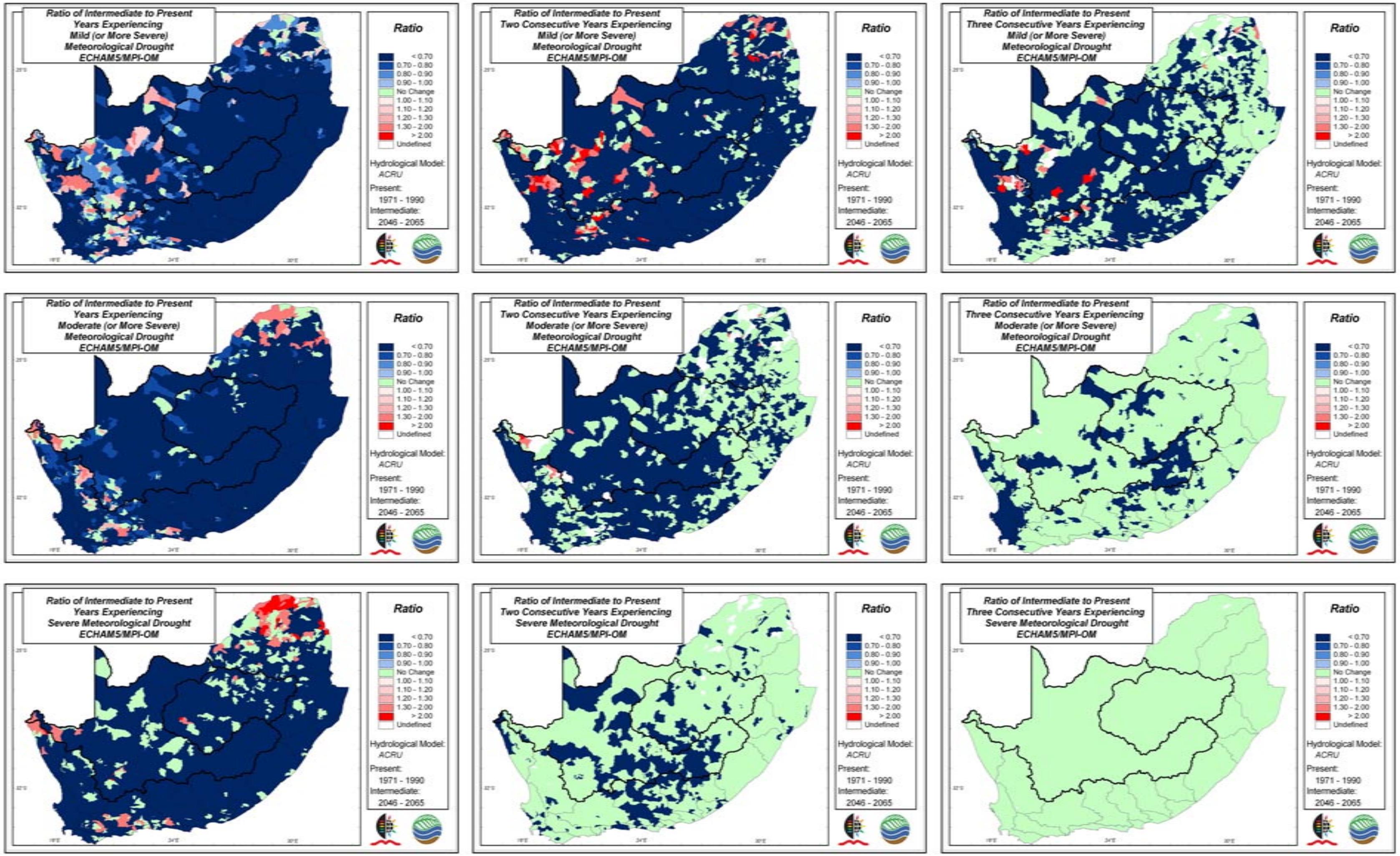


Figure 7.20 Ratios of intermediate future to present frequencies of one, two and three year meteorological droughts for selected levels of severity, derived from downscaled daily rainfall output from the ECHAM5/MPI-OM GCM

Table 7.13 Percentage area of the Orange River Catchment projected to experience an increase, decrease, or no change in meteorological droughts in the intermediate and more distant futures, derived from computations using downscaled daily rainfall output from the ECHAM5/MPI-OM GCM

Attribute		Percentage Area of the Orange River Catchment					
		Intermediate Future			More Distant Future		
Drought Severity	Direction of Change	1 Year Drought	Consecutive Droughts 2 Years	Consecutive Droughts 3 Years	1 Year Drought	Consecutive Droughts 2 Years	Consecutive Droughts 3 Years
Mild (or more severe)	No Change	4.5	10.2	30.9	1.4	4.6	27.2
	Decrease	87.7	81.6	65.4	96.7	92.1	70.8
	Increase	7.8	8.2	3.7	1.9	3.3	2.0
Moderate (or more severe)	No Change	4.5	25.8	78.5	0.7	24.8	77.7
	Decrease	94.0	71.2	21.1	97.7	73.0	21.1
	Increase	1.5	3.0	0.4	1.6	2.2	1.2
Severe	No Change	14.1	69.0	100.0	4.2	68.7	99.7
	Decrease	84.4	30.7	0.0	94.2	30.4	0.0
	Increase	1.5	0.3	0.0	1.6	0.9	0.3

Moving down Figure 7.20 from the ratios for all drought severities, i.e. mild drought (and more severe) in the top row, to the ratios for droughts that are moderate (and more severe) in the middle row, to the ratios for severe droughts in the bottom row, the area within the Orange River Catchment projected to experience a change in drought occurrences decreases. Increasing the drought severity in a different way, i.e. by increasing the number of successive drought years from one to two to three, shows a similar trend of decreasing changes with increased drought duration. By and large, those Quinary Catchments in the west that are projected to experience an increase in the number of drought years (Figure 7.20: top left) are also projected to experience an increase in the frequency of two consecutive drought years (Figure 7.20: top middle).

The small area projected to experience an increase in severe droughts diminishes when looking at two successive severe drought years, while there is absolutely no change, countrywide, for severe droughts occurring three years in a row. The zero change in three consecutive severe droughts is, however, attributed largely to the shortness of the record length at only 20 years.

The spatial variation for the drought occurrence ratios of the more distant future to present climate (Figure 7.21) show a much clearer pattern than those shown in Figure 7.20, with most of South Africa projected to experience decreases in the frequencies of drought years, and with increases in the drought frequencies limited to the west coast of the country. This band of decreases extends into the western-most Quinaries of the Orange River Catchment and, while the total area of increased droughts diminishes with increasing drought severity, from mild through moderate to severe, the area affected in the Orange River Catchment remains relatively constant (Figure 7.21 and Table 7.13). Furthermore, a greater area of the Orange River Catchment is projected to experience a reduction in drought occurrences in the more distant future compared to the intermediate future.

As already shown for the intermediate future climate scenario, as the severity of the drought is increased from mild to severe, both in terms of magnitude and duration, it is more likely that the drought frequency will remain similar, and even the same, as it is at present.

7.3.3 Hydrological droughts

As was the case with meteorological droughts, the point of departure to this section is a brief overview of the spatial variation of hydrological droughts, derived from simulations using historical daily climate data from the QnCD. This serves as a reference for the ratio analyses of hydrological droughts between the intermediate future and present climate scenarios, and the more distant future and present climate scenarios, with results derived from ECHAM5/MPI-OM GCM output, which is then used as input into the *ACRU* hydrological model.

7.3.3.1 Results M: Spatial patterns of frequencies of hydrological drought years, modelled using historical observed climate data, per Quinary Catchment

Figure 7.22 shows the spatial variation of the frequency of two consecutive and three consecutive drought years for various thresholds of hydrological drought, *viz*. mild, moderate and severe droughts. As mentioned in Section 7.3.2.1, the number of

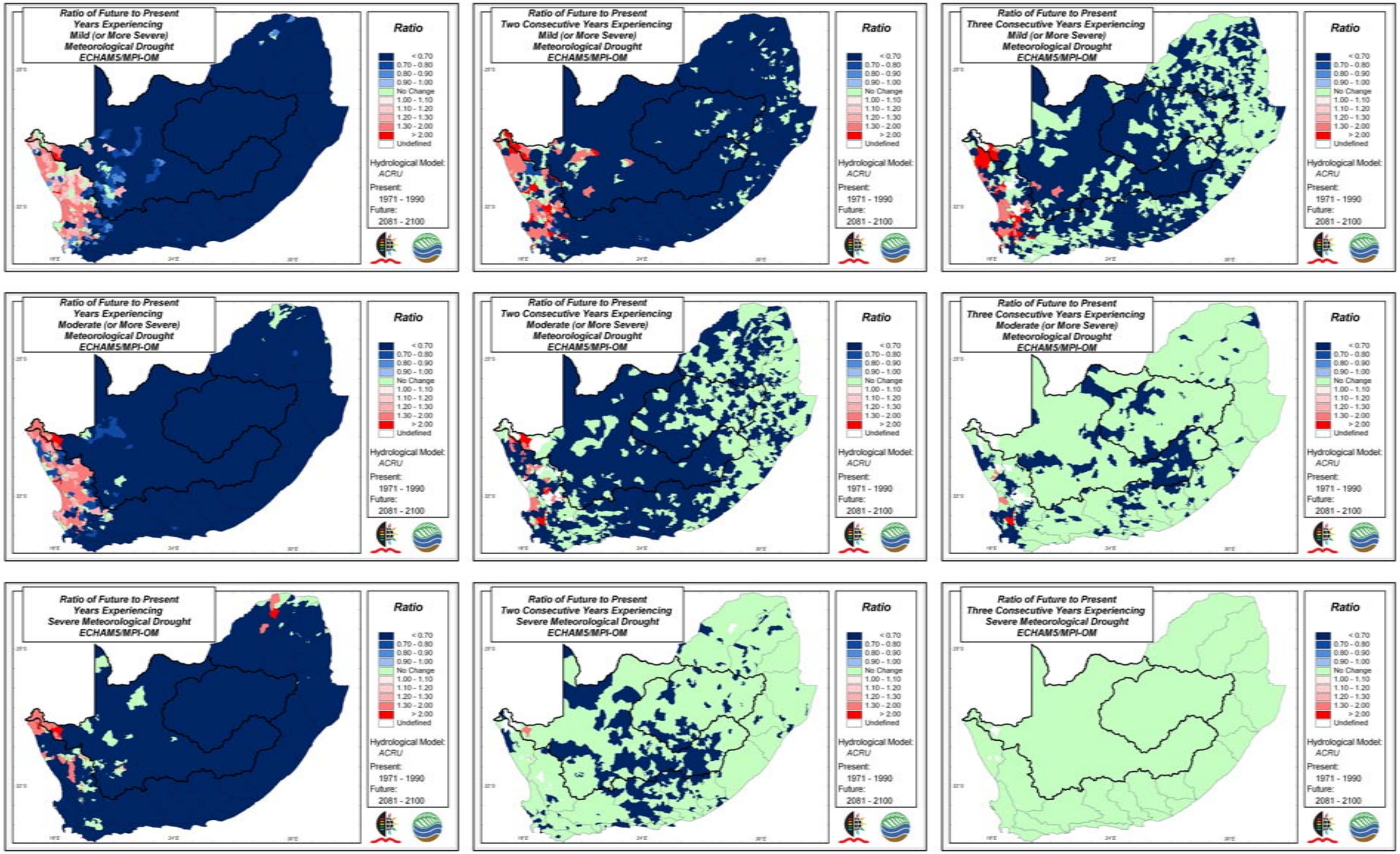


Figure 7.21 Ratios of more distant future to present frequencies of one, two and three year meteorological droughts for selected levels of severity, derived from downscaled daily rainfall output from the ECHAM5/MPI-OM GCM

individual (i.e. single year) droughts has not been mapped because, according to the definitions of drought used in this study (cf. Section 7.3.1), the number of occurrences for the mild (or more severe), moderate (or more severe) and severe droughts would be approximately 17, 10 and 5, respectively, within the 50 years of daily streamflows simulated using historical daily climate data from the QnCD.

The simulated multi-year hydrological droughts using historical rainfall data (Figure 7.22) display a different spatial pattern to the meteorological drought equivalent (Figure 7.19). While the most frequently occurring multi-year meteorological droughts are shown to occur in the high rainfall eastern regions of the Orange River Catchment, multi-year hydrological droughts occur most frequently in the more arid west. Generally, those Quinary Catchments through which the Orange River flows experience fewer multi-year hydrological droughts. This is the result of the numerous tributary streamflow contributions from all over the catchment, which mitigate the effect along the main river that localised droughts in individual tributaries may have.

7.3.3.2 Results N: Projected changes in frequencies of hydrological droughts with climate change in the intermediate and more distant futures

A very similar spatial variation to that observed for design floods (Section 7.2) may be seen in the ratio maps of annual hydrological drought occurrences between the intermediate future and present climates (Figure 7.23, top left), i.e. there is a band of increasing drought occurrences extending from the northeast of South Africa, across the Orange River Catchment, through to the south of the country, with much of the southern areas of the Orange River Catchment being affected. However, where design streamflows were shown to be decreasing in Figure 7.13, hydrological droughts are shown to be increasing, and vice versa. Therefore, regardless of which extremes are being analysed, be they floods or droughts, extreme flows are increasing and decreasing in similar areas. What this implies is that while a particular area is projected to experience a decrease in exposure to one extreme, e.g. floods, that area is projected to experience an increase in the opposite extreme, i.e. droughts.

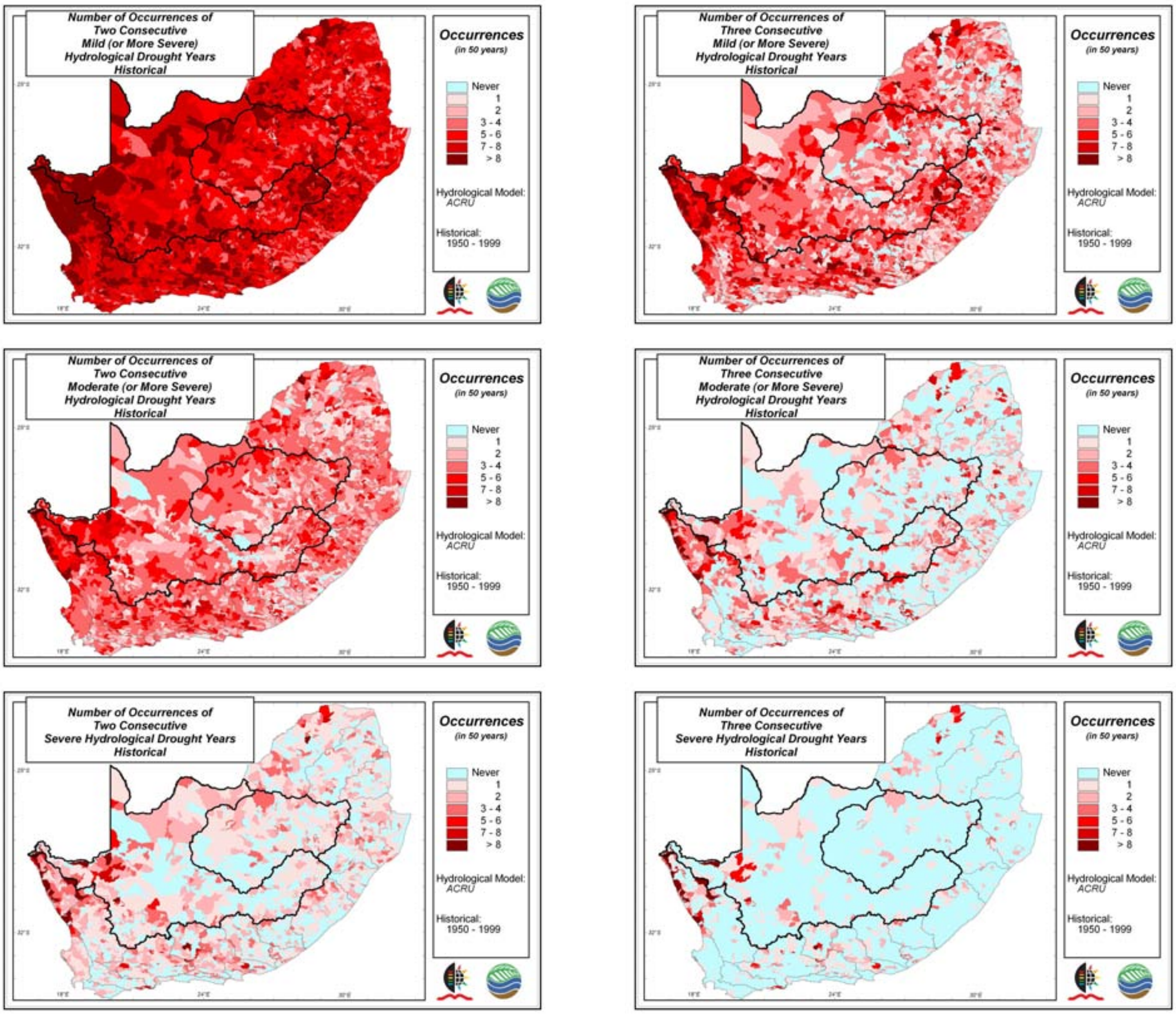


Figure 7.22 Number of occurrences of two and three consecutive years of hydrological droughts of differing severity, in 50 years of streamflow data, derived from *ACRU* simulations using historical daily climate data from the QnCD

Moving down the maps in Figure 7.23 to shift focus from mild to moderate, and then further down to severe droughts, shows that with increasing drought severity the area of the Orange River Catchment that is projected to experience an increase in drought occurrences diminishes, while the area projected to experience the same number of droughts, or fewer, expands. This is also shown in Table 7.14. Furthermore, the spatial variation of the projected increases in hydrological droughts in the intermediate future becomes more disparate with increasing severity.

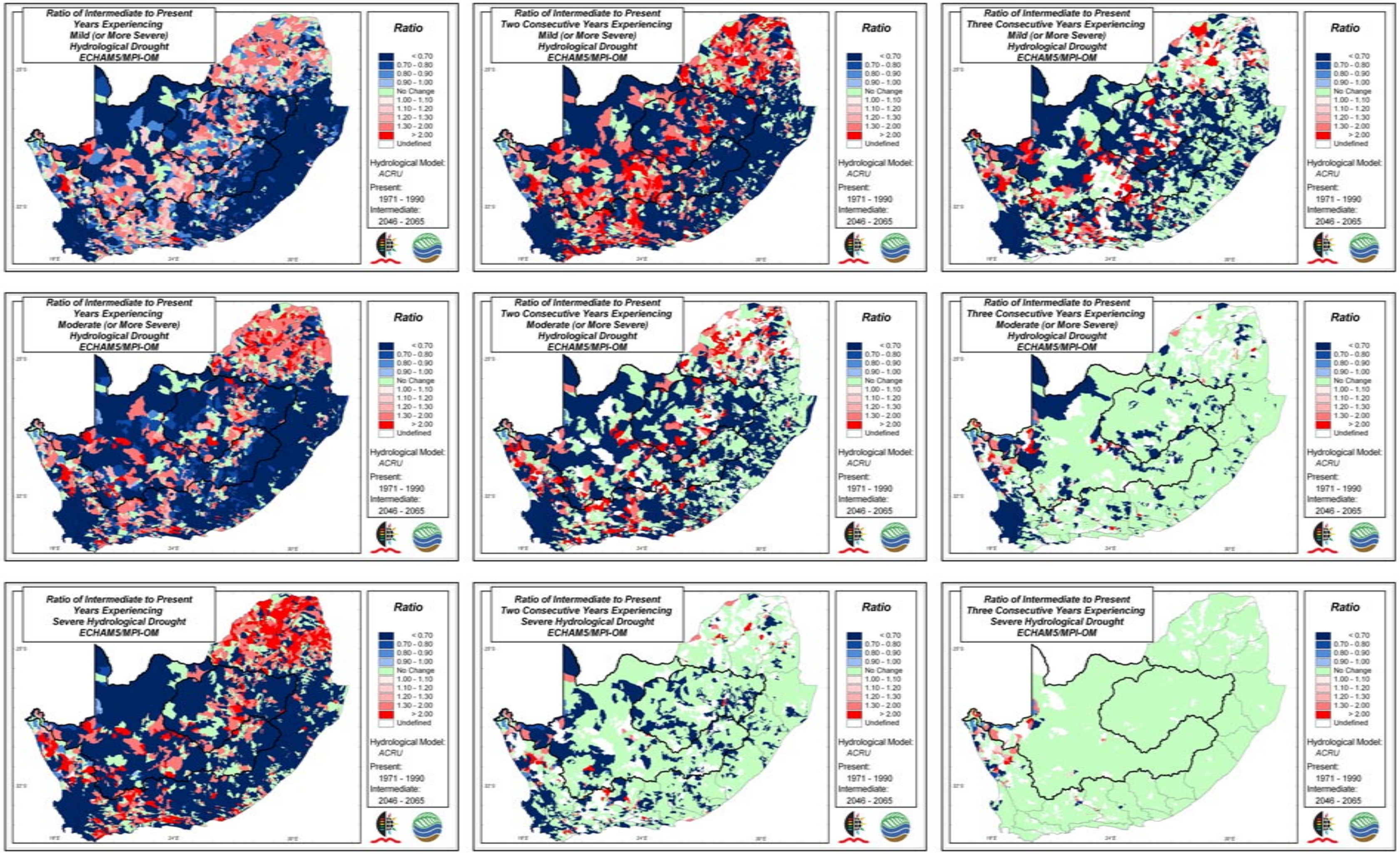


Figure 7.23 Ratios of intermediate future to present frequencies of one, two and three year hydrological droughts for selected levels of severity, derived from *ACRU* simulations using downscaled daily climate output from the ECHAM5/MPI-OM GCM

Moving from the left to the right maps, across the top of Figure 7.23, which shows the differences between changes in annual droughts and multi-year droughts of two and three years' duration, respectively, it is evident that the projected increases in drought frequency expand in extent and magnitude from the annual to two year droughts, but then diminishes for three year droughts. Furthermore, with increasing drought duration, the area of the Orange River Catchment that is projected to experience hydrological droughts at the same frequency as with the present climate, increases. This trend is also present when comparing annual hydrological droughts with two and three year droughts of increased severity, except that there is no increase in drought frequency from the one to two year droughts, but rather a steady decline in the area that is projected to experience drought increases from one to two to three year droughts (Table 7.14).

Table 7.14 Percentage area of the Orange River Catchment projected to experience an increase, decrease, or no change in hydrological droughts in the intermediate and more distant futures, derived from computations using downscaled daily climate output from the ECHAM5/MPI-OM GCM

Attribute		**Percentage Area of the Orange River Catchment**					
		Intermediate Future			**More Distant Future**		
Drought Severity	**Direction of Change**	**1 Year Drought**	**Consecutive Droughts 2 Years**	**Consecutive Droughts 3 Years**	**1 Year Drought**	**Consecutive Droughts 2 Years**	**Consecutive Droughts 3 Years**
Mild (or more severe)	**No Change**	9.2	11.1	26.2	4.7	5.4	29.8
	Decrease	66.0	60.3	52.1	87.8	83.4	62.2
	Increase	24.8	28.6	21.7	7.5	11.2	8.0
Moderate (or more severe)	**No Change**	10.1	28.0	68.7	4.2	23.2	73.7
	Decrease	70.9	53.3	20.3	87.5	67.5	20.1
	Increase	19.0	18.7	11.0	8.3	9.3	6.2
Severe	**No Change**	13.2	58.9	90.5	8.6	62.8	91.0
	Decrease	69.6	27.5	5.5	85.1	29.4	4.9
	Increase	17.2	13.6	4.0	6.3	7.8	4.1

It has already been mentioned that the 20 year period of data is too short to identify multi-year droughts with much confidence, and that this is a possible reason for the vast area of "No Change" that is projected for the more severe and the longer duration droughts. However, notwithstanding this shortcoming, there are still many areas in the Orange River Catchment which do not display any simulated multi-year drought under present climatic conditions, but are projected to experience multi-year droughts in the intermediate future. These are areas are indicated as “Undefined” in Figure 7.23.

An interesting observation is that the spatial patterns of the meteorological droughts (Figure 7.20) are very different to those of the hydrological droughts (Figure 7.23). Where it was noted in the annual *meteorological* drought analysis (Section 7.3.2) that less that 10% of the Orange River Catchment was projected to experience an increase in mild droughts, and less than 2% of the catchment being affected by increases in moderate or severe annual droughts, the annual *hydrological* droughts are projected to increase over almost 25% of the Orange River Catchment for mild droughts, while approximately 20% and 15% of the catchment is projected to be affected by increases in moderate and severe annual hydrological droughts, respectively. This trend of projected hydrological droughts being more extensive in area than the projected meteorological droughts also holds true for multi-year droughts.

The reason for this amplification may be due to the projected increases in temperature in the intermediate future climate, which in turn increases potential evaporation. These factors may lead to drier antecedent soil conditions before rainfall events and therefore larger rainfall events being required to produce runoff, as the initial abstractions of rainfall before runoff can be generated are greater with drier soils.

This assumption appears to be validated by the threshold analysis shown in Figure 7.24, in which it can be seen that the number of days per annum with effective rainfall (> 2 mm) is increasing over just about the entire Orange River Catchment. However, moving down Figure 7.24, it becomes evident that more of the Orange River Catchment is projected to experience a decline in the number of rain days per annum as the threshold for rainfall is shifted to the larger, runoff-producing events. The spatial variation displayed for the ratio of intermediate future to present days per annum with rainfalls greater than 25 mm is strikingly similar to that for annual hydrological droughts, supporting the hypothesis that hydrological droughts may be the result of a decrease in rainfall events large enough to supply sufficient water to

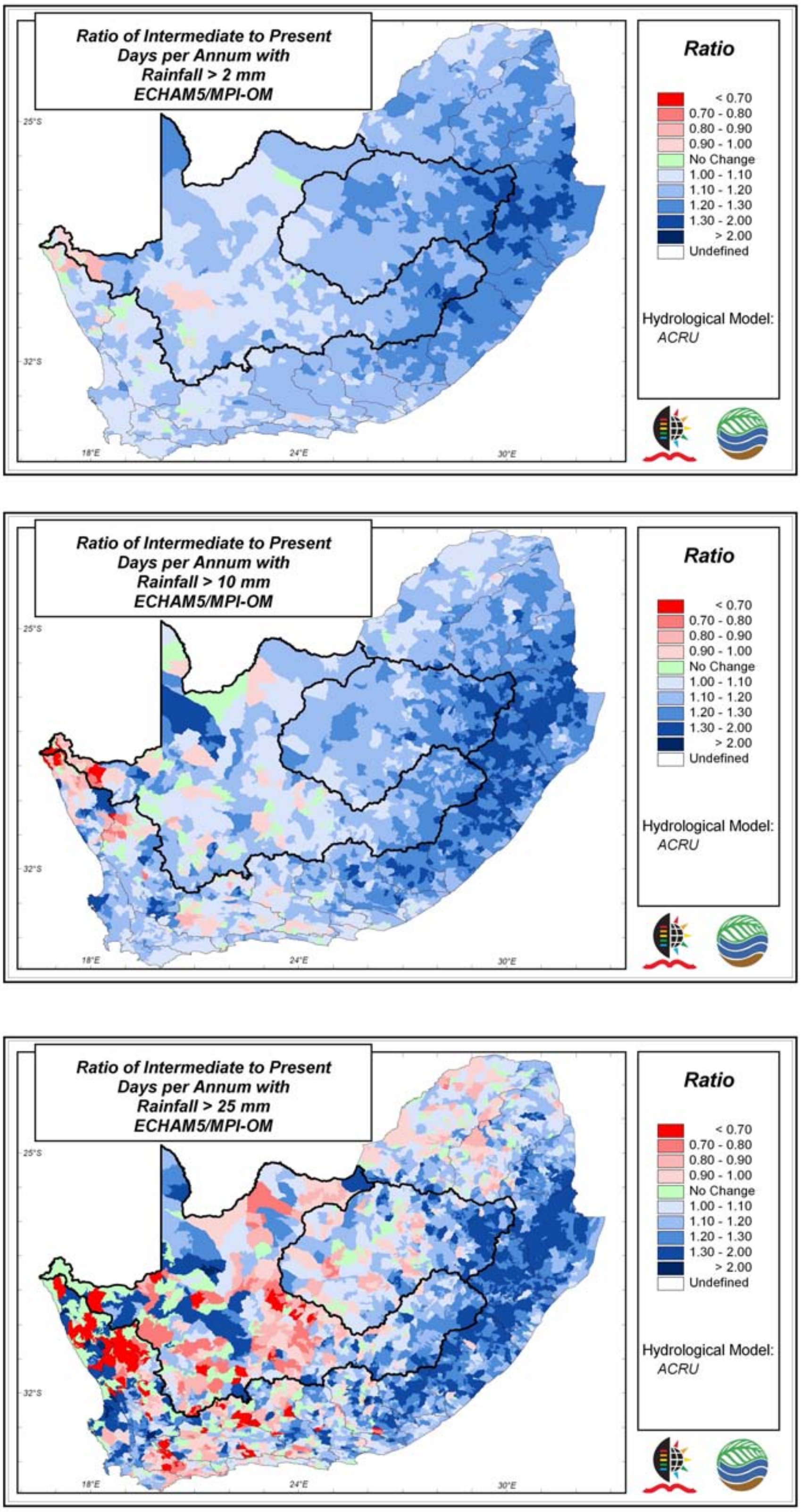


Figure 7.24 Ratios of intermediate future to present, number of days per annum with daily rainfall greater than 2 mm (top), 10 mm (middle) and 25 mm (bottom), derived from downscaled daily rainfall output from the ECHAM5/MPI-OM GCM

replenish dry soils and still reach the rivers as runoff. These decreases in runoff-producing rainfall events also provide some insight into the spatial variation observed for projected design floods.

Projections using ECHAM5/MPI-OM GCM output for the more distant future display very different spatial patterns of hydrological droughts (Figure 7.25) to those shown for the intermediate future. From the intermediate future (2046 - 2065) to the more distant future (2081 - 2100), the band of increasing droughts across South Africa disappears, the trend of increasing droughts projected for the northeast of the country weakens, while there is a strengthening of the hydrological drought increases along the west coast of South Africa. With these changes comes a reduction of the area projected to experience an increase in hydrological drought frequencies in the more distant future, regardless of the severity or duration of the droughts – a point which is confirmed by the information in Table 7.14.

There is not much of a change in the spatial patterns when shifting the focus from annual hydrological droughts that are defined as mild (or more severe), to those that are moderate (or more severe), to only those droughts regarded as severe. However, increasing the severity of the two, and three, consecutive year hydrological droughts shows a shrinking of the area projected to experience increases in hydrological droughts, as was the case for the intermediate future projections. Furthermore, other trends noticed in the analysis of hydrological droughts in the intermediate future are also apparent for hydrological droughts in the more distant future, *viz*. that fewer Quinary Catchments are projected to experience more frequent droughts, and that more Quinaries are projected to experience the same frequency of droughts, with increasing drought duration from one to two to three years. This once again raises the question of the use of a relatively short record length of only 20 years for future climate scenarios when analysing multi-year droughts.

When comparing the meteorological and hydrological droughts for the more distant future, there appears to be more correlation between the two analyses than was visible for the intermediate future. This may be due to the spatial patterns of projected changes in effective rainfall days being similar to those of the projected changes of the larger rainfall events (Figure 7.26). The pattern of areas in the

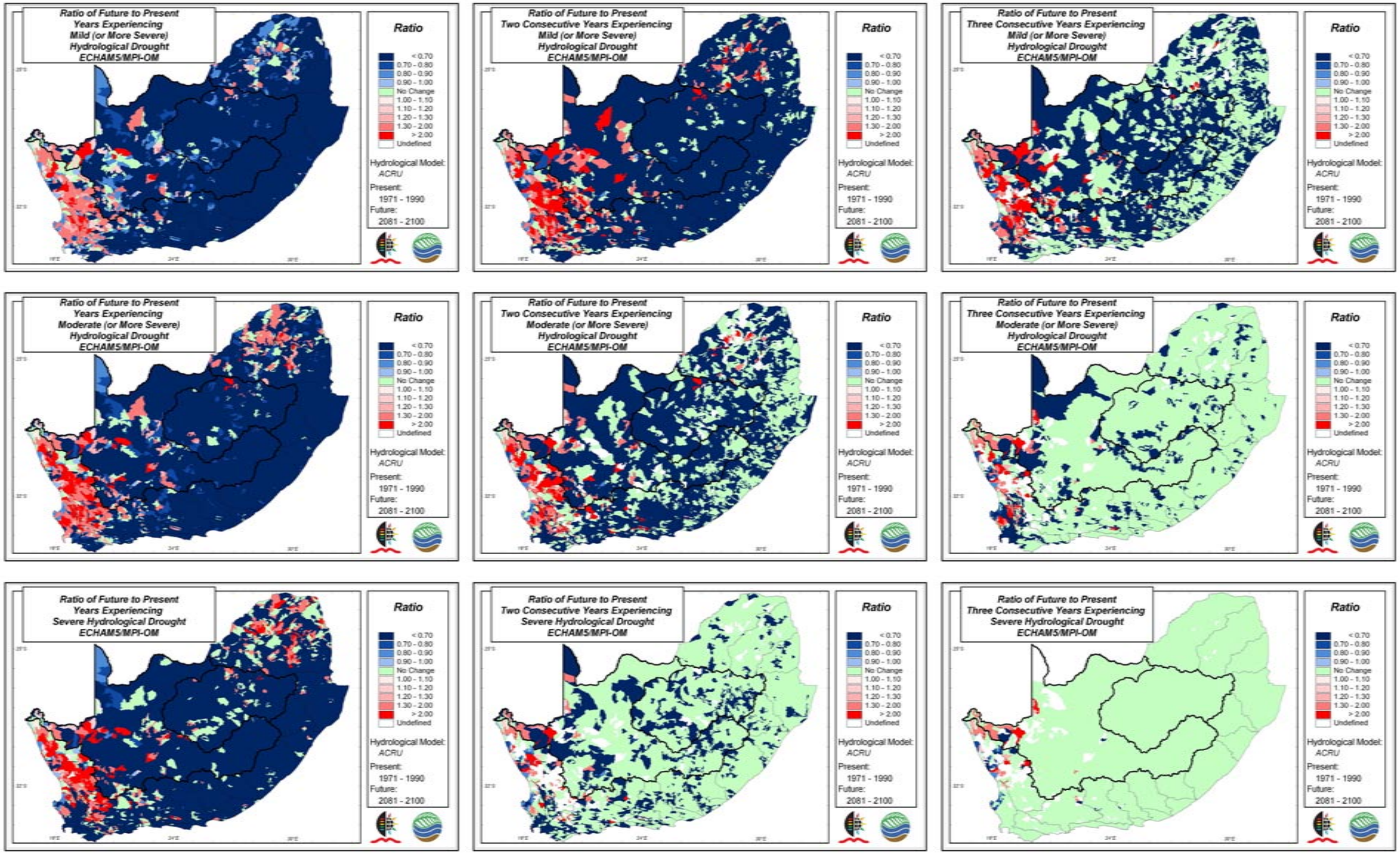


Figure 7.25 Ratios of more distant future to present frequencies of one, two and three year hydrological droughts for selected levels of severity, derived from *ACRU* simulations using downscaled daily climate output from the ECHAM5/MPI-OM GCM

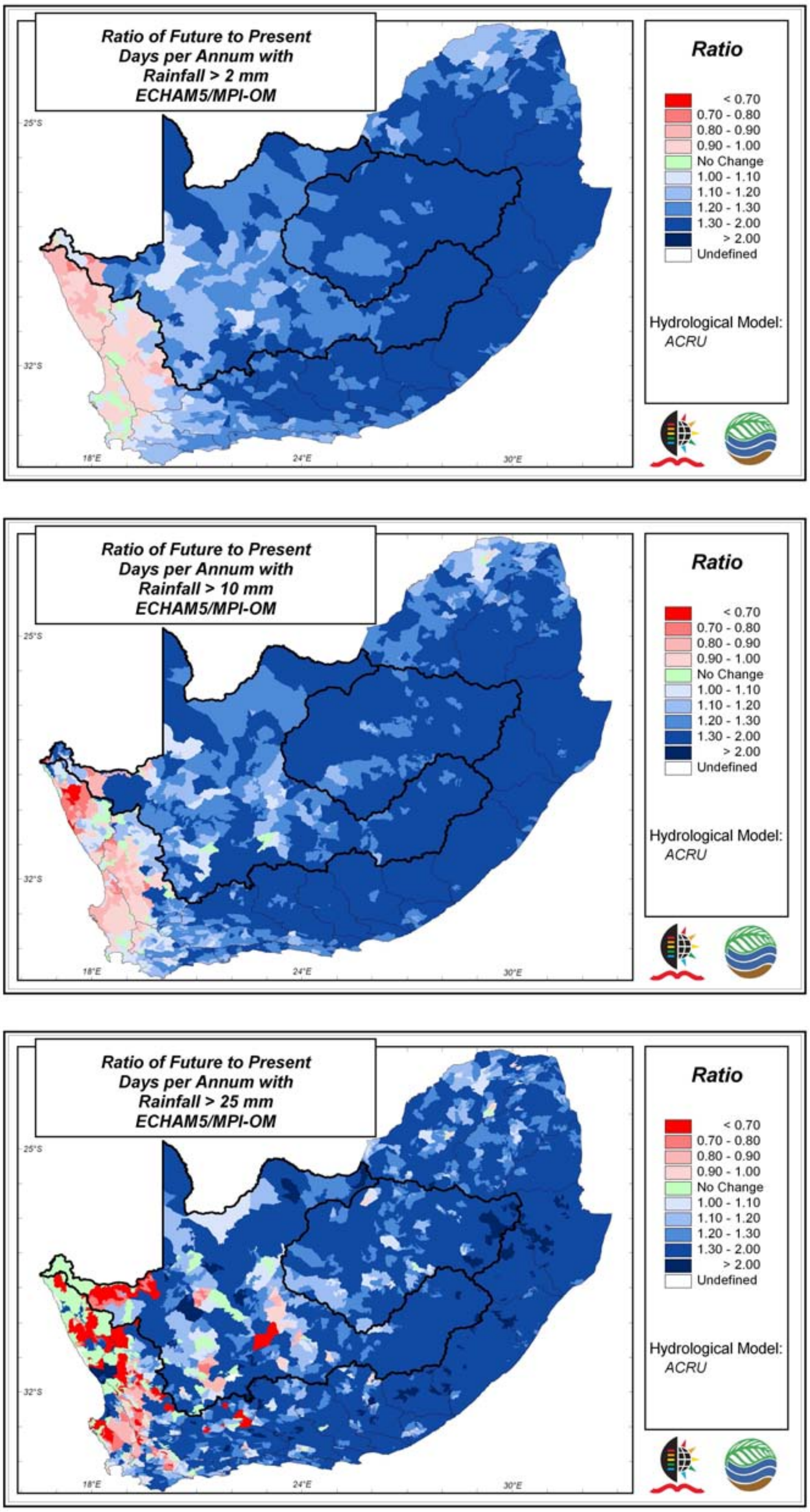


Figure 7.26 Ratios of more distant future to present, number of days per annum with daily rainfall greater than 2 mm (top), 10 mm (middle) and 25 mm (bottom), derived from downscaled daily rainfall output from the ECHAM5/MPI-OM GCM

Orange River Catchment experiencing increases in one extreme (e.g. floods) and decreases in the other (i.e. droughts) appears to exist for projections into the more distant future as well.

7.3.4 Methodology: How certain are we of changes in meteorological and hydrological droughts in the Orange River Catchment?

An uncertainty analysis, based on the hypothesis that *meteorological and hydrological droughts will increase in frequency in future climates*, as is suggested by the IPCC (2007b), was carried out using the scale of confidence levels shown in Table 7.4. In the same way as for the uncertainty analyses carried out for previous sections of this thesis, the intermediate future is assessed using five GCMs, *viz*. CGCM3.1(T47), CNRM-CM3, ECHAM5/MPI-OM, GISS-ER and IPSL-CM4, but owing to the unavailability of the distant future scenario for the CGCM3.1(T47) GCM, the distant future is assessed with only the remaining four of the above-mentioned GCMs. It is acknowledged that comparisons between the intermediate and more distant future scenarios may be misleading due to different numbers of GCMs being used to produce the respective results. However, as explained in Section 7.1.6, this study has its focus on techniques and, hence, comparisons have been made between the intermediate and more distant future scenarios, for demonstrative purposes.

7.3.4.1 Results O: Uncertainty analysis of projected changes in meteorological droughts with climate change in the intermediate and more distant futures

A very strong message is conveyed from Figures 7.27 and 7.28 in that there is little confidence in the hypothesis that the frequency of meteorological droughts will increase in the intermediate and more distant futures. Furthermore, the overwhelmingly low confidence in the hypothesis is present for droughts of varying severity, both in terms of magnitude and duration. Breaking down what is presented in Figures 7.27 and 7.28 into more detail, it is shown in Table 7.15 that, in both the intermediate and more distant futures, and regardless of the drought severity or duration, for most of the Orange River Catchment none of the GCMs used in this

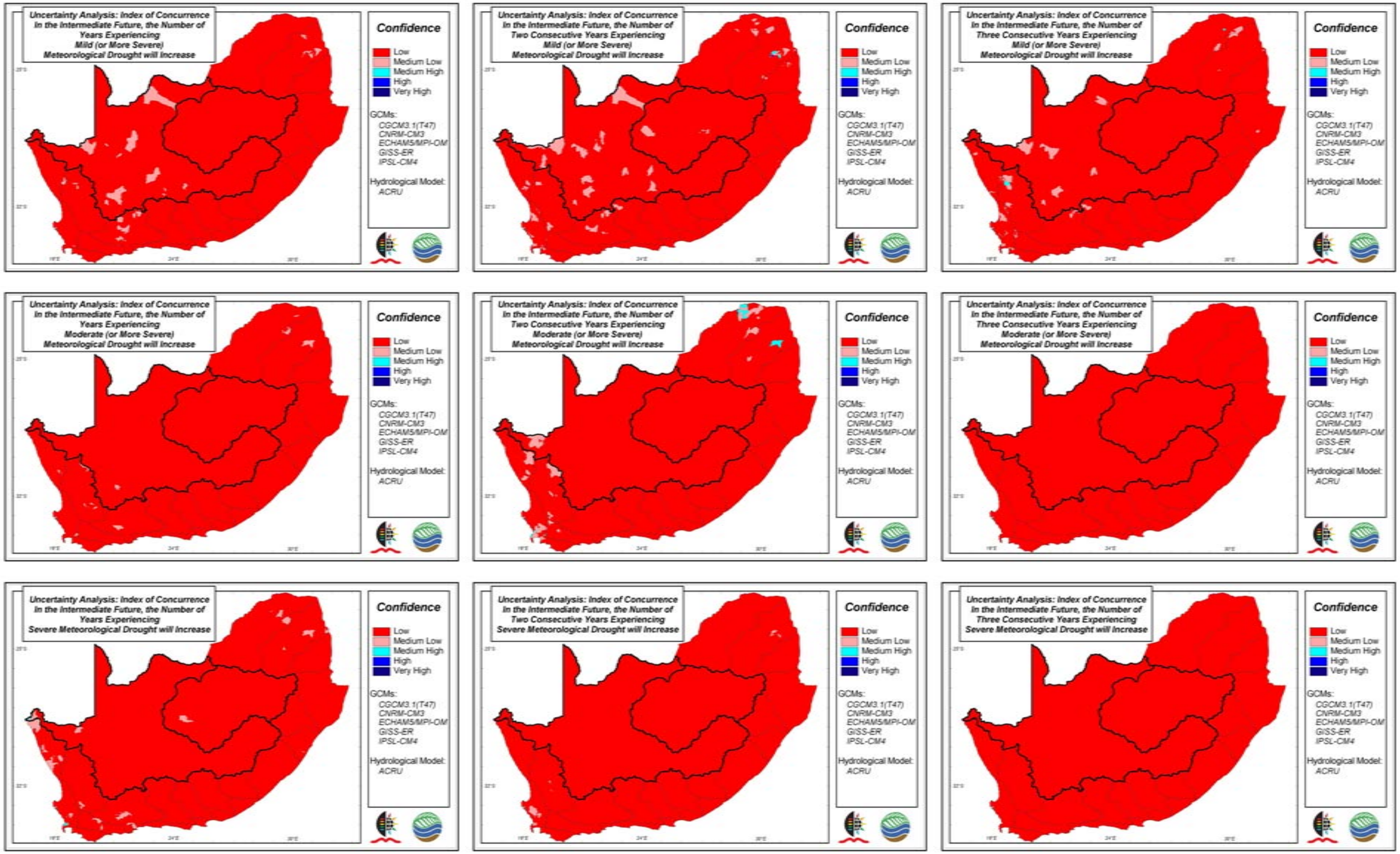


Figure 7.27 Levels of confidence in the hypothesis that meteorological droughts of increasing severity (top to bottom) and increasing duration (left to right) will increase in the intermediate future, derived from downscaled daily rainfall output from multiple GCMs

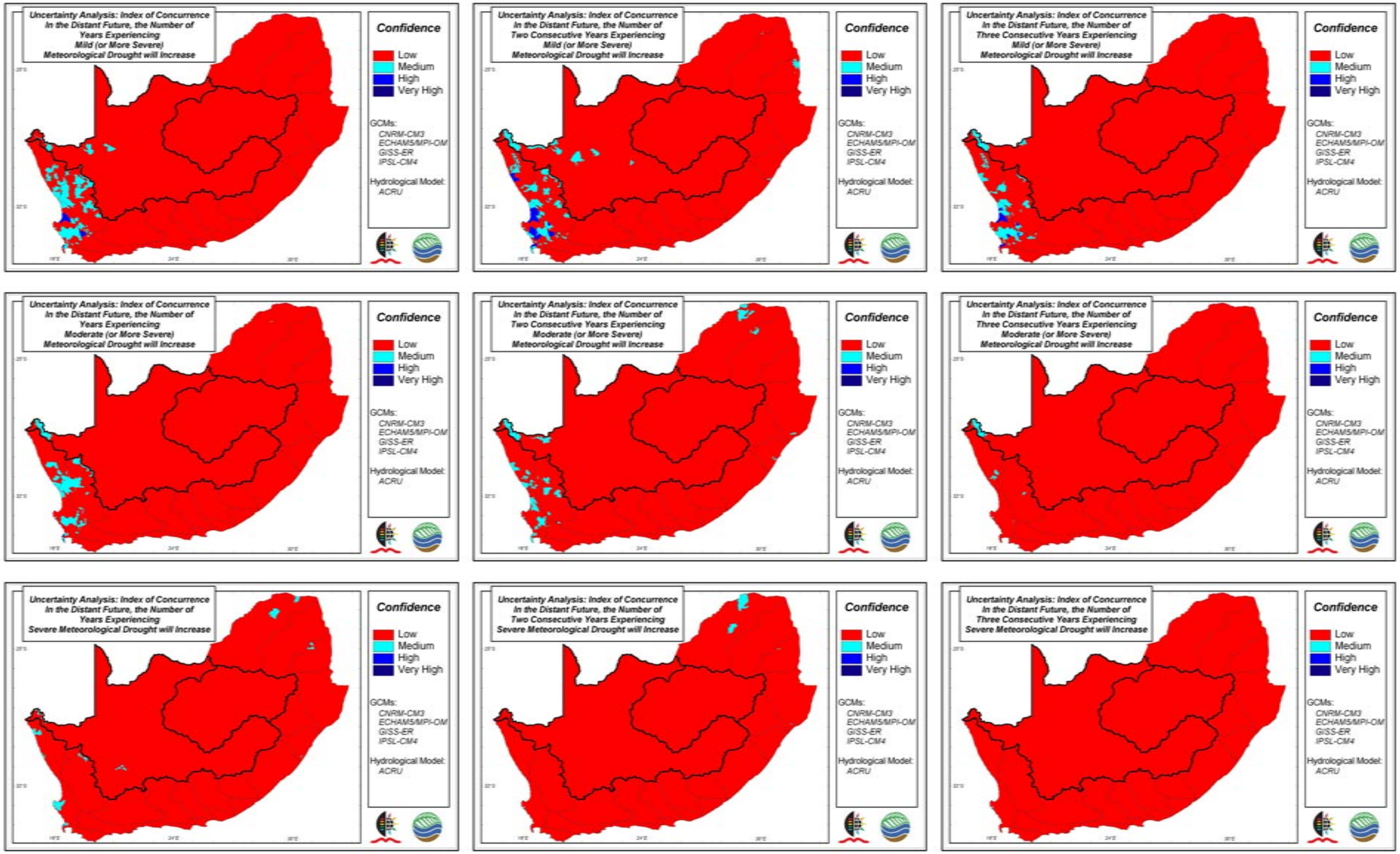


Figure 7.28 Levels of confidence in the hypothesis that meteorological droughts of increasing severity (top to bottom) and increasing duration (left to right) will increase in the more distant future, derived from downscaled daily rainfall output from multiple GCMs

study project that there will be increases in the frequency of droughts. It can further be seen that in virtually all cases the remainder of the Orange River Catchment has only one GCM out of five – or four – projecting an increase in drought frequency in the intermediate and more distant futures. This is a classic example of a hypothesis being conditioned by literature-based generalisations on future drought increases in southern Africa, which are often based on simulations conducted at a global scale, e.g. Arnell (1999; 2003), Milly *et al*. (2005), Nicol and Kaur (2009), Wang (2005) and the IPCC (2001b; 2007a; 2007b; 2012). In this study the inverse of the hypothesis – that the magnitude and frequency of meteorological droughts will increase in the future – is shown to generally be the case for the five GCMs used. It is, however, acknowledged that this may be a sample bias and that using more GCMs, and more SRES scenarios, may have yielded different results. Furthermore, different definitions of drought, which includes analyses at the monthly level, may also have yielded different results.

Table 7.15 Percentage area of the Orange River Catchment with various levels of GCM agreement on the hypothesis that meteorological droughts will increase in the intermediate and more distant futures

Attribute		**Percentage Area of the Orange River Catchment**					
		Intermediate Future			**More Distant Future**		
Drought Severity	**GCMs in Agreement**	**1 Year Drought**	**Consecutive Droughts**		**1 Year Drought**	**Consecutive Droughts**	
			2 Years	**3 Years**		**2 Years**	**3 Years**
Mild (or more severe)	**0 GCMs**	65.0	67.0	67.8	85.5	77.9	78.8
	1 GCM	30.6	27.6	30.1	13.8	20.3	20.4
	2 GCMs	4.4	5.4	2.1	0.7	1.8	0.7
Moderate (or more severe)	**0 GCMs**	62.7	69.9	100.0	74.6	74.5	87.1
	1 GCM	37.2	29.4	0.0	24.8	24.6	12.3
	2 GCMs	0.1	0.7	0.0	0.6	0.9	0.5
Severe	**0 GCMs**	65.6	85.7	96.2	68.5	84.6	98.4
	1 GCM	33.7	14.3	3.8	31.3	15.4	1.6
	2 GCMs	0.6	0.0	0.0	0.2	0.0	0.0

It has been shown in Figures 7.27 and 7.28, as well as in Table 7.15, that there is very little confidence in the hypothesis that meteorological droughts will increase in the intermediate and more distant futures. However, what is not shown here and is useful to water managers, is whether this low confidence implies that present frequencies and magnitudes of meteorological droughts will remain the same, or whether they will decrease in an intermediate or more distant future climate. Table

7.16 provides this information, where a particular direction of change is assigned to a Quinary Catchment if more than half of the available GCMs agree on the respective direction of change. If this condition is not achieved, then the direction of change for that Quinary Catchment is labelled "Inconclusive".

Table 7.16 Percentage area of the Orange River Catchment projected by > 50% of the GCMs used in this study to experience an increase, decrease, or no change in meteorological droughts in the intermediate and more distant futures

Attribute		**Percentage Area of the Orange River Catchment**					
		Intermediate Future			**More Distant Future**		
Drought Severity	**Direction of Change**	**1 Year Drought**	**Consecutive Droughts 2 Years**	**Consecutive Droughts 3 Years**	**1 Year Drought**	**Consecutive Droughts 2 Years**	**Consecutive Droughts 3 Years**
Mild (or more severe)	**Decrease**	100.0	97. 6	22.9	98.4	95.9	9.9
	Increase	0.0	0.0	0.0	0.0	0.0	0.0
	Same	0.0	0.3	60.8	0.0	0.0	41.1
	Inconclusive	0.0	2.1	16.3	1.6	4.1	49.0
Moderate (or more severe)	**Decrease**	100.0	63.9	0.1	99.0	54.5	0.0
	Increase	0.0	0.0	0.0	0.0	0.0	0.0
	Same	0.0	24.3	99.9	0.0	8.2	92.3
	Inconclusive	0.0	11.8	0.0	1.0	37.3	7.7
Severe	**Decrease**	98.6	1.6	0.0	97.6	1.5	0.0
	Increase	0.1	0.0	0.0	0.0	0.0	0.0
	Same	0.3	95.9	100.0	0.0	75.6	100.0
	Inconclusive	1.0	2.5	0.0	2.4	22.9	0.0

It may be seen in Table 7.16 that in the intermediate future the majority of the GCMs agree that every Quinary Catchment in the Orange River Catchment will experience a decrease in the number of meteorological drought years, both when assessing mild (and more severe) droughts and moderate (and more severe) droughts. Only one Quinary Catchment, *viz.* the one at the outlet of the Orange River into the Atlantic Ocean, has three GCMs projecting an increase in severe droughts. Other than this, no other areas are projected by three or more GCMs to experience an increase in meteorological droughts in the future, regardless of drought magnitude or duration. One trend that can be seen is that as the drought duration is increased from one to two to three years, the area projected to experience a decrease in droughts shrinks, while the area that is projected to remain the same enlarges.

A similar pattern is seen in Table 7.16 when focussing on outputs derived from the more distant future climate scenarios. One major difference, however, is the increase in the area labelled “Inconclusive”. This is a direct result of only having four GCMs for analysis of distant future climate projections. Therefore, those “blue” Quinaries indicating medium confidence in Figure 7.28 do not show up as increases in Table 7.16, as medium confidence in the more distant future analyses results from two GCMs being in agreement, which is short of the three required to assign a likely direction of change in this study.

It has been shown that the agreement of the GCMs with the hypothesis that meteorological droughts will increase in the intermediate and more distant futures is very low. However, Table 7.16 indicates that the GCMs tend to agree that meteorological droughts, both in the intermediate and more distant futures, are generally likely to either decrease or remain the same. Table 7.17 shows the overall agreement of the GCMs, i.e. when they give the same signal, and clearly shows, particularly in regard to one year droughts, that the GCMs used in this study are in high agreement over almost the entire Orange River Catchment.

Table 7.17 Percentage area of the Orange River Catchment with various levels of GCM agreement on projecting a direction of change in meteorological droughts in the intermediate and more distant futures*

Attribute		Percentage Area of the Orange River Catchment					
		Intermediate Future			More Distant Future		
Drought Severity	Agreement of GCMs	1 Year Drought	Consecutive Droughts		1 Year Drought	Consecutive Droughts	
			2 Years	3 Years		2 Years	3 Years
Mild (or more severe)	**5 GCMs**	49.4	36.9	4.1			
	4 GCMs	43.1	45.2	22.2	73.9	56.7	6.5
	3 GCMs	7.5	15.8	57.4	24.5	39.2	44.5
	High Confidence +	92.5	82.1	26.3	98.4	95.9	51.0
Moderate (or more severe)	**5 GCMs**	44.8	6.6	64.4			
	4 GCMs	52.2	22.9	32.1	59.2	14.2	55.5
	3 GCMs	3.0	58.7	3.5	39.8	48.5	36.9
	High Confidence +	97.0	29.5	96.5	99.0	62.7	92.4
Severe	**5 GCMs**	35.8	33.0	96.1			
	4 GCMs	53.3	43.1	3.9	45.8	34.1	98.4
	3 GCMs	10.0	21.4	0.0	51.8	43.0	1.6
	High Confidence +	89.1	76.1	100.0	97.6	77.1	100.0

*** Shaded area implies non-applicable case**

7.3.4.2 Results P: Uncertainty analysis of projected changes in hydrological droughts with climate change in the intermediate and more distant futures

Similar to what was shown for meteorological droughts, Figures 7.29 and 7.30 indicate low confidence in the hypothesis that the frequency of hydrological droughts in the Orange River Catchment will increase in the intermediate and more distant futures. This overall picture is confirmed by the information in Table 7.18, which shows that, for the intermediate and the more distant future, over 80% of the Orange River Catchment has only one, or not a single, GCM in agreement with the hypothesis that the frequency of hydrological droughts will increase. This is another example of a hypothesis being conditioned by generalisations on future drought increases in southern Africa from the literature (cf. Section 7.3.4.1). Indeed, in this study the five GCMs used generally show the inverse to be the case. It is, again, acknowledged that this may be the result of a sample bias and that the results may have been different had information from more GCMs – and SRES scenarios – been available for this study.

Table 7.18 Percentage area of the Orange River Catchment with various levels of GCM agreement on the hypothesis that hydrological droughts will increase in the intermediate and more distant futures

Attribute		**Percentage Area of the Orange River Catchment**					
		Intermediate Future			**More Distant Future**		
Drought Severity	**GCMs in Agreement**	**1 Year Drought**	**Consecutive Droughts**		**1 Year Drought**	**Consecutive Droughts**	
			2 Years	**3 Years**		**2 Years**	**3 Years**
Mild (or more severe)	**0 GCMs**	44.6	36.7	43.7	63.1	50.8	59.2
	1 GCM	42.6	46.8	43.0	31.3	41.9	36.0
	2 GCMs	12.3	14.6	12.2	5.4	7.1	4.8
Moderate (or more severe)	**0 GCMs**	40.8	46.4	65.9	56.8	51.5	71.0
	1 GCM	48.7	42.5	29.6	37.7	43.6	26.5
	2 GCMs	10.1	10.7	4.1	5.5	4.9	2.3
Severe	**0 GCMs**	39.8	58.2	81.3	56.6	65.0	84.9
	1 GCM	50.7	34.7	16.3	39.6	31.7	13.5
	2 GCMs	9.1	6.9	2.2	3.9	3.3	1.7

In the more distant future (Figure 7.30), there is a suggestion that the lower reaches of the Orange River may experience an increase in hydrological drought frequencies. This is the case for mild, moderate and more severe annual droughts, as well as two

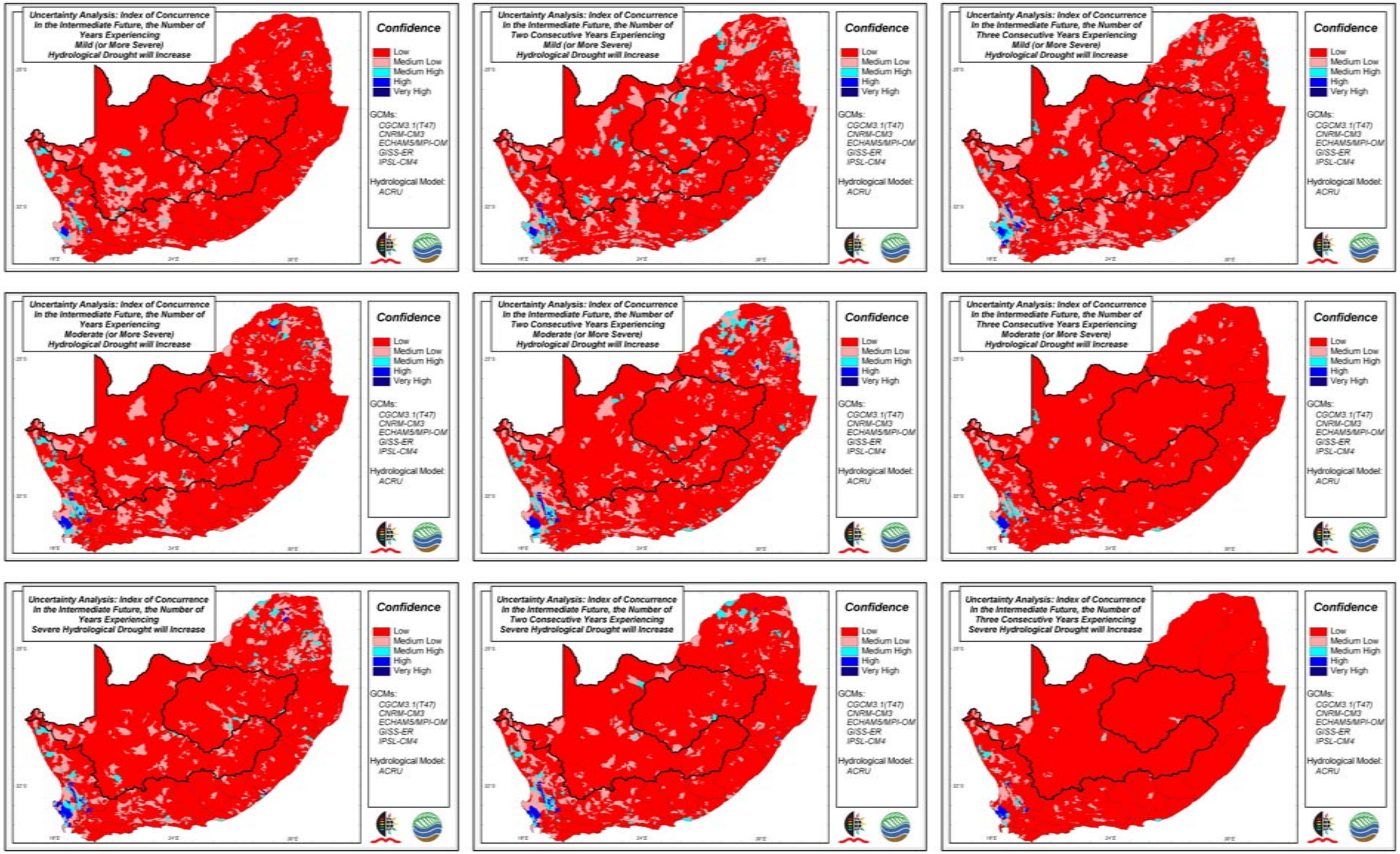


Figure 7.29 Levels of confidence in the hypothesis that hydrological droughts of increasing severity (top to bottom) and increasing duration (left to right) will increase in the intermediate future, derived from *ACRU* simulations using downscaled daily climate output from multiple GCMs

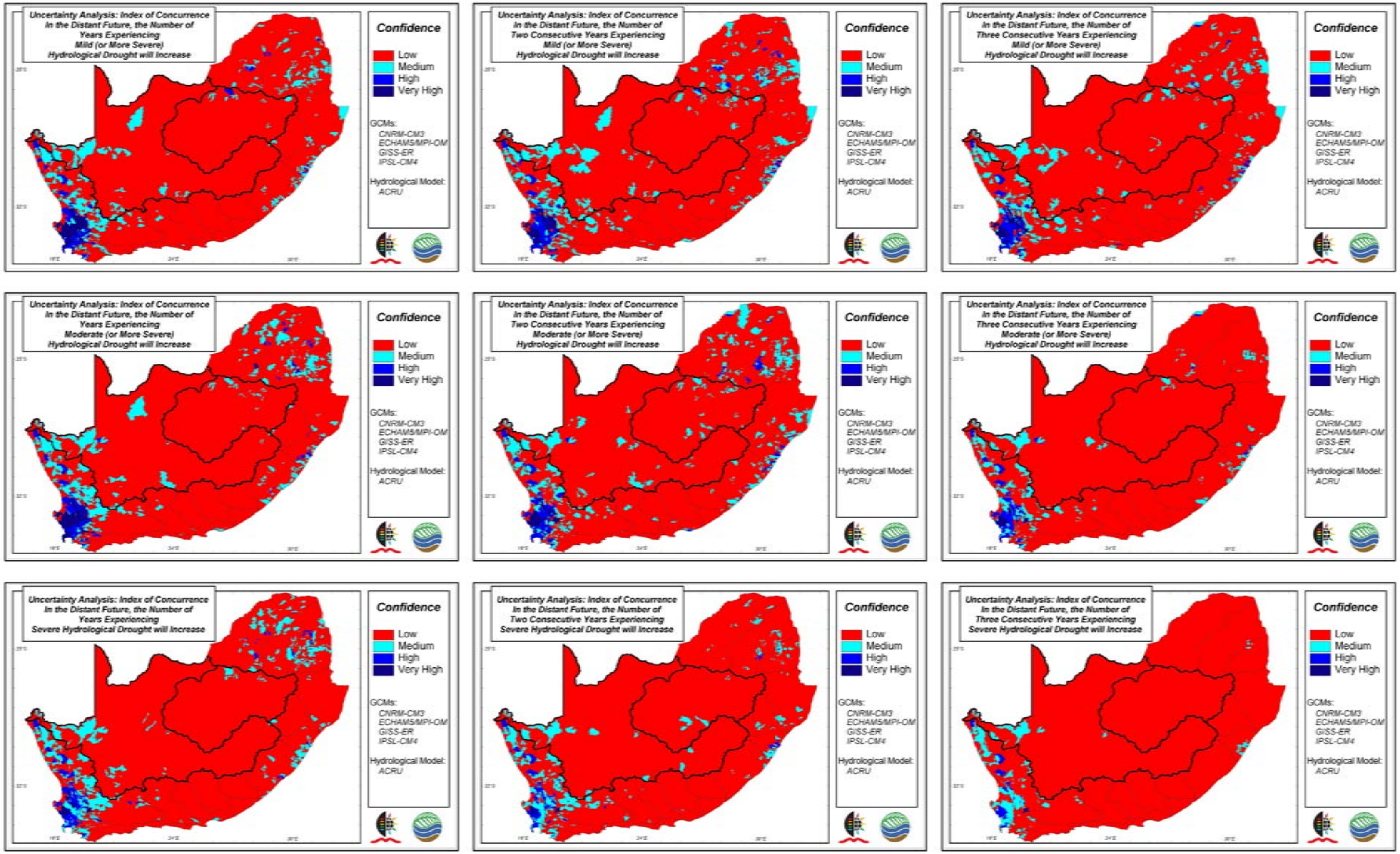


Figure 7.30 Levels of confidence in the hypothesis that hydrological droughts of increasing severity (top to bottom) and increasing duration (left to right) will increase in the more distant future, derived from *ACRU* simulations using downscaled daily climate output from multiple GCMs

and three consecutive drought years. This appears to be the expansion of a trend prevalent on the west coast of South Africa, and is particularly strong in the Western Cape. However, the level of concurrence with the hypothesis – that the frequency and magnitude of future hydrological droughts will increase – in the lower Orange River Catchment is, by and large, two GCMs out of four, resulting in only medium confidence that hydrological droughts may increase.

Table 7.19 indicates the projected directions of change in hydrological drought frequencies, if at all evident, based on more than half of the available GCMs giving the same signal. The figure shows a very similar picture to that for meteorological droughts, *viz*. that hydrological droughts of varying magnitudes and durations will decrease, or remain the same, in the intermediate and more distant futures.

Table 7.19 Percentage area of the Orange River Catchment projected by > 50% of the GCMs used in this study to experience an increase, decrease, or no change in hydrological droughts in the intermediate and more distant futures

Attribute		**Percentage Area of the Orange River Catchment**					
		Intermediate Future			**More Distant Future**		
Drought Severity	**Direction of Change**	**1 Year Drought**	**Consecutive Droughts 2 Years**	**Consecutive Droughts 3 Years**	**1 Year Drought**	**Consecutive Droughts 2 Years**	**Consecutive Droughts 3 Years**
Mild (or more severe)	**Decrease**	97.5	90.5	37.5	90.3	83.7	26.6
	Increase	0.5	1.9	1.1	0.2	0.1	0.0
	Same	0.1	1.2	33.6	0.1	0.1	14.5
	Inconclusive	1.9	6.4	27.8	9.4	16.1	58.9
Moderate (or more severe)	**Decrease**	97.7	60.0	7.0	89.9	46.1	3.0
	Increase	0.3	0.4	0.4	0.1	0.1	0.1
	Same	0.1	23.2	86.9	0.1	6.5	76.0
	Inconclusive	1.9	16.4	5.7	9.9	47.3	20.9
Severe	**Decrease**	95.2	13.3	6.5	89.0	9.2	2.5
	Increase	0.5	0.4	0.3	0.0	0.0	0.0
	Same	0.6	77.0	91.6	0.2	58.3	90.7
	Inconclusive	3.7	9.3	1.6	10.8	32.5	6.8

Further investigation of Table 7.19 shows that when increasing the drought severity from mild to moderate to severe, or increasing the drought duration from one to two to three years, the area of the Orange River Catchment that is projected to experience fewer droughts shrinks, while the area that is projected to be unaffected expands. This shift towards a zero change with increasing drought severity is likely to be the consequence of only having 20 years of data for analysis.

Moving to an analysis of GCM concurrence with one another (Table 7.20), regardless of the projected direction of change, the apparent trends are very similar to those evident in same the analysis for meteorological droughts (cf. Table 7.17). For all hydrological drought severities and durations there is higher agreement amongst the GCMs in the more distant future than in the intermediate future. The agreement of the GCMs when projecting mild (or more severe) droughts decreases when increasing the number of consecutive drought years from one to two to three. Furthermore, for projections of severe droughts occurring in three consecutive years, more than three quarters of the Orange River Catchment has the same signal projected by all GCMs, for both the intermediate and more distant future climate scenarios. This is due to the high incidence of projected zero changes, likely resulting from the time series used being limited to only 20 years.

Table 7.20 Percentage area of the Orange River Catchment with various levels of GCM agreement on projecting a direction of change in hydrological droughts in the intermediate and more distant futures*

Attribute		**Percentage Area of the Orange River Catchment**					
		Intermediate Future			**More Distant Future**		
Drought Severity	**Agreement of GCMs**	**1 Year Drought**	**Consecutive Droughts**		**1 Year Drought**	**Consecutive Droughts**	
			2 Years	**3 Years**		**2 Years**	**3 Years**
Mild (or more severe)	**5 GCMs**	27.3%	17.3%	2.4%			
	4 GCMs	47.4%	45.6%	18.4%	48.5%	29.0%	7.0%
	3 GCMs	23.4%	30.7%	51.4%	42.2%	55.0%	34.1%
	High Confidence +	74.7%	62.9%	20.4%	90.7%	84.0%	41.1%
Moderate (or more severe)	**5 GCMs**	23.1%	2.4%	26.4%			
	4 GCMs	53.8%	23.4%	44.0%	42.1%	6.8%	29.8%
	3 GCMs	21.3%	57.8%	23.9%	48.1%	45.8%	49.2%
	High Confidence +	76.9%	25.8%	70.4%	90.2%	52.6%	79.0%
Severe	**5 GCMs**	19.8%	20.6%	75.7%			
	4 GCMs	53.2%	35.1%	14.8%	31.7%	21.0%	77.0%
	3 GCMs	23.2%	35.1%	7.8%	57.5%	46.5%	16.2%
	High Confidence +	53.0%	55.7%	90.5%	89.2%	67.5%	93.2%

*** Shaded area implies non-applicable case**

A comparison of results from Table 7.20 with those from Table 7.17 shows that there is less agreement amongst the GCMs for hydrological drought projections than for meteorological drought projections. This is due to several factors, which include different projected temperatures from the different GCMs, hence different levels of evaporation. This, in turn, affects the soil water balance and, when combined with different projected rainfall attributes such as the number of rain days, event magnitudes and persistent sequences of wet/dry, wet/wet, dry/dry and dry/wet day combinations, it comes as no surprise that these factors, together with the complexities introduced by the hydrological cycle, increase the uncertainty of hydrological projections.

7.3.5 Summary of main findings

- Most of the Orange River Catchment is projected by the GCMs used in this study to experience decreases in the frequencies of meteorological and hydrological droughts, in both the intermediate and more distant futures, regardless of the magnitude or duration of the events. If droughts are to occur, they are projected to most likely be experienced in the western regions of the catchment.
- The most severe meteorological and hydrological droughts are more likely to occur in the future at the same rate as they do at present. This, however, may be the result of using only a 20 year record for the drought analyses.
- The spatial patterns of hydrological droughts appear to be related more to the projected number of days per year with larger rainfall events, rather than to the number of effective rainfall (i.e. smaller) days per year.
- Projections from the ECHAM5/MPI-OM GCM indicate that for both the intermediate and more distant future climates, those areas projected to experience an increase in floods are simultaneously projected to experience a decrease in hydrological droughts, and vice versa. Therefore, all of the Orange River Catchment is projected to experience increased exposure to one of the extremes, either floods or droughts.
- Although the GCMs used in this study do not agree with the hypothesis that droughts will increase in the future, they do agree with each other over most of the Orange River Catchment. The same signal of change of annual meteorological drought frequencies in the intermediate and distant future is

projected with at least high confidence for approximately 90% or more of the Orange River Catchment.

7.4 Sediment Yield

Soil erosion is a serious problem in southern Africa and is the result of one, or a combination of several, of the following factors, *viz*. semi-arid climatic conditions, high rainfall intensities, shallow erodible soils, limited/degraded land cover and/or substandard conservation management practices (Lorentz and Schulze, 1995). Rooseboom and Lotriet (1992) emphasise the significance of the issue by highlighting over 600 references prior to 1990, which had been included in the "Bibliography on Soil Erosion and Sediment Production Research in Southern Africa" (Weaver, 1989). Rooseboom *et al*. (1992) estimated that the standardised mean annual sediment yield in southern Africa varied between 30 and 335 $t.km^{-2}$ across nine relatively homogeneous sediment yield regions. Sediments can become trapped in reservoirs, thereby reducing the storage capacity and decreasing the reservoir design life (Rooseboom, 1992; Gleick, 2000). Furthermore, elevated concentrations of suspended sediments in flowing water reduce the quality of water in the rivers (Kienzle *et al.*, 1997). Therefore, sediment yield is a potential hydrological hazard, either through the reduction of useable water by impeding water quality or reducing water storage, or alternatively by creating an increased flooding hazard, especially when sedimentation occurs in dams constructed for flood mitigation, or by reducing the carrying capacity of rivers (Tucker and Slingerland, 1997; Takeuchi, 2002; Newson, 2009).

The Universal Soil Loss Equation, USLE (Wischmeier and Smith, 1978), has received recognition as an empirical method useful for initial planning and design purposes (Schulze *et al.*, 2008a). Empirical equations derived from this method, which can be applied at a catchment scale to estimate sediment yield, such as the Revised Universal Soil Loss Equation, RUSLE (Renard *et al.*, 1991), and the Modified Universal Soil Loss Equation, MUSLE (Williams, 1975), have an advantage in that the components of these equations have been researched extensively for southern African conditions (Lorentz and Schulze, 1995). The daily stormflow event-based MUSLE, however, is a hydrologically driven simulator and has been widely verified world-wide as well as in South Africa (Kienzle *et al.*, 1997). Furthermore, the MUSLE accounts for erosive and transport energies through the inclusion of stormflow volume and peak discharge (Williams and Berndt, 1977; van Zyl and Lorentz, 2003), respectively, both of which are projected to change in the intermediate and distant futures (cf. Section 7.2).

This section on sediment yield commences with a description of the methodology adopted for its computation. This is followed by analyses of sediment yields over the Orange River Catchment using historical climate data, and then using climate scenarios projected by the ECHAM5/MPI-OM GCM, by way of example. Finally, a quantitative uncertainty analysis, based on the hypothesis that *sediment yields will increase, in both magnitude and variability, in future climates* is performed using all five of the GCMs available for this study.

7.4.1 Methodology: Computation of sediment yields

The *ACRU* model uses hydrological drivers to estimate sediment yield, Y_{sd}, on an event basis whenever stormflow occurs (Lorentz and Schulze, 1995). Sediment yield at any Quinary Catchment outlet may be estimated in *ACRU* using the MUSLE, which is a function of stormflow, peak discharge, soil erodibility, catchment slope, land cover and management, and support practice, and is expressed as (Lorentz and Schulze, 1995):

$$Y_{sd} = \alpha_{sy} (Q_v q_p)^{\beta_{sy}} K \times LS \times C \times P \qquad (7.11)$$

where

Y_{sd}	=	sediment yield from an individual stormflow event (t),
Q_v	=	stormflow volume for the event (m^3),
q_p	=	peak discharge for the event (m^3.s^{-1}),
K	=	soil erodibility factor (t.h.N^{-1}.ha^{-1}),
LS	=	slope length and gradient factor (dimensionless),
C	=	cover and management factor (dimensionless), and
P	=	support practice factor (dimensionless).

The MUSLE coefficients, α_{sy} and β_{sy} are location specific (Simons and Sentürk, 1992) and are determined for specific climatic zones (Lorentz and Schulze, 1995). However, the internationally accepted default values of 8.934 for α_{sy} and 0.56 for β_{sy}, which have also been used in previous South African studies (e.g. Kienzle *et al*., 1997) were adopted for this study.

In order to simulate sediment yield the peak discharge for each stormflow event needs to be estimated for each Quinary Catchment (cf. Equation 7.11). For these simulations the Soil Conservation Service (SCS) peak discharge equation, as modified for use on natural catchments in South Africa by Schulze and Schmidt (1995) is used (cf. Section 7.2.2.1).

The land cover factor (Figure 7.31: top left) was estimated in this study using attributes of the 70 Acocks' Veld Types (cf. Section 5.2.2.5) given by Schulze (2004). Since baseline land cover conditions were assumed the management practice factor did not apply for these simulations, and was thus set to 1. The slope length and gradient factor was calculated from each Quinary Catchment's average slope gradient (Figure 7.31: top right), determined from a 200 m resolution Digital Elevation Model (Horan, 2008), and an equation which relates slope gradient to the slope length factor developed by Schulze (1979). The soil erodibility factor (Figure 7.31: bottom right) was determined by Schulze and Horan (2008) using the AUTOSOILS computer program (Pike and Schulze, 1995 and updates) with the Institute for Soil, Climate and Water (ISCW) Land Type soil classes. Since sediment eroded at one location may be stored temporarily and subsequently remobilised several times before reaching the catchment outlet (van Zyl and Lorentz, 2003), a factor proportioning the amount of sediment generated from a stormflow event, and which reaches the outlet to the respective Quinary Catchment on the day of the event, is included in the *ACRU* model (Schulze, 1995). The remainder of the sediment exits the respective Quinary Catchment over the following days and is calculated using an exponential decay function.

From the top left map in Figure 7.31, it can be gleaned that the vegetation cover decreases from east to west across the Orange River Catchment, with the exception of the bushlands in northern regions. The top right map in Figure 7.31 shows that the catchment is, by and large, very flat, with the exception of the steeper slopes at the extreme lower reaches of the Orange River, as well as those in the east of the catchment, especially in the highlands of Lesotho. The soil erodibility map (bottom right of Figure 7.31) indicates that the most erodible soils are located in the northern regions of the Orange River Catchment, with the erodibility decreasing towards the southeast. It is expected that the highest sediment yields will result in those areas where steep slopes, highly erodible soils and poor vegetative cover coincide.

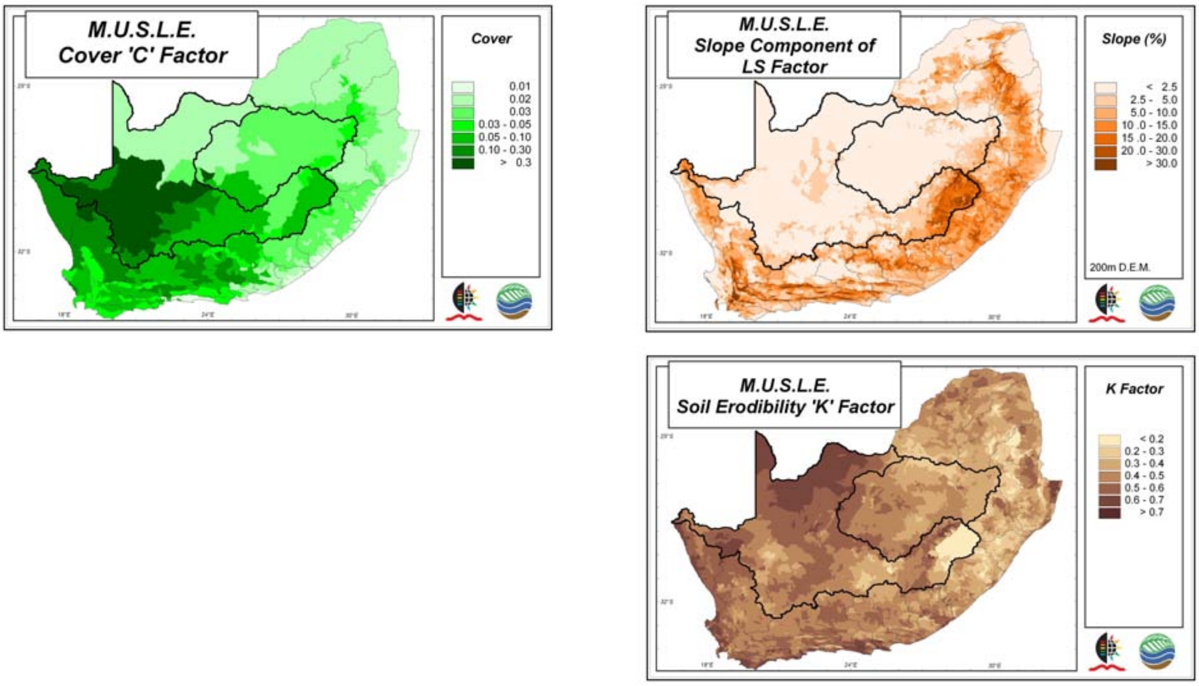


Figure 7.31 Spatial distributions over South Africa of the (top left) cover and management factor, C, (top right) the mean catchment slope used in slope length calculations and (bottom right) the soil erodibility factor, K, all used in the Modified Universal Soil Loss Equation (MUSLE) in computations of event-based sediment yield

7.4.2 Results Q: Spatial patterns of sediment yields, modelled using historical observed climate data, per Quinary Catchment

Equation 7.11 indicates that spatial patterns of sediment yield can result from any one of several factors, or a combination of those factors. Mean annual sediment yields (Figure 7.32: top left) under baseline land cover conditions appear to be closely related to the slope of the catchment, with the highest simulated values,

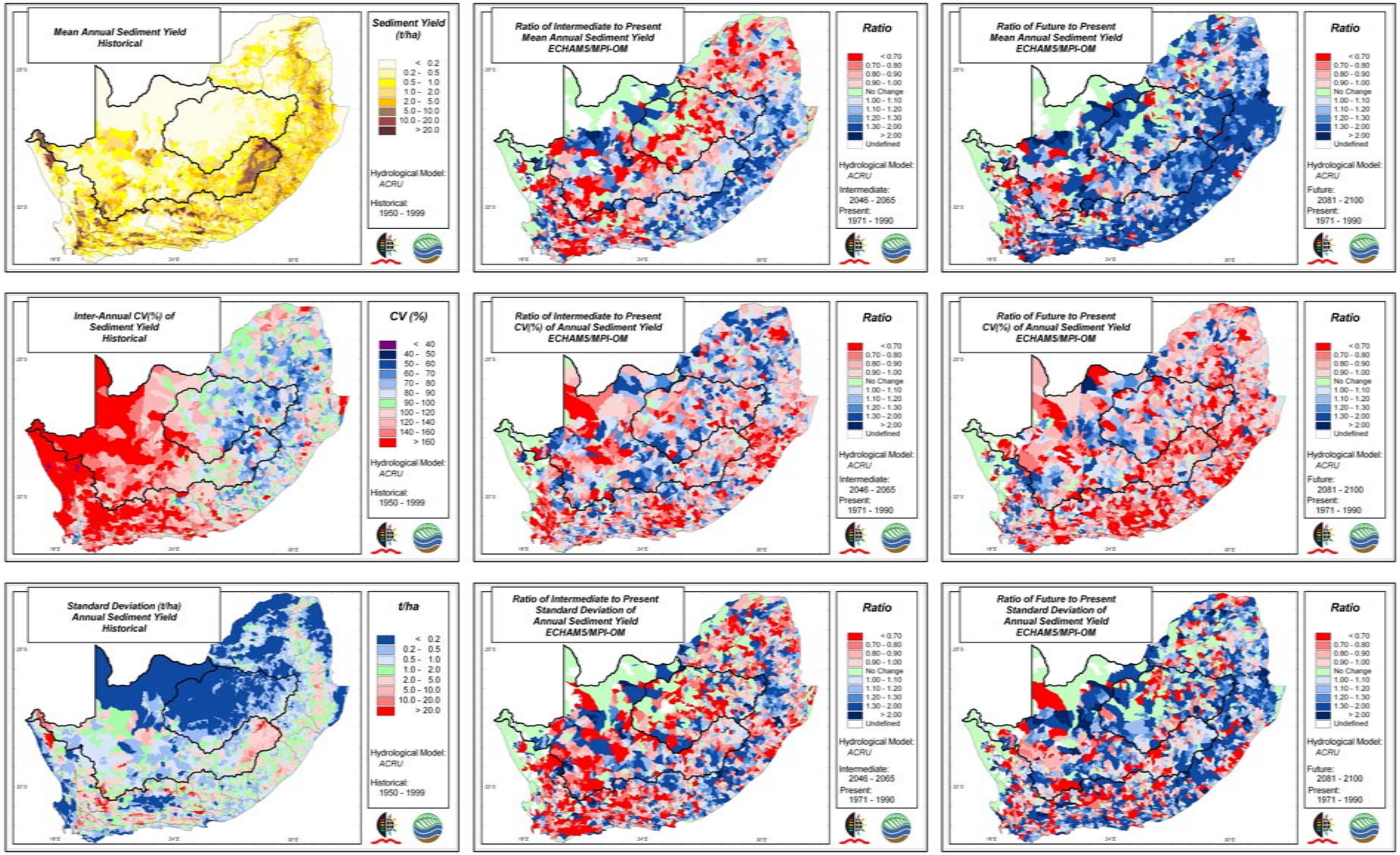


Figure 7.32 Ratios of intermediate to present (centre), and more distant future to present (right), mean annual sediment yields with their inter-annual variability, expressed by both the coefficient of variation and standard deviation, derived from *ACRU* simulations using downscaled daily climate output from the ECHAM5/MPI-OM GCM, compared with baseline values derived from *ACRU* simulations using historical daily climate data from the QnCD (left)

> 20 t/ha, present at the source of the Orange River in Lesotho, and the lowest values, < 0.2 t/ha, occurring across the western regions of the Vaal River Catchment, spreading westwards across the northern regions of the Orange River Catchment. The values of mean annual sediment yield occurring in those regions in the southwest of the Orange River Catchment appear to be partly influenced by the increasing soil erodibility (Figure 7.31: bottom right) from east to west across the catchment, but are also largely due to the high cover factor in this region, as indicated in the top left map of Figure 7.31. The increase in soil erodibility, as well as the cover factors, is largely influenced by the increasing aridity from east to west across the Orange River Catchment.

With respect to the year-to-year variability of sediment yield, expressed through the coefficient of variation (CV%), the already high CV% in the east of the catchment (60 - 90%) increases westwards to values exceeding 160% (Figure 7.32: middle left). More than half of the Orange River Catchment has a simulated inter-annual CV% of sediment yields in excess of 100%. The standard deviation of annual sediment yield (Figure 7.32: bottom left) shows that the high CV% indicated in the west of the Orange River Catchment is accompanied by some of the largest absolute deviations, in some cases exceeding 20 t/ha.

A finding that is indicative of the amplifying effects of the hydrological cycle, especially for higher order responses such as sediment yields, is that for many Quinary Catchments the differences between the lowest annual sediments in 10 years and the highest annual sediments in 10 years is up to, and sometimes exceeds, an order of magnitude, as shown by the maps in left-hand column of Figure 7.33.

7.4.3 Results R: Projected changes in sediment yields with climate change in the intermediate and more distant futures

The intermediate future projections, based on computations with climate output from the ECHAM5/MPI-OM GCM, indicate a clear band of projected increases in annual sediment yields extending from the east coast of South Africa into the eastern regions of the Orange River Catchment (Figure 7.32: top middle). A band of

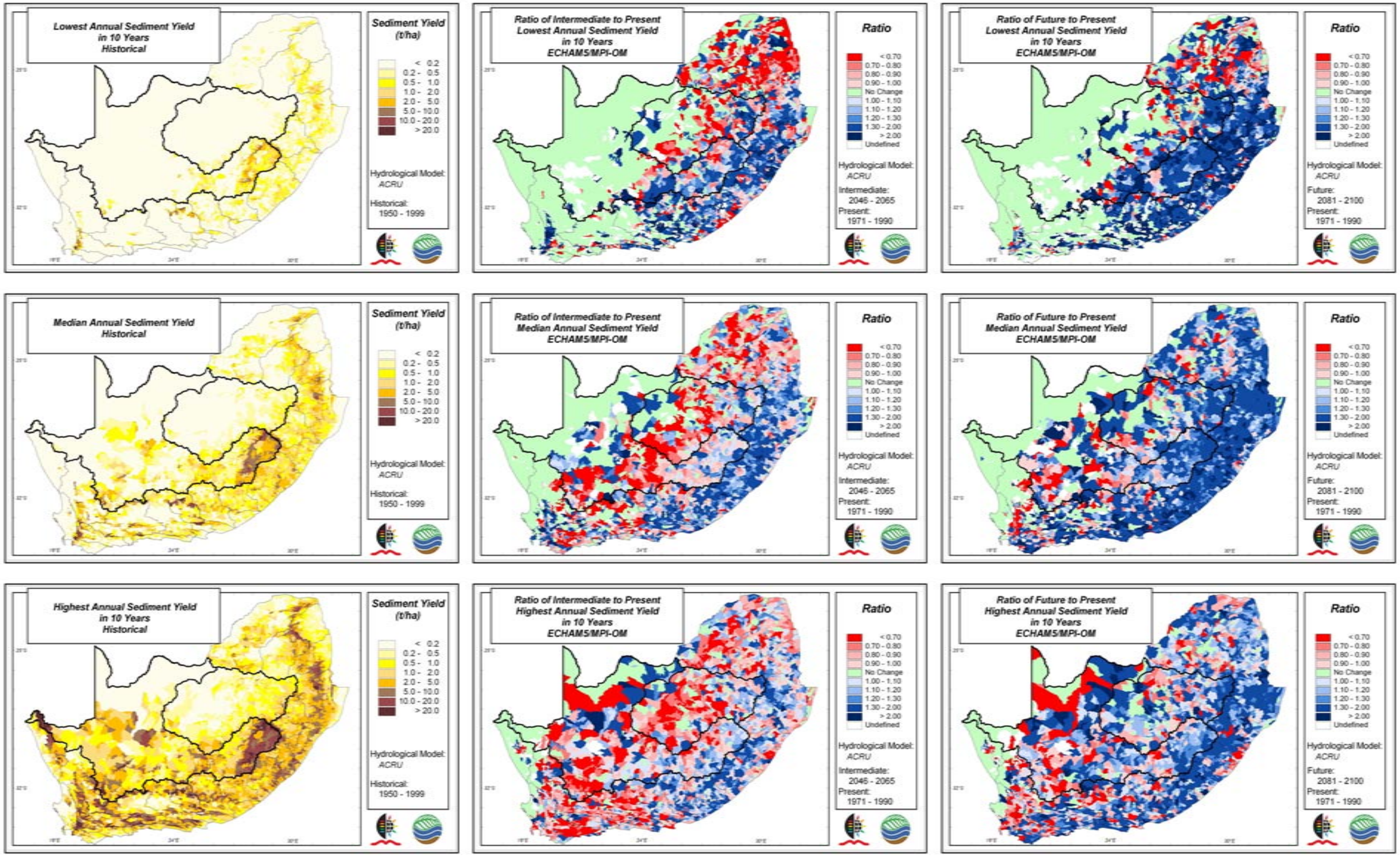


Figure 7.33 Ratios of intermediate to present (centre), and more distant future to present (right), median annual as well as the lowest and highest annual sediment yields in 10 years, derived from *ACRU* simulations using downscaled daily climate output from the ECHAM5/MPI-OM GCM, compared with baseline values derived from *ACRU* simulations using historical daily climate data from the QnCD (left)

predominantly decreasing sediment yields stretches across the catchment from the northeast to the southwest of South Africa, similar to what was observed for design rainfall (cf. Sections 7.1.3 and 7.1.5) and design floods (cf. Section 7.2.1.3). Many of the western-most Quinaries, as well as the northern Quinaries, making up approximately one quarter of the Orange River Catchment (Table 7.21), are projected to have similar sediment yields in the intermediate future to those under present climatic conditions. This is largely due to no sediment yielding runoff events occurring in the arid/semi-arid west and north.

The ‘red’ band indicating decreasing sediment yields, evident in the intermediate future, all but disappears in the distant future while the area indicating increases in sediment yields appears to grow in extent and magnitude (Figure 7.32: top right). This is confirmed in Table 7.21, where it can be seen that, although the area projected to experience no changes remains relatively constant from the intermediate to more distant future, the projected increases in sediment yields in the intermediate future, which covers approximately one third of the Orange River Catchment, expands to cover about 55% of the catchment in the more distant future. Therefore, approximately 20% of the Orange River Catchment reverses from having projected decreases in mean annual sediment yields between 2046 and 2065, to having projected increases between 2081 and 2100. Furthermore, the percentage area of the Orange River Catchment projected to experience increases in sediment yields in excess of 30% grows from 13% in the intermediate future to over 30% in the more distant future. This raises serious concerns for water managers, both with regard to water quality and reservoir storage capacity. Both these issues threaten the already scarce (cf. Section 1.2) water resources of the Orange River Catchment.

Although the spatial pattern of year-to-year deviations of sediment yields in the intermediate future (Figure 7.32: middle), expressed through the CV%, is difficult to interpret, it can be seen in Table 7.21 that approximately 40% of the Orange River Catchment is projected to experience increased variability, while just over half the catchment is to experience decreased variability. In the more distant future, a greater area of the Orange River Catchment is projected to experience decreases in CV% (Figure 7.32: middle right). This, however, is the result of projected increases in the mean annual sediment yields in the more distant future. Comparing the CV% to the standard deviation shows that, although one third of the Orange River Catchment is projected to experience an increase in CV% in the more distant future, almost half the catchment will experience increases in absolute deviations from the mean (Table 7.21).

Table 7.21 Percentage area of the Orange River Catchment projected to experience an increase, decrease, or no change in sediment yields in the intermediate and more distant futures, derived from computations using downscaled daily climate output from the ECHAM5/MPI-OM GCM

Attribute	Percentage Area of the Orange River Catchment											
	Intermediate Future						More Distant Future					
Direction of Change	**Mean**	**CV%**	**Standard Deviation**	**10th Percentile**	**Median**	**90th Percentile**	**Mean**	**CV%**	**Standard Deviation**	**10th Percentile**	**Median**	**90th Percentile**
No Change	23.7	7.5	24.0	55.6	34.0	15.9	20.9	5.5	19.2	52.7	29.4	12.3
Decrease	44.0	50.7	44.8	24.0	38.5	50.2	23.6	60.3	33.6	16.9	23.1	33.6
Increase	32.3	41.8	31.2	20.4	27.5	33.9	55.5	34.2	47.2	30.4	47.5	54.1
Decrease > 30%	19.2	11.2	21.6	15.0	19.8	21.8	11.4	14.2	15.8	13.4	11.2	15.1
Increase > 30%	13.0	12.7	18.1	13.0	12.6	13.8	31.7	7.2	26.8	22.6	29.4	27.9

Figure 7.33 (middle column of maps) shows the projected changes to the lowest annual sediment yields in 10 years, the median annual sediment yields and the highest annual sediment yields in 10 years for the intermediate future, based on computations with climate output from the ECHAM5/MPI-OM GCM. Moving from the lowest annual sediment yields in 10 years to the highest annual sediment yields in 10 years shows large areas of “no change” in west and north of the Orange River Catchment decreasing in areal extent. This decrease results from increasing projected changes, in both directions, with increasing magnitude of sediment yielding events. It can be seen in Figure 7.33 and Table 7.21 that, regardless of the magnitude, the extent of projected decreases in annual sediment yields is always greater than the extent of projected increases.

In the more distant future (Figure 7.33: right-hand column of maps) the area of “no change” is very similar to that projected for the intermediate future. As alluded to earlier, this is largely due to no sediment yielding events occurring in the arid/semi-arid west and north. A similar pattern to that for the intermediate future is noticed when moving from the lowest annual sediment yields in 10 years to the highest annual sediment yields in 10 years – i.e. there is an increase in the area projected to experience changes, in both directions, in annual sediment loads. The major difference, though, is that in the more distant future the area of the Orange River Catchment projected to experience increases in annual sediment yields is consistently greater than the projected decreases. Once again, this is particularly concerning for water resources managers due to the potential reduction of an already scarce water resource through the effects on water quality and storage, and also owing to the potential increased flood hazards resulting from sedimentation. Another concerning factor is that for both the intermediate and more distant futures, and for all magnitudes of annual sediment yields, large portions of Lesotho, which is the source of the Orange River, and the location of major water storage and transfer schemes, are projected to experience increased annual sediment yields.

7.4.4 Methodology: How certain are we of projected changes in sediment yields in the Orange River Catchment?

As for previous sections (e.g. design rainfalls), a quantitative uncertainty assessment was performed for the intermediate future, and the more distant future, sediment yield projections using the scale described in Table 7.4, and based on the hypothesis that *annual sediment yields will increase and become more variable with future climates*. The intermediate future is assessed using five GCMs, *viz*. CGCM3.1(T47), CNRM-CM3, ECHAM5/MPI-OM, GISS-ER and IPSL-CM4. The distant future is assessed with only four of the above-mentioned GCMs as the distant future scenario for the CGCM3.1(T47) model was unavailable. As already mentioned (cf. Section 7.1.6), having one less GCM for the more distant future may be misleading when comparing the results from the intermediate and more distant future scenarios.

7.4.5 Results S: Uncertainty analysis of projected changes in sediment yields with climate change in the intermediate and more distant futures

Despite the dampening effect that the Schmidt and Schulze (1984) lag equation has on projected peak discharges for future climates (cf. Section 7.2.2), the general consensus from the selected GCMs is one of concurrence with the hypothesis that annual sediment yields will increase with projected climates of the intermediate and more distant futures. The top left map in Figure 7.34 shows that mean annual sediment yields are projected to increase in the intermediate future across most of the Orange River Catchment, with the highest confidence in the east, and decreasing in a westwards direction. Table 7.22 shows that two thirds of the catchment has three or more GCMs in agreement with the hypothesis, with half of this area having four or more GCMs agreeing that mean annual sediment yields will increase.

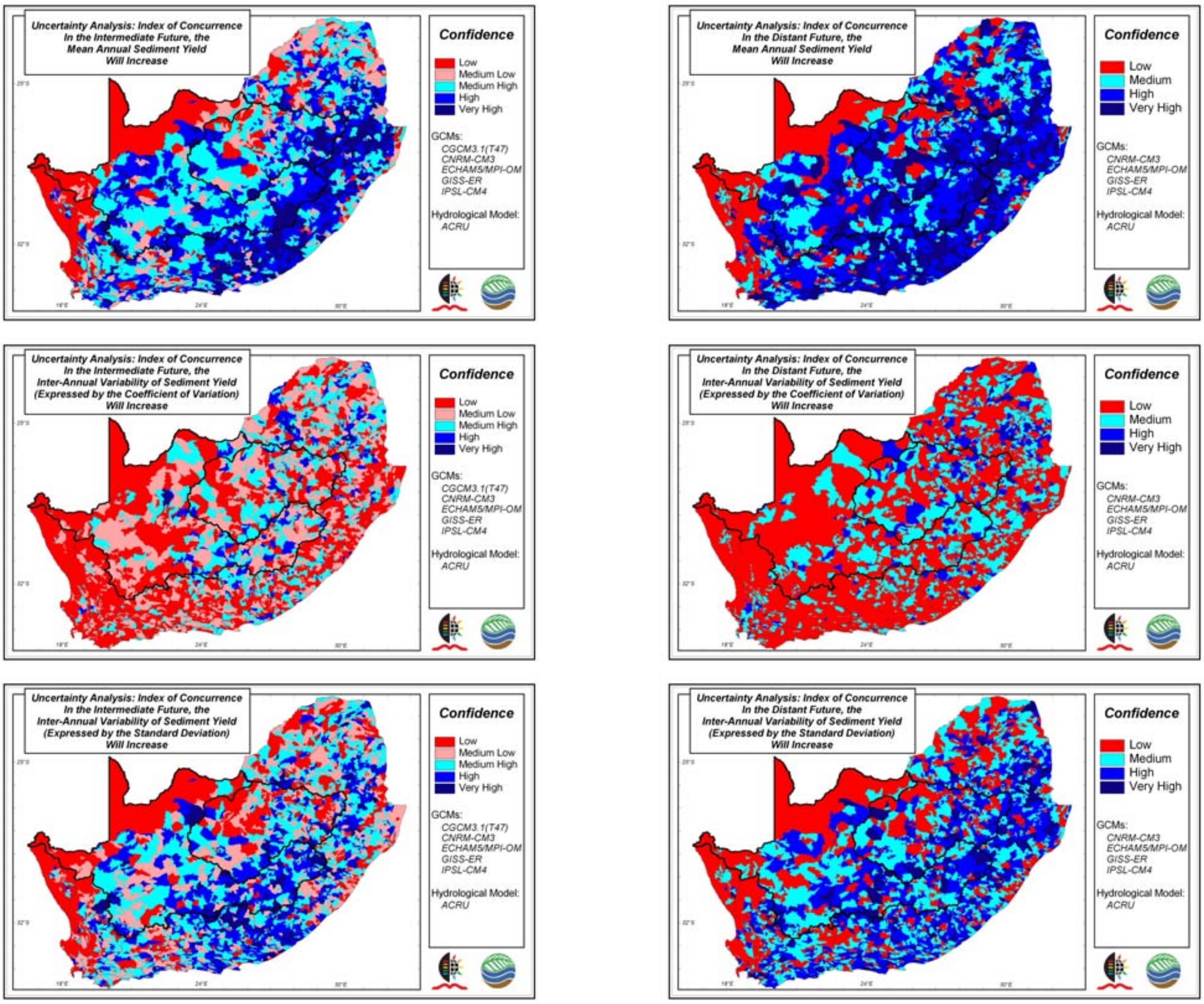


Figure 7.34 Levels of confidence in the hypothesis that mean annual sediment yields, as well as their inter-annual variability, will increase in the intermediate and more distant futures, derived from *ACRU* simulations using downscaled daily climate output from multiple GCMs

Mean annual sediment yields projected for the distant future (Figure 7.34: top right) display a similar spatial pattern, also with decreasing confidence in a westwards direction. However, in the more distant future, a greater area of the Orange River Catchment is projected to experience increases in mean annual sediment yields. Table 7.22 shows that three quarters of the catchment is projected, with medium (or greater) confidence, to experience increases in annual sediment yields. Just over 55% of the catchment displays high (or greater) confidence in the hypothesis.

Table 7.22 Percentage area of the Orange River Catchment with medium (or greater) and high (or greater) confidence in the hypothesis that sediment yields will increase in the intermediate and more distant futures, derived from computations using downscaled daily climate output from the five GCMs used in this study

Attribute	**Percentage Area of the Orange River Catchment**											
	Intermediate Future						**More Distant Future**					
Confidence	**Mean**	**CV%**	**Standard Deviation**	**10th Percentile**	**Median**	**90th Percentile**	**Mean**	**CV%**	**Standard Deviation**	**10th Percentile**	**Median**	**90th Percentile**
Medium +	68.0	27.8	52.2	28.6	50.9	67.4	75.2	38.7	64.8	39.8	63.0	74.2
High +	34.5	6.9	26.2	15.5	25.8	33.7	55.2	9.1	35.1	28.0	44.6	50.8

The middle and bottom rows of maps in Figure 7.34 show the spatial variation of confidence in the hypothesis that the inter-annual variability of sediment yields will increase in the intermediate and more distant futures. As for mean annual sediment yields, confidence in the hypothesis appears to be greatest in the east, decreasing westwards. Table 7.22 indicates that medium (or greater) confidence in the hypothesis covers less than one third of the Orange River Catchment when assessing inter-annual variability according to CV%. However, this extends to over half the catchment when absolute deviations from the mean are considered. Similar trends are present for projections of inter-annual variability in the more distant future. However, the area with medium (or greater), and high (or greater), confidence in the hypothesis expands from the intermediate to more distant future projections.

It is shown above that annual sediment yields are projected to increase over much of the Orange River Catchment (Figure 7.34: top row of maps). However, Figure 7.35

indicates that the degree of concurrence with the hypothesis depends largely on the magnitude of the sediment yielding events. According to results based on computations with climate output from the five GCMs used in this study, the areal extent of projected increases in years with the lowest annual sediment yields in 10 years, is approximately half that for those increases projected for years with the highest annual sediment yields in 10 years (Table 7.22).

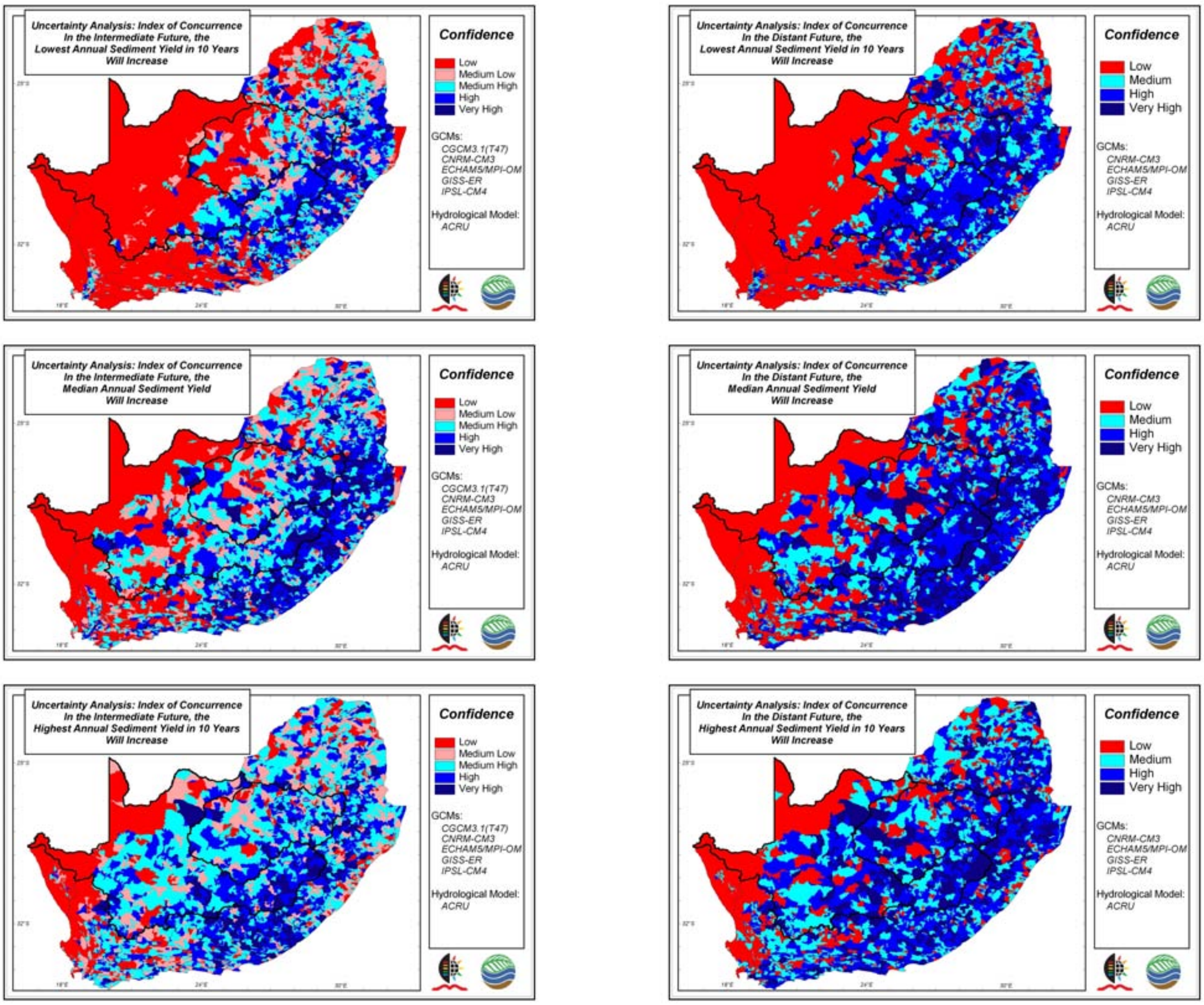


Figure 7.35 Levels of confidence in the hypothesis that median annual sediment yields, as well as the lowest and highest annual sediment yields in 10 years, will increase in the intermediate and more distant futures, derived from *ACRU* simulations using downscaled daily climate output from multiple GCMs

Similar to the results displayed in Figure 7.34, the spatial variations displayed in Figure 7.35 indicate the highest confidence in the east of the catchment and the lowest in the west. The low confidence in the hypothesis apparent in the west and northern regions of the Orange River Catchment is due to there being no changes as the climate changes, resulting from the lack of sediment yielding events.

Similar trends are evident in the more distant future. However, the area displaying medium (or greater) and high (or greater) confidence is consistently greater in the more distant future than in the intermediate future (Table 7.22). This is largely due to the increases in rainfall, and consequent increases in stormflow volumes, projected by most of the GCMs. However, as noted in previous sections, this may also be attributed to using fewer GCMs for the uncertainty analysis for the more distant future scenario.

7.4.6 Summary of main findings

- Simulated sediment yields, using historical daily climate data from the QnCD, appear to be highly correlated with catchment slope.
- Results based on computations with climate output from the GCMs used in this study indicate projected increases in annual sediment loads over most, but especially in the east, of the Orange River Catchment in the intermediate future. The magnitudes and extent of these increases are greater for the more distant future projections.
- Significant portions of the Orange River Catchment are projected to experience increased variability of annual sediment yields in the intermediate future, both in relative and absolute terms. The extent of these increases in variability expands into the more distant future.
- The largest projected changes in annual sediment yields are located in Lesotho, i.e. at the source of the Orange River – the location of major water storage and water transfer schemes; and already highlighted as being, hydro-ecologically, particularly sensitive.

- Increases in sediment yields are projected for future climates despite the dampening influences that the lag equation used has on peak discharge and, therefore, the sediment yield computed with the MUSLE.

8. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

The Orange River Catchment has been shown to be characterised by a high intra- and inter-annual climate variability, which manifests itself in streamflow regimes that are generally unreliable. In the near future, the region is likely to be subjected to additional water stresses related to its anticipated population growth and to socio-economic development, with current projections indicating the possibility of major imbalances between water supply and demand by 2020 already (cf. Section 1.2).

At the present time, planning and management strategies in place in the Orange River Catchment account only for the projected growth in population and the increased demand on the water resources, but not any projected impacts of climate change. Climate change is postulated to add further stresses to a system already heavily impacted upon by current development and natural climate variability, to which adaptive strategies and adaptation policies will have to be directed.

Up until the 1990s the conventional approaches to water resources management in South Africa were characterised by clearly defined problems that needed engineering solutions, such as dam construction and/or inter-catchment transfers, in order to manage adequate supplies of water for society's needs (Schulze, 2003e; Pahl-Wostl *et al.*, 2005b). However, there has been a growing awareness that water resources management requires a more integrated and holistic approach (FP6, 2004; Rahaman and Varis, 2005). Owing to the acknowledgment of uncertainties within the natural system, and regarding the rates and magnitudes of climate change, there is a need for *proactive* strategies at local and national levels to manage water resources, rather than the current more *reactive* strategies. For this reason alone, Adaptive Water Resources Management (AWRM) is believed to be a timely extension of the IWRM approach as it acknowledges uncertainty and is flexible in that it allows for the adjustment of actions based on information learned about the system (Pahl-Wostl *et al.*, 2005a; Boesch *et al.*, 2006). Furthermore, it is suggested that climate risk management be imbedded within the AWRM framework (Aerts and Droogers, 2009).

The objective of the research presented in this thesis was to develop techniques to integrate state-of-the-art climate projection scenarios – which forms part of the first step of the adaptive management cycle – downscaled to the regional/local scale, with hydro-climatic hazard determination – which forms part of the first step in the risk management process – in order to simulate projected impacts of climate change on hydro-climatic hazards in the Orange River Catchment. The techniques developed in this study can be used by decision-makers to produce and analyse the results from hydro-climatic hazard scenarios in order to make informed *proactive* decisions as a response to projected future impacts of hydro-climatic hazards – all within a framework of AWRM.

8.1 Methodology

In this study, hydro-climatic output is simulated for each of the 1 443 hydrologically interlinked Quinary Catchments that make up the Orange River Catchment within South Africa and Lesotho, using information from the Quinary Catchments Database (QnCD). This database has been populated with 50 years (1950 - 1999) of daily rainfall, temperature and reference crop evaporation values, as well as with hydrologically relevant soils and land cover information, for each Quinary Catchment. This information is used as input into the daily time step *ACRU* hydrological model in order to simulate daily streamflows per individual Quinary Catchment, and for accumulated streamflows.

In order to simulate streamflows for projected future climate scenarios, the daily rainfall and temperature outputs from five GCMs, *viz.* CGCM3.1(T47), CNRM-CM3, ECHAM5/MPI-OM, GISS-ER and IPSL-CM4, all empirically downscaled to over 2 500 rainfall stations and more than 400 temperature stations in southern Africa, are used as input into the *ACRU* model, whilst keeping each Quinary Catchment's soils and land cover information unchanged.

Ratios of the point scale GCM-derived intermediate future (2046 - 2065) and/or more distant future (2081 - 2100) climate occurrences and statistics to the point scale GCM-derived present climate (1971 - 1990) occurrences and statistics were computed in this study to facilitate the assessment of potential impacts of climate change. Any potential impacts of climate change could then be assessed in relative terms by evaluating whether the ratio of future to present was > 1 or < 1. In most cases in this thesis the techniques which developed and assessed were demonstrated using the projections from the ECHAM5/MPI-OM GCM, which, relative to the other four available GCMs, represents the El Niño Southern Oscillation most adequately (van Oldenborgh *et al.*, 2005) and is considered to provide "middle of the road" projections of future climates over southern Africa (CSAG, 2008). Furthermore, these analyses are presented in conjunction with maps of the corresponding baseline condition, derived from the 50 years of historical daily climate data from the QnCD.

Quantitative uncertainty analyses were performed for all hydro-climatic hazard analyses in this study. These analyses assigned a level of confidence to a predetermined hypothesis, based on the level of agreement with the hypothesis of results derived from computations using output from the five available GCMs.

Major discussion points surrounding the methodology include the implications of only simulating the South African portion of the Orange River Catchment; the choice of hydrological model; and the selection of specific GCMs. It has already been mentioned that the decision to limit this study to within South Africa's borders was governed by data constraints within the Orange River Catchment in the neighbouring countries. From a South African water management perspective this was not considered to be problematic for two reasons: Firstly, streamflow from Botswana is believed to not have reached the Orange River via the Molopo River for some 1 000 years as sand dunes near Noenieput have blocked its course (DWAF, 2007c; UNDP-GEF, 2008); and secondly, the water requirements downstream of the Fish River and Orange River confluence are currently supplied with water from within South Africa, *viz*. the Vanderkloof Dam (DWAF, 2007c).

However, the second point above simultaneously highlights a disadvantage of excluding the Namibian portion of the Orange River Catchment. Water releases from the Vanderkloof Dam occur well in advance of demand since the water can take up to six weeks to traverse the 1 400 km to the mouth. Therefore, any streamflow from the Fish River into the Orange River will add to the water already released from Vanderkloof Dam since it is currently not possible to stop or store the additional water once it has been released (DWAF, 2007c). By simulating the entire Orange River Catchment it may have been possible to assess whether or not flows from Namibia were projected to increase in the future which, in turn, could have guided a change in the operating rules for the Vanderkloof Dam.

The suitability of the hydrological model adopted for this study has been discussed in Chapter 5 of this thesis. However, the *ACRU* model is not without shortcomings. Schulze (2005d) notes that more research is required to improve the manner in which the *ACRU* model simulates transmission losses especially in semi-arid areas, interflow, hillslope processes, as well as the baseflow processes which are represented by relatively simple algorithms. Further shortcomings with the model were identified in this study, which concern the way that the model estimates peak discharge (elaborated upon in Sections 8.4 and 8.6). Despite these limitations, the fact that the *ACRU* model is a physical-conceptual, process-based model which has been widely verified under South African hydrological conditions (cf. reviews of verification studies by Schulze (1995; 2008b)) makes it an ideal tool for climate change impact studies, as the model requires no optimisation of parameters (i.e. external calibration), which may render it to be biased to the climate to which it was calibrated.

The GCM and scenario selection was based entirely on what information was available at the appropriate resolution when this study commenced (and are still the only GCMs available at the resolution of Quinaries as of May 2012). It is acknowledged that the five GCMs from one emission scenario (A2) presented in this study is a small sample of the total number of GCMs and emission scenarios used in the IPCC's Fourth Assessment Report (IPCC, 2007b). However, the previous, most comprehensive climate change impacts study on hydrological responses undertaken in South Africa (Schulze, 2005a) only used one Regional Climate Model (RCM), also from one emission scenario and at a resolution of Quaternary Catchments. The use of five GCMs at Quinary level in this study therefore marks a significant improvement in the attempt to understand what the impacts of climate change on hydrological processes may be, particularly as the use of additional GCMs may help decision-makers decide on which projections are robust, and which contain greater uncertainties. While only the A2 emission scenario was assessed, this scenario is not a stabilisation scenario (Nakićenović *et al.*, 2000) and may therefore be considered to be a more conservative representation of the future climate, particularly for the distant future. Nonetheless, it is believed that there is important information from the use of GCM output from the A2 scenario (especially in the light of observed global greenhouse gas emissions having exceeded those projected by the A2 scenario in every year to date since the emissions scenarios were published in 2000 (Schulze, 2012)) that can be provided to help water resource managers and other stakeholders assess the risk of future climate projections on water resources.

8.2 Projected Impacts of Climate Change on Major Hydrological Drivers and Responses Using the ECHAM5/MPI-OM GCM

An assessment of the projected changes to average conditions of hydrological drivers such as temperature, evaporation and rainfall, is presented in this thesis not only to set the scene of what a future climate may hold, but also because the changes in the average conditions of these drivers of hydrological processes are expected to be amplified by the hydrological system, certainly in the case of rainfall, thereby potentially presenting challenges in future to water resources managers as well as to other stakeholders of the water sector, such as farmers.

Projections by the ECHAM5/MPI-OM GCM indicate that there will be increases in temperatures and evaporation in the intermediate and more distant futures. This supports the message conveyed by the IPCC since 1990 that the Earth's climate is warming and will continue to do so into the future (IPCC, 1990; IPCC, 1996; IPCC, 2001a; IPCC, 2007b). The projected increases in atmospheric demand are of concern for water managers in as much as *additional* evaporation losses from open water bodies (i.e. major and smaller dams as well as wetlands) in the South African and Lesotho components of the Orange River Catchment, over and above the already high losses under present climatic conditions, are projected to be > 1 000 million m^3 by the intermediate future and ~ 2 400 million m^3 by the more distant future (Schulze, 2011). Furthermore, in the agricultural sector enhanced crop evaporation will need to be balanced with increased water supply, either in the form of additional rainfall or irrigation.

The projected increases in rainfall (and consequently streamflow) in this study are, in parts of the Orange River Catchment, contrary to the latest IPCC projections for southern Africa (IPCC, 2007a; IPCC, 2007b), which indicate a decrease in rainfall (and hence runoff) over large tracts of the region, especially for the period 2080 – 2099. Possible reasons for the different results obtained in this study include the following: a different baseline period was used as a reference against which future changes were measured (1971 – 1990 vs 1980 – 1999); GCM rainfall has been downscaled in this study from the relatively coarse resolution for global studies in the IPCC reports to > 2 600 rainfall stations in South Africa and from that adjusted to be representative at the Quinary level; and a different emissions scenario (A2) was used in this study, compared to the A1B stabilisation scenario presented by the IPCC (2007a; 2007b). This highlights the importance of adopting a multi-model (GCM), and multi-scenario (SRES), approach to climate change modelling.

At first glance it appears that the aforementioned increase in atmospheric demand could well be met by an increase in water supply, both in terms of rainfall and streamflow, which will undoubtedly be welcomed by water resources managers. However, these increases in rainfall and, especially, streamflow are accompanied by increased variability, which not only implies a possibility of future increase in floods and droughts, but also reduces the certainty with which water resources managers can operate in the future. This is particularly concerning as the largest projected increases occur in the Vaal and Upper Orange WMAs where most of the major water supply dams are located. Consequently, water resources managers will need to improve their water planning capabilities.

Furthermore, with respect to the projected changes in the inter-annual variations of rainfall and streamflow, it was found that in many cases the CV% (a relative descriptor of variability) and the SD (a more absolute descriptor of variability) yielded contrasting results. This was the result of the magnitude of change in the SD, from present to future climate scenarios, being smaller than the magnitude of the change in the mean. This raises the issue of which statistic for describing changes in variability is more appropriate to water managers, particularly since the choice in statistic could determine whether or not the water manager decides that adaptive action is necessary to manage future variability.

Displaying both measures of variability, together with the mean, may be the most appropriate way of presenting changes in variability, such as those changes projected in this study, as different water managers may place more value in one or other of the two statistics. For example, the dryland farmer may welcome the reduced inter-annual rainfall CV% with an increased SD, where increased fluctuations in rainfall occur around an elevated average. Meanwhile, the same result for streamflows into a dam may raise concerns around the adequacy of the dam's volume and/or spillway capacity to cope with the increase in fluctuations around an even bigger increase in the mean. By displaying the CV% together with the SD and the mean allows water mangers to understand the basis for the change in CV% and, hence, adds valuable information with which to base decisions regarding changes in variability. If, however, only a single indicator of variability had to be selected in the water sector, it would have to be the SD as it relates to actual volume changes in variability. Once again, it is suggested that the SD be presented together with the mean in order to better understand the implications of any changes in variability.

8.3 Design Rainfalls

Long duration design rainfalls were computed using the widely applicable and used Log-Pearson Type III extreme value distribution (Kite, 1988), fitted to an annual maximum series (AMS). For short duration design rainfalls, however, a method developed by Smithers and Schulze (2003) was modified by the author of this thesis, to be used in conjunction with GCM rainfall output. This methodology utilises an index storm approach and is based on L-moments. Growth curves which relate design rainfall, scaled by the mean of the AMS, to return periods are utilised in conjunction with the calculated mean of the AMS at the required location, for which daily GCM output exists, to compute the design rainfall depth for the specified duration and return period. This approach to estimating changes in extreme rainfall marks a significant improvement to the relatively simplistic, time-averaged manner in which changes in rainfall intensity have been estimated in the IPCC's Fourth Assessment Report (IPCC, 2007b), which according to New *et al.* (2006) may be inadequate to capture changes in intensity. However, it must be borne in mind that the validation of the growth curves was performed on long duration data (owing to the inability of the GCMs to produce sub-daily output) and based on these findings it was assumed that the growth curves for short durations would also be applicable in the future. This assumption should be tested in future studies when sub-daily GCM output becomes available.

In order to estimate projected impacts of climate change on future design rainfalls, which is a primary input for many deterministic design flood estimation methods used in South Africa, downscaled daily climate output from the ECHAM5/MPI-OM GCM were used by way of example, and results suggest that both short duration and long duration design rainfalls are projected to increase over vast portions of the Orange River Catchment, in both the intermediate and the more distant futures. These results concur with the findings of previous studies of observed and modelled rainfall in southern Africa (Mason *et al.*, 1999; Schulze *et al.*, 2005a; Tadross *et al.*, 2005; New *et al.*, 2006; IPCC, 2007b), which indicate that rainfall intensities in southern Africa are increasing. They are also in line with the IPCC's special report on extremes (IPCC, 2012). Furthermore, the results from this study indicate that the magnitude of the change in the future increases with increasing return period, a trend also evident in the maps presented by Schulze *et al.* (2005a).

The results from the uncertainty analysis indicated that the level of agreement amongst the five GCMs decreased as the event duration and frequency decreased. This indicates that GCMs may still be failing to simulate individual extreme events, but are better at producing multi-day extremes.

An understanding of the regional consequences brought about from the projected changes in long duration rainfalls may be gleaned from the results and discussion around design floods, presented in Section 7.2 and Section 8.4, respectively. However, a major concern for many stakeholders in the water sector will be the impacts of increases in short duration design rainfall on the urban environment. Many of the urban centres in the Orange River Catchment are likely to experience an increase in design rainfalls. Water managers and other stakeholders in the water sector will, therefore, need to incorporate these findings into risk management strategies in order to assess: 1) how the current population and infrastructure may be affected, and 2) future planning for a growing population. Key considerations will include current vs projected 100 year floodlines, whether current stormwater systems and stormwater management strategies are adequate for anticipated changes in rainfall intensities and how an increase in rainfall intensity may impact on the serviceability of civil structures.

8.4 Design Floods

As was the case for the long duration design rainfalls, design floods were computed using the widely utilised Log-Pearson Type III extreme value distribution (Kite, 1988) fitted to an AMS of accumulated streamflows for the respective duration, as well as to the AMS of daily peak discharges per Quinary Catchment. Design streamflows modelled with the *ACRU* model are projected to increase over vast portions of the Orange River Catchment in the intermediate and more distant futures when using climates projected by the five GCMs used in this study. This is in agreement with reports by the IPCC that a warmer, more variable climate increases the risk of flooding (IPCC, 2007a; IPCC, 2012). Furthermore, Schulze (2005b) indicated that spatial shifts in hydro-climatic zones due to climate change could impart significant changes in design stormflows and peak discharges due to changes in antecedent catchment wetness. The magnitudes of the projected changes in design streamflows are greater than those projected for the equivalent design rainfalls, i.e. changes in design rainfall become amplified by the hydrological system. Unlike design rainfall, the projected changes are independent of the duration of design event. The confidence of the projections decreases, however, when increasing the return period.

Design peak discharges were largely found to be decreasing with the intermediate and more distant future scenarios, which is an apparent contradiction to the findings for design streamflows. While it is possible that the increases in design streamflows are occurring at event durations that are not the critical duration (i.e. the event duration that causes the greatest peak discharge) for the respective catchments, it is hypothesised that these results were to be largely due to the MAP variable in the Schmidt and Schulze (1984) lag equation which was used in the calculation of peak discharges, with MAP in that equation having been used as a surrogate for land cover density and the soil’s water holding capacity rather than as a climatic variable *per se*. Furthermore, the peak discharge results represent only the flood peaks generated for each incremental (Quinary) catchment, and therefore do not reflect the larger peaks that would have been generated had the floods been routed along the entire length of the respective rivers.

It is likely that a different method for estimating a catchment's response time, such as a method based on catchment characteristics only, as well as routing the flood peak along the entire river reach, would increase the confidence in the hypothesis that design peak discharges will increase in future climates.

The results from the analysis of design flood projections are of concern for water managers, especially as the largest increases are projected in the east of the Orange River Catchment where the majority of the major dams are located. This raises questions around whether or not the dams, and their spillways, are designed to cope with the projected increases in design floods and also whether climate change may bring about changes to current dam operating rules. Furthermore, the widespread projected increases in design floods may require a reassessment of current flood warning systems and disaster management strategies.

8.5 Droughts

In this study, a year experiencing mild (or more severe) drought is defined to have occurred if that year's rainfall or streamflow is less than or equal to the 33rd percentile of the present series of annual rainfalls or streamflows, i.e. if it occurs on average once every three years or less frequently. Similarly, a moderate (or more severe) drought is defined here as occurring on average only once every five years (20th percentile) or less frequently, while severe droughts are defined as occurring only once in ten years (10th percentile) or less frequently, as calculated from the present rainfall or streamflow record.

The projected changes in droughts that emanated from this study have indicated quite emphatically (at high levels of confidence across more than 90% of the Orange River Catchment as defined for this study) that the incidence of drought in the future will be less than what has been experienced to date. When droughts, be they meteorological or hydrological, are experienced in the future they are more likely to occur in the western, drier regions of the Orange River Catchment, with a greater likelihood of there being hydrological droughts than meteorological droughts. These results are contrary to what has been presented in the literature, e.g. Arnell (1999; 2003), Milly *et al*. (2005), Nicol and Kaur (2009), Wang (2005) and the IPCC (2001b; 2007a; 2007b; 2012), and on which the hypothesis adopted in this study (*viz.* that the magnitude and frequency of droughts would increase in the future) was based. It is, however, acknowledged that these results may reflect a sample bias and that the inclusion of additional GCMs and SRES emissions scenarios may have yielded different results.

There may be several explanations for the different results obtained in this study when compared to those presented by the researchers and organisations mentioned above. These include differences in:

- the spatial resolution at which the studies were carried out – this study was carried out at the Quinary catchment scale compared to the coarser, more global scales used in the other studies;
- the GCMs and SRES scenarios that have been used; and
- the definitions of drought that have been used – this study analysed droughts at an annual scale whereas the aforementioned studies often analysed droughts using the Palmer Drought Severity Index, which is applied at the weekly to monthly scales.

The issue highlighted above regarding differences in drought projections from different GCMs and different dryness indices is common to the findings presented in the IPCC's special report on extremes (IPCC, 2012).

It was shown in this study that the results for meteorological and hydrological droughts were different. It was shown, through a rainfall threshold analysis, that changes in hydrological droughts were related more to changes in the number of larger rainfall events per annum, than to the number of effective (i.e. smaller) rainfall events per year. This highlights the importance of analysing droughts from different perspectives. Furthermore, it is noted by Rouault and Richard (2003) that hydrological and agricultural droughts, too, can be out of phase. This highlights the importance of clearly communicating to water managers and other stakeholders in the water sector what type of drought is being referred to, as the incidence and impacts of the different drought types on various economic sectors can be appreciably different (Rouault and Richard, 2003).

8.6 Sediment Yields

Sediment yield at any Quinary Catchment outlet is estimated in the *ACRU* model using the Modified Universal Soil Loss Equation (MUSLE) on an event-by-event basis whenever stormflow occurs, and is a function of stormflow, peak discharge, erodibility properties of soils, a slope factor, a cover factor (for both canopy and ground/mulch) and management practice (e.g. conservation structures).

Simulated sediment yields, using historical daily climate data from the QnCD, show high correlation in the Orange River Catchment with slope. Previous studies in South Africa using the same equation for the computation of sediment yields (e.g. Schulze and Perks, 2000; Schulze *et al.*, 2005a) did not identify or emphasise this correlation, most likely due to the gross averaging of catchment slopes when working at Quaternary (instead of Quinary) Catchment scale. Furthermore, these simulations indicate that the difference between the lowest and highest sediment yields in 10 years can be an order of magnitude, once again highlighting the amplification of changes in climatic conditions in the hydrological cycle.

Results based on computations with climate output from the GCMs used in this study indicate projected increases in annual sediment loads in the east of the Orange River Catchment in the intermediate future. The magnitude and spatial extent of these increases is greater (approximately double) for the more distant future projections. The GCMs display high agreement that sediment yields will increase in the eastern regions of the Orange River Catchment in the future, with the largest increases projected in Lesotho, i.e. at the source of the Orange River, which is the location of major water storage and water transfer schemes. These findings are contrary to those presented by Schulze and Perks (2000) and, later, Schulze *et al.* (2005a), who indicated that sediment yields in the Lesotho region were projected to decrease in future climates. The findings from this study indicate a potential for serious problems for water managers, as well as for water users, owing to a likelihood of a reduction in the water resource, either through reduced storage capacity or increased water quality issues (Rooseboom, 1992; Gleick, 2000; Takeuchi, 2002; DWAF, 2004e), with the latter potentially posing a series of knock-on effects owing to the highly interconnected nature of the Orange River system.

Confidence in the hypothesis, that sediment yields would increase in the future, was found to be greater for years experiencing the highest annual sediment yields in 10 years than for those years with the lowest annual sediment yields in 10 years. This is an important finding inasmuch as it indicates a shift in the distribution of sediment yielding events to more large events, which – as already mentioned - may have negative repercussions for water quality and water storage, i.e. decreasing an already scarce water resource in the Orange River Catchment. Furthermore, a reduction in capacity for reservoirs and rivers to store water creates an added flood risk (Tucker and Slingerland, 1997; Takeuchi, 2002). Water managers will need to consider various management strategies to cope with the projected increases in sediment yield, such as increasing the heights of dams, introducing sediment gates or other sediment removal methods such as dredging. Furthermore, at source measures should be investigated such as land rehabilitation and the application of appropriate farming management practices to reduce the amount of sediment that reaches the rivers and reservoirs.

The above-mentioned increases in sediment yields are projected for future climates despite the dampening influences that the lag equation which was used has on the estimation of peak discharge and, therefore, on the sediment yields computed with the MUSLE. This is largely due to the projected increases in stormflow having a greater relative influence in the equation than any decreases in peak discharge resulting from longer catchment response times. It is postulated that projected increases in sediment yields would be of greater magnitude and extent with the use of a different lag equation.

8.7 Contributions to New Knowledge

This study has contributed to new knowledge in the climate change and hydrological fields in South Africa in a number of ways. First, it contributed significantly to the development of the new Quinary Catchments Database for southern Africa, which is envisaged to be a tool with which operational decisions can be made at both local and national scales, and for both current and projected future climatic conditions. The author of this thesis contributed to the development of the QnCD by:

- Disaggregating the QCD and reconfiguring the flowpaths for all 1 946 Quaternary Catchments (cf. Section 5.2.1) according to the rules determined by Schulze and Horan (2009);
- Calculating rainfall adjustment factors for the representative rainfall station of each Quinary Catchment, with the station selection determined by the author, for baseline and future scenarios (cf. Section 5.2.2.1 and Section 5.3.2); and
- Populating the QnCD with all climatic and catchment input parameters required by the *ACRU* model.

Secondly, using this database, this study is the first ever climate change impacts study in South Africa which has focussed specifically on modelling hydro-climatic hazards. This, therefore, fills an important knowledge gap. From the hazards study a number of "surprise" findings have been identified. These are discussed below.

- It is widely stated in the literature that climate variability in southern Africa is projected to increase in the future. However, this statement is dependent on which variability statistic is used. In this study the CV% often indicated a decrease in variability, yet the standard deviation indicated the opposite. This is an important finding, particularly since the choice in statistic could determine whether or not the water manager decides that adaptive action is necessary to manage future variability (cf. Section 8.2).
- The GCMs used in this study tend to agree more with one another when estimating design events (rainfall and streamflow) for longer durations and for shorter return periods. This indicates that GCMs may still be failing to simulate individual extreme events.
- Spatially, projected changes in meteorological and hydrological droughts are different, owing to the complexities introduced by the hydrological system. Despite an increase in the projected number of days with effective rainfall (> 2 mm) in the future, hydrological droughts are still projected to occur in certain areas, and these appear to be related to changes in the number of days with rainfall > 25 mm. This is important as only reporting either one of

meteorological or hydrological droughts may result in unnecessary action being taken by decision-makers, or no action taken when it may be required.

- The spatial variation of projected changes in the number of rain days > 25 mm also appears to control spatial differences of changes to design streamflows and sediment yields, for both the intermediate and more distant futures.
- As a result, many areas may be exposed to increases in hydrological hazards (i.e. hydrological drought, floods and/or sediment yields) because often where one extreme is projected to decrease, the other is projected to increase.
- Sediment yields show high correlation with slope across South Africa. Previous studies in South Africa that used the same equation for the computation of sediment yields (MUSLE) did not identify or emphasise this correlation, possibly due to the gross averaging of catchment slopes when working at Quaternary (instead of Quinary) Catchment scale.

Thirdly, in order to understand how rainfall intensities might change in future climates, an index storm approach based on L-moments has been modified by the author of this thesis, in order to facilitate the use of GCM-derived daily rainfall data to estimate short duration (< 24 hour) design rainfall. Therefore, projected future short duration design rainfalls, for a specified duration and return period, can now be estimated at any location within South Africa for which GCM-derived daily rainfall information exists. This approach to estimating changes in extreme rainfall marks a significant improvement to the relatively simplistic, time-averaged manner in which changes in rainfall intensity have been estimated in the IPCC's Fourth Assessment Report, which may be inadequate to capture changes in intensity.

8.8 Recommendations for Future Research

Based on the experiences in undertaking this study, the following recommendations for future research in this field are made:

- Actual land use should replace baseline land cover so that a better representation of the current status of hydrological responses can be achieved, as well enabling the assessment of climate change and hydrological hazard impacts on specific sectors, such as agriculture.

- Output from additional GCMs and SRES emission scenarios should be used in order to provide a more meaningful quantitative uncertainty analysis in which the potential for sample bias is reduced.
- Areal rainfall adjustments of downscaled point rainfall data for future projections should be carried out using gridded rainfall projections from the respective GCM and SRES emission scenarios, rather than assuming a stationary relationship between point and areal rainfall, which has been derived from historical observed data.
- Projected future lapse rate regions should be developed from GCM output for minimum and maximum temperatures, and for each month of the year, in order to facilitate more realistic temperature adjustments at locations of interest where there are no temperature stations. This would enable adjustments to be made based on projected future lapse rates, as opposed to assuming that the current lapse rates and their regions will remain stationary in future climates.
- The effects of applying different drought definitions should be evaluated, including analysing droughts at a monthly level in order to identify any intra-annual variations in projected short duration droughts.
- A longer time series is needed when analysing potential changes in extreme events, especially for high return period rainfall and flood events, as well as for multi-year droughts.
- Although design streamflows in this study were based on accumulated flows from all upstream Quinary Catchments, the peak discharges were calculated only for each Quinary Catchment outlet, as the specific peak discharge equation used is not valid for large areas. It is therefore suggested that future research includes the routing of the entire hydrograph down the channel, as it is both the flood volume and flood peak that are important to engineers when considering hydrological design. This, however, would require information regarding channel hydraulics properties at the Quinary Catchment scale.
- A different equation for the estimation of catchment lag needs to be developed, or adapted, for use in future climate change impacts studies where the calculation of peak discharge is required, as the equation used in this study, in effect, assumes changes in the density of land cover and the soil's

water holding capacity when changes are made to the MAP. This makes it difficult to assess whether changes are due to climate change attributes *per se*, or to the inadvertently changed land cover/soil properties. An equation that uses only physical catchment characteristics, or that does not use climate parameters as a surrogate for land cover and soil attributes, is recommended.

- More effort needs to be placed into obtaining baseline data for the other countries within the Orange River Catchment, particularly for Botswana and Namibia, so that decisions can be made on a catchment-wide scale and not only restricted to those areas within the boundaries of South Africa and Lesotho.

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The techniques and the regional/local scale scenarios of potential changes in hydro-climatic hazards due to climate change, which were developed in this study, are available for use by water managers, and other stakeholders in the water sector, for making decisions under uncertainty within the framework of adaptive water resources management. Although the next IPCC study may report different projections of future climates, the framework, as well as the analytical techniques (mapping and interpretive), developed in this study will allow for the production of hydro-climatic scenarios, particularly those pertaining to hydro-climatic hazards. These scenarios can then be fed into the next iteration of the adaptive management cycle, whereby understanding gained in each of the scenarios, from this study and those in the future, may lead to re-assessments of the problem, new questions and new options to try, in a continual cycle of improvement.

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APPENDICES

All of the following programs were written by the author and applied in the determination of hydrological hazards using historical and GCM-derived data. These programs include:

- Extraction of the Annual Maximum Series (AMS) from a rainfall or streamflow record;
- Reformatting of output into a suitable format so that it could be imported into GIS for graphical display of the results;
- Extracting homogeneous regions per quinary for short duration design rainfall estimation;
- Expressing design streamflows in depth equivalents;
- Calculation of meteorological and hydrological droughts;
- Extracting number of raindays greater than, less than or equal to a selected threshold;
- Calculating the ratios of future to present projections; and
- Calculation of the index of concurrence used in the uncertainty analyses.

A Annual Maximum Series

The following program was written to extract the AMS, in hydrological years, from a rainfall or streamflow record. The AMS of the largest daily value of each year of record was extracted. Furthermore, the largest consecutive two, three, four, five, six and seven day values of each year of record were also extracted so that multi-day design events could be calculated.

This program was looped to read in all 5838 sxxxx.001 files, i.e. each Quinary Catchment's daily spreadsheet file. The particular program demonstrated below was used to extract the AMS for the calculation of design ***rainfall***. The same program, however set to read in the streamflow variables of the s*.001 files, was used to extract the AMS for design ***streamflow***, i.e. SIMSQ and CELRUN. Further variations, other than reading in a different variable, were made to the AMS extraction program used for design ***peak discharges*** as there was no accumulation of daily values performed, i.e. only the daily AMS was extracted. This was done for historical and all GCM scenarios.

The Log-Pearson Type III extreme value distribution was subsequently fitted to the extracted one to seven day AMSs (Equations 7.1 to 7.6). This was done using a previously developed stand-alone program.

****

```
PROGRAM AMS
!
!     Author: D.M.Knoesen
!     Date: 08/05/2008
!
Implicit None

REAL :: rain1(1000000)
 REAL :: rain2(1000000)
 REAL :: rain3(1000000)
 REAL :: rain4(1000000)
 REAL :: rain5(1000000)
 REAL :: rain6(1000000)
 REAL :: rain7(1000000)

 REAL ::    AET(1000000), AET1(1000000),  AET2(1000000),  APAN(1000000),
ASOEV(1000000),ATRAN1(1000000)
 REAL :: ATRAN2(1000000), CAYD(1000000),CELRUN(1000000), D_POT(1000000),
DEF1(1000000),  DEF2(1000000)
 REAL ::    DPE(1000000),  EOP(1000000),    EP(1000000),  ERFL(1000000),
ES(1000000),  PERC(1000000)
 REAL :: POSOEV(1000000),POTR1(1000000), POTR2(1000000),
QPEAK(1000000),QUICKF(1000000), REQIR(1000000)
 REAL ::    RFL(1000000),  RUN(1000000), RUNCO(1000000),SEDYLD(1000000),
SIMSQ(1000000),  STO1(1000000)
 REAL ::   STO2(1000000),STQIR(1000000),  SUR1(1000000),  SUR2(1000000),
SURIR(1000000),SW_MAX(1000000)

!INTEGER :: counter(1000000)
 INTEGER ::     day(1000000)
 INTEGER ::     mon(1000000)
 INTEGER ::   month(1000000)
 INTEGER ::      yr(1000000)
 INTEGER ::    year(1000000)
 INTEGER :: i,io,norows,cntdy
 INTEGER :: hyer,cats,cate,catn,loop,inum

 CHARACTER(len=252) :: line
 CHARACTER (len=50) :: path
 CHARACTER (len=09) :: ifle
 CHARACTER (len=13) :: ofle

open(10,file='getams.inp',action='read')
read(10,*)hyer
```

```
read(10,*)cats,cate
read(10,'(a50)')path
close(10)

do catn=cats,cate
  ifle='sxxxx.001'
  write(ifle(2:5),'(i4.4)')catn
  open(20,file=trim(path)//ifle,action='read',iostat=io)
  if (io.ne.0) then
!   write(6,*)'File missing...',catn
    close(20)
    cycle
  endif

  do loop=01,07
    ofle='exxxx_yy.amsi'
    write(ofle(02:05),'(i4.4)')catn
    write(ofle(07:08),'(i2.2)')loop
    inum=20+loop
    open(unit=inum,file=ofle,action='write')
  enddo

! write(21,*)'Station Name'

!Obtain number of lines in the input file

      norows=0
      DO i=1,1000000
            READ(20,*,IOSTAT=io) line
            IF (io.lt.0) THEN
              norows = i-1
              EXIT
            ENDIF
      ENDDO

        if (norows.le.1) then
          write(6,*)'File too short...',catn,norows
        close(20)
          cycle
        else
        REWIND(20)
        endif

! write(6,*) norows
      READ(20,*,end=999)line
      norows=norows-1
!Read in the input file

      DO i=1,norows
            READ(20,102)
day(i),month(i),year(i),AET(i),AET1(i),AET2(i),APAN(i),ASOEV(i),ATRAN1(i),A
TRAN2(i),CAYD(i),CELRUN(i),D_POT(i),DEF1(i),DEF2(i),DPE(i),EOP(i),EP(i),ERF
L(i),ES(i),PERC(i),POSOEV(i),POTR1(i),POTR2(i),QPEAK(i),QUICKF(i),REQIR(i),
RFL(i),RUN(i),RUNCO(i),SEDYLD(i),SIMSQ(i),STO1(i),STO2(i),STQIR(i),SUR1(i),
SUR2(i),SURIR(i),SW_MAX(i)
            102 FORMAT
(I2,1x,I2,1x,I4,F5.1,1x,F5.1,1x,F5.1,1x,F5.1,1x,F6.1,1x,F7.1,1x,F7.1,1x,F6.
2,1x,F7.2,1x,F6.2,1x,F5.1,1x,F5.1,1x,F5.1,1x,F5.2,1x,F5.2,1x,F6.1,1x,F5.2,1
x,F5.2,1x,F7.1,1x,F6.1,1x,F6.1,1x,F8.2,1x,F7.2,1x,F6.1,1x,F5.1,1x,F6.2,1x,F
6.2,1x,F16.6,1x,F7.2,1x,F5.1,1x,F5.1,1x,F6.2,1x,F7.1,1x,F7.1,1x,F6.2,1x,F7.
1)
```

```
!           read(20,199) day(i),month(i),year(i),rain(i)
!           199 format (i2,1x,i2,1x,i4,1x,f7.1)
      END DO
999     close(20)

!Sort months for hydrological year calculation
      DO i=1,norows
            IF (month(i).ge.10.and.month(i).le.12) then
            mon(i)=month(i)-9
            ELSE
            mon(i)=month(i)+3
            ENDIF
!           write(21,*) (mon(i))
      END DO

!Sort years for hydrological year calculation
      DO i=1,norows
      yr(i)= year(i)
      END DO

      DO i=1,norows
            IF (mon(i).ge.4) THEN
            yr(i)=yr(i)-1
            ENDIF
!           write(21,*) yr(i), i
      END DO

!Calculation of daily AMS by hydrological year

      DO i=1,norows
!           rain1(i)=rain(i)
            rain1(i)=RFL(i)
!           write(21,111) (rain1(i))
!           111 format(f6.2)
      ENDDO

      cntdy=0
      DO i=1,norows
      cntdy=cntdy+1
      IF (yr(i).eq.yr(i+1).and.rain1(i).ge.rain1(i+1))Then
            rain1(i+1)=rain1(i)
            end if
      IF (yr(i).ne.yr(i+1).and.cntdy.ge.365)Then
            WRITE(21,100) yr(i),rain1(i)
            100 FORMAT(I4,1x,F6.2)
            cntdy=0
            end if
!     write(6,*) cntdy
      ENDDO
        close(21)

!Calculation of 2-day AMS by hydrological year
! this writes the 2-day sequence
      do i=1,norows
!           rain2(i)=rain(i+1) + rain(i)
            rain2(i)=RFL(i+1) + RFL(i)
      enddo
!     do i=1,norows
!           write(21,100) month(i),year(i),rain2(i)
```

```
!           100 FORMAT(I2,1x,I4,1x,F6.2)
!     enddo

!this extracts the AMS from the 2-day sequence
      cntdy=0
      DO i=1,norows
      cntdy=cntdy+1
!     counter(i)=i
      IF (yr(i).eq.yr(i+1).and.rain2(i).ge.rain2(i+1))Then
            rain2(i+1)=rain2(i)
            end if
      IF (yr(i).ne.yr(i+1).and.cntdy.ge.365)Then
            WRITE(22,101) yr(i),rain2(i)
            101 FORMAT(I4,1x,F6.2)
            end if
!     IF (counter(i).eq.norows-1) Then
!           WRITE(22,101) yr(norows),rain2(norows)
!     ENDIF
      ENDDO
        close(22)

!Calculation of 3-day AMS by hydrological year
! this writes the 3-day sequence
      do i=1,norows
!           rain3(i)=rain(i+2) + rain(i+1) + rain(i)
            rain3(i)=RFL(i+2) + RFL(i+1) + RFL(i)
      enddo
!     do i=1,norows
!           write(21,100) month(i),year(i),rain3(i)
!           100 FORMAT(I2,1x,I4,1x,F6.2)
!     enddo

!this extracts the AMS from the 3-day sequence
      cntdy=0
      DO i=1,norows
      cntdy=cntdy+1
!     counter(i)=i
      IF (yr(i).eq.yr(i+1).and.rain3(i).ge.rain3(i+1))Then
            rain3(i+1)=rain3(i)
            end if
      IF (yr(i).ne.yr(i+1).and.cntdy.ge.365)Then
            WRITE(23,101) yr(i),rain3(i)
!           101 FORMAT(I4,1x,F6.2)
            end if
!     IF (counter(i).eq.norows-2) Then
!           WRITE(23,101) yr(norows),rain3(norows)
!     ENDIF
      ENDDO
        close(23)

!Calculation of 4-day AMS by hydrological year
! this writes the 4-day sequence
      do i=1,norows
!           rain4(i)=rain(i+3) + rain(i+2) + rain(i+1) + rain(i)
            rain4(i)=RFL(i+3) + RFL(i+2) + RFL(i+1) + RFL(i)
      enddo
!     do i=1,norows
!           write(21,100) month(i),year(i),rain4(i)
!           100 FORMAT(I2,1x,I4,1x,F6.2)
!     enddo
```

```
!this extracts the AMS from the 4-day sequence
      cntdy=0
      DO i=1,norows
      cntdy=cntdy+1
!     counter(i)=i
      IF (yr(i).eq.yr(i+1).and.rain4(i).ge.rain4(i+1))Then
            rain4(i+1)=rain4(i)
            end if
      IF (yr(i).ne.yr(i+1).and.cntdy.ge.365)Then
            WRITE(24,101) yr(i),rain4(i)
!           101 FORMAT(I4,1x,F6.2)
            end if
!     IF (counter(i).eq.norows) Then
!           WRITE(24,101) yr(norows),rain4(norows)
!     ENDIF
      ENDDO
        close(24)

!Calculation of 5-day AMS by hydrological year
! this writes the 5-day sequence
      do i=1,norows
!           rain5(i)=rain(i+4) + rain(i+3) + rain(i+2) + rain(i+1) +
rain(i)
            rain5(i)=RFL(i+4) + RFL(i+3) + RFL(i+2) + RFL(i+1) + RFL(i)
      enddo
!     do i=1,norows
!           write(21,100) month(i),year(i),rain5(i)
!           100 FORMAT(I2,1x,I4,1x,F6.2)
!     enddo

!this extracts the AMS from the 5-day sequence
      cntdy=0
      DO i=1,norows
      cntdy=cntdy+1
!     counter(i)=i
      IF (yr(i).eq.yr(i+1).and.rain5(i).ge.rain5(i+1))Then
            rain5(i+1)=rain5(i)
            end if
      IF (yr(i).ne.yr(i+1).and.cntdy.ge.365)Then
            WRITE(25,101) yr(i),rain5(i)
!           101 FORMAT(I4,1x,F6.2)
            end if
!     IF (counter(i).eq.norows) Then
!           WRITE(25,101) yr(norows),rain5(norows)
!     ENDIF
      ENDDO
        close(25)

!Calculation of 6-day AMS by hydrological year
! this writes the 6-day sequence
      do i=1,norows
!           rain6(i)=rain(i+5) + rain(i+4) + rain(i+3) + rain(i+2) +
rain(i+1) + rain(i)
            rain6(i)=RFL(i+5) + RFL(i+4) + RFL(i+3) + RFL(i+2) + RFL(i+1) +
RFL(i)
      enddo
!     do i=1,norows
!           write(21,100) month(i),year(i),rain6(i)
!           100 FORMAT(I2,1x,I4,1x,F6.2)
!     enddo
```

```
!this extracts the AMS from the 6-day sequence
      cntdy=0
      DO i=1,norows
      cntdy=cntdy+1
!     counter(i)=i
      IF (yr(i).eq.yr(i+1).and.rain6(i).ge.rain6(i+1))Then
            rain6(i+1)=rain6(i)
            end if
      IF (yr(i).ne.yr(i+1).and.cntdy.ge.365)Then
            WRITE(26,101) yr(i),rain6(i)
!           101 FORMAT(I4,1x,F6.2)
            end if
!     IF (counter(i).eq.norows) Then
!           WRITE(26,101) yr(norows),rain6(norows)
!     ENDIF
      ENDDO
        close(26)

!Calculation of 7-day AMS by hydrological year
! this writes the 7-day sequence
      do i=1,norows
!           rain7(i)=rain(i+6) + rain(i+5) + rain(i+4) + rain(i+3) +
rain(i+2) + rain(i+1) + rain(i)
            rain7(i)=RFL(i+6) + RFL(i+5) + RFL(i+4) + RFL(i+3) + RFL(i+2) +
RFL(i+1) + RFL(i)
      enddo
!     do i=1,norows
!           write(21,100) month(i),year(i),rain6(i)
!           100 FORMAT(I2,1x,I4,1x,F6.2)
!     enddo

!this extracts the AMS from the 7-day sequence
      cntdy=0
      DO i=1,norows
      cntdy=cntdy+1
!     counter(i)=i
      IF (yr(i).eq.yr(i+1).and.rain7(i).ge.rain7(i+1))Then
            rain7(i+1)=rain7(i)
            end if
      IF (yr(i).ne.yr(i+1).and.cntdy.ge.365)Then
            WRITE(27,101) yr(i),rain7(i)
!           101 FORMAT(I4,1x,F6.2)
            end if
!     IF (counter(i).eq.norows) Then
!           WRITE(27,101) yr(norows),rain7(norows)
!     ENDIF
      ENDDO
        close(27)
enddo

END PROGRAM AMS
```

B Reformatting of Output from the stand-alone EVD program

The following program was written to reformat the output from the stand-alone EVD program so that the data (historical and GCM-derived) were in a suitable format to be imported into GIS.

*****

```
PROGRAM CSV
!
!     Author: D.M.Knoesen
!     Date: 28/07/2008
!
Implicit None

      integer, parameter :: max = 165000
      CHARACTER(len=121) :: line
      INTEGER, DIMENSION(max) :: subcat,xday
      REAL, DIMENSION(max) :: two,five,ten,twenty,fifty,hundred
      INTEGER :: i,io,norows

      open(10,file='his_extdat.txt')

      open(11,file='his_evd_1d_2yr.csv')
      open(12,file='his_evd_1d_5yr.csv')
      open(13,file='his_evd_1d_10yr.csv')
      open(14,file='his_evd_1d_20yr.csv')
      open(15,file='his_evd_1d_50yr.csv')
      open(16,file='his_evd_1d_100yr.csv')

      open(21,file='his_evd_2d_2yr.csv')
      open(22,file='his_evd_2d_5yr.csv')
      open(23,file='his_evd_2d_10yr.csv')
      open(24,file='his_evd_2d_20yr.csv')
      open(25,file='his_evd_2d_50yr.csv')
      open(26,file='his_evd_2d_100yr.csv')

      open(31,file='his_evd_3d_2yr.csv')
      open(32,file='his_evd_3d_5yr.csv')
      open(33,file='his_evd_3d_10yr.csv')
      open(34,file='his_evd_3d_20yr.csv')
      open(35,file='his_evd_3d_50yr.csv')
      open(36,file='his_evd_3d_100yr.csv')

      open(41,file='his_evd_4d_2yr.csv')
      open(42,file='his_evd_4d_5yr.csv')
      open(43,file='his_evd_4d_10yr.csv')
      open(44,file='his_evd_4d_20yr.csv')
      open(45,file='his_evd_4d_50yr.csv')
```

```
      open(46,file='his_evd_4d_100yr.csv')

      open(51,file='his_evd_5d_2yr.csv')
      open(52,file='his_evd_5d_5yr.csv')
      open(53,file='his_evd_5d_10yr.csv')
      open(54,file='his_evd_5d_20yr.csv')
      open(55,file='his_evd_5d_50yr.csv')
      open(56,file='his_evd_5d_100yr.csv')

      open(61,file='his_evd_6d_2yr.csv')
      open(62,file='his_evd_6d_5yr.csv')
      open(63,file='his_evd_6d_10yr.csv')
      open(64,file='his_evd_6d_20yr.csv')
      open(65,file='his_evd_6d_50yr.csv')
      open(66,file='his_evd_6d_100yr.csv')

      open(71,file='his_evd_7d_2yr.csv')
      open(72,file='his_evd_7d_5yr.csv')
      open(73,file='his_evd_7d_10yr.csv')
      open(74,file='his_evd_7d_20yr.csv')
      open(75,file='his_evd_7d_50yr.csv')
      open(76,file='his_evd_7d_100yr.csv')

! Obtain number of lines in the input file
      DO i=1,1000000
            READ(10,*,IOSTAT=io) line
            IF (io<0) THEN
            norows = i-1
            EXIT
            END IF
      END DO
      REWIND(10)

      write(6,*) norows

      DO i=1,norows/4
            READ(10,20)
subcat(i),xday(i),two(i),five(i),ten(i),twenty(i),fifty(i),hundred(i)
            20 format (1x,i4,1x,i2,17x,6(f16.2))
            21 format (i4.4,A1,f16.2)
            READ(10,*)
            READ(10,*)
            READ(10,*)

            IF(xday(i).eq.1) then
            write(11,21) subcat(i),",",two(i)
            write(12,21) subcat(i),",",five(i)
            write(13,21) subcat(i),",",ten(i)
            write(14,21) subcat(i),",",twenty(i)
            write(15,21) subcat(i),",",fifty(i)
            write(16,21) subcat(i),",",hundred(i)
            ENDIF

            IF(xday(i).eq.2) then
            write(21,21) subcat(i),",",two(i)
            write(22,21) subcat(i),",",five(i)
            write(23,21) subcat(i),",",ten(i)
            write(24,21) subcat(i),",",twenty(i)
            write(25,21) subcat(i),",",fifty(i)
            write(26,21) subcat(i),",",hundred(i)
            ENDIF
```

```
            IF(xday(i).eq.3) then
            write(31,21) subcat(i),",",two(i)
            write(32,21) subcat(i),",",five(i)
            write(33,21) subcat(i),",",ten(i)
            write(34,21) subcat(i),",",twenty(i)
            write(35,21) subcat(i),",",fifty(i)
            write(36,21) subcat(i),",",hundred(i)
            ENDIF

            IF(xday(i).eq.4) then
            write(41,21) subcat(i),",",two(i)
            write(42,21) subcat(i),",",five(i)
            write(43,21) subcat(i),",",ten(i)
            write(44,21) subcat(i),",",twenty(i)
            write(45,21) subcat(i),",",fifty(i)
            write(46,21) subcat(i),",",hundred(i)
            ENDIF

            IF(xday(i).eq.5) then
            write(51,21) subcat(i),",",two(i)
            write(52,21) subcat(i),",",five(i)
            write(53,21) subcat(i),",",ten(i)
            write(54,21) subcat(i),",",twenty(i)
            write(55,21) subcat(i),",",fifty(i)
            write(56,21) subcat(i),",",hundred(i)
            ENDIF

            IF(xday(i).eq.6) then
            write(61,21) subcat(i),",",two(i)
            write(62,21) subcat(i),",",five(i)
            write(63,21) subcat(i),",",ten(i)
            write(64,21) subcat(i),",",twenty(i)
            write(65,21) subcat(i),",",fifty(i)
            write(66,21) subcat(i),",",hundred(i)
            ENDIF

            IF(xday(i).eq.7) then
            write(71,21) subcat(i),",",two(i)
            write(72,21) subcat(i),",",five(i)
            write(73,21) subcat(i),",",ten(i)
            write(74,21) subcat(i),",",twenty(i)
            write(75,21) subcat(i),",",fifty(i)
            write(76,21) subcat(i),",",hundred(i)
            ENDIF

      end do

END PROGRAM CSV
```

C Extracting Homogeneous Regions Per Quinary for Short Duration Design Rainfall Estimation

The following program was written to assign each Quinary Catchment to one of the seven relatively homogeneous regions (Figure 7.4) identified by Smithers and

Schulze (2003) and used for the estimation of short duration design rainfall in Section 7.1.4.2.

*****

```
PROGRAM GET_REGION
!
!     Author: D.M.Knoesen
!     Date: 26/08/2008
!
!     Searches lat and long and extracts JCS long-duration region (1-7)
!
Implicit None

      integer, parameter :: max = 1000000

      CHARACTER(len=255) :: line

      INTEGER, DIMENSION(max) :: latmin, longmin, qlatmin, qlongmin, region
      INTEGER i,io,norows, numrows, k


      open(1,file='Sagrid_mod.txt')
      open(2,file='Quin_lat_long.txt')
      open(3,file='Quin_regions.txt')


!Obtain number of lines in the input file
      DO i=1,max

            READ(1,*,IOSTAT=io) line
            IF (io<0) THEN
            norows = i-1
            EXIT
            END IF

      END DO
      REWIND(1)

      DO i=1,max

            READ(2,*,IOSTAT=io) line
            IF (io<0) THEN
            numrows = i-1
            EXIT
            END IF

      END DO
      REWIND(2)


!Read in the input file


      DO i=1,norows
            READ(1,*) latmin(i),longmin(i),region(i)
            1 FORMAT (i4,2x,i4,2x,i1)
```

```
      end do

close(1)

      DO i=1,numrows
            READ(2,2) qlatmin(i),qlongmin(i)
            2 FORMAT (i4,2x,i4)
      end do

close(2)

      DO i=1,numrows
      DO k=1,norows


      IF(k.eq.norows.and.qlatmin(i).ne.latmin(norows).and.qlongmin(i).ne.lo
ngmin(norows))then
            write(3,3) i, qlatmin(i), qlongmin(i),0
            exit
            END IF

            IF(qlatmin(i).eq.latmin(k).and.qlongmin(i).eq.longmin(k))then
            write(3,3) i, qlatmin(i), qlongmin(i),region(k)
            3 FORMAT (i4.4,1x,i4,1x,i4,1x,i4)
            exit
            END IF
            END DO
      END DO

END PROGRAM GET_REGION
```

D Expressing Design Streamflows in Depth Equivalents

The following program was written to convert the design streamflows presented in Section 7.2.1.1 from volumes to depth equivalents.

****

```
PROGRAM CELRUNMM_CSV
!
!     Author: D.M.Knoesen
!     Date: 21/01/2009
!
Implicit None

REAL :: avalue, simarea, celarea
INTEGER :: day,RP,XYR,i,asubcat,bsubcat
CHARACTER(len=3) :: imstr
CHARACTER(len=1) :: ddaayy
CHARACTER(len=80) :: dummy

DO day=1,7

      DO RP=1,6
```

```
            IF (RP.eq.1) THEN
            XYR=2
            ELSEIF (RP.eq.2) THEN
            XYR=5
            ELSEIF (RP.eq.3) THEN
            XYR=10
            ELSEIF (RP.eq.4) THEN
            XYR=20
            ELSEIF (RP.eq.5) THEN
            XYR=50
            ELSEIF (RP.eq.6) THEN
            XYR=100
            ENDIF

            IF (XYR.lt.10) THEN
            WRITE(imstr(1:1),'(I1)') XYR
            dummy='d_'//imstr(1:1)//'yr.csv'
            ENDIF
            IF (XYR.ge.10.and.XYR.lt.100) THEN
            WRITE(imstr(1:2),'(I2)') XYR
            dummy='d_'//imstr(1:2)//'yr.csv'
            ENDIF
            IF (XYR.eq.100) THEN
            WRITE(imstr(1:3),'(I3)') XYR
            dummy='d_'//imstr(1:3)//'yr.csv'
            ENDIF

            WRITE(ddaayy(1:1),'(I1)') day

            OPEN(1,file='his_evd_'//ddaayy//dummy)
            OPEN(2,file='layare.csv')
            OPEN(3,file='his_XmmX_'//ddaayy//dummy)
!           OPEN(3,file='his_mm_'//ddaayy//dummy)
            READ(2,*)
            DO i=1,5838

                  READ(1,10) asubcat, avalue
                  READ(2,30) bsubcat, simarea, celarea
                  WRITE(3,20) asubcat,",",avalue/simarea/1000
!                 WRITE(3,20) asubcat,",",avalue/celarea/1000
                  10 FORMAT (I4.4,1x,F21.2)
                  20 FORMAT (I4.4,A1,F16.2)
                  30 FORMAT (I4.4,1x,F8.2,1x,F10.2)

            END DO

            CLOSE(1)
            CLOSE(2)
            CLOSE(3)

      END DO

END DO

END PROGRAM CELRUNMM_CSV
```

E Calculation of Meteorological and Hydrological Droughts

The following program was written to calculate droughts. The particular version below was used to read in raw GCM data, perform an on-the-fly rainfall correction, and perform the respective drought duration and severity calculations. Variations of this program were used for calculations involving historical rainfall data, as well as hydrological droughts for historical and GCM-derived streamflow output from the *ACRU* model.

****

```
PROGRAM Drought
!
!      Author: D.M.Knoesen
!      Date: 20/12/2008
!
Implicit None

      integer, parameter :: max = 99000

      CHARACTER(len=255) :: line
      character (len=3)  :: cgcm,cfol
      character (len=15) :: ifle
      character (len=8)  :: stid

      INTEGER, DIMENSION(max) :: day,month,year,munth,yaar,yr
      INTEGER i,io,norows,hystrt,hyend,qid1,mnth
      REAL montot, yeartot
      INTEGER
D1001,D1002,D1003,D2001,D2002,D2003,D3301,D3302,D3303,D5001,D5002,D5003
      INTEGER
YD1001,YD1002,YD1003,YD2001,YD2002,YD2003,YD3301,YD3302,YD3303,YD5001,YD500
2,YD5003
      REAL, DIMENSION(max) :: RFL,CELRUN,SIMSQ,MTOT,YTOT
      REAL, DIMENSION(max) ::
Jan10,Feb10,Mar10,Apr10,May10,Jun10,Jul10,Aug10,Sep10,Oct10,Nov10,Dec10,Ann
10
      REAL, DIMENSION(max) ::
Jan20,Feb20,Mar20,Apr20,May20,Jun20,Jul20,Aug20,Sep20,Oct20,Nov20,Dec20,Ann
20
      REAL, DIMENSION(max) ::
Jan33,Feb33,Mar33,Apr33,May33,Jun33,Jul33,Aug33,Sep33,Oct33,Nov33,Dec33,Ann
33
      REAL, DIMENSION(max) ::
Jan50,Feb50,Mar50,Apr50,May50,Jun50,Jul50,Aug50,Sep50,Oct50,Nov50,Dec50,Ann
50
      real, dimension(12) :: pptc
      INTEGER, DIMENSION(max) ::
Drought10,Drought20,Drought33,Drought50,D10,D20,D33,D50
```

```
      INTEGER, DIMENSION(max) ::
YDrought10,YDrought20,YDrought33,YDrought50,YD10,YD20,YD33,YD50
!__________________________________________________
CHARACTER(len=4) :: imstr
CHARACTER(len=80) :: dummyi, dummya, dummyb, dummyc, dummyd
!CHARACTER(len=80) :: dummyo
INTEGER iloop, j, GE
INTEGER nloop

            write(6,*) "Enter [GCM abbreviation,scenario] e.g. ccc,pr3"
        read(5,'(a3,1x,a3)')cgcm,cfol

        ifle='pptcor.xxx'
        write(ifle(08:10),'(a3)')cfol
!       write(6,62)ifle
!62     format("PPTCOR file: ",a65)
        open(30,file=ifle,action='read')
        read(30,*)

      nloop=5838
!     nloop=2500

      do iloop=1,nloop
        read(30,*)qid1,(pptc(mnth),mnth=1,12)

        if (iloop.ne.qid1) then
          write(6,*)'ERROR...quinary ID out of phase'
          write(6,*)iloop,qid1
          stop
        endif

          ifle='gcmfol_xxxx.txt'
          write(ifle(01:03),'(a3)')cgcm
          write(ifle(04:06),'(a3)')cfol
          write(ifle(08:11),'(i4.4)')iloop
!         write(6,61)ifle
!61       format("Input  file: ",a45)
          open(1,file=ifle,action='read')

            WRITE(IMSTR(1:4),'(I4.4)')iloop
!           dummyi='s'//imstr(1:4)//'.001'
!           dummyi='s'//imstr(1:4)//'.001'
            dummya='s'//imstr(1:4)//'.mon'
            dummyb='s'//imstr(1:4)//'.yr'

!     open(1,file=dummyi)
      open(2,file=dummya)
      open(3,file=dummyb)

!__________________________________________________

!Obtain number of lines in the input file
      DO i=1,max

            READ(1,*,IOSTAT=io) line
            IF (io<0) THEN
            norows = i-1
            EXIT
            END IF

      END DO
```

```
      REWIND(1)

! write(6,*) norows
!     READ(1,*)
!     norows=norows-1
!Read in the input file

      WRITE(6,*) iloop

      DO i=1,norows
!         READ(1,102) day(i),month(i),year(i),CELRUN(i),RFL(i),SIMSQ(i)
!102      FORMAT (i2,1x,I2,1x,i4,53x,F15.9,115x,F15.9,39x,F15.9,50x)

          read(1,102)stid,year(i),month(i),day(i),rfl(i)
 102      format(a8,i4,i2,i2,f5.0)

          rfl(i) = rfl(i) * pptc(month(i))
      end do
        close(1)
        write(6,*)norows

      hystrt=0
      Do i=1,366
            If (hystrt.eq.0.and.day(i).eq.1.and.month(i).eq.10) Then
            hystrt=i
            End if
      End do

!     write(6,*) "Hydrological year begins on:
",day(hystrt),month(hystrt),year(hystrt)

      hyend=0
      Do i=1,norows
            If (hyend.eq.0.and.day(i).eq.30.and.month(i).eq.9) Then
                  If (norows-i.lt.365) Then
                  hyend=i
                  End if
            End if
      Enddo

!     write(6,*) "Hydrological year ends on:
",day(hyend),month(hyend),year(hyend)

      montot=RFL(hystrt)

DO i=hystrt,hyend
      IF (month(i).eq.month(i+1)) THEN
      montot=montot+RFL(i+1)
      ELSE
      write(2,10) month(i),year(i),montot
            10 FORMAT (i2,1x,I4,1x,F15.9)
      montot=RFL(i+1)
      ENDIF
ENDDO

      yeartot=RFL(hystrt)

DO i=hystrt,hyend
      IF (month(i).eq.9.and.day(i).eq.30) THEN
      write(3,11) year(i),yeartot
            11 FORMAT (I4,1x,F15.9)
```

```
      yeartot=RFL(i+1)
      ELSE
      yeartot=yeartot+RFL(i+1)
      ENDIF
ENDDO

close(2)
close(3)

ENDDO
close(30)

      open(11,file='pr3_drought.txt')

      DO i=1,max

            READ(11,*,IOSTAT=io) line
            IF (io<0) THEN
            norows = i-1
            EXIT
            END IF

      END DO
      REWIND(11)
write(6,*)norows/4
      DO i=1,norows/4
            READ(11,20)
Jan10(i),Feb10(i),Mar10(i),Apr10(i),May10(i),Jun10(i),&
            &Jul10(i),Aug10(i),Sep10(i),Oct10(i),Nov10(i),Dec10(i),Ann10(i)

            READ(11,*)
            READ(11,*)
            READ(11,*)
            20 FORMAT (32x,13(1x,F11.2))
      ENDDO
rewind(11)
      DO i=1,norows/4
            READ(11,*)
            READ(11,20)
Jan20(i),Feb20(i),Mar20(i),Apr20(i),May20(i),Jun20(i),&
            &Jul20(i),Aug20(i),Sep20(i),Oct20(i),Nov20(i),Dec20(i),Ann20(i)

            READ(11,*)
            READ(11,*)
      ENDDO
rewind(11)
      DO i=1,norows/4
            READ(11,*)
            READ(11,*)
            READ(11,20)
Jan33(i),Feb33(i),Mar33(i),Apr33(i),May33(i),Jun33(i),&
            &Jul33(i),Aug33(i),Sep33(i),Oct33(i),Nov33(i),Dec33(i),Ann33(i)

            READ(11,*)
      ENDDO
rewind(11)
      DO i=1,norows/4
            READ(11,*)
            READ(11,*)
            READ(11,*)
```

```
            READ(11,20)
Jan50(i),Feb50(i),Mar50(i),Apr50(i),May50(i),Jun50(i),&
            &Jul50(i),Aug50(i),Sep50(i),Oct50(i),Nov50(i),Dec50(i),Ann50(i)

      ENDDO

!           write(6,20)
Jan10(2500),Feb10(2500),Mar10(2500),Apr10(2500),May10(2500),Jun10(2500),&
!
      &Jul10(2500),Aug10(2500),Sep10(2500),Oct10(2500),Nov10(2500),Dec10(25
00),Ann10(2500)
!           write(6,20)
Jan20(2500),Feb20(2500),Mar20(2500),Apr20(2500),May20(2500),Jun20(2500),&
!
      &Jul20(2500),Aug20(2500),Sep20(2500),Oct20(2500),Nov20(2500),Dec20(25
00),Ann20(2500)
!           write(6,20)
Jan33(2500),Feb33(2500),Mar33(2500),Apr33(2500),May33(2500),Jun33(2500),&
!
      &Jul33(2500),Aug33(2500),Sep33(2500),Oct33(2500),Nov33(2500),Dec33(25
00),Ann33(2500)
!           write(6,20)
Jan50(2500),Feb50(2500),Mar50(2500),Apr50(2500),May50(2500),Jun50(2500),&
!
      &Jul50(2500),Aug50(2500),Sep50(2500),Oct50(2500),Nov50(2500),Dec50(25
00),Ann50(2500)

      nloop=5838
!     nloop=2500

      do iloop=1,nloop

            WRITE(IMSTR(1:4),'(I4.4)')iloop
            dummya='s'//imstr(1:4)//'.mon'
            dummyb='s'//imstr(1:4)//'.yr'
            dummyd='s'//imstr(1:4)//'.droughtmo'
            dummyc='s'//imstr(1:4)//'.droughtyr'

      open(2,file=dummya)
      open(3,file=dummyb)
      open(12,file=dummyd)
      open(16,file=dummyc)

!__________________________________________________

!Obtain number of lines in the input file
      DO i=1,max

            READ(2,*,IOSTAT=io) line
            IF (io<0) THEN
            norows = i-1
            EXIT
            END IF

      END DO
      REWIND(2)

      DO i=1,norows
            READ(2,10) munth(i),yaar(i),MTOT(i)
      ENDDO
```

```
DO i=1,norows

      Drought10(i)=0
      IF (munth(i).eq.10.and.MTOT(i).le.Oct10(iloop)) Then
      Drought10(i)=1
      ENDIF
      IF (munth(i).eq.11.and.MTOT(i).le.Nov10(iloop)) Then
      Drought10(i)=1
      ENDIF
      IF (munth(i).eq.12.and.MTOT(i).le.Dec10(iloop)) Then
      Drought10(i)=1
      ENDIF
      IF (munth(i).eq.1.and.MTOT(i).le.Jan10(iloop)) Then
      Drought10(i)=1
      ENDIF
      IF (munth(i).eq.2.and.MTOT(i).le.Feb10(iloop)) Then
      Drought10(i)=1
      ENDIF
      IF (munth(i).eq.3.and.MTOT(i).le.Mar10(iloop)) Then
      Drought10(i)=1
      ENDIF
      IF (munth(i).eq.4.and.MTOT(i).le.Apr10(iloop)) Then
      Drought10(i)=1
      ENDIF
      IF (munth(i).eq.5.and.MTOT(i).le.May10(iloop)) Then
      Drought10(i)=1
      ENDIF
      IF (munth(i).eq.6.and.MTOT(i).le.Jun10(iloop)) Then
      Drought10(i)=1
      ENDIF
      IF (munth(i).eq.7.and.MTOT(i).le.Jul10(iloop)) Then
      Drought10(i)=1
      ENDIF
      IF (munth(i).eq.8.and.MTOT(i).le.Aug10(iloop)) Then
      Drought10(i)=1
      ENDIF
      IF (munth(i).eq.9.and.MTOT(i).le.Sep10(iloop)) Then
      Drought10(i)=1
      ENDIF

      Drought20(i)=0
      IF (munth(i).eq.10.and.MTOT(i).le.Oct20(iloop)) Then
      Drought20(i)=1
      ENDIF
      IF (munth(i).eq.11.and.MTOT(i).le.Nov20(iloop)) Then
      Drought20(i)=1
      ENDIF
      IF (munth(i).eq.12.and.MTOT(i).le.Dec20(iloop)) Then
      Drought20(i)=1
      ENDIF
      IF (munth(i).eq.1.and.MTOT(i).le.Jan20(iloop)) Then
      Drought20(i)=1
      ENDIF
      IF (munth(i).eq.2.and.MTOT(i).le.Feb20(iloop)) Then
      Drought20(i)=1
      ENDIF
      IF (munth(i).eq.3.and.MTOT(i).le.Mar20(iloop)) Then
      Drought20(i)=1
      ENDIF
      IF (munth(i).eq.4.and.MTOT(i).le.Apr20(iloop)) Then
      Drought20(i)=1
```

```
ENDIF
IF (munth(i).eq.5.and.MTOT(i).le.May20(iloop)) Then
Drought20(i)=1
ENDIF
IF (munth(i).eq.6.and.MTOT(i).le.Jun20(iloop)) Then
Drought20(i)=1
ENDIF
IF (munth(i).eq.7.and.MTOT(i).le.Jul20(iloop)) Then
Drought20(i)=1
ENDIF
IF (munth(i).eq.8.and.MTOT(i).le.Aug20(iloop)) Then
Drought20(i)=1
ENDIF
IF (munth(i).eq.9.and.MTOT(i).le.Sep20(iloop)) Then
Drought20(i)=1
ENDIF

Drought33(i)=0
IF (munth(i).eq.10.and.MTOT(i).le.Oct33(iloop)) Then
Drought33(i)=1
ENDIF
IF (munth(i).eq.11.and.MTOT(i).le.Nov33(iloop)) Then
Drought33(i)=1
ENDIF
IF (munth(i).eq.12.and.MTOT(i).le.Dec33(iloop)) Then
Drought33(i)=1
ENDIF
IF (munth(i).eq.1.and.MTOT(i).le.Jan33(iloop)) Then
Drought33(i)=1
ENDIF
IF (munth(i).eq.2.and.MTOT(i).le.Feb33(iloop)) Then
Drought33(i)=1
ENDIF
IF (munth(i).eq.3.and.MTOT(i).le.Mar33(iloop)) Then
Drought33(i)=1
ENDIF
IF (munth(i).eq.4.and.MTOT(i).le.Apr33(iloop)) Then
Drought33(i)=1
ENDIF
IF (munth(i).eq.5.and.MTOT(i).le.May33(iloop)) Then
Drought33(i)=1
ENDIF
IF (munth(i).eq.6.and.MTOT(i).le.Jun33(iloop)) Then
Drought33(i)=1
ENDIF
IF (munth(i).eq.7.and.MTOT(i).le.Jul33(iloop)) Then
Drought33(i)=1
ENDIF
IF (munth(i).eq.8.and.MTOT(i).le.Aug33(iloop)) Then
Drought33(i)=1
ENDIF
IF (munth(i).eq.9.and.MTOT(i).le.Sep33(iloop)) Then
Drought33(i)=1
ENDIF


Drought50(i)=0
IF (munth(i).eq.10.and.MTOT(i).le.Oct50(iloop)) Then
Drought50(i)=1
ENDIF
IF (munth(i).eq.11.and.MTOT(i).le.Nov50(iloop)) Then
```

```
            Drought50(i)=1
            ENDIF
            IF (munth(i).eq.12.and.MTOT(i).le.Dec50(iloop)) Then
            Drought50(i)=1
            ENDIF
            IF (munth(i).eq.1.and.MTOT(i).le.Jan50(iloop)) Then
            Drought50(i)=1
            ENDIF
            IF (munth(i).eq.2.and.MTOT(i).le.Feb50(iloop)) Then
            Drought50(i)=1
            ENDIF
            IF (munth(i).eq.3.and.MTOT(i).le.Mar50(iloop)) Then
            Drought50(i)=1
            ENDIF
            IF (munth(i).eq.4.and.MTOT(i).le.Apr50(iloop)) Then
            Drought50(i)=1
            ENDIF
            IF (munth(i).eq.5.and.MTOT(i).le.May50(iloop)) Then
            Drought50(i)=1
            ENDIF
            IF (munth(i).eq.6.and.MTOT(i).le.Jun50(iloop)) Then
            Drought50(i)=1
            ENDIF
            IF (munth(i).eq.7.and.MTOT(i).le.Jul50(iloop)) Then
            Drought50(i)=1
            ENDIF
            IF (munth(i).eq.8.and.MTOT(i).le.Aug50(iloop)) Then
            Drought50(i)=1
            ENDIF
            IF (munth(i).eq.9.and.MTOT(i).le.Sep50(iloop)) Then
            Drought50(i)=1
            ENDIF

      write(12,30)
munth(i),Drought10(i),Drought20(i),Drought33(i),Drought50(i)
            30 FORMAT (i2,4(1x,I4))

      end do

!Obtain number of lines in the input file
      DO i=1,max

            READ(3,*,IOSTAT=io) line
            IF (io<0) THEN
            norows = i-1
            EXIT
            END IF

      END DO
      REWIND(3)

      DO i=1,norows
            READ(3,11) yr(i),YTOT(i)
      ENDDO

      DO i=1,norows

            YDrought10(i)=0
            IF (YTOT(i).le.Ann10(iloop)) Then
            YDrought10(i)=1
            ENDIF
```

```
            YDrought20(i)=0
            IF (YTOT(i).le.Ann20(iloop)) Then
            YDrought20(i)=1
            ENDIF

            YDrought33(i)=0
            IF (YTOT(i).le.Ann33(iloop)) Then
            YDrought33(i)=1
            ENDIF

            YDrought50(i)=0
            IF (YTOT(i).le.Ann50(iloop)) Then
            YDrought50(i)=1
            ENDIF

            write(16,12)
yr(i),YDrought10(i),YDrought20(i),YDrought33(i),YDrought50(i)
                  12 FORMAT (i4,4(1x,I4))

      ENDDO

      close(2,status = "delete")
      close(3,status = "delete")
      close(12)
      close(16)

ENDDO
      close(11)
      open(13,file='1m_2m_3m_drought_spells.txt')
      open(17,file='1y_2y_3y_drought_spells.txt')
!     open(15,file='1m_2m_3m_drought_spells.header')


      nloop=5838
!     nloop=2500

      do iloop=1,nloop

            WRITE(IMSTR(1:4),'(I4.4)')iloop
            dummyd='s'//imstr(1:4)//'.droughtmo'
            dummyc='s'//imstr(1:4)//'.droughtyr'

      open(12,file=dummyd)
      open(16,file=dummyc)

!___________________________________________________

!Obtain number of lines in the input file
      DO i=1,max

            READ(12,*,IOSTAT=io) line
            IF (io<0) THEN
            norows = i-1
            EXIT
            END IF

      END DO
      REWIND(12)

      DO i=1,norows
```

```
            READ(12,40) D10(i),D20(i),D33(i),D50(i)
            40 FORMAT (2x,4(1x,I4))
      ENDDO
close(12,status = "delete")

      D1001=0
      D1002=0
      D1003=0
      D2001=0
      D2002=0
      D2003=0
      D3301=0
      D3302=0
      D3303=0
      D5001=0
      D5002=0
      D5003=0

      DO i=1,norows

            D1001=D1001+D10(i)
            D2001=D2001+D20(i)
            D3301=D3301+D33(i)
            D5001=D5001+D50(i)

            IF(i.ge.2.and.D10(i-1).eq.1.and.D10(i).eq.1) THEN
            D1002=D1002+1
            ENDIF
            IF(i.ge.2.and.D20(i-1).eq.1.and.D20(i).eq.1) THEN
            D2002=D2002+1
            ENDIF
            IF(i.ge.2.and.D33(i-1).eq.1.and.D33(i).eq.1) THEN
            D3302=D3302+1
            ENDIF
            IF(i.ge.2.and.D50(i-1).eq.1.and.D50(i).eq.1) THEN
            D5002=D5002+1
            ENDIF

            IF(i.ge.3.and.D10(i-2).eq.1.and.D10(i-1).eq.1.and.D10(i).eq.1)
THEN
            D1003=D1003+1
            ENDIF
            IF(i.ge.3.and.D20(i-2).eq.1.and.D20(i-1).eq.1.and.D20(i).eq.1)
THEN
            D2003=D2003+1
            ENDIF
            IF(i.ge.3.and.D33(i-2).eq.1.and.D33(i-1).eq.1.and.D33(i).eq.1)
THEN
            D3303=D3303+1
            ENDIF
            IF(i.ge.3.and.D50(i-2).eq.1.and.D50(i-1).eq.1.and.D50(i).eq.1)
THEN
            D5003=D5003+1
            ENDIF

      ENDDO

      write(13,50)
iloop,D1001,D1002,D1003,D2001,D2002,D2003,D3301,D3302,D3303,D5001,D5002,D50
03
            50 FORMAT (i4.4,12(1x,I3.3))
```

```
!Obtain number of lines in the input file
      DO i=1,max

            READ(16,*,IOSTAT=io) line
            IF (io<0) THEN
            norows = i-1
            EXIT
            END IF

      END DO
      REWIND(16)

      DO i=1,norows
            READ(16,22) YD10(i),YD20(i),YD33(i),YD50(i)
                  22 FORMAT (4x,4(1x,I4))
      ENDDO
close(16,status = "delete")

      YD1001=0
      YD1002=0
      YD1003=0
      YD2001=0
      YD2002=0
      YD2003=0
      YD3301=0
      YD3302=0
      YD3303=0
      YD5001=0
      YD5002=0
      YD5003=0

      DO i=1,norows

            YD1001=YD1001+YD10(i)
            YD2001=YD2001+YD20(i)
            YD3301=YD3301+YD33(i)
            YD5001=YD5001+YD50(i)

            IF(i.ge.2.and.YD10(i-1).eq.1.and.YD10(i).eq.1) THEN
            YD1002=YD1002+1
            ENDIF
            IF(i.ge.2.and.YD20(i-1).eq.1.and.YD20(i).eq.1) THEN
            YD2002=YD2002+1
            ENDIF
            IF(i.ge.2.and.YD33(i-1).eq.1.and.YD33(i).eq.1) THEN
            YD3302=YD3302+1
            ENDIF
            IF(i.ge.2.and.YD50(i-1).eq.1.and.YD50(i).eq.1) THEN
            YD5002=YD5002+1
            ENDIF

            IF(i.ge.3.and.YD10(i-2).eq.1.and.YD10(i-
1).eq.1.and.YD10(i).eq.1) THEN
            YD1003=YD1003+1
            ENDIF
            IF(i.ge.3.and.YD20(i-2).eq.1.and.YD20(i-
1).eq.1.and.YD20(i).eq.1) THEN
            YD2003=YD2003+1
            ENDIF
```

```
            IF(i.ge.3.and.YD33(i-2).eq.1.and.YD33(i-
1).eq.1.and.YD33(i).eq.1) THEN
            YD3303=YD3303+1
            ENDIF
            IF(i.ge.3.and.YD50(i-2).eq.1.and.YD50(i-
1).eq.1.and.YD50(i).eq.1) THEN
            YD5003=YD5003+1
            ENDIF

      ENDDO

      write(17,50)
iloop,YD1001,YD1002,YD1003,YD2001,YD2002,YD2003,YD3301,YD3302,YD3303,YD5001
,YD5002,YD5003


ENDDO

      write(15,*)"sub_cat",",","10yr Droughts",",","2 Consecutive 10yr
Droughts",",","3 Consecutive10yr Droughts",",",&
      &"5yr Droughts",",","2 Consecutive 5yr Droughts",",","3 Consecutive
5yr Droughts",",",&
      &"3yr Droughts",",","2 Consecutive 3yr Droughts",",","3 Consecutive
3yr Droughts",",",&
      &"2yr Droughts",",","2 Consecutive 2yr Droughts",",","3 Consecutive
2yr Droughts"

close(13)
close(17)
close(15)

END PROGRAM Drought
```

F Extracting Number of Raindays Greater Than, Less Than or Equal to a Selected Threshold

The following program was written to extract the number of days on which the daily rainfall was:

- Equal to 0 mm;
- Less than or equal to 1 mm;
- Greater than 1 mm;
- Greater than 2 mm;
- Greater than 5 mm;
- Greater than 10 mm;
- Greater than 20 mm; and
- Greater than 25 mm.

This analysis was performed on the projected daily rainfall from each of the five GCMs used in this study. Selected output from these analyses is presented in 7.3.3.2.

****

```
PROGRAM Thresh_CSV
!
!     Author: D.M.Knoesen
!     Date: 12/01/2009
!
Implicit None

      integer, parameter :: max = 99000
      CHARACTER(len=255) :: line
      INTEGER, DIMENSION(max) :: subcat
      REAL, DIMENSION(max) ::
deq0,dle1,dgt1,dgt2,dgt5,dgt10,dgt20,dgt25,value
      INTEGER i,io,norows
!__________________________________________________
INTEGER iloop, j

      open(1,file='rflthr.all',action='read')
      open(11,file='rflthr_EQ0.csv',action='write')
      open(12,file='rflthr_LE1.csv',action='write')
      open(13,file='rflthr_GT1.csv',action='write')
      open(14,file='rflthr_GT2.csv',action='write')
      open(15,file='rflthr_GT5.csv',action='write')
      open(16,file='rflthr_GT10.csv',action='write')
      open(17,file='rflthr_GT20.csv',action='write')
      open(18,file='rflthr_GT25.csv',action='write')

!__________________________________________________

!Obtain number of lines in the input file
      DO i=1,max
            READ(1,*,IOSTAT=io) line
            IF (io<0) THEN
            norows = i-1
            EXIT
            END IF
      END DO
      REWIND(1)

      WRITE(6,*) norows

!Read in the input file

      DO i=1,norows
          read(1,102)
subcat(i),deq0(i),dle1(i),dgt1(i),dgt2(i),dgt5(i),dgt10(i),dgt20(i),dgt25(i
)
 102      format(i4,36x,8(1x,f6.1))
      end do
        close(1)
```

```
DO j=1,8
      DO i=1,norows

      IF(j.eq.1) THEN
            value(i)=deq0(i)
      ENDIF

      IF(j.eq.2) THEN
            value(i)=dle1(i)
      ENDIF

      IF(j.eq.3) THEN
            value(i)=dgt1(i)
      ENDIF

      IF(j.eq.4) THEN
            value(i)=dgt2(i)
      ENDIF

      IF(j.eq.5) THEN
            value(i)=dgt5(i)
      ENDIF

      IF(j.eq.6) THEN
            value(i)=dgt10(i)
      ENDIF

      IF(j.eq.7) THEN
            value(i)=dgt20(i)
      ENDIF

      IF(j.eq.8) THEN
            value(i)=dgt25(i)
      ENDIF

            write(10+j,103) subcat(i),",",value(i)
 103      format(i4.4,a1,f6.1)
      ENDDO
ENDDO

close(11)
close(12)
close(13)
close(14)
close(15)
close(16)
close(17)
close(18)

END PROGRAM Thresh_CSV
```

G Calculating the Ratios of Future to Present Projections

The following program was written to calculate the ratios of future to present projections for the various analyses undertaken in this study and presented in Chapter 7. These ratios were calculated for each of the five GCMs used in this study.

The program demonstrated below was used for the calculation of ratios for long duration design rainfall. Variations of this program were applied to:

- Short duration design rainfall;
- Design floods
  - Streamflows
  - Peak discharges
- Droughts
  - Meteorological
  - Hydrological
- Sediment Yields.

*****

```
PROGRAM RATIO_CSV
!
!     Author: D.M.Knoesen
!     Date: 07/11/2008
!
Implicit None

REAL :: avalue,bvalue
INTEGER :: day,RP,XYR,i,asubcat,bsubcat
CHARACTER(len=3) :: imstr
CHARACTER(len=1) :: ddaayy
CHARACTER(len=80) :: dummy

DO day=1,7

      DO RP=1,6

            IF (RP.eq.1) THEN
            XYR=2
            ELSEIF (RP.eq.2) THEN
            XYR=5
            ELSEIF (RP.eq.3) THEN
            XYR=10
            ELSEIF (RP.eq.4) THEN
            XYR=20
            ELSEIF (RP.eq.5) THEN
            XYR=50
            ELSEIF (RP.eq.6) THEN
            XYR=100
            ENDIF

            IF (XYR.lt.10) THEN
            WRITE(imstr(1:1),'(I1)') XYR
            dummy='d_'//imstr(1:1)//'yr.csv'
            ENDIF
            IF (XYR.ge.10.and.XYR.lt.100) THEN
            WRITE(imstr(1:2),'(I2)') XYR
```

```
            dummy='d_'//imstr(1:2)//'yr.csv'
            ENDIF
            IF (XYR.eq.100) THEN
            WRITE(imstr(1:3),'(I3)') XYR
            dummy='d_'//imstr(1:3)//'yr.csv'
            ENDIF

            WRITE(ddaayy(1:1),'(I1)') day

            OPEN(1,file='fut_evd_'//ddaayy//dummy)
            OPEN(2,file='int_evd_'//ddaayy//dummy)
            OPEN(3,file='fut_ovr_int_evd_'//ddaayy//dummy)

            DO i=1,5838

                  READ(1,10) asubcat, avalue
                  READ(2,10) bsubcat, bvalue
                  WRITE(3,20) asubcat,",",avalue/bvalue
                  10 FORMAT (I4.4,1x,F16.2)
                  20 FORMAT (I4.4,A1,F16.2)

            END DO

            CLOSE(1)
            CLOSE(2)
            CLOSE(3)

      END DO

END DO

END PROGRAM RATIO_CSV
```

H Calculation of Uncertainty

The following program was written to calculate how often the different GCMs were in agreement with regards to their climate change projections. The output from this program was then input into a spreadsheet where various statistics were calculated for use in the uncertainty analyses presented in Chapter 7.

The particular program presented below was applied to long duration design rainfall. Variations of this program were applied to:

- Short duration design rainfall;
- Design floods
  - Streamflows
  - Peak discharges
- Droughts
  - Meteorological

- ➢ Hydrological
- Sediment Yields.

*****

```
PROGRAM UNCERTAINTY_CSV
!
!     Author: D.M.Knoesen
!     Date: 17/12/2008
!
Implicit None

REAL :: ips_value, gss_value, ech_value, crm_value, ccc_value
REAL :: inc, decr, same
INTEGER :: day,RP,XYR,i,asubcat,bsubcat,csubcat,dsubcat,esubcat
CHARACTER(len=3) :: imstr
CHARACTER(len=1) :: ddaayy
CHARACTER(len=80) :: dummy

DO day=1,7

      DO RP=1,6

            IF (RP.eq.1) THEN
            XYR=2
            ELSEIF (RP.eq.2) THEN
            XYR=5
            ELSEIF (RP.eq.3) THEN
            XYR=10
            ELSEIF (RP.eq.4) THEN
            XYR=20
            ELSEIF (RP.eq.5) THEN
            XYR=50
            ELSEIF (RP.eq.6) THEN
            XYR=100
            ENDIF

            IF (XYR.lt.10) THEN
            WRITE(imstr(1:1),'(I1)') XYR
            dummy='d_'//imstr(1:1)//'yr.csv'
            ENDIF
            IF (XYR.ge.10.and.XYR.lt.100) THEN
            WRITE(imstr(1:2),'(I2)') XYR
            dummy='d_'//imstr(1:2)//'yr.csv'
            ENDIF
            IF (XYR.eq.100) THEN
            WRITE(imstr(1:3),'(I3)') XYR
            dummy='d_'//imstr(1:3)//'yr.csv'
            ENDIF

            WRITE(ddaayy(1:1),'(I1)') day

            OPEN(10,file='C:\KnoesenD\PhD\Analysis\Extreme
Values\RFL\IPS\int_ovr_pr3_evd_'//ddaayy//dummy)
            OPEN(11,file='C:\KnoesenD\PhD\Analysis\Extreme
Values\RFL\GSS\int_ovr_pr3_evd_'//ddaayy//dummy)
```

```
            OPEN(12,file='C:\KnoesenD\PhD\Analysis\Extreme
Values\RFL\ECH\int_ovr_pr3_evd_'//ddaayy//dummy)
            OPEN(13,file='C:\KnoesenD\PhD\Analysis\Extreme
Values\RFL\CRM\int_ovr_pr3_evd_'//ddaayy//dummy)
            OPEN(14,file='C:\KnoesenD\PhD\Analysis\Extreme
Values\RFL\CCC\int_ovr_pr3_evd_'//ddaayy//dummy)
            OPEN(15,file='5gcms_unc_int_ovr_pr3_evd_'//ddaayy//dummy)
            OPEN(16,file='5gcms_int_ovr_pr3_evd_'//ddaayy//dummy)

            DO i=1,5838

                  inc = 0
                  decr = 0
                  same = 0

                  READ(10,22) asubcat,ips_value
                  READ(11,22) bsubcat,gss_value
                  READ(12,22) csubcat,ech_value
                  READ(13,22) dsubcat,crm_value
                  READ(14,22) esubcat,ccc_value
                  22 FORMAT (I4.4,1x,F16.2)

                  IF (ips_value.gt.1.01) Then
                  inc = inc + 1
                  ELSEIF (ips_value.lt.0.99) Then
                  decr = decr+1
                  ELSE
                  same = same+1
                  ENDIF


                  IF (gss_value.gt.1.01) Then
                  inc = inc + 1
                  ELSEIF (gss_value.lt.0.99) Then
                  decr = decr+1
                  ELSE
                  same = same+1
                  ENDIF

                  IF (ech_value.gt.1.01) Then
                  inc = inc + 1
                  ELSEIF (ech_value.lt.0.99) Then
                  decr = decr+1
                  ELSE
                  same = same+1
                  ENDIF

                  IF (crm_value.gt.1.01) Then
                  inc = inc + 1
                  ELSEIF (crm_value.lt.0.99) Then
                  decr = decr+1
                  ELSE
                  same = same+1
                  ENDIF

                  IF (ccc_value.gt.1.01) Then
                  inc = inc + 1
                  ELSEIF (ccc_value.lt.0.99) Then
                  decr = decr+1
                  ELSE
                  same = same+1
```

```
            ENDIF


            WRITE(15,20) asubcat,",",inc
            WRITE(16,10) asubcat,",",inc,",",decr,",",same
            10 FORMAT (I4.4,A1,F16.2,A1,F16.2,A1,F16.2)
            20 FORMAT (I4.4,A1,F16.2)

        END DO

        CLOSE(10)
        CLOSE(11)
        CLOSE(12)
        CLOSE(13)
        CLOSE(14)
        CLOSE(15)
        CLOSE(16)

    END DO

END DO

END PROGRAM UNCERTAINTY_CSV
```