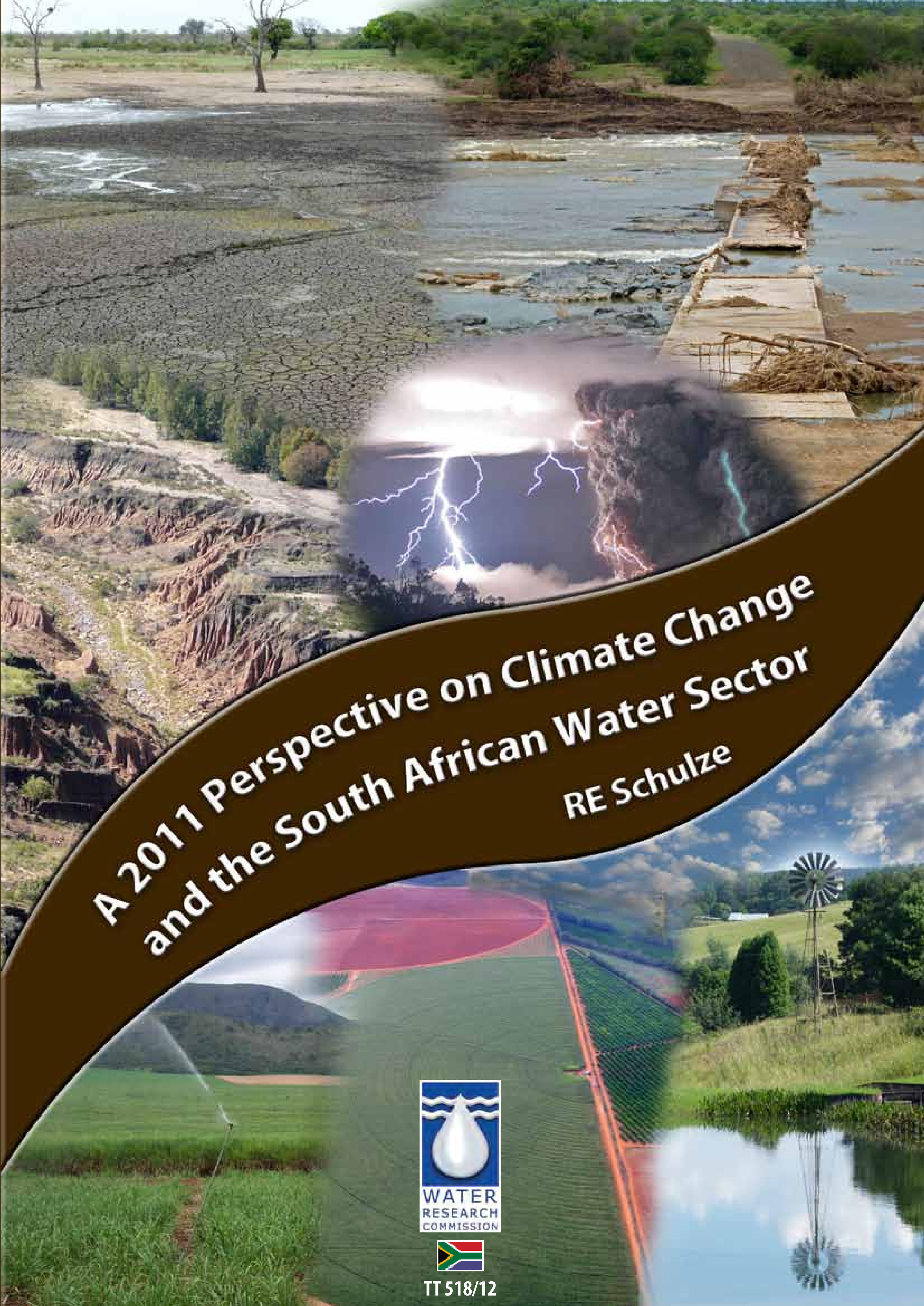

A 2011 Perspective on Climate Change and the South African Water Sector

RE Schulze

WATER RESEARCH COMMISSION

TT 518/12

A 2011 PERSPECTIVE ON CLIMATE CHANGE AND THE SOUTH AFRICAN WATER SECTOR

R.E. Schulze

Report to the
Water Research Commission

by

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

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R.E. Schulze

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A Contribution Towards WRC Project K5/1843:
An Evaluation of the Sensitivity of Socio-Economic Activities to Climate Change in Climatically Divergent South African Catchments

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BACKGROUND INFORMATION

CHAPTER 1.1

CLIMATE CHANGE AND *THE SOUTH AFRICAN WATER SECTOR: SETTING THE SCENE ON A 2011 PERSPECTIVE*

R.E. Schulze

The Climate Change Context

There is an overwhelming body of evidence, contained in thousands of scientific papers and summarised in a series of seminal reports emanating from the International Panel on Climate Change (most recently IPCC, 2007), that anthropogenically induced greenhouse gas emissions, often expressed through increases in atmospheric CO_2 concentrations (**Figure 1.1.1** bottom maps: left), are increasing and with that global temperatures and sea level (**Figure 1.1.1** bottom maps; middle and right). These and other pieces of climate change evidence have been used by the International Geosphere-Biosphere Program (IGBP, 2009) to produce a composite climate change index, akin to composite stock exchange indices, and **Figure 1.1.1** (top) shows the clear rise in this index since 1980.

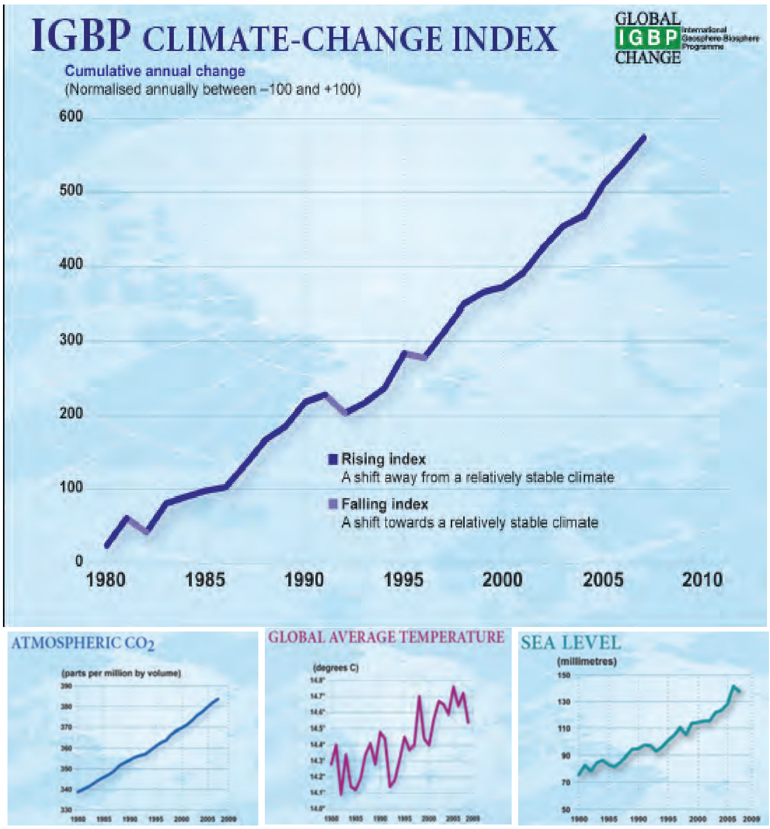

Figure 1.1.1 The IGBP's composite climate change index (top) and (bottom) some of the indicators used in its derivation (IGBP, 2009)

With further projected changes in global climates into the future, changes in the South African water sector will be inevitable, especially since the regional climate in South Africa is dependent on global climate, both today and in the future. No one knows exactly how the future global climate will develop (cf. **Chapter 2.1**) and what the resultant consequences in South Africa will be in, for example, the water sector. However, South Africa lies in one of the regions of the world that is most vulnerable to climate variability and change (IPCC, 2007).

Impacts from a changing climate are likely to be considerable to the water sector, with different regions of the country likely to be affected in many different ways. For this reason alone local scale analyses are needed to assess potential impacts (Andersson *et al*., 2009). Changes in mean annual streamflow and its variability are anticipated, and with that many knock-on effects ranging from reservoir operating rules to design hydrology and flood management.

Dispelling Misconceptions on Climate Change Impacts over South Africa

There are many misconceptions in the popular and even the official as well as scientific literature in South Africa with regard to projected changes in magnitude and direction of key climate change variables and the possible impacts of these. These have arisen either out of ignorance, and / or by citing from dated research results (e.g. the Country Studies Report; DEAT, 2000), and / or having pre-conceived ideas that climate change implies only "gloom and doom" on the one hand, or is a non-issue on the other, and / or taking isolated statements / cases / criticisms out of context and disregarding the overwhelming body of evidence on climate change, and / or having been "conditioned" by what turn out to be very broad generalisations contained in IPCC reports. It is hoped that in light of findings in this Report some of these misconceptions will be dispelled.

Why a Focus on Climate Change and South Africa's Water Sector?

South Africa's water resources, already subjected to high hydro-climatic variability both over space and over time, are a key constraint to the country's continued economic development and the sustainable livelihoods of its people.

It should be stressed that because

- water is arguably the primary medium through which early (and subsequent) climate change impacts will be felt by people, ecosystems and economies, and because
- a large proportion of South Africa's population is impoverished (thus rendering them particularly vulnerable to impacts of climate change), and
- many of the fragile ecosystems in South Africa (both terrestrial and aquatic) are implicitly or explicitly water dependent,
- it has become urgently necessary to gain a comprehensive understanding of the physical drivers and the hydrological responses of climate change in a South African water sector context in order to
- develop science based strategies and plans of action to adapt to climate change through an integrated approach to land and water management as the cornerstone to establishing effective resilience to the projected impacts of climate change.

To the above need to be added that

- water-related infrastructure (e.g. dams, irrigation projects, inter-basin transfers, stormwater drains etc) is typically a long term investment with a design life of 50 - 100 years, is very expensive, essentially irreversible once constructed and is designed to cope with currently (but not necessarily future) expected extremes of floods and droughts, that
- any changes in rainfall, be they up or down, are amplified in changes of hydrological responses (in the case of year-to-year variability the amplification from rainfall to runoff can be 2 - 5 fold; Schulze, 2003), that
- climate change is not going to be experienced evenly throughout the country, with some areas "winners", other areas "losers" and others still are likely to become real "hotspots of concern", and that
- climate change does not occur on a "clean sheet" of virgin catchments not yet impacted upon by human interventions on the land and in the channel, but will rather be superimposed onto already water stressed catchments with complex land uses, water engineered systems and a strong socio-political as well as economic historical footprint.

The above factors have also been endorsed in the 2011 Second National Communication of South Africa to the UNFCCC.

Accounting for and adapting to potential effects of climate change in South Africa's water sector are therefore seen as imperatives - indeed, non-consideration of potential effects of climate change and adaptation on the country's water sector should be viewed as an act of omission.

With its strong policies and laws to protect water resources and ensure their efficient and equitable use (e.g. the National Water Act [NWA] of1998; the National Water Resource Strategy [NWRS] of 2004), South Africa has the potential to lead the continent in adapting to climate change. However, the water sector is currently characterised by capacity constraints, inadequate funding, a reliance on ageing bulk infrastructure and erratic water quality, especially in smaller municipalities and rural areas (Stuart-Hill and Schulze, 2010). Climate change adds one more layer of concern to the already challenged water sector.

Objectives of the Research Leading to this Report

This report forms a component of a solicited three year Water Research Commission project titled

An Evaluation of the Sensitivity of Socio-Economic Activities to Climate Change in Climatically Divergent South African Catchments

and awarded to a consortium led by the University of KwaZulu-Natal's School of Bioresources Engineering and Environmental Hydrology. With the impacts of climate change being potentially disastrous on a regional scale and with the knock-on effects possibly having serious implications for the national economy, with vulnerable communities likely to be most seriously affected, a major goal of this project was to take current knowledge on climate change in South Africa to a new level, updating it and making it more relevant as well as usable for water managers within their decision making processes. In so doing, the project was tasked with making use of output from state-of-the-art General Circulation Models (GCMs) from the IPCC's Fourth Assessment Report (IPCC, 2007) to make projections, at a finer spatial scale than in previous studies, of possible changes to the South African water sector associated with anticipated global climate change, and then to use those scenarios to evaluate the sensitivity and adaptability of current socio-economic activities and the likely socio-economic impacts resulting from expected climatic changes.

****

After "Setting the Scene" the remaining two chapters of **Section 1** provide a brief overview of South Africa and some background on terminology used. This is followed in **Section 2** by chapters on downscaling climate models, databases and models and a chapter on verification of outputs from GCMs. In **Section 3** projections of first order climate change impacts are presented (i.e. on temperature and rainfall), while in **Section 4** the focus is on changes to second order climate derivatives. After an introductory chapter on water resources complexities and hydrological challenges in light of climate change, the other six chapters in **Section 5** cover projected changes in hydrological responses to climate change, while in **Section 6** possible changes to hydrological and meteorological drought frequencies and severities are evaluated. **Sections 7** and **8** cover, respectively, our current understanding of projected changes to design rainfall and streamflows, and to practical applications such as evaporation from open water bodies, irrigation and rainwater harvesting. In the final **Section 9** a summary of the main findings is presented and issues of adaptation to climate change in the South African water sector are addressed.

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CHAPTER 1.2

SOUTH AFRICA: A BRIEF OVERVIEW

R.E. Schulze

Setting the Scene

By way of introduction to the Report on climate change and the South African water sector a very brief background on its physical geography and its people is provided in this Chapter. The purpose of this is to show the highly diverse nature of South Africa's physiography, its inhabitants and the socio-economic milieu which, on the one hand, they have shaped and which, on the other hand, they have responded to either voluntarily or involuntarily through history, politics and the physical environment. Much of the socio-demographic information is given at the scale of provinces and statistics for the RSA have been derived from the most recent population census at the time of writing, *viz*. the 2001 census (Statistics SA, 2003).

South Africa: The Study Area Covered

While the Report's title refers to the *South African* water sector, the geographical entity covered by this Report comprises the Republic of South Africa with its nine provinces (*viz*. Limpopo, Mpumalanga, North West, Northern Cape, Gauteng, Free State, KwaZulu-Natal, Eastern Cape and Western Cape) plus the Kingdoms of Swaziland and Lesotho. Where a focus is specifically on the Republic of South Africa, the abbreviation RSA is used. Furthermore, the term "South" has been used in the Report in preference to "southern", as the latter has a different political connotation (e.g. as in SADC, which includes over a dozen member states). The provinces of the RSA plus the two other countries, as well as major roads and towns, are shown in **Figure 1.2.1**.

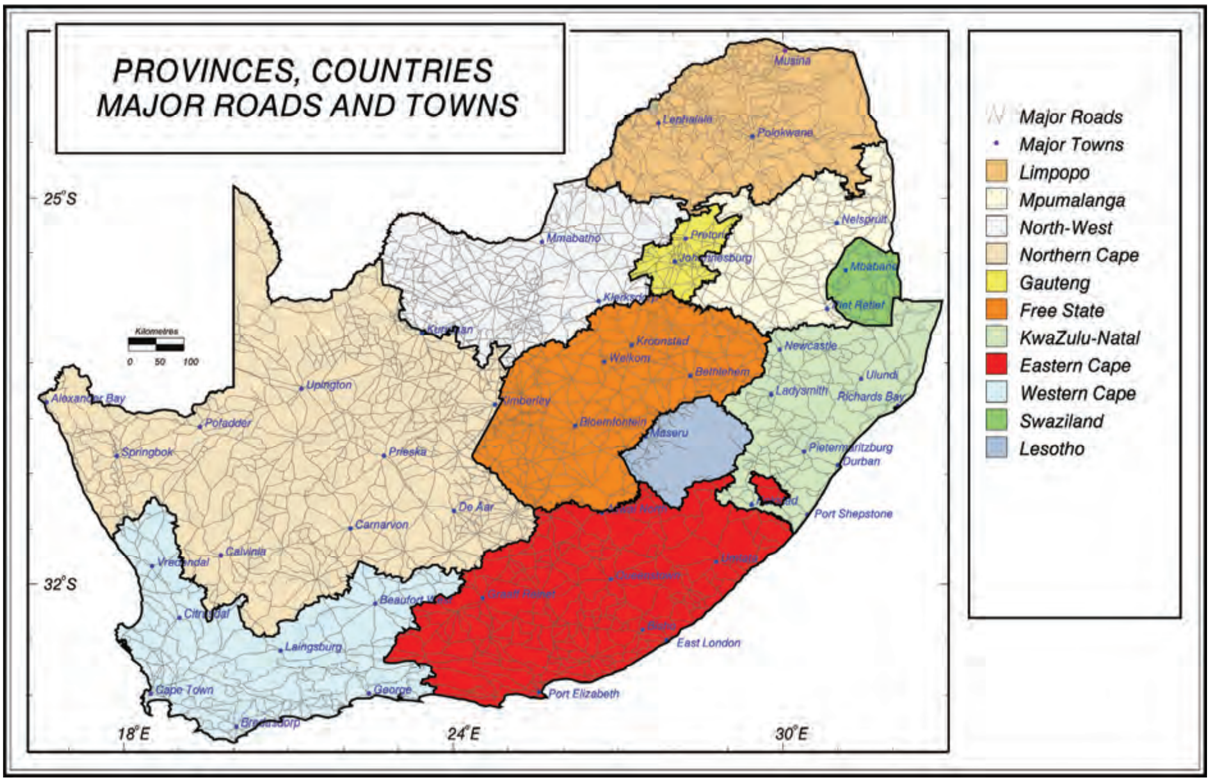

Figure 1.2.1 Provinces, countries, major roads and towns (Official spelling of town names as of July 2006)

Table 1.2.1 shows the Northern Cape to be the largest of the nine provinces at 361 830 km^2, while Gauteng is 21 times smaller at only 17 010 km^2. The total study area is 1 266 052 km^2, of which the RSA covers over 96 %.

Table 1.2.1 Areal and demographic information (Sources: Statistics SA, 2003; Unicef, 2005)

Province / Country	Area (km^2)	Area as % of Total	Population Density	Highest Levels of Education (Adults > 20 Years)			
				No School	Primary	Secon-dary	Higher
Limpopo	123910	9.8	42.6	33.4	19.6	40.1	6.8
Mpumalanga	79490	6.3	39.3	27.5	21.8	44.8	5.9
North West	116320	9.2	31.5	19.9	26.8	47.5	5.9
N. Cape	361830	28.6	2.3	18.2	29.3	46.4	6.1
Gauteng	17010	1.3	519.5	8.4	16.7	62.3	12.6
Free State	129480	10.2	20.9	16.0	29.5	48.2	6.3
KwaZulu-Natal	92100	7.3	102.3	21.9	22.6	48.6	6.9
E. Cape	169580	13.4	38.0	22.8	27.2	43.7	6.3
W. Cape	129370	10.2	35.0	5.7	23.1	59.9	11.2
RSA	1219090	96.3	36.8	17.9	22.4	51.2	8.4
Swaziland	17404	1.4	59.4				
Lesotho	29558	2.3	60.8				
Totals / Ave	1266052	100.0	37.6				

The Physical Environment 1: Altitude, its Importance in Hydrological Studies and its Distribution over South Africa

Topography is an invariate (i.e. static) feature of the physical landscape which is described by altitude *per se*, as well as the rate of change of altitude over distance. As such, altitude (**Figure 1.2.2**) exerts major influences on features of climate and hence on hydrological responses.

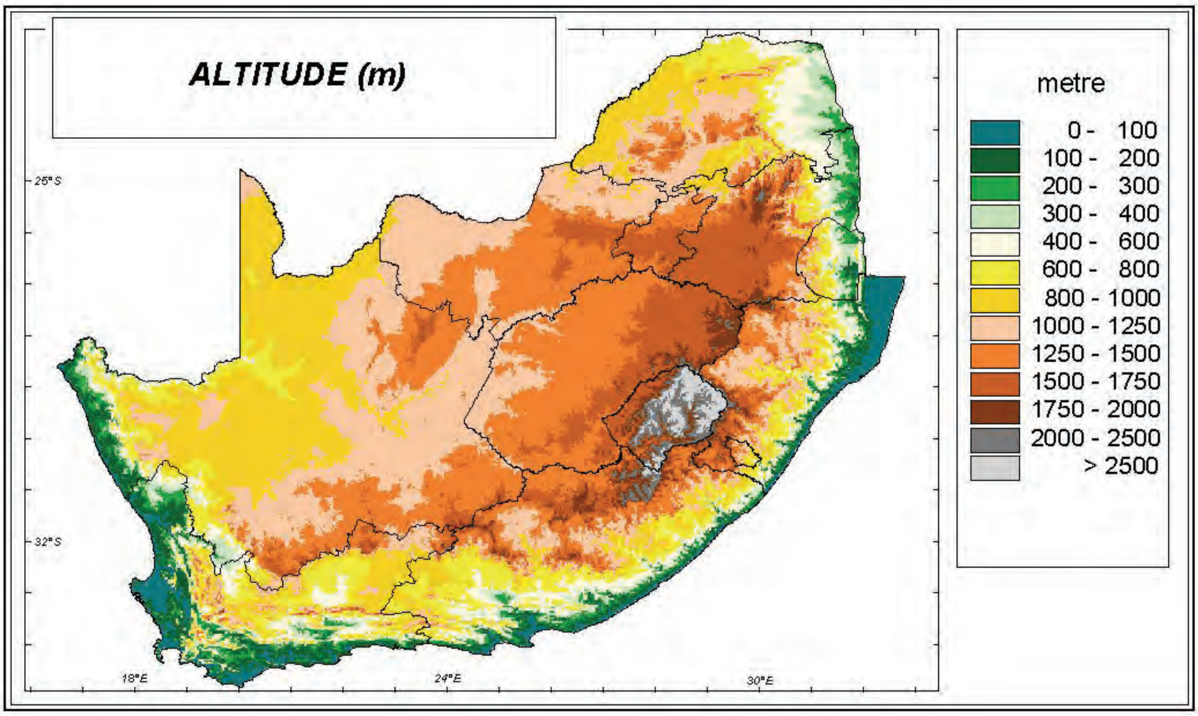

Figure 1.2.2 Altitude

On a macroscale (i.e. scale of 10s to 100s of km) and mesoscale (1-10 km) altitude can act as a *barrier* to rain-bearing air masses (e.g. in the Western Cape in winter); alternatively it can force moist air to rise by *orographic lifting*, resulting in windward facing slopes to experience not only more total rainfall, but also more raindays as well as often more rainfall per rainday (e.g. KwaZulu-Natal side of the Drakensberg in summer; Schulze, 1979). High altitudes associated with a steep altitude gradient are also a cause of increased thunderstorm activity and, with that, higher incidences of stormflow producing events.

In regard to temperatures, higher altitudes are generally the major cause of reduced temperatures and with that reduced evaporative losses from the soil, from plants and from water bodies.

The accompanying map (**Figure 1.2.2**) illustrates that physiographically, five major characteristics dominate the distribution of altitudes over South Africa, *viz*.

- a generally narrow coastal strip of low altitudes, widening only along the northeastern coast of KwaZulu-Natal (with extensions into the "lowveld" areas of eastern Swaziland, Mpumalanga and Limpopo) and the "flats" of the Western Cape,
- the so-called Great Escarpment, stretching from 20 °E to 31 °E at about 200 - 300 km inland from the south and east coasts,
- peaking in altitude in the Drakensberg mountain range of KwaZulu-Natal and Lesotho and its extensions making up the Maluti mountains of Lesotho, and
- a vast interior plateau inland of the Great Escarpment dropping gently from the east at around 1500 m to the west at around 1000 m altitude.

The Physical Environment 2: Mean Annual Precipitation (MAP), its Importance and its Distribution over South Africa

The MAP (mm) characterises the long term quantity of water available to a region for hydrological purposes. Not only is MAP important as a general statistic in its own right, but it is probably also the one climatic variable best known to hydrologists, and to which they can relate many other responses, for example, a catchment's lag time used in peak discharge estimations (Schmidt and Schulze, 1984).

The overall feature of the distribution of MAP over South Africa (**Figure 1.2.3**) is that it decreases fairly uniformly westwards from the escarpment across the interior plateau. Between the escarpment and the ocean in both the southern and the eastern coastal margins there is the expected complexity of rainfall patterns induced by irregularities of terrain. According to Lynch (2004), approximately 20 % of South Africa receives less than 200 mm MAP, and 47 % receives less than 400 mm per annum, this being the result of the presence of subtropical high pressure cells which inhibit rainfall generation because of predominantly subsiding air. Only about 9 % of South Africa receives a MAP in excess of 800 mm. KwaZulu-Natal is the wettest of South Africa's nine provinces, while the Western Cape has the highest range of MAP within any of the provinces, and the highest individual point rainfall at an estimated 3 198 mm per annum (Lynch, 2004).

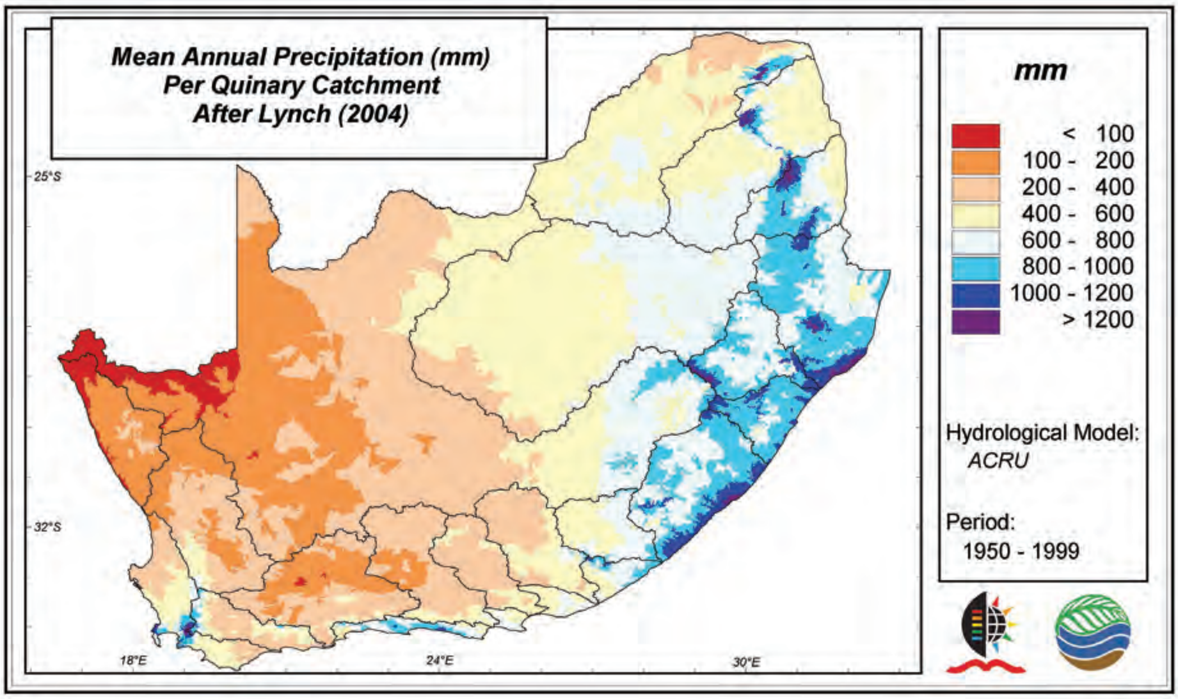

Figure 1.2.3 Mean Annual Precipitation over South Africa (Source Data: Lynch, 2004)

The RSA’s Socio-Economic Milieu 1: Demographic Indicators

Of the ~ 50 million inhabitants of South Africa an estimated 94 % reside in the RSA (**Table 1.2.1**). Within the RSA, the population make-up by group is as follows:

- Black African: 79.0 % (ranging from 97.2 % in Limpopo to 26.7 % in the Western Cape),
- White: 9.6 % (19.9 % in Gauteng; 2.4 % in Limpopo),
- Coloured: 8.9 % (53.9 % in the Western Cape; 0.2 % in Limpopo),
- Indian / Asian: 2.5 % (8.5 % in KwaZulu-Natal; 0.2 % in Limpopo).

By home language, 23.8 % speak isiZulu, 17.6 % isiXhosa, 13.3 % Afrikaans, 9.4 % Sepedi, 8.2 % English, 8.2 % Setswana, 7.9 % Sesotho, 4.4 % Xitsonga, 2.7 % Siswati, 2.3 % Tshivenda, 1.6 % IsiNdebele and the remainder other home languages. The overall population density in South Africa is 37.6 inhabitants / km^2 (**Table 1.2.1**). This, however, varies from 520 / km^2 in the highly urbanised Gauteng to only 2.3 / km^2 in the largely semi-arid Northern Cape, with the province with the second highest population density being KwaZulu-Natal at 102 / km^2.

The RSA’s Socio-Economic Milieu 2: Educational Indicators

Up to 2001 nearly 18 % of the RSA’s population had received no schooling, a percentage which is nearly doubled at 33.4 % in Limpopo, while in the Western Cape it is only 5.7 % (**Table 1.2.1**). The incidence of no formal schooling whatsoever was highest amongst Black Africans (22.3 %), followed by Coloureds (8.3 %), Indians / Asians (5.3 %) and Whites (1.4 %).

Overall, 22.4 % of the population had by 2001 received only some or complete primary schooling (as low as 16.7 % in Gauteng and over 29 % in the Free State and Northern Cape). The percentage having received some / complete secondary education stood at 51.2 % for the country, but only at 40.1 % in Limpopo and around 60 % in the two “most highly educated” provinces of the Western Cape and Gauteng. These last named two provinces also contained the highest percentages of population with some form of higher / tertiary education (Western Cape 11.2 %; Gauteng 12.6 %) which, overall, only 8.4 % of the RSA’s inhabitants had experienced. Post-matriculation education had been enjoyed largely by Whites (29.8 %) and Indians / Asians (14.9 %) and, up to 2001, less so by Coloureds (4.9 %) and Black Africans (5.2 %).

The RSA’s Socio-Economic Milieu 3: Levels of Employment

A key socio-economic indicator is the level of employment which, according to the 2001 population census, stood at 41.6 % for the RSA as a whole, but varied by more than a factor of two from a low of 26.1 % in the Western Cape to a high of 54.6 % in the Eastern Cape (**Table 1.2.2**). It is mainly Black Africans who suffer from unemployment (50.2 %), followed by Coloureds (27.0 %), Indians / Asians (16.9 %) and Whites (6.3 %).

Table 1.2.2 Socio-economic indicators in the RSA, by province (Source: Statistics SA, 2003)

Province / Country	Unemployment (%) of 15 - 65 Year Olds	Dwelling Types		
		Traditional	Informal	Formal
Limpopo	48.8	19.7	6.6	70.7
Mpumalanga	41.1	12.9	16.0	67.3
North-West	43.8	5.3	22.3	68.6
Northern Cape	33.4	3.5	12.5	80.2
Gauteng	36.4	1.3	23.9	65.6
Free State	43.0	7.2	26.1	62.9
KwaZulu-Natal	48.7	27.9	10.8	56.6
Eastern Cape	54.6	38.1	11.0	47.3
Western Cape	26.1	2.2	16.2	78.4
RSA	41.6	14.8	16.4	63.8

The main employment sectors in the RSA in 2001 were

- Services (community, social, personal) 29.1 %
- Trade 15.2 %

• Manufacturing	12.6 %
• Agriculture	10.0 %
• Finance	9.4 %
• Construction	5.4 %
• Transport	4.6 %
• Mining	4.0 %

The RSA's Socio-Economic Milieu 4: Types of Dwelling

In regard to dwelling types (**Table 1.2.2**), only 1.3 % and 2.2 % would have been constructed with traditional materials in the highly urbanised Gauteng and the Western Cape, respectively, while in 2001 some 38 % of households in the Eastern Cape and 27 % in KwaZulu-Natal were still housed in traditional dwellings. A high proportion - over 20 % - of dwellings in the Free State, Gauteng and North West province were of the informal (shack) type in 2001, with formal housing making up over 70 % of dwellings only in Limpopo and the Western Cape.

The RSA's Socio-Economic Milieu 5: Water Supply to Households

By 2001, ~ 61 % of households had water piped to at least the yard, if not into the dwelling, but this ranged from over 80 % in Gauteng and the Northern and Western Cape provinces to below 40 % in Limpopo and the Eastern Cape (**Table 1.2.3**). Alternatives to that are piped water to a community stand (usually within 200 m of the dwelling), or water from boreholes (still relatively important in the North West and Limpopo provinces) or springs (still relatively important in the Eastern Cape). It nevertheless is disturbing that a significant percentage of households in the Eastern Cape (23 %) and KwaZulu-Natal (~ 13 %) were, in 2001, still reliant on rivers and streams as their sources of domestic water supply.

Table 1.2.3 Main supply of water to households in the RSA, by province (Source: Statistics SA, 2003)

Province / Country	Piped Water to Yard (%)	Piped Water to Community Stand (%)	Borehole (%)	Spring (%)	River / Stream (%)
Limpopo	38.4	39.6	5.4	2.2	6.3
Mpumalanga	59.2	27.5	3.3	0.9	3.0
North West	52.7	33.4	6.1	0.3	0.5
Northern Cape	81.7	14.9	0.6	0.0	1.0
Gauteng	83.6	13.9	0.2	0.0	0.1
Free State	70.6	25.1	0.6	0.2	0.1
KwaZulu-Natal	49.5	23.7	4.2	3.4	12.9
Eastern Cape	37.0	25.4	1.7	6.7	23.0
Western Cape	85.2	13.1	0.1	0.0	0.2
RSA	61.3	23.2	2.4	1.9	6.7

Concluding Thoughts

Vast disparities exist between the nine provinces of South Africa with respect to population densities, educational indicators as well as those related to the socio-economic well-being of South Africa's peoples. While history, past and current social engineering as well as the discoveries of mineral resources have all shaped the societal and economic geography of South Africa, significant role players are also the climate and, associated with that, the availability of water. These and other aspects of the biophysical environment are examined in regard to potential impacts of climate change on South Africa's water sector in subsequent sections of this Report, but are preceded in **Chapter 1.3** by some background on nomenclature and terminology.

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CHAPTER 1.3

CLIMATE CHANGE AND THE
SOUTH AFRICAN WATER SECTOR: TERMINOLOGY

R.E. Schulze

By way of further introduction and background, users will be taken through some important concepts that are central to the theme of this Report, including the key words and phrases making up the title of the Report, as well as terminology and notations used.

Climate Change and the Water Sector: Some Definitions of Weather, Climate, Climate Variability and Climate Change

At the outset it is important that a distinction be made between the terms weather and climate.

- ***Weather*** is the sum total of prevailing atmospheric variables at a given place and at any instant or brief period of time. Weather is an everyday experience - one talks of “today’s weather” (Trewartha and Horn, 1980). Weather is made up of real phenomena, which we can observe and experience with our senses and which we can, in part, measure with accuracy. Such weather phenomena include heat, warmth, humidity, wind movement, lightning, rainbows, fog, clouds, rain, snow or hail (Brauner, 2002).
- ***Climate***, on the other hand, refers to a more enduring regime of the atmosphere and it represents a composite of day-to-day weather conditions and atmospheric elements within a specified place or region and over a long period of time. It is, however, more than just “average weather”, for it also includes the dynamic and intricate variations occurring diurnally (i.e. day vs. night), daily, monthly, seasonally and annually and in addition includes evaluations of extreme events and the variability about the norm (Kendrew, 1949). *Climate* consists of figures. For that reason climate *per se* can neither be “experienced”, nor is it measurable in the true sense of the word. Climate is, therefore, a “mathematical artefact, which does not occur in reality” (Steht and von Storch, 1999).

The concept of variability of climate has already been alluded to above. As an important factor in its own right, but especially in regard to its significance within the context of climate change, the concept is elaborated upon below as a prelude to defining climate change *per se*.

- ***Climate Variability*** signifies any deviation from the long-term expected value. It is an entirely natural phenomenon, is *reversible* and *non-permanent*. An example would be the droughts in southern Africa which are associated with the El Niño - Southern Ocean phenomenon. Climate variability has time scales which can range from
    - diurnal (within the course of a day, e.g. time of occurrence of convective thunderstorms), to
    - daily (i.e. variations from one day to the next) to
    - intra-seasonal (e.g. the variability of a specific month’s values from one year to the next), to
    - inter-annual (e.g. year-to-year variability) and
    - decadal (e.g. consecutive wet years or dry years).
- ***Climate Change***, on the other hand, is *irreversible* and *permanent*, where a trend over time (either positive or negative) is superimposed over naturally occurring variability. The most common cited contemporary example of climate change is anthropogenically forced global warming, and the associated trends in increased temperature which result from the enhanced greenhouse effect through increased atmospheric emissions of greenhouse gases. The time scale of this climate change is decades to centuries and the trend is more likely to occur in steps than linearly over time.

A key feature of climate change is that while there are projected changes in *means* of climatic variable over time, it is at the outer ends of distributions of variables, when critical thresholds are exceeded and extremes are experienced (in the case of rainfall when either floods or droughts beyond a tolerable limit occur), that the frequencies of the changes become manifestly more significant than the changes in means, as is illustrated in **Figure 1.3.1**.

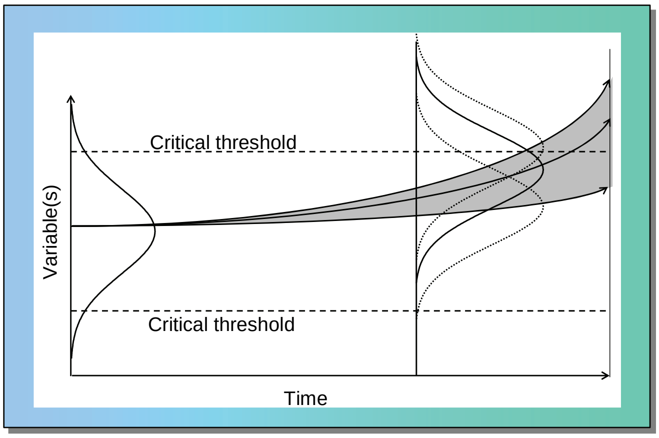

Figure 1.3.1 Schematic illustrating how frequencies in extremes become more significant over time when the means of a variable change over time (After IPCC, 2001)

Runoff Related Definitions

1. Catchment

A catchment is a topographically defined basin, or watershed area, which collects water and drains it at an exit. In this Report, the term also frequently refers to a fifth level so-called Quinary Catchment as defined and delineated by the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal (cf. **Chapter 2.2**). There are 5 838 hydrologically cascading, interlinked Quinary Catchments in the RSA, Lesotho and Swaziland. In results that follow, the runoff responses can either assume the Quinary Catchments to be individual spatial entities from which a response is computed, or the hydrological response can be accumulated, i.e. the streamflow generated within a Quinary Catchment is added to that of downstream catchments, and any runoff from upstream catchments is taken into account when a given catchment's runoff is calculated.

2. Runoff

Runoff, in the context of this Report, is water generated from a topographically defined catchment and which flows in defined channels. It consists of stormflows plus baseflows. In this Report the term streamflow is *not* used synonymously with runoff (see definition below).

In an operational catchment, runoff includes any seepage, environmental flow releases and overflows from the reservoirs in a catchment, if they are present - which is not the case in any of the simulations in this Report in which baseline catchment conditions are assumed.

3. Stormflow

Stormflow is the component of runoff generated at or near the surface within the catchment from a specific rainfall event. Part of that stormflow has a rapid (or quickflow) response, with runoff occurring on the same day as the rainfall; the remainder is made up of delayed stormflows from near-surface lateral flows. The fraction of rapid stormflow response is related inversely to catchment size (the bigger the area, the less the same-day stormflow), vegetation density and the soil's infiltrability, while it responds directly with the degree of urbanisation (the more the urbanisation, the higher the same day response) and catchment slope.

It is largely from stormflow events that, for example, reservoirs are filled and peak discharges for selected return periods are computed, while the detachment process in sediment yield generation from a catchment is highly correlated to stormflow volume from an individual event.

4. Baseflow

Baseflow is of the contribution to runoff from previous rainfall events where rainfall has percolated through the soil horizons into the vadose and groundwater zones and then contributes as very slow delayed flow to streams whose channels are "connected" to the groundwater.

Baseflows, by constituting the "dry weather" flows which are significant in sustaining flows into the non-rainy seasons, are important for ecological flows and also have different water chemistries to those of stormflows.

5. Streamflow

Streamflow, within the context of this Report and the *ACRU* model which was used in the simulations of hydrological responses, is the term given to the runoff generated from the catchment / sub-catchment under consideration, plus the runoff from all upstream subcatchments, i.e. it is the integrated flow of the entire upstream area.

Methods of Spatial Analysis Used in this Report

This Report contains maps as well as descriptive background text and scientific sections. Since the Report is comprised of thematic maps developed from specialised methods of spatial analyses, these are described briefly below.

1. Quinary Catchments Database (QnCDB)

The Quinary Catchments Database (QnCDB), described in detail in **Chapter 2.2**, consists of a single relational data repository for the 5 838 interlinked Quinary Catchments (QnCs) in the RSA, Lesotho and Swaziland which cascade streamflows downstream to either discharge into the ocean or into neighbouring countries. Each QnC in the QnCDB is populated with soils and baseline land cover information (**Chapter 2.2**) as well as being linked to daily temperature, rainfall, solar radiation and crop evapotranspiration data files for

- the historical (or baseline) climate period from 1950 - 1999 (Lynch, 2004; Schulze and Maharaj, 2004), and for
- three climate scenarios, *viz*. the
  - present (1971 - 1990)
  - intermediate future (2046 - 2065) and
  - more distant future (2081 - 2100)

  derived from projections of five Global Climate Models, i.e. GCMs (**Chapter 2.2**).

The QnCDB operates with the daily time step physical - conceptual and multi-purpose *ACRU* agrohydrological model (Schulze, 1995 and updates).

2. The 1' x 1' Latitude by Longitude Raster (Grid)

The basis of much of the climatic mapping over South Africa at Quinary Catchments level is a 1 arc minute of a degree latitude x longitude (~1.7 km x 1.7 km) raster, or grid, of altitudes. All *monthly* rainfall and *daily* temperature derived parameters were determined from the 1' x 1' raster, of which there are 422 591 points covering the RSA, Lesotho and Swaziland.

Statistical Terminology Used

1. Means and Medians

Many evaluations on hydrological responses are based on *median* values, i.e. the middle value in a distribution and thus the 50th percentile, with half the values higher and half lower than that value. *Means*, on the other hand, being the average of all values in a distribution, are highly influenced by extreme events and outliers in a non-normally distributed series, as is the case with rainfall or streamflow. Means in a rainfall sequence have a fixed minimum value (of zero), but no fixed upper values. Because the median may be viewed as an "expected" value which is not skewed by extremes and outliers (as means are), it is frequently the preferred statistic of the two.

2. "Dry" and "Wet" Years; "Low" and "High" Yields

In this Report "dry" years are represented by the 10th percentile of a distribution, i.e. the "driest" year in 10 years. Conversely, "wet" years are represented by the 90th percentile, i.e. the "wettest" year in 10. Note that unlike means, monthly values at a specified percentile *cannot* be added to give the annual percentile value, as individual distributions for each month and for annual totals are computed independently.

3. Standard Deviation

The standard deviation is an absolute measure of dispersion of values about the mean, irrespective of whether the mean is high or low, and is given in the original units of the observed value as

$$s_x = \sqrt{V_x}$$

where V_x is the *variance* about the mean, defined as a measure of dispersion relative to the scatter of the values about their mean, and for observed values x is defined by

$$V_x{}^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2$$

4. *Coefficient of Variation*

The coefficient of variation, CV(%) is a relative measure of dispersion, as it facilitates relative comparisons of variability in that it takes account of the magnitude of the mean and is independent of the original unit of measure in being expressed as a percentage. It is expressed, for example for observed values x, as

$$z_x = \frac{s_x}{\bar{x}}$$

In the chapters which follow the coefficient of variation is abbreviated as CV(%) rather than as z_x.

5. *Skewness Coefficient*

The *skewness coefficient* measures the symmetry of the data. A skewness of 0 indicates that the data / simulated values are distributed symmetrically. Positive values indicate that the upper tail of the distribution curve is longer than the lower tail and a negative value of skewness indicates that the lower tail is longer. The usual definition, for example for observed values x, is

$$g_x = \frac{n}{s_x^3(n-1)(n-2)}\sum_{i=1}^{n}(x_i - \bar{x})^3$$

Some Symbols, Abbreviations, Terms and Notations

- Symbols
  > : greater than ≥ : greater than or equal to
  < : less than ≤ : less than or equal to
  ~ : approximately
- Commonly Used Abbreviations
  E : Total evaporation (mm)
  E_r : Reference crop evapotranspiration (mm)
  GCM : General Circulation Model
  MAP : Mean annual precipitation (mm)
  MAT : Mean annual temperature (°C)
  T_{mx}, T_{mn} : Monthly means of daily maximum and minimum temperatures (°C)
  T_{mxd}, T_{mnd} : Values of daily maximum and minimum temperatures (°C).
- Interchangeable Terms
  Rainfall and *Precipitation* are used interchangeably, but imply the rainfall component of precipitation (excluding snow, fog, dew or hail).
  General Circulation Model and *Global Climate Model* are used interchangeably in this Report
- Notation of Rates, e.g.
  Millimeter per annum : mm/a (rather than mm.a^{-1})
- Spatial / Temporal Terms
  Inter- : between, e.g. inter-annual variability denotes variability between one year and the next
  Intra- : within, e.g. intra-seasonal differences are differences within a season, i.e. from one month to the next.
  South Africa : In the context of this Report, South Africa includes the Republic of South Africa plus Lesotho and Swaziland. Where only the Republic of South Africa is implied, this is abbreviated as the RSA.

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SECTION 2

DOWNSCALING, DATABASES AND MODELS

CHAPTER 2.1

GENERAL CIRCULATION MODELS AND DOWNSCALING FOR SOUTH AFRICAN CLIMATE CHANGE IMPACTS STUDIES:
A 2011 PERSPECTIVE

R.E. Schulze, D.M. Knoesen, R.P. Kunz and T.G. Lumsden

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 often fail to characterise the impacts at a more local scale (Bergant *et al*. 2006). However, water (as well as other) managers require information to be at the more local scale in order to assess local vulnerabilities to potential climate change and explore local adaptation options. Therefore, climate change impact 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).

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 gasses 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, and 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 “storylines” (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

Uncertainties inherent in GCMs have been well documented (UKCIP, 2003; Cox and Stephenson, 2007; Giorgi *et al*., 2008; Jacob van den Hurk, 2009; Schulze, 2009). 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, which poses problems in many parts of the world, including most of southern Africa, where convective rainfall is a dominant form of precipitation;
- Difficulty in simulating the intensity, frequency and distribution of extreme rainfall (IPCC, 2007);
- Tending to simulate too many light rainfall events (< 2 mm.day^{-1}) and generally too few heavy rainfall events (> 10 mm.day^{-1}), whilst maintaining a fairly realistic mean precipitation (IPCC, 2007);

- Poorly representing major drivers of climate variability, such as the El Niño - Southern Oscillation phenomenon (Hulme *et al*., 2001), which is associated with a broad band of variability throughout southern Africa (Tyson, 1996); and
- Poorly accounting for climatological variables which represent other atmospheric conditions that lead to high magnitude precipitation and flood-producing events.

These factors tend to reduce the accuracy of precipitation output from GCMs. Additionally, global mean temperatures can be quite unrepresentative at the local scale (Jacob and van den Hurk, 2009) and so, therefore, can any subsequent estimations of potential evaporation. Therefore, there remain questions surrounding the usability of direct GCM output in detailed 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 impact 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 and local adaptation options need to be considered (Schulze, 2009). It is due to this discontinuity that GCM output needs to be translated from the coarse to more local scales by the process of regional climate downscaling (Hewitson *et al*., 2005a; Giorgi *et al*., 2008).

Approaches to Regional Climate Downscaling

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

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 GCM is then used to define the boundary conditions for the RCM, 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 GCM 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. Empirical / Statistical Downscaling

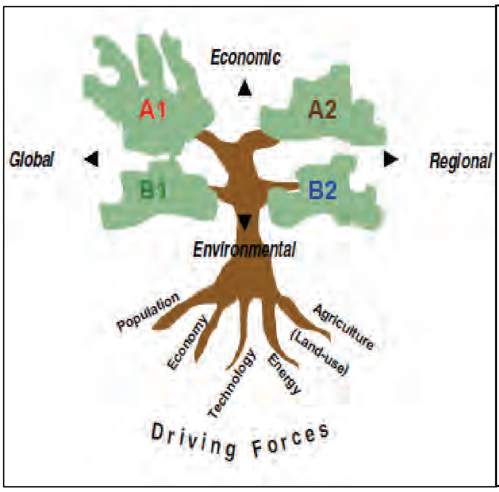
Empirical / statistical downscaling represents an empirical equivalent of the RCM. Whereas the RCM uses the GCM fields to provide input to numerical representation of the physics of the climate system dynamics, empirical downscaling seeks to do the same using empirical formulations derived from observational 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 for, say, 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).

Representation of Regional Climate Change Scenarios for Hydrological and Other Impacts Assessments at the Quinary Spatial Scale in South Africa

Daily climate values from climate change scenarios produced for application at national and more local level impact assessments were obtained from the Climate Systems Analysis Group (CSAG) at the University of Cape Town. These scenarios were made available in point format and included daily rainfall as well as daily maximum and minimum temperatures. In order to apply these values from the climate scenarios in hydrological impacts assessments, techniques had to be developed to represent the scenarios at the scale of catchments, rather than at point scales. The development of these techniques is described in this Chapter. As was the case for the development of the Quinary Catchments Database (QnCDB; cf. **Chapter 2.2**), the representation of the local climate change scenarios was achieved in collaboration with researchers working on WRC Project K5/1562 (Schulze *et al*., 2010), because these scenarios also formed a significant component of that project. What follows below therefore represents a summary of the abovementioned WRC Project final report's Chapter 9 by Lumsden *et al*. (2010).

Description of Climate Change Scenarios

The climate change scenarios developed by CSAG for application in this project were derived from global scenarios produced by five GCMs, all of which were applied in the IPCC's (2007) Fourth Assessment Report (AR4). Details of the five GCMs used in this study are provided in **Table 2.1.1**. All of the future global climate scenarios that were downscaled by CSAG to point scale for use in this Report were based on the A2 emissions scenario (cf. **Figure 2.1.1**) defined by the IPCC SRES (Nakićenović *et al*., 2000).



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 dematerialization and introduction of clean technologies
B2	A world of emphasis on local solutions to economic and environmental sustainability

Figure 2.1.1 SRES scenario storylines considered by the IPCC (After Nakićenović *et al*., 2000; graphic from IPCC-TGICA, 2007)

The point scale climate change scenarios were generated by empirically downscaling (cf. above) the GCM simulation output. The points at which scenarios were produced were the locations of the climate stations used in the empirical downscaling process. Scenarios of daily rainfall were produced at 2 642 southern African stations (**Figure 2.1.2**; cf. **Box 2.1.1**), while daily maximum and minimum temperature scenarios were produced at 440 and 427 stations, respectively (**Figure 2.1.3**; cf. **Box 2.1.2**). The lack of climate stations over Lesotho and Swaziland is of concern in climate change studies, but this reflects the reality of the relatively sparse observation networks of high quality, long duration and readily available data in those countries (Lumsden *et al*., 2010).

Regional climate change scenarios were developed for "present", "intermediate future" and "more distant future" climates represented by the following time periods, the latter two of which were defined by the IPCC:

- present climate: **1971 - 1990** (from a possible 1961 - 2000),
- intermediate future climate: **2046 - 2065**, and
- more distant future climate: **2081 - 2100**.

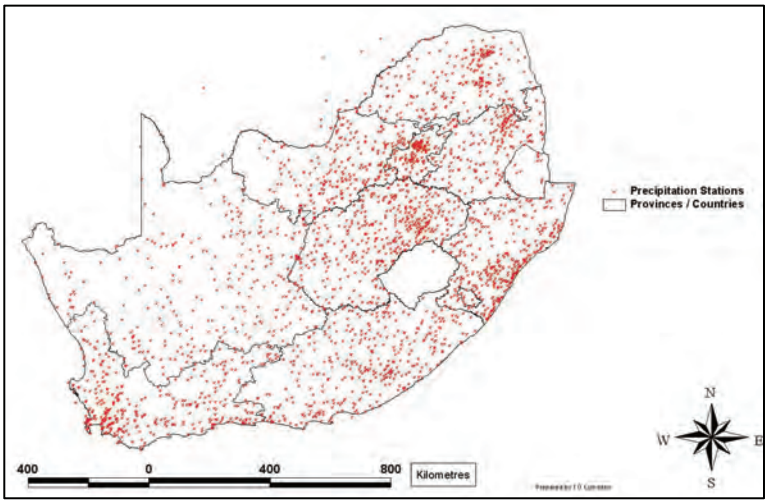


Figure 2.1.2 Climate stations for which point scale climate change scenarios for daily rainfall were developed (Lumsden *et al*., 2010; based on information from CSAG)

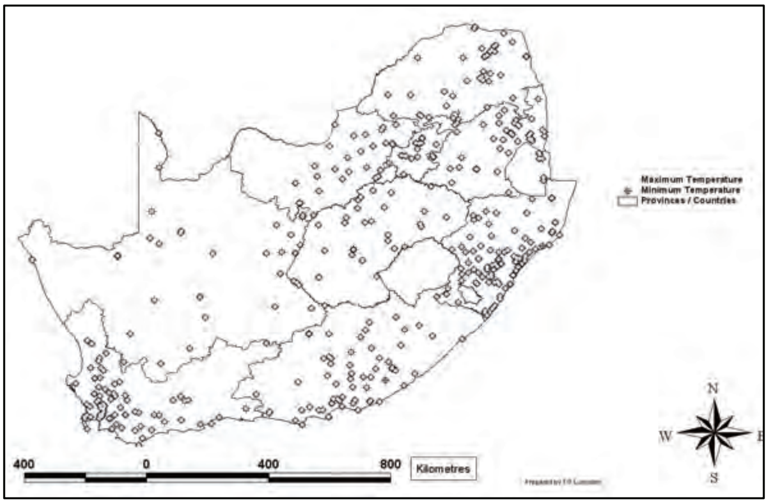


Figure 2.1.3 Climate stations for which point scale climate change scenarios for daily temperature were developed (Lumsden *et al*., 2010; based on information from CSAG)

Table 2.1.1 Information on GCMs, the global climate change scenarios of which were empirically downscaled by CSAG to point scale for application in this project

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

Box 2.1.1 Methodology Used to Represent Point Scale Scenarios of Rainfall at the Scale of Quinary Catchments (Adapted from Lumsden *et al*., 2010)

The representation of the point scale scenarios of rainfall at the scale of Quinaries was achieved using the same "driver" station approach adopted for baseline historical conditions (cf. **Chapter 2.2**). The number of driver stations previously selected for baseline conditions and for which data on future rainfall scenarios were also available, was determined to be 1 023 (from the set of 2 642 possible stations). These driver stations were used to represent future climatic conditions in their associated Quinary Catchments, which numbered 4 863 (Lumsden *et al*., 2010). Therefore, alternative driver stations for the remaining 975 Quinary Catchments (out of the total of 5 838), and for which future rainfall scenarios were available, needed to be selected. The criteria used to re-select these driver stations were (Lumsden *et al*., 2010):

- 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, and
- Reliability of the observed record.

Driver stations were assigned to 687 of the above 975 Quinary Catchments, where those stations already served as driver stations for other catchments. The number of driver stations concerned numbered 134. To the remaining 288 Quinary Catchments, stations were assigned that had not previously been used as driver stations. This resulted in 38 new driver stations being selected, bringing the total number of rainfall driver stations used in assessing future rainfall impacts to 1 061 (Lumsden *et al*., 2010).

As was the case for the baseline historical climate (cf. **Chapter 2.2**), 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. This resulted in the development of a unique representative rainfall record for each Quinary Catchment.

This was based on the assumption that the monthly adjustment factors calculated for the baseline historical climate (cf. **Chapter 2.2**) would also be applicable under the GCM derived climates considered (present, intermediate future and distant future). This assumption was made in the absence of fine resolution (e.g. one arc minute) national grids of median monthly rainfall for these new climate periods, which would ideally have been required if adjustment factors specific to the periods were to have been calculated. In the calculation of the adjustment factors for the baseline historical climate, limits were placed on the magnitude of the adjustment factors to prevent unrealistic adjustments being made to the driver station data. These limits ensured that adjustment factors fell between 0.5 and 2.0. These limits were relaxed relative to previous studies (e.g. Schulze *et al*., 2005; Schulze, 2008) where the factors were constrained to being between 0.7 and 1.3. The relaxed adjustments were deemed necessary because of the finer scale of modelling performed in this study (Quinary Catchments) relative to previous studies (Quaternary Catchments). Quaternary Catchment driver stations are now assumed to drive their component Quinary Catchments, which are often distinctly different from one another in their topographic characteristics (Lumsden *et al*., 2010).

Box 2.1.2 Methodology Used to Represent Point Scale Scenarios of Temperature at the Scale of Quinary Catchments (Adapted from Lumsden *et al*., 2010)

An examination of the climate stations for which scenarios of temperature change were obtained from CSAG yielded 425 stations that had both maximum and minimum temperature data sets. Of these 425 stations, 21 had immediately adjacent 'twin' stations with identical geographical coordinates (i.e. the same station, but reporting to two different data agencies). Since only one station at a particular location could be considered for application in hydrological modelling, the quality of the historical (observed) records of the 42 (21 x 2) implicated stations were analysed to identify the 'better' station of the two at each location. This resulted in 404 unique stations being identified for representation of maximum and minimum temperatures in the 5 838 Quinary Catchments across the RSA, Lesotho and Swaziland (Lumsden *et al*., 2010).

Box 2.1.2 Methodology Used to Represent Point Scale Scenarios of Temperature at the Scale of Quinary Catchments (Adapted from Lumsden *et al*., 2010) (continued)

The methodology adopted to represent maximum and minimum temperatures at Quinary Catchment scale involved selecting the two most representative stations for each Quinary Catchment, and obtaining a daily weighted average of their data. The two stations' data were simultaneously adjusted to account for differences between the stations' altitudes and that of the respective Quinary. This was done using the adiabatic temperature lapse rates (i.e. the rate of change of temperature with altitude) which had been determined for each month of the year, and separately for maximum and minimum temperatures, by Schulze and Maharaj (2004) for 12 defined lapse rate regions in southern Africa (Schulze, 1997). Only temperature stations falling within the specific lapse rate region relevant to a particular Quinary Catchment were considered for representation of temperature in that catchment. In certain lapse rate regions, some stations were excluded from consideration based on altitude related criteria (Lumsden *et al*., 2010). Modifications were made to the algorithm developed by Schulze and Maharaj (2004) for selecting target stations for infilling of missing data at representative control stations, and these modifications are described in detail in Lumsden *et al*. (2010).

Once the two 'best' temperature stations to represent a Quinary Catchment had been identified, the data from these stations were then assigned a weighted average in order to obtain the final temperature record for the catchment. As mentioned previously, adiabatic temperature lapse rates were also simultaneously applied to each station's data (Lumsden *et al*., 2010).

Checks identical to the ones done on historical data by Schulze and Maharaj (2004) were performed on the daily maximum (T_{mxd}) and minimum (T_{mnd}) temperature values from the GCMs to ensure that they would comply with certain logical requirements and those of the *ACRU* hydrological model. These checks were performed both before and after any adjustments (i.e. lapse rate adjustments and weighted averaging) were applied to the downscaled GCM data and they included the following (Lumsden *et al*., 2010):

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

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

- $T_{mxd} < 0$ °C.

Where instances of the former two checks were found in the raw downscaled GCM values, the relevant days' temperature values were altered to comply with the requirements of *ACRU* (Schulze and Maharaj, 2004). Data were again checked after lapse rate adjustments and weighted averaging had been completed and, if necessary, altered to ensure compliance with the *ACRU* model input requirements. Where instances of the last check were found, i.e. $T_{mxd} < 0$ °C, no alterations to the maximum temperatures were made (before or after lapse rate adjustments and weighted averaging), but these instances were flagged for future reference. Examples of the data checks before and after lapse rate adjustments and weighted averaging are detailed in Lumsden *et al*. (2010).

- All the scenarios included a daily time series of rainfall for each climate period. In analyses carried out in this project, only 20 of the 40 years of the "present" climate values were used in comparative studies with the intermediate and distant future climates in order to consider an equal number of years in all periods. 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 GCM's present climate and intermediate future climate, relative to the shorter interval (35 years) between the intermediate future climate and the more distant future climate. 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.

A Note of Caution on the GCMs Used in this Study

Overall changes in future scenarios of climate depend strongly on

- *which* GCMs were used, and
- *how many* GCMs were in the ensemble used.

The five GCMs which were available for use in this study, *viz*. CGCM3.1(T47), CNRM-CM3, ECHAM5/MPI-OM, GISS-ER and IPSL-CM4 are considered by climatologists to produce rainfall output possibly on the wet side of the spectrum (Hewitson, 2010. Personal communication), and this has to be borne in mind in interpreting any impacts in which rainfall is an input variable. Furthermore, an error in GISS GCM's rainfall values for parts of South Africa was reported halfway through the project and all statistics from multiple GCMs involving rainfall had to be re-calculated in order to eliminate the known error from that GCM. Simulations involving temperature derivatives only were, however, not affected. The impact of this rainfall error is evaluated in **Chapter 2.4** on GCM validation studies.

Approaches Adopted in This Study

1. The Link with the Quinary Catchments Database

In this study climatic and / or hydrologically related output is simulated for each of the 5 838 interlinked Quinary Catchments that make up the RSA, Lesotho and Swaziland, using information from the Quinary Catchments Database, QnCDB (Schulze and Horan, 2010; **Chapter 2.2**). The QnCDB 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.

In order to simulate hydrological attributes for the intermediate (2046 - 2065) and more distant (2081 - 2100) future climate scenarios, the downscaled daily rainfall and temperature values from the various GCMs are input into the *ACRU* models, whilst keeping each Quinary's soils and land cover information constant.

2. Assessments of Future Projections Using the Ratio Approach

In order to assess projected changes of the GCM-derived output between the intermediate future and present, or the more distant future and present, or the more distant and intermediate future climate scenarios, these changes were expressed as ratios. 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, where > 1 implies a projected increased impact in the variable being compared while a ratio < 1 implies a projected decrease in the comparison between future and present. Projections into the future are thus expressed as relative changes rather than as absolute changes. However, in order to gain an idea what the relative change could imply, maps of the corresponding baseline condition for the variable under study are also given. The baseline maps are derived from 50 years of historical daily climate values from the QnCDB used as input to the hydrological model. .

3. Case Studies Using Projections from a Single GCM

In some in this Report the results presented are derived from computations using downscaled daily climate output from a single emission scenario from a single GCM. The use of a single GCM projection - the limitations of which are well appreciated and documented (Hewitson *et al*., 2005b; IPCC, 2007; Schulze *et al*., 2007) - obviously fails to capture the range of possible futures projected by the use of multiple GCMs or the mean of a range of scenarios. As a consequence, a meaningful description of an expected median change cannot be achieved from those specific results, which were often used in the development of mapping and analytical techniques as well as to facilitate the interpretation of the resulting hydro-climatic hazard scenarios rather than on providing decision-makers with a range of possible futures. In these cases, of the five GCMs available for this study it was the ECHAM5/MPI-OM GCM that was selected, 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, as is also shown in the GCM validation chapter (**Chapter 2.4**).

4. Representing Confidence in Results 1: The Index of Concurrence Approach

There are many ways of expressing confidence in results being correct, conversely, of expressing uncertainty in the results. The IPCC has published an uncertainty guidance note (IPCC, 2007) that defines a framework for the treatment of uncertainties and where uncertainty is assessed quantitatively, the IPCC's scale of confidence levels, together with the appropriate terminology, is used, as shown in **Table 2.1.2**.

One method of expressing confidence / uncertainty is to pose a hypothesis related to projected change and then to assess how, for many of the GCMs used in a study, that specific hypothesis was met for each spatial unit, in this case the Quinary Catchment. **Table 2.1.3** shows how the IPCC scale was adapted for the hypothesis approach when used with the five GCMs available for this study, *viz*. CGCM3.1(T47), CNRM-CM3, ECHAM5/MPI-OM, GISS-ER and IPSL-CM4 (cf. **Table 2.3.1**). However, the more distant future scenario for the CGCM3.1(T47) GCM was unavailable and **Table 2.1.3** also illustrates how the confidence scale was applied when outputs from only four GCMs could be utilised, as was the case for the more distant future climate projections in this study.

Table 2.1.2 Scale of confidence levels for quantitative assessment of uncertainty as defined by the IPCC (IPCC, 2007)

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

Owing to the discrepancy in the number GCMs available for the intermediate and more distant future scenarios, i.e. respectively five and four, or when the GISS GCM is omitted four and three, 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.

Table 2.1.3 Scale of confidence levels for quantitative assessment of uncertainty when using the Index of Concurrence (Knoesen, 2011)

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	Only 1 out of the 5 GCMs gives same signal	Only 1 out of 4 GCMs gives same signal

5. Representing Confidence in Results 2: The Median of Ratios of Change

Median changes in ratios are computed from output from multiple GCMs, on the assumption that the median of the changes simulated from the various GCMs used in this study will be a better reflection of what might happen in future climates than results from just one or two GCMs. A second index of confidence used in this study was therefore to map the median of the ratios of change of an attribute between the intermediate to present climate scenarios from all GCMs used, and similarly between the more distant future and present. In the case of results derived from five GCMs, the third ranked ratio was mapped for each Quinary; however, when outputs from only four GCMs were available, the average of the second and third ranked ratios was mapped.

6. Representing Confidence in Results 3: The Index of Consistency of Change

The Index of Consistency of Change (ICC) is a composite statistic which, by weighting, combines

- the consistency of the *direction of change* for a specific indicator when the outputs from the five GCMs are compared (in the case of the intermediate future projection vs. present climate), or the output from four GCMs in the case of the more distant future, with

- an index of the *degree of dispersion* of the changes between the outputs of the five (or four) GCMs.

Of the many statistical measures of dispersion which were tested, the median absolute deviation (or MAD) and the average absolute deviation (AAD) proved useful and robust in quantifying the variability of the GCM ratios, with the absolute deviation of an element of a dataset being the absolute difference between that element and a measure of central tendency, in this instant the median to avoid problems caused by "outlier" ratios.

The ICC is defined as the product of the median absolute deviation and the average absolute deviation, expressed as a percentage, i.e.

$$ICC = 100 * (1 - MAD) * (1 - AAD)$$

where $MAD = \text{median}(|X_i - \text{median}|)$
$AAD = \text{average}(|X_i - \text{median}|)$ for $0.75 < (1 - AAD) < 1.00$

A third simple statistic was used to account for the direction of change derived from each GCM. If all GCM ratios are above (or equal to) unity (i.e. ≥ 1.0), or below unity (i.e. < 1.0), then the ICC value is not adjusted. However, if one GCM ratio is in the opposite direction, then the ICC is reduced by 0.75 to indicate that 3 of the 4 GCMs are in agreement with respect to direction of change. If two GCMs show an increase and two show a decrease, the ICC is reduced by 0.50 to indicate the GCMs are not in agreement and the direction of change cannot be determined.

On maps the ICC is shown as very high, high, moderate, low and very low.

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CHAPTER 2.2

THE SOUTH AFRICAN QUINARY CATCHMENTS DATABASE

R.E. Schulze, M.J.C. Horan, R.P. Kunz, T.G. Lumsden and D.M. Knoesen

The Concept of Quinary Catchments

The erstwhile South African Department of Water Affairs and Forestry (DWAF; now DWA - the Department of Water Affairs) delineated the RSA, together with Swaziland and Lesotho, into 22 Primary Catchments, which in turn have been disaggregated into Secondary, then Tertiary and finally, into 1 946 interlinked and hydrologically cascading Quaternary Catchments (QCs), as shown in **Figure 2.2.1**. This "fourth level" of discretisation has, to date, constituted the most detailed spatial level of operational catchment in the DWA for general planning purposes.

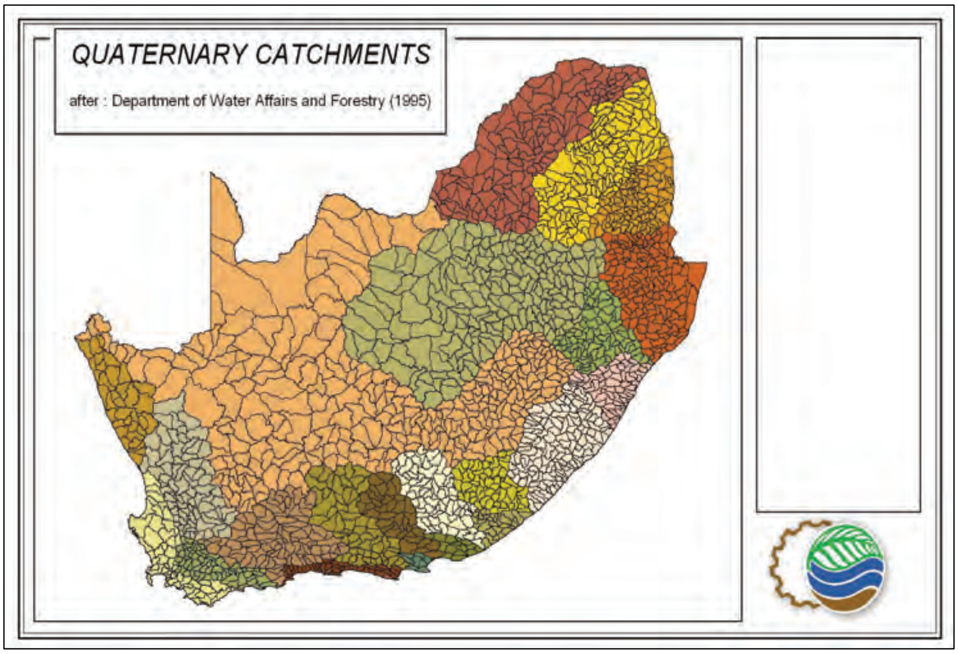

Figure 2.2.1 Primary and Quaternary catchments covering the RSA, Lesotho and Swaziland (After Midgley *et al*., 1994)

Schulze and Horan (2007; 2010) have shown that many fourth level Quaternary Catchments in southern Africa are physiographically too diverse for hydrological responses from them to be considered relatively homogeneous. By applying Jenks' optimisation procedures available within the ArcGIS software suite, a three-fold altitude break based sub-delineation of QCs into fifth level Quinary Catchments (the Upper, Middle and Lower Quinaries of a QC) has been carried out (**Figure 2.2.2**). These Quinary Catchments were then configured within the QC configuration, such that the outflow of the Upper Quinary enters the Middle, which in turn flows into the Lower Quinary. However, the Lower Quinary outflow of a QC does not enter the Upper Quinary of the next downstream Quaternary Catchment, because that QC's Upper Quinary may be at a higher altitude than the Lower Quinary of the immediate upstream Quaternary. Therefore, the outflow of the Lower Quinary has been configured to rather enter the downstream Quaternary at its exit (Schulze and Horan, 2010). A schematic of the flowpath configuration between Quinaries and Quaternaries, taken from the Upper Thukela Catchment, is given in **Figure 2.2.3**.

The sub-delineation of Quaternary into Quinary Catchments has resulted in 5 838 hydrologically interlinked and cascading Quinaries (**Figure 2.2.4**) covering the RSA, Lesotho and Swaziland. These have been demonstrated to be physiographically considerably more homogeneous than the Quaternaries (Schulze and Horan, 2007; 2010) and on a national and smaller scale are considered to be relatively homogeneous hydrological (as well as agricultural) response zones.

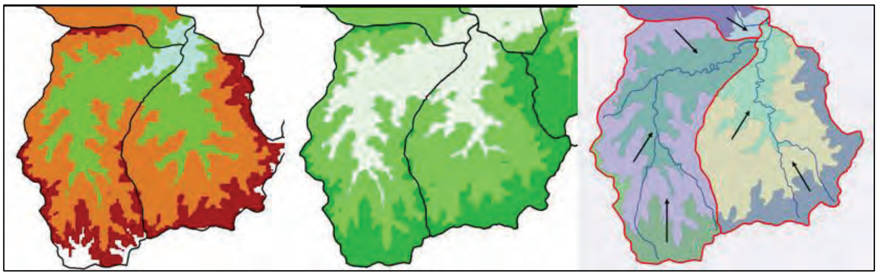

Figure 2.2.2 Sub-delineation of Quaternary Catchments from altitude (left) into three Quinaries by natural breaks (middle) with flow paths (right) of water (Schulze and Horan, 2010)

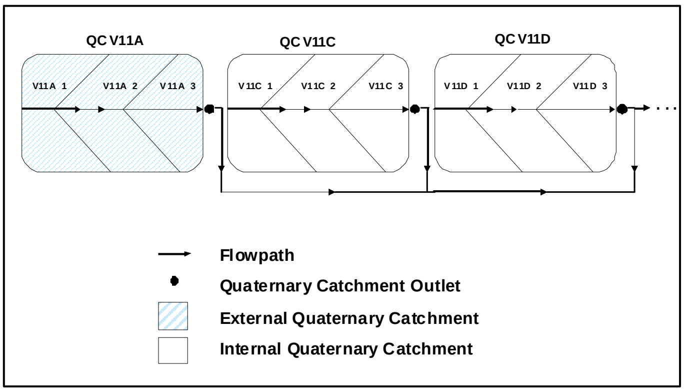

Figure 2.2.3 Flowpaths between Quinary and Quaternary Catchments, with the example taken from the Upper Thukela Catchment (Schulze and Horan, 2010)

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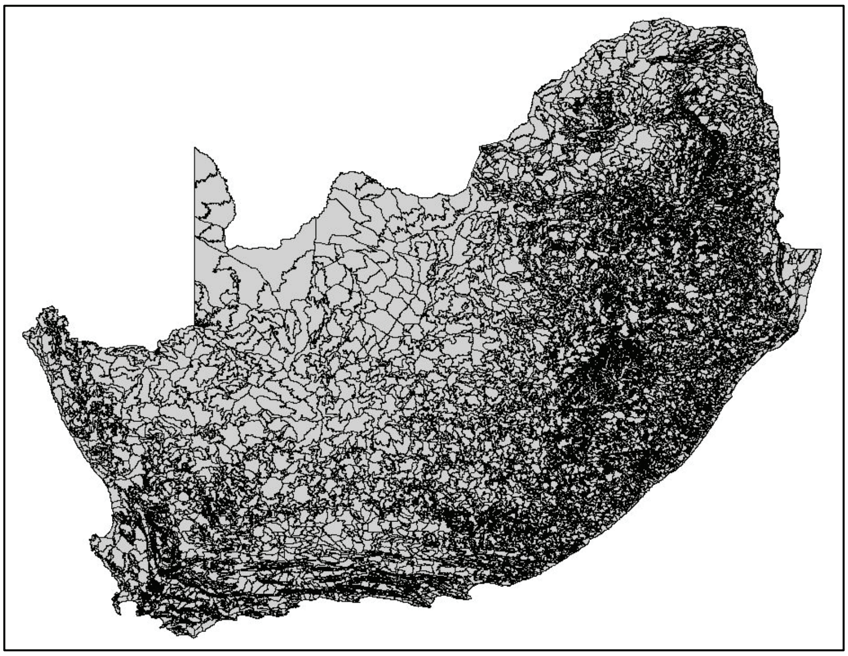

Figure 2.2.4 Delineation of the RSA, Lesotho and Swaziland into 5 838 hydrologically interlinked and cascading Quinary Catchments (Schulze and Horan, 2010)

From a Quaternary to Quinary Catchments Database

Following the delineation of the southern African countries of the RSA, Lesotho and Swaziland into hydrologically interlinked Quinary Catchments, the formerly used Quaternary Catchments Database (QCB; e.g. Schulze *et al*., 2005) needed to be expanded to form a new database, *viz*. the Southern

African Quinary Catchments Database (QnCDB). The expansion of the QCD to the newly created QnCDB was achieved in collaboration with researchers from another climate change impacts study (Schulze *et al*., 2010a) reported on more fully in Water Research Commission (WRC) Report No. 1562/1/10, as the QnCDB was a vital component of that project as well. The remainder of this Chapter consists of extracts of the above-mentioned WRC report's Chapter 7 (Schulze *et al*., 2010b)

A summary of the key climatic and catchment input into the QnCDB, and the link to the *ACRU* model is described below. The focus of the climatic input is primarily on baseline historical conditions. The preparation of climate inputs derived from climate change scenarios is discussed only briefly here, with greater detail being provided in **Chapter 2.1**.

Daily Rainfall Input per Quinary Catchment

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

1. *Estimations of Daily Rainfall Values for Simulations under Baseline Historical Climatic Conditions*

As reported in Schulze *et al.* (2010b), a comprehensive database (1950 - 2000) of quality controlled (and infilled where necessary) rainfall data consisting of > 300 million rainfall values from 12 153 daily rainfall stations in southern Africa was compiled by Lynch (2004). From that database, a rainfall station had to be selected for each of the 5 838 Quinary Catchments, with that station's data considered representative of the daily rainfall of that Quinary (Schulze *et al*., 2010b). This was accomplished by assigning the previously selected station representing the rainfall of the parent Quaternary Catchment to also represent the three Quinary Catchments within the Quaternary. The selection of the stations representing the Quaternary Catchments involved first determining the centroid of each of the Quaternary Catchments. The Daily Rainfall Extraction Utility (Kunz, 2004) was then used to extract the 10 closest rainfall stations to each catchment's centroid.

These 10 stations were ranked by the Kunz (2004) Utility using 10 reliability criteria, described in Schulze *et al*. (2005*)*, with the best ranked station being subjected to further manual evaluation. In total, 1 244 stations were selected, the daily rainfall values from which were to "drive" the hydrology of the 1 946 Quaternaries. 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 Quaternaries (Schulze *et al*., 2010b).

In response to further research during the course of this project, the representative (or "driver") station for 11 Quaternary Catchments was changed in order to improve the representation of rainfall in those catchments, resulting in the total number of driver stations reducing from 1 244 to 1 240. These 1 240 stations were then used to generate 50 years (1950 - 1999) of daily rainfall for each of the 5 838 Quinary Catchments based on the assumption made above, *viz*. that each Quaternary Catchment's driver station would also be used to represent the rainfall of the associated three Quinary Catchments (Schulze *et al*., 2010b), but with adjustments.

The selection of driver stations was followed by the determination of multiplicative month-by-month rainfall adjustment factors (from the one arc minute raster of median monthly rainfalls created by Lynch, 2004) for each Quinary Catchment and these were then applied to the driver station's daily records in order to render the driver station's daily rainfall to be more representative of that of the Quinary. This resulted in a unique 50 year daily rainfall record for each of the 5 838 Quinaries for application with the *ACRU* model. The monthly adjustment factors were derived by first calculating the spatial averages of all the one arc minute (~1.7 x 1.7 km) gridded median rainfall values for each month within a Quinary. The ratios of these catchment averages of median monthly rainfalls to the driver station's median monthly rainfalls were then calculated to arrive at 12 monthly adjustment factors (Schulze *et al*., 2010b).

2. *Estimations of Daily Rainfall Values for Simulations with GCM Derived Present and Future Climate Scenarios*

Procedures are described in detail in **Chapter 2.1**.

Daily Temperature Input per Quinary Catchment

Daily maximum and minimum temperature values facilitate estimations to be made, either implicitly or explicitly, of solar radiation, vapour pressure deficit and potential evaporation (Schulze, 2008). Using these variables, in addition to rainfall, as input into hydrological models such as *ACRU*, the generation of soil moisture content, runoff and / or irrigation demand becomes possible (Schulze *et al*., 2010b). A summary of the methodology for estimations of daily maximum and minimum temperature values, as described in detail by Schulze *et al.* (2010b) under baseline historical climatic conditions, is given below.

1. *Estimations of Daily Values of Maximum and Minimum Temperatures for Simulations under Baseline Historical Climatic Conditions*

Procedures outlined in detail by Schulze and Maharaj (2004) enable the generation of a 50 year historical time series (1950 - 1999) of daily maximum and minimum temperatures at any unmeasured location in the RSA, Lesotho and Swaziland at a spatial resolution of one arc minute of latitude / longitude (~1.7 x 1.7 km) for the 429 700 grid points covering the region. At each of these 429 700 grid points the maximum and minimum temperatures were computed for each day of the 50 year data period from two selected, independent temperature stations and by use of regional and monthly lapse rates (Schulze and Maharaj, 2004). At each grid point the daily values derived from these two stations were then averaged in order to modulate any biases (from lapse rates or station data) emanating from either of the two stations' generated records (Schulze *et al*., 2010b). Excellent verifications of results from this methodology were achieved (Schulze and Maharaj, 2004).

From the study of Schulze and Maharaj (2004) representative grid points were determined for each of the 5 838 Quinary Catchments covering the study area. The selection of the representative grid points was achieved by first calculating the mean altitude of each Quinary from a 200 m Digital Elevation Model. Grid points (preferably within the catchment) were then selected to represent each of the Quinary Catchments with the use of a selection algorithm based on distance between the selected grid point and the Quinary centroid, together with the difference in altitudes of the stations relative to the catchment mean altitude (Schulze *et al*., 2010b).

The resulting 50 year series of daily maximum and minimum temperatures for each Quinary Catchment was then used to generate daily estimates of solar radiation (Schulze and Chapman, 2008a) and vapour pressure deficit (Schulze and Chapman, 2008b), details of which are described in Schulze *et al.* (2010b). From these, daily values of reference potential evaporation as well as potential crop evapotranspiration could be computed, as described below.

2. *Estimations of Daily Values of Maximum and Minimum Temperatures for Simulations with GCM Derived Present and Future Climate Scenarios*

Procedures are described in detail in **Chapter 2.1**.

Estimations of Daily Values of Reference Crop Evapotranspiration 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. The various methods all yield different estimates under different climatic conditions, and a reference potential evaporation (E_r) therefore has to be selected as that evaporation against which other methods must be adjusted appropriately. In simulating the hydrological landscape with a vegetative cover and / or under irrigation, 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 evapotranspiration, replacing the A-Pan and other techniques (Schulze *et al*., 2010b).

1. *Estimations of Daily Values of Reference Crop Evapotranspiration for Simulations under Baseline Historical Climatic Conditions*

As reported in more detail by Schulze *et al.* (2010b), the estimates of the Penman-Monteith equation used in the Quinary Catchments Database are derived from daily maximum and minimum temperatures, and hence the equation's components such as daily solar radiation, daily saturated vapour pressures and vapour pressure deficits, are generated from daily temperatures over southern Africa on a 1' x 1' (~ 1.7 x 1.7 km) raster for 50 years, based on research by Schulze and Maharaj (2004).

The original form of the Penman-Monteith equation (Monteith, 1981) may be written as

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

where

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

Using the FAO (1992) adaptation of the above equation, reference crop evapotranspiration could be derived from daily maximum and minimum temperatures (Schulze and Maharaj, 2004), and empirical temperature based expressions from South African research on shortwave solar radiation (Schulze and Chapman, 2008a) and actual vapour pressure (Schulze and Chapman, 2008b). The details of the derivations are not repeated here as they are given in **Chapter 4.1** of this Report and also in Schulze *et al*. (2010b).

Using the various equations alluded to above, the 50 year daily maximum and minimum temperature series generated at each of 429 700 grid points over South Africa (Schulze and Maharaj, 2004) could then be used to estimate 50 years' daily reference crop evapotranspiration by the Penman-Monteith technique at each of those points. For baseline hydrological simulations with the Quinary Catchments database the same representative points that were selected for daily temperature estimates were used and the daily Penman-Monteith values at those points were then input into the database (Schulze *et al*., 2010b).

2. Estimations of Daily Values of Reference Crop Evapotranspiration for Simulations with GCM Derived Present and Future Climate Scenarios

The 20 year series of daily maximum and minimum temperatures generated for each of the three GCM derived climate scenarios (i.e. present, intermediate future and more distant future) for each of the GCMs used in this study (cf. **Chapter 2.1**) and for each Quinary Catchment, were used in combination with the temperature based equations and approaches described above to produce equivalent 20 year series of daily reference crop evapotranspiration (Schulze *et al*., 2010b).

Soils Information

As elaborated upon in **Chapter 2.3**, 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*., 2010b):

- thickness (m) of the topsoil and the subsoil;
- soil water contents (m/m) at
  - saturation (porosity),
  - drained upper limit (also commonly referred to as field capacity), and
  - permanent wilting point (i.e. the lower limit of soil water availability to plants);
- rates of saturated drainage from topsoil horizon into the subsoil, and from the subsoil horizon into the intermediate groundwater zone, and the
- erodibility of the soil (Schulze *et al*., 2010b).

Values of these variables have been derived by Schulze and Horan (2008) using the AUTOSOILS decision support tool (Pike and Schulze, 1995 and updates) applied to the soils database from the Institute for Soil, Climate and Water (SIRI, 1987 and updates) for each of the soil mapping units, called Land Types, which cover South Africa, on the basis that the hydrological properties of all the soil series making up an individual Land Type were area-weighted. For each Quinary Catchment the values of the hydrological soils variables required by the *ACRU* model were derived from the Land Types identified in that Quinary, again on an area-proportioned basis (Schulze *et al*., 2010b).

Baseline Land Cover Information

It is reported in Schulze *et al.* (2010b) 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. For the RSA, Lesotho and Swaziland the 70 Veld Types delineated by Acocks (1988) have become the recognised baseline (i.e. reference) land cover for application in hydrological impact studies (cf. Schulze, 2004).

Based on a set of working rules, month-by-month hydrological attributes, given in Schulze (2004), were assigned to each of the 70 Acocks Veld Types and were incorporated into the Quinary Catchments Database. These attributes are (Schulze *et al.*, 2010b):

- the water use coefficient (K_{cm}),
- interception loss per rainday (I_l),
- fraction of roots in the topsoil (R_A),
- a coefficient of infiltrability (*c*) dependent on rainfall intensity estimates, and
- soil surface cover by litter ($C_{s\%}$), an index of suppression of soil water evaporation by a litter / mulch layer.

For each of the 5 838 Quinaries in the database the spatially most dominant Veld Type was then selected as the representative baseline land cover (Schulze *et al*., 2010b).

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CHAPTER 2.3

THE HYDROLOGICAL MODEL USED IN CLIMATE CHANGE IMPACT STUDIES ON THE SOUTH AFRICAN WATER SECTOR

R.E. Schulze

The Significance of the Water Sector in Climate Change Studies (This Section has been adapted from Schulze, 2010)

The superpositioning of a potential “speeding up” and “energizing” of the hydrological cycle through climate change in an era when water management is already faced with many climate related challenges, does not simplify matters for decision makers in the water sector, particularly if one bears in mind the amplification effects of changes in rainfall attributes on hydrological responses and the vital links of water to the aquatic ecosystem, to other cycles (e.g. nitrogen, carbon) and other sectors (e.g. agriculture, transport, health or risk management). Appropriate hydrological models will become an increasingly important tool in addressing the consequences of many of these changes. The first question which presents itself is what is required, by way of process representations, of a suitable model for assessing impacts of climate change on the hydrological system (Schulze, 2005), secondly, once a model has been selected, what its attributes are and thirdly, how the major state variables and outputs which are relevant to modelling responses to projected future climates, are computed.

Model Requirements for Effective Climate Change Impact Studies on the Hydrological System (This Section has been adapted from Schulze, 2005; 2010)

1. What Makes Up the Hydrological System that We Need to Model?

From the above it becomes patently clear that modelling impacts of climate change on hydrological responses involves two “streams” of action, but which need to be merged (Schulze, 2005). This is illustrated in **Figure 2.3.1**. On the one hand,

- climate change demands an innovative approach to modelling *hydrological processes*, because perturbations in the drivers of these processes (e.g. ΔP, ΔT and ΔCO_2 and the feedbacks of the latter on transpiration) will result in changes in evaporative demand, changes in the partitioning of rainfall into the different runoff components (e.g. stormflow, baseflow) and, hence, changes in water quality (e.g. sediment yield).
- In essence these response changes occur on the *landscape component* of the catchment on which natural land cover and soils properties may already have been altered by human actions.
- Key climate change issues in regard to the landscape component include direct changes in responses of runoff processes to the altered climatic drivers, but also indirect changes, for example, to the hydrological baseline against which impacts are assessed, or to altered water quantity and quality responses resulting from spatial changes in land use patterns associated with new climates (Schulze, 2005).

On the other hand,

- *water resources practitioners and managers* have to grapple, now and in future climates, with balancing the supply of water (be it from rivers, groundwater, impoundments, return flows or water transfers) with the demand for water (e.g. from basic human and ecological needs to requirements for the urban / industry sectors, power and irrigation) and to allocate available water, now and under projected future climatic conditions, in a sustainable manner through holistic planning, i.e. Integrated Water Resources Management (IWRM).
- In most instances allocation of water involves manipulations of the *channel component* of the catchment through “controls” of storage (e.g. dams), releases (e.g. for urban, irrigation or environmental demands) and routing of water (e.g. for flood control or through inter-basin transfers).
- Key climate change related challenges in this instance generally revolve around engineering issues of changes in supply / demand, limits to the design of hydraulic structures in regard to system failure, as well as around environmental consequences of changes in natural flow regimes

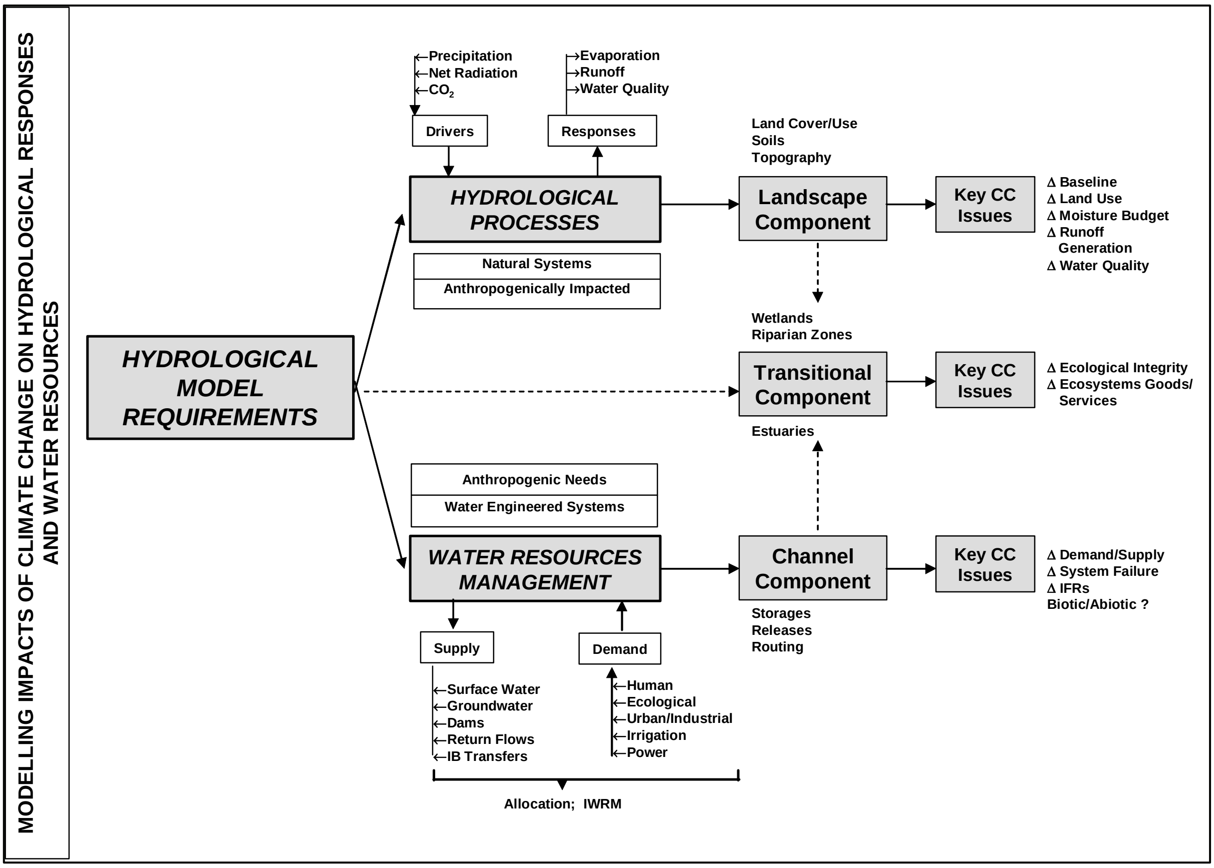

Figure 2.3.1 Hydrological model requirements under conditions of climate change (Schulze, 2005)

including in-stream flow requirements and other abiotic / biotic effects downstream (Schulze, 2005).

Wedged, in a manner of speaking, between the landscape and channel components are the

- *intermediate / transitional components* of the hydrological system, such as the wetlands, riparian zones and estuaries.
- These sensitive and often fragile ecosystems are frequently in delicate equilibria with the natural environment, and they may “flip” as a consequence of upstream landscape and channel manipulations. Under conditions of global warming these ecosystems may become even more fragile and / or sensitive.
- Key challenges in regard to wetlands, riparian zones and estuaries will need to be assessments of changes in their functioning and to the goods and services these ecosystems provide (Schulze, 2005).

For pro-active management all the above challenges have to be met explicitly or implicitly by appropriate hydrological modelling. Some model requirements are, therefore, listed and discussed below.

2. Requirements for Modelling Hydrological Processes

a. The need to be able to model explicitly the dynamics of different streamflow generation mechanisms

Streamflow is made up of various components which are generated by different mechanisms and are generated from different (and dynamic) source areas within a catchment, both of which may alter with climate change. The different streamflow components display different properties and hydrological functions (Schulze, 2005), with

- *overland flows*, which may be generated either from connected (adjunct) impervious areas, or from saturated zones of variable areas, or when rainfall intensities exceed infiltrability, and with these flows having short residence times of minutes to hours, being event-based, removing / transporting sediments and other surface material (e.g. fertilizers, pesticides, industrial pollutants) and being critical in peak discharge estimations as well as in water quality determinations; whereas

- *subsurface stormflows* having slower response times and displaying different water chemistries; and
- *baseflows*, which are sustained by recharge through the soil profile or from preferential zones within a catchment, having long memories, displaying slow decay, a different water chemistry again and having a different criticality in that they maintain different biological functions to those of stormflows.

The proportions of these components of streamflow will vary, *inter alia*, with changed attributes of rainfall patterns and antecedent catchment wetnesses associated with climate change (Schulze, 2005), as well as with altered land uses which are anticipated under future climates. Because of their variable residence times / lags, as well as their different origins within a catchment and their associated properties in regard to water quantity and quality, these streamflow components need to be *modelled explicitly* as *distinct individual components* (and not by empirical hydrograph separation) if certain key questions in their responses to climate change, and IWRM in general, are to be answered adequately.

b. The need to distinguish clearly between landscape based and channel based processes
Within morphologically similar landscapes, hydrological processes which occur down hillslopes tend to be *repetitive*, with the hillslope elements of the catchment being the generators of streamflow in its different forms.

- Catchment (as distinct from channel) processes under conditions of climate change need therefore to be modelled separately by *water budgeting* procedures, which are complex and may not always be fully understood (Schulze, 2005).
- Channel processes, on the other hand,
    - tend to be *additive* with catchment size,
    - are *attenuated* by channel characteristics of slope, shape and roughness as well as by transmission losses to floodplains, banks and alluvial beds and by open water evaporation,
    - may be *manipulated* (e.g. by abstractions, diversions and impoundments, **Figure 2.3.1**) and
    - need to be modelled *hydraulically*, with often complex equations describing relatively well understood relationships.

If catchment and channel processes, as well as those of transitional hydrological features (the riparian zones, wetlands and estuaries) are not separated explicitly in models used for climate change impact studies, and IWRM in general, scaling problems emerge in parameterisations between smaller and larger catchments (Schulze, 2005).

c. The ability to model hillslope processes
Be it impacts of fertilizer or pesticide movement, the different generation mechanisms of streamflow or sediment production, or water demand by land uses in riparian vs. upslope areas, these are all influenced by hillslope hydrological processes and pathways with the respective thresholds, rates, accumulations and feedbacks of the different elements making up the landscape, *viz*. the crest, the scarp, the midslope, the footslope and the riparian zone. The hillslope elements and their accumulative downslope interactions need to be represented in a conceptually sound manner in order to answer prognostically the many questions which catchment managers will be posing in the near future, and which are likely to be exacerbated by climate change (Schulze, 2005).

d. The ability to model the different processes which may dominate in different climatic regimes
Southern Africa displays a wide climatic range with mean annual precipitations from < 50 mm to > 3 000 mm (Lynch, 2004), some rain falling with low intensity, occasionally as snow and some associated with high intensity convective storms. The rainfall is, furthermore, highly variable both within a year and from one year to the next (Schulze, 2008b). This precipitation falls on landscapes varying from steep montane areas to undulating hills to plains. All this implies a highly variable spatio-temporal conversion of precipitation to streamflow, as well as a regionally and seasonally variable partitioning of the streamflow into overland flows, subsurface stormflows, baseflows or even snowmelt

and, in the case of the groundwater table, this may or may not be “connected” to the channel, depending again on season and location.

For example, groundwater recharge may be through the soil matrix in more humid areas or by transmission losses in more arid zones, while evaporation losses may be dominated by riparian zone processes, or by transpiration, or by soil water evaporation, depending on climatic regimes and vegetation coverage, or evaporation rates may be influenced strongly by slope and aspect. By way of another example, mountain catchments’ hydrology may be dominated by poorly understood precipitation : altitude gradients which vary with rain vs. snow, with rainfall intensities, numbers of rainfall days and event magnitudes, since all of these change with elevation.

Climate change will alter the spatial patterns of hydroclimatic regimes. Directly, or by surrogate means, the various processes which under present climatic conditions may be present or absent, or may dominate in specific hydroclimatic regimes, will have to be encapsulated in model process representations for effective modelling of climate change impacts on water resources (Schulze, 2005).

e. The ability to model different intensities of land management practices

Identical broad land cover categories can produce significantly different hydrological responses, depending on the level or intensity of management practices. Thus, for example, grassland in overgrazed vs. well managed conditions can change sediment yield by a factor of four or more (Schulze, 2003; Schulze and Horan, 2007), or annual crops grown on fields with vs. without contour banks, or under conventional vs. conservation tillage practices, can yield significantly different magnitudes of total runoff, in addition to changes in the partitioning of that runoff into stormflows vs. baseflows (Lumsden *et al*., 2003; Schulze, 2005).

In an era when, in southern Africa, streamflow reduction activities, best management practices, payments for ecosystems goods and services and the polluter pays principle are integral components of water management, and where land uses are likely to shift spatially in future with the result that adaptive management practices are likely to be applied, models have to be able to simulate differences in land use management practices realistically under present and, particularly, future climatic conditions.

f. The need for a daily time step, conceptual-physical, process-based and non-linear dynamic response model

In order to model potential impacts of global change on hydrological processes and responses (the top component in **Figure 2.3.1**), in line with the model requirements discussed above, such a model needs the following attributes (Schulze, 2005):

- be *conceptual* in that it conceives of a one or multi-dimensional system in which important processes and couplings are idealised, and
- be *physical* to the degree that the physical processes are represented explicitly through observable variables (Eagleson, 1983).
- The model should, at minimum, be of the functional deterministic category (i.e. threshold based, with initial and boundary conditions) in its process representation (Schulze, 1998).
- Hydrological processes should account for present and future climate exchanges of water vapour, CO_2 and energy (e.g. precipitation attributes, streamflow generation responses, evaporation and transpiration together with its CO_2 driven feedbacks for modelling plant-soil interactions of future climates),
- modified by characteristics of the
    - *soil* (surface infiltrability, subsurface transmissivity of soil water and water holding capacity),
    - *land cover and land use / management* (e.g. with above-ground attributes related to intra-seasonal biomass; surface attributes of soil protection by litter / mulch or of tillage practices; below-ground attributes relating to root distribution), and
    - *topographic features* of the landscape (altitude, slope, aspect, toposequence and topographic position).
- The model should reproduce non-linear and scale-related catchment responses explicitly, where these may be associated with
    - *spatial heterogeneity* in surface processes (e.g. topography, soils, rainfall, evaporation, land use),

  - *non-linearities* responding to episodic events (e.g. rainfall), cyclicity (e.g. seasons, evaporation), hillslope processes (e.g. on and below surface), immediate responses (e.g. surface runoff from connected impervious areas; saturated overland flow), rapid responses (e.g. stormflow), ephemerality (e.g. discontinuous flows during the year), continuous responses (e.g. groundwater movement) and delayed responses (e.g. baseflow),
  - *thresholds which are required* for surface and subsurface streamflow processes to commence, and
  - *dominant processes which change with scale or human interference*, including emerging properties (e.g. advection) and representations of disturbance regimes (e.g. drainage of fields, changes in streamflow regimes resulting from dam construction / abstractions / return flows), gradual changes in land use intensification over time (e.g. agriculture and urbanisation), or in extensification (e.g. overgrazing impacts), or abrupt changes resulting from fires or flooding.
- As such the model should essentially be devoid of parameter adjustment, since parameterisation "hides" the reason for changes in hydrological responses while a conceptual-physical model "provides" the reason and should, in theory, not require external calibration procedures to produce robustly acceptable results under current and projected future climates.
- Furthermore, for most operational modelling, simulations should take place at daily time steps since the day is the shortest *universal natural time step,* and climate variables from GCMs are nowadays output at daily values. Furthermore, diurnality encapsulates (albeit not perfectly) many hydrologically related processes which are important in climate change studies (e.g. evaporation, transpiration and many discrete rainfall events), while many operational decisions are currently, and in future climates will also be, made according to daily conditions (e.g. irrigation, reservoir releases) and daily climate data for baseline hydrological conditions are readily available.
- Model output for impact studies of projected climate change within a framework of IWRM will have to address management conflicts for a range of spatial scales from upslope vs. downslope impacts, upstream vs. downstream impacts, as well as those within vs. between Water Management Areas (Schulze, 2005; Schulze, 2008a).

The major advantage of such daily time step, conceptual-physical, non-linear response models is that, because of their high level of process representation and physically based boundary conditions, they may be used with confidence in extrapolations involving "what-if" scenarios of hitherto unmeasured land management strategies, extreme events or climate variability which may be associated with global change and which are essential ingredients of IWRM. One such model that aspires to encapsulate the attributes outlined above is the *ACRU* model, some details of which are given below.

The *ACRU* Modelling System: Model Attributes (This Section has been adapted from Schulze, 2005; 2010)

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 studies in southern Africa, was selected as the preferred simulation tool as it complies with many of the premises and principles outlined above and is centred around the following objectives and attributes (**Figures 2.3.2** and **2.3.3**):

- It is a *daily time step, conceptual-physical* model,
- with variables (rather than optimised parameters values) estimated from physically based characteristics of the catchment, and
- with the model revolving around daily *multi-layer soil water budgeting*.
- As such, the model has been developed essentially into a versatile total evaporation model (**Figure 2.3.3**), structured to be highly sensitive to climate drivers and to land cover, land use and management changes on the soil water and runoff regimes, and with its water budget being responsive to supplementary watering by irrigation, to changes in tillage practices, enhanced atmospheric CO_2 concentrations associated with climate change, or to the onset and degree of plant stress, which may change with global warming.
- *ACRU* is a *multi-purpose* model which integrates the various water budgeting and runoff production components of the terrestrial hydrological system (**Figure 2.3.2**). It can be applied as a versatile model for design hydrology (including flow routing through channels and dams), crop yield estimation, reservoir yield simulation, ecological requirements, wetlands hydrological responses, riparian zone processes, irrigation water demand and supply, water resources assessment, planning optimum water resource utilisation / allocation, conflict management in

water resources and land use impacts - in each case with associated risk analyses - and all of which can respond differently with climate change.

- *ACRU* can operate at multiple scales as a *point* model or as a *lumped* small catchments model, on large catchments or at national scale as a *distributed* cell-type model with flows taking place from “exterior” through “interior” cells according to a predetermined scheme, with the facility to generate individually requested outputs at each subcatchment’s exit.
- The model includes a *dynamic input option* to facilitate modelling of hydrological responses to climate or land use or management changes in a time series, be they long term / gradual changes (e.g. urbanisation or climate trends), or abrupt changes (e.g. construction of a dam), or changes of an intra-annual nature (e.g. crops with non-annual cycles).

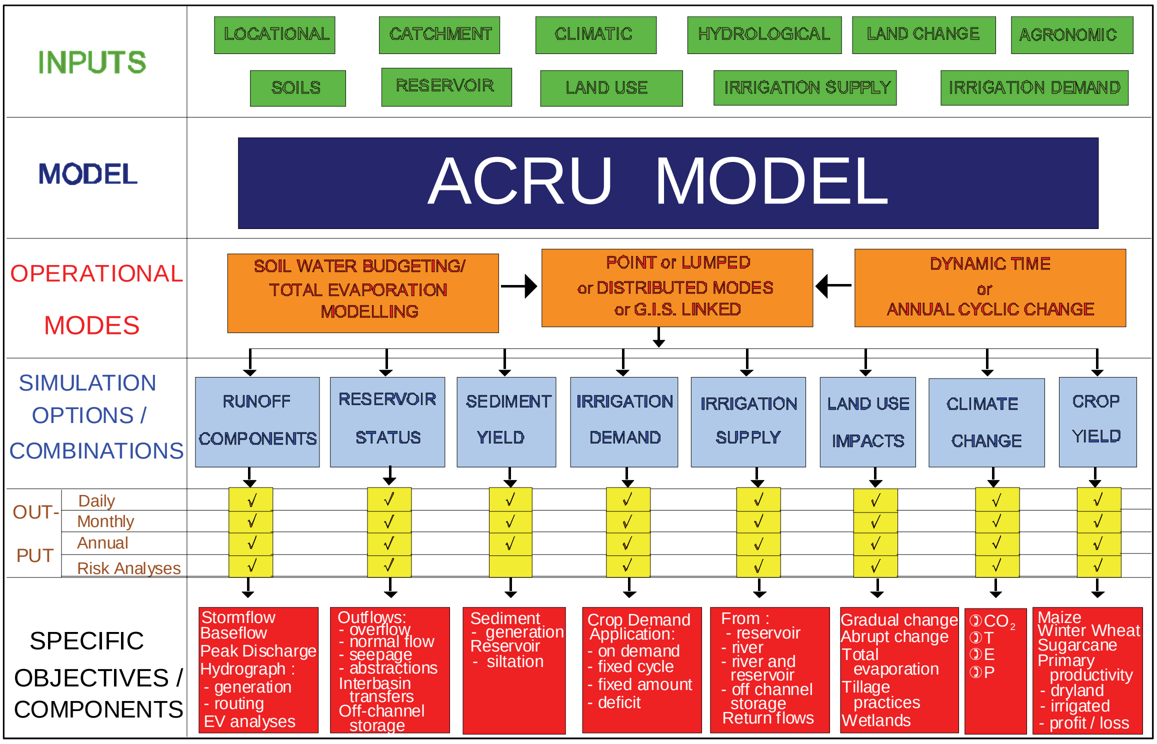

Figure 2.3.2 General structure and multi-purposeness of the *ACRU* model (After Schulze, 1995)

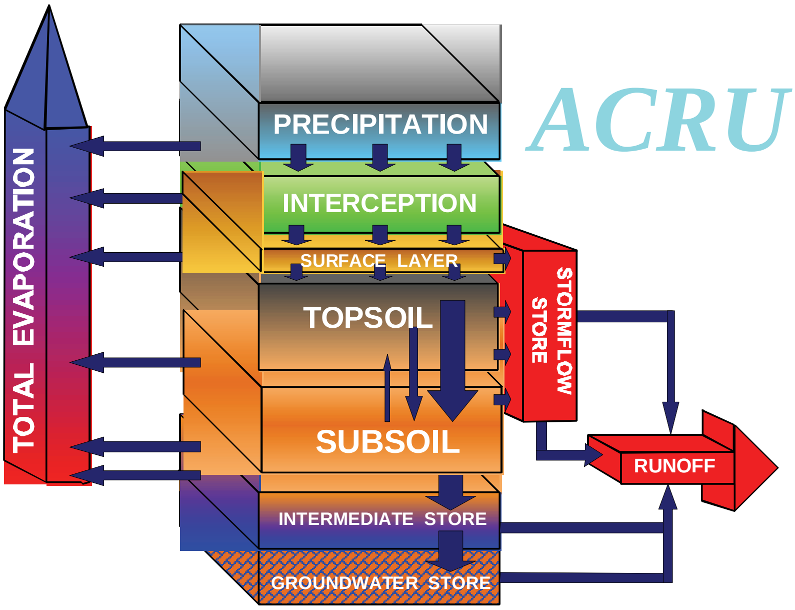

Figure 2.3.3 Schematic of major processes represented in the *ACRU* model (After Schulze, 1995)

- The *ACRU* model has been linked to the Southern African National Quaternary and Quinary Catchments Databases (cf. **Chapter 2.2**) for applications at a range of scales in the RSA, Lesotho and Swaziland for climate change impacts and other studies.

General Structure of the *ACRU* Model

Multi-layer soil water budgeting by partitioning and redistribution of soil water is depicted in **Figure 2.3.3**. That rainfall and / or irrigation application not abstracted as interception or as stormflow (either rapid response or delayed), first enters through the surface layer and "resides" in the topsoil horizon. When that is "filled" to beyond its drained upper limit (field capacity) the "excess" water percolates into the subsoil horizon as saturated drainage at a rate dependent on respective horizon soil textural characteristics, wetness and other drainage related properties. Should the soil water content of the bottom subsoil horizon of the plant root zone exceed the drained upper limit, saturated vertical drainage / recharge into the intermediate and eventually groundwater stores occurs, from which baseflow may be generated at an exponential decay rate dependent on geological / aquifer characteristics and the groundwater store.

Unsaturated soil water redistribution, both upwards and downwards, also occurs, but at a rate considerably slower than the water movement under saturated conditions, and is dependent, *inter alia*, on the relative wetnesses of adjacent soil horizons in the root zone. Evaporation takes place from water previously intercepted by the crop's or vegetation's canopy, as well as simultaneously from the various soil horizons, in which case it is either split into separate components of soil water evaporation (from the topsoil horizon only) and plant transpiration (from all horizons in the root zone), or combined, as total evaporation.

Evaporative demand on the plant is estimated, *inter alia*, according to atmospheric demand (through a reference potential evaporation) and the plant's stage of growth. The roots absorb soil water in proportion to the distributions of root mass density within the respective horizons, except when conditions of low soil water content prevail, in which case the relatively wetter horizons provide higher proportions of soil water to the plant in order to obviate plant stress as long as possible.

It is vital in agrohydrological impacts modelling to determine at which point in the depletion of the plant available water reservoir plant stress actually sets in, since stress implies a soil water extraction below optimum, the necessity to irrigate, as well as implying a reduction in crop yield. In modelling terms, this problem may be expressed as the critical soil water content at which total evaporation, E, is reduced to below the vegetation's maximum evaporation, E_m (formerly termed "potential evapotranspiration"). E equals E_m until a certain fraction of maximum (profile) available soil water to the plant, *PAW*, is exhausted (**Figure 2.3.4**). Research shows that the critical soil water fraction at which stress commences varies according to atmospheric demand and the critical leaf water potential of the respective vegetation, the latter being an index of the resilience of the vegetation to stress situations. The implications of stress setting in at such different levels of soil water content (cf. **Figure 2.3.4**) are significant in terms of total crop evaporation, crop production modelling and irrigation scheduling.

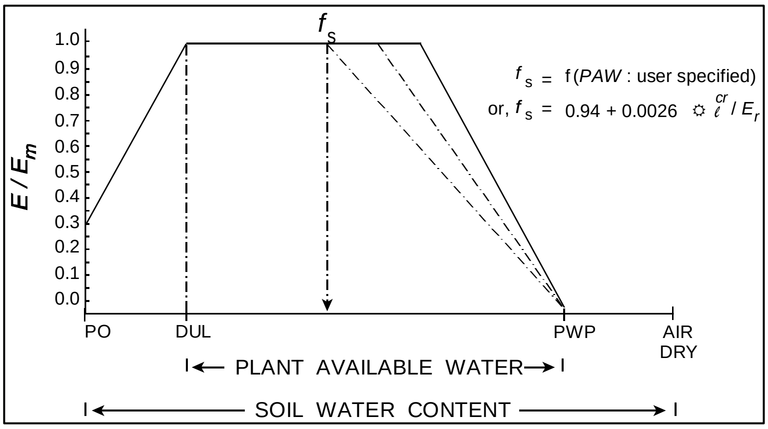

Figure 2.3.4 Interrelationships used in *ACRU* between soil water content and the ratio of E : E_{tm} which expresses the level of plant water stress (Schulze, 1995)

Generation of Stormflows with the *ACRU* Model

Stormflow, Q, is defined as the water which is generated from a specific rainfall event, either at or near the surface in a catchment or subcatchment, and which contributes to flows of streams within that catchment / subcatchment (**Figure 2.3.5**). It is largely from stormflow events that, for example, reservoirs are filled and design runoffs for selected return periods are computed. Furthermore, the soil detachment process in the production of sediment yield from a catchment is highly correlated with the volume of stormflow from an event. Important statistics on stormflows include annual means, inter-annual variabilities, magnitudes in wet and dry years and the number of stormflow events per annum exceeding critical thresholds.

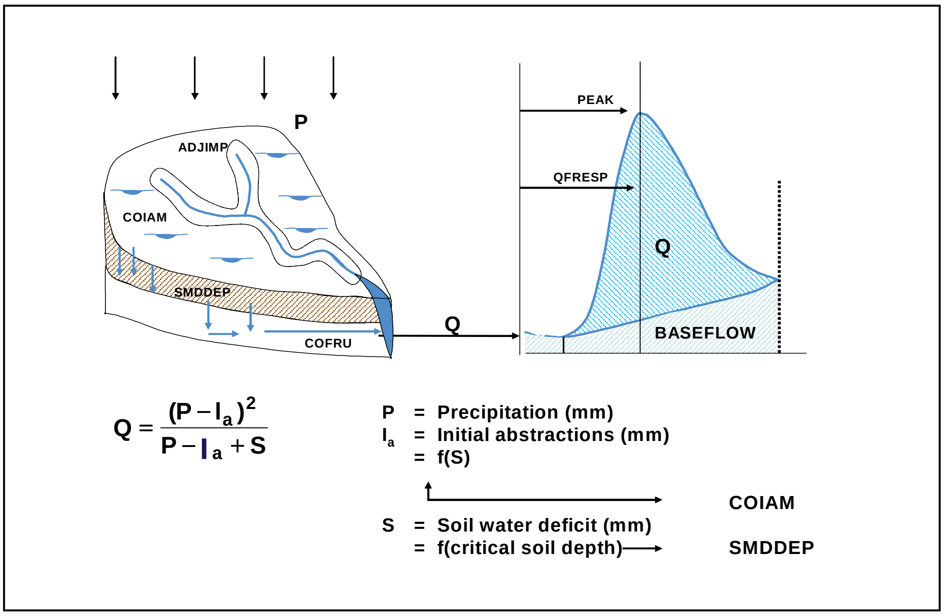

Figure 2.3.5 Schematic of runoff generating mechanisms in the *ACRU* model

Stormflow can be generated from both the impervious parts of the catchment connected directly to a stream (e.g. paved surfaces, roofs, permanently saturated areas directly adjacent to a stream; *ACRU* variable name ADJIMP in **Figure 2.3.5**) and from the pervious portions of a catchment. The amount of the stormflow which is generated from the pervious areas (expressed either as a depth equivalent in mm, or as a volume in m^3) in essence depends on the magnitude of the rainfall event (P in **Figure 2.3.5**) and how wet the catchment is just prior to the rainfall event.

Stormflow, Q_s, is computed in the *ACRU* model (Schulze, 1995 and updates) in mm equivalents as

$$Q_s = (P_n - I_a)^2 / (P + I_a + S) \quad \text{for } P_n > I_a$$

in which

P_n = net rainfall (mm), i.e. gross (measured) rainfall minus canopy interception losses,

I_a = initial abstractions (mm) before stormflow commences, consisting mainly of that infiltration which occurs between the beginning of the rainfall event and the beginning of storm runoff, plus any depression storage, and

S = the soil's potential maximum retention (mm), which is equated to the soil water deficit and is an expression of the wetness or dryness of the soil.

In *ACRU*, the soil water deficit S is calculated by the daily multi-layer soil water budget, and for computations of stormflow a critical soil depth, D_{sc} (SMDDEP, in m, in **Figure 2.3.5**) is defined from which S is determined. The depth of D_{sc} accounts for the different dominant runoff producing mechanisms which may vary in different climates, as well as with catchment land uses, tillage practices, litter / mulch cover and soil conditions. This depth is therefore generally shallow in more arid areas characterised by eutrophic (i.e. poorly leached and drained) soils and high intensity storms which would produce predominantly surface runoff, but is generally deeper in high rainfall areas with dystrophic (highly leached, well-drained) soils where interflow and "push-through" runoff generating mechanisms predominate. For all hydrological simulations in this report, D_{sc} was defined as the thickness of the topsoil.

A major determinant of initial abstractions is soil water content. In order to eliminate estimations of both I_a and S in the equation above, I_a is expressed as a coefficient, c, of S, where c is an index of infiltrability into the soil and varies with rainfall intensity (in the thunderstorm season: smaller c), tillage practice and surface cover / litter / mulch (Schulze, 1995). For all simulations of baseline hydrological responses in this document, the c of I_a was input as that value assigned on a month-by-month basis (*ACRU* variable COIAM in **Figure 2.3.5**) by Schulze (2004) for the 70 baseline land cover types found in South Africa, as defined by Acocks (1988). For simulations with other land uses (including fire and degradation / rehabilitation regimes) the monthly values of the c of I_a were taken from Schulze (2008b), in which all assumptions are explained.

Not all stormflow generated from a rainfall event exits the catchment on the same day as the rainfall occurs, and the fraction that does depends on the size of the catchment, the catchment's slope and other factors (Schulze, 1995). This necessitates a stormflow response coefficient, F_{sr}, to be input, which controls the "lag" of stormflows and is effectively an index of interflow (*ACRU* variable name QFRESP in **Figure 2.3.5**). In all simulations on all sub-catchments in this document, F_{sr} was set at 0.3, a value which has been found experimentally to be typical in South Africa for use at the spatial scale of Quaternary and Quinary Catchments (e.g. Kienzle *et al*., 1997; Warburton *et al*., 2010) when the *ACRU* model's flow routing option is not used, as in this case.

Generation of Baseflows with the *ACRU* Model

Baseflows consist of contributions to runoff from the intermediate / groundwater store which had been previously recharged. These contributions are made up of slow and delayed flows to the catchment's streams. In the *ACRU* model it is assumed that the groundwater store is always "connected" to the stream system. Unlike many other models which compute baseflow indirectly from total runoff hydrographs with an empirically derived "separation curve", *ACRU* computes baseflow explicitly from recharged soil water stored in the intermediate / groundwater zone (Schulze, 1995).

The stored water is derived from rainfall of previous events which has been redistributed through the various soil horizons and has drained into the intermediate / groundwater store when the deepest soil horizon's water content exceeds its drained upper limit (field capacity). The *rate of drainage* of this "excess" water out of the deepest soil horizon *into the groundwater store* depends on that horizon's soil texture class, which in this Report has been input to vary from catchment to catchment according to soil attributes (cf. Quinary Catchments Database; **Chapter 2.2**).

The rate of release of water from the groundwater store into the stream is determined by a release coefficient, F_{bff}, which is dependent *inter alia* on the geology, area and slope of the catchment. F_{bff} operates as a "decay" function which is input for a catchment as a single value (COFRU in **Figure 2.3.5**), but based on experiences with *ACRU* in many catchment studies, F_{bff} is not a constant decay function, but is enhanced or decreased internally in *ACRU*, dependent on the magnitude of the previous day's groundwater store, S_{gwp}, such that empirically

$$F_{bff} = F_{bfi}\,\big[[[(S_{gwp})^2 - S_{gwp}] / 1000 + 1.3] / 11\big]$$

where

F_{bff} = final baseflow release coefficient
F_{bfi} = input baseflow release coefficient and
S_{gwp} = magnitude of previous day's intermediate / groundwater store (mm).

For all simulations in this document an experimentally determined typical value of F_{bff} of 0.009 (Kienzle *et al*., 1997) has been applied in all Quinary Catchments in the study area.

Peak Discharge

The peak discharge is the highest flow rate of a hydrograph (cf. **Figure 2.3.5**). In the *ACRU* model an estimate of the peak discharge associated with each day's stormflow volume generated for the selected simulation period can be made by assuming a single triangular unit hydrograph. For these simulations the SCS peak discharge equation (USDA, 1972), modified significantly by Schulze and Schmidt (1995) is used. In its modified version

$$q_p = 0.2083 Q_s A / 1.83\, L$$

where

q_p = peak discharge ($m^3.s^{-1}$),
Q_s = stormflow depth (mm) from an individual catchment,
A = catchment area (km^2),
L = catchment lag (response) time (h)
= $\dfrac{A^{0.35} MAP^{1.1}}{41.67 y^{0.3}\, \bar{I}30^{0.87}}$ and
1.83 = a multiplier which was computed assuming high intensity rainfall to be associated with annual maximum one day storms over relatively small catchments,

with the lag equation having been developed by Schmidt and Schulze (1984) using several hundred hydrographs from over 20 research catchments at seven hydro-climatically divergent regions in the USA and South Africa, and in which

A = catchment area (km^2),
MAP = mean annual precipitation (MAP in mm),
Y = mean catchment slope (%), determined in the case of this Report 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 the lag equation above (i.e. L =), the potential effects of climate change on catchment lag, and hence peak discharge, can be estimated. MAPs for the intermediate future and distant future were calculated as described in **Chapter 2.2**, while the methodology developed in **Chapter 7.1** (**Box 7.1.3**) was used to calculate the magnitude of the 2 year return period, 30 minute rainfall intensity for each Quinary Catchment.

Generation of Sediment Yields with the *ACRU* Model

Complex deterministic models are available to estimate erosion processes and sediment transport. However, these models are limited in their application owing to their reliance on calibration. The Universal Soil Loss Equation, USLE (Wischmeier and Smith, 1978), is an equation which has received recognition as an empirical method useful for planning and design purposes. This method is the foundation for other empirical equations which is then applied at a catchment scale to estimate sediment yield, such as the daily stormflow event based Modified Universal Soil Loss Equation, MUSLE (Williams, 1975), which has been widely verified world-wide and in South Africa (Kienzle *et al.*, 1997).

Sediment yield at any Quinary outlet (or that of any other spatial unit) may be estimated using the *ACRU* model, with the MUSLE imbedded and expressed as

$$Y_{sd} = \alpha_{sy} (Q_v \, x \, q_p)^{\beta_{sy}} K \, x \, LS \, x \, C \, x \, P$$

where

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

The MUSLE coefficients, α_{sy} and β_{sy} are location specific (Simons and Sentürk, 1992) and are determined for specific climatic zones. However, default values set at 8.934 for α_{sy} and 0.56 for β_{sy} were used in sediment yield simulations for this research.

Information needed for each Quinary Catchment when estimating sediment yield thus includes

- the stormflow volume for each event (using the equations given earlier in this Chapter, but with the mm equivalent Q converted to a volume Q_v in m^3 by multiplying out for area);
- the peak discharge (m^3) for each event (using the equations given earlier in this Chapter);
- the 30 minute rainfall intensity (mm/h) for the 2 year return period, f_{30}, used in the peak discharge equation and computed for historical data as outlined in **Chapter 7.1** and for climate change studies in South Africa by techniques developed by Knoesen (2011) and also described in **Chapter 7.1**;
- the soil erodibility factor, K, determined from the ISCW's soil land types using the AUTOSOILS program (Pike and Schulze, 1995 and updates) and mapped in detail for South Africa by Schulze and Horan (2008), with the map shown in **Chapter 5.7**;
- the slope length factor, calculated from each Quinary Catchment's average slope gradient determined from a 200 m resolution Digital Elevation Model and an equation developed by Schulze (1979) which relates slope gradient to the slope length factor, with the slope length factor mapped for South Africa in **Chapter 5.7**;
- the cover and management factor, C, as determined by Schulze (2004) and mapped for baseline land cover conditions over South Africa in **Chapter 5.7**;
- the support practice factor, P, not applicable for these simulations under baseline land cover conditions and thus set to 1; and
- a factor proportioning the amount of the sediment generated from a stormflow event and which reaches the outlet to the respective Quinary Catchment on the day of the event, in order to account for sediment eroded at one location and which may be stored temporarily only to be subsequently remobilised several times before reaching the catchment outlet (van Zyl and Lorentz, 2003), and set for this study at 0.45 (Schulze, 1995).

The Irrigation Water Budget as Represented in the *ACRU* Model

For applications of irrigation, conceptually sound but robust algorithms have been developed and incorporated into *ACRU* to simulate the major processes of the irrigation water budget, *viz.*

- evaporation of water from the soil surface and
- transpiration from the crop, both in relation to atmospheric demand,
- available soil water with particular reference to rooting characteristics, as well as
- stormflow and
- deep percolation.

These processes are illustrated schematically in **Figure 2.3.6**.

1. Evaporation from the Soil Surface, E_s : General

Evaporation of soil water is a complex process, but it has been generalised into two stages. The first stage of the evaporation process is the constant rate, or the energy limiting, phase. When the soil can no longer supply water at a rate to use all the available energy for evaporation, the soil limiting, or second phase, begins.

2. First Stage Soil Water Evaporation: The Constant Rate / Energy Limited Phase

In Stage 1 of the soil water evaporation process, evaporation from the soil is limited primarily by the atmospheric demand for water above the soil surface, or reference potential evaporation E_r.

The effect of crop canopy shading on the supply of energy to the soil surface is represented by the percentage shading of the soil surface ($S_{g\%}$) measured near solar noon. In *ACRU*'s irrigation routines the relationship between bare soil and the evaporation from a shaded soil is given as

$$E_s / E_{sm} = exp(-0.017 S_{g\%})$$

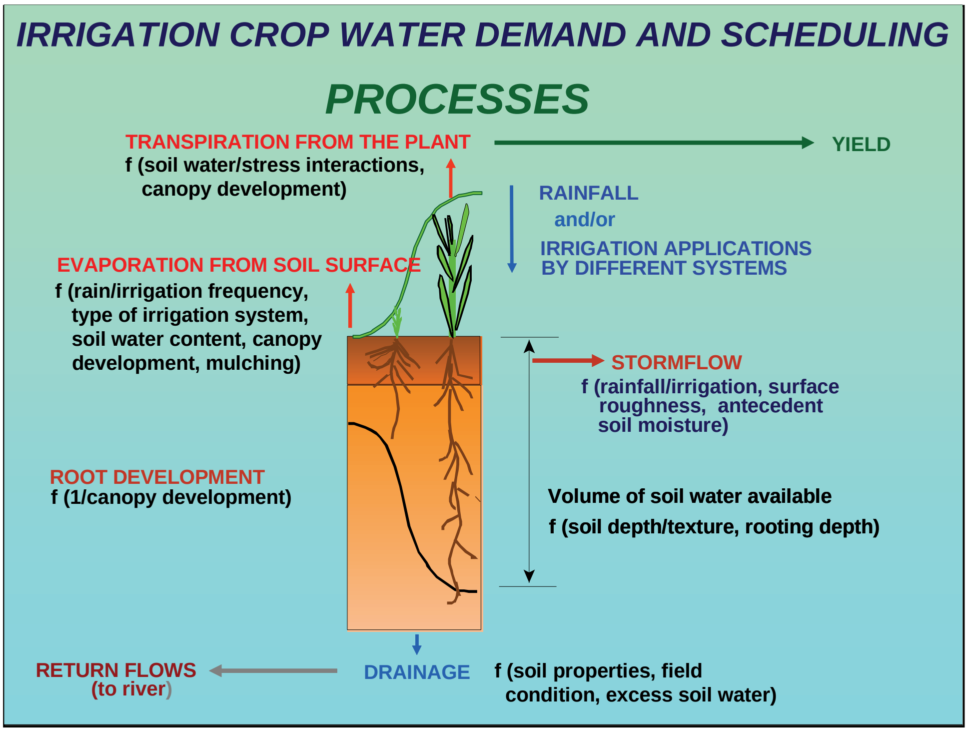

Figure 2.3.6 Schematic of the main processes of the irrigation water budget in *ACRU*

where

E_s = evaporation from the soil surface (mm/day),
E_{sm} = evaporation from a wet uncovered soil surface (mm/day),
$\equiv$ maximum soil water evaporation, and
$S_{g\%}$ = percentage of ground shaded, measured near solar noon.

For a fully grown crop $S_{g\%}$ depends on the crop type and the planting density. However, for most crops grown under irrigation, values for $S_{g\%}$ approach 100 % towards the end of the vegetative period. The variation in $S_{g\%}$ during the growing season is accounted for in *ACRU*'s irrigation routines by assuming a linear relationship between the rate of increase / decrease of $S_{g\%}$ and the rate of increase / decrease of the crop coefficient (K_{cm}), *viz.*

$S_{g\%} = 0$ for $K_{cm} < 0.30$
$S_{g\%} = (S_{\%mx} / (K_{cS\%mx} - 0.30)) \times (K_{cm} - 0.30)$ for $K_{cm} < K_{cs\%mx}$
$S_{g\%} = S_{\%mx}$ for $K_{cm} > K_{cs\%mx}$

where

K_{cm} = crop coefficient,
$K_{cS\%mx}$ = crop coefficient when $S_{g\%}$ is at its maximum (typically at the end of the vegetative period), and
$S_{\%mx}$ = maximum per cent of ground area shaded (measured near noon and typically taken as 100 % for most irrigated crops).

3. *Second Stage Soil Water Evaporation: The Rapidly Declining, Soil Regulated Phase*

During Stage 2 soil water evaporation, the soil begins to regulate the drying rate and evaporation decreases rapidly. Stage 2 evaporation has usually been modelled with a square root of time relation. The transition to second stage drying is assumed to occur when cumulative soil water evaporation from a defined topsoil layer reaches a soil specific upper limit threshold, U_l (mm). The hydraulic properties of the soil play the major role in determining the amount of drying before Stage 1 evaporation ends and Stage 2 evaporation begins. In *ACRU*'s irrigation routines Stage 2 soil water evaporation proceeds as follows:

$$E_s = \alpha_s . t^{0.5} - E_{s2cum}$$

where

E_s = evaporation from the soil surface (mm/day),

E_{s2cum} = cumulative Stage 2 evaporation from the soil surface (mm),
α_s = soil water transmission rate factor, and
t = days since the start of Stage 2 evaporation (day).

If any rainfall or irrigation occurs during Stage 1, the rainfall or irrigation is subtracted from the cumulative total of Stage 1 evaporation. If any rainfall or irrigation occurs during Stage 2 evaporation, E_s is calculated as follows:

$$E_s = \alpha_s t^{0.5} - E_{s2} + P_g + I_{rr} \quad \text{for} \quad P_g + I_{rr} < E_{sl}$$
$$E_s = E_{s1} \quad \text{for} \quad P_g + Irr > E_{sl}$$

and, in addition, if $P_g + I_{rr} > E_{s1}$, then

$$E_{s1cum} = U_l - (P_g + I_{rr})$$

or, if $U_l - (P_g + I_{rr}) < 0$

$$E_{s1cum} = 0$$

where
P_g = precipitation (mm),
I_{rr} = irrigation (mm),
E_{s1} = potential Stage 1 soil water evaporation (mm/day),
U_l = upper limit threshold for Stage 1 evaporation (mm/day), and
E_{s1cum} = cumulative Stage 1 evaporation (mm).

During Stage 1 or 2 evaporation, the amount of water available for evaporation is the amount deemed to be available in the top 150 mm of the soil profile.

4. Maximum Transpiration, E_{tm}

In the irrigation routines maximum transpiration, E_{tm}, when soil water content is not limiting, is based on the concept that E_{tm} is related to the standard crop coefficient. A further refinement to this concept takes into consideration that soil surface wetness has been added, whereby E_{tm} is reduced when the soil surface is wet and increased when the soil surface is dry, according to

$$E_{tm} = \text{minimum of } (E_r \cdot K_{cmod} \text{ or } E_r - E_s) \text{ for } K_{cm} < 1.0$$

$$E_{tm} = E_r \cdot K_{cm} - E_s \quad \text{for } K_{cm}$$

where
K_{cm} = standard crop coefficient, and
K_{cmod} = transpiration coefficient
= $(K_{cm} - 0.06) - (0.2E_s / 0.8E_r)$.

5. Soil Water Deficits and Transpiration

Transpiration takes place within the soil-plant-atmosphere continuum. For transpiration to proceed at potential rates, the atmospheric demand for water must be balanced by the flow of water from the soil to the plant roots and from the root surface to the leaves.

Slabbers (1980) states that in many plants leaf diffusion resistance is constant over a certain range of leaf water potential and then increases abruptly when that falls below an apparently critical value ψ^{cr}_l. This translates to transpiration, E_t, equalling maximum transpiration, E_{tm}, at ample soil water supply, until a certain fraction of the maximum available soil water is depleted. Below this threshold soil water content there is a reduction in E_t depending on the remaining available soil water and E_{tm}. Slabbers (1980) described these relationships as

$$E_t = E_{tm} \quad \text{for } \theta_{tmm} > f_s \cdot \theta_{mxmm}$$
$$E_t = E_{tm} \cdot \theta_{tmm} / (f_s \cdot \theta_{mxmm}) \quad \text{for } \theta_{tmm} <= f_s \cdot \theta_{mxmm}$$

where
θ_{mxmm} = maximum available soil water (mm),
= $(DUL - PWP) \cong$ Root depth (mm),
DUL = drained upper limit (mm/mm),
PWP = permanent wilting point (mm/mm),

θ_{tmm} = actual soil water content (mm) at time t, and
f_s = fraction of available soil water at which a reduction in E_{tm} starts.

Slabbers (1980) derived an expression for f_s, *viz*.

$$f_s = 0.94 + 0.0026(\psi^{cr}_l / E_r$$

Values for ψ^{cr}_l, for a range of different crops are given in the *ACRU* User Manual (Smithers and Schulze, 1995 and updates).

6. Rooting Characteristics

In *ACRU*'s irrigation routines the amount of water available in the soil is determined with reference to the zone in which the majority of root activity occurs, R_z. This root zone is dynamic, accounts for root growth and is calculated by assuming a linear relationship to crop coefficients, *viz*.

$R_z = 0.12$ for $K_{cm} < 0.3$
$R_z = 0.12 + (R_{zmx} - 0.12)(K_{cmr} - 0.3)$ for $K_{cmr} > K_{cm} > 0.3$
$R_z = R_{zmx}$ for $K_{cm} > K_{cmr}$

where
R_z = zone in which the majority of root activity occurs (m),
R_{zmx} = maximum depth of the R_z for a fully mature crop (m), and
K_{cmr} = crop coefficient when the rooting depth reaches a maximum (normally at the end of the vegetative stage).

It is assumed that R_z plays the major role in regulating the volume of soil water available for root water uptake and that plants can extract water at potential rates from wherever it is available within this single zone, according to the constraints already described above by the various equations.

Whilst the majority of soil water uptake occurs from R_z, smaller amounts of water are taken up due to limited rooting activity in the soil below R_z, but within the maximum rooting depth, R_{mx}. Plant water uptake in the zone R_{zmx} to R_{mx} is restricted as a result of limited root-soil contact (i.e. incomplete root colonisation), but can play a role in reducing crop water stress. The supply of water from soil where rooting activity is limited is represented in *ACRU* by redistributing water from the R_{mx} zone to the R_z zone, where it is available for uptake by the plant. Water is redistributed according to gradients in water contents between the two zones. Typical initial values for the maximum rooting depths of crops R_{zmx} and R_z, are given in the *ACRU* User Manual (Smithers and Schulze, 1995 and updates)

7. Daily Rainfall Adjustment for Irrigation Areas

The rainfall information used in the irrigation water budget is from the identical rainfall input file as that used for the entire catchment. However, the catchment's rainfall input may not be representative of the specific location at which irrigation is being practised, and an irrigation rainfall adjustment multiplier can thus be applied to the catchment's daily rainfall values.

8. Stormflow Generation from Irrigated Areas

Stormflow from irrigated areas, Q_{si}, is generated when rain exceeding a threshold magnitude falls onto the wet irrigated area. Under certain rainfall regimes in South Africa and certain modes of irrigation scheduling applied, this stormflow, carrying with it phosphates in suspension, can constitute a significant proportion of the irrigation water applied (Schulze and Dunsmore, 1984). It is computed in the *ACRU* model as a modified version of the SCS equation (Schulze, 1995 and updates) in mm equivalents as

$$Q_{si} = (P_{ni} - I_{ai})^2 / (P_{ni} + I_{ai} + S_i) \qquad \text{for } P_{ni} > I_{ai}$$

in which
P_{ni} = net rainfall (mm) on the irrigated area, i.e. gross (measured) rainfall minus irrigation canopy interception losses,
I_{ai} = initial abstractions (mm) from the irrigated area before stormflow commences, consisting mainly of that infiltration which occurs between the beginning of the rainfall event and the beginning of storm runoff, plus any depression storage,
= cS_i, with
c = coefficient of initial abstraction, and

S_i = the irrigated soil's potential maximum retention (mm), which is equated to the soil water deficit from a critical depth of soil, D_{si}.

Because of tilled soils and the high random roughness associated with irrigated fields, a coefficient of initial abstraction, *c*, of 0.3 is recommended for irrigated lands. The critical depth of the soil from which stormflow can be generated, D_{si}, is set at 0.3 m for irrigation routines.

9. Deep Percolation and Irrigation Recharge

If, at the end of a day, the soil water content of the irrigated area is above its drained upper limit (*DUL*), either because persistent rains fall onto an already wetted irrigated area or because under certain modes of irrigation scheduling water is applied onto a soil which has not yet been sufficiently depleted of soil water, drainage (i.e. deep percolation) of water out of the root zone into the catchment's overall baseflow store is initiated. Schulze and Dunsmore (1984) have shown that in certain irrigation projects in South Africa this deep percolation, which leaches the soil of nitrates, can make up a significant proportion of the irrigation water applied. Deep percolation from irrigated fields is initiated in the *ACRU* model at a rate as in the equation below:

$$K_{ir} = (\theta_{tmm} - \theta_{DULmm}) \cdot K_{sir} \quad \text{for } \theta_{tmm} > \theta_{DULmm}$$

where

K_{ir} = drainage of water into the baseflow store from irrigated fields (mm/day),
K_{sir} = saturated drainage coefficient from the irrigated field,
= $(\theta_{POmm} - \theta_{DULmm})/\theta_{POmm}$,
θ_{tmm} = actual soil water content (mm equivalent),
θ_{DULmm} = soil water content at drained upper limit (mm), and
θ_{POmm} = soil water content at porosity (mm).

Thus, depending on the drainage rate, soil water in the root zone can be depleted simultaneously by transpiration, evaporation from the soil surface and by deep drainage for a number of days. Recharge of the 'surplus' irrigated water from the catchment's overall baseflow store is released into the streamflow downstream of the irrigated area via a decay function.

10. Options for Irrigation Scheduling in the ACRU Model

The type of irrigation scheduling carried out depends, *inter alia*, on the irrigation system (i.e. equipment), the level of management, water availability, climatic conditions, the type of crop and its stage of growth. Five modes of irrigation scheduling are available in the *ACRU* model, *viz*.

- demand mode scheduling according to soil water depletion levels,
- demand mode scheduling to a planned deficit,
- irrigation with a fixed cycle and fixed amounts of water application,
- irrigation with a fixed cycle and varying amounts of water application, and
- irrigating according to a pre-determined schedule,

and the mode may be changed from one to another on a month-by-month basis in the course of a year, depending on crop and climatic demand or other irrigation constraints, for example, the level of farm management. The scheduling options and other aspects of the irrigation water budget in *ACRU* are shown schematically in **Figure 2.3.7**.

Only demand mode scheduling according to soil water depletion levels will be described in this Report as it is the only option for applications in climate change impact studies, the reason being that for a given crop and soil it varies from application to application and from place to place *solely* as a function of climate drivers, *viz*. rainfall and evaporative demand.

Demand Mode Scheduling According to Soil Water Depletion Levels is applied when irrigating to avoid crop water stress, by scheduling an application of water to the soil just before it has dried to a level where crop water stress sets in. It is considered a desirable scheduling strategy, because it involves an irrigation application only when it is necessary to prevent crop water stress (Schulze, 1984). Water requirement occurs when the depletion of water in the active root zone, R_z, has reached a critical level, usually 50 % of the plant available water (*PAW*), i.e. $f = 0.5$. In this mode of scheduling, the soil profile is recharged to its drained upper limit (field capacity).

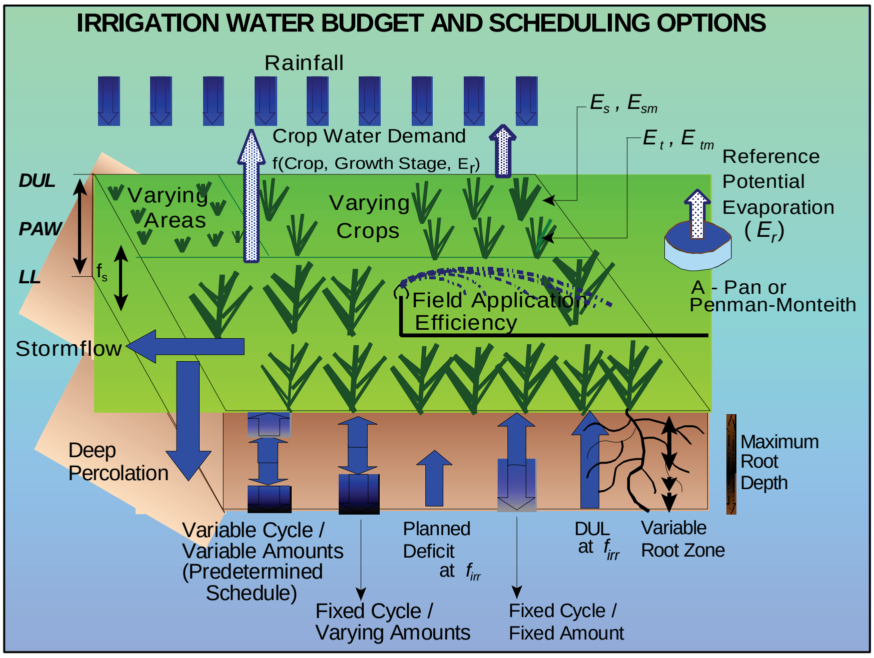

Figure 2.3.7 Schematic of the irrigation water budget in *ACRU* and scheduling options available (After Schulze, 1995 and updates)

When scheduling according to soil water depletion levels the interval between successive irrigation applications is variable (according to crop water demand) and stored irrigation water supply is used efficiently because water is only applied when necessary. A high level of management is required when irrigation applications are scheduled according to soil water depletion levels.

Verification of *ACRU* Model Output

The *ACRU* model is arguably the most comprehensively verified (as against calibrated) model in southern Africa (Schulze, 2008a), and in addition to verifications of end-product outputs such as streamflow (cf. **Photo 1**), its components of baseflow and stormflow or sediment yield, internal state variables such as soil water content have been verified against observed data.

Photo 1 Illustration of a streamflow gauging structure on the Mvoti river in KwaZulu-Natal, data from which have been used in streamflow verification studies (Photo: R.E. Schulze)

Some of the more comprehensive verification studies from South Africa are reported in Schulze (1995). Since 1995, Kienzle *et al*. (1997), Pike and Schulze (2001), Royappen *et al*. (2002), Dzukamanja *et al*. (2005) and Warburton *et al*. (2010) have undertaken detailed further verification studies using South African catchment data, an example of which is given in **Figure 2.3.8**, while other verification studies have been undertaken on observed catchment data from the USA (Schulze, 1984; Schmidt *et al*., 1986), Germany (Herpertz, 1994; 2001), Swaziland (Dlamini, 2001), Eritrea (Ghile, 2004) and Zimbabwe (Butterworth *et al*., 1999). More specifically in a context of impacts of land use,

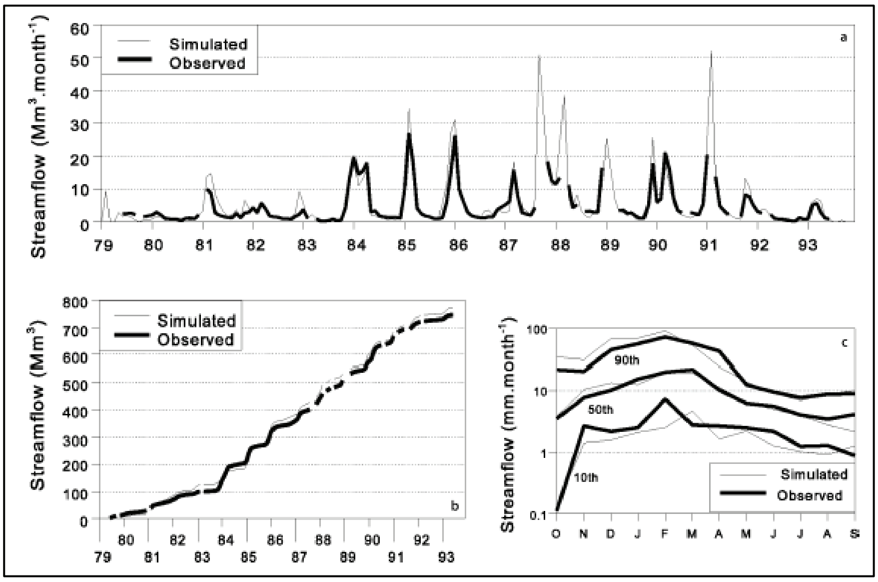

Figure 2.3.8 An example of a verification of streamflow with the *ACRU* model taken from the Lions River Quaternary Catchment in the Mgeni system (After Kienzle *et al*., 1997)

verifications have been undertaken by Schulze and George (1987), Haywood and Schulze (1990), Lumsden *et al*. (1998), Jewitt and Schulze (1999), Kienzle *et al*. (1997), Schmidt *et al*. (1998), Lumsden *et al*. (2003) and Warburton *et al*. (2010).

Model Links to Databases

As has already been alluded to, the *ACRU* model has been linked to historical daily climate databases for the 5 838 Quinary Catchments covering South Africa (cf. **Chapter 2.2**), as well as to daily climate output for present and future scenarios from Global Climate Models (GCMs), downscaled to Quinaries (cf. **Chapter 2.1**), to accomplish analyses of climate change impacts on water resources in South Africa.

For application in climate change studies, rainfall and potential evaporation input in the *ACRU* model are perturbed in accordance with changes from regionally downscaled GCMs. A further option available in *ACRU*, but not used in this study, is modelling the enhanced CO_2 feedback on losses, in which a distinction is made between C3 and C4 pathways in crops.

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CHAPTER 2.4

ON THE VERIFICATION OF OUTPUTS FROM THE GENERAL CIRCULATION MODELS USED IN THIS STUDY

R.E. Schulze

Uncertainties in Climate Change Impact Studies 1: In GCM Output (A Revisit)

Outputs from GCMs form the basis for climate change impact assessments. However, as has already been alluded to in **Chapter 2.1**, 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 and local adaptation options need to be considered. It is due to this discontinuity that GCM output needs to be translated from the coarse to more local scales by the process of regional climate downscaling (Hewitson *et al*., 2005a; Giorgi *et al*., 2008). Before any downscaling is performed, however, there remain many uncertainties inherent in GCMs (cf. **Figure 2.4.1**). Some of these are revisited briefly here in light of projected impacts of climate change on the hydrological cycle.

These uncertainties are well documented (e.g. UKCIP, 2003; Cox and Stephenson, 2007; Giorgi *et al*., 2008; Jacob and van den Hurk, 2009), especially in regard to the limitations resulting from GCMs' being 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). Major hydrologically relevant uncertainties include:

- Failure to simulate individual convective rainfall events, owing to the coarse spatial resolutions of GCMs, this being especially important over most of southern Africa, where convective rainfall is a dominant form of precipitation;
- Difficulty in simulating the intensity, frequency and distribution of extreme rainfall (IPCC, 2007);
- Tending to simulate too many small rainfall events (< 2 mm/day) and generally too few heavy rainfall events (> 10 mm/day), whilst maintaining a fairly realistic mean precipitation (IPCC, 2007); and
- Poorly representing major drivers of climate variability, such as the El Niño - Southern Oscillation phenomenon (Hulme *et al*., 2001), with which are associated years of generally high flows and low flows throughout southern Africa.

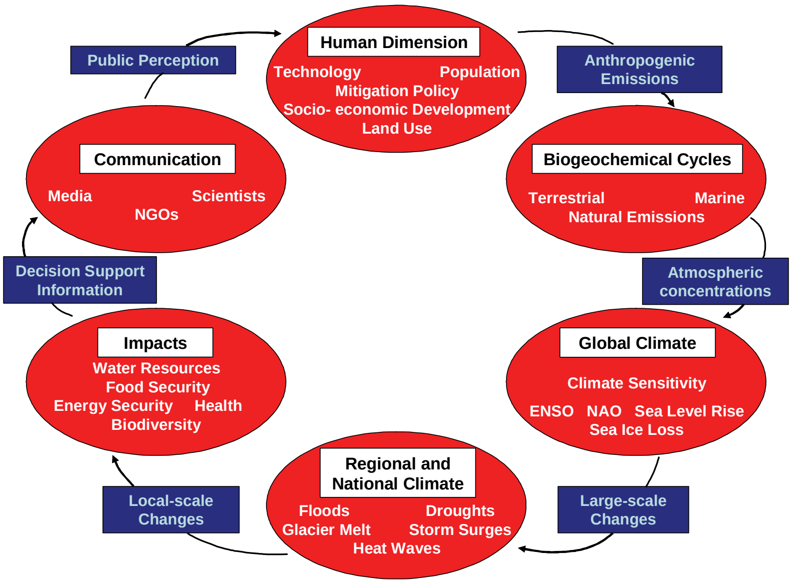

Figure 2.4.1 Sources of uncertainty in regional climate change prediction and their connections (Giorgi *et al*., 2008)

These factors tend to reduce the accuracy of precipitation output from GCMs. Additionally, critical temperature indicators can be quite unrepresentative at the local scale (Jacob and van den Hurk, 2009) and so, therefore, can any subsequent estimations of potential evaporation. As with impact studies in a wide range of disciplines, there therefore remain questions surrounding the usability of GCM derived output in detailed hydrological studies, in which individual precipitation events and potential evaporation, which is derived from temperature, are the major drivers of hydrological responses at the local scale and are the primary climate inputs into hydrological models.

Some of these questions are addressed in this Chapter by way of verification studies.

Uncertainties in Climate Change Impact Studies 2: In the Downscaling Procedures to the Quinary Catchments Scale

In **Chapter 2.1** the empirical downscaling technique is explained, as are the various steps undertaken in adjusting GCM output, which had been downscaled by the Climate Systems Analysis Group (CSAG) at the University of Cape Town to climate station level, in order to obtain daily values of rainfall and temperatures to be representative of their respective Quinary Catchments. Each of these many steps introduces elements of uncertainties, some of which may be self-correcting and others possibly additive. However, since most end results of this climate change impact study were expressed as ratios of change, many of the above errors would have been largely self-correcting.

Uncertainties in Climate Change Impact Studies 3: In the Observed Historical Datasets

Despite stringent quality control and procedural checks, neither the historical daily temperature values generated across South Africa by Schulze and Maharaj (2004) on a 1 arc minute raster (i.e. ~ 1.6 x 1.6 km) and then converted to a data series for each Quinary, nor the historical daily rainfall values generated by Lynch (2004) at rainfall station level, nor the selection of the 1 061 rainfall driver stations (cf. **Chapters 2.1** and **2.2**) by the Kunz (2004) Rainfall Utility to drive the hydrology of 5 838 Quinaries are considered to be perfect. It may therefore be that in some areas of South Africa the references against which GCM outputs are being tested are not entirely error free. This is one of the hypotheses tested later in this Chapter.

Uncertainties in Climate Change Impact Studies 4: In the Hydrological Model Used

While the individual processes contained in the conceptual-physical *ACRU* model (Schulze, 1995 and updates), as well as internal state variables such as soil water content and final model outputs such as runoff and sediment yield have been widely verified in over 100 studies (Schulze, 2008), no model gives a perfect representation of all hydrological processes and responses. It is, however, argued that in this study the *same* model was used throughout, and for each Quinary Catchment the *same* configuration and the *same* soils and land cover attributes were used, with only climate scenarios changing. Since most end results of this climate change impact study were expressed as ratios of change, any model errors would thus have been largely self-cancelling.

Verification: What do We Understand by the Term in the Context of this Study?

In this Chapter results are presented on verification studies between values of rainfall as well as of maximum and minimum temperatures parameters from the five GCMs provided to this study by CSAG (cf. **Chapter 2.1**), and which had been empirically downscaled, against the corresponding rainfall values derived from Lynch (2004) and temperature values derived from Schulze and Maharaj (2004).

To *verify* implies to "test the accuracy, or establish the truth or correctness, of something by examination or by comparison with known data or some standard" (Oxford English Dictionary; English Usage Dictionary). “Known data” in this instance are values of rainfall and temperature derived by Lynch (2004) and Schulze and Maharaj (2004) from observations. Verification also implies “confirmation”, “certification” or “accreditation”, while the Cassels Dictionary further explains it as “evidence” and “to demonstrate” the truth, to “settle the question”, and / or to “prove”. A verification is thus a measure of the performance of a model.

Verification thus implies the following:

- demonstrating that the behaviour (i.e. output) of a simulation model, in this case the output from empirically downscaled GCMs, is consistent with the behaviour of the physical system (i.e. that GCM output reflects the signals of observed values);
- and in doing so, determining if the GCM's output *information* (*Note*: simulation model output does *not* constitute data, but information or values) has sufficient accuracy for the model's intended use, *viz*. to assess projected impacts of climate change on water resources related issues in order to make science informed adaptation strategies.
- It is thus a process to determine if the differences between historically observed and GCM simulated values are sufficiently small (or not) and thereby establishing a level of confidence (or lack thereof) in the climate model.

Verification studies should be objective, i.e. subject to formal and rigorous statistical tests of goodness-of-fit, according to the problem at hand and the region in which the verification is undertaken (e.g. in arid areas goodness-of-fit statistics of highly variable climate parameters such as rainfall is not expected to be as high as in humid regions).

When verifying model output, in this case from GCMs, the assumption is made that the observations against which the verification is made are valid, i.e. that the historical data of rainfall and temperature at the Quinary Catchment scale are "perfect" and contain no errors. This assumption will be tested later in this Chapter.

Methodology Used in Verification Studies

In order to perform verifications on those outputs of the GCMs which were considered relevant to this study, hydrologically critical indicators were first selected. For this study these were

- monthly means of daily maximum temperatures, represented by the values from January as the hottest month, and important in the estimation of potential evaporation (cf. **Chapter 4.1**);
- monthly means of daily minimum temperatures, represented by the values from July as the coldest month, and also important in the estimation of potential evaporation (cf. **Chapter 4.1**);
- the number of days per year with a rainfall of 10 mm or more, as a test to ascertain whether the downscaled GCMs could capture the significant rainfall events adequately, with 10 mm per day generally being a threshold for stormflows and sediment yields to be generated from a catchment; and
- the number of days per year with a rainfall of 25 mm or more, as an even more stringent test to ascertain whether the downscaled GCMs could capture the hydrologically even more significant rainfall events adequately, with 25 mm per day generally resulting in a distinct hydrograph.

The relevant values of the indicators listed above were extracted for each of the 5 838 Quinary Catchments covering South Africa from the daily and statistical output files generated with the *ACRU* model. This was done for the overlapping period from 1971 to 1990 of historical daily rainfall and temperature data (i.e. the "observed" data) and output from the 5 GCMs available for this study (the "simulated" values). Results are shown either as scatterplots, as maps or in tabular summaries.

Verifications of January (Mid-Summer) Maximum and July (Mid-winter) Minimum Temperatures

Scatterplots of monthly means of daily maximum temperatures for January (mid-summer) derived from each of the five available GCMs vs. historically observed values for the 20 year period 1971 - 1990, are shown in **Figure 2.4.2**. Each dot represents results from one Quinary Catchment. In each scatterplot the red regression line represents the best fit, with its equation also in red, while the black line and equation in black represent the regression forced through zero. The bottom right graph summarises the results in displaying only the regression lines. Similarly, in **Figure 2.4.3** the scatterplots of monthly means of daily minimum temperatures for July (mid-winter) derived from the five GCMs vs. historically observed values for the 20 year period 1971 - 1990, are shown. Salient results from the verifications are summarised in **Table 2.4.1**.

- Based on the scatterplots in **Figure 2.4.2** and the statistical summaries in **Table 2.4.1**, it may be seen that for mid-summer, represented by January, the R^2 of monthly means of daily maximum temperatures between the GCM derived values and observations for the same time period are acceptably high for all 5 GCMs at between 0.70 and 0.78, considering the diversity of climatic regimes found across the 5 838 Quinary Catchments making up South Africa.

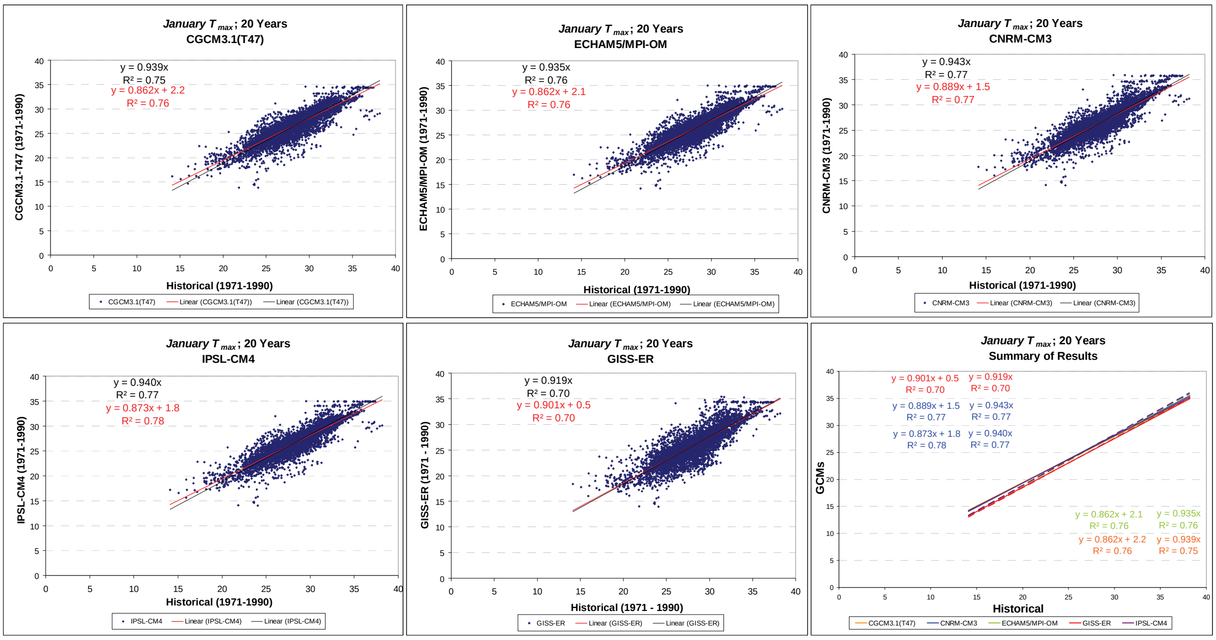

Figure 2.4.2 Scatterplots of GCM derived vs. historically observed monthly means of daily maximum temperatures in January (mid-summer) for the 20 year period 1971 - 1990, with each dot representing results from one Quinary Catchment

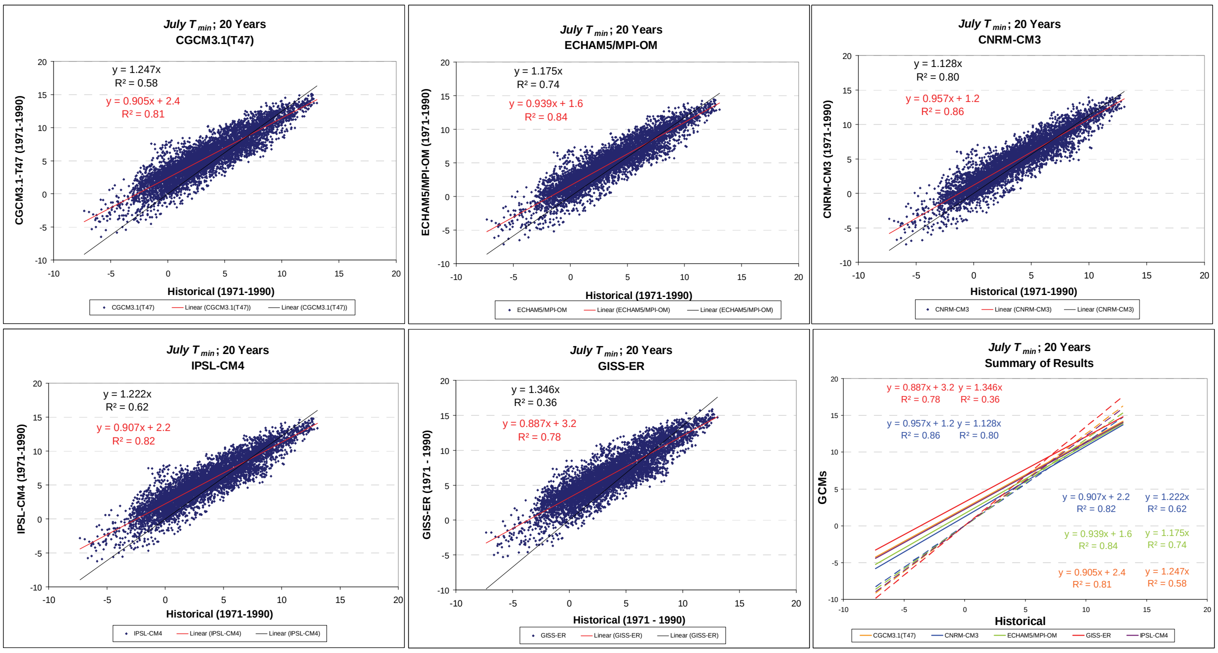

Figure 2.4.3 Scatterplots of GCM derived vs. historically observed monthly means of daily minimum temperature in July (mid-winter) for the 20 year period 1971 - 1990, with each dot representing results from one Quinary Catchment

Table 2.4.1 Performance statistics from verifications of January maximum and July minimum temperatures between outputs from downscaled GCMs vs. historical observations, per Quinary Catchment in South Africa

GCM	January Maximum Temperatures							July Minimum Temperatures						
	Regression				Through Zero			Regression				Through Zero		
	Slope	Int	R^2	Rank	Slope	R^2	Rank	Slope	Int	R^2	Rank	Slope	R^2	Rank
CGCM3.1(T47)	0.862	2.2	0.76	5	0.939	0.75	3	0.905	2.4	0.81	4	1.247	0.58	4
ECHAM5/MPI-OM	0.862	2.1	0.76	4	0.935	0.76	4	0.939	1.6	0.84	2	1.175	0.74	2
CNRM-CM3	0.889	1.1	0.77	2	0.943	0.77	1	0.957	1.2	0.86	1	1.128	0.80	1
IPSL-CM4	0.873	1.8	0.78	3	0.940	0.77	2	0.907	2.2	0.82	3	1.222	0.62	3
GISS-ER	0.901	0.5	0.70	1	0.919	0.70	5	0.887	3.2	0.78	5	1.346	0.36	5

- With slopes of the regression equations consistently less than the perfect 1.0, but > 0.86, mid-summer maximum temperatures are slightly under-simulated by all 5 the GCMs, but with the under-simulations being higher (by up to 3 °C; **Figure 2.4.2**) in those Quinaries experiencing high January maxima.
- The implication is that the GCMs are not consistently capturing day-time high temperatures in the summer months.
- From a perspective of combining the rankings of the R^2, the slope and the intercept by multiplying out the square roots of those respective rankings and then summing them, the best performing GCMs for January maximum temperature are GISS-ER and CNRM-CM3 while the worst performing of the five GCMs are CGCM3.1(T47) and EHAM5/MPI-OM. However, when the regression is forced through zero, the rankings change, with CNRM-CM3 coming out as the best ranked and GISS-ER as the worst ranked of the 5 GCMs. This illustrates already that assigning any of the GCMs as being the “best” is fraught with problems of interpretation.
- There is already an indication from **Figure 2.4.2** that it may be the same Quinary Catchments that may be resulting in the outlier and inlier points that are seen in each of the scatterplots.
- In comparison, the mid-winter (July) minimum temperature verifications shown in **Figure 2.4.3**, with their statistical summaries in **Table 2.4.1**, appear to be generally better than those for their January maximum counterparts.
- R^2 values are consistently higher (0.78 to 0.86) and slopes of the regression equations closer to unity (0.887 to 0.957), with the intercepts slightly worse than those January maxima.
- Unlike the overall under-simulations of summer maximum temperatures, winter minima tend to be over-simulated, and while in the warmer regions winter minima are well simulated, the over-simulation can be up to 3 - 5 °C in the very cold interior parts of South Africa.
- The best overall performing of the 5 GCMs for July means of daily minimum temperatures for the 5 838 Quinaries, according to the statistics given in **Table 2.4.1**, was CNRM-CM3 (rank 1 for the complete regression and when forced through zero) while GISS-ER simulated least satisfactorily.

Verifications of Number of Days per Annum with Rainfalls Exceeding Thresholds of 10 mm and 25 mm

Scatterplots of GCM simulated days per annum with rainfalls exceeding 10 mm and 25 mm vs. those derived from historical data are shown for each of the 5 GCMs used in this study for the 5 838 Quinaries covering South Africa in **Figures 2.4.4** and **2.4.5**, with performance statistics of the verifications summarised in **Table 2.4.2**.

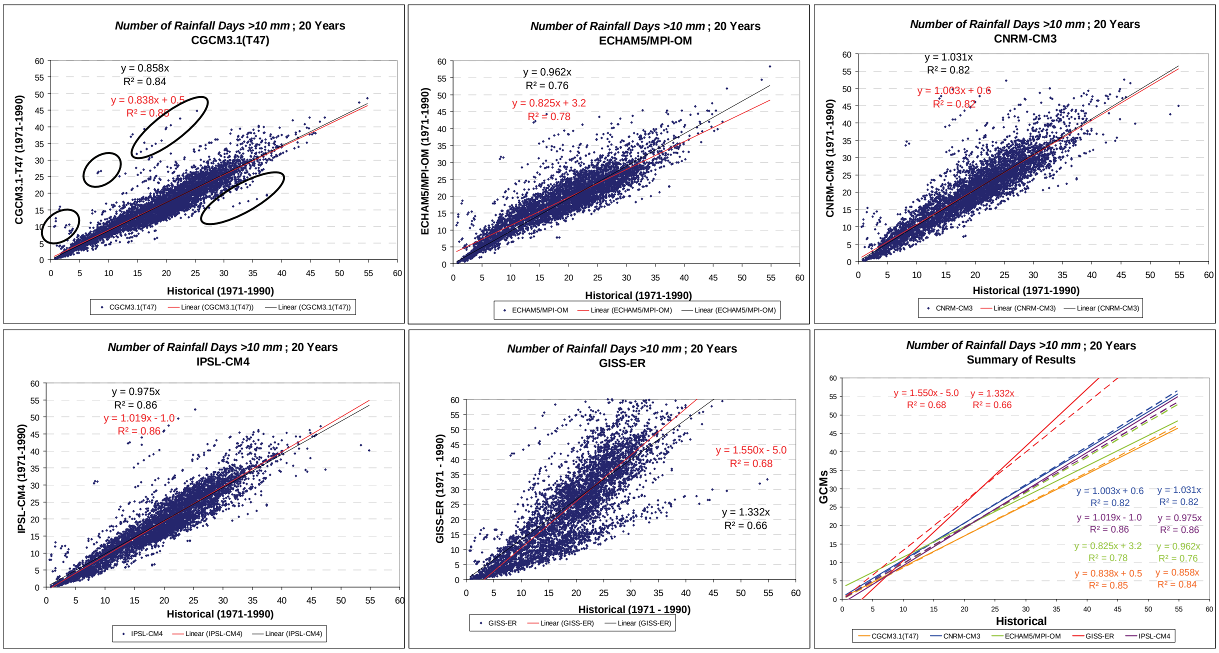

Figure 2.4.4 Scatterplots of GCM derived vs. historically observed number of days per year with 10 mm or more of rainfall per day for the 20 year period 1971 - 1990, with each dot representing results from one Quinary Catchment

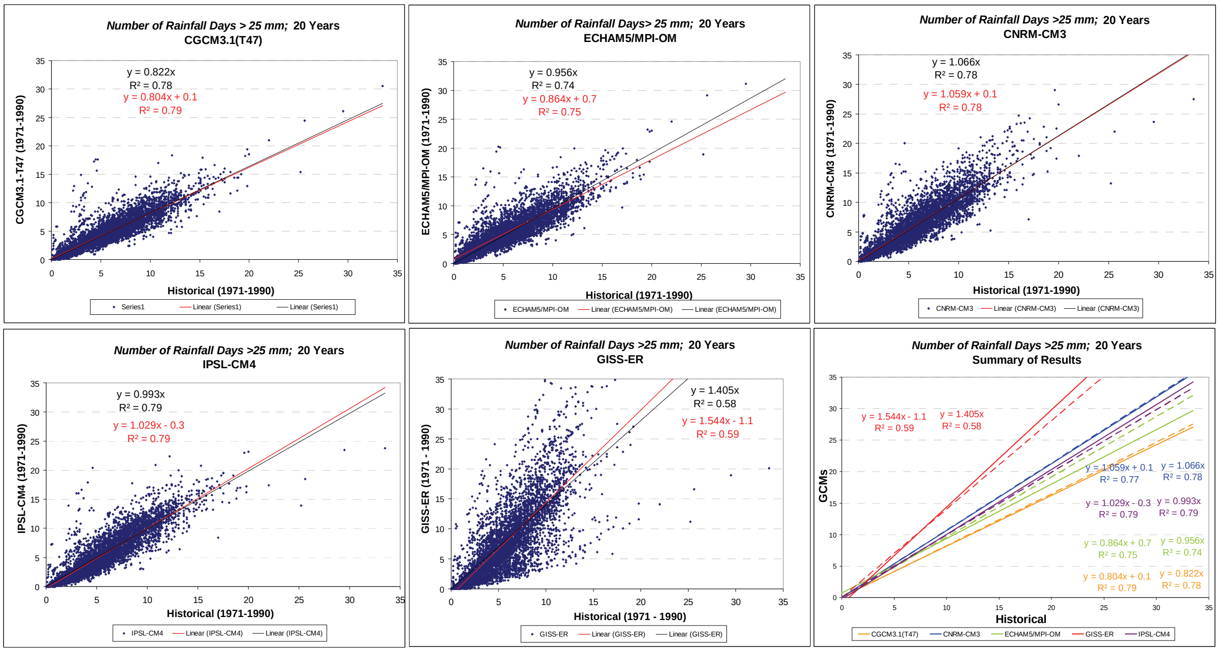

Figure 2.4.5 Scatterplots of GCM derived vs. historically observed number of days per year with 25 mm or more of rainfall per day for the 20 year period 1971 - 1990, with each dot representing results from one Quinary Catchment

Table 2.4.2 Performance statistics on numbers of days per year with rainfall ≥ 10 mm and ≥ 25 mm between outputs from downscaled GCMs vs. historical observations, per Quinary Catchment in South Africa

GCM	Days with Rainfall > 10 mm							Days with Rainfall > 25 mm						
	Regression				Through Zero			Regression				Through Zero		
	Slope	Int	R^2	Rank	Slope	R^2	Rank	Slope	Int	R^2	Rank	Slope	R^2	Rank
CGCM3.1(T47)	0.838	0.5	0.85	1	0.858	0.84	3	0.804	0.1	0.79	2	0.822	0.78	3
ECHAM5/MPI-OM	0.825	3.2	0.78	4	0.982	0.76	2	0.864	0.7	0.75	4	0.956	0.74	3
CNRM-CM3	1.003	0.6	0.82	1	1.031	0.82	4	1.059	0.1	0.78	1	1.066	0.78	2
IPSL-CM4	1.019	1.0	0.86	1	0.975	0.86	1	1.029	0.3	0.78	3	0.993	0.79	1
GISS-ER	1.550	5.0	0.68	5	1.332	0.66	5	1.544	1.1	0.59	5	1.405	0.58	5

- When assessing the verifications of the numbers of days per annum with rainfall exceeding 10 mm and 25 mm, the scatterplots in **Figure 2.4.4** and **2.4.5** and the summary of results in **Table 2.4.2** show clearly that the GISS-ER GCM performs markedly worse than the other four GCMs. This study was subsequently advised through the CSAG in 2010 that the Goddard Institute for Space Studies (GISS) had detected an error in its rainfall generation in southern Africa, particularly in a block covering KwaZulu-Natal, the Free State and Eastern Cape, as shown in **Figure 2.4.6**. Following this announcement, the rainfall related maps in this report showing results from multiple GCMs then had to be re-done, omitting the GISS-ER GCM's results.

Figure 2.4.6 Regions within South Africa where an error was identified by the GISS with rainfall estimates from the GISS-ER GCM (Source of information: CSAG, 2010)

- Verifications on days with rainfall > 10 mm for the other four GCMs display overall satisfactory statistics, with R^2 values in the range of 0.78 to 0.86, slopes varying from 0.825 to 1.019 and intercepts from 0.5 to 3.2, with the lowest performance from ECHAM5/MPI-OM.
- The scatterplots of verifications on days with rainfall above specific thresholds exhibit more Quaternaries as outliers and inliers than those of temperature variables, as shown in **Figures 2.4.4 and 2.4.5**. As in the case of temperature, it is apparently the same Quinaries that result in the outliers and inliers which appear on the scatterplots of all GCMs and, by way of example, some of these groups of anomalies have been ringed in **Figure 2.4.4**.
- For the more stringent test of days per year with rainfall > 25 mm, the statistics are not quite as good as for > 10 mm and, barring GISS-ER results, R^2 values are in the range of 0.75 to 0.79, slopes vary from 0.804 to 1.059, while the intercepts are better at 0.1 to 0.7.

Is it Important to Omit Results from the GISS-ER GCM?

Numerous visual comparisons were undertaken to assess the significance of the decision to omit results from the GISS-ER GCM. For relatively broad representations, for example on annual rainfall statistics, the mapped differences are small and certainly do not alter overall patterns of change, as illustrated in **Figure 2.4.7**. For higher order statistics such as changes in standard deviations and for projected changes in patterns across South Africa for more specific times of the year the visual differences are somewhat more apparent, as shown in **Figure 2.4.8**, but the overall "big picture" still does not change as markedly as anticipated. The results from the GISS-ER GCM were nevertheless omitted from further multiple GCM analyses involving rainfall and, in some cases, also temperature.

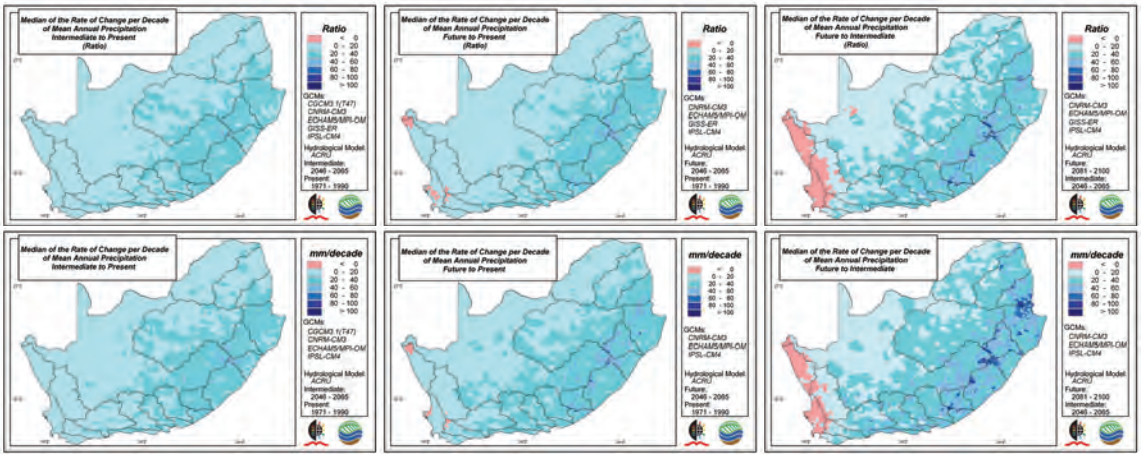

Figure 2.4.7 Maps of median rates of change per decade in mean annual precipitation for various time periods illustrating the small differences between including results from the GISS-ER GCM (top row) and excluding the GIS-ER results (bottom row)

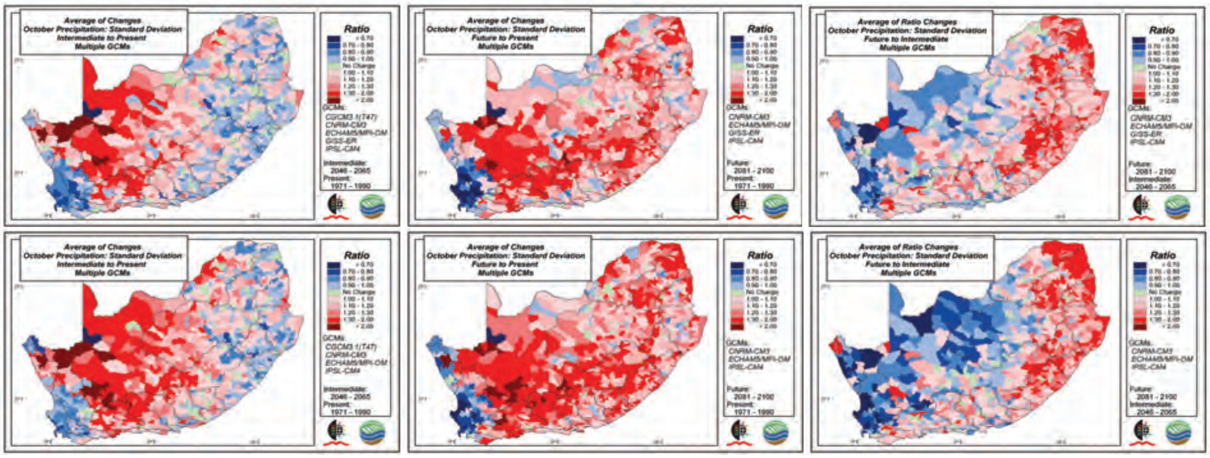

Figure 2.4.8 Maps of averages of changes in the standard deviation of October precipitation for various time periods illustrating the small differences between including results from the GISS-ER GCM (top row) and excluding the GIS-ER results (bottom row)

Spatial Error Analyses of Critical Temperature and Rainfall Variables

Following the statistical verifications in the sections above, an attempt was made to identify *where* in South Africa the errors occurred between the GCM derived and historical variables, and whether spatial patterns of errors varied from variable to variable. Thus, the spatial error analysis of January (mid-summer) maximum temperatures in **Figure 2.4.9** shows small errors of < 0.5 °C and between 0.5 °C and 1.0 °C (top left and centre maps) to occur for 3 or more GCMs in patches in the east, while errors of 1.0 to 2.0 °C (top right) are found for the majority of the GCMs used in this study in the northern third of the region and in patches in the east. On the other hand, large errors in January maxima in excess of 2 °C (bottom left) are found for three or more GCMs in the central parts and what are considered very large differences between GCM and observed, *viz*. > 3 °C, are identified in the south and central areas (bottom right map).

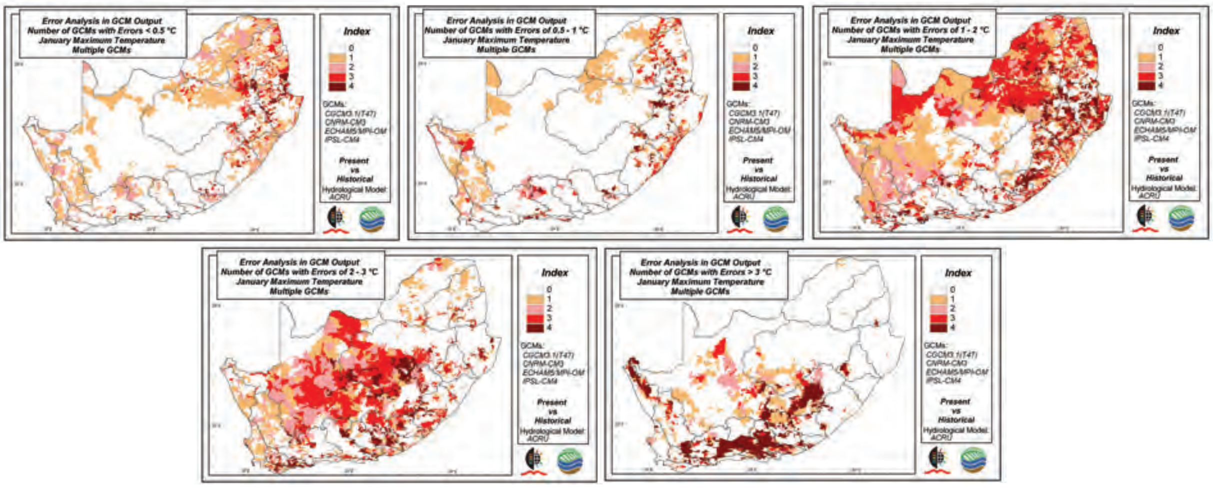

Figure 2.4.9 Spatial comparison of errors of different magnitudes of January (mid-summer) maximum temperatures between GCM derived vs. historically observed values

The spatial analysis for July (mid-winter) minimum temperatures shown in **Figure 2.4.10**, on the other hand, displays quite different error patterns across South Africa to those of January maxima for the same categories of differences between GCM derived and historically observed values for an identical time period of 1971 - 1990.

The conclusions reached from the above analyses is that errors between maximum and minimum temperatures are not spatially concurrent and that errors of different magnitudes occur at different locations for both maximum and minimum temperatures. As a summary, the spatially averaged errors from the 4 GCMs used in this particular study, given in **Figure 2.4.11**, show that for January maximum

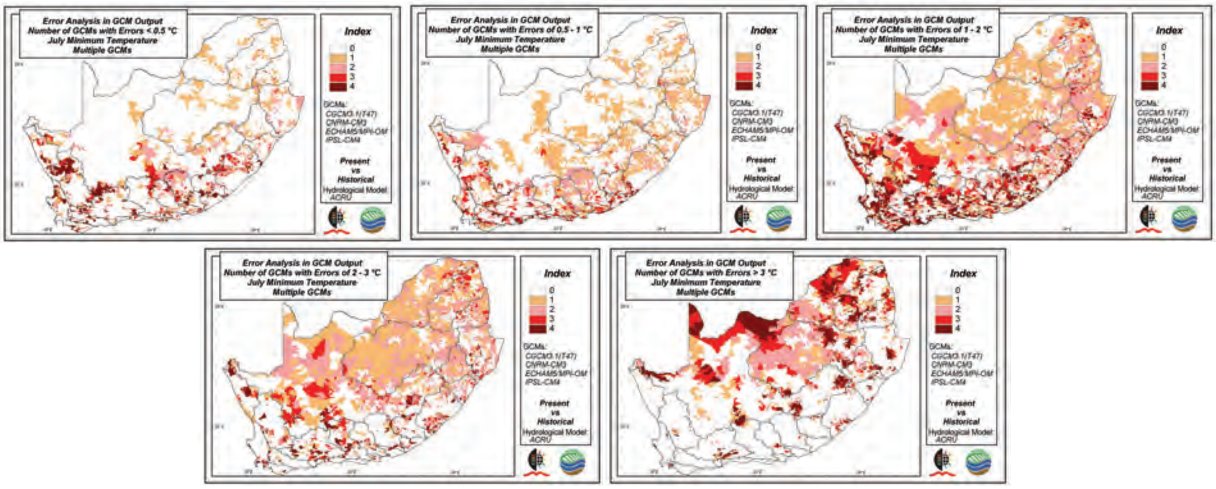

Figure 2.4.10 Spatial comparison of errors of different magnitudes of July (mid-winter) minimum temperatures between GCM derived vs. historically observed values

temperatures the major errors are found in the central - south regions of South Africa while for mid-winter minima the largest errors are located in the northern parts. The spatial discrepancies of maximum and minimum temperature errors may have hydrological repercussions in analyses of projected changes in evaporative losses, as an important driver of evaporation is the vapour pressure deficit which is derived from temperature ranges.

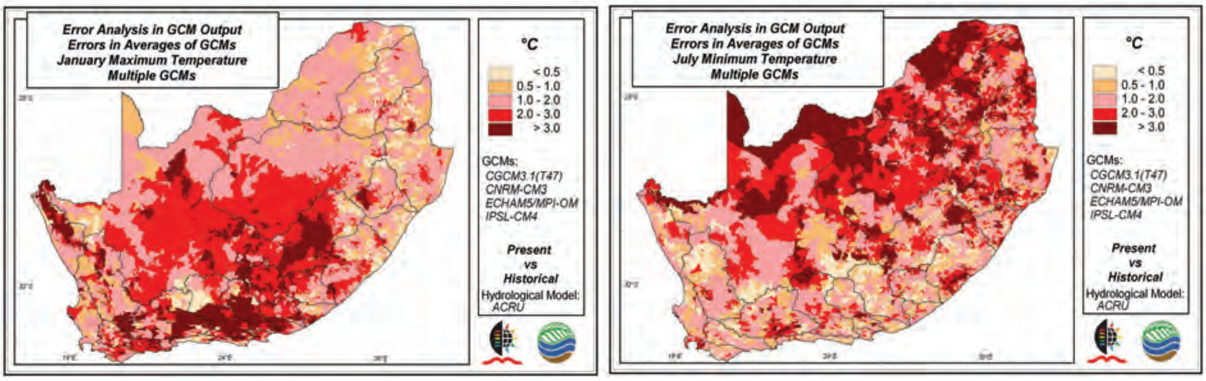

Figure 2.4.11 Comparison of error analyses between January (mid-summer) maximum and July (mid-winter) minimum temperatures

In the case of the spatial error analysis of a hydrologically critical rainfall statistic, *viz*. the number of days per annum with rainfall events exceeding 10 mm, areas where small (10 - 20 %) and medium (20 - 50 %) differences between GCM derived and historically observed values for the same period 1971 - 1990 are found to concur in the southern half and northeastern periphery of South Africa (**Figure 2.4.12** top maps). What appear as larger (50 - 100 %) and very large (> 100 %) differences occur over relatively small patches, mainly in the southern half of the region. Significantly, however, the patches of apparently large discrepancies between GCM and observed big rainfall events overlaps almost entirely with those areas identified by Warburton and Schulze (2005) as having a statistically low reliability of observed rainfall data (cf. **Figure 2.4.12** middle maps and **Figure 2.4.12** bottom map).

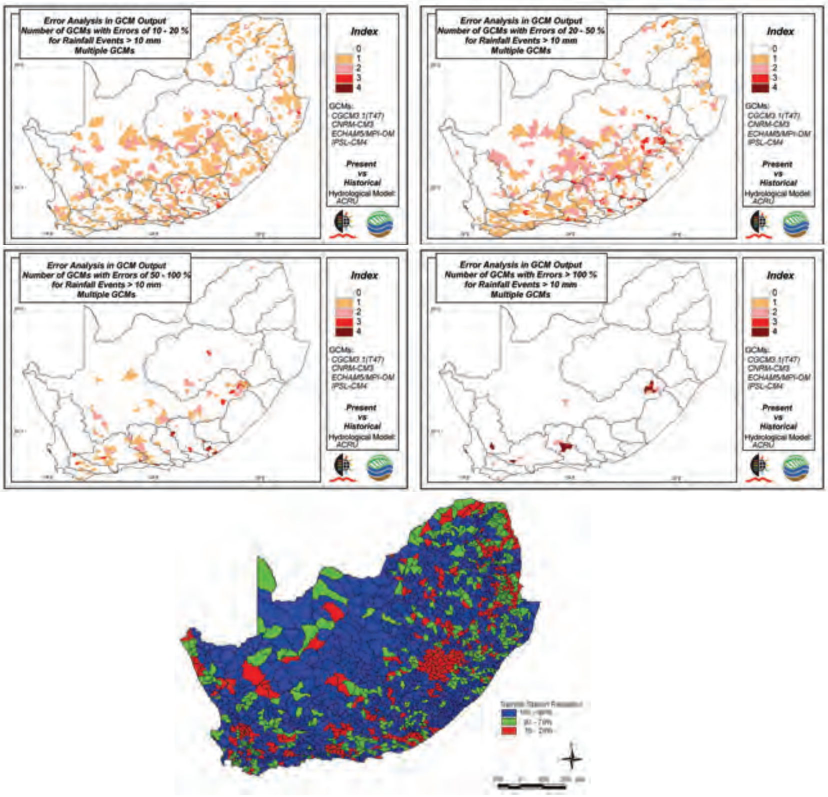

Figure 2.4.12 Spatial comparison of errors of different magnitudes between days per annum with rainfalls >10 mm derived from GCMs vs. historical observations (top rows), and a map of reliability of rainfall estimates from Warburton and Schulze (2005)

On the Question of Whether there is a “Best” GCM for Use in South Africa

Considering the vast amount of time and effort expended in producing maps of projected impacts of climate change on hydrological (and other) responses from multiple GCMs with the limited expertise available in South Africa, the question is often posed if climate change impact studies could not be simplified by identifying one “best” GCM for this region and applying just that one. While the international and local climate change literature warns against the danger of using a single GCM’s output (e.g. Hewitson *et al*., 2005b; Schulze *et al*., 2005; Schulze *et al*., 2010; Knoesen, 2011) in regard to South African studies) because of the uncertainties remaining in climate change projections (e.g. Cox and Stephenson, 2007; Giorgi *et al*., 2008; Jacob and van den Hurk, 2009), the hypothesis of possibly identifying a “best” GCM for South Africa was nevertheless tested using the 5 GCMs originally available for this study.

Assuming values of hydrological variables mapped across South Africa and derived from historically observed daily precipitation and temperature to be “correct” (although it has been shown by Lynch, 2004; Schulze and Maharaj, 2004; Warburton and Schulze, 2005; that this is not so everywhere), areas were mapped where a particular GCM’s output for a variable performed “best” against values for that variable derived from the historical values for the same time period, *viz*. 1971 - 1990. Areas were also mapped where that particular GCM performed “second best” (on condition that second best was within 2 % of another GCM which was the best). In **Figure 2.4.13** the “best” GCM is always shaded in a dark hue of a specific colour (e.g. ECHAM5/MPI-OM in blue) while a lighter hue of the same colour is used where that GCM qualified as “second best”.

Two observations are made from the results in **Figure 2.4.13**, *viz*.

- no one GCM dominates as being the “best” or even “second best” over the whole of South Africa, although one or the other GCM might be the “best” over a specific area; and
- for different hydrologically important variables such as reference potential evaporation or rainfall or accumulated streamflows the patterns of where one or the other GCM performs “best” differs quite markedly from one variable to the next; and, in short,
- there is therefore no single “best” GCM for use in climate change impact studies in South Africa.

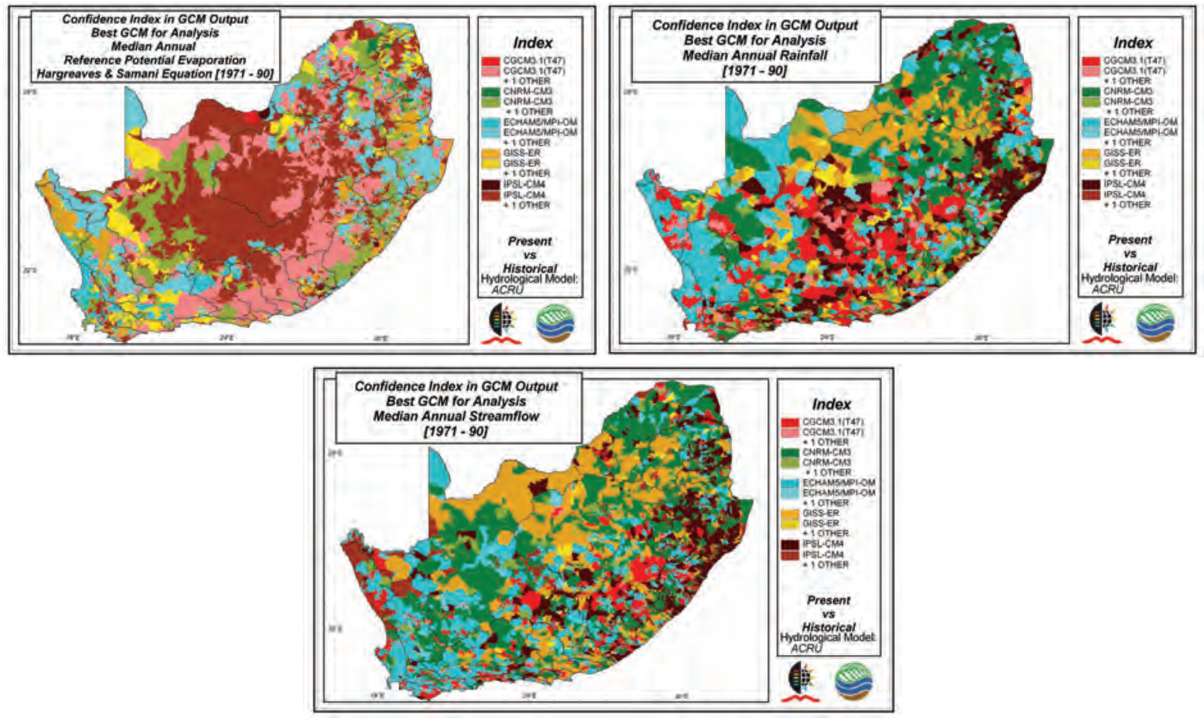

Figure 2.4.13 Spatial analysis of “best” and “second best” GCMs for different hydrological variables

Concluding Thoughts

This verification study used outputs from the 5 GCMs applied in this research in order to assess the performance of those specific GCMs in regard to their usefulness in impact studies of projected climate change on hydrological responses. By and large the verifications showed the final selection of GCMs to generate relatively good results for hydrologically critical temperature and rainfall parameters. Spatial error analyses showed apparent errors in GCM output to vary by parameter and it was determined that no single GCM was the "best" for all regions within South Africa, nor for all hydrological drivers and responses. Some of the apparent GCM output errors can, in fact, be attributed to errors in the historical datasets which were used as the control in the verifications. The same Quinary Catchments appear to produce outlier results with all the GCMs used, which begs the question of re-checking the historical datasets. There furthermore appear to be regional biases in GCM outputs and subsequent impact studies should therefore consider regional bias corrections to temperature and rainfall output before being used with hydrological models.

However, many of these apparent errors and causes of uncertainties are considered to be largely self-cancelling and / or largely eliminated since the impacts in the chapters which follow are expressed as ratio changes between projected future and present climates, both derived from GCMs, with these projected changes then mapped as the mean or median of the results from the multiple GCMs used.

Acknowledgement

The scatterplots and maps presented in this Chapter were produced by Lauren Bulcock, whose input is acknowledged with thanks.

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SECTION 3

PROJECTED CHANGES TO FIRST ORDER CLIMATE VARIABLES

CHAPTER 3.1

CLIMATE CHANGE AND
ANNUAL TEMPERATURE STATISTICS:
A 2011 PERSPECTIVE

R.E. Schulze and R.P. Kunz

The Importance of Temperature

Temperature is a basic climatological parameter used frequently as an index of the energy status of the environment. It is the one climatic variable for which there is a high degree of certainty that it will increase with global warming. Temperature has a direct effect on all forms of life on earth. It affects a wide range of processes which, in the context of crops and natural vegetation, includes biomass production, areas within which crops can grow optimally or where a given natural vegetation type can occur in regard to temperature limits, under current as well as future climates. This affects hydrological responses indirectly. More directly, temperature affects rates of evaporation now and under projected global warming (cf. **Chapter 2.1**).

Because temperature measurement is a simple procedure, because long term temperature data are relatively abundant, and because the physical basis for interpolating and extrapolating temperature values to locations where it is not measured is well understood, it is not surprising that temperature *per se*, and derivatives thereof, are frequently used as input variables to a wide range of hydrological and other applications, from the estimation of solar radiation and relative humidity to utilising those two variables in estimations of potential evaporation.

It is for all of the above-mentioned reasons that projected changes in annual temperature statistics are addressed in this Chapter.

By the term temperature the *air temperature* at Stevenson screen height is usually inferred, and this is taken as being representative of the surrounding area.

Factors Affecting the Distribution of Temperature over South Africa

Since isotherms on temperature maps are constructed using estimates of temperature parameters at locations where temperature is not measured, these estimates have to be derived from equations containing variables which physically and intuitively account for the main factors affecting the distribution of temperature. In previous studies in South Africa, Schumann and le Roux (1940) had shown that altitude, total monthly rainfall and latitude all had a significant influence on mean monthly temperatures, while Schulze (1979; 1982; 1983) also used altitude and latitude, and in addition longitude, in the development of multiple regression equations for temperature in KwaZulu-Natal. The factors used in the 1997 *South African Atlas of Agrohydrology and -Climatology* (Schulze, 1997) and which generally influence the distribution of temperatures are as follows:

- ***Latitude***: South Africa extends from 22 °S - 34 °S, and with increasing latitude southwards, temperatures generally decrease, all else being equal.
- ***Altitude***: Generally the higher the altitude, the lower the temperature. However, the rate of decrease of temperature with altitude, i.e. the so-called standard adiabatic *lapse rate*, is not constant, but varies with season, region, proximity to oceans, altitude and between maximum and minimum temperatures (cf. Schulze and Maharaj, 2004).
- ***Continentality*** (i.e. distance from ocean): Oceans have a moderating influence on temperature, with relatively smaller variations near marine locations giving way rapidly to increases in daytime and decreases in night-time temperatures inland, where less humid conditions favour strong daytime solar radiation and night-time outgoing radiation.
- ***Temperature Region***: South Africa is made up of a series of regions in which different dominant factors determine temperature regimes in different seasons of the year, with different interactions between the factors. This is so because the country is flanked by a warm ocean along the east and south coasts and a cold ocean along its west coast, a narrow coastal strip rising rapidly to over 3 000 m altitude often within 150 km and a vast interior plateau - and all of this within the

22 °S to 34 °S latitudinal zone which is characterised by seasonally variable air masses / synoptic conditions. It is for these reasons that temperature *regions* are an important factor affecting temperatures. Temperature regions were originally delimited by Clemence (1986), were subsequently modified by physiography (Schulze and Maharaj, 1991) and were used extensively in the generation of the 50 year time series of daily temperature for each Quinary Catchment making up South Africa (Schulze and Maharaj, 2004).

- ***Topographic Index***: Night-time cold air drainage into valley bottoms, resulting from radiative cooling of uplands and valley slopes under clear sky conditions, is well documented in South Africa. Occurring during the cooler months, cold air drainage assumes importance in hilly inland areas (Tyson *et al*., 1976).
- ***Longitude***: This factor is region dependent, being important mainly in those regions with an east-west alignment.

All these factors affect the potential evaporation over South Africa through their influence on temperature parameters. Of these factors latitude, altitude, continentality, the topographic index and longitude are in essence invariate factors, but their interactions with perturbed synoptic conditions resulting from global warming are likely to have important macro- to micro-climatic effects on temperature regimes.

Annual Temperature Statistics

Of the various statistics of annual temperature, mean annual temperature, MAT, represents one of the very broadest of indices of the environmental status of a location. While in itself not a particularly useful statistic because it has integrated and smoothed the effects of diurnal, monthly and seasonal patterns of maximum and minimum temperatures, it is nevertheless commonly used as a descriptor of the climate of a location or region and as a point of departure in climate change studies. The method by which MAT has been derived for South Africa is described in **Box 3.1.1**.

Box 3.1.1 Determination of Statistics of Annual Temperatures over South Africa

Time series of daily maximum and minimum temperatures from over 970 qualifying temperature stations from the RSA, Lesotho and Swaziland were generated from quality controlled data for a common 50 year period (1950 - 1999) using the infilling and record extension techniques developed by Schulze and Maharaj (2004). From these time series at the point locations (i.e. at the qualifying temperature stations), 50 years of daily maximum and minimum temperature values were generated at each of 422 591 one arc minute (~ 1.7 km x 1.7 km) raster points covering South Africa, using regionally and seasonally determined lapse rates and other physically appropriate spatial interpolation approaches. These are given in detail in Schulze and Maharaj (2004).

From this gridded daily temperature database a raster point was selected near the centroid of each Quinary Catchment and at an altitude approximating that of the mean altitude of that Quinary, to represent typical temperatures for that Quinary (cf. **Chapters 2.1** and **2.2**). The daily temperature time series at that point was then used to compute annual temperature statistics for the historical (i.e. baseline) time period.

For present and intermediate future climate projections the daily temperature outputs from the five GCMs available to this study were used, downscaled to station values and adjusted by lapse rates to be representative of temperatures of Quinary Catchments. The same procedure was followed for more distant future climate scenarios, except that output from only four GCMs was available.

From these daily values of maximum and minimum temperatures, statistics of annual temperatures could then be computed for South Africa for the GCM derived scenarios.

Distribution Patterns over South Africa of Annual Temperature Statistics under Baseline (Historical) Climatic Conditions

Patterns of mean annual temperatures in **Figure 3.1.1** display two major characteristics, *viz*.

- high MATs exceeding 22 °C along the northeastern coastal belt and the eastern border, and to a lesser extent along the northern border, of South Africa, and
- the temperature irregularities induced by topographic features, for example, the lower the MATs along the escarpment perimeter of South Africa and particularly the low MATs over most of Lesotho (< 12 °C).

A belt of negative values of the skewness coefficient is evident from northwest to the southeast across South Africa, while positive values persist along the coastal periphery (**Figure 3.1.1** top right). In regard to absolute variability, standard deviations of annual temperatures display high values in excess of 0.50 °C in the interior, with values below 0.35 °C along the coastal periphery and up to ~ 400 km inland, reflecting the moderating oceanic influence on temperature variability (**Figure 3.1.1** bottom left). In regard to relative deviations of annual temperatures, the high values of the coefficient of variation in the highlands of Lesotho (**Figure 3.1.1** bottom right) are the result of the low temperatures there as much as of high absolute variability of annual temperatures.

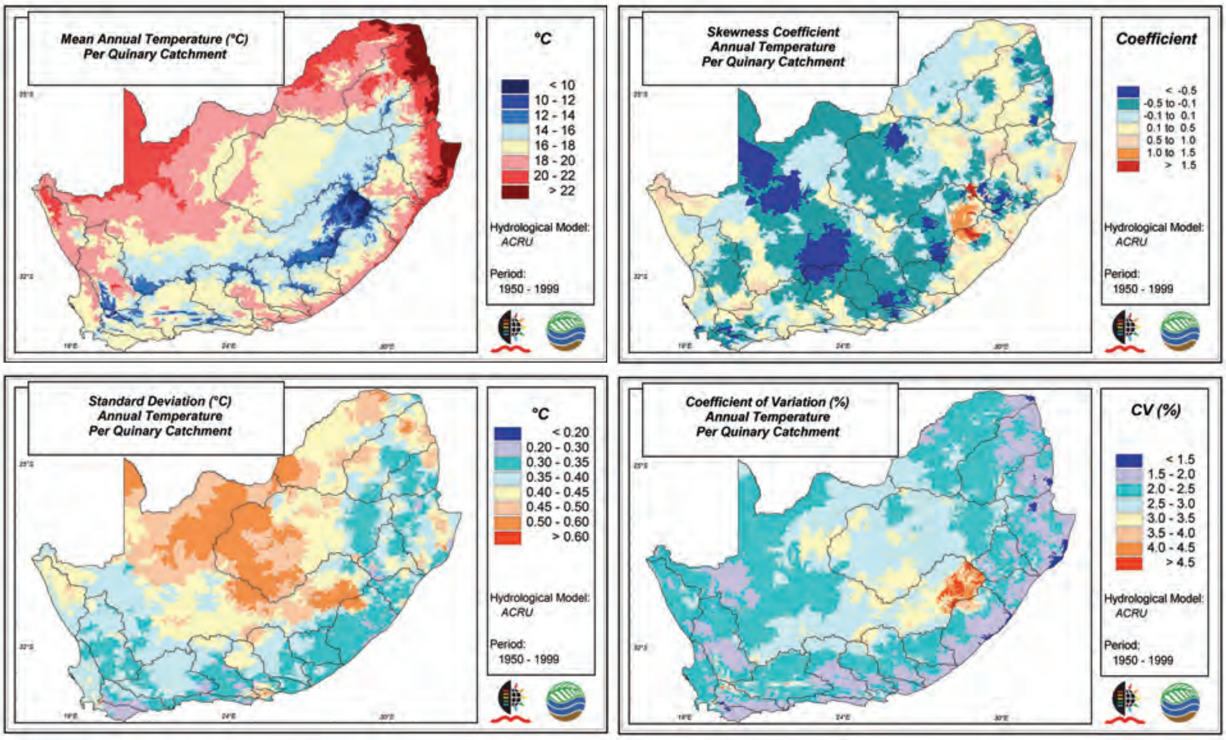

Figure 3.1.1 Mean annual temperature (top left), the skewness coefficient of annual temperatures (top right), as well as the standard deviation and coefficient of variation of annual temperatures (bottom left and right), for baseline (historical; 1950 - 1999) climatic conditions

Averages of Changes in Projected Future Means of Annual Temperatures, and Rates of Change per Decade, Using Output from Multiple GCMs

Using output generated from multiple GCMs with the A2 emissions scenarios (cf. **Chapter 2.1**), **Figure 3.1.2** (left) shows that by the intermediate future (2046 - 2065) the coastal periphery of South Africa, extending inland to ~ 200 km, is projected to experience MAT increases averaging 2.0 - 2.5 °C, with most of the interior showing increases of between 2.5 and 3.0 °C and with the extreme northwest averaging increases in excess of 3 °C. By the more distant future towards the end of this century, the south and east coast belts, up to ~ 100 km inland, are projected to experience MATs 4.0 - 5.0 °C higher than those of the present, with the central interior likely to have MATs in excess of 6 °C of today's values (**Figure 3.1.2** middle).

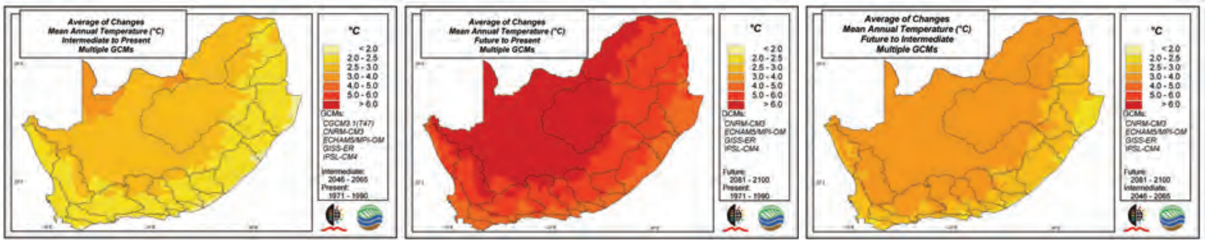

Figure 3.1.2 Average of changes (°C), using output from multiple GCMs, of mean annual temperatures between the intermediate future and present (left), the more distant future and present (middle) and the more distant and intermediate future climate scenarios (right)

Expressing these increases in MATs from multiple GCMs as changes *per decade*, which is easier for users to conceptualise, it is shown in **Figure 3.1.3** (left) that in the 7.5 decades from the present (1971 - 1990) to the intermediate future (2046 - 2065) the projected rate of increase is 0.25 - 0.50 °C per decade. However, for the 11 decades which span the period from the present to the more distant future, the average rate of increase is 0.50 - 0.75 °C, i.e. a near doubling (**Figure 3.1.3**, middle). If the A2 emissions scenario does, indeed, play out then the implication is that in the 3.5 decades from the intermediate future (2046 - 2065) to the more distant future (2081 - 2100) the rate of temperature increase is in excess of 0.75 °C per decade over much of South Africa's interior and, indeed > 1.0 °C per decade in the central and northwest interior covering much of the Northern Cape and North West provinces (**Figure 3.1.3**, right).

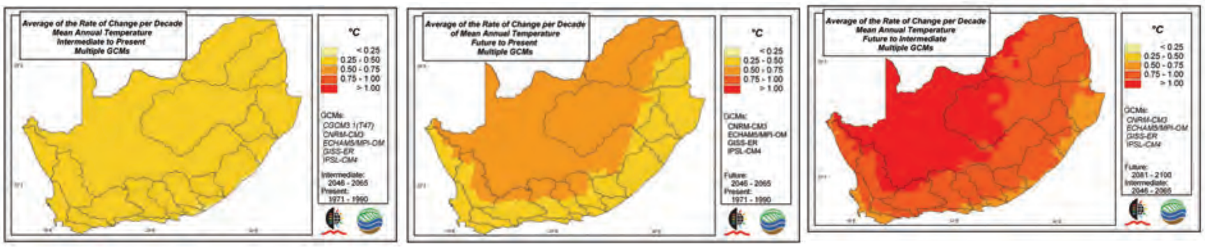

Figure 3.1.3 Average of changes (°C) per decade, using output from multiple GCMs, of mean annual temperatures between the intermediate future and present (left), the more distant future and present (middle) and the more distant and intermediate future climate scenarios (right)

These results highlight two features of projected global warming from the multiple GCMs used in this study, *viz*.

- the moderating influence of the oceans with both the intermediate and the more distant future projections displaying progressively higher changes in MATs from coast to the interior and, secondly,
- the accelerating increase in temperatures projected over time, which is well illustrated by the decadal change maps (**Figure 3.1.3**) with the rate of change per decade in the more distant future being nearly twice that of the rate to the intermediate future.

Averages of Ratio Changes in the Variability of Annual Temperatures, Using Output from Multiple GCMs

Changes in the inter-annual variability of temperature have repercussions in the year-to-year variability in evaporative losses (cf. **Chapters 4.1** and **9.1**) and in numbers of irrigation applications per annum (cf. **Chapter 9.2**). When assessing changes in the variability of temperature it is important to apply an *absolute* statistic of variability such as the standard deviation (as defined in **Chapter 1.3**). **Figure 3.1.4** (left) shows that by the middle of this century in the intermediate future the average of the ratio changes in the standard deviation of annual temperatures is projected to increase by ~ 10 % over much of South Africa, with increases in excess of 30 % in the north. However, some (mainly mountainous) regions in the south and west display areas with no marked change and even areas where the inter-annual variability of temperature is projected to decrease by up to 10 %.

When the average of year-to-year variability of temperatures projected by multiple GCMs in the more distant future period is compared with that of the present period (**Figure 3.1.4**, middle), the entire country displays increases in variability in excess of 30 % (i.e. ratios > 1.30) and in the extreme northeast even a doubling of the present standard deviation. The reason for this is the marked increase in variability of annual temperatures in the 35 year period between the intermediate and more distant future scenarios (**Figure 3.1.4**, right) - indicative again of the significant changes in climates which could occur later in the century if the A2 emission scenarios become a reality in the future.

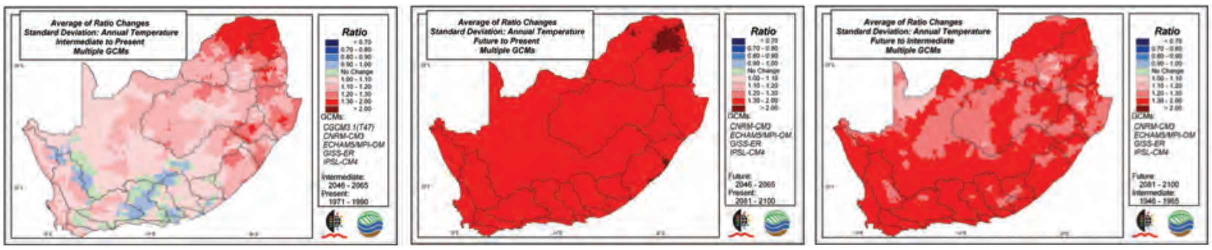

Figure 3.1.4 Average of changes, using output from multiple GCMs, in the standard deviation of annual temperatures between the intermediate future and present (left), the more distant future and present (middle) and the more distant and intermediate future climate scenarios (right)

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CHAPTER 3.2

CLIMATE CHANGE AND
JANUARY MAXIMUM AND JULY MINIMUM TEMPERATURE STATISTICS:
A 2011 PERSPECTIVE

R.E. Schulze and R.P. Kunz

Importance of Intra-Annual Temperature Fluctuations (Adapted from Schulze and Maharaj, 2008)

- Monthly statistics of January day-time maximum temperatures and July night-time minima represent, respectively, the mid-summer and mid-winter extremities of temperatures.
- High day-time temperatures are important hydrologically in that they affect rates of evaporation, occurrences and levels of plant water stress and frequencies of irrigation applications.
- Low night-time minima influence the beginning and end of periods of plant senescence and, with that, periods of active transpiration and hence active soil water loss.
- Both day-time maximum and night-time minimum temperatures are projected to increase markedly with global warming, but not at the same rate nor with the same spatial patterns.
- The methodology used to compute daily maximum and minimum temperatures for baseline and future climate scenarios is described in **Box 3.2.1**.

Box 3.2.1 Determination of Monthly Means of Daily Maximum and Minimum Temperatures over South Africa (Adapted from Schulze and Maharaj, 2008)

Time series of daily maximum and minimum temperatures from over 970 qualifying temperature stations were generated from quality controlled data for the common 50 year period 1950 - 1999 using infilling and record extension techniques developed by Schulze and Maharaj (2004). From these time series at the point locations (i.e. at the qualifying temperature stations), 50 years of daily maximum and minimum temperature values were generated at each of 422 591 one arc minute (~ 1.7 km x 1.7 km) raster points covering South Africa, using regionally and seasonally determined lapse rates and other physically appropriate spatial interpolation approaches. These are given in detail in Schulze and Maharaj (2004).

From this gridded daily temperature database a raster point was selected near the centroid of each Quinary Catchment and at an altitude approximating that of the mean altitude of that Quinary, to represent typical temperatures for that Quinary (cf. **Chapters 2.1** and **2.2**). The daily temperature time series at that point was then used to compute monthly temperature statistics for the historical (i.e. baseline) time period.

For present and intermediate future climate projections the daily temperature outputs from five GCMs available to this study were used, downscaled to station values and adjusted by lapse rates to be representative of temperatures of Quinary Catchments. The same procedure was followed for more distant future climate scenarios, except that output from only four GCMs was available.

From these daily values of maximum and minimum temperatures, changes in January maximum and July minimum temperature statistics could be computed for South Africa.

January Means of Daily Maximum, and July Means of Daily Minimum, Temperatures and Their Standard Deviations, for Baseline (Historical) Climatic Conditions

As a reference against which to assess impacts of climate change, the historical record (**Figure 3.2.1**) shows that January (mid-summer) means of daily maximum temperatures are in excess of 32 °C in the northwest, while the lowest values are found along the escarpment at < 22 °C. Standard deviations of January maxima do not peak in phase with the highest temperatures in the northwest, but rather in the central northern areas. Standard deviations are lowest along the coast where inter-annual variability is moderated by oceanic effects.

The highest July (mid-winter) means of daily minimum temperatures, at > 6 to > 10 °C occur along the western, southern and eastern borders of South Africa. Much of the interior experiences July minima at ~ freezing point, with the Lesotho highlands at < - 2 °C. Standard deviations for July minimum temperatures are again lowest along the coast at < 1 °C, and rarely exceed 1.5 °C in the inland.

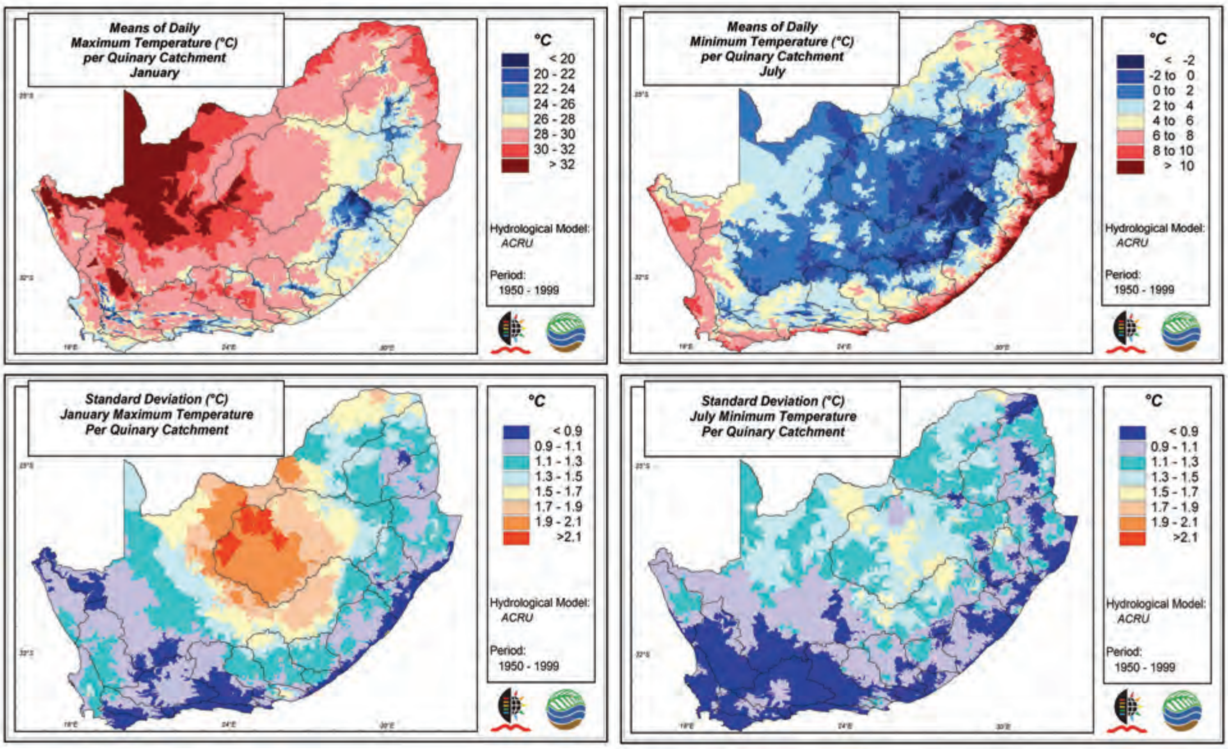

Figure 3.2.1 January means of daily maximum and July means of daily minimum temperatures (top row), and their standard deviations (bottom row), derived from baseline (historical; 1950 - 1999) daily temperature values

Averages of Changes in Projected Future Means of Summer Month Maximum and Winter Month Minimum Temperatures, and Rates of Change per Decade, Using Output from Multiple GCMs

In climate change studies it is important to appreciate that

- geographic patterns of changes in maximum and minimum temperatures are different and vary throughout the year in both the intermediate future and the more distant future, and that
- projections of temperature differences between the more distant future and the present are considerably higher than those for the intermediate future and present.

These two points are illustrated clearly in **Figures 3.2.2** to **3.2.5** in which averages of changes, derived from multiple GCMs, of January (summer) maximum (Jan_{mx}) and July (winter) minimum (Jul_{mn}) temperatures are shown. **Figure 3.2.2** (left), for example, shows that by the intermediate future averaged Jan_{mx} temperature increases are 2 °C - 3 °C with essentially an east to west gradient, while Jul_{mn} temperatures are up by a wider range from < 2 °C to > 3 °C, but with essentially a south to north gradation (**Figure 3.2.3**, left).

By the more distant future the average increases from the multiple GCMs range from 4 °C in the east for Jan_{mx} to > 6 °C in the northwest (**Figure 3.2.2**, middle), while the range for Jul_{mn} temperatures is once again wider with increases < 4 °C along the southwest coast, but with the area where projected averages are > 6 °C higher than the present increasing considerably in the interior (**Figure 3.2.3**, middle).

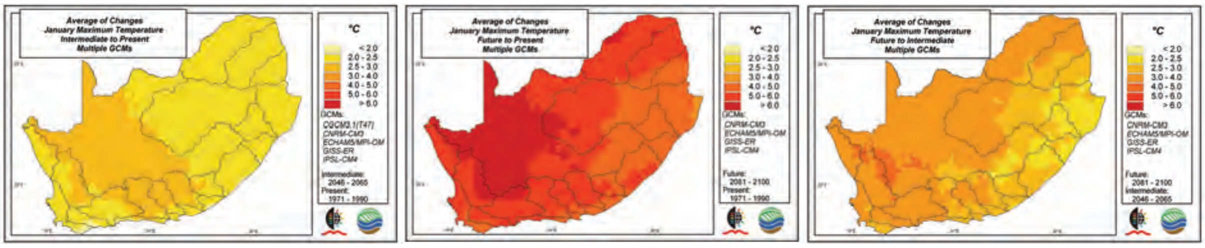

Figure 3.2.2 Average of changes (°C), using output from multiple GCMs, of means of daily maximum temperatures for January between the intermediate future and present (left), the more distant future and present (middle) and the more distant and intermediate future climate scenarios (right)

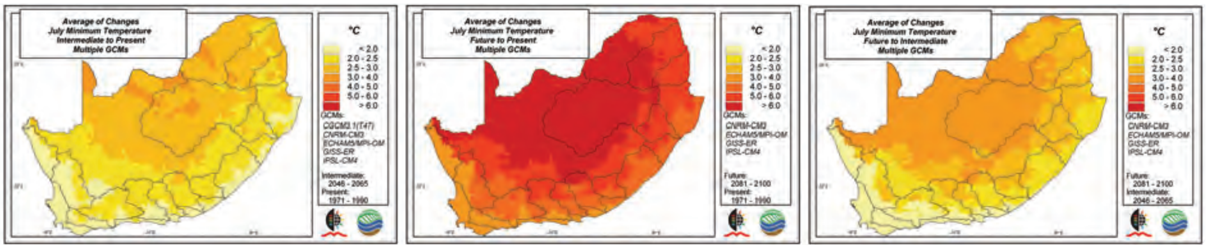

Figure 3.2.3 Average of changes (°C), using output from multiple GCMs, of means of daily minimum temperatures for July between the intermediate future and present (left), the more distant future and present (middle) and the more distant and intermediate future climate scenarios (right)

For both *Jan*$_{mx}$ and *Jul*$_{mn}$ temperatures the right hand maps of **Figures 3.2.2** and **3.2.3** show marked increases for the period between the intermediate and more distant futures. This observation is emphasised in **Figures 3.2.4** (right) and **3.2.5** (right) in which rates of change *per decade* are shown. Average rates of change per decade from multiple GCMs for both *Jan*$_{mx}$ and *Jul*$_{mn}$ temperatures are 0.25 - 0.50 °C / decade between the present and intermediate future, but between 0.50 °C and > 1.00 °C / decade between the intermediate and more distant future periods.

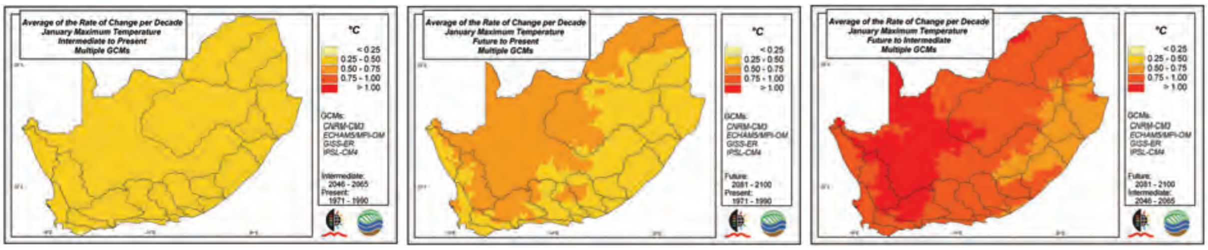

Figure 3.2.4 Average of change (°C) per decade, using output from multiple GCMs, of means of daily maximum temperatures for January between the intermediate future and present (left), the more distant future and present (middle) and the more distant and intermediate future climate scenarios (right)

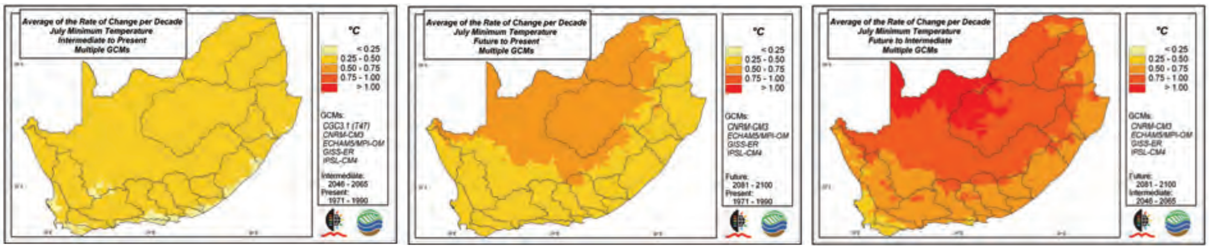

Figure 3.2.5 Average of change (°C) per decade, using output from multiple GCMs, of means of daily minimum temperatures for July between the intermediate future and present (left), the more distant future and present (middle) and the more distant and intermediate future climate scenarios (right)

Once again these results emphasise the projected acceleration of temperature increases beyond the mid-century if the A2 emissions scenarios were to materialise.

Averages of Ratio Changes in the Variability of Summer Month Maximum and Winter Month Minimum Temperatures, Using Output from Multiple GCMs

It is frequently stated in the literature that climates are likely to become more variable in future (e.g. IPCC, 2007). Using output from multiple GCMs to test this hypothesis in regard to changes in the variability of temperatures, the averages of ratio changes between the intermediate future and present climate scenarios in the standard deviation of maximum temperatures in January (i.e. in mid-summer), given in **Figure 3.2.6** (left) show reductions of ~ 10 % along the west, southeast and east coasts and their hinterlands as well as in an east to west strip. On the other hand, the central areas of South Africa display either no changes or increases in January temperature standard deviations by up to 10 %. *This map shows clearly that patterns of changes in the variability of January day-time high temperatures are neither uniform in direction nor in magnitude.*

By the end of the century (**Figure 3.2.6**, middle) very different changes in the variability of January maxima has emerged, with the central and northern interior displaying strong increases in variability (changes > 30 %), while the west coast shows strong reductions in temperature variability by up to 30 % (and more in places). This strengthening of patterns of variability in both directions is partially explained by the projected changes in standard deviations between the intermediate and more distant time periods (**Figure 3.2.6**, right).

For minimum temperatures in July (mid-winter) the averaged year-to-year variabilities derived from multiple GCMs display entirely different spatial patterns, with virtually the entire South Africa showing increases by the intermediate future of up to a doubling in places (**Figure 3.2.7**, left). Strong increases (> 30 %) in the year-to-year variability of July minima between the more distant future and present are highly concentrated in the western half and eastern quarter of South Africa (**Figure 3.2.7**, middle), despite some reductions projected in the period between the intermediate and more distant future climate scenarios (**Figure 3.2.7**, right).

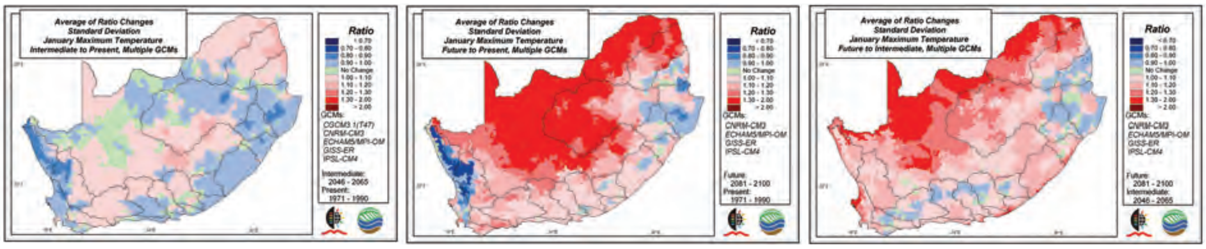

Figure 3.2.6 Averages of ratio changes, using output from multiple GCMs, in the standard deviations of January maximum temperatures between the intermediate future and present (left), the more distant future and present (middle) and the more distant and intermediate future climate scenarios (right)

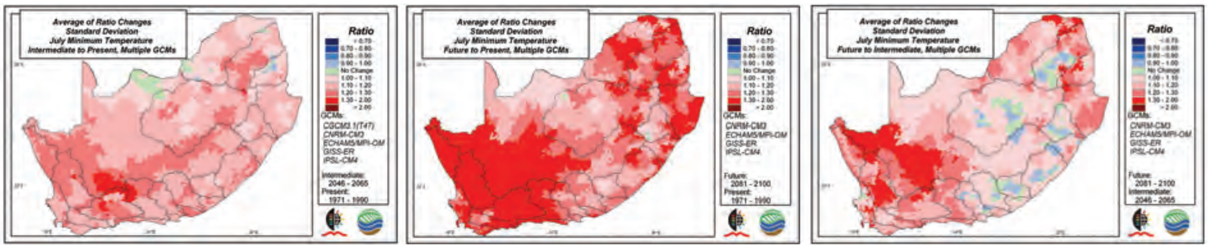

Figure 3.2.7 Average of ratio changes, using output from multiple GCMs, in the standard deviations of July minimum temperatures between the intermediate future and present (left), the more distant future and present (middle) and the more distant and intermediate future climate scenarios (right)

References

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CHAPTER 3.3

RAINFALL: BACKGROUND

R.E. Schulze

The Importance of Rainfall in Water Resources Studies

In hydrology, among the various individual climatic parameters which influence the generation of runoff, certainly in South Africa the most important is considered to be rainfall, as it is the fundamental driving force and pulsar input in many hydrological processes. In the South African context, limitations in water availability are frequently a restrictive factor in economic development.

In any detailed regional study of water resources, be it for current or for projected future climatic conditions, the focus is invariably on the patterns of rainfall in time and over an area, by asking initially

- how much it rains,
- where it rains (its spatial distribution),
- when it rains (its seasonal / temporal distribution),
- how frequently it rains, and
- what the duration and intensity of rainfall events are.

In their analyses of rainfall, however, the concerns of water resource managers (and others, such as agricultural planners) go further, since they need to consider also

- how variable the rainfall is from year to year, or for a given month, and
- how frequently droughts of a certain level of severity are likely to recur.

Since rainfall is temporally and spatially the most variable climatic element in regard to runoff production, accurate estimates of rainfall at a point or over a Quinary Catchment are therefore a basic requirement for hydrological studies, be they for baseline (historical) climatic conditions or for projections of future climates.

In hydrology a fundamental truism is that the runoff response to rainfall is non-linear, with a larger proportion of rainfall being converted to runoff when a catchment is wetter, either because a region is inherently in a high rainfall zone (as illustrated in **Figure 3.3.1**) or because the soil water content just prior to a rainfall event may have been high as a result of previous rainfall. Hydrological models are thus particularly sensitive to the rainfall input and any errors in rainfall estimates are amplified in streamflow simulations. This implies that the success of hydrological simulation studies depends to a large extent on the accuracy with which either rainfall data are observed, or rainfall values are generated from climate models such as GCMs, and how rainfall values from a point location (i.e. from a raingauge) may be adjusted to represent an area such as a Quinary Catchment.

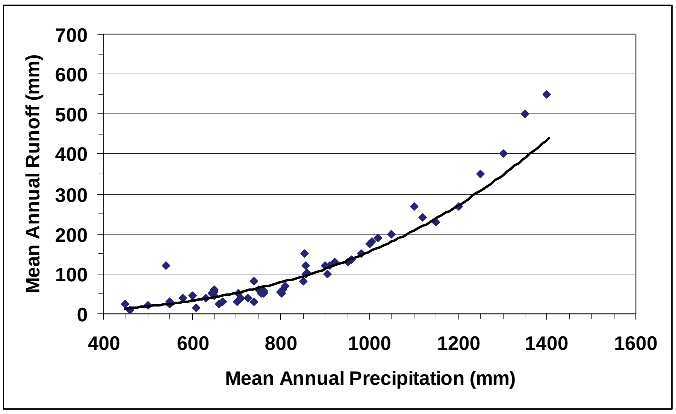

Figure 3.3.1 Rainfall : runoff relationship for selected streamflow gauging points in the summer rainfall region of South Africa (After van Biljon, Cornelius and Moore, 1987)

Many of the issues alluded to above have been addressed from a South African perspective in the *South African Atlas of Climatology and Agrohydrology* (Schulze, 2008), including

- problems associated with rainfall estimation at a point
  - what sample is actually measured by a standard South African raingauge?
  - how accurately does a raingauge measure rainfall at a point?
- raingauge networks
  - a brief history of rainfall monitoring over South Africa
  - general design considerations of raingauge networks;
- considerations regarding the spatial distribution of rainfall over a catchment as influenced, for example, by
  - altitude,
  - continentality,
  - aspect, and
  - rainfall type;
- the question of the minimum rainfall record length required for agrohydrological modelling;
- other problems associated with daily rainfall records which are of importance in agrohydrological modelling, such as
  - the standard rainfall day,
  - date phasing human error,
  - errors in data capturing,
  - extreme events, or
  - fog;
- missing rainfall records and approaches to infilling missing data;
- a suggested technique for estimating areal rainfall over a catchment, with
  - a brief overview of previous work in South Africa
  - a recommended technique for estimating daily areal rainfall in South Africa, viz. the driver station approach, including advantages of the driver station approach and disadvantages; and
- sources of rainfall data / information in southern Africa (Schulze, 2008).

Only some of the issues are raised again below because of their specific relevance to this climate change study.

Factors, which may Change with Global Warming, Affecting the Spatial Distribution of Rainfall over a Catchment (Adapted from Schulze, 2008)

1. Background

The problems associated with the spatial variation in rainfall and errors in calculating representative areal values and their hydrological effects have been considered by many researchers. All highlight the importance of preserving the spatial rainfall input and incorporating, ideally, some sort of distributed rainfall input into catchment models such as *ACRU*, even when the total rainfall depth at a raingauge is considered not to be in serious error.

The most important considerations in determining areal rainfall rely on the quantification of those factors which influence the spatial distribution of rainfall, especially the physiographic characteristics of a catchment. Mountain ranges, local topography and other physiographic features, as well as the prevailing synoptic conditions, influence the occurrence and the spatial distribution of rainfall. The variations of rainfall with altitude, slope, aspect, exposure, steepness or areal location have been investigated widely, particularly using various forms of multiple regression techniques, and for southern Africa have been documented, *inter alia*, by Whitmore (1972), Schulze (1979), Hughes (1982), Dent, Lynch and Schulze (1989) and Lynch (2004). However, the degree to which these influences on rainfall frequencies and magnitudes will change in future climates remains largely unknown.

2. Altitude

Rainfall over an area may vary considerably as a consequence of differences in altitude (cf. **Figure 3.3.2**). Whitmore (1972) stressed that over South Africa, for example, the elevation change over an area, rather than altitude *per se*, would give a better indication of the role that relief plays in the distribution of rainfall. The escalation in rainfall with rising altitude was shown by Schulze (1983), working in KwaZulu-Natal, to be the result of both an increase in the magnitude per rainfall event, as

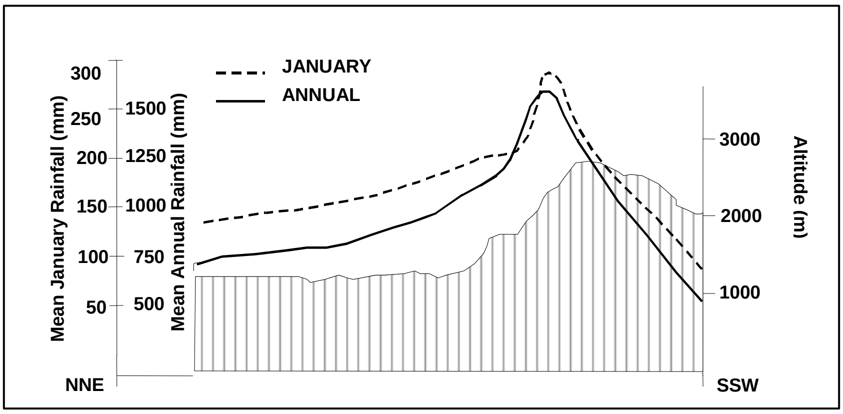

Figure 3.3.2 The rainfall : altitude relationship along a cross-section of the Drakensberg between Bergville (NNE, on the left) in KwaZulu-Natal and Mothelsesane in Lesotho (SSW, on the right), illustrating both the effects of altitude and of continentality on rainfall (After Schulze, 1979)

well as an increase in the number of rain-bearing events. Even small terrain features may play an important role in enhancing rainfall, with relatively small hills of the order of 50 m above the general ground level having been known to cause an increase of 25 % in rainfall amounts by causing the formation of low level feeder clouds with droplets too small for independent rainfall, but large enough to be coalesced by rain falling from above (e.g. Storebo, 1964). Thus, an appreciable variation in rainfall, especially under frontal systems, may occur over relatively small areas.

3. Continentality

Continentality, i.e. a measure of the distance inland from a coast or the position of a site with respect to the source of moisture, was found by Whitmore (1972) to account for 22 % of the variation in MAP in the Western Cape region. The further inland a moisture laden air mass must travel, the more likely it is that the precipitable water will be reduced due to the orographic effect of previous upliftings. The bias in the distribution of rainfall on windward vs. leeward slopes, with a flatter gradient of rainfall increase on the windward side as the moisture-laden air ascends, cools and condensation can take place, the rainfall peak occurring before the altitude peak and the steeper decline of rainfall on the leeward side as a result of less precipitable water remaining and air heating up when it is descending, is illustrated well by Schulze (1979) for the Drakensberg region between KwaZulu-Natal and Lesotho (**Figure 3.3.2**).

4. Aspect

Another important consideration in the spatial distribution of rainfall is aspect, particularly in association with direction of rain-bearing wind.

5. Rainfall Type

Because of the marked seasonal variation in rainfall type in southern Africa, with predominantly frontal systems occurring in winter and convective storms in summer, it must be stressed that these two systems will not necessarily be affected by the same topographic and meteorological conditions. Frontal systems are far more extensive and uniform than the isolated convectional systems. Hence, rainfall type is another factor affecting the areal distribution of rainfall and is likely to be markedly influenced by latitudinal shifts of rain-bearing synoptic situations in future climates.

It is factors such as the above that require careful consideration in the preparation of rainfall input for agrohydrological models in order for the rainfall to be representative of a catchment, particularly in a physiographically heterogeneous catchment, or when the driver rainfall station's record may be non-representative of the catchment's *true* rainfall. How these factors have been considered in this climate change study, or what assumptions have had to be made, has been discussed in **Chapter 2.2**.

Technique Used in this Study for Estimating Areal Rainfall: The "Driver Station" Approach

1. A Brief Overview of Previous Work on Areal Rainfall Estimation in South Africa

The accuracy of areal rainfall estimated from point measurements depends on numerous factors. A review in Schulze (1995) found that classical methods such as the Thiessen polygon, isohyetal or inverse distance square methods performed inconsistently and could yield large errors in areal rainfall. Trend surface analysis, a form of multiple regression approach, was found to estimate areal rainfall successfully at annual and monthly levels, also in mountainous areas, but less so for daily estimates over a catchment (Schulze, 1976), and the variables found to be significant, as well as multiplier constants associated with them, would of course change under different climatic regimes and, hence, with climate change. Again at annual and monthly levels, Dent *et al*. (1989) and Lynch (2004) went one step further and used a combination of multiple regression analysis plus linear interpolation of residuals to generate gridded images of median monthly rainfall for southern Africa. However, caution is expressed by Whitmore (1972), that non-orographic rainfall is not reflected accurately by multiple regression methods, although on the whole that method describes areal rainfall adequately.

Particularly in a climate change context in which GCMs frequently represent climate variables by grid boxes of considerable size (cf. **Chapter 2.1**), it must be borne in mind that the spatial averaging of areal precipitation which takes place results in a dampening in magnitudes of individual rainfall events and their intensities at discrete locations, as well as an increase in the number of events at specific locations, which cannot even be accounted for by standard areal reduction factors.

2. The Driver Station Approach

There is no perfect technique for estimating areal rainfall, for the "best" technique will depend on

- the size of catchment under consideration,
- the topography of the catchment (low relief or mountainous area),
- the availability of input data required by the various techniques, and in particular
- the type of problem for which the simulation is to provide results, be it for design (planning) or for operational hydrology.

The approach to estimating daily areal rainfall values used in this study is the so-called “driver station” approach, which has been used in the South African Quinary Catchments Database (cf. **Chapter 2.2**) to undertake simulations with the *ACRU* model.

The driver station approach is carried out according to the following steps:

- A representative station selected to "drive" the hydrological response of a catchment or subcatchment is chosen according to the following criteria:
  - it is as close as possible to, or within, the catchment
  - its altitude is representative of the catchment's mean altitude
  - it has a long continuous record with a minimum of missing or suspect data and
  - where data are missing, the next best driver station (according to the above criteria) is used to estimate the missing rainfall.
- The median monthly precipitation of the driver station is compared to the median monthly precipitation of the catchment, which can be estimated from the one arc minute raster of median monthly precipitation developed for South Africa by Lynch (2004). From the comparison of the driver station and catchment median monthly precipitation values, month-by-month precipitation adjustment factors can then be derived and input.

The major advantage of this approach is the preservation of statistical properties of point rainfall. This becomes especially valid if one assumes that rainfall is a random process and in climate change studies in which spatial averaging can dampen higher order statistical properties. Its main disadvantage lies in an oversimplified representation of daily areal rainfall. One can question if, say, a 100 - 200 km^2 large catchment's areal rainfall can be represented realistically by a single raingauge. If no rainfall is recorded at the driver station, the method presumes that no rain has fallen on that day anywhere in the catchment. Alternatively, if a heavy rainfall event has been recorded for a particular day, the method assumes that this heavy rainfall event, which might have resulted from a small cell convective storm, occurred over the entire catchment.

Conclusions (Adapted from Schulze, 2008)

Rainfall is the major driving force to responses in the agrohydrological system, be it under present climatic conditions or those projected to be experienced under future climate scenarios. This chapter has therefore highlighted the importance of accurate rainfall data as an input to hydrological models, particularly in light of hydrological responses probably being more sensitive to rainfall than to any other climatic input.

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CHAPTER 3.4

CLIMATE CHANGE AND
ANNUAL PRECIPITATION STATISTICS:
A 2011 PERSPECTIVE

R.E. Schulze and R.P. Kunz

Mean Annual Precipitation, MAP: Concepts (Adapted from Schulze and Lynch, 2008)

- The MAP (mm) characterises the long term quantity of water available to a region for hydrological (and agricultural) purposes.
- Not only is MAP important as a general statistic in its own right, but it is probably also the one climatic variable best known to hydrologists and others, and to which they can relate many other things.
- In South African hydrological studies MAP has, for example, been used as a variable related to monthly rainfall distribution, to design flood prediction and to the number of raindays (e.g. Schulze, 1983; Schmidt and Schulze, 1987).
- While simple to calculate and attractive to use, the concept of MAP nevertheless has its weaknesses, in that in South Africa
  - negative departures of annual precipitation (i.e. the low rainfall years) are more numerous than positive ones (i.e. the higher than average years), and therefore annual rainfalls are not distributed normally (i.e. they have a positive skew), and
  - MAPs are frequently inflated by a few very high annual totals from very wet years, especially in areas of low rainfall.
- A summary of the methodology for mapping annual precipitation statistics for this study is given in **Box 3.4.1**.

Box 3.4.1 Methodologies for Mapping Annual Precipitation Statistics: A Reminder

The methodologies for obtaining daily precipitation values for each Quinary Catchment for the 50 year baseline (historical) period from 1950 - 1999 has been described in detail in **Chapter 2.2**, and for the 20 year present (1971 - 1990), the intermediate future (2046 - 2065) and more distant future (2081 - 2100) scenarios from the five GCMs used in this study in **Chapter 2.1**.

From these daily values annual totals were calculated for each hydrological year from October to September, and these were then used to compute MAP, wettest and driest years in 10 as well as standard deviations, coefficients of variation and skewness coefficients for the various climate scenarios presented.

Interesting Findings on Stations with Highest and Lowest Annual Precipitation in the Historical Record (Adapted from Lynch, 2004)

The station with the *highest rainfall from observed long term records* in South Africa from Lynch’s (2004) study is Robertsvlei in the southwest corner of the Western Cape, with a MAP of 2 088 mm, a lowest annual rainfall of 1 294 mm (in 1974) and highest annual total of 3 222 mm (in 1978).

The station with the *lowest rainfall from observed long term records* in South Africa, according to Lynch’s (2004) study, is Vioolsdrift along the RSA / Namibia border in the Orange River valley, with a MAP of only 47 mm, a lowest annual rainfall of only 1.7 mm (in 1979) and a highest annual total of 128 mm (in 1997).

Variability of Annual Precipitation: Concepts

The average amount of precipitation need not necessarily be a constraint to successfully carrying out a water resources operation - in fact one can get by with, and adapt ones practices and operating rules to, a low rainfall if one has the assurance that the rains will fall when needed or as expected. Average annual precipitation maps, however, do not show the natural year-to-year variability of rainfall that occurs. For this reason both a measure of *absolute variability*, *viz*. the standard deviation, and a statistic of *relative variability*, *viz*. the coefficient of variation expressed as a percentage, i.e. CV (%), were mapped (cf. **Chapter 1.3** for definitions and equations of variability statistics). The higher the variability, the more variable the year-to-year (i.e. inter-annual) rainfall of a locality is. Because the CV (%) considers deviations from averages by taking cognisance of whether the region has a high or low rainfall, it can be used for relative comparisons of variability between one region and the next. Variability of annual precipitation is an index of climatic risk, indicating a likelihood of fluctuations in, for example, streamflows or reservoir storage from year to year.

A rule of thumb established some 70 years ago already by Conrad (1941) from analyses of rainfalls worldwide, is that the higher the MAP the lower its inter-annual variability was likely to be. In other words, areas with a low annual rainfall are likely to be doubly worse off, because they will additionally suffer from high deviations around their already low average rainfall. This inverse relationship between inter-annual variability and MAP has been documented in several previous studies of rainfall over South Africa (e.g. Schulze, 1979; 1983) and becomes an important consideration in climate change studies.

Distribution Patterns over South Africa of Annual Precipitation Statistics under Baseline (Historical) Climatic Conditions (Adapted from Schulze and Lynch, 2008)

As a baseline against which to assess changes in annual rainfall characteristics with projected future climates, some features under historical climatic conditions (1950 - 1999) are first described.

According to Lynch's (2004) study, approximately 20 % of South Africa receives less than 200 mm MAP, and 47 % receives less than 400 mm per annum (**Figure 3.4.1**), this being the result of the presence of subtropical high pressure cells which inhibit rainfall generation because of predominantly subsiding air. Only about 9 % of South Africa receives a MAP in excess of 800 mm (**Figure 3.4.1**).

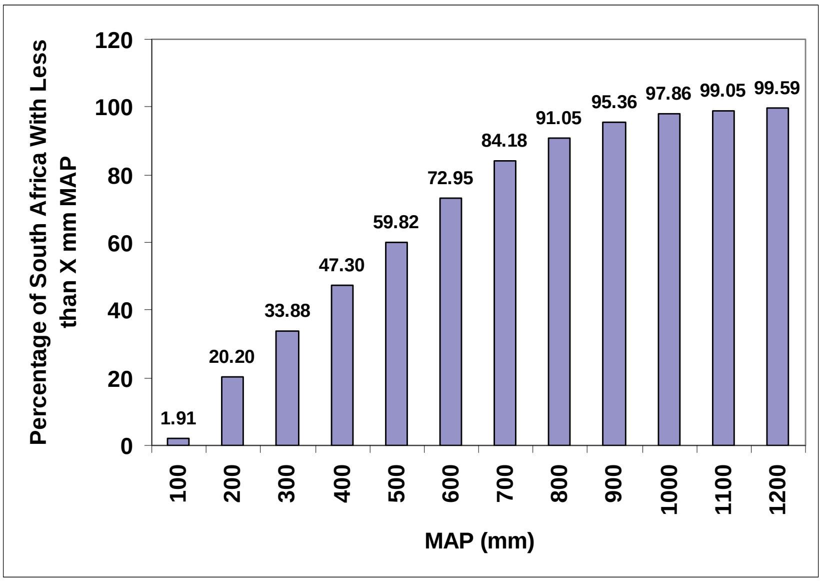


Figure 3.4.1 Percentages of South Africa receiving less than threshold values of MAP (Source: Lynch, 2004)

The overall feature of the distribution of MAP over South Africa (**Figure 3.4.2** top left) is that it decreases fairly uniformly westwards from the escarpment across the interior plateau. Between the escarpment and the ocean in both the southern and the eastern coastal margins there is the expected complexity of rainfall patterns induced by irregularities of terrain. KwaZulu-Natal is the wettest of South Africa's nine provinces, while the Western Cape has the highest range of MAP within any of the provinces, and the highest individual point rainfall at an estimated 3 198 mm per annum (Lynch, 2004).

In regard to the skewness of historical rainfalls (**Figure 3.4.2** top right), with the exception of patches in the northeast and extreme south where annual rainfall totals are negatively skewed, the overall picture is one of positively skewed annual rainfall, indicative of the upper tail of the distribution curve of annual rainfalls being longer than the lower tail, with the highest values in the more arid northwest with its erratic annual rainfall.

Standard deviations of annual rainfalls, a measure of absolute year-to-year variability, are generally highest (in mm equivalents) in the wetter east and lowest (in mm equivalents) in the more arid west with its low annual rainfall (**Figure 3.4.2** bottom left). This pattern is, however, essentially reversed in the case of year-to-year variability in relation to the mean, expressed through the coefficient of variation CV (%), with the map of CV (%) of annual rainfall illustrating a general westward increase from less than 20 % in the Quinary Catchments of the higher rainfall areas, mainly along the eastern seaboard, to over 50 % in the Northern Cape (**Figure 3.4.2** bottom right). It is important to note that on a monthly or seasonal basis, rainfall variability is considerably higher than on an annual basis (cf. **Chapter 3.5**). The map of inter-annual CV (%) is thus a “best case” scenario of relative rainfall variation.

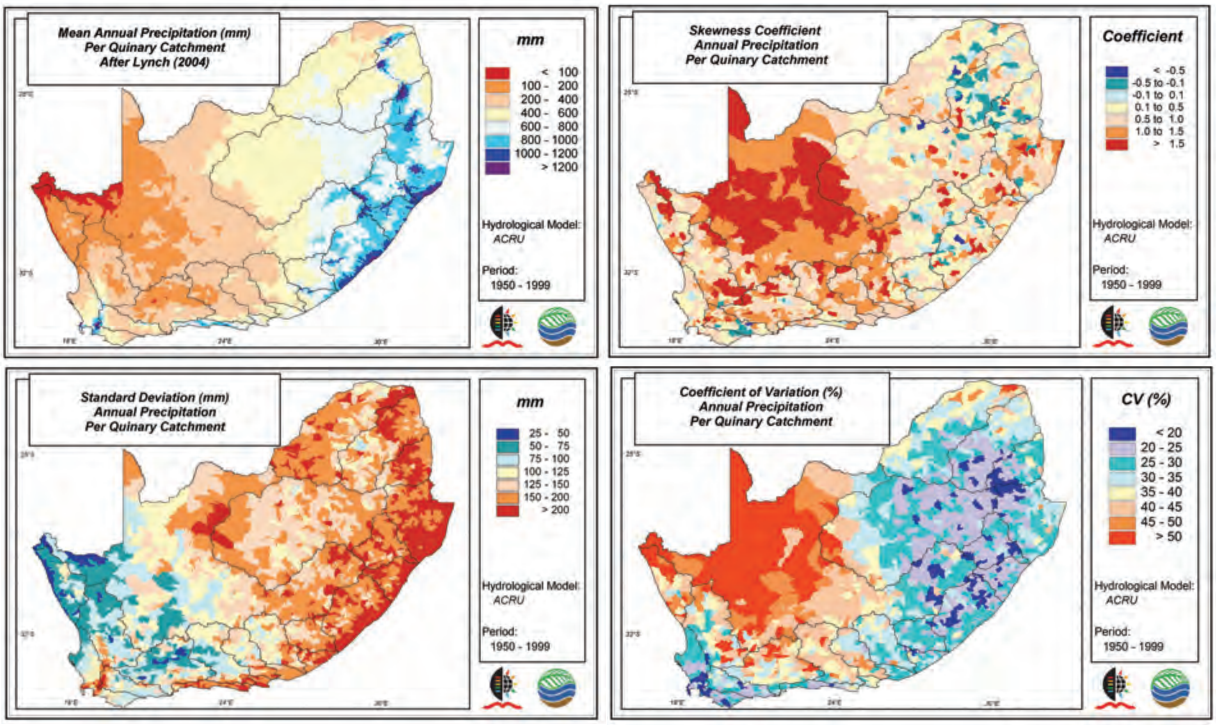


Figure 3.4.2 Mean annual precipitation (top left), the skewness coefficient of annual precipitation (top right), as well as the standard deviation and coefficient of variation of annual precipitation (bottom left and right), for baseline (historical; 1950 - 1999) climatic conditions

A Note of Caution on GCM Derived Rainfall Scenarios into the Future

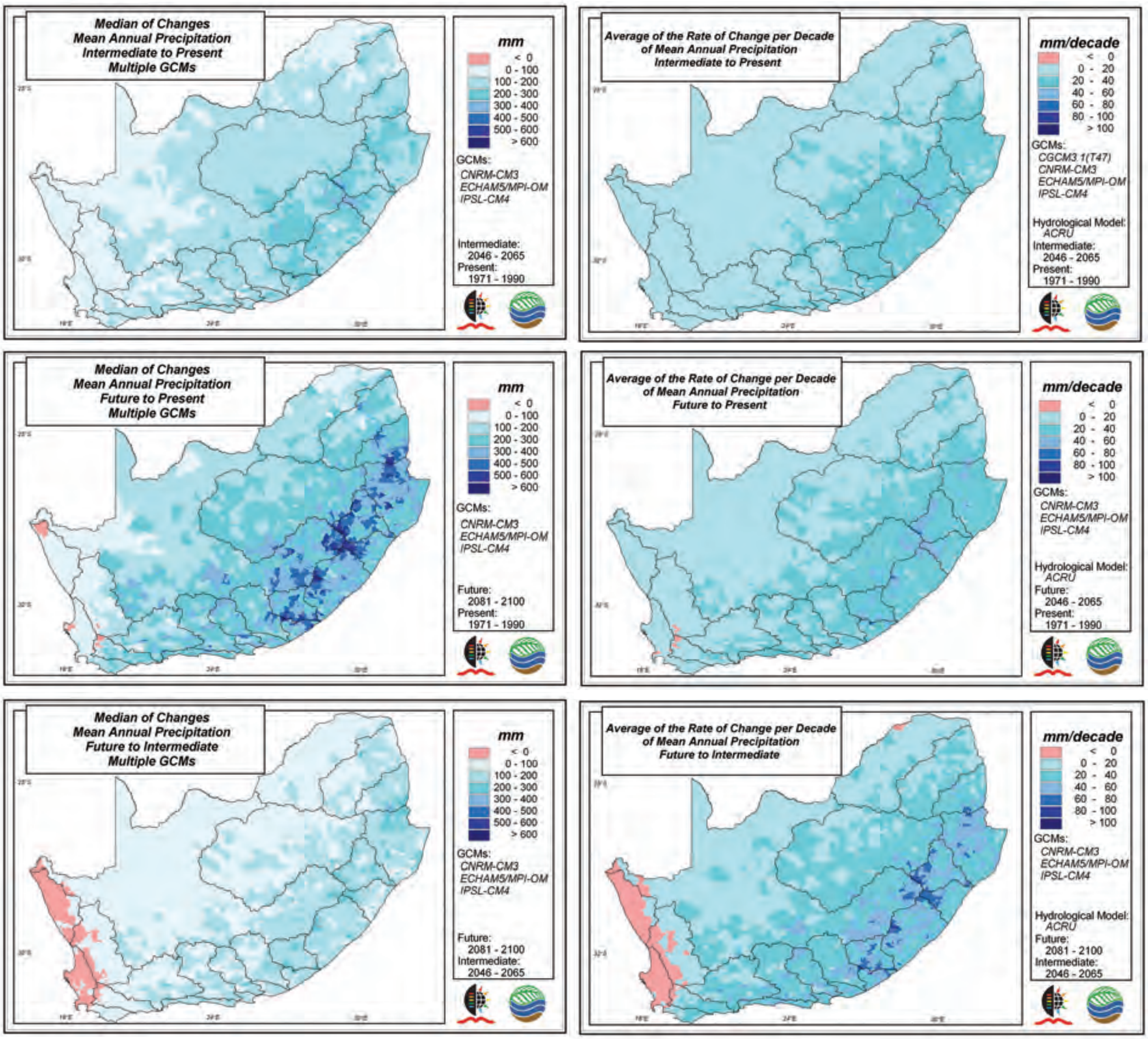
Confidence in overall changes in future scenarios of climate depend strongly on

- *which* GCMs were used, and
- *how many* GCMs were in the ensemble used.

The five GCMs which were available for use in this study, *viz*. CGCM3.1(T47), CNRM-CM3, ECHAM5/MPI-OM, GISS-ER and IPSL-CM4 are considered by climatologists to produce rainfall output somewhat on the wet side of the spectrum (Hewitson, 2010. Personal communication). This has to be borne in mind when interpreting any impacts in which rainfall is an input variable. Furthermore, in the course of this project it was brought to the attention of the research team that an error in the rainfall component of the GISS-ER GCM had been identified in certain parts of southern Africa. In order to err on the conservative, all rainfall and rainfall derived variables (e.g. streamflows etc) in this Report were therefore re-run to exclude output from the GISS-ER.

Medians of Changes in MAP under Future Climate Scenarios, Using Output from Multiple GCMs

Projected medians of changes in MAP from the ensemble of GCMs used in this research show an overall wetting into the intermediate future, very slight in the west (< 100 mm) and more pronounced at 200 - 300 mm in the east, particularly in the more mountainous areas (**Figure 3.4.3** top left). By the more distant future, intensifications in changes in MAP become evident, with areas of slight decreases in the west and quite marked increases in the east from 200 mm and up to 500 mm along the escarpment and in mountainous runoff producing areas (**Figure 3.4.3** middle left). These increases are significant in light of the amplification effect any changes in rainfall have on runoff. The period of significant change in the west appears to be in the latter half of the century when the medians of changes in MAP from the multiple GCMs used display clear drying there (**Figure 3.4.3** bottom left). The section which follows will, however, shed some more light on the changes described above.



Median of Changes Mean Annual Precipitation Intermediate to Present Multiple GCMs

Average of the Rate of Change per Decade of Mean Annual Precipitation Intermediate to Present

Median of Changes Mean Annual Precipitation Future to Present Multiple GCMs

Average of the Rate of Change per Decade of Mean Annual Precipitation Future to Present

Median of Changes Mean Annual Precipitation Future to Intermediate Multiple GCMs

Average of the Rate of Change per Decade of Mean Annual Precipitation Future to Intermediate

Figure 3.4.3 Medians of changes in mm (left column) and in mm per decade (right column), of mean annual precipitation between the intermediate future and present (top row), the more distant future and present (middle row) and the more distant and intermediate future climate scenarios (bottom row), using outputs from multiple GCMs

Rates of Change per Decade of MAP under Future Climate Scenarios, Using Output from Multiple GCMs

It is sometimes difficult to conceptualise the rates of climate change into the future, in part because the difference between the intermediate future and the present in this study is 75 years while that between the more distant and intermediate futures is only 35 years. It is for this reason that rates of change *per decade* were assessed (**Figure 3.4.3** right column). The overall rate of change in MAP from the present to the intermediate future is < 20 mm / decade, except in the east where it can increase up to 40 mm / decade (**Figure 3.4.3** top right). When comparing rates of change up to the more distant future (**Figure 3.4.3** middle right) the spatial patterns remain essentially similar, but with decreases in MAP evident in the southwest and a larger area shown with increases between 20 and 40 mm / decade. Again, the crucial period of change is that in the latter half of the century between the intermediate and more distant future climate scenarios, when consistent drying is shown along the entire west coast and wetting accelerates in the east, with mountainous areas projected from the multiple GCMs used to experience increases in MAP up to 40 - 80 mm / decade. Once again it needs to be emphasised that climatologists consider the GCMs which were available when this study was undertaken tend to be on the wet side.

Changes in the Inter-Annual Variability of Precipitation, Based on Output from Multiple GCMs

The maps of averaged ratio changes in the inter-annual variabilities of rainfalls show standard deviations (absolute variability) to be intensifying from the present into the intermediate to the more distant future, with significant increases in the year-to-year variability of annual precipitation in the east (from 30 % up to a doubling), but with decreases in the west (**Figure 3.4.4**). The overall increase in rainfall variability has severe repercussions on the management of water resources and operations of major reservoirs as well as on the year-on-year consistency of agricultural production.

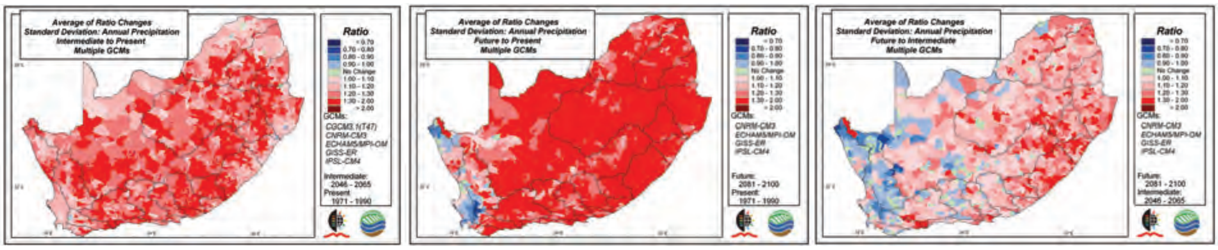


Figure 3.4.4 Average of ratio changes, using output from multiple GCMs, in the standard deviation of annual precipitation between the intermediate future and present (left), the more distant future and present (middle) and the more distant and intermediate future climate scenarios (right)

A very different picture of inter-annual variability of rainfall is, however, presented by the averaged changes in the coefficient of variation (CV %), which is a *relative measure of variability*, with large areas displaying decreases in annual CVs (**Figure 3.4.5**), particularly when the changes in CVs between the more distant future and present climate scenarios are assessed (**Figure 3.4.5**, middle). Because CV (%) is defined as the percentage ratio of standard deviations to means, this reversal in patterns illustrates that projected *changes in the means* of annual precipitation by the GCMs used in this study are higher than *changes in the absolute deviations*.

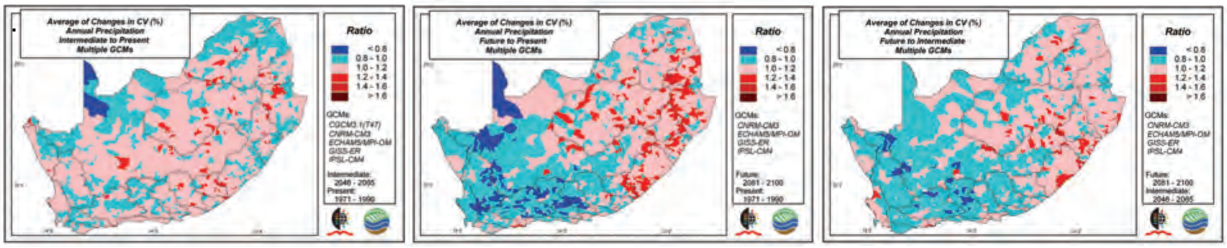


Figure 3.4.5 Average of ratio changes, using output from multiple GCMs, in the coefficient of variation of annual precipitation between the intermediate future and present (left), the more distant future and present (middle) and the more distant and intermediate future climate scenarios (right)

This difference in the patterns between two statistics of variability shows that the general statement of projected climate variability to increase with global warming is dependent on the statistic selected, and that an absolute (rather than a relative) measure of variability should be used in climate change impact studies.

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CHAPTER 3.5

CLIMATE CHANGE AND
MONTHLY RAINFALL STATISTICS:
A 2011 PERSPECTIVE

R.E. Schulze and R.P. Kunz

Why Monthly Rainfall Totals? (Adapted from Schulze and Lynch, 2008)

- There are many water resources problems and decisions for which MAPs or even wet / dry season precipitation totals, be they high or low, are of relatively little consequence, because an intra-year distribution of rainfall is required (Schulze, 1997).
- Monthly rainfall values then serve as an important tool in describing such an intra-year distribution.
- It should, however, be borne in mind that the use of the calendar month is but a *time step of convenience* for describing temporal patterns of rainfall, in that it breaks up annual precipitation into components of time long enough to smooth out many of the irregularities of daily rainfalls (Schulze, 1997).
- Nevertheless, large differences in rainfall can exist from one month to the next.
- Some of these differences result from major rainfall generating mechanisms changing from one month to the next, for example, when general and more low intensity frontal rains of winter and early summer are replaced with more localised convective and often high intensity storms which characterise the mid-to-late summer months in the summer rainfall regions of South Africa. Such rainfall generating mechanisms are likely to alter under conditions of climate change.

Why Map Medians Rather than Means of Monthly Rainfall?

- The median is the middle value when a data series is ranked from highest to lowest.
- It therefore designates a statistically *expected* value, with as many years having monthly values higher than the median as there are years with monthly values lower than the median value.
- Mean rainfall values are frequently inflated by a few extreme events, or outlier events, that may have occurred over a period of time - a phenomenon which is especially prevalent in more arid regions and in generally drier months of the year (Schulze, 1997), and which becomes more important when relatively short periods are analysed, as in the case of the 20 year time slices used in this climate change Report.
- For rainfall regimes such as those generally experienced under current climatic conditions in South Africa, and which are projected to occur in future climates, the mean is therefore frequently not as representative of expected conditions as the median.

Cardinal Months

Cardinal months are selected months which are considered to be representative of the major seasons of the year. In this Report the four cardinal months are

- *January*, representative of the three southern hemisphere summer months December to February,
- *April*, representing the autumn months March to May,
- *July*, representing the winter months June to August, and
- *October*, representing the three southern hemisphere spring months September to November.

Distribution Patterns over South Africa of Precipitation Statistics in Cardinal Months under Baseline (Historical) Climatic Conditions

As a point of departure to assessing projected future changes in monthly rainfall patterns, baseline conditions are described for cardinal months. **Figure 3.5.1** (top left) shows January median rainfalls reflecting typical patterns of the summer rainfall region with highs of > 160 mm in the east decreasing to < 5 mm in the west, while in July most of the summer rainfall region of South Africa records < 5 mm, but with the winter and all year rainfall regions of the west and south recording monthly medians

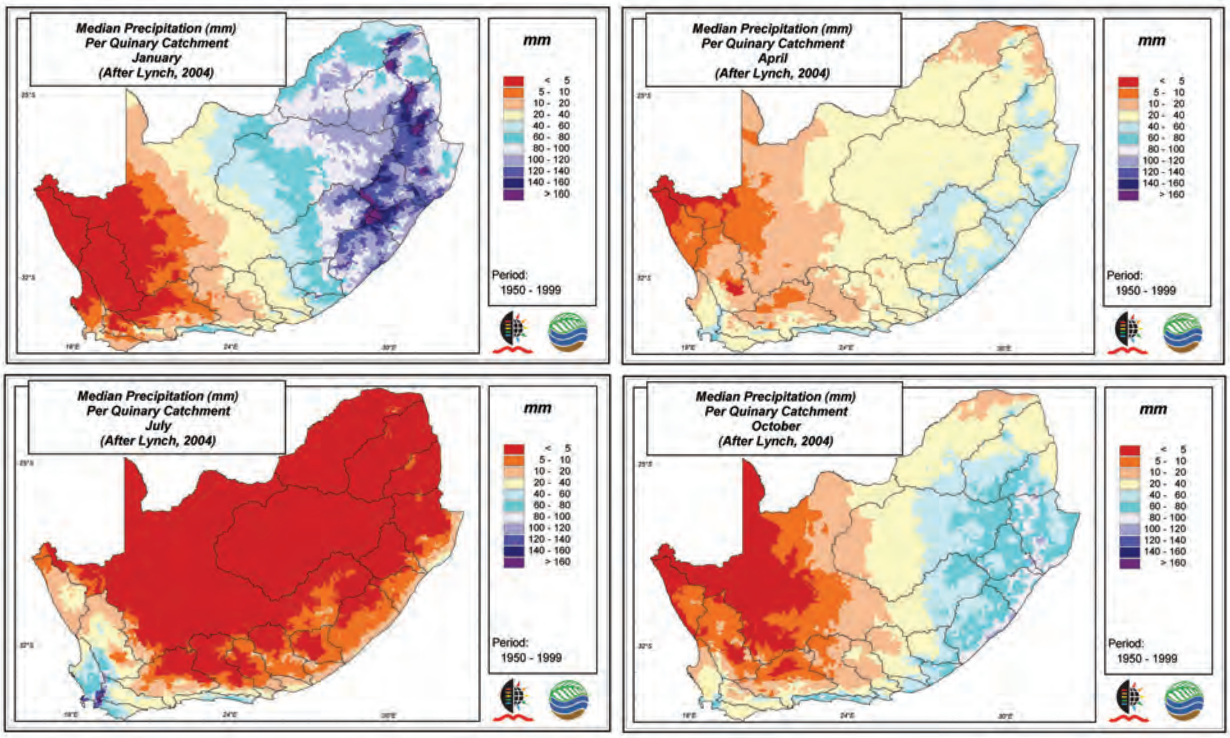


Figure 3.5.1 Baseline (historical; 1950 - 1999) median precipitation for the cardinal months January, April, July and October (Source information: Lynch, 2004)

of up to 60 mm. The majority of areas in South Africa experience virtually no winter rainfall with medians < 5 mm for July, the exceptions being the east coast where medians of up to 40 mm are recorded and the all year region in the south, but especially the winter rainfall region in the southwest, where July medians range from 60 to 150 mm. April and October display rainfall distributions typical of transitional months with some characteristics of the summer and winter rainfall regions evident.

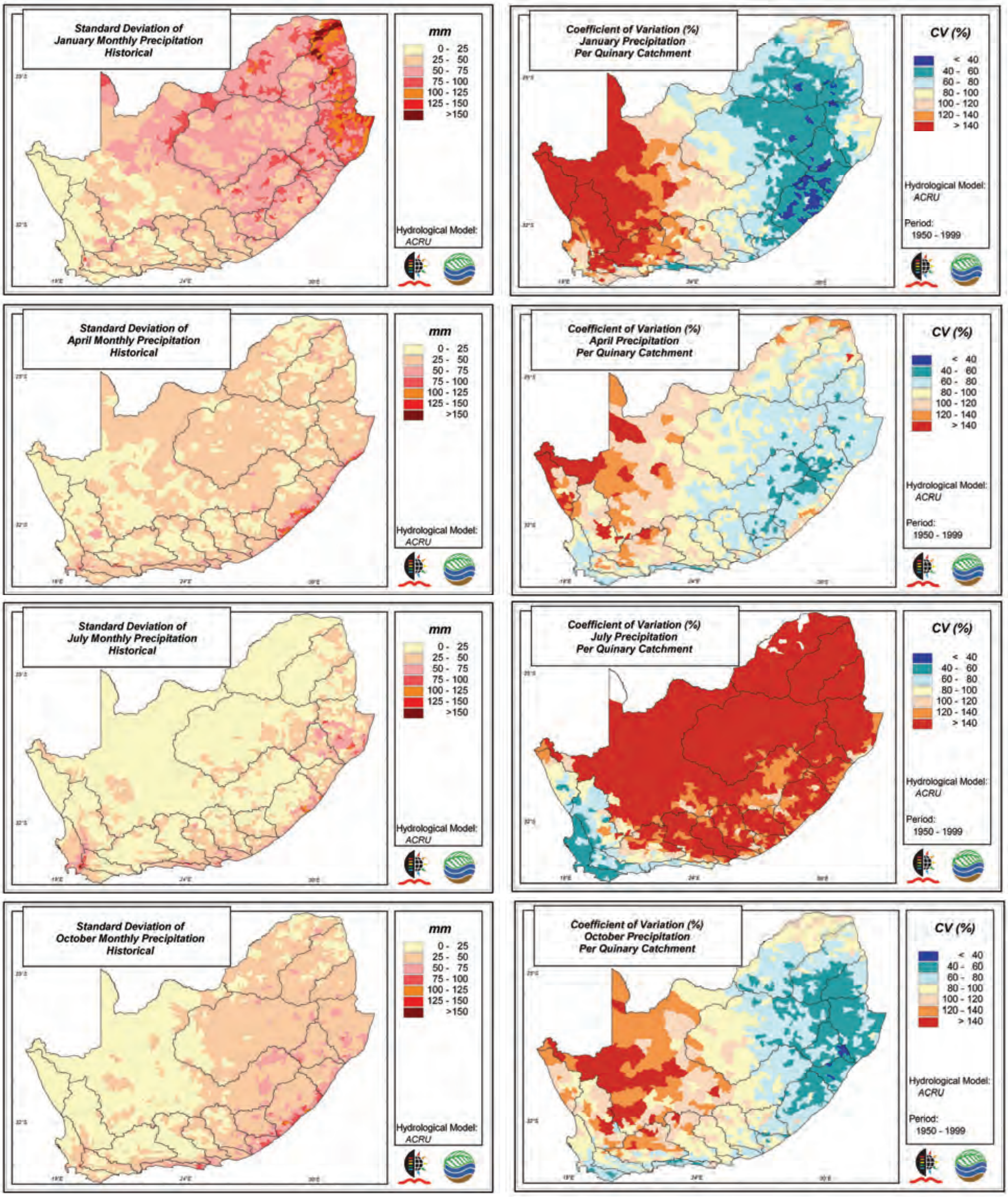
For baseline (historical; 1950 - 1999) climatic conditions, **Figure 3.5.2** shows for each of the four cardinal months two indicators of the variability of rainfall, *viz*. the standard deviation, an absolute measure of variability, in the left column and the coefficient of variation (CV %), which is a statistic of variability expressed relative to its mean. In phase with rainfall magnitudes, the standard deviations in January's rainfalls are low in the west at < 25 mm and high in the east at up to 100 mm. The April values are much more even at 25 - 50 mm for the month, while in July the high values are in the winter rainfall region as well as along the south and east coast regions and the hinterlands. For October the standard deviations display a clear division with values < 25 mm in the west and 25 - 50 mm in the east.

Expressed in relative terms, CVs of January rainfalls, typical of a mid-summer month, range from a low of < 40 % in the high rainfall eastern parts of South Africa to > 140 % in the more arid west - an inverse of actual rainfall. In July (winter) the inverse occurs, with most of the summer rainfall region experiencing high CVs in excess of 140 %, while in the winter and all year rainfall regions in the west and south CVs in this period of high rainfall decrease to < 80 % and even < 40 %, with the transitional months of April and October tending more towards summer CVs, albeit with more muted patterns.

The inclusion, and the value, of both an absolute and a relative indicator of variability is again illustrated in this case, as the patterns of the two are very different and the impacts of climate change on them is also likely to be different (Section to follow).

Medians of Changes between Future and Present Precipitation in Cardinal Months, Based on Output from Multiple GCMs

Before a more detailed interpretation is given, a number of general points are made below from the maps of medians of ratio changes in monthly rainfall derived from multiple GCMs assuming the A2 emissions scenarios (**Figure 3.5.3**).



Standard Deviation of January Monthly Precipitation Historical

Coefficient of Variation (%) January Precipitation Per Quinary Catchment

Standard Deviation of April Monthly Precipitation Historical

Coefficient of Variation (%) April Precipitation Per Quinary Catchment

Standard Deviation of July Monthly Precipitation Historical

Coefficient of Variation (%) July Precipitation Per Quinary Catchment

Standard Deviation of October Monthly Precipitation Historical

Coefficient of Variation (%) October Precipitation Per Quinary Catchment

Figure 3.5.2 January (top row), April, July and October (bottom row) standard deviations (left column) and coefficients of variation (right column) for baseline (historical; 1950 - 1999) climatic conditions (Source information: Lynch, 2004)

Changes in distribution patterns over South Africa of medians of precipitation in cardinal months (as well as of higher order statistics, cf. **Figure 3.5.4**), *are not uniform*, but can vary markedly in

- *direction* (i.e. ratios can change from > 1 designating a more severe future of a variable or statistic to < 1 indicating a more benign future), in
- *intensity* (i.e. ratios can be only slightly > 1 or < 1, or more considerably so), as well as varying
- *spatially within South Africa* in a given month for a specific statistic,
- *between different months of the year* for the same statistic, but in particular

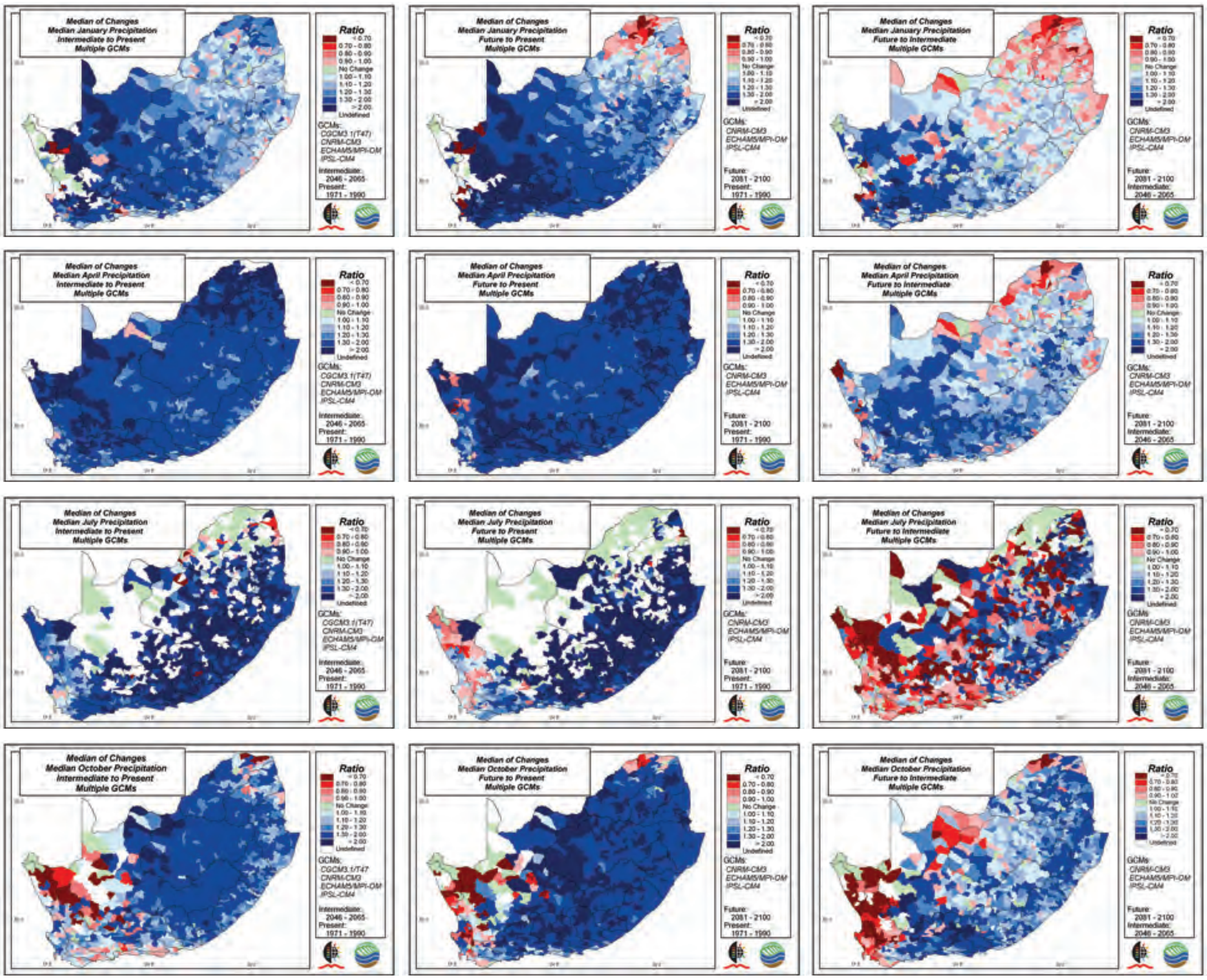


Figure 3.5.3 Medians of ratio changes of the expected (50th percentile) rainfall for January (top row), April, July and October (bottom row) between the intermediate future and present (left column), the more distant future and present (middle column) and the more distant and intermediate future climate scenarios (right column), using outputs from multiple GCMs

- *between the intermediate future and the more distant future* for the same statistic, with this last-named difference suggesting an
- *intensification and acceleration of impacts* of climate change over time, especially when considering that the time difference between the intermediate future (2046 - 2065) and present (1971 - 1990) is 7.5 decades while the span between the more distant future (2081 - 2100) and the intermediate future is only 3.5 decades.

In regard to medians of ratio changes in rainfall in the four cardinal months (**Figure 3.5.3**), five features bear commenting on:

- A recurring feature is a general *wetting trend* of varying intensity and distribution in all three periods of change considered. It is particularly pronounced *in the east*. A wetting trend there in general is projected to be beneficial to South Africa's water availability, but could be detrimental in regard to flood damage and soil losses.
- There is a *drying trend* evident *in the west*, mainly towards the end of its rainy season in spring (i.e. October), e.g. in the intermediate future to present ratios, in the more distant future to present and particularly in the intermediate to more distant future period, but also in the middle of the rainy season in July in the latter half of the century. Combined with increases in temperature, repercussions on irrigation demand and water resources could thus be severe in the west.

- Elsewhere the GCMs used in this study display a *drying trend* in the latter half of this century in the middle and towards the end of the wet season (i.e. January, April) *in the northern areas* of South Africa, with projected negative impacts on water availability there.
- Some areas display no changes in rainfall amounts between the three time periods under review. This occurs mainly in the dry season of the summer rainfall area (July).
- The area which is *transitional between the summer and winter rainfall* areas in South Africa (cf. **Chapter 3.7**) frequently displays marked relative increases in rainfall.

Averages of Changes between Future and Present Inter-Annual Variability of Rainfall in Cardinal Months, Expressed by the Standard Deviation and Based on Output from Multiple GCMs

The very distinct differences in the spatial distributions of the two statistics of rainfall variability, *viz*. the *standard deviation* (a statistic indicating absolute variability) and the *coefficient of variation* (a statistic indicating relative variability) were shown for historical rainfall in **Figure 3.5.2**. This illustrates clearly that the *choice of statistic* with which to assess possible changes in the variability of future climates *is crucial*, and it was decided that for this Chapter the *standard deviation,* as an *indicator of absolute variability*, be used as it is not influenced by simultaneous changes in means, as is the case when the CV is used.

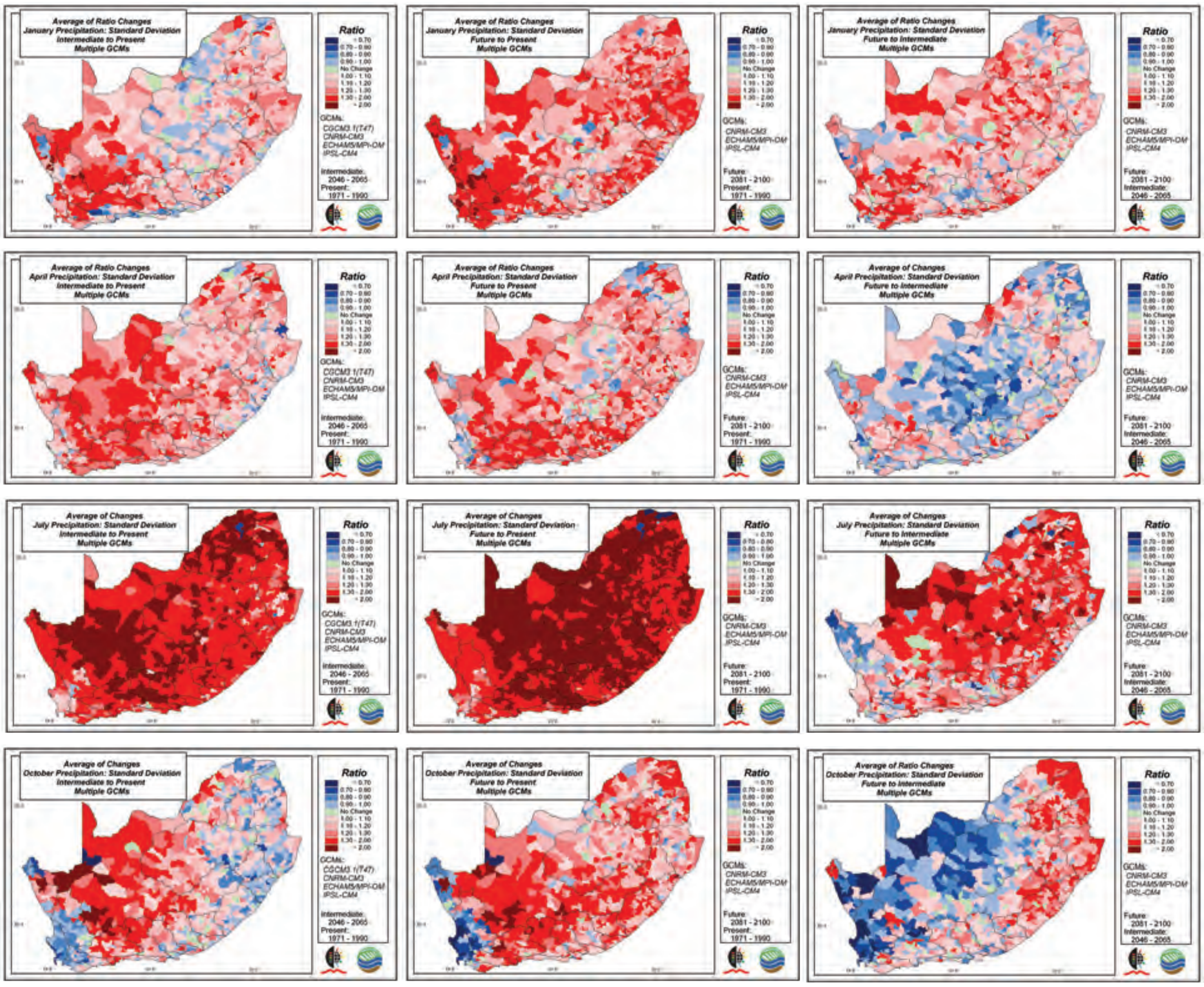


Figure 3.5.4 Averages of ratio changes in the standard deviation of January (top row), April, July and October (bottom row) rainfall between the intermediate future and present (left column), the more distant future and present (middle column) and the more distant and intermediate future climate scenarios (right column), using output from multiple GCMs

Figure 3.5.4 shows that for the period from the present to the intermediate future (by mid-century) marked differences in averaged ratio changes of standard deviations may be seen in the four cardinal months representing summer (January), autumn (April), winter (July) and spring (October), as are differences in direction and intensity within a given month. January and April display a narrow coastal strip of decreased rainfall variability into the future, but with a general increase over the interior which intensifies into autumn.

By mid-winter virtually the entire South Africa displays significant increases in the inter-annual variability of rainfall, in the range of > 30 % to more than doubling. Over much of the country this has little impact on water resources as mid-winter coincides with the dry season, but in the winter rainfall region of the southwest it does. By October (spring) when the rainy season starts for much of the country, a very different spatial picture of rainfall variability emerges, with the eastern half of South Africa and the southwest showing reductions in year-to-year rainfall, with only the semi-arid central interior showing averaged increases in variability.

When comparing the more distant future rainfall variability with that of the present, the patterns for the individual cardinal months remain essentially similar to those between the intermediate future and present scenarios, but where there are differences these can often be explained by the changes to standard deviations which occur between the mid- and late century periods (2046 - 2065 vs. 2081 - 2100).

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CHAPTER 3.6

CLIMATE CHANGE AND
THRESHOLDS OF DAILY RAINFALL AMOUNTS EXCEEDED:
A 2011 PERSPECTIVE

R.E. Schulze and L.M. Bulcock

Revisiting Reasons for Hydrological Analyses at Daily Time Steps

In **Chapter 2.3** on the *ACRU* model an entire section was devoted to reasons for modelling hydrological responses at *daily* time steps, be these responses under current climatic conditions or using projections of future climates. By way of introduction to an analysis of thresholds of *daily* rainfall amounts exceeded, the main reasons for using daily time steps which were given in **Chapter 2.3** are summarised again below.

- The day, and diurnality, is a *universal natural time step*, which is not the case for either the second or the minute, nor the hour, week or month. The next natural time step up from the day is the season, and that certainly displays no universality.
- Diurnality encapsulates, albeit not perfectly, many hydrologically related processes (e.g. evaporation, transpiration and discrete rainfall events occur per day), while many operational decisions are made according to daily conditions (e.g. irrigation, reservoir operations).
- There are, however, two other major reasons for using daily time steps in hydrological modelling. The first is the availability of daily rainfall data, with South Africa having a considerable number of rainfall stations with long duration and quality controlled daily rainfall data (Lynch, 2004; **Chapter 2.3**), and with daily rainfall values now being available from GCMs for climate change studies (cf. **Chapter 2.1**).
- Secondly, daily time step hydrological models provide a vast array of potential and realistic and, in the context of the National Water Act (NWA, 1998) as well as of Integrated Water Resource Management, highly relevant output which weekly and even less so monthly time step models can not provide, e.g. on irrigation water requirements, reservoir status, reservoir operations, short duration design rainfalls, flood volumes, peak discharge estimations, instream flow requirements, event based sediment yields, wetlands hydrological responses, phosphorus / nitrate loadings, flow routing through channels / reservoirs, near real-time catchment soil water states, impacts of land management, soil water content in various soil horizons, climate change impacts with CO_2 transpiration feedbacks, explicit generation of stormflow, interflow and baseflow, or rainfall above critical threshold analyses.
- There are, nevertheless, some limitations to hydrological modelling at a daily time step. These include problems of missing data, daily raingauges in South Africa being read in the mornings at 08:00 when an actual rainfall event may fall across the 08:00 limit and be recorded as rainfall on two days, while corresponding daily streamflow records are given from midnight to midnight, as well as large areas in South Africa having a poor rainfall station network (Lynch, 2004) and the temporal distribution of rainfall in the course of a day not being accounted for easily with daily time step input.

Examples of the Importance of Thresholds of Daily Rainfall Being Exceeded

Confirming the frequently made statement that South Africa is generally a relatively dry region, is that approximately 1/3 of the region records no rainfall on over 300 days in an average year (**Figure 3.6.1** top left). On the days on which it rains, certain thresholds of rainfall become important, and the frequency that such thresholds may be exceeded (or not) is an important consideration in climate change studies in hydrology.

While 1 mm on a given day is considered a threshold for initial abstractions from impervious areas (cf. **Chapter 8.4**), under South African conditions 2 mm per day is generally accepted as exceeding plant interception (Schulze, 2004) and implies that on any given day rainfall in excess of the 2 mm threshold has actually wet the soil. A threshold of 5 mm per day implies that the rainfall is likely to have compensated for evaporative losses on that day (cf. **Chapter 4.1**) while 10 mm is often used as a lower threshold for the generation of stormflow (Schulze, 1981) and sediment yield (as well as the curtailment of agricultural field operations), with a daily rainfall in excess of 25 mm usually resulting in a more significant hydrograph being generated. Furthermore, in drawing up engineering contracts, the number of days per month with 10 mm or more rainfall is often used in a formula to calculate extensions of contract time lost due to so-called “abnormal rainfall”.

The methodology of determining the number of days per annum with rainfall above critical thresholds is summarised in **Box 3.6.1**.

Distribution Patterns over South Africa of the Mean Number of Days per Year with Rainfalls Exceeding Critical Threshold Values under Baseline (Historical) Climatic Conditions

With the large number of rainless days already having been alluded to (cf. **Figure 3.6.1** top left), the number of days on which ≥ 1 mm falls is relatively low, with < 20 rainfall days in the west and up to ~ 100 days in parts of the east, with similar patterns for the 2 mm threshold (**Figure 3.6.1**). For ≥ 5 mm per day the range is from < 5 to > 60 days. For the runoff producing threshold of 10 mm per day, ~ 10 % of South Africa experiences fewer than 5 such events per annum in the arid west, with this figure increasing to 20 - 30 runoff producing rains in parts of the east. For the more significant 25 mm threshold, ~ 1/12th of South Africa averages only one such rainfall per year, but in patches along the east coast and the inland mountain areas an average of up to 12 “major” events can be recorded annually (**Figure 3.6.1** bottom).

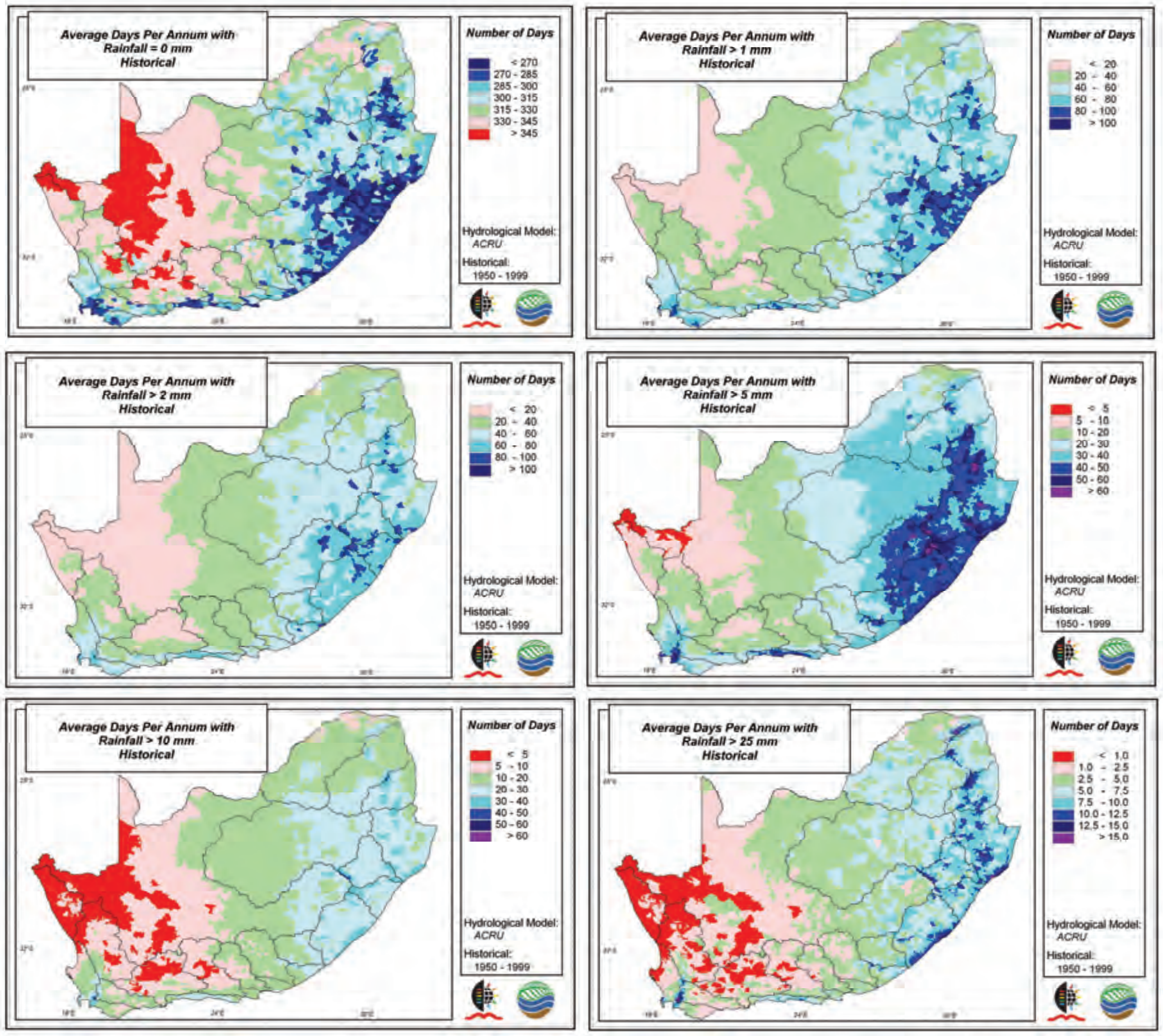

Figure 3.6.1 Average number of days per annum with specified rainfall amounts per day being exceeded, for baseline (historical; 1950 - 1999) climatic conditions

Box 3.6.1 Determination of Number of Days per Annum with Rainfall above Specified Threshold Values

Methodologies for obtaining quality controlled daily rainfall values for each Quinary Catchment for the 50 year baseline (historical) period from 1950 - 1999 have been described in **Chapter 2.2**, and for the 20 year present (1971 - 1990), the intermediate future (2046 - 2065) and more distant future (2081 - 2100) climate scenarios from the GCMs used in this study in **Chapter 2.1**. For each of the 5 838 Quinaries covering the RSA, Lesotho and Swaziland, the number of days exceeding the various critical thresholds were then extracted and the results analysed in order to produce maps.

Ratio Changes of Future to Present Thresholds of Daily Rainfall Exceeded, Using Output from Multiple GCMs

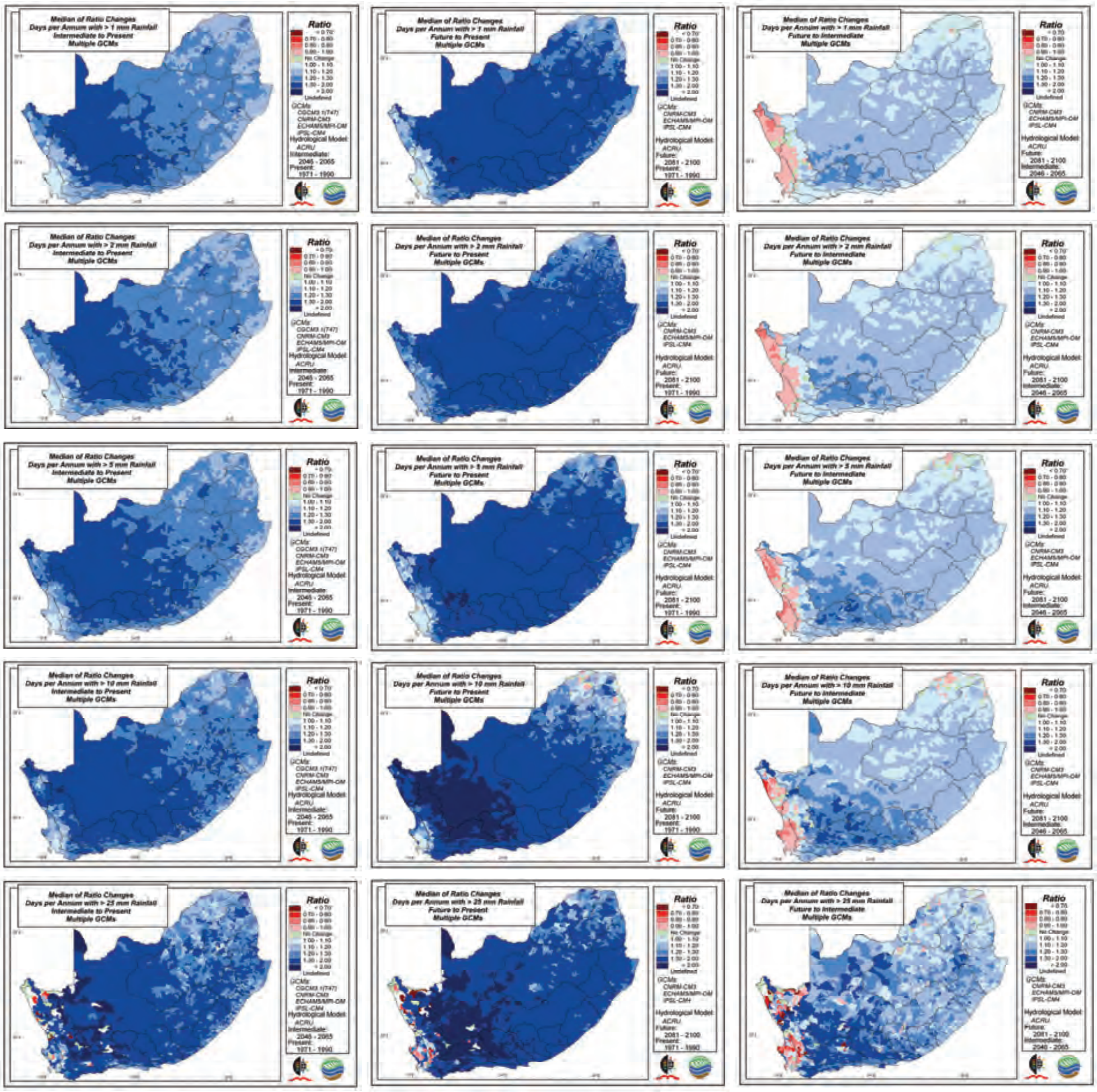

Figure 3.6.2 Medians of ratio changes in days per annum with thresholds of 1, 2, 5, 10 and 25 mm of rainfall per day being exceeded (top to bottom) for the intermediate future to present (left column), the more distant future to present (middle column) and the more distant to intermediate future time periods (right column), derived from output of multiple GCMs

Medians of ratio changes in days per annum with hydrologically critical magnitudes of daily rainfall being exceeded are shown in **Figure 3.6.2** for rainfall thresholds of 1, 2, 5, 10 and 25 mm (top to bottom) for the intermediate future to present (left column), the more distant future to present (middle column) and the more distant to intermediate future time periods (right column).

Irrespective of the threshold rainfall, more days are generally projected to occur when results between the intermediate future and present climate scenarios are compared for the multiple GCMs available for this study, with increases around 10 % in the east and west, 10 - 20 % in the central - east and 20 - 30 % in the more arid central - west (**Figure 3.6.2** left column). There is, however, a weak signal of little change for the heavy rainfall days > 25 mm along the west coast.

Into the more distant future there is a general intensification of increases in the number of days on which the various thresholds are exceeded and an expansion of areas with higher increases, except for days with high rainfalls along the vulnerable west coast where first indications are of the numbers of days with rainfall above 25 mm, is projected to decline (**Figure 3.6.2** middle column).

However, the 110 year time difference between the present and more distant future (1971 -1990 vs. 2081 - 2100) obliterates an area of *consistent decreases* in the number of days per year with critical thresholds of rainfall being exceeded in the latter half of the century, *viz*. the west coast. When ratio changes between the intermediate and more distant future are assessed (i.e. 2046 - 2065 vs. 2081 - 2100), a *decrease is displayed for all threshold values analysed*, but with signs of greater intensity for the higher thresholds (> 10 and 25 mm per day), which are hydrologically more critical in that they are the runoff producing events. This could have major repercussions for long term water resources planning in the Western Cape province.

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SECTION 4

PROJECTED CHANGES TO SECOND ORDER CLIMATE RELATED DERIVATIVES

CHAPTER 4.1

CLIMATE CHANGE AND *REFERENCE EVAPORATION BY THE PENMAN-MONTEITH METHOD:*

A 2011 PERSPECTIVE

R.E. Schulze, R.P. Kunz and L.M. Bulcock

Potential Evaporation: Concepts and Definitions

All atmospheric moisture originates from the earth's surface, where water in its liquid (mostly) and solid phases is transformed into water vapour at an evaporating surface and is transported vertically into the atmospheric boundary layer. This water originates from two processes, *viz*.

- *evaporation* from water surfaces, from water intercepted by plants after precipitation and from the soil surface when it is wet after rainfall, and
- *transpiration*, physically the same process as evaporation, but representing the water loss through stomata on the leaves (mainly) of plants.

Evaporation is controlled by three atmospheric conditions, *viz*.

- the capacity of air to take up more water vapour (with this capacity increasing rapidly at higher temperatures and being determined also by the relative humidity, *RH*, of air - the lower the *RH* the more favourable the conditions for evaporation)
- the amount of energy available for the latent heat used in the process of evaporation (with the energy provided mainly by solar radiation) and
- the degree of turbulence (related to wind) in the lower atmosphere (where the turbulence is necessary to replace the saturated air layers above the evaporating surface with unsaturated, drier air from higher levels or from different air masses).

These three factors create an *atmospheric demand* and when this demand can be met fully, e.g. when soils are wet and vegetation covers the ground completely and is growing actively, so-called *potential evaporation* (E_p) is taking place. All three of the above factors are subject to change with global warming, and in the context of this Report the first two are accounted for by perturbations in the temperature regime.

The accurate estimation of E_p is vital in hydrology, for it is the driving force of the total amount of water which can be evaporated from open water bodies such as dams, wetlands or river channels and be "consumed" by a plant system through the evaporation and transpiration processes. This amount of water "consumed" by vegetation is termed *total evaporation*, E, and E may be taking place at potential rate (wet soil conditions) or at an *actual evaporation* rate which can either be equal to E_p or lower (when soils dry out and plants are under water stress). It is estimated that overall in South Africa E makes up 91 % of the MAP (Whitmore, 1971). All of this evaporation is returned to the atmosphere and the 91 % is considerably higher than the worldwide average of 65 % of MAP evaporating again.

There are many methods of estimating E_p, ranging from complex physically based equations to simple measurements and even simpler surrogates based on single variables such as temperature. These methods all yield different answers under different climatic conditions, and a *reference potential evaporation*, E_r (with its inherent advantages and defects), therefore has to be selected as that evaporation against which other methods must be adjusted appropriately.

In selecting E_r in hydrology one has, in a manner of speaking, to serve two masters. On the one hand, when considering crop growth and irrigation, one should select a *reference crop evapotranspiration*. On the other hand, from a water engineering viewpoint, the E_r must be meaningful in describing evaporative losses from an open water body such as a dam, and hence a case may be argued for a reference potential evaporation related to an evaporation tank. In this Report only a crop E_r, *viz*. the method followed by Penman-Monteith equation, is presented.

Reference Crop Evaporation: A Definition

The FAO (1992) definition of Penman-Monteith derived reference crop evaporation (E_{rpm}) is

> *"The rate of evapotranspiration from a hypothetical crop with an assumed crop height of 0.12 m, a fixed canopy resistance of 70 s.m^{-1} and albedo of 0.23, which would closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and not short of water"* (p 12).

Background to the FAO Penman-Monteith Method for Reference Crop Evaporation

- The A-pan, while providing an index of open water evaporation, is intrinsically not suitable as a reference for the estimation of crop water requirements.
- This is so not only because of inherent problems associated with its small dimensions, advection, dependence on local site conditions (including rainfall) as well as installation and maintenance procedures (cf. Schulze and Maharaj, 2008), but also because a crop displays some fundamentally different properties to that of an open water body in its evaporation processes, even when not under any soil water stress.
- *Inter alia*,
  - a crop's reflection of shortwave radiation (albedo) is 3 - 4 times greater than that of a water body (0.18 - 0.25 vs. 0.05 - 0.07); furthermore,
  - because of its non-uniform height above the ground and its aerodynamic roughness, a crop offers a greater resistance to wind than an open water body; thirdly,
  - the crop leaves offer a canopy resistance to the transpiration process.
- Based on exhaustive comparative studies of methods to estimate potential evaporation and transpiration from cropped surfaces, which could be used as a reference for estimating irrigation water requirements, an FAO expert consultancy in 1990 (FAO, 1992) recommended the acceptance of a modified Penman-Monteith equation (Penman, 1948; Monteith, 1981) as a reference for crop evaporation.

Approaches to Mapping Penman-Monteith Reference Crop Evaporation over South Africa

The maps in this Report are based on a deterministic and fundamental approach in which

- daily maximum and minimum temperatures were generated over South Africa on a 1' x 1' (~ 1.7 x 1.7 km) raster for a 50 year period, based on techniques used by Schulze and Maharaj (2004),
- from which values of daily saturated vapour pressure could be computed,
- which were combined with empirically determined month-by-month gridded values of actual vapour pressure for South Africa (Schulze *et al*., 2008) to give daily values of the vapour pressure deficit at each raster point, and linked to
- gridded daily values of solar radiation determined for South Africa by modifications to the Bristow and Campbell (1984) equation, as described by Schulze and Chapman (2008).
- The equations describing the above approaches are given in **Box 4.1.1**.
- For each of the 5 838 Quinary Catchments in South Africa an altitudinally representative grid point near the centroid of the Quinary was selected to represent the Quinary, as described in **Chapter 2.2**, and the daily reference crop evaporation was then computed at that point.

Distribution Patterns over South Africa of Annual and Seasonal Reference Crop Evaporation Statistics by the Penman-Monteith Approach under Baseline (Historical) Climatic Conditions

As a point of departure in assessing potential impacts of climate change, patterns of mean annual reference crop evaporation are first presented for the historical (1950 - 1999) climate record. These range from ~ 1 000 mm in the Lesotho highlands and around 1 200 mm along the higher altitude eastern and southern escarpment of South Africa to > 2 600 mm in the Northern Cape semi-desert, with much of the interior experiencing annual E_{rpm} rates between 1 600 and 0 mm (**Figure 4.1.1**, top).

Year-to-year variability of E_{rpm} is remarkably low across South Africa (**Figure 4.1.1**, bottom maps) with standard deviations of annual E_{rpm} only ranging between 20 and 70 mm which, when converted to a variability indicator relative to the mean, yields coefficients of variation generally < 5 %, with much of the west < 2.5 %. Inter-annual CVs of rainfall, on the other hand, range from 20 to > 50 %.

Box 4.1.1 The Penman-Monteith Method

The original form of the Penman-Monteith equation (Monteith, 1981) may be written as

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

$8ET_o$ = latent heat influx of evaporation (kJ/m^2 /s),
R_n = net radiation flux at surface (kJ/m^2 /s),
G = soil heat flux (kJ/m^2 /s),
ρ = atmospheric density (kg/m^3),
c_p = specific heat moist air (kJ/kg/°C),
$(e_a - e_d)$ = vapour pressure deficit (kPa),
r_c = crop canopy resistance (s/m),
r_a = aerodynamic resistance (s/m),
$)$ = slope of the vapour pressure curve (kPa/°C),
$($ = psychrometric constant (kPa/°C), and
λ = latent heat of vaporisation (MJ/kg).

Adapting the above equation to the given definition of reference crop evaporation, and multiplying out constants according to derivations and formulae given in FAO (1992), the above equation may be simplified to the following formula:

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

where
E_{rpm} = reference crop evaporation (mm/day),
R_n = net radiation at the crop surface (MJ/m^2/day),
T_{xd} = average daily air temperature (°C) at screen height, and
u_2 = daily mean windspeed at 2 m height (m/s), assumed (in the absence of measurements) to be 1.6 m/s,

with the other variables defined as above.

What remains is for T_{xd}, Δ, γ, R_n, e_d and e_a to be formulated. The formulations are a combination of the simplifications of FAO (1992) derived equations and empirical expressions developed specifically from South African research.

T_{xd} = mean daily air temperature (°C)
= $(T_{mxd} + T_{mnd}) / 2$, with
  T_{mxd} = daily maximum temperature (°C) (cf. Schulze and Maharaj, 2004)
  T_{mnd} = daily minimum temperature (°C) (cf. Schulze and Maharaj, 2004),
e_a = saturated vapour pressure (kPa)
= $0.6108\ exp\{(17.27\ T_{xd})(T_{xd} + 237.3)\}$,
e_d = actual vapour pressure (kPa)
= empirically derived for South Africa on a month-by-month basis (cf. Schulze *et al*., 2008),
Δ = delta, i.e. slope of vapour pressure curve (kPa/°C)
= $[4098\{0.6108\ exp((17.27\ T_{xd}) / T_{xd} + 237.2)\}] / (T_{xd} + 237.3)^2$,
γ = psychrometric "constant" (kPa / °C)
= $P_a \times 0.665 / 10^3$, with
  P_a = atmospheric pressure (kPa), determined from altitude, *viz*.
  = $101.3[(293 - 0.065z) / 293]^{5.26}$, with
  z = altitude (m) above mean sea level,
R_n = $R_{sn} - R_{lw}$, with
  R_{sn} = net shortwave (solar) radiation (MJ/m^2/day)

Box 4.1.1 The Penman-Monteith Method (continued)

= $(1 - 0.23)\ R_s$, with albedo of short grass assumed to be 0.23, and
R_s = $0.75\ R_a(1 - 1/T_{ra}^{2.5})[1 - exp(-\ bT_{ra}^{c})]$, with
R_a = extraterrestrial solar radiation, from tables or standard formulations (cf. Schulze and Chapman, 2008),
T_{ra} = daily temperature range (cf. Schulze and Maharaj, 2004),
b, c = empirically derived for South Africa, by region and month (cf. Schulze and Chapman, 2008), and
R_{lw} = net longwave radiation (MJ/m^2/day)
= $0.5(4.903/10^9)\{(T_{mxd} + 273.16)^4 + (T_{mnd} + 273.16)^4\}(0.34 - 0.14e_d^{0.5})\ [1.35\ R_s / \{R_a(0.75 + 2z/10^5)\} - 0.35]$

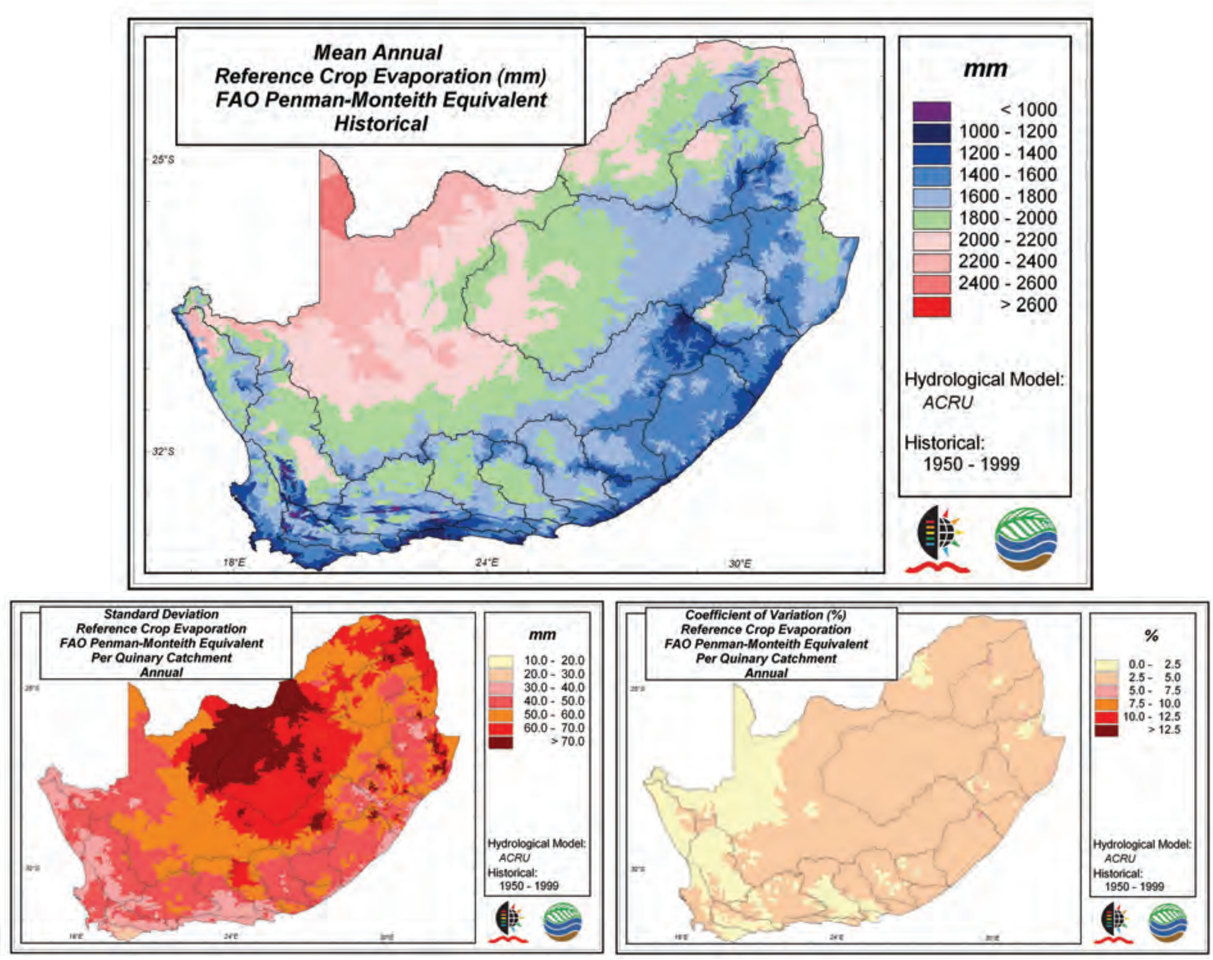

Figure 4.1.1 Mean annual reference crop evaporation by the Penman-Monteith approach (top) and inter-annual variability statistics (bottom maps), derived from baseline (historical; 1950 - 1999) daily data

In the seasonal analysis, mid-summer monthly E_{rpm} averages, represented by January, range from 150 mm in the east and south to 300 mm in the central west (**Figure 4.1.2**, left column). By autumn (April) these values drop to < 100 mm in the mountains, are 100 - 150 mm over the bulk of South Africa and > 150 mm along the northern and eastern periphery, while in winter (July) most of the region experiences reference crop evaporation values of < 100 mm per month, except again in the sub-tropical north and east. By springtime (October) values have increased again to 100 - 150 mm in the east and south, but are up to 200 - 250 mm in the northwest. As with annual values, monthly CVs are low at 2.5 - 10 %, with higher variability in the central areas (**Figure 4.1.2**, right column).

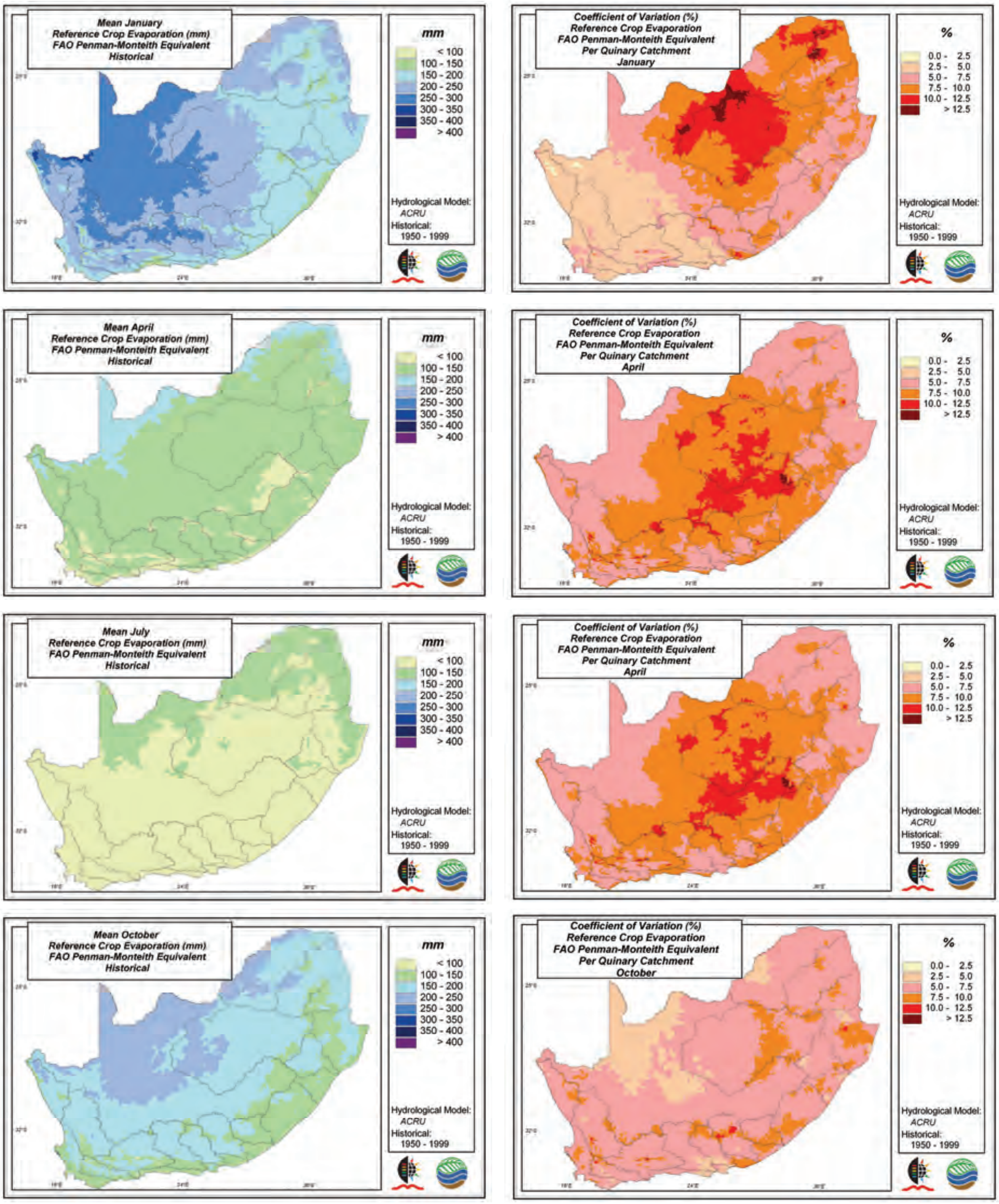

Figure 4.1.2 Means (left column) and coefficients of variation (right column) of reference crop evaporation by the Penman-Monteith approach for the months of January (representing summer conditions; top row), April (autumn; second row), July (winter; third row) and October (spring; bottom row), derived from baseline (historical; 1950 - 1999) daily data

In all the above analyses it should be borne in mind that A-pan evaporation equivalents are ~ 1.2 times the Penman-Monteith values.

Changes, at Provincial Level, in January and July Reference Crop Evaporation by the Penman-Monteith Approach for Increases in Temperature

A sensitivity analysis at provincial level shows that in January a 1 °C temperature increase is simulated to increase crop evaporation by ~ 3.5 % (2.9 - 3.8 %) while a 2 °C and 3 °C increase would enhance crop evaporation by ~ 7 % (5.7 - 8.4 %) and 10.5 % (9.2 - 11 9 %) respectively (**Table 4.1.1**). Areas of relatively high increases in January are in the more humid areas (Swaziland, KwaZulu-Natal, Mpumalanga) while relatively low increases occur in the more arid interior regions (e.g. Northern Cape, Free State). Winter, i.e. July, increases are relatively higher than summer increases, particularly in the coastal provinces (**Table 4.1.2**). These observations are illustrated graphically in **Figure 4.1.3**.

Table 4.1.1 Changes, with increases in temperature, in January (mid-summer) reference crop evaporation by the Penman-Monteith approach in the nine provinces of the RSA as well as Swaziland and Lesotho

Province / Country	Present Climate			Temperature = T + 1 °C		Temperature = T + 2 °C		Temperature = T + 3 °C	
	Mean	20 %ile	80 %ile	Mean	% Increase	Mean	% Increase	Mean	% Increase
Limpopo	162	153	174	168	3.7	174	7.4	179	10.5
Mpumalanga	145	132	158	150	3.4	155	6.9	161	11.0
North West	178	164	196	184	3.4	189	6.2	195	9.6
Northern Cape	202	191	214	207	2.5	212	4.7	218	7.9
Gauteng	152	146	158	157	3.3	163	7.2	168	10.5
Free State	174	158	188	179	2.9	184	5.7	190	9.2
KwaZulu-Natal	143	130	157	148	3.5	154	8.4	160	11.9
Eastern Cape	160	141	180	166	3.8	171	6.9	177	10.6
Western Cape	171	151	193	177	3.5	183	7.0	188	9.9
Swaziland	146	130	160	151	3.4	157	7.5	163	11.6
Lesotho	148	110	146	153	3.3	158	6.8	163	10.1

Table 4.1.2 Changes, with increases in temperature, in July (mid-winter) reference crop evaporation by the Penman-Monteith approach in the nine provinces of the RSA as well as Swaziland and Lesotho

Province / Country	Present Climate			Temperature = T + 1 ° C		Temperature = T + 2 ° C		Temperature = T + 3 ° C	
	Mean	20 %ile	80 %ile	Mean	% Increase	Mean	% Increase	Mean	% Increase
Limpopo	89	83	95	93	4.5	97	9.0	101	13.5
Mpumalanga	76	66	87	79	3.9	83	9.2	87	14.4
North West	80	76	86	84	5.0	88	10.0	91	13.8
Northern Cape	69	59	78	72	4.3	76	10.1	79	14.5
Gauteng	74	70	78	77	4.1	81	9.5	85	14.9
Free State	68	62	73	71	4.4	74	8.8	78	14.7
KwaZulu-Natal	73	66	80	77	5.5	81	11.0	85	16.4
Eastern Cape	62	57	67	65	4.8	69	11.3	73	17.7
Western Cape	54	47	61	58	7.4	61	12.9	65	20.3
Swaziland	82	73	90	86	4.9	90	9.8	94	14.6
Lesotho	52	47	58	55	5.7	58	11.5	61	17.3

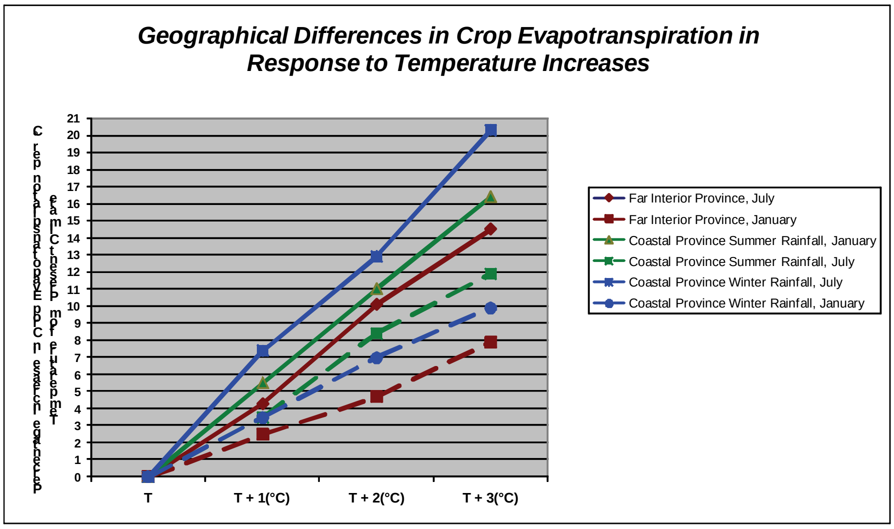

Figure 4.1.3 Geographical differences in crop evaporation by the Penman-Monteith approach for increases in temperature

Ratio Changes of Future to Present Annual and Seasonal Statistics of Reference Evaporation by the Penman-Monteith Approach, Using Outputs from Multiple GCMs

Using output from the multiple GCMs used in this study, **Figure 4.1.4** (left) shows that by the intermediate future (2046 - 2065) an increase in annual reference crop evaporation around 5 - 10 % is projected over most of South Africa, with patches increasing by > 10 %, especially along the west coast. By the more distant future (2081 - 2100), however, the medians of the projections display annual increases of 15 - 20 % in the far interior, but 20 - 25 % along the western, southern and eastern periphery of the country up to ~ 400 km inland (**Figure 4.1.4**, right).

Projected changes in reference crop evaporation are, however, neither seasonally nor spatially consistent, with the lowest increases for both intermediate future to present and for more distant future to present shown for mid-summer (January) and the highest increases for autumn (April), with high changes also evident in mid-winter (July) in the winter rainfall region (**Figure 4.1.5**).

*The implications of these projected increases in E_{rpm} could be significant to water resource managers, and in **Chapters 4.2**, **9.1** and **9.2** respectively, implications on soil water, evaporation losses from water bodies and irrigation are discussed.*

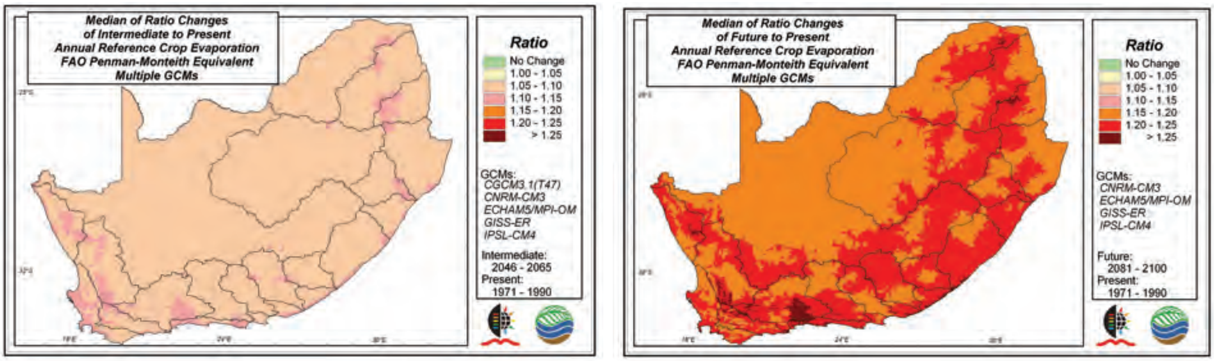

Figure 4.1.4 Medians of ratio changes of intermediate future to present (left) and more distant future to present annual reference crop evaporation by the Penman-Monteith approach, derived from output of multiple GCMs

The inter-annual variability of reference evaporation is projected to increase over much of the northeastern half of South Africa and the west coast by the intermediate future (**Figure 4.1.6,** top row), while in the central west and south coast areas the prognosis is for a reduction in year-to-year variability of E_{rpm}. However, by the more distant future a higher variability of year-to-year variability of E_{rpm} is projected virtually everywhere, particularly in the west, north and east.

The projected future year-to-year variabilities of reference crop evaporation in the different seasons display quite patchy spatial patterns of increases and decreases, both within the representative months of January (mid-summer), April (autumn), July (mid-winter) and October (spring) and between the months (**Figure 4.1.6**, second to fifth rows). However, the variability is projected to generally increase into the more distant future compared with the intermediate future (**Figure 4.1.6**, right column of maps).

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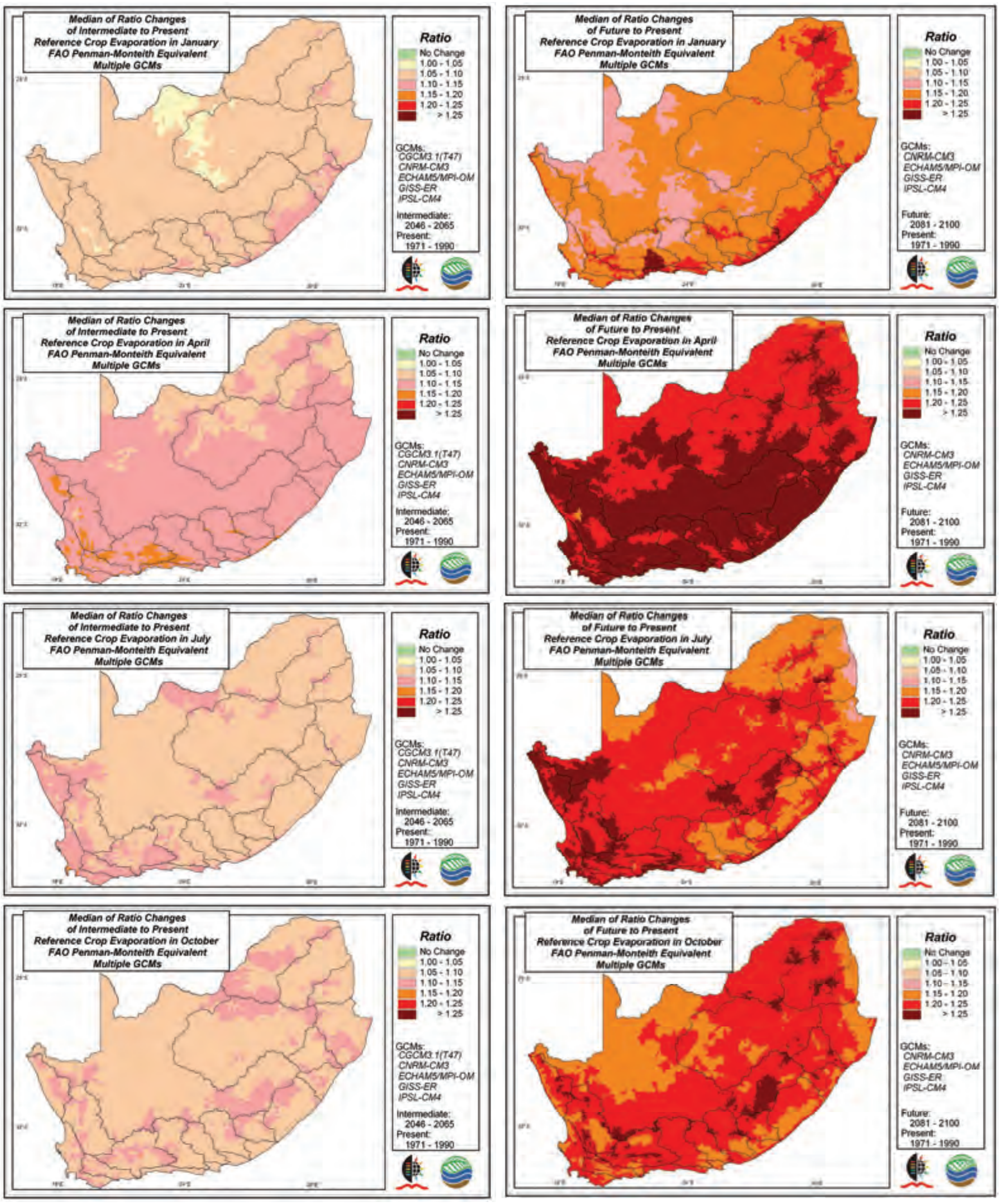
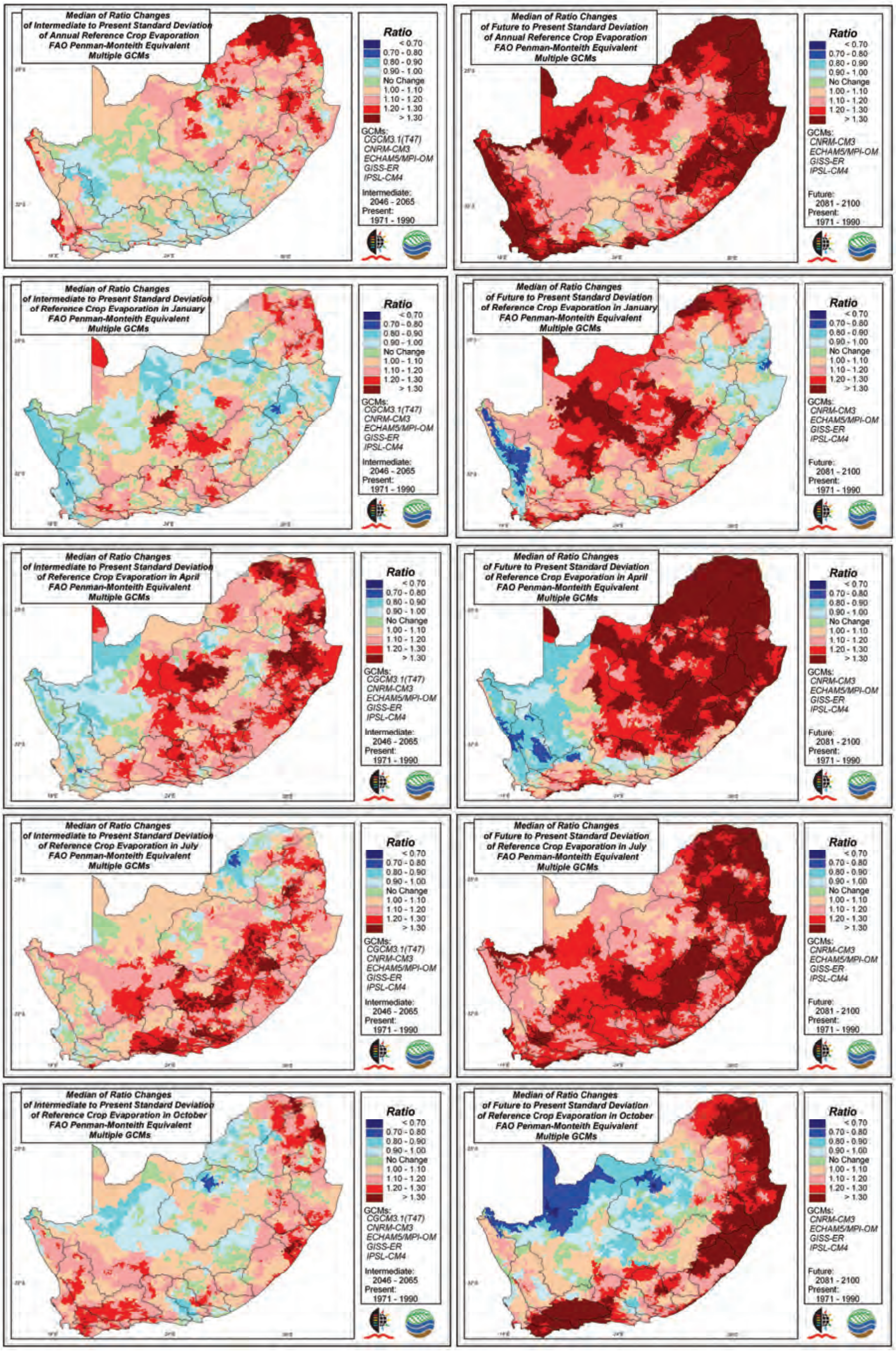


Figure 4.1.5 Medians of ratio changes of intermediate future to present (left column of maps) and more distant future to present (right column of maps) reference crop evaporation by the Penman-Monteith approach for January (top row), April (second row), July (third row) and October (bottom row), derived from output of multiple GCMs



Median of Ratio Changes of Intermediate to Present Standard Deviation of Annual Reference Crop Evaporation FAO Penman-Monteith Equivalent Multiple GCMs

Median of Ratio Changes of Future to Present Standard Deviation of Annual Reference Crop Evaporation FAO Penman-Monteith Equivalent Multiple GCMs

Median of Ratio Changes of Intermediate to Present Standard Deviation of Reference Crop Evaporation in January FAO Penman-Monteith Equivalent Multiple GCMs

Median of Ratio Changes of Future to Present Standard Deviation of Reference Crop Evaporation in January FAO Penman-Monteith Equivalent Multiple GCMs

Median of Ratio Changes of Intermediate to Present Standard Deviation of Reference Crop Evaporation in April FAO Penman-Monteith Equivalent Multiple GCMs

Median of Ratio Changes of Future to Present Standard Deviation of Reference Crop Evaporation in April FAO Penman-Monteith Equivalent Multiple GCMs

Median of Ratio Changes of Intermediate to Present Standard Deviation of Reference Crop Evaporation in July FAO Penman-Monteith Equivalent Multiple GCMs

Median of Ratio Changes of Future to Present Standard Deviation of Reference Crop Evaporation in July FAO Penman-Monteith Equivalent Multiple GCMs

Median of Ratio Changes of Intermediate to Present Standard Deviation of Reference Crop Evaporation in October FAO Penman-Monteith Equivalent Multiple GCMs

Median of Ratio Changes of Future to Present Standard Deviation of Reference Crop Evaporation in October FAO Penman-Monteith Equivalent Multiple GCMs

Figure 4.1.6 Medians of ratio changes of intermediate future to present (left) and more distant future to present standard deviations of annual reference evaporation by the Penman-Monteith approach derived from output of multiple GCMs

CHAPTER 4.2

CLIMATE CHANGE AND
SOIL WATER CONTENT:
A 2011 PERSPECTIVE

R.E. Schulze, R.P. Kunz and L.M. Bulcock

The Importance of Soil Water Content in Hydrology

In hydrology information on soil water content is vital since

- the need to irrigate occurs when the actual soil water content, θ, is less than the critical soil water content at which plant stress commences, *viz*. θ_{fs} (cf. **Chapter 9.2**). Furthermore,
- the total evaporation of a plant / soil system, E, is less than the maximum evaporation that could take place, E_m, when either
    - an excess of soil water prevails and plants cannot transpire (grow) at their maximum because they suffer from anoxia (lack of oxygen) when $\theta > DUL$ (i.e. drained upper limit), or when
    - a deficiency of soil water is experienced because $\theta < \theta_{fs}$ and transpiration is again reduced to being below its maximum (this Chapter). Additionally,
- the soil water content within a critical depth of the upper soil horizon(s) is crucial to the generation of runoff from a given amount of rainfall (e.g. Schulze, 1984; cf. **Chapter 5.2**), with significantly less runoff resulting from dry vs. wet soils, be it on a day-to-day basis in continuous modelling (e.g. with the *ACRU* model) or in the estimation of design runoff (e.g. Schmidt and Schulze, 1987; Schulze *et al*., 1993).
- To the above it needs to be added that in agricultural in-field operations the trafficability of farm machinery in a field, as well as the potential compactability of the soil, are all linked to the level of the water content of the soil (Bezuidenhout *et al*., 2006).

Objectives of Mapping Classes of Soil Water Content Related to Levels of Plant Stress

Different levels of soil water content are related to different levels of water stress in plants. The objective of soil water stress mapping in this study was to determine, for each Quinary Catchment with its unique characteristics of rainfall and reference crop evaporation, as well as with its unique soils (cf. **Chapter 2.2**), the number of days per year at which soil water content would exceed critical thresholds for plant stress to either occur or not, and if stress occurred, at what level it would be. For these simulations the vegetation cover of each Quinary Catchment was assumed to consist of natural vegetation represented by the dominant Acocks (1988) Veld Type in that Quinary. Definitions of different levels of stress and model input / assumptions are given in **Box 4.2.1**. Simulations were carried out for baseline (historical) climatic conditions as well as for projected future climates.

Box 4.2.1 Definitions of Soil Water Stress (Adapted from Schulze, Hull and Maharaj, 2008)

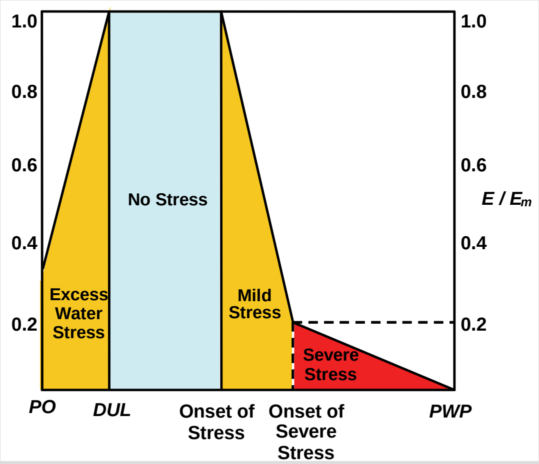


Figure 4.2.1 Schematic of different levels of soil water related plant stress

Box 4.2.1 Definitions of Soil Water Stress (Adapted from Schulze, Hull and Maharaj, 2008) (continued)

With reference to **Figure 4.2.1**,

- ***Excess soil water stress*** *occurs when actual soil water content exceeds that at the drained upper limit, i.e.*

$$\theta > \theta_{DUL}$$

 and total evaporation, *E*, drops to below its maximum, E_m

- ***No soil water stress*** occurs when the plant can transpire at its maximum rate (i.e. $E = E_m$) with the soil water content then below that of the *DUL*, but exceeding the soil water content at a specified fraction of *PAW* (i.e. plant available water) at which plant stress commences, *viz*. θ_{fs}, which in this case has been set at 0.4 *PAW*,

$$\theta_{DUL} > \theta > \theta_{fs}$$

$$\text{i.e.} \quad \theta_{DUL} > \theta > 0.4(\theta_{DUL} - \theta_{PWP}) + \theta_{PWP}$$

 where *PWP* is the permanent wilting point.

- ***Mild soil water stress*** is experienced when soil water content is below the stress fraction, θ_{fs}, but the plant is still transpiring at more than 20% of its maximum evaporation, i.e.

$$\theta_{fs} > \theta > 0.2\ E/E_m$$

$$\theta_{fs} > \theta > 0.6\ (\theta_{fs} - \theta_{PWP}) + \theta_{PWP}$$

- ***Severe soil water stress*** is defined as the soil water content at which total evaporation has been reduced to below 20 % of maximum evaporation, i.e.

$$\theta < 0.2\ E/\mathrm{E}_m$$

Box 4.2.2 Inputs to the *ACRU* Model for the Simulation of Soil Water Stress Levels

The soils and plant input in order to assess soil water stress levels over South Africa have already been mentioned above.

For baseline (i.e. historical) climatic conditions the daily time step *ACRU* model (Schulze, 1995 and updates) was run for each Quinary Catchment using data for the 50 year time period 1950 - 1999, while for climate change impact studies the model was run for present (1971 - 1990), intermediate future (2046 - 2065) and more distant future (2081 - 2100) climate scenarios using daily output from each of the GCMs used in this study (cf. **Chapter 2.1**). From the respective daily output files of soil water content in the top- and subsoils which were created for each Quinary Catchment, classes of soil water stress could then be computed and mapped.

Distribution Patterns over South Africa of the Number of Days per Year which Experience Different Levels of Soil Water Stress under Baseline (Historical) Climatic Conditions

Areas within South Africa experiencing *no soil water stress* (**Figure 4.2.2** top left) range from > 120 days in the eastern parts of KwaZulu-Natal, Lesotho and the Eastern Cape to fewer than 20 days in the semi-arid northwest. Under current climatic conditions *mild soil water stress* (**Figure 4.2.2** top right) occurs, on average, on > 70 days per year over much of the east, but on < 30 days in the drier northeastern and northwestern parts of South Africa. The latter are areas which are rather characterised by *severe soil water stress* conditions, shown in **Figure 4.2.2** (bottom left) to be experienced on average over 275 and even > 325 days per year. On the other hand, severe stress in the more humid east reduces to fewer than 125 days per annum. Plant *stress due to waterlogging* on days when water content exceeds the soil's drained upper limit (field capacity) occurs on > 40 days per annum, on average, in the wetter eastern third of the country. Waterlogged conditions are,

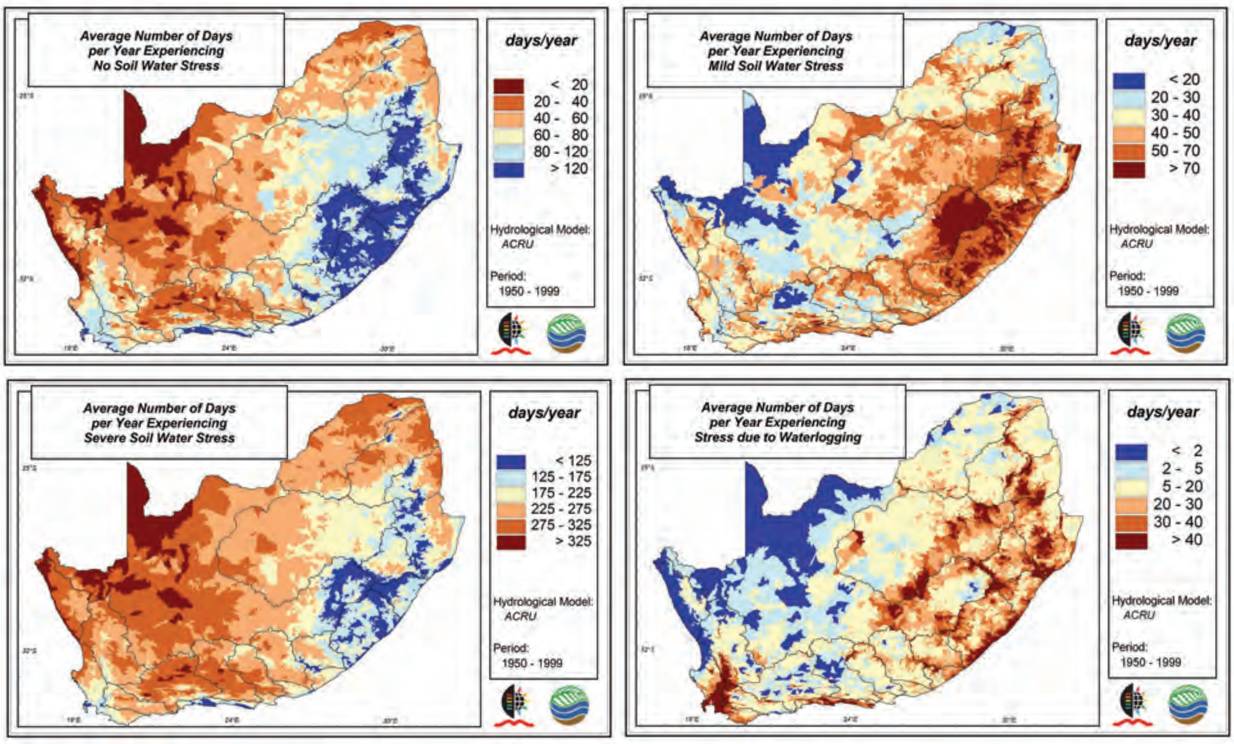


Figure 4.2.2 Average number of days per year experiencing no soil water stress (top left), mild stress (top right), severe soil water stress (bottom left) and stress due to waterlogging (bottom right) for current (1950 - 1999) climatic conditions

however, rare occurrences under the semi-desert conditions of the Northern Cape, with fewer than 2 waterlogged days annually.

Ratios of Future to Present Average Number of Days per Year Experiencing Different Levels of Soil Water Stress, Using Output from Multiple GCMs

Changes in soil water stress under projected future climates are expressed as medians of ratio changes of the various stress categories, derived from output of the multiple GCMs used in conjunction with the *ACRU* model. The interpretation of results depends on ones point of departure, which can be either from a perspective of no stress (as used below) or from the perspective of severe water stress.

For conditions of *no soil water stress*, the majority of South Africa is projected to experience more such days into the intermediate future (i.e. more days of optimal plant growth and maximum evaporation), except in the southwest Cape, where desiccation is projected to result in plants experiencing fewer days without stress (**Figure 4.2.3** top left). Into the more distant future over the 110 years from the present, 3/4 of the region is projected to have fewer days with no plant stress (**Figure 4.2.3** top middle). This observation can be deceptive as the eastern regions are likely to display increases in waterlogged conditions, and hence fewer no stress days. In the west, desiccation is projected to become more intensive. This is confirmed by the changes in days with no soil water stress in the 35 years between the intermediate and more distant future (**Figure 4.2.3** top right).

For *mild stress conditions* resultant decreases into the intermediate future are shown along the coast and especially in the Eastern Cape and Lesotho, with the remainder of the country displaying more days with mild stress (**Figure 4.2.3** second row, left). These patterns are intensified into the more distant future (**Figure 4.2.3** second row, middle).

Based on the GCM projections used, days with *severe soil water stress* show a general reduction into the intermediate future, except along the west coast where little change is projected (**Figure 4.2.3** third row, left). However, by the more distant future, the southwest displays more stress days while in ~ 95 % of the region a reduction in the number of days per year with severe stress is shown (**Figure**

4.2.3 third row, middle).

Stress due to waterlogging is projected to increase markedly into the intermediate future, except along the west coast where fewer waterlogged days are projected (**Figure 4.2.3** bottom left). These patterns intensify when changes between the more distant future and the present are considered (**Figure 4.2.3** bottom middle).

The implications of these findings are that in the east runoff generation is likely to be enhanced and dryland agriculture would benefit, while the converse is projected to occur in the west. This study does show up the need for the use of output from more GCMs to come to more definite conclusions.

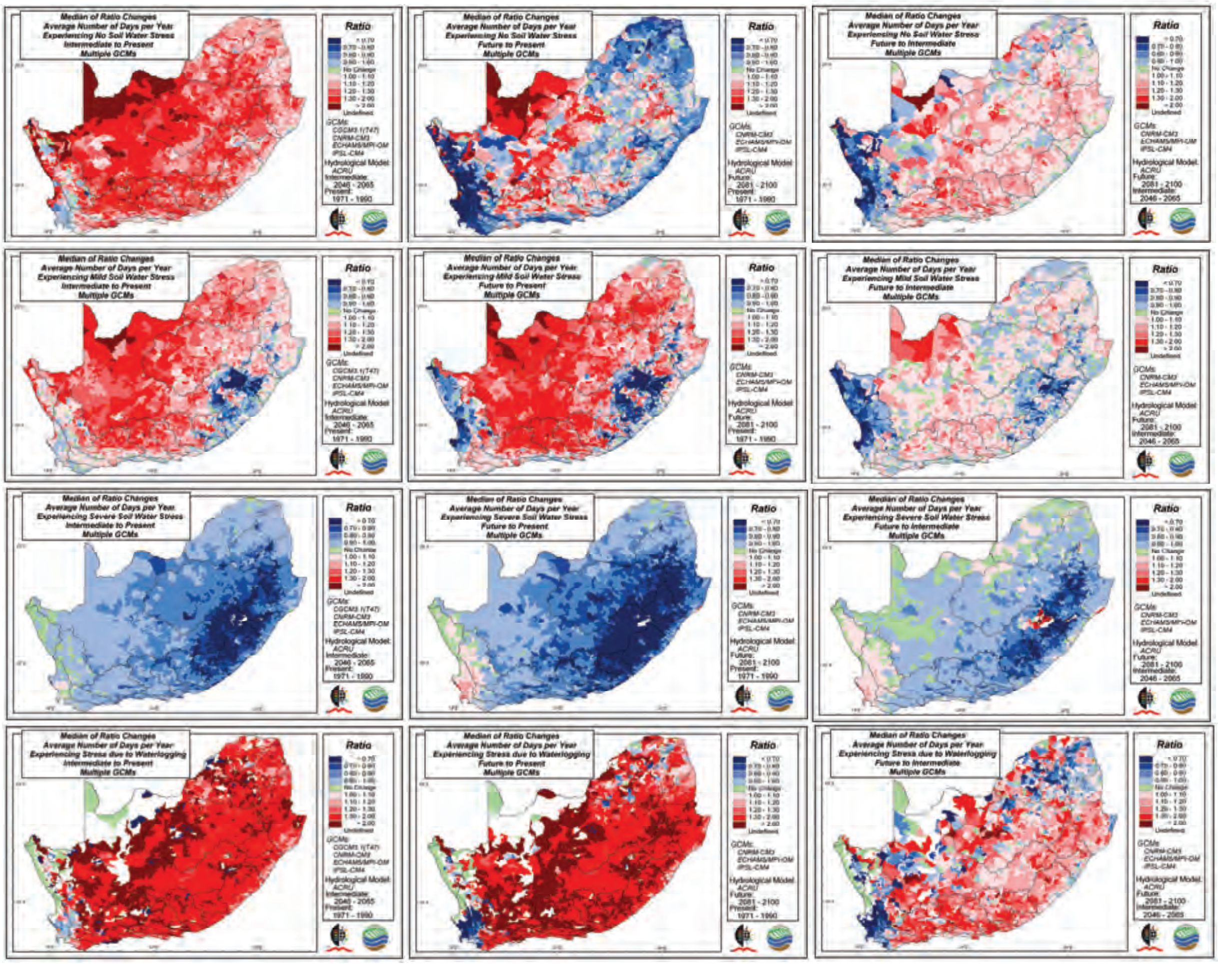


Figure 4.2.3 Medians of ratios of intermediate future to present (left column), more distant future to present (middle column) and more distant to intermediate future (right column) average number of days per year experiencing no soil water stress (top row), mild stress (second row), severe soil water stress (third row) and stress due to waterlogging (bottom row), derived with the *ACRU* model from multiple GCMs

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SECTION 5

PROJECTED CHANGES IN HYDROLOGICAL RESPONSES

CHAPTER 5.1

WATER RESOURCES AND HYDROLOGICAL CHALLENGES IN SOUTH AFRICA WITHIN A CLIMATE CHANGE CONTEXT

R.E. Schulze

Complexities in the Management of Water Resources in South Africa

Water has become central, and a critical, input to many of South Africa's economic activities which make significant contributions both to the country's GDP and its employment levels, be it in regard to

- water needs in the mining, industrial and domestic sectors,
- sustaining terrestrial and aquatic ecosystems, or
- providing water to the agriculture sector, both for irrigation or rainfed farming, for commercial or subsistence farmers or for livestock,
- water for recreational purposes,
- to support power generation, or
- to meet increasing demands and expectations of an expanding population in order to improve peoples' standards of living.

.

In order to protect, develop, use, conserve, manage and control South Africa's water resources as encapsulated in the aims of the RSA's National Water Act of 1998 (NWA, 1998) is, for many reasons, already proving very challenging. These challenges may be grouped into broad themes which include the following:

- a harsh biophysical environment,
- the legal, administrative and governance environment,
- the present state of water resources in South Africa,
- some critical water use sectors,
- environmental issues, and
- the state of South Africa's water quality,

all of which are likely to be exacerbated by projected climate change.

The Harsh Biophysical Environment

1. Semi-Aridity

South Africa is, overall, largely semi-arid. This is the result not only of its relatively low MAP which averages around 480 mm (ranging from < 50 to > 3 300 mm; Lynch, 2004; **Chapters 3.3** and **3.4**) compared with a world average of 860 mm, but also because of the high atmospheric demand, i.e. potential evaporation, which prevails over the region. This semi-aridity renders the natural environment a high risk and a largely water limiting one.

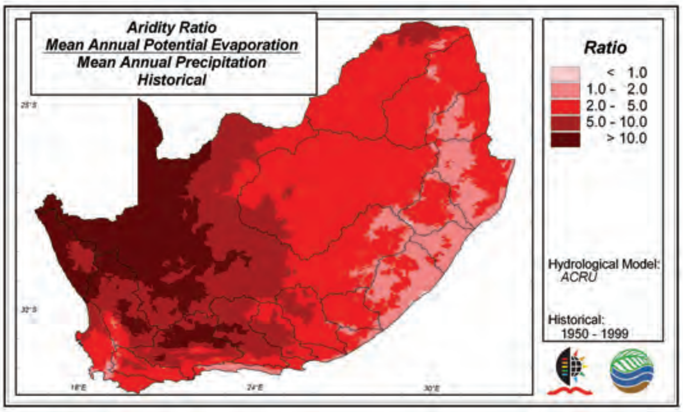

Figure 5.1.1 The aridity index over South Africa

The relative dryness of the region may be expressed by an aridity index in which a ratio is computed between mean annual potential evaporation (in this case by the Penman-Monteith method; cf. **Chapter 4.1**) and mean annual precipitation. It may be seen in **Figure 5.1.1** that this ratio is already above 1 in the wet eastern parts of the country and the index increases to more than 10 in the more arid west, implying that on an annual basis the potential evaporation is, on average, over 10 times as high as the rainfall there - most certainly an indicator of overall aridity.

2. The Low Conversion of Rainfall to Runoff

South Africa experiences a low conversion of rainfall to runoff. The heterogeneity of rainfall patterns is amplified in the spatial and temporal heterogeneity of streamflows (e.g. Schulze, 2005). A feature of maps of mean annual runoff (MAR) is the disparity between low runoff generating areas in the west and north, with one third of the region producing less than the equivalent of 10 mm runoff, and the belt of relatively high runoff stretching from the Western Cape mountains through the all year rainfall region to the former Transkei, with KwaZulu-Natal being the wettest province and Swaziland, Mpumalanga and parts of Lesotho also having relative abundances of surface water (cf. **Chapter 5.2** and **5.4**). Runoff patterns reflect a combination of precipitation characteristics (e.g. the amount of rainfall, its intensity, the concentration of the rainfall season and the persistence of raindays, i.e. whether rain falls on consecutive days causing high runoff responses, or as isolated events) and soil characteristics (e.g. water holding capacity, drainage rates).

As important as the spatial patterns of runoff are, however, is the low conversion of rainfall to runoff already alluded to. The heterogeneous spatial and temporal distributions of rainfall (cf. **Chapters 3.4** and **3.5**) result in a low overall conversion rate of rainfall to runoff which, according to Whitmore (1971), averages only ~ 9 % for South Africa as a whole. **Figure 5.1.2** shows that over much of the interior of South Africa the ratio of MAR to MAP is indeed < 10 %, with significant tracts in the west at < 5% and only small parts exceeding a MAR to MAP ratio > 20 %. This low conversion rate is the consequence as much of an overall paucity of rainfall as it is of very high evaporative demand, as shown in the maps of potential evaporation in **Chapter 4.1**. While the conversion rate of rainfall to runoff is likely to increase in areas where more rainfall is projected to occur under future climates, it is in areas where rainfall is projected to decrease that the conversion to runoff is anticipated to decline markedly, as the runoff : rainfall relationship is a non-liner one and any changes in rainfall will be amplified in its runoff responses.

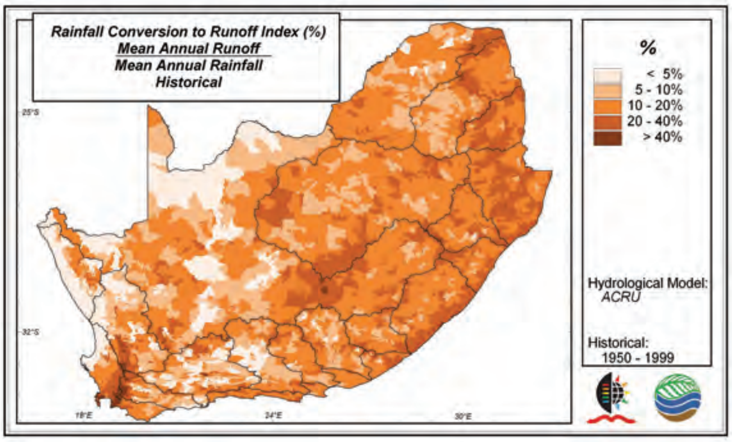

Figure 5.1.2 Ratios of MAR to MAP over South Africa, illustrating the low conversion rate of rainfall to runoff

3. The High Variability and Sensitivity of the Runoff : Rainfall Relationship

The very high inter-annual coefficient of variation (CV%) of streamflows (cf. **Chapter 5.4**), and monthly flow variabilities nearly twice as high as annual ones (Schulze and Lynch, 2008), are a feature of surface water responses in South Africa. The main implication of the high year-to-year flow variability is that for high assurances of yield of water, dams have to be designed with full storage capacities well in excess of those in most other countries of the world. Patterns of the CV of runoff are patchier than those of rainfall (cf. **Figure 5.4.2** vs. **Figure 3.4.2**) reflecting, in part, the important role of local events and catchment characteristics in the runoff generating processes.

Even more significant from a water resources perspective than the high CVs of runoff *per se*, particularly in light of the likely intensification of the hydrological cycle with global warming, is that the ratios of CVs of annual runoff to annual rainfall are very high - of the order of 2 to 4 over much of South Africa, and even as high as 6 and more in places (**Figure 5.1.3**). This indicates clearly the high sensitivity of runoff to rainfall which water resource managers in South Africa have to cope with, and which may become amplified under future climatic conditions.

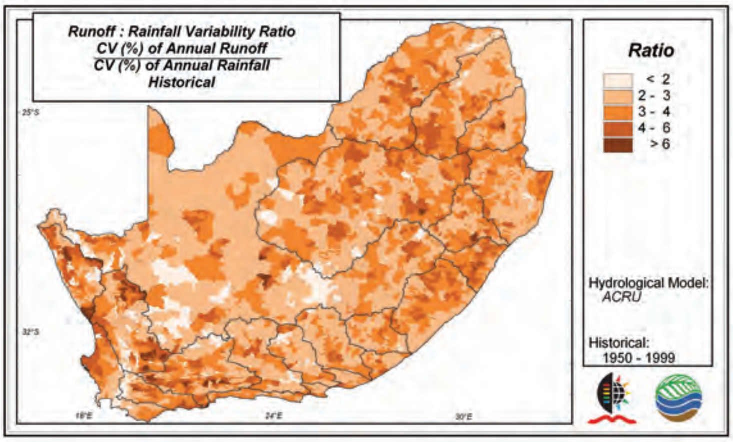

Figure 5.1.3 Ratios of the inter-annual coefficient of variation of runoff to that of rainfall, illustrating the amplification of any changes in the rainfall regime

4. On Outlier Events or Years of High Flows Distorting the Annual Means of Streamflows

Streamflow responses are influenced significantly by extreme events of rainfall. Statistically, the distribution of a runoff series is thus frequently highly skewed. One or two excessive floods or very wet years in even a relatively long 50 year time series can thus bias the mean of annual (and shorter duration) streamflows markedly, especially in more arid areas where flows are generally low, and can create a wrong impression of what constitutes a "mean" annual streamflow. The same applies to stormflows and to recharge into the groundwater zone. This strong influence of extreme events on mean flows is illustrated clearly in **Figure 5.1.4** which shows *means* of annual streamflow series to be up to 25% higher than *medians* over much of South Africa, and up to 50% higher in places.

In the case of streamflow analyses, where any excesses of water are "lost" to a catchment by flood waters exiting that catchment, the median should thus be preferred to the mean, because it reflects a middle, or expected, value with as many years having more streamflow than the median value as years having less. However, in the case of recharge into the groundwater zone, which constitutes a "store" of water which is generally not "lost" to a catchment, the mean can be used, because the water can still be utilised beneficially either through baseflow or as a groundwater abstraction long after the event which gave rise to that store of water having occurred.

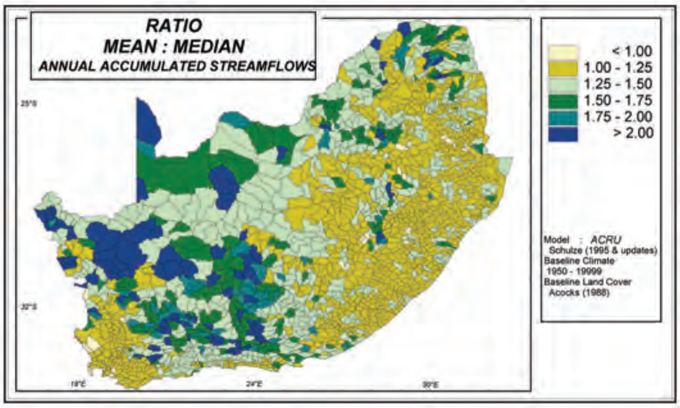

Figure 5.1.4 Ratios of mean to median annual streamflows per Quaternary Catchment, illustrating that time series of streamflows in South Africa frequently have a skewed distribution as a result of extreme events (Schulze *et al*., 2008)

With extremes of climate, and thus of hydrological responses, projected to increase under future climatic conditions, it becomes very important that for many analyses the medians rather than the means of flows should therefore be used.

Legal, Administrative and Governance Challenges

- A core tenet of the National Water Act of 1998 (NWA, 1998) is that water is a social, environmental, economic (i.e. tradable) and therefore, by implication, a public good - as opposed to individuals having a private right to the water. This implies a shift in managers' and stakeholders' mindsets, as does the commitment to the delivery of potable water and water for sanitation to an entire nation's population in pursuit, *inter alia,* of fulfilling the Millennium Development Goals and the implementation of the human and environmental reserve. Further key issues are the 'polluter pays' principle, the establishment of Catchment Management Agencies and South Africa's international water obligations to downstream countries. The implementation of these paradigm shifts in water management are likely to be put to the test even more under the challenges that climate change bring to the table than under current climatic conditions.
- A number of recent developments in the South African water scene do, however, make the challenge of coping with, and adapting to, climate change easier than in the past. These include
    - a growing consciousness (not only at the global) at the South African level within the Department of Water Affairs as well as at provincial and local government levels to integrate and, eventually, to mainstream climate change into water resources planning;
    - the merger of Water and Environmental Affairs under one Ministry, which is creating an opportunity for better coordination of water and environmental governance also in light of climate change, with the Department of Environmental Affairs mandated to developing and updating a National Climate Change Response Strategy while Water Affairs is committed to developing a water sector adaptation strategy;
    - the mandatory five-yearly updates of the National Water Resource Strategy, with each update placing a greater emphasis on climate change impacts, always in light of the state of knowledge at the time of the update;
    - the launch of the DWA's Water for Growth and Development (WfGD) Framework in 2009 which takes a 25 - 30 year perspective for promoting economic growth and social development without compromising long-term sustainability of water resources, and thus potentially being able to accommodate projected climate change impacts meaningfully;
    - the establishment of the National Planning Commission which creates a platform for improving integrated development planning in which water, now and in the future, plays a central role as a limiting resource for social development and economic growth.

The positives outlined above are tempered by constraints which are likely to increase the additional challenges of climate change when it is superimposed onto an already stressed water sector. These include:

- a shortage of capacity, both technical and managerial, to implement the NWA, with limited progress being made in building such a competent task force with the skills necessary to implement the NWA; and allied to that
- a lack of compliance monitoring and regulation enforcement, especially in the field of water pollution prevention and illegal abstractions;
- monitoring networks / systems which do not take early climate change detection into account and information management systems which are not accessible to all sector partners;
- the slow evolution of designated Water Management Areas (WMAs) into semi-autonomous Catchment Management Agencies (CMAs) with a mandate to manage and co-ordinate water related activities, and with the WMAs not coinciding with provincial and local government administrative boundaries; and
- the slow registration of water users and compulsory licensing to reallocate water between users, with focus on the most stressed catchments.

The State of Water Resources in South Africa

Complex population distributions, demographic characteristics (cf. **Table 1.2.1** in **Chapter 1.2**) and historical growth and development patterns in South Africa away from sources of water, the need for redress in the water sector as well as the high expectations of the entire population to be fully supplied with potable water, the high degree and rate of urbanisation (in both the formal and informal sectors), deteriorating water quality, legal commitments of water for the environment and international water commitments all render the management of water resources a challenging task, especially when viewed against the heterogeneous spatial and temporal distribution of streamflow and challenges posed by climate change.

In terms only of water quantity, four key issues to be considered in light of climate change are:

- the already generally stressed state of water resources,
- already complex water engineered systems,
- complexities of transboundary waters, and
- problems associated with aging infrastructure.

1. *Generally Stressed State of Water Resources*

- Of a natural MAR (mean annual runoff) of ~ 49 000 million m^3/a, less than one third is still available as reliable yield, and water resources in 10 of the 19 originally designated WMAs were, by the year 2000, already nearly fully developed and utilized, with five WMAs already short of water and with the situation envisaged to worsen by 2025 (**Figure 5.1.5**; NWRS, 2004).

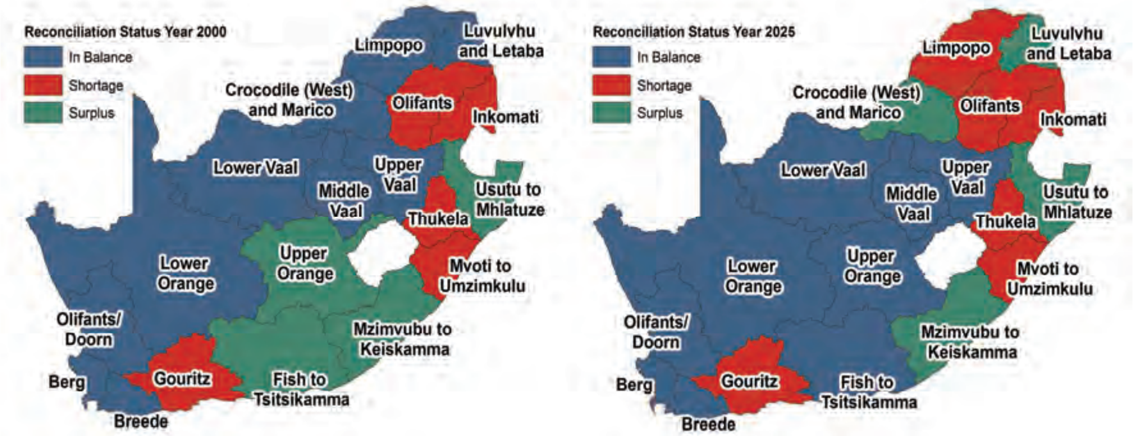

Figure 5.1.5 The reconciliation status of water resources in South African Water Management Areas in 2000 (left) and projected future water status by 2025 if current trends of use continue without accounting for climate change (NWRS, 2004)

- If the approach to water use were to continue at the current business-as-usual rates, the DWA estimates that within two decades water availability would be the limiting factor for achieving a high level economic growth trajectory of 4 - 6 % per annum.
- The Department estimates that an additional 3 000 million m^3 per annum of water will be needed to meet the projected demand in 2030 to ensure adequate resources are available for socio-economic development. The cost of making additional water available will continue to rise in the future and this would determine where water intensive industries should be located (NWRS, 2004).
- None of the issues named above have accounted for possible effects of climate change, which might exacerbate the situation in certain regions while giving a measure of reprieve in other regions.

2. *Complex Water Engineered Systems*

- Complex water engineered systems have been developed across South Africa, both
  - *on the catchment*, through land cover conversion and land use management, with
    - ▫ *acceleration* of hydrological responses, e.g. through urbanisation (be it formal with stormwater systems, or informal) or through large and small irrigation projects (with canals

        and their losses, on-field losses, balancing dams, enhanced evapotranspiration and deep percolation losses) on the one hand, and
    - ▫ *retardation* of responses (e.g. by conservation practices by farmers) on the other; and
  - *in the channels*, through
    - ▫ construction of thousands of smaller dams and 320 major dams each with a full supply capacity exceeding 1 000 000 m^3 and a total capacity of 32 400 million m^3, i.e. ≡ 66% of MAR (NWRS, 2004), and with 54 of those dams having surface areas exceeding 1 000 ha and 10 exceeding 10 000 ha (Wikipedia, 2010).
- The implications of this dam storage capacity being a relatively high proportion of the average amount of water available, and with many of the best dam sites already having been utilised, implies that additional dam yield in future is likely to be less efficient and provide a smaller "safe yield" than that from existing dams.
- Furthermore, significant inter-basin transfer schemes have been developed to overcome the imbalance between demand for water and assured supply, with such schemes currently operational in 17 of the 19 originally designated WMAs (**Figure 5.1.6**).
- Some of these existing schemes may benefit from climate change if runoff in the supplying catchments were to be enhanced, while others are likely to be impacted negatively either if the receiving catchments have higher demands or if the supplying catchments experience less, or more variable, runoff or can only supply water of inferior quality.

Figure 5.1.6 Inter-basin transfer schemes in South Africa (NWRS, 2004)

3. *Transboundary Waters*

- Some of the major rivers in South Africa do not respect international political boundaries. These river systems are either
  - *transboundary*, i.e. they cross national boundaries, these including the Limpopo, Inkomati, Pongola and Orange, which together drain ~ 60% of South Africa, contribute ~ 40% of its total surface water and support ~ 70% of the population and GDP (NWRS, 2004); and / or are
  - *contiguous*, i.e. they form national boundaries, such as the Orange and Limpopo (**Figure 5.1.7**).

Figure 5.1.7 Transboundary catchments involving the RSA (NWRS, 2004)

- Transboundary waters include ~ 4 800 million m^3 per annum and 700 million m^3 per annum of water that originates, respectively, from Lesotho and Swaziland and which drains naturally into South Africa (NWRS, 2004).
- With South Africa being a signatory to several international agreements, questions in regard to climate change arise in that these agreements may need to be amended such that neither party gains nor loses unduly and that equity is sustained into a climatically changing future.

4. Aging Infrastructure

While hydraulic structures generally have a long design life ranging from 20 to 200 years, many dams and associated water resources infrastructure were built before the 1970s already and the spillways, gates, pipelines and canals and associated infrastructure need regular maintenance and occasional major rehabilitation to extend the lifespan of these assets (NWRS, 2004). It would be prudent to factor in climate change when funding is sought for maintenance and rehabilitation, not only for state owned, but also for municipal owned infrastructure, much of which has backlogs in maintenance.

On Some Critical Water Use Sectors

1. Energy

While accounting for only 2 % of South Africa's total water utilisation, the South African energy sector's dominantly coal-fired thermal power stations (currently supplying 93 % of the country's total energy requirements) is considered to be a strategic water user (NWRS, 2004) and receives preferential allocation of water resources at typically a 99.5 % level of assurance. It will be important to factor in climate change when assurances of water supply are considered and when planning the new thermal power stations in Limpopo province, which is considered more vulnerable to projected impacts of climate change on its water resources than many other regions in South Africa (cf. chapters that follow).

2. Agriculture

The agriculture sector, primarily through irrigation by ~ 20 000 medium to large scale and ~ 150 000 small scale irrigators on ~ 1.4 million ha (> 1.1 % of the RSA), utilises more than 60 % of South Africa's total water, often in relatively low rainfall areas (**Figure 5.1.8**) where either supplementary irrigation is very high or total irrigation is practiced, much of it still using relatively inefficient modes of irrigation. Climate change can have major repercussions both on irrigation water supply (local and remote through canal systems) and projected increases in irrigation water demands in many areas (cf. **Chapters 4.1** and **8.2**), as well as on impacting the environment through enhanced deep percolation and surface runoff losses from irrigated lands (**Chapter 8.3**). It will need to be considered very carefully from an overall water resources perspective in any development of future irrigation projects, be they large scale or at community scale.

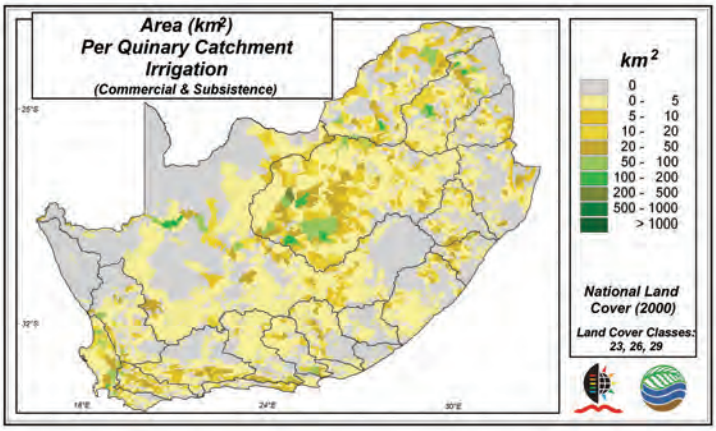

Figure 5.1.8 Location of irrigated areas in South Africa (Information source: NLC, 2000)

3. Industrial and Mining

The 'heart' of the South African economy, and probably growing at a faster rate than other major water user sectors, industry and mining contribute approximately 25 % to the RSA's GDP, account for ~ 54 % of all exports and employ ~ 25 % of the work force (StatsSA, 2010). The two sectors use approximately 11 % of the total water which is usually provided at a generally high assurance of supply around 98 % (NWRS, 2004). A major concern with climate change is in the industry and mining sectors' high impacts on pollution of raw water, with a speeding up of many chemical reactions with increases in temperature and impacts potentially felt far downstream.

4. Forestry

As is the case with irrigation, commercial production forestry in the RSA covers ~ 1.1 % of the country's area, with 40 % in each of the Mpumalanga / Limpopo and KwaZulu-Natal regions and 11 % in the Eastern Cape (Genesis Report, 2005; **Figure 5.1.9**). A major concern in regard to production forestry is the additional water that the trees utilise over and above that of the natural vegetation they would replace, and as such they have been declared a so-called 'Stream Flow Reduction Activity' (SFRA). Using information contained in Gush *et al*. (2002), in the Genesis Report (2005) and in Schulze (2008) it has been calculated that production forestry utilises an additional 922 million m^3 of water, which is equivalent to 1.8 % of South Africa's MAR, with 47 % of this additional water used in Mpumalanga / Limpopo, 43 % in KwaZulu-Natal and the remaining 10 % in the Eastern and Western Cape region. Of this *additional* water usage, or SFRA, *Eucalyptus* species / hybrids contribute 47 % to the total SFRAs, *Pinus* species 46 % and wattle 10 %.

The concerns regarding climate change are not so much the additional 760 000 ha which the forestry industry estimates is required to keep the country self-sufficient in timber (of which probably only somewhere between 100 000 and 200 000 ha can be accommodated from a water resources perspective under current climatic conditions), because projections show that into the intermediate future (2046 - 2065) considerable expansions of both *Eucalyptus* and *Pinus* species could take place from purely climatic considerations (**Figure 5.1.10**), but rather whether SFRA legislation will be flexible enough to factor in climate change when potential new growth areas are considered that are not in present headwater catchments.

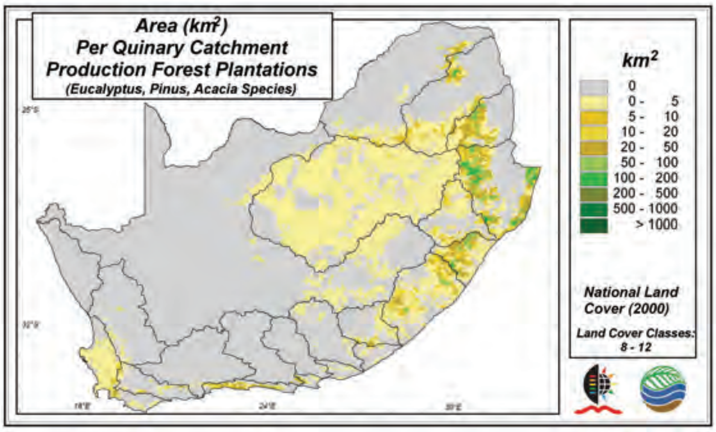

Figure 5.1.9 Location of production forest plantation areas in South Africa (Information source: NLC, 2000)

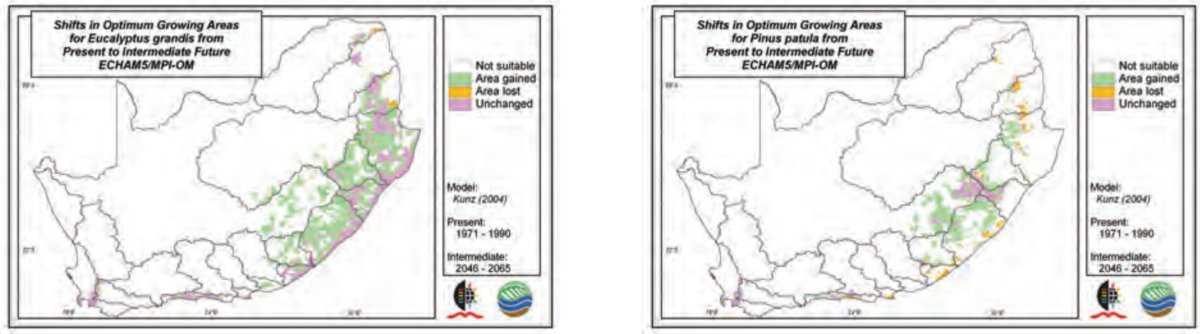

Figure 5.1.10 Projected expansion and contraction of areas which are climatically suitable for *Eucalyptus grandis* (left) and *Pinus patula* (right) to be grown economically in the intermediate future (2046 - 2065) according to growth models using output from the ECHAM5/MPI-OM General Circulation Model (Schulze and Kunz, 2010)

5. *Invasive Alien Plants*

While invasive alien plants are estimated to currently reduce the yields of dams and run-of-river supply systems by about 695 million m^3 per annum (Cullis *et al*., 2007), which is equivalent to only 1.4 % of the RSA's MAR, the predominantly riparian location of the invasives (**Photo 5.1.1**), and hence their relatively easy access to water, gives them the potential to rapidly proliferate under warmer conditions of future climates, and with their relatively high biomass (**Photo 5.1.1**) and year round growth these invasives could reduce MAR considerably more than at present if not kept in check by physical clearance.

Photo 5.1.1 Invasive alien plants in the Eastern Cape, showing their riparian location and high, evergreen biomass (Photo: R.E. Schulze)

On Matters Environmental

- With its wide diversity of climatic conditions, South Africa hosts over 220 river ecosystem and nearly 800 wetland ecosystem types, often with high levels of endemism, ranging from those found in the sub-tropical areas in the northeast of the country to those in cool and warmer temperate summer runoff regimes to those associated with winter rainfall / runoff regions.
- However, nearly 60 % of South Africa's river ecosystem types are threatened, 25 % critically so, while nearly two-thirds of the wetland ecosystem types are threatened, nearly 50 % critically so.
- These facts have to be viewed in light of South Africa's very comprehensive and progressive National Water Act (NWA, 1998) in which the aquatic environment, through the environmental reserve, has been designated a *legitimate* and *prioritised water user* in South Africa and *not* one in competition with development.
- However, the environmental "reserve" raises many challenges in an already complex and sophisticated water-engineered system, including
  - the determination of environmental reserve requirements,
  - its implementation and monitoring,
  - especially in prioritised stressed catchments which need protection, and
  - the need to simplifying procedures to classifying the desired environmental state of water resources.
- Climate change is likely to exacerbate the many pressures already existing on freshwater ecosystems, not only through added anthropogenic stresses linked to new abstraction patterns, or new point and non-point sources of pollution, or habitat destruction, but also through more fundamental and conceptual challenges around
  - having to set new baselines for the environmental reserve with changing river regimes (as a result of both changes in the timing of high and low flows and their magnitudes) and
  - having to re-assess estuarine and wetlands functions.

The Issue of Water Quality

- Different users of water as well as different ecosystems have different water quality requirements. They also respond differently to changes in the state of water quality for their specific use.
- At the present time (2011) the generally poor state of South Africa's water quality is cause for major concern as it has placed the country's water resources under pressure by becoming a threat to human health, to ecosystems and to water security alike.
- The NWRS (2004) and Ashton (2009) have identified the major sources of pollution of the RSA's water resources, the locations of which have been mapped by Ashton (2009), as including
    - *mines*, both existing and closed, in the form of acidity and metals content, mainly in the coal, gold and orefields of Gauteng, the Free State, North West and parts of the Northern Cape, KwaZulu-Natal, Mpumalanga and southern Limpopo (**Figure 5.1.11** bottom left);
    - *sewage effluent discharges* into non-existent or dysfunctional wastewater treatment plants, mainly as pathogens, in many of the formal and informal urban areas (**Figure 5.1.11** bottom middle);
    - *industrial effluents*, mainly chemicals and toxins in the urban, peri-urban and outlying industrial zones (also **Figure 5.1.11** bottom middle);
    - *non-point source pollution* from agricultural and other land use sources, primarily agrochemicals on the Highveld resulting in eutrophication, and salinity through irrigation return flows in the southwest and the Fish River basin in the Eastern Cape (**Figure 5.1.11** top left);
    - *acid atmospheric deposits* in the form of micro-pollutants mainly from coal-fired power plants in the Highveld region (**Figure 5.1.11** top right);
    - *over-abstraction of groundwater* in the semi-arid regions of the northwest and far north (**Figure 5.1.11** top middle); and
    - *excessive soil losses and sedimentation*, frequently triggered by overgrazing, and mainly in the former homelands and independent states within the RSA as well as in the semi-arid Karoo (**Figure 5.1.11** bottom right).
- These sources of pollution affect surface water resources, aquatic ecosystems, wetlands, estuaries and groundwater resources alike.

Agricultural Chemicals (fluoride & / or nitrates) **Groundwater Contamination** **Acid Atmospheric Deposits**

Metals from Mining **Urban & Industrial Effluent (pathogens, nutrients, organics)** **Excessive Sediments**

Figure 5.1.11 Locations of major sources of pollution in the RSA (Source: Maree, 2010, based on information from Ashton, 2009)

- Climate change is likely to exacerbate many of these forms of pollution, particularly with chemical reactions generally speeding up with increases in temperature while other processes are dependent on water movement through the soil profile, which is dependent on rainfall characteristics that are projected to change in future climates.

- Areas of particular concern in regard to future and emerging pressures on water quality have been identified by the DWA (2010), and are shown in **Figure 5.1.12**. The causes of these future problems include:
    - urban expansion, primarily in the Witwatersrand, Cape Town and Durban surrounds;
    - possible new forestry areas in the Eastern Cape;
    - new areas suitable for irrigation in the middle and lower reaches of the Orange catchment;
    - expansion of coalfields in southern Lesotho / northern parts of the Eastern Cape and on the Highveld as well as in the Waterberg area of Limpopo;
    - new power stations in the Waterberg area; and
    - new areas of heavy industry (such as coal to liquid fuels) in the Waterberg and central Mpumalanga areas (**Figure 5.1.12**).

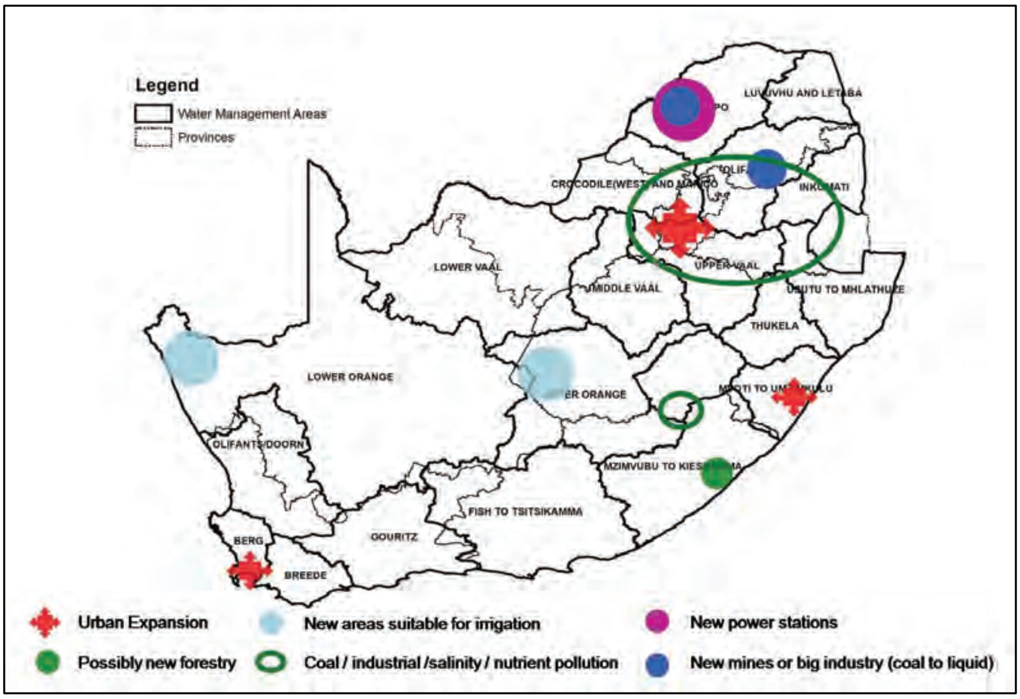

Figure 5.1.12 Areas of future concern in regard to water quality (DWA, 2010)

Looking into the Future

In this introductory chapter to assessing more direct projected impacts of climate change on South Africa's water sector which are addressed in the chapters which follow, the focus has been on

- the already existing harsh biophysical environment,
- the legal, administrative and governance environment,
- the present state of water resources in South Africa,
- some critical water use sectors of concern,
- environmental issues, and
- the state of South Africa's water quality.

All the above already formidable challenges to water resources planners and operators are likely to be exacerbated by enhanced greenhouse gas induced global warming and associated climatic change, with its projected intensification of the hydrological cycle which includes any changes in rainfall being amplified in its conversion to runoff. Additional climate change related stressors in the field of water resources include projected changes in the magnitudes and spatial distributions of extreme events as well as shifts in the magnitudes and timing of runoff, and changes in sediment yields, with possible "hydrological hotspots" of concern requiring early identification and adaptive action. The climate change phenomenon is anticipated to add to already existing challenges and complexities in the South African water sector.

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CHAPTER 5.2

CLIMATE CHANGE AND *STORMFLOWS:* A 2011 PERSPECTIVE

R.E. Schulze and R.P. Kunz

Stormflow: Definition and its Significance

Stormflow, Q_s, is defined as the water which is generated from a specific rainfall event, either at or near the surface in a catchment or subcatchment, and which contributes to flows of streams within that catchment / subcatchment. The amount of the stormflow which is generated (expressed either as a depth equivalent in mm, or as a volume in m^3) in essence depends on the magnitude of the rainfall event and how wet the catchment is just prior to the rainfall event. Not all stormflow generated from a rainfall event exits the catchment on the same day as the rainfall occurred, and the fraction that does, depends on the catchment's size and its slope, and effectively in the *ACRU* model that fraction accounts for lags of flows which occur within a catchment, including lags of stormflows associated with interflow.

It is largely from stormflow events that, for example, reservoirs are filled and design runoffs for selected return periods are computed. Furthermore, the soil detachment process in the production of sediment yield from a catchment is highly correlated with the volume of stormflow from an event. Important statistics on stormflows include annual means, inter-annual variabilities, magnitudes in wet and dry years and the number of stormflow events per annum exceeding critical thresholds. In order to map statistics on stormflows for this Report, the *ACRU* model (Schulze, 1995; cf. **Chapter 2.3**) was used. Equations describing the computation of stormflows have already been given within a broader context of the *ACRU* model as a whole in **Chapter 2.3**, and are repeated below within the specific context of this Chapter

Box 5.2.1 Computation of Stormflow with the *ACRU* Model

Stormflow, Q_s, defined as the water which is generated in a catchment either at or near the surface from a specific rainfall event, is computed in the *ACRU* model (Schulze, 1995 and updates) in mm equivalents as

$$Q_s = (P_n - I_a)^2 / (P + I_a + S) \qquad \text{for } P_n > I_a$$

in which

P_n = net rainfall (mm), i.e. gross (measured) rainfall minus canopy interception losses,

I_a = initial abstractions (mm) before stormflow commences, consisting mainly of that infiltration which occurs between the beginning of the rainfall event and the beginning of storm runoff, plus any depression storage, and

S = the soil's potential maximum retention (mm), which is equated to the soil water deficit and is an expression of the wetness or dryness of the soil.

In *ACRU*, the soil water deficit S is calculated by the daily multi-layer soil water budget, and for computations of stormflow a critical soil depth, D_{sc} (m), is defined from which S is determined. The depth of D_{sc} accounts for the different dominant runoff producing mechanisms which may vary in different climates, as well as with catchment land uses, tillage practices, litter / mulch cover and soil conditions. For all hydrological simulations in this Report, D_{sc} was defined as the thickness of the topsoil.

Box 5.2.1 Computation of Stormflow with the *ACRU* Model (continued)

A major determinant of initial abstractions is soil moisture content. In order to eliminate estimations of both I_a and S in the equation above, I_a is expressed as a coefficient, c, of S, where c is an index of infiltrability into the soil and varies with rainfall intensity (thunderstorms ≡ smaller c), tillage practice and surface cover / litter / mulch (Schulze, 1995). For all simulations in this Report, the c of I_a was input as that value assigned on a month-by-month by Schulze (2004) for the 70 baseline land cover types (Acocks, 1988) found in South Africa (cf. Schulze, 2004).

Not all stormflow generated from a rainfall event exits the catchment on the same day as the rainfall occurs, and the fraction that does depends on the size of the catchment, the catchment's slope and other factors (Schulze, 1995). This necessitates a stormflow response coefficient, F_{sr}, to be input, which controls the "lag" of stormflows and is effectively an index of interflow. For all simulations on all subcatchments in this Report, F_{sr} was set at 0.3, i.e. 30 % exits the subcatchment on the day the stormflow event occurs, with 30 % of the remainder exiting the following day and so on. This value has been found experimentally to be typical in South Africa for use at the spatial scale of Quinary Catchments (e.g. Warburton *et al*., 2010).

Box 5.2.2 Mapping Stormflows over South Africa

In order to map various statistics of stormflows, Q_s, over South Africa, the Quinary Catchments Database, QnCD (cf. **Chapter 2.2**) was used. In the QnCD a 50 year time series of quality controlled daily rainfall (Lynch, 2004) is used with a corresponding 50 year time series of daily temperatures (Schulze and Maharaj, 2004) in conjunction with soil properties (cf. Schulze and Horan, 2008) and baseline land cover characteristics (Schulze, 2004) to generate hydrological responses with the daily time step and conceptual-physical *ACRU* model (Schulze, 1995 and updates) for each of 5 838 Quinary Catchments (QnCs) into which the RSA, Lesotho and Swaziland have been delineated. From the daily Q_s output file for each QnC, various statistics were then derived which have been mapped.

Distribution Patterns over South Africa of Annual Stormflow Statistics under Baseline (Historical) Climatic Conditions

With individual Q_s events being largely dependent on magnitudes and sequences of runoff producing rainfall events in association with soil characteristics (in particular the thickness of the critical topsoil horizon and its moisture status just prior to a rainfall event), it stands to reason that the highest mean annual stormflows, in excess of 80 mm, occur in the humid eastern third of South Africa with its high number of significant rainfall events (cf. **Chapter 3.6**) and in the mountainous regions in the extreme southwest with their shallow soil profiles (**Figure 5.2.1** top left). Mean annual Q_s in the more arid west, on the other hand, reduces to < 2 mm equivalent per annum.

That a high variation in Q_s is experienced from one year to the next is already shown by the median Q_s being considerably lower than the mean (**Figure 5.2.1** top right), especially in the more arid west, but even more markedly so by the mapped differences, sometimes by a factor of up to 10, between the lowest stormflows in 10 years vs. the highest Q_s in 10 years (cf. **Figure 5.2.1** bottom left vs. bottom right)..

It is small wonder, therefore, that the standard deviations of annual stormflows are very high throughout the region (**Figure 5.2.2** left), with the inter-annual coefficient of variation of Q_s, a variability statistic in relation to the mean, displaying values of 50 to 100 % in the east while in the more arid west large areas have CVs in excess of 200 % and even > 400 % (**Figure 5.2.2 right**).

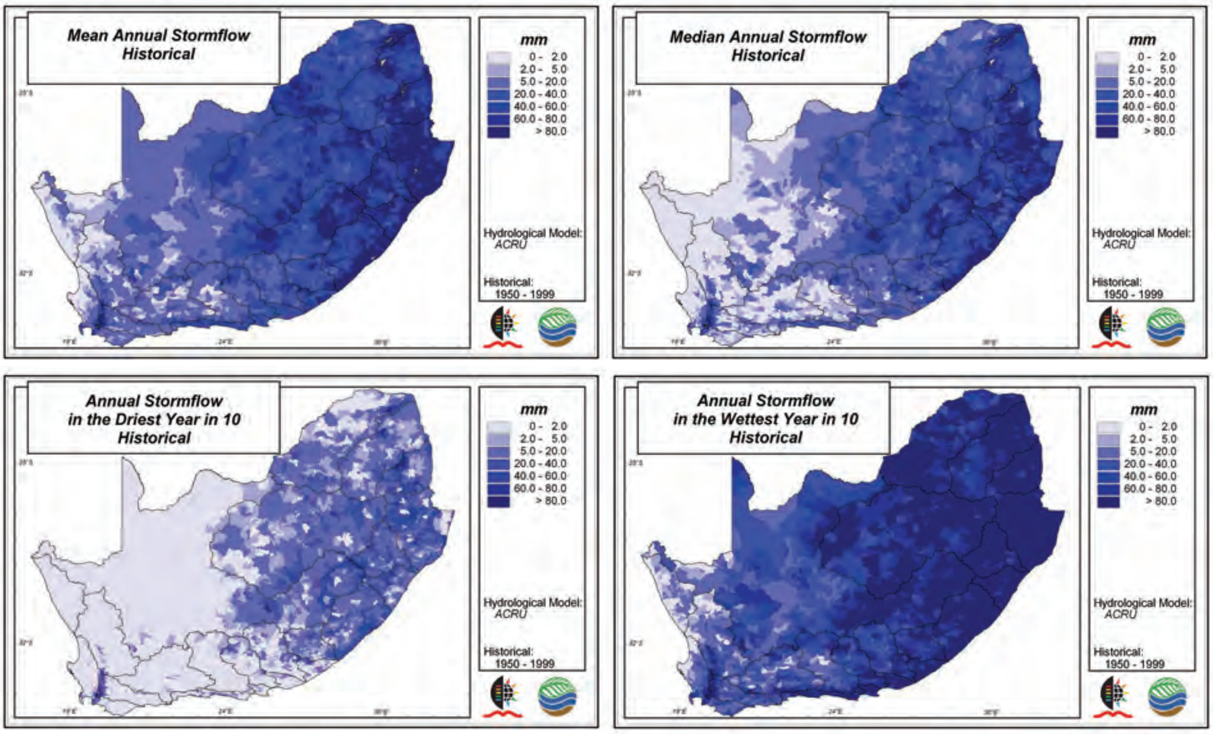

Figure 5.2.1 Mean annual stormflows (top left), median annual stormflows (top right) and the lowest and highest stormflows in 10 years (bottom left and right), simulated with the *ACRU* model under baseline (historical; 1950 - 1999) climatic conditions

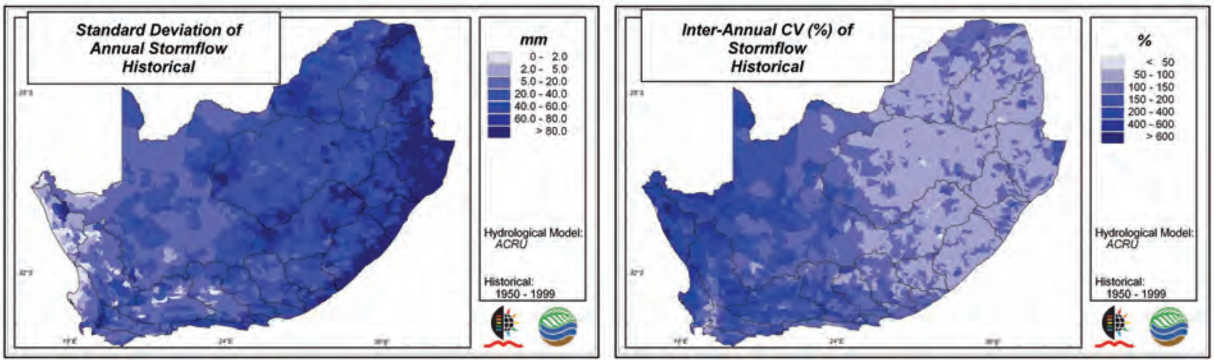

Figure 5.2.2 Standard deviation (mm) of annual stormflows (left) and the inter-annual coefficient of variation (CV %) of stormflows, simulated with the *ACRU* model under baseline (historical; 1950 - 1999) climatic conditions

The Relative Importance of Stormflows to Total Runoff

The fact that high intensity thunderstorm events produce a high proportion of South Africa's runoff is shown by > 95 % of the region's runoff being made up of mainly of stormflows (**Figure 5.2.3**). The only area where very little of the runoff (< 10 %) is in the form of stormflows is in the southwest, where rainfall is predominantly frontal and of low intensity.

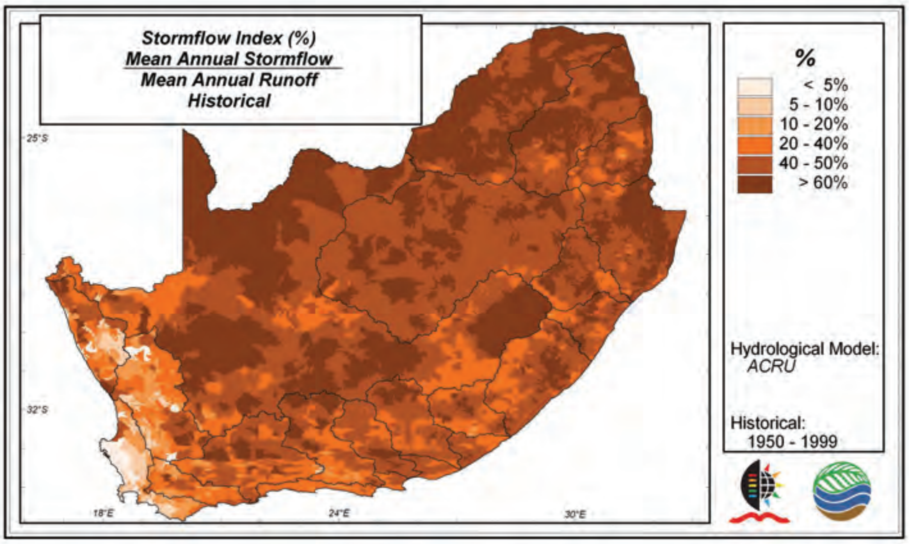

Figure 5.2.3 Mean annual stormflows as a percentage of mean annual runoff, simulated with the *ACRU* model under baseline (historical; 1950 - 1999) climatic conditions

Ratio Changes of Future to Present Annual Stormflow Statistics Using Outputs from Multiple GCMs

Medians of changes in stormflows into the future, based on outputs from multiple GCMs, display a distinct west to east pattern for typical years (**Figure 5.2.4** top left), with the west coast and its hinterland showing clear reductions into the intermediate future which persist into the more distant future (**Figure 5.2.4** top middle and right). However, there is an abrupt shift to a band of marked projected increases in Q_s in the area which is transitional between the winter and summer rainfall regions and the more semi-arid areas, with the high increases then tapering down to more moderate projected increases towards the moister eastern regions (**Figure 5.2.4** top left). For the year in 10 with the lowest stormflows (**Figure 5.2.4** middle row), the region of decreases expands eastwards to cover ~ half of South Africa, with a very abrupt transition to projected increases in Q_s, while for wet years virtually the entire South Africa shows projected increases in stormflows, especially in the winter-summer rainfall transitional area (**Figure 5.2.4** bottom row).

In interpreting projected changes into the future of the year-to-year variability of stormflows, the maps of standard deviation (**Figure 5.2.5** top row), which is a statistic of absolute variability, show increases across virtually the entire South Africa, but especially so in the central west which is already the area of greatest increases in stormflow *per se*. The central west region thus appears highly vulnerable to changes in stormflows, with both the actual stormflows plus their year-to-year variability increasing. However, in terms of changes in the variability of stormflows into the future relative to changes in the means of stormflows, the maps of CVs (**Figure 5.2.5** bottom row) show general reductions. As already alluded to in previous chapters, this illustrates the importance of depicting, and interpreting, both indicators of absolute and relative changes in variability.

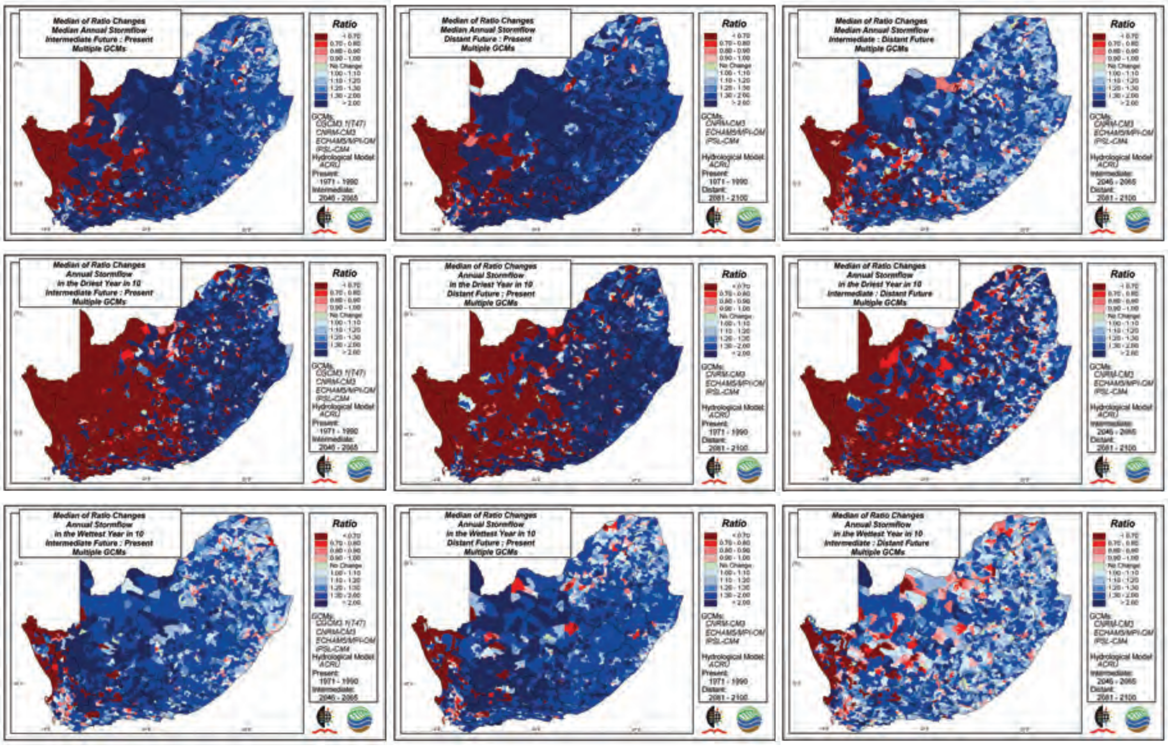

Figure 5.2.4 Medians of ratio changes of intermediate future to present (left column), more distant future to present (middle column) and more distant to intermediate future (right column) annual stormflows in a median year (top row), the year with the lowest stormflows in 10 years (middle row) and the year with the highest stormflows in 10 years, derived with the *ACRU* model from output of multiple GCMs

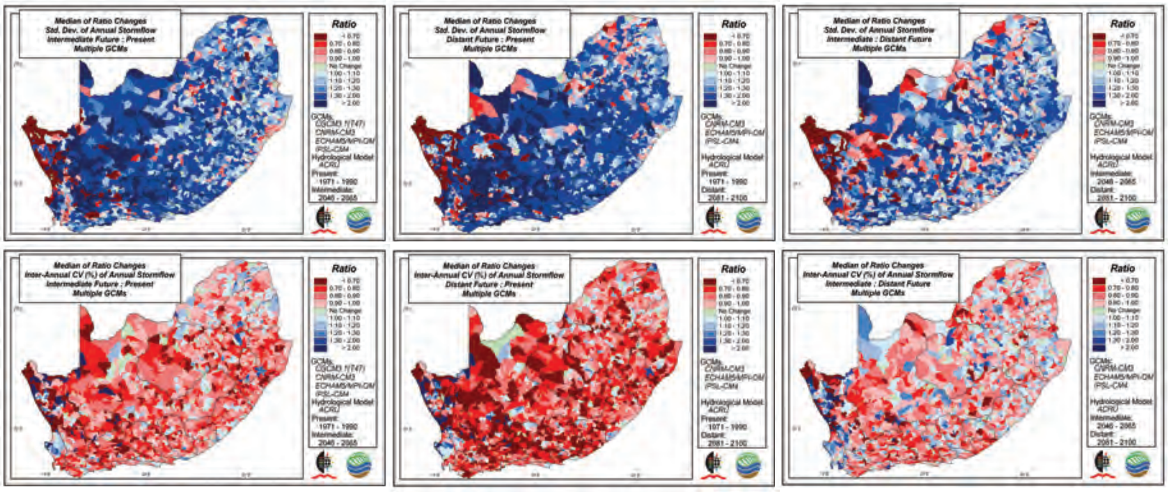

Figure 5.2.5 Medians of ratio changes of intermediate future to present (left column), more distant future to present (middle column) and more distant to intermediate future (right column) of standard deviations of annual stormflows (top row) and of the inter-annual coefficient of variation of stormflows (bottom row), derived with the *ACRU* model from output of multiple GCMs

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CHAPTER 5.3

CLIMATE CHANGE,
RECHARGE INTO THE GROUNDWATER STORE AND BASEFLOW:
A 2011 PERSPECTIVE

R.E. Schulze, R.P. Kunz and L.M. Bulcock

The Significance of Groundwater, Recharge and Baseflows in South Africa (Adapted from Schulze, Horan, Lumsden and Warburton, 2008)

With the over-utilisation of surface water resources in many parts of South Africa, groundwater supply will have to play a major role in future growth of the region because of its relative cost effectiveness, particularly in diffuse supply situations. Reliable assessments of exploitable groundwater resources are therefore essential, particularly for sustainable development in semi-arid areas, which are more heavily dependent on groundwater than the moister areas. This is important especially during periods of drought, when groundwater is often the sole exploitable and reliable water resource for survival (Bredenkamp *et al*., 1995).

However, the subterranean water stores which may become depleted through abstractions have to be recharged (replenished) over a period of time by rainfall. The accurate estimation of recharge rates and magnitudes is not a simple task.

Baseflows, i.e. the dry weather and non-rainy season streamflows which are sourced from the groundwater store, take on hydrological significance in that they constitute the so-called “low flows” which sustain aquatic habitats and the dry season flows into reservoirs, as well as providing a source of water to people who have not yet been supplied with reticulated water and to livestock.

Recharge, the Groundwater Store and Baseflow in the Context of the *ACRU* Model (Adapted from Schulze, Horan, Lumsden and Warburton, 2008)

At the outset, a distinction needs to be made between recharge to the groundwater store and baseflows.

- *Recharge to groundwater* under natural catchment conditions is that portion of rainfall reaching an aquifer either
  - by following preferential flow paths via fractures, or
  - by infiltrating from free flowing or standing water in river channels or local surface depressions, or thirdly
  - by draining through the soil column.
- There are many methods of estimating recharge, including the use of chemical tracers, lysimeters, isotopes or groundwater level observations. These have been reviewed, for example, by Bredenkamp *et al*. (1995) and can be used in relationships either to predict recharge (e.g. by log-log relationships against MAP) or to map recharge to groundwater (Bredenkamp *et al*., 1995; Vegter, 1995).
- In the *ACRU* model (Schulze, 1995 and updates) *recharge* of soil water takes place into an intermediate / groundwater store which is located below the normally active root zone. This recharge takes place when rainwater has drained through the top- and then out of the subsoil horizons (in which roots are assumed to be present) when those horizons’ respective soil water contents exceed their drained upper limits (cf. **Chapters 2.3** and **4.1**).
- Drainage rates of soil water into the groundwater store are slower for heavy (i.e. clayey) than for light (i.e. sandy) textured soils because the hydraulic conductivity is dependent on soil texture.
- The *ACRU* model approach to estimating recharge complements the excellent geohydrologically and geochemically based approaches to groundwater recharge in South Africa by Bredenkamp *et al*. (1995) and Vegter (1995).
- There are important advantages, however, to the daily modelling approach of estimating recharge through the soil profile, in that it can account *explicitly* for
  - different soil properties within a catchment,
  - different natural land cover as well as human-induced land management impacts (e.g. of

  afforestation, overgrazing) in that catchment, and for
  - computing recharge from individual rainfall events, and hence for monthly and annual totals under average, wet or dry conditions.
- Furthermore, a model such as *ACRU* can also account *implicitly* for rainfall intensity (and hence the initial infiltration of rainfall into the soil) by regional and seasonal changes to the coefficient of initial abstraction, for example, by reducing the coefficient in the convective rainfall period December to March, or by increasing it in the winter rainfall region (e.g. Schulze, 2004).
- The *ACRU* modelling technique for estimating recharge has been verified directly in a study by Kienzle and Schulze (1992) and indirectly by the many verification studies which include baseflow as a major component of runoff, as reviewed, for example, in Schulze and Smithers (2004) or by Warburton *et al*., (2010).
- *Baseflows*, in contrast to recharge, consist of contributions to runoff from the intermediate / groundwater store which had been previously recharged. These contributions are made up of slow and delayed flows to the catchment's streams (**Photos 1** and **2**).
- ***In the ACRU model as used in this Report it is assumed that the groundwater store is always "connected" to the stream system, i.e. whatever water has recharged through the soil profile into the groundwater store becomes available for baseflow through a decay function. In the maps which follow, the amount of recharge through the soil profile is thus synonymous with the baseflow which eventually, over time, reaches the stream.***
- The computation of baseflows in the *ACRU* model is discussed in **Box 5.3.1** and mapping procedures are outlined in **Box 5.3.2**.

Box 5.3.1 Computation of Recharge, and Hence Baseflows, with the *ACRU* Model

- Unlike many other models, which compute baseflows indirectly from total runoff hydrographs with an empirically derived "separation curve", *ACRU* computes daily baseflows explicitly from recharged soil water stored in the intermediate / groundwater zone (Schulze, 1995).
- The stored water is derived from rainfall of previous events which has been redistributed through the various soil horizons and has drained (recharged) into the intermediate / groundwater store when the deepest soil horizon's water content exceeds its drained upper limit (field capacity; cf. **Chapter 2.3**).
- The *rate of drainage* of this "excess" water out of the deepest soil horizon *into the groundwater store* depends on that horizon's soil texture class, which in this Report has been input to vary from Quinary to Quinary according to soil attributes (cf. Schulze and Horan, 2008).
- The rate of release of water from the groundwater store into the stream as baseflow is determined by a release coefficient, F_{bff}, which is dependent, *inter alia*, on the geology, area and slope of the catchment.
- F_{bff} operates as a "decay" function which is input for a catchment as a single value (COFRU in **Figure 2.3.5**), but based on experiences with *ACRU* in many catchment studies, F_{bff} is not a constant decay function, but is enhanced or decreased internally in *ACRU* as a function of the magnitude of the previous day's groundwater store, S_{gwp}, such that it has been found empirically from catchment studies in South Africa (Kienzle and Schulze, 1992) that

$$F_{bff} = F_{bfi} \Big[[[(S_{gwp})^2 - S_{gwp}] / 1000 + 1.3 \Big] / 11 \Big]$$

where
F_{bff} = final baseflow release coefficient
F_{bfi} = input baseflow release coefficient and
S_{gwp} = magnitude of previous day's intermediate / groundwater store (mm).

- For all simulations in this Report an experimentally determined typical value of F_{bff} of 0.009 (Kienzle *et al*., 1997) has been applied in all Quinary Catchments in the study area.

Distribution Patterns over South Africa of Annual Recharge Statistics of Groundwater through the Soil Profile, and Hence Baseflow, under Baseline (Historical) Climatic Conditions

Recharge through the soil profile is not a continuous process, but occurs in "pulses", defined here as those days on which water exits the bottom of the subsoil horizon as a result of, for example, rain

Box 5.3.2 Mapping Groundwater Recharge, and Hence Baseflows, over South Africa

In order to map various statistics of recharge into the groundwater zone, and hence baseflows, over South Africa, the Quinary Catchments Database, QnDB (cf. **Chapter 2.2**), was utilised. In the QnDB a 50 year time series of quality controlled daily rainfall (Lynch, 2004) is used together with a corresponding 50 year time series of daily temperatures (Schulze and Maharaj, 2004) and in conjunction with soil properties (cf. Schulze and Horan, 2008) and baseline land cover characteristics (Schulze, 2004) to generate a baseflow response with the daily time step conceptual-physical *ACRU* model (Schulze, 1995 and updates) for each of 5 838 Quinary Catchments (QnCs) into which the RSA, Lesotho and Swaziland have been delineated. From the daily output file of baseflows for each QnC, various statistics were derived and these were then mapped.


Photo 1
Example of Baseflow


Photo 2
Example of Baseflow

falling on a wet catchment or a sequence of days with rain having “saturated” the bottom horizon of soil to beyond its drained upper limit (DUL). Note that a single day’s heavy rainfall may result in saturated water exiting the subsoil horizon over several days, i.e. with several “pulses”, depending on the amount of soil water content above the DUL and the drainage rates of the soil, which in turn depends on its texture (cf. Schulze and Horan, 2008).

The number of recharge “pulses” in a specific catchment and year will depend on

- vegetation and land use characteristics of the catchment (e.g. the denser and / or deeper rooted the vegetation is, the more the soil profile can dry out and the more rainfall is required for the drainage threshold to be reached),
- soil profile characteristics (e.g. the thinner the profile, the more frequently it can be “filled” and recharge events are triggered), and on the
- frequency of recharge producing rainfall events.

These characteristics have determined the spatial distribution of the mean number of recharge events per year, which Schulze *et al*. (2008) have shown in **Figure 5.3.1** vary at Quaternary Catchment level from fewer than 2 events in the central western areas to > 20 in the east and the higher lying areas in the winter rainfall in the west, where multi-day rainfalls on catchments with thin soil are the likely cause of the high number of recharge events, and in a few catchments even > 40 recharge events per year, not all of which may have been significant in magnitude, however.

For the reasons given above, distribution patterns of groundwater recharge, and hence baseflow, statistics display a general lack of the smooth regional patterns. An added reason is that in this Report the spatial unit for recharge is the individual Quinary Catchment and baseflows have therefore not been smoothed from accumulated flows from upstream QCs.

Expected high values of recharge / baseflows occur in the eastern and southwestern areas of South Africa and low values in the centre west. However, many unexpected patches of highs and lows are present in **Figure 5.3.2**, these patches reflecting either thin soils or, in the case of Lesotho, a lack of detail in the soil maps which were available to this research. The high values in the east and south

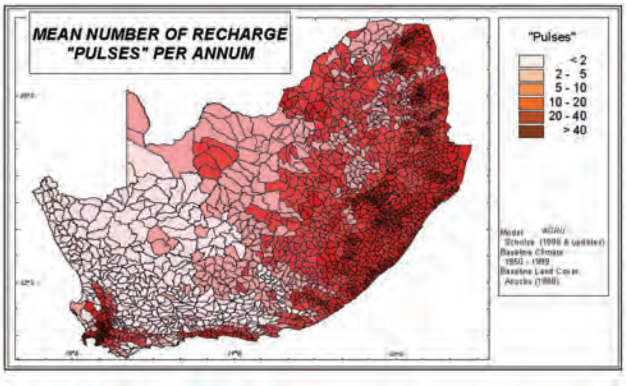

Figure 5.3.1 Mean number of recharge “pulses” per annum from Quaternary Catchments (Schulze *et al*., 2008)

display annual means of up to 200 mm while ~ half the region experiences a mean annual recharge < 25 mm (**Figure 5.3.2** top left). Significantly, annual medians of recharge display markedly lower values than means (**Figure 5.3.2** top right), with those areas showing high median annual values being more compact than in the case of means.

These differences are already an indicator that recharge, and hence high baseflows, are often dependent on a few large events in the year. It becomes eminently clear that recharge into the groundwater store is a complex process of interactions between rainfall characteristics and soil attributes when the map of the lowest recharge in 10 years is compared with that of the highest recharge in 10 years. The difference in many areas is 5 - 10 fold (cf. **Figure 5.3.2** bottom left vs. right). In another simulation study Schulze *et al*. (2008) have shown that in the year with lowest recharge in 10 years ~ 90% of South Africa generates the equivalent of < 1 mm of baseflow from the recharged groundwater store in such a dry year.

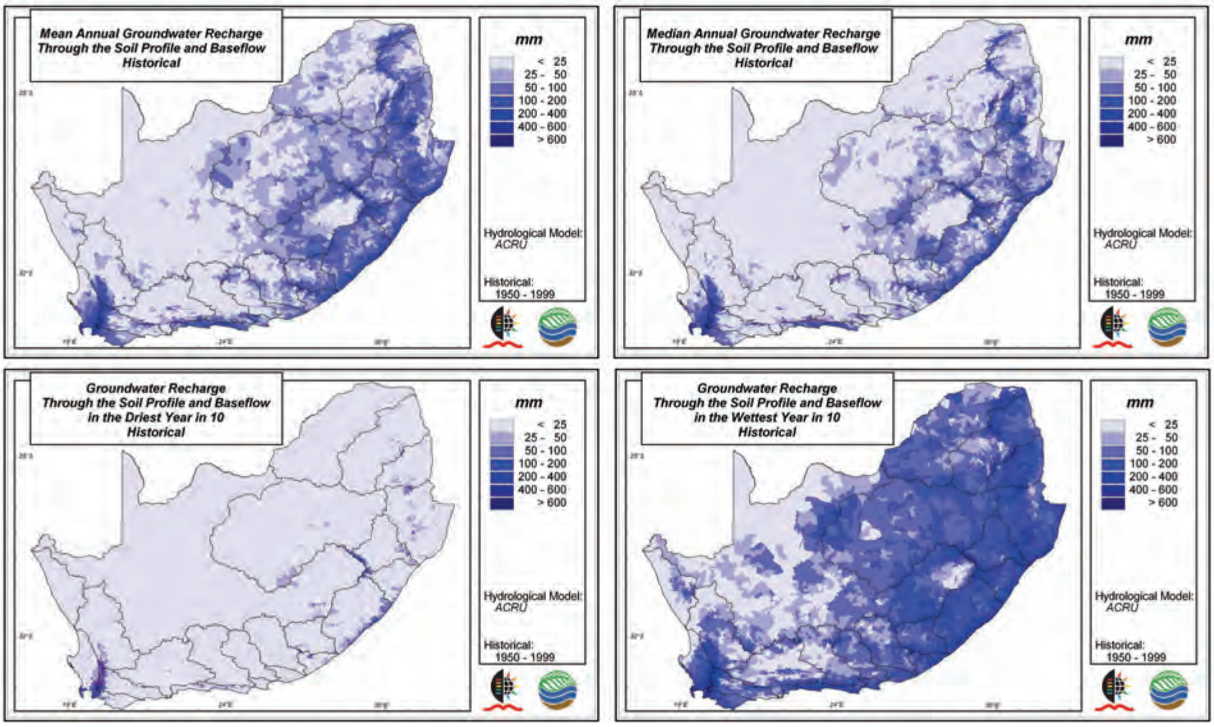

Figure 5.3.2 Mean annual recharge into the groundwater store through the soil profile (top left), the median annual recharge (top right) and the lowest and highest recharge into the groundwater store in 10 years (bottom left and right), simulated with the *ACRU* model under baseline (historical; 1950 - 1999) climatic conditions

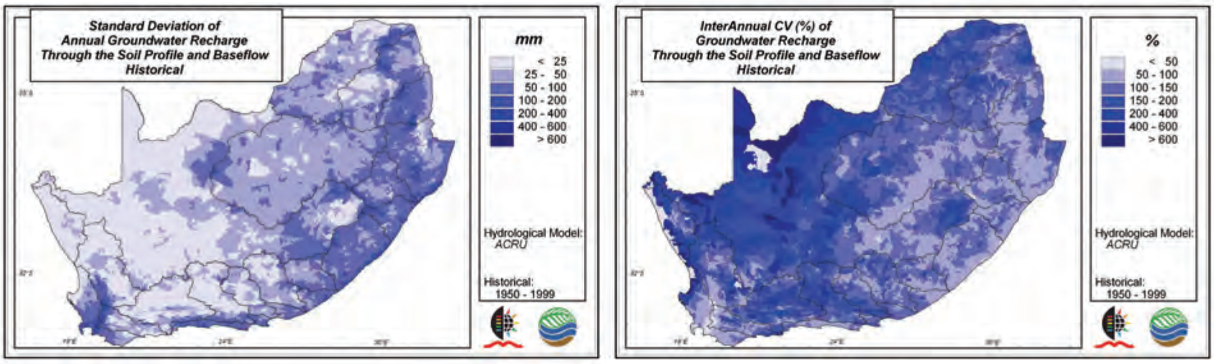

Figure 5.3.3 Standard deviation (mm) of annual recharge into the groundwater store through the soil profile (left) and the coefficient of variation (CV %) of annual recharge, simulated with the *ACRU* model under baseline (historical; 1950 - 1999) climatic conditions

As a consequence, standard deviations of annual recharge are very high, resulting in inter-annual CVs (%) of 150% over many parts of South Africa and even > 400% in parts (**Figure 5.3.3**).

The Relative Importance of Baseflows to Total Runoff

Because of the mechanisms by which baseflows are generated (multi-day rainfalls or rain falling on a near-saturated soil), it stands to reason that baseflows dominate total runoff along the west and south coasts of South Africa with their winter / all year low intensity rainfalls mainly of the frontal variety (**Figure 5.3.4**). Over large tracts of the interior, on the other hand, the more sustained dry season baseflows make up less than 20 % of the total runoff with consequences, for example, on dam operating rules, environmental flow releases and water available for abstraction from rivers.

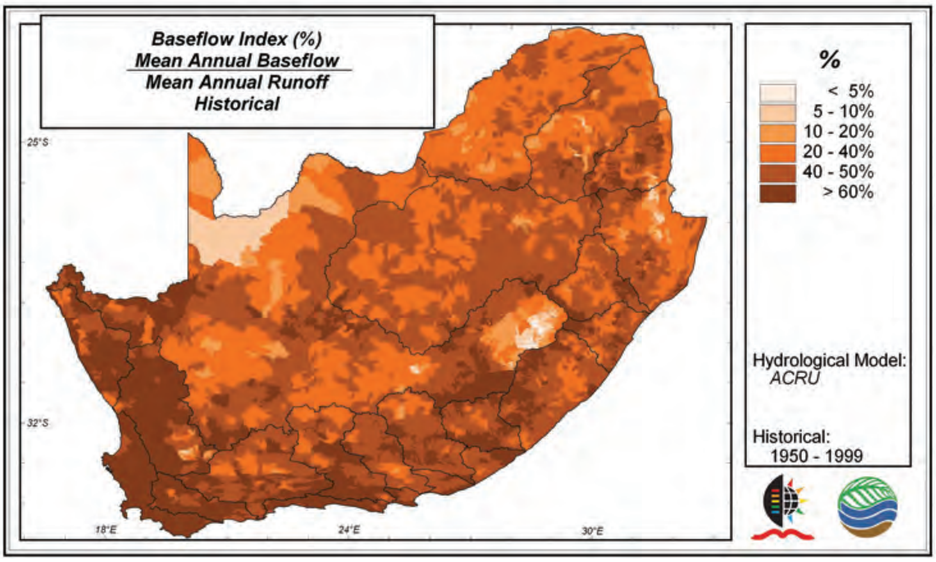

Figure 5.3.4 Mean annual baseflows as a percentage of mean annual runoff, simulated with the *ACRU* model under baseline (historical; 1950 - 1999) climatic conditions

Ratio Changes of Future to Present Annual Statistics of Groundwater Recharge through the Soil Profile and Baseflow, Using Outputs from Multiple GCMs

A feature of projected changes in recharge into the groundwater store from the multiple GCMs used in this study is the very different patterns of change which emerge between median, dry and wet years (**Figure 5.3.5**). Characteristic of changes under median conditions into the intermediate future is a wide band of increases in recharge stretching from northeast to southwest and covering ~ 80 % of South Africa (**Figure 5.3.5** top left), the areal extent of which increases into the more distant

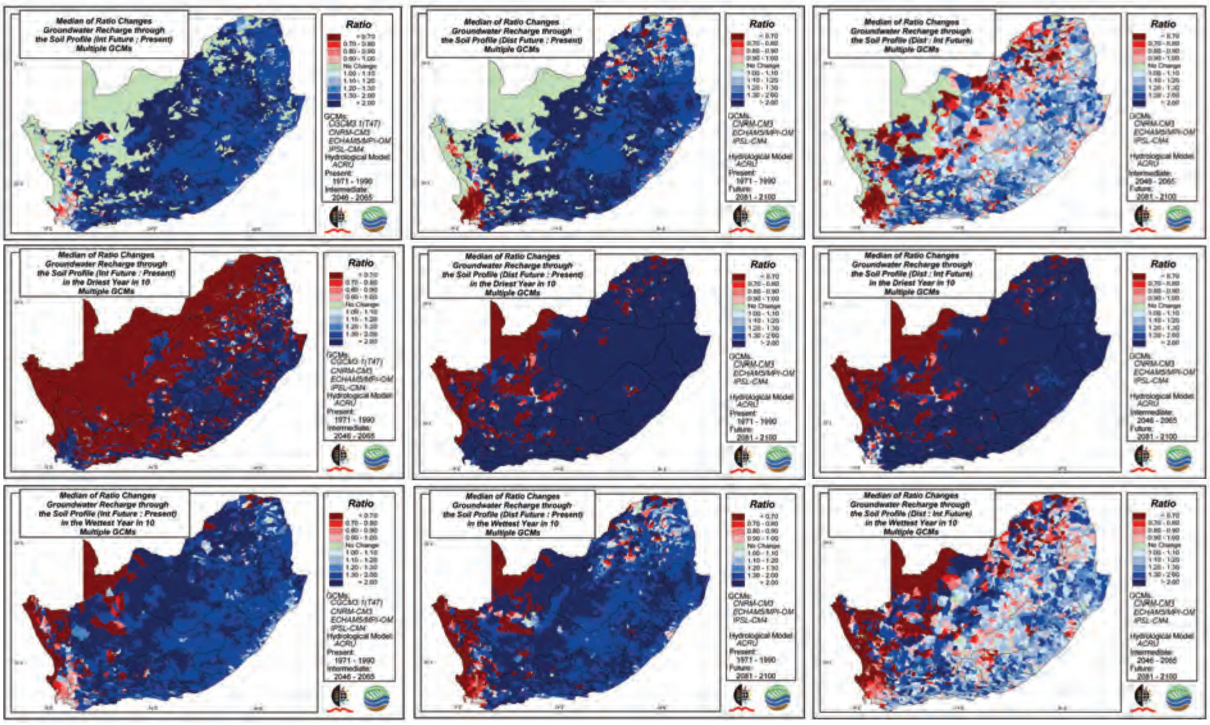

Figure 5.3.5 Medians of ratio changes of intermediate future to present (left column), more distant future to present (middle column) and more distant to intermediate future (right column) of recharge into the groundwater store through the soil profile in a year of median recharge (top row), the year with the lowest recharge in 10 years (middle row) and the year with the highest recharge in 10 years, derived with the *ACRU* model from output of multiple GCMs

future (**Figure 5.3.5** top middle). There is a significant area in the arid northwest showing no change in recharge under median conditions into the intermediate future (i.e. from few pulses of recharge under present climatic conditions to equally few pulses in future), but a relatively small area in the extreme southwest displaying decreases in recharge (**Figure 5.3.5** top left), with the area of decreases expanding into the more distant future (**Figure 5.3.5** top middle) mainly as a result of a major decline in recharge projected in the 35 years between the intermediate and more distant future period (i.e. 2046 - 2065 vs. 2081 - 2100; **Figure 5.3.5** top middle).

The spatial patterns of projected changes in recharge derived from the multiple GCMs used in this study are very different in the driest year in 10, with a northeast to southwest line dividing South Africa into an area of significant reductions in recharge (to < 70 % of present) on the equator - side of the line and significant increases south of that line (**Figure 5.3.5** middle left). This dividing line shifts in a northwesterly direction by the more distant future, by which time the projections from the GCMs used display a doubling of recharge over ~ 90 % of South Africa (**Figure 5.3.5** middle row, centre map).

Projected recharge in wet years display different patterns again, with a general decrease along the west coast region compared with a general increase projected across ~ 95 % of South Africa (**Figure 5.3.5** bottom left), with these patterns intensifying into the more distant future (**Figure 5.3.5** bottom middle) as a result of projected reductions in recharge in the latter half of the century (**Figure 5.3.5** bottom right).

The implications of these projected changes in recharge into the groundwater store are important not only to the more arid parts of South Africa in which people and livestock rely heavily on groundwater as their primary source of water, but also on the sustained dry season flows from the baseflow component of streamflow which, with our current understanding of climate change from analyses of the GCMs used in this study, is projected to decrease in the southwest of South Africa but increase elsewhere. The repercussions also have implications on the management of the ecological reserve.

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Photo 1 - http://www.cees.iupui.edu/Research/Water_Resources/CIWRP/images/CiceroCreek/2003-12-04
Photo 2 - http://www.internal.eawag.ch/~yegkubge/Necker%20Unterlauf%202.jpg

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CHAPTER 5.4

CLIMATE CHANGE AND
ANNUAL STREAMFLOW STATISTICS:
A 2011 PERSPECTIVE

R.E. Schulze and R.P. Kunz

Definitions Revisited

Detailed definitions of runoff related terms have already been provided in **Chapter 1.3**, to which the reader should refer. Only certain salient points, as they apply to this Chapter, are repeated here.

A ***catchment*** is a topographically defined basin, or watershed area, which collects water and drains it at an exit. In this Chapter, however, the term refers to a fifth level Quinary Catchment (QnC) as defined and delineated by the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal (Schulze and Horan, 2010; cf. **Chapter 2.2**). There are 5 838 hydrologically cascading, interlinked Quinary Catchments in the RSA, Lesotho and Swaziland. In results that follow, the hydrological responses are accumulated, i.e. the ***streamflow*** generated within a Quinary Catchment from the stormflow and baseflow components of runoff (cf. **Chapters 5.2** and **5.3**) is added to that of downstream catchments, and any runoff from upstream catchments is taken into account when a given catchment's streamflow is calculated.

The methodology for the computation of daily streamflows is summarized in **Box 5.4.1**.

Box 5.4.1 Computation of Streamflows with the *ACRU* Model: A Summary

Daily values of streamflows were computed with the *ACRU* simulation model (Schulze, 1995 and updates), the fundamentals of which are summarised in **Chapter 2.3**, with more details on estimations of stormflows and baseflows making up runoff and eventually streamflows having been provided in **Chapters 5.2** and **5.3** respectively.

All computations utilised the climate, soils, land cover and QnC databases outlined in **Chapters 2.1** and **2.2**, assuming a baseline land cover represented by Acocks' (1988) Veld Types, the hydrological attributes of which are described by Schulze (2004) and soils attributes by Schulze and Horan (2008).

Distribution Patterns over South Africa of Annual Streamflow Statistics under Baseline (Historical) Climatic Conditions

Mean annual streamflows across South Africa (**Figure 5.4.1** top left) range from < 5 mm equivalent along the west coast to > 250 mm equivalent along parts of the east coast, the Drakensberg mountains and the mountains of the southwest Cape. Some very high gradients (rapid changes) in MAP over very short distances are evident in the southern and southwest Cape. In interpreting the MAP over South Africa the generally low conversion of rainfall in runoff (averaging only ~ 9 %) shown in **Chapter 5.1** (**Figure 5.1.2**) needs to be borne in mind.

Median annual streamflows (**Figure 5.4.1** bottom left) follow similar spatial patterns to those of means, although (with what appear to the eye) slightly dampened. **Figure 5.1.4** in **Chapter 5.1** does illustrate, however, that this dampening is of the order of 10 - 20 % in the east and south and > 50 % in parts of the arid areas of the west.

When comparing the highest annual streamflows in 10 years with the lowest in 10 years (**Figure 5.4.1** top right and bottom right), huge differences are evident. Over large parts of the wetter east the difference is 6 times while in the more arid areas the difference is a factor of 8.

These huge differences in streamflows between dry and wet years are testimony to high inter-annual variability of the hydrological regime in South Africa, as displayed in **Figure 5.4.2**, in which the map of the inter-annual coefficient of variation shows CVs in the more arid west to be in excess of 100 %, with this index of relative variability reducing to 50 - 80% in the east with its steadier flows from year-to-year. Clearly discernible on the map of CVs (**Figure 5.4.2** right) is the moderating influence of the larger rivers with considerably lower CVs. These lower CVs are the result of these larger rivers being fed by large catchment areas which receive rainfall at different times during the wet season year and often having their headwaters in the high runoff mountainous areas with significant baseflows. Among the mainstems of the larger rivers displaying lower CVs than the surrounding areas are the Orange and Vaal flowing towards the west, the Berg and Breede in the south and the Thukela, Mfolozi, Pongola and Olifants discharging in an easterly direction.

The relatively low annual streamflows in combination with high inter-annual variability of flows render many parts of South Africa already water stressed, with frequent hydrological droughts being experienced (cf. **Chapter 6.2**) while also subjected to occasional major flooding (cf. **Chapter 7.3**).

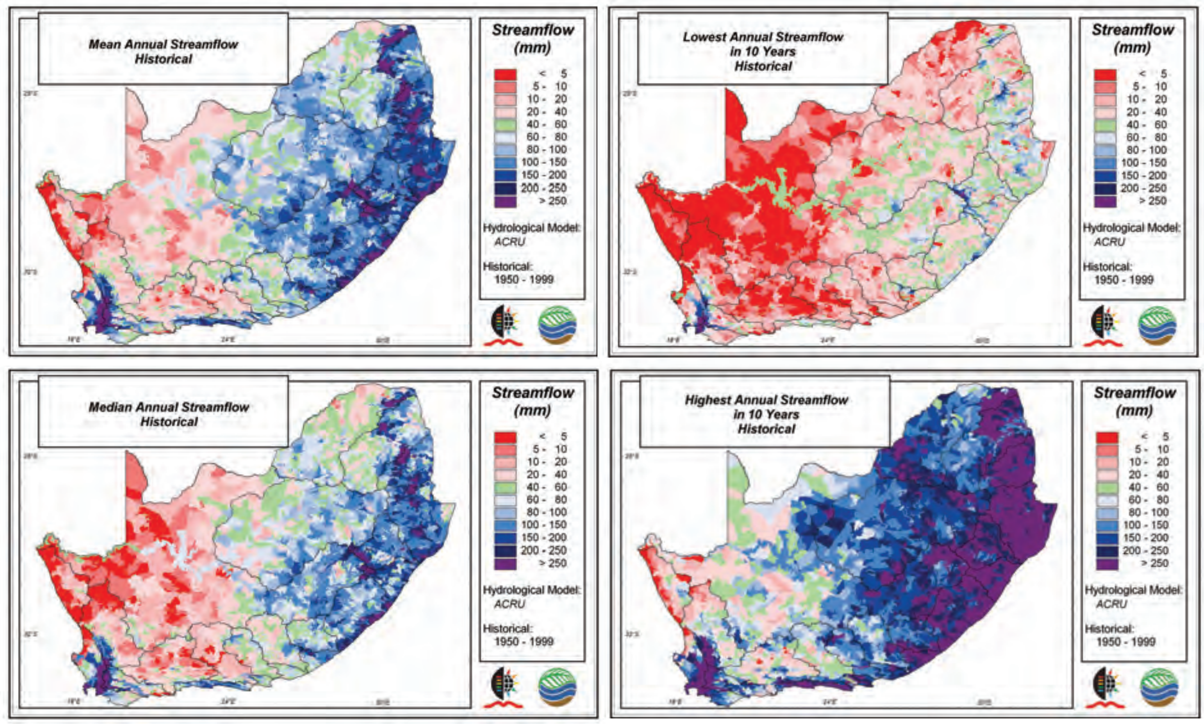

Figure 5.4.1 Mean annual streamflow (top left), median annual streamflow (bottom left) and the lowest and highest annual streamflows in 10 years (top and bottom right), simulated with the *ACRU* model under baseline (historical; 1950 - 1999) climatic conditions

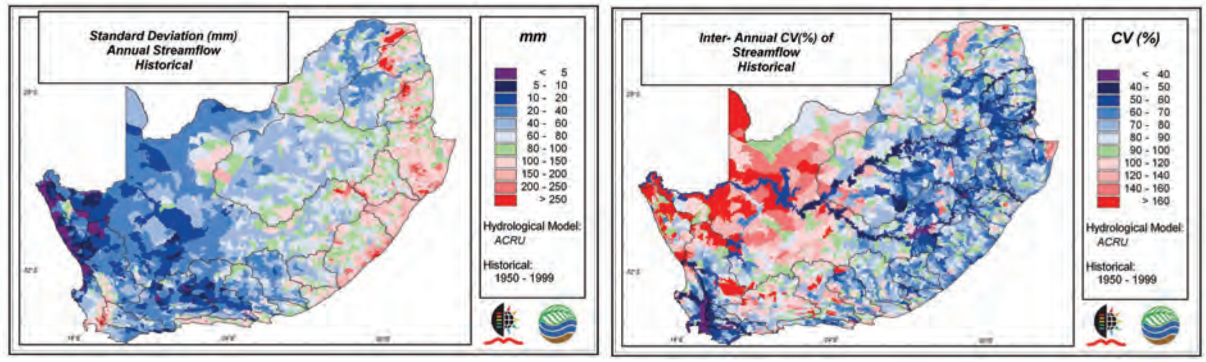

Figure 5.4.2 Standard deviation (mm) of annual streamflows (left) and the inter-annual coefficient of variation (CV %) of streamflows, simulated with the *ACRU* model under baseline (historical; 1950 - 1999) climatic conditions

The Dilemma of Simulating Streamflows in Endorheic (i.e. Internally Drained) Areas within South Africa

Large areas of the more arid northern parts of South Africa are endorheic, i.e. they have internal drainage with no channels / streamflows exiting the areas, as in **Figure 5.4.3** (left). The endorheic areas are affirmed by the very few, if any, rivers that are shown on the 1:50 000 topographical maps of those areas. This is well illustrated in **Figure 5.4.3** (right) by the significant tracts of endorheic areas in the Waterberg catchments in Limpopo.

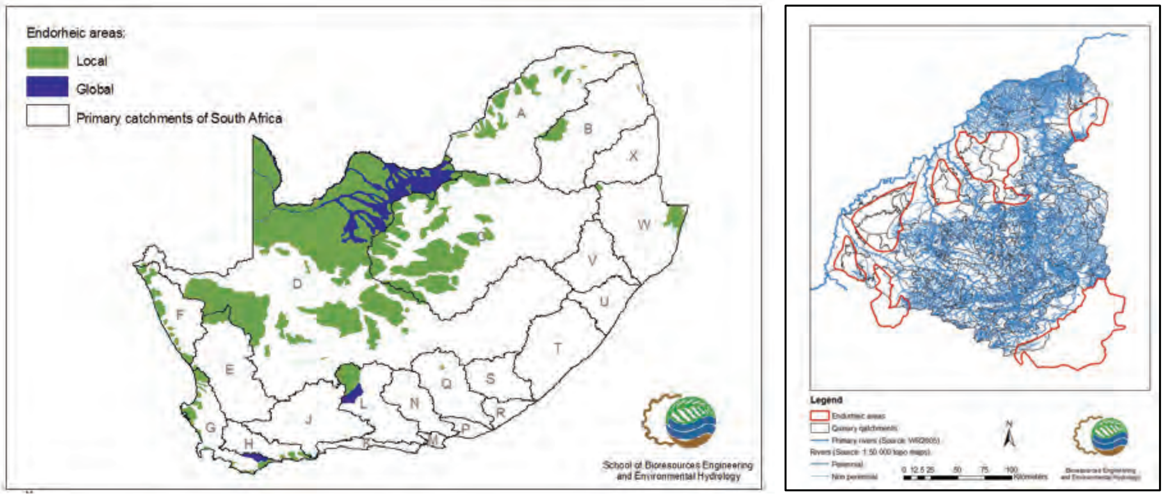

Figure 5.4.3 Endorheic, i.e. internally drained, areas in South Africa (left) and in the Waterberg catchments (right), with the latter illustrating the virtual absence of rivers where internal drainage exists (Sources: Midgley *et al*., 1994; Schulze *et al*., 2011)

While rules are under development for simulating endorheic areas with the *ACRU* model (Schulze *et al*., 2011), none of the results shown in this Chapter (nor in any others) have been generated with the endorheic option invoked in *ACRU* model runs. Consequently, systems such as the middle to lower Orange and, to a lesser extent, the Limpopo (cf. **Figure 5.4.3** left) have inflated values of streamflows (e.g. in **Figure 5.4.1**) as the flows from the endorheic areas never exit into the mainstem rivers. Note that stormflows and baseflows (**Chapters 5.2** and **5.3**), which are computed on an individual subcatchment basis in *ACRU* and are, as such, not accumulated downstream, are not affected if they occur in internally drained areas.

What will, however, be shown in subsequent maps in this Chapter which depict impacts of projected climate change, are changes in streamflows with the endorheic areas greyed out.

Ratio Changes of Future to Present Annual Streamflow Statistics Using Outputs from Multiple GCMs

From **Figure 5.4.4** it may be seen that from the multiple GCMs used in this study large tracts of South Africa are projected to have increases in annual streamflows by ~ 20 - 30%, irrespective of whether it be a year of median flows or a year with the 1 : 10 year low or high flows. However, the southwestern Cape displays projected reductions in streamflows, especially in the crucial wet years (**Figure 5.4.4** bottom row) when dams are filled.

The flow projected reductions in the southwest of the country are much more evident in the maps depicting ratio changes between the more distant future and the present than from the present into the intermediate future in the next 40 years (**Figure 5.4.4** middle column vs. left column of maps). These reductions are projected to occur especially in the 35 years making up the time period between the intermediate and more distant future periods (i.e. 2046 - 2065 vs. 2071 - 2100), not only in the southwest, but also to a lesser extent over the northern parts (**Figure 5.4.4** right column).

These results highlight the need to assess climate change impacts using output from more climate models.

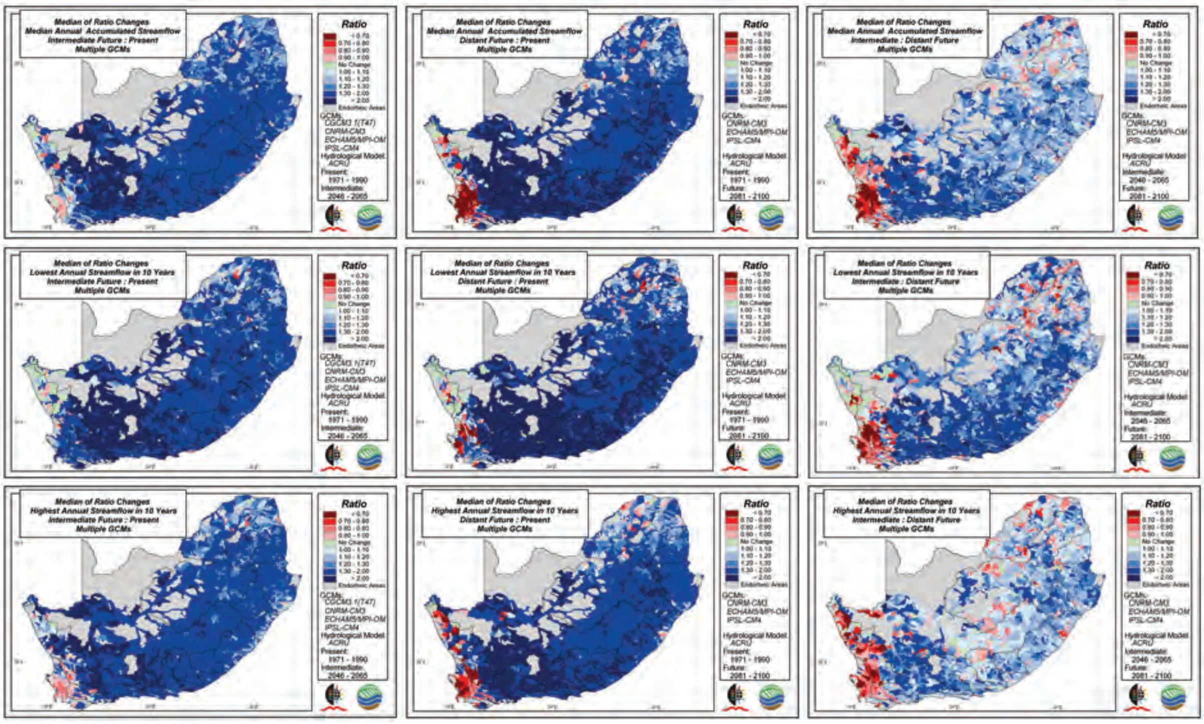

Figure 5.4.4 Medians of ratio changes of intermediate future to present (left column), more distant future to present (middle column) and more distant to intermediate future (right column) annual streamflows in a year of median flows (top row), the year with the lowest annual streamflows in 10 years (middle row) and the year with the highest annual streamflows in 10 years, derived with the *ACRU* model from output of multiple GCMs, and with endorheic areas greyed out

In **Figure 5.4.5** ratio changes in the projected inter-annual variability of streamflows are shown. In the top row standard deviations, a statistic of absolute variability (i.e. in terms of actual m³ or mm equivalents of flow), displays increases into the intermediate future of around 20 to 30 % and even more, rendering the management of water resources more challenging than at present. The exception is the southwestern Cape where variability is projected to decrease, especially into the more distant future. In the latter part of the century (**Figure 5.4.5** top right) a strong decrease in absolute variability of annual streamflows is projected from the outputs of multiple GCMs not only in the southwest, but also in the south and in parts of the north of South Africa.

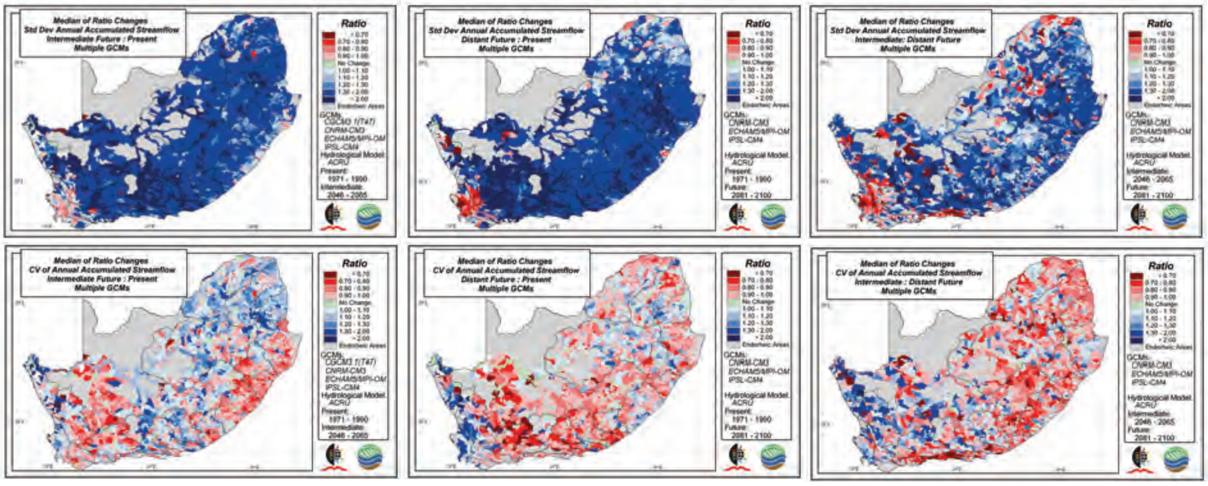

Figure 5.4.5 Medians of ratio changes of intermediate future to present (left column), more distant future to present (middle column) and more distant to intermediate future (right column) of standard deviations of annual streamflows (top row) and of the inter-annual coefficient of variation of streamflows (bottom row), derived with the *ACRU* model from output of multiple GCMs, with endorheic areas greyed out

In terms of relative variability, i.e. taking into account also changes in the magnitudes of flow, the ratio changes in inter-annual coefficient of variation into the intermediate future some 40 years from now displays a strong decline along the east coast and western interior, but CVs are projected to increase along the west coast and in a broad band across the country trending south to north (**Figure 5.4.5** bottom left). Into the more distant future a strengthening of increases in CVs is projected along the west coast; similarly, a strengthening of decreases in CVs is evident in the western interior and in general the areas with decreases in CVs expands.

In regard to future management of water resources, what is crucial is to identify those areas within South Africa where both the standard deviations and the CVs of annual streamflows increase, as they indicate that variability is increasing more rapidly than magnitudes of flows. The results derived by hydrological simulations with the *ACRU* model using climate outputs from multiple GCMs indicate that into the intermediate future such “hotspot” areas of enhanced variability are along the west coast and the broad south to north band in the central areas of South Africa, with the west coast projected to be even worse off in regard to variability of streamflows into the more distant future (**Figure 5.4.5**).

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CHAPTER 5.5

CLIMATE CHANGE AND
THRESHOLDS OF DAILY STREAMFLOW AMOUNTS EXCEEDED:
A 2011 PERSPECTIVE

R.E. Schulze and L.M. Bulcock

Critical Thresholds of Daily Streamflows

In much the same way that hydrologically critical thresholds of daily rainfall were identified in **Chapter 3.6** and projected ratio changes to the frequency of such rainfalls under climate change were mapped, so critical thresholds of daily streamflow amounts are identified in this Chapter and impacts of projected climate change on them are evaluated. *Accumulated streamflows* per Quinary Catchment (i.e. including all flows from catchments upstream of the Quinary in question) and, in the case of analyses using the historical record, also the *runoff from individual Quinaries*, were all generated with the *ACRU* model (Schulze, 1995 and updates) using soils and land cover information from the Quinary Catchments Database (**Chapter 2.2**). For the climate change component of the study five critical thresholds of streamflow were identified. They are the number of days per annum with

- zero flow,
- ≥ 0.1 mm equivalent daily flow, indicating anything above a trickle of (usually) baseflow which more than compensates for any evaporative losses from the stream,
- ≥ 0.5 mm equivalent daily flow, indicating anything above steady streamflows,
- ≥ 1 mm equivalent daily flow, indicating strong flows often from stormflows and thus of relatively short duration, except in large catchments where such flows can result from a regional flood, and
- ≥ 2 mm equivalent daily flow, indicative of quite significant local or regional flooding.

For the threshold analysis based on historical rainfall input to the *ACRU* model, the zero flow threshold is replaced by any flow with a positive value and maps are shown of critical thresholds exceeded for both accumulated streamflows and the individual Quinary Catchment's runoff. The methodology used in the threshold analysis is described in **Box 5.5.1**.

Box 5.5.1 Determination of Numbers of Days per Annum with Runoff from Individual Quinaries as well as with Accumulated Streamflows above Specified Threshold Values

Methodologies for generating daily runoff values with the *ACRU* model from individual Quinary Catchments, as well as values of streamflows accumulated from the catchment in question plus all upstream Quinaries, have been described in **Chapters 2.2**, **2.3** and **5.4** for the 50 year baseline (historical) period from 1950 - 1999 and for the 20 year present (1971 - 1990), intermediate future (2046 - 2065) and more distant future (2081 - 2100) scenarios from the various GCMs used in this study. For each of the 5 838 Quinaries covering the RSA, Lesotho and Swaziland the number of days exceeding the various critical thresholds of runoff and accumulated streamflows were then extracted and the results analysed in order to produce maps.

Distribution Patterns over South Africa of the Mean Number of Days per Annum with Accumulated Streamflows and Individual Catchment Runoff Exceeding Critical Threshold Values under Baseline (Historical) Climatic Conditions

Thresholds of runoff which are exceeded at individual Quinary Catchment level are important where water users have access only to local water supplies, while users with access to accumulated flows, especially from larger catchments, can take a more regional perspective to their water resources planning. Using the methodology to extract critical thresholds of daily accumulated streamflows and individual catchment runoff as summarised in **Box 5.5.1**, the major difference between the accumulated streamflow exceedence (left column of maps in **Figure 5.5.1**) and those from individual Quinaries (right column of maps in **Figure 5.5.1**) is that for the accumulated streamflows the more

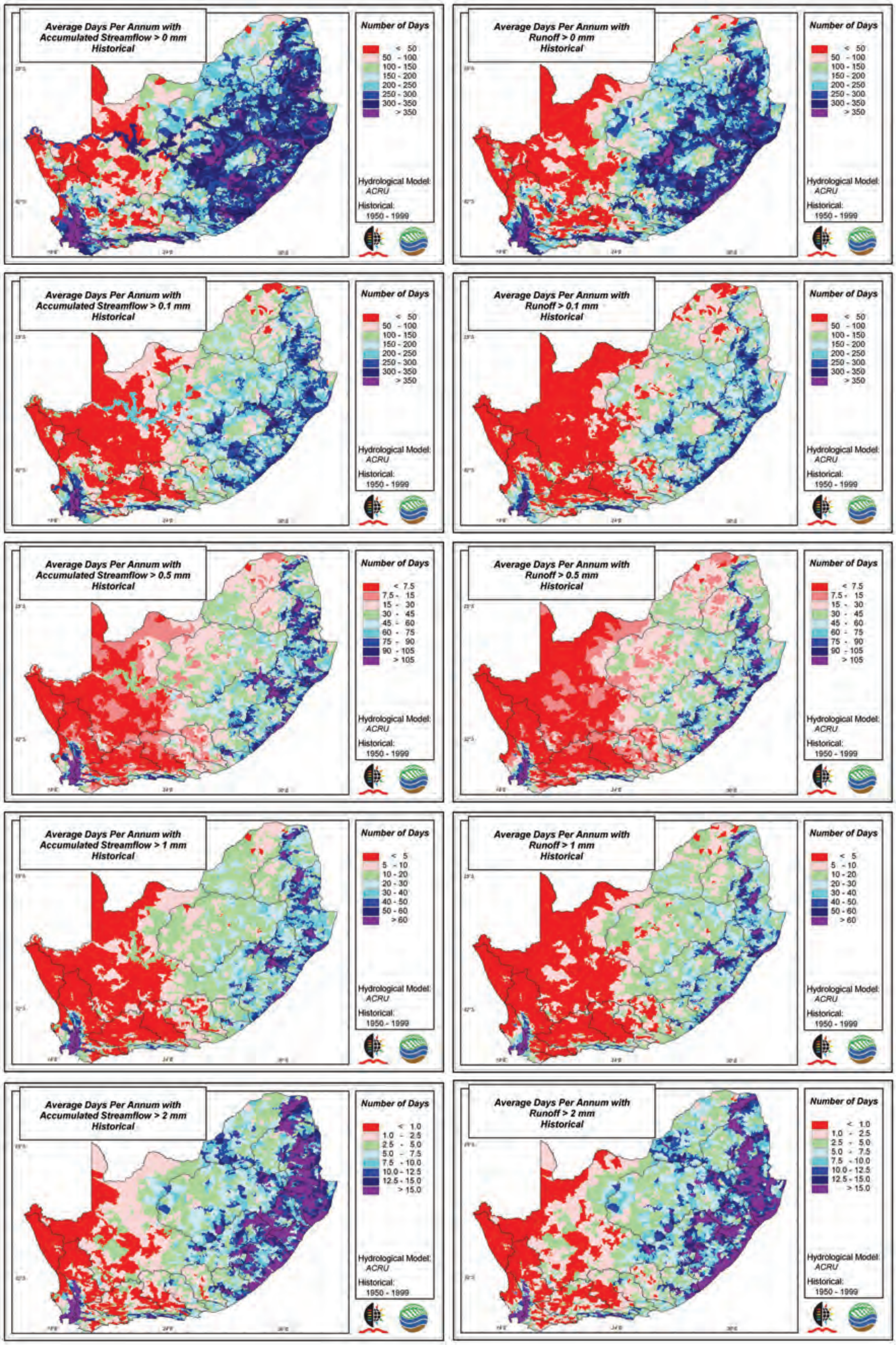

Figure 5.5.1 Average number of days per annum with accumulated streamflow (left column) and individual catchment runoff (right column) exceeding critical thresholds of flow, for baseline (historical; 1950 - 1999) climatic conditions

sustained flows of the larger river systems become clearly visible for zero flows and for the lower thresholds up to 0.5 mm per day. Thus, for example, the Orange, Vaal, Berg, Breede, Thukela, Mfolozi, Komati and other larger systems become clearly visible for accumulated flows, but not for the individual catchment flows. For the higher threshold flows which mimic flood conditions these differences are no longer visible because of the attenuating effect of larger catchments on daily flows. Furthermore, both sets of maps of **Figure 5.5.1** clearly show up the low number of days per year with any substantial flows in the semi-arid west in contrast to the high number of days per annum on which threshold flows are exceeded in the southwest as well as along the east coast and mountainous hinterland areas.

Ratio Changes of Future to Present Thresholds of Daily Streamflows Exceeded, Using Climate Output from Multiple GCMs as Input to the *ACRU* Hydrological Model

Results derived from multiple GCMs show that into the intermediate future fewer days with zero flows are projected, except in the north where ratio changes > 1 denote an increase in days without flow (**Figure 5.5.2** top left). Into the more distant future somewhat of a reversal of patterns is evident with the east central areas changing from fewer to more days with zero flows when compared to the GCMs' present climate scenarios, and many areas in the northeast now displaying fewer days with zero flows (**Figure 5.5.2** top row, middle map). These reversals may be explained by the period in the second half of this century between the intermediate and more distant future (i.e. between 2046 - 2065 and 2081 - 2100) identifying a distinct area in the northeast of declining number of days per year with zero flows while during those 35 years the remainder of South Africa shows ratios of change > 1, denoting more days with zero flows (**Figure 5.5.2** top row, right map).

Spatial patterns of ratio changes in the number of days with low flow thresholds (≥ 0.1 mm per day) to high flow thresholds (≥ 2 mm per day) are essentially similar into the intermediate future, but with greater increases in the number of days per annum with low flow than with high flow thresholds, and with the decreases in the southwest becoming more pronounced for the high flow days.

Into the more distant future the areas in the southwest with decreases in flows above specified thresholds expands for all the thresholds evaluated (**Figure 5.5.2** middle row), with the main reason for this being in the observation that the GCMs project significant decreases in thresholds exceeded in the second half of the century between the 2050s and the 2090s.

The repercussions of the decreases in the number of days per year that streamflow thresholds are exceeded may become critical to water resources planners in the southwest, as the days with significant inflows into storage dams is projected to decrease according to the outputs of the GCMs used in this study.

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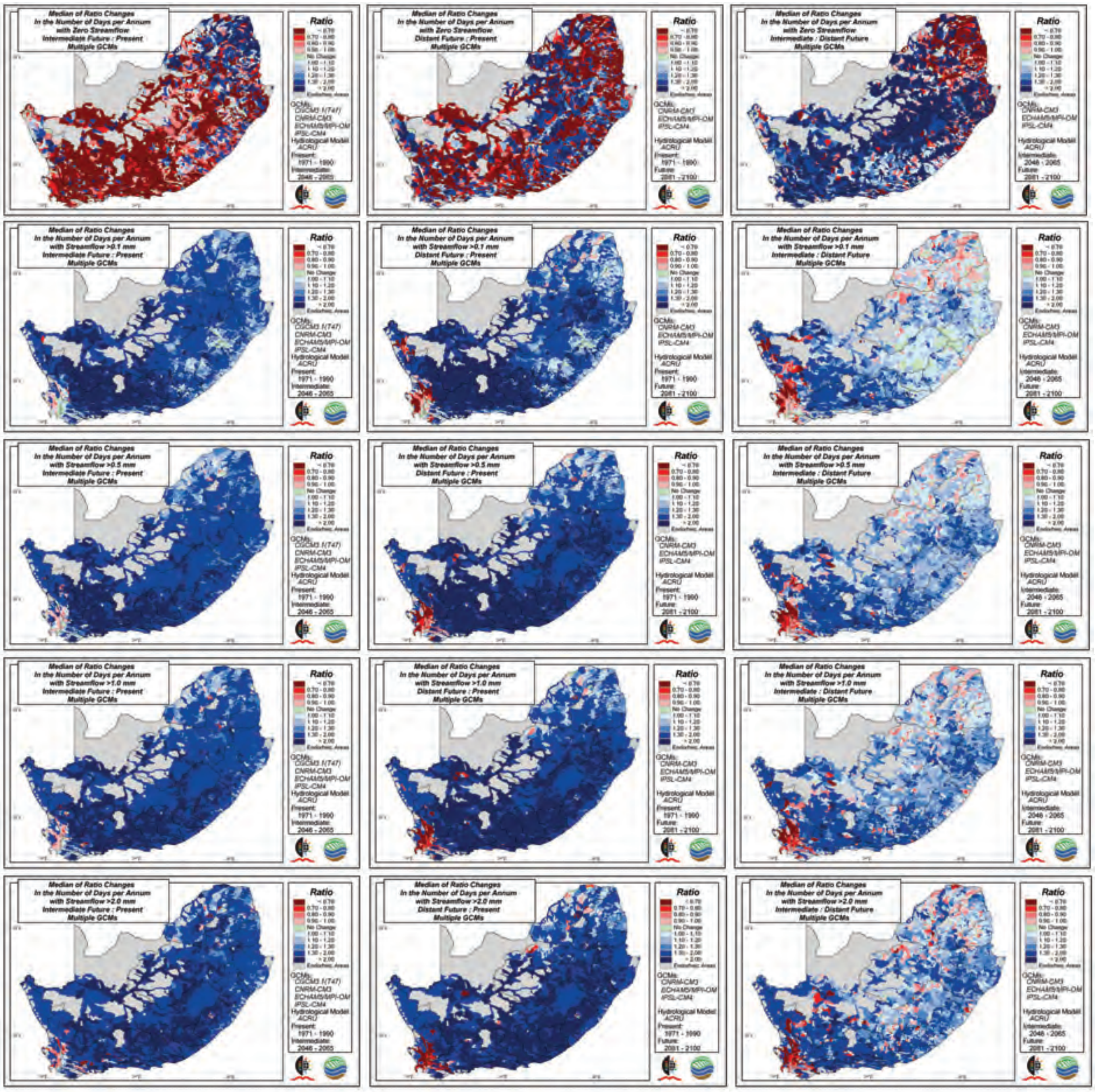

Figure 5.5.2 Medians of ratio changes in days per annum with thresholds of zero, 0.1, 0.5, 1.0 and 2.0 mm equivalent of accumulated streamflow per day being exceeded (top to bottom) for the intermediate future to present (left column), the more distant future to present (middle column) and the more distant to intermediate future time periods (right column), derived when outputs from multiple GCMs are used as inputs to the *ACRU* hydrological model

CHAPTER 5.6

CLIMATE CHANGE AND *PEAK DISCHARGE:* A 2011 PERSPECTIVE

D.M. Knoesen and R.E. Schulze

Background

The estimation of the peak flow from a flood is an important component with respect to the design of hydraulic structures such as spillways from dams or stormwater systems in urban areas, as well as peak discharge being used as a variable in estimations of the sediment yield from a catchment. Peak discharge from catchments is related closely to the volume of stormflow generated from that catchment (Schmidt and Schulze, 1984) and hence an accurate estimation of stormflow volumes (cf. **Chapter 5.2**) is of primary importance in determining peak discharge. The use of a daily hydrological model such as *ACRU* (cf. **Chapter 2.3**), in which the magnitude of a rainfall event is considered in conjunction with soil water status (i.e. the wetness or dryness of a catchment), enables stormflow to be modelled accurately, and therefore facilitates a realistic estimation of peak discharge, as has been shown in numerous studies (e.g. Schmidt and Schulze, 1984; Dunsmore *et al*., 1986).

Peak discharge in hydraulic design is usually expressed in m^3 per second for a specified return period, i.e. the highest peak discharge expected once in 10 years or in 20 years, with the return period depending on design life and / or economic value of the structure. Equations describing the computation of peak discharge have already been given within a broader context of the *ACRU* model as a whole in **Chapter 2.3**, and are repeated in **Box 5.6.1** below within the context of this Chapter.

Box 5.6.1 Estimation of Peak Discharge in the *ACRU* Model

In the *ACRU* model an estimate of the peak discharge associated with each day's stormflow volume generated can be made by assuming a single triangular unit hydrograph. For these simulations the SCS peak discharge equation (USDA, 1972), modified significantly by Schulze and Schmidt (1995) for application in South Africa, is used. In its modified version

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

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)

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

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

with the lag equation (L =) having been developed by Schmidt and Schulze (1984) using several hundred hydrographs from over 20 research catchments at seven hydro-climatically divergent regions in the USA and South Africa, and in which

A = catchment area (km^2),

Box 5.6.1 Estimation of Peak Discharge in the *ACRU* Model (continued)

MAP = mean annual precipitation (mm),
Y = mean catchment slope (%), determined in this study from a 200 m digital elevation model,
$\bar{I}_{30}$ = 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 effects of vegetation and soils on catchment lag.

In the lag equation given above (L =), both MAP and the 2 year return period 30 minute rainfall intensity are climate variables the values of which are projected to change in future climates, while in the main peak discharge equation (q_p =) the stormflow component, which is dependent on antecedent wetness conditions of the catchment and the day's rainfall, is also climate, and hence climate change, dependent. MAP for the intermediate future and distant future was calculated as described in **Chapter 3.4**, while the methodology developed in **Chapter 7.1** was used to calculate the magnitude of the 2 year return period, 30 minute rainfall intensity for each Quinary Catchment.

The Log-Pearson Type III extreme value distribution, described in detail in **Chapter 7.2**, was used to compute the design peak discharge (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, has been calculated based on the simulated stormflow generated from each runoff producing event for each individual Quinary, and not the accumulated streamflows. The reason for this is that the *ACRU* model, in its standard version, does not yet contain a routine to route sediments through a series of catchments which would reflect the complexities of the entrainment, transport and deposition processes at play when sediments move down a series of catchments. Selected results from the design peak discharge analysis are presented below, with projected changes into the future only shown up to the 20 year return period as the time slices from GCM analyses comprised only of 20 years and not longer and it is statistically imprudent to extrapolate beyond the length of ones record.

Distribution Patterns over South Africa of Design Peak Discharges for Selected Return Periods, Computed per Quinary Catchment under Baseline (Historical) Climatic Conditions

With peak discharge from a catchment being dependent on its slope, stormflow, MAP, a rainfall intensity index and especially its area, it is not expected that its spatial distribution will always follow intuitively logical patterns. This is reflected in the maps making up **Figure 5.6.1**, which show low values in the south and west of South Africa for the 2 year return period, reflecting to a large degree the low rainfall intensities there (cf. **Chapter 7.1**; **Figure 7.1.4**). Peak discharges become larger towards the more arid northwest for increases in recurrence intervals from the 5 to the 10 and 20 year return periods, mainly as a result of the large catchment areas there (Knoesen, 2011) and the infrequently occurring very large floods in those semi-desert areas which show up in, say, the 1 : 20 peaks but not in the 1 : 2 year peaks (cf. **Chapter 7.3**).

Ratio Changes of Future to Present Design Peak Discharges for Selected Return Periods, Using Outputs from Multiple GCMs

Projecting into the intermediate future, the maps of changes in peak discharge in **Figure 5.6.2** (left column of maps), based on the analyses from multiple GCMs, show

- first, a relatively clear west/east division within South Africa, with increases in peak discharges foreseen in the west and decreases in the east,

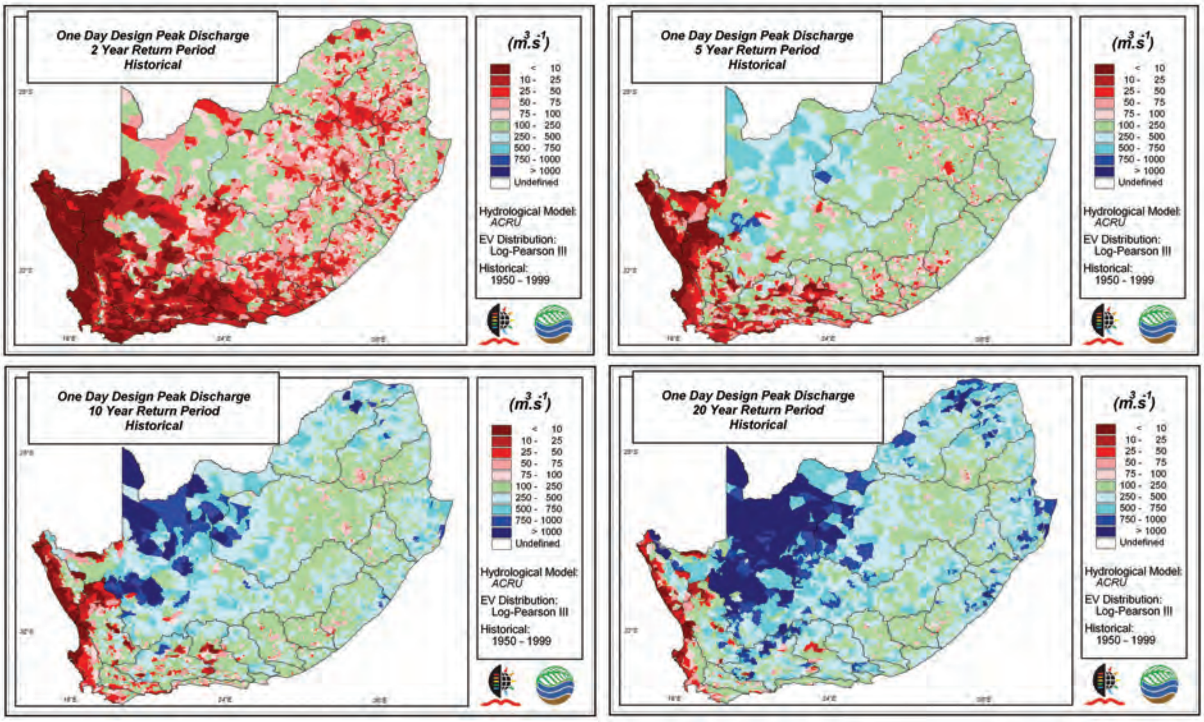

Figure 5.6.1 One day peak discharge values for the 2, 5, 10 and 20 year return periods, derived from catchment characteristics and baseline (historical; 1950 - 1999) climate data

- second, a shrinking of the area of projected increases in peak discharge in the west as the return periods of the peak flows increase from 2 to 5, 10 and 20 years, and
- third, that the highest projected increases in peak discharge appear to be in the transitional areas between the winter and summer rainfall regions, which are highly sensitive to patterns of changes in seasonal climates of the future.

The maps depicting projected changes in peak discharge into the more distant future of 2081 - 2100 (**Figure 5.6.2** middle column) indicate an intensification of the increases in the west and, similarly, more marked decreases in peak discharges from Quinary catchments in the east. A reason for this intensification may lie in the projected changes to peak discharge following similar spatial patterns in the 35 year period between the intermediate (2046 - 2065) and the more distant future climates (2081 - 2100; **Figure 5.6.2** right column).

Looking into the Future: Need for a Re-Assessment of the Lag Equation for Use in Peak Discharge Estimations

For greater confidence in the estimation of peak discharge in future studies it should be borne in mind that the use of MAP as a climatic variables in the Schmidt and Schulze (1984) lag equation, although seemingly attractive for climate change analyses, should be re-assessed (Knoesen, 2011). The reason for this is that MAP is not used as a direct climatic variable *per se*, but (as already alluded to in **Box 5.6.1**) rather a surrogate variable to represent soils and above-ground biomass. 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. Therefore, the increases or decreases in MAP projected by the various GCMs are, in effect, creating either a denser or less dense 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 (Knoesen, 2011). Since MAP lies in the numerator of the lag equation given in **Box 5.6.1** and has an exponent > 1, any increases in MAP thus result in increases in catchment lag, thereby resulting in a decreased peak discharge, with the converse being the case for decreases in

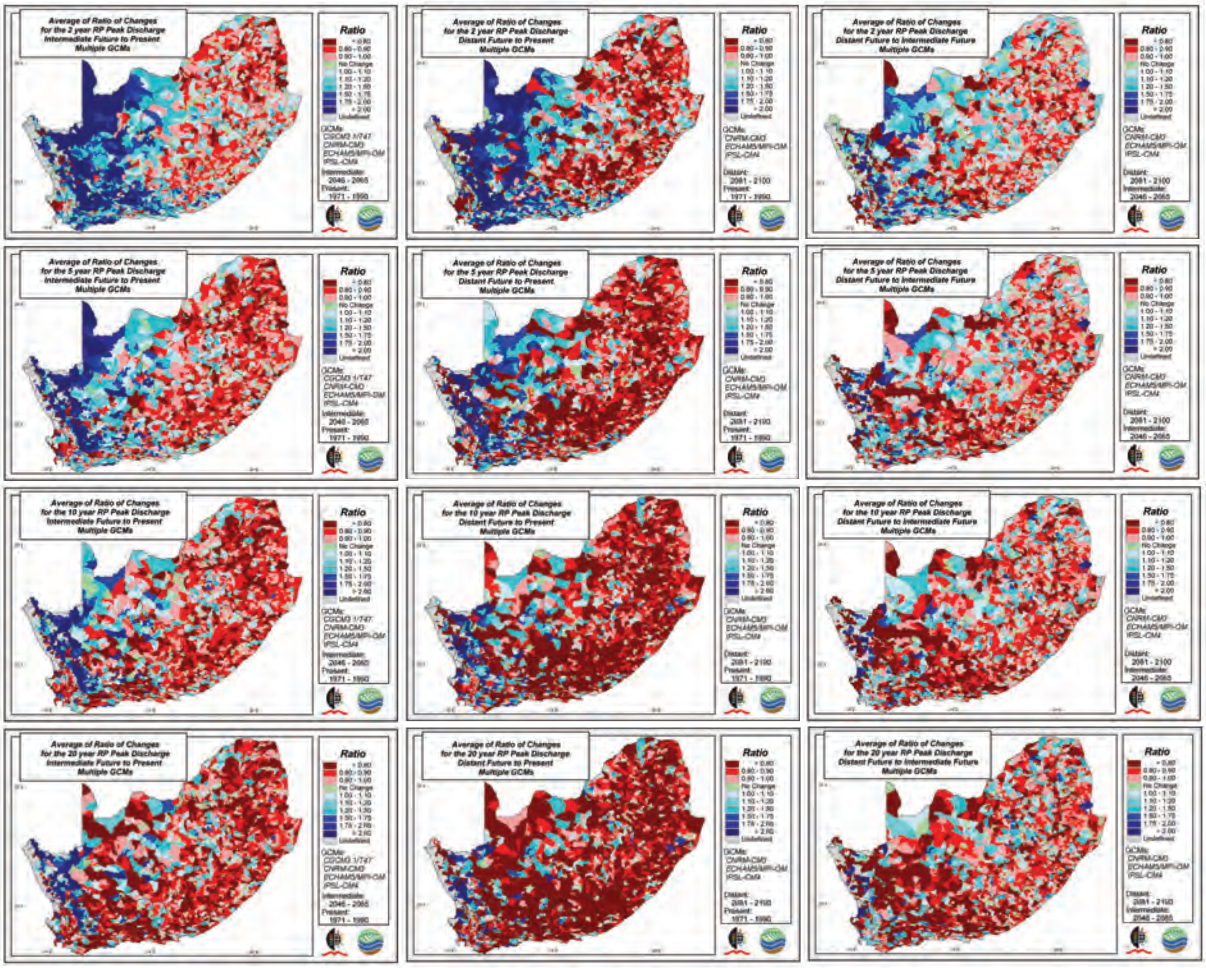

Figure 5.6.2 Averages of ratio changes of intermediate future to present (left column), more distant future to present (middle column) and more distant to intermediate future (right column) peak discharges from Quinary Catchments for the 2 year return period (top row), the 5 year (second row), the 10 year (third row) and the 20 year return period (bottom row), derived with the *ACRU* model from output of multiple GCMs

MAP in future. Owing to this, the results from the design peak discharge analysis are likely to be lower where MAP is projected to increase in future and higher where MAP is projected to decrease in future. A re-assessment of the lag equation should thus be considered for future studies.

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CHAPTER 5.7

CLIMATE CHANGE AND
SEDIMENT YIELD:
A 2011 PERSPECTIVE

R.E. Schulze. D.M. Knoesen and R.P. Kunz

Sediment Yield: Background (Adapted from Schulze, Lorentz, Horan and Maharaj, 2008; Knoesen, 2011)

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 (1992) estimated that the average annual sediment yield in southern Africa varied between 30 and 330 t.km^2. Sediments can become trapped in reservoirs, thereby reducing the storage capacity for irrigation and other uses, and decreasing a reservoir's design life. Furthermore, elevated concentrations of suspended sediments in flowing water reduce the quality of water in the rivers (Kienzle *et al*., 1997), including its use for irrigation. Therefore, sediment yield is a potential agrohydrological 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).

Modelling Sediment Yield

Complex deterministic models are available to estimate erosion processes and sediment transport. However, these models are limited in their application owing to their reliance on calibration.

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*., 2008). 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 (**Box 5.7.1**), 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.

Box 5.7.1 Estimation of Sediment Yield per Quinary Catchment Using the Modified Universal Soil Loss Equation, MUSLE (Adapted from Schulze, Lorentz, Horan and Maharaj, 2008; Knoesen, 2011)

Sediment yield, Y_{sd}, is estimated in the *ACRU* model on a daily event-by-event basis whenever stormflow occurs, and is a function of stormflow, peak discharge, erodibility properties of soils, catchment slope, cover factors (both canopy and ground / mulch) and management support practice (e.g. conservation structures). Sediment yield at any Quinary Catchment outlet may be estimated in *ACRU* using the MUSLE, which is expressed as

$$Y_{sd} = \alpha_{sy} (Q_v \, x \, q_p)^{\beta_{sy}} K \, x \, LS \, x \, C \, x \, P$$

where Y_{sd} = sediment yield (t) from an individual stormflow event,
Q_v = stormflow volume for the event (m^3),
q_p = peak discharge for the event (m^3/s),
K = soil erodibility factor (t h/N/ha),

Box 5.7.1 Estimation of Sediment Yield per Quinary Catchment Using the Modified Universal Soil Loss Equation, MUSLE (continued)

LS = slope length and gradient factor (-),
C = cover and management factor (-), and
P = support practice factor (-).

The MUSLE coefficients, α_{sy} and β_{sy} are location specific (Simons and Sentürk, 1992) and are determined for specific climatic zones. However, default values set at 8.934 for α_{sy} and 0.56 for β_{sy} were assumed in sediment yield simulations for this Report.

When the sediment yield option is selected, the stormflow and peak discharge for each Quinary Catchment (QnC) need to be simulated for each stormflow event.

Stormflow, Q_s, defined as the water which is generated in a catchment either at or near the surface from a specific rainfall event, is computed in the *ACRU* model (Schulze, 1995 and updates) in mm equivalents as

$$Q_s = (P_n - I_a)^2 / (P + I_a + S) \qquad \text{for } P_n > I_a$$

in which
P_n = net rainfall (mm), i.e. gross (measured) rainfall minus canopy interception losses,
I_a = initial abstractions (mm) before stormflow commences, consisting mainly of that infiltration which occurs between the beginning of the rainfall event and the beginning of storm runoff, plus any depression storage, and
S = the soil's potential maximum retention (mm), which is equated to the soil water deficit and is an expression of the wetness or dryness of the soil.

The mm equivalent is converted to m^3 using the Quinary's area.

In *ACRU*, the soil water deficit S is calculated by the daily multi-layer soil water budget (Schulze, 1995), and for computations of stormflow a critical soil depth, D_{sc} (m) is defined from which S is determined. For all hydrological simulations in this Report, D_{sc} was defined as the thickness of the topsoil.

A major determinant of initial abstractions is soil moisture content. In order to eliminate estimations of both I_a and S in the equation above, I_a is expressed as a coefficient, c, of S, where c is an index of infiltrability into the soil and varies with rainfall intensity (thunderstorms ≡ smaller c), tillage practice and surface cover/litter/mulch (Schulze, 1995). For all simulations in this Report, the c of I_a was input as that value assigned on a month-by-month by Schulze (2004) for the 70 baseline land cover types (Acocks, 1988) found in South Africa (Schulze, 2004).

Not all stormflow generated from a rainfall event exits the catchment on the same day as the rainfall occurs. This necessitates a stormflow response coefficient, F_{sr}, to be input, which controls the "lag" of stormflows and is effectively an index of interflow. For all simulations on all Quinaries in this Report, F_{sr} was set at 0.3, a value which has been found experimentally to be typical in South Africa for use at the spatial scale of Quinary Catchments.

For simulations of peak discharge the SCS peak discharge equation, modified by Schulze and Schmidt (1995), is used. In this equation

$$q_p = 0.2083 Q_s A / 1.83\ L$$

where
q_p = peak discharge (m^3/s),
Q_s = stormflow depth (mm), 5
A = catchment area (km^2),

Box 5.7.1 Estimation of Sediment Yield per Quinary Catchment Using the Modified Universal Soil Loss Equation, MUSLE (continued)

L = catchment lag (response) time (h),
= $(A^{0.35}MAP^{1.1}) / (41.67S_{\%}^{0.3}f_{30}^{0.87})$,
with MAP = mean annual precipitation (mm),
$S_{\%}$ = average catchment slope (%), and
f_{30} = 30 minute rainfall intensity (mm/h) for the 2 year return period.

Information needed for each Quinary Catchment thus includes

- stormflow volume and peak discharge for each event (cf. **Box 5.7.1**);
- the 30 minute rainfall intensity (mm/h) for the 2 year return period, f_{30}, used in the peak discharge equation and computed for climate change studies in South Africa by techniques developed by Knoesen (2011);
- the soil erodibility factor, *K*, determined from the ISCW's soil land types using the AUTOSOILS program (Pike and Schulze, 1995) and shown in **Figure 5.7.1** (top);
- the slope length factor, calculated from each Quinary Catchment's average slope gradient determined from a 200 m resolution Digital Elevation Model and an equation which relates slope gradient to the slope length factor developed by Schulze (1979), shown for South Africa in **Figure 5.7.1** (bottom left);
- the cover and management factor, *C*, as determined by Schulze (2004) and shown in **Figure 5.7.1** (bottom right),
- the support practice factor, *P*, not applicable for these simulations under baseline land cover conditions and thus set to 1; and
- a factor proportioning the amount of the sediment generated from a stormflow event and which reaches the outlet to the respective Quinary Catchment on the day of the event, in order to account for sediment eroded at one location and which may be stored temporarily only to be subsequently remobilised several time before reaching the catchment outlet (van Zyl and Lorentz, 2003), and set for this study at 0.45 (Schulze, 1995)

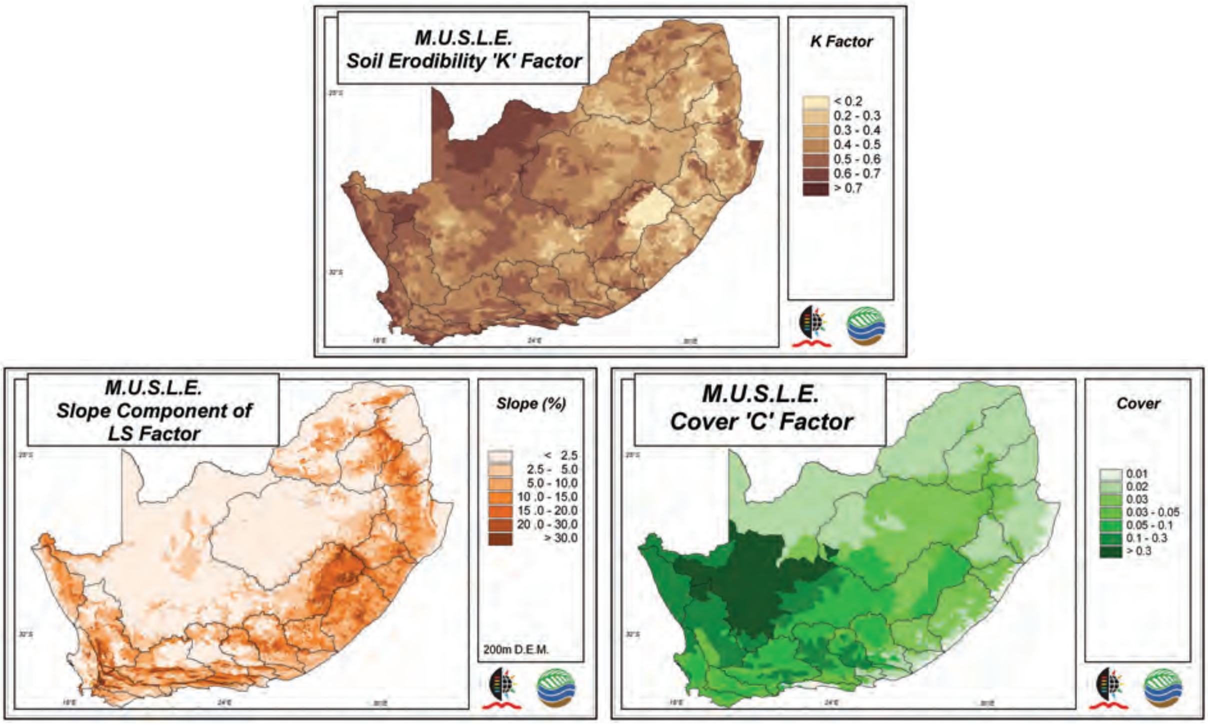

Figure 5.7.1 Distributions over South Africa of the Modified Universal Soil Loss Equation's soil erodibility, slope length and cover factors (Knoesen, 2011)

Box 5.7.2 Mapping Sediment Yield over South Africa

In order to map various statistics of sediment yield over South Africa, the Quinary Catchments Database (cf. **Chapter 2.2**) was used in conjunction with the daily time step *ACRU* model (**Chapter 2.3**). The information contained in the data files for current (historical) climate and for the various GCM derived climate scenarios used is described in **Chapters 2.1** and **2.2**. From the daily output files of sediment yield (t) and the area of each Quinary Catchment, various statistics expressing sediment yield in t/ha were derived and these have been mapped.

Distribution Patterns over South Africa of Annual Sediment Yield Statistics under Baseline Land Cover and Baseline (Historical) Climatic Conditions

Mean annual sediment yields under baseline land cover conditions range from < 0.2 t/ha to > 10 t/ha (**Figure 5.7.2** top left), with spatial patterns which are often difficult to interpret because of the multiplicity of interacting factors, but with a strong relationship between sediment yields and the slope length factor (cf. **Figure 5.7.1**). Because means of sediment yields are statistically highly skewed

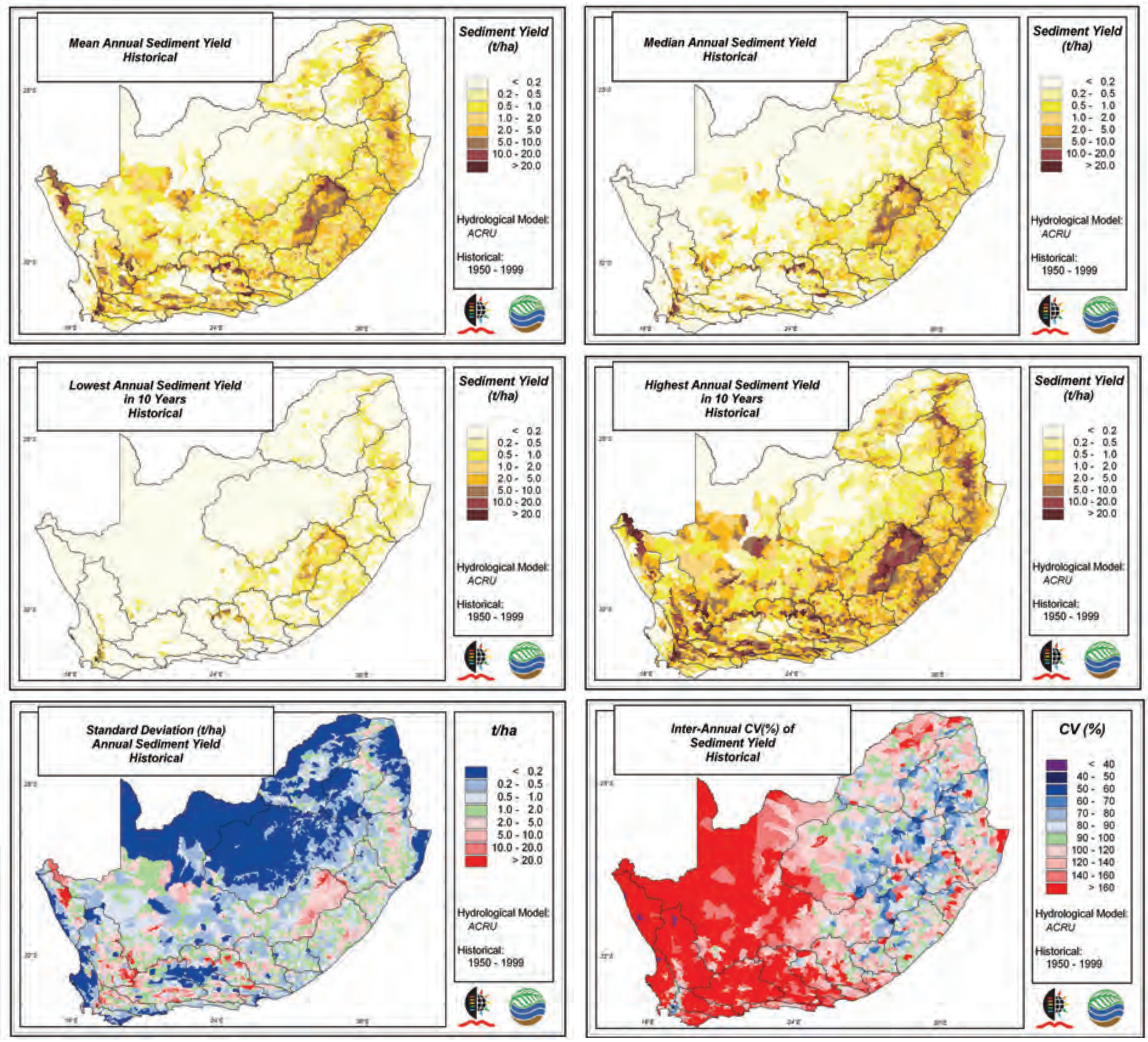

Figure 5.7.2 Mean annual sediment yield (top left), median annual sediment yield (top right), the lowest and highest sediment yields in 10 years (middle row, left and right), and the inter-annual variability in sediment yields expressed by the standard deviation (bottom left) and the coefficient of variation (bottom right), simulated with the *ACRU* model under baseline (historical; 1950 - 1999) climatic conditions

because of the impacts of a few major outlier events, it comes as no surprise that median annual sediment yields are considerably lower in places (**Figure 5.7.2** top right). Year-to-year variability of sediment yields is generally high, as testified by the differences between lowest annual sediment yields in 10 years and highest in 10 years being up to an order of magnitude (**Figure 5.7.2** middle row) - a further confirmation of the amplification effects in hydrological responses resulting from any changes in rainfall conditions, especially for higher order responses such as sediment yields. This is borne out by the high values of the variability statistics of annual sediment yields which were used (**Figure 5.7.2** bottom row), with highest absolute variability (standard deviation) in an arc around the escarpment of the coastal hinterland while in relative terms (CV %) the highest variability is concentrated in the more arid west and in the far north.

Ratio Changes of Future to Present Annual Sediment Yield Statistics, Derived Using Outputs from Multiple GCMs

Interpretation of averages of ratio changes of median annual sediment yields shows that into the intermediate future some 40 years from now (2046 - 2065) a general increase of 30 - 100 % (i.e. ratio changes of 1.30 to 2.00) is projected in the more arid west of South Africa, with increases in the wetter east being somewhat less at 10 - 20 % and patches of reductions even projected (**Figure 5.7 3** top left). These patterns of change are generally projected to persist into the more distant future some 80 years from now, except that the mountainous areas of the southwest display distinct reductions in sediment yields (**Figure 5.7.3** top middle), which are confirmed in the 35 year period from the intermediate to the more distant future (**Figure 5.7.3** top right).

Projections of changes in sediment yields in more extreme years show similar patterns of increases for the lowest yields in 10 years (**Figure 5.7.3** middle row). In the year in 10 with highest sediment yields (**Figure 5.7.3** bottom row) the projected increases are somewhat less intense and more varied, but with the reductions in the southwest now a very distinct feature, while in the latter decades of the century more patches of reductions in sediment yields appear (**Figure 5.7.3** bottom right).

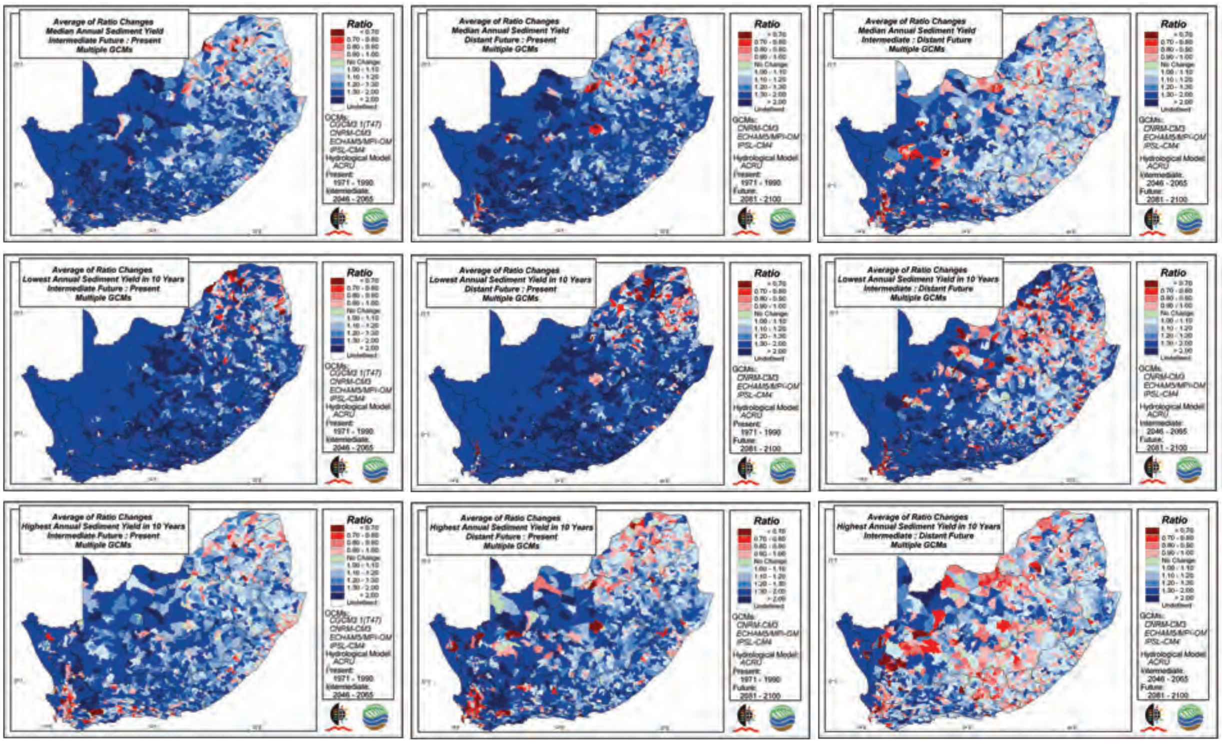

Figure 5.7.3 Averages of ratio changes of intermediate future to present (left column), more distant future to present (middle column) and more distant to intermediate future (right column) in sediment yields in a year of median yields (top row), the year with lowest sediment yields in 10 years (middle row) and the year with highest yields in 10 years, derived with the *ACRU* model from output of multiple GCMs

Ratio Changes of Future to Present Variability of Annual Sediment Yields, Derived Using Outputs from Multiple GCMs

Projected changes in standard deviations of sediment yields display a general increase in actual year-to-year variability in terms of t/ha lost (**Figure 5.7.4** top maps), the exceptions being reductions in the mountain regions of the southwest and random patches elsewhere, with the latter decades of the century showing up more areas of actual reductions (**Figure 5.7.4** top right).

In regard to changes in inter-annual variability relative to changes in means of sediment yields, i.e. the coefficient of variation, **Figure 5.7.4** (bottom maps) shows very different patterns to those of changes in absolute sediment yields, with much of South Africa displaying reductions in this variability statistic, especially in the present to more distant future and the intermediate to more distant future periods (**Figure 5.7.4** bottom maps). This illustrates that for sediment yields the projected changes in means into the future are greater than the projected changes in actual tonnages per hectare of sediment yielded from a catchment. The exception to this is the west coast region where, relative to mean changes in sediment yields, actual variability from year-to-year is increasing, but off a low base (cf. **Figure 5.7.2** top left).

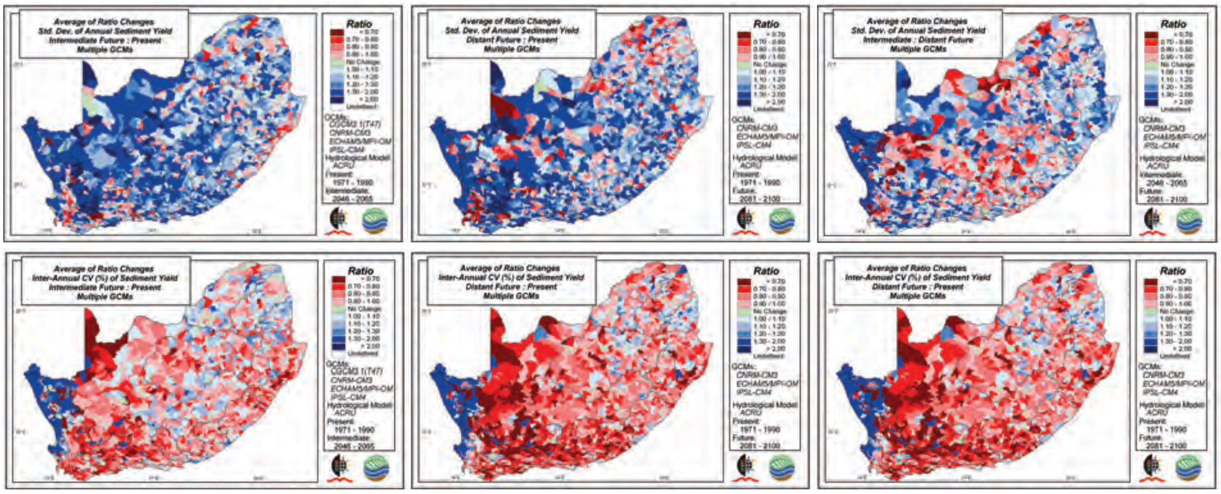

Figure 5.7.4 Averages of ratio changes of intermediate future to present (left column), more distant future to present (middle column) and more distant to intermediate future (right column) standard deviations of annual sediment yields (top row) and inter-annual coefficients of variation of sediment yields (bottom row), derived with the *ACRU* model from output of multiple GCMs

The interpretations in this Section of this Chapter show that great care needs to be taken in selecting relevant variability statistics when evaluating projected impacts of climate change.

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SECTION 6

PROJECTED CHANGES TO METEOROLOGICAL AND HYDROLOGICAL DROUGHTS

CHAPTER 6.1

CLIMATE CHANGE AND *METEOROLOGICAL DROUGHT:* A 2011 PERSPECTIVE

R.E. Schulze, D.M. Knoesen and R.P. Kunz

Droughts

Drought may be described as a creeping, slow on-setting natural hazard, which can manifest itself either through a lack of precipitation, or from a lack of available soil moisture for crops, or a reduction of streamflows below a critical threshold, or of the amount of water stored in reservoirs, or reduced levels of groundwater (Schulze, 2003; 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, 2003). Owing to the projected increases in temperature and changes in rainfall amounts and variability in future climates, it is anticipated that the frequency as well as the duration and magnitude of droughts will change, either increasing or decreasing, with potentially severe economic, social and environmental implications. It is therefore necessary to try and assess how these hazards might change in future climates.

This Chapter on droughts commences with some definitions relevant to this study, followed in **Box 6.1.1** by a description of the methodology adopted for the computation of meteorological droughts. Thereafter an analysis is undertaken on meteorological droughts using historical data, which sets the scene for an evaluation of impacts of climate change on meteorological droughts as projected when using the GCMs selected for this study. Similar analyses are then performed in **Chapter 6.2** for hydrological droughts.

Meteorological vs. Hydrological Drought

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.

Drought Duration

In regard to *drought duration*, in numerous previous studies a drought has be defined as a sustained period in which *monthly* precipitation or streamflow at a given location is below the long-term average (e.g. 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 UNDP (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 months* (in the case of historical droughts) or *years* (for both historical droughts and projected changes) having been analysed.

Drought Severity

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 in **Chapter 6.2**) 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").
- *Severe* droughts occur only once in ten years or less frequently (i.e. ≤ 10th percentile).

Box 6.1.1 Methodology for the Computation of Meteorological Drought

In order to calculate whether or not meteorological droughts are projected to occur more frequently or less frequently in the intermediate and more distant future climates, the above-mentioned thresholds for mild, moderate and severe droughts were applied to determine what magnitude would constitute a drought under present (i.e. 1971 - 1990) climatic conditions when using output derived from the each of the GCMs available in this study, *viz*. CGCM3.1(T47), CNRM-CM3, ECHAM5/MPI-OM and IPSL-CM4 (having, in the final analysis, omitted results from GISS-ER because of problems encountered in its computation of rainfall; cf. **Chapter 2.4**). 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 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.

Distribution Patterns over South Africa of Frequencies of Occurrence of Consecutive Months and Consecutive Years of Meteorological Droughts of Different Severities under Baseline (Historical) Climatic Conditions

Figure 6.1.1 shows the spatial variation of the frequency of occurrence of two consecutive and three consecutive *months* of drought for the three levels of severity of meteorological droughts for the 50 year period of historical data, *viz*. 1950 -1999. Owing to the definitions of drought used in this study (see above), the number *individual* drought months (or years in the interpretation to follow in **Figure 6.1.2**) have not been mapped, as the number of occurrences in the 50 year historical dataset for the mild (or more severe), moderate (or more severe) and severe droughts would be approximately 17 (i.e. 50/3), 10 (i.e. 50/5) and 5 (i.e. 50/10), respectively.

Figure 6.1.1 illustrates that regardless of the severity of the drought, or whether the prolonged dry period lasts two months or three months, that South Africa is in a drought-prone region. A number of observations may be made from **Figure 6.1.1**:

- There is an overall southwest to northeast trend line across South Africa, with frequencies of meteorological drought occurrences being higher to the north of the trend line and lower south of it.
- As expected, the frequencies of droughts for both 2 consecutive and 3 consecutive months decreases as the severity of drought increases from mild to moderate to severe.
- Similarly, as expected, the frequencies of meteorological drought occurrences of 3 consecutive months are lower than those of 2 consecutive months.

The distributions over South Africa of two and three consecutive years of meteorological drought of different severities are shown in **Figure 6.1.2**. For 2 consecutive drought years of *mild severity* (i.e. occurring statistically at least once in three years; **Figure 6.1.2** top left) the frequency of occurrence in the 50 years of record averages 5 - 6 times, i.e. it has a statistical recurrence interval of 1 : 6 to 1 : 8 years, with patches only experiencing such droughts once in 25 years while elsewhere the return period is 1 : 6 years.

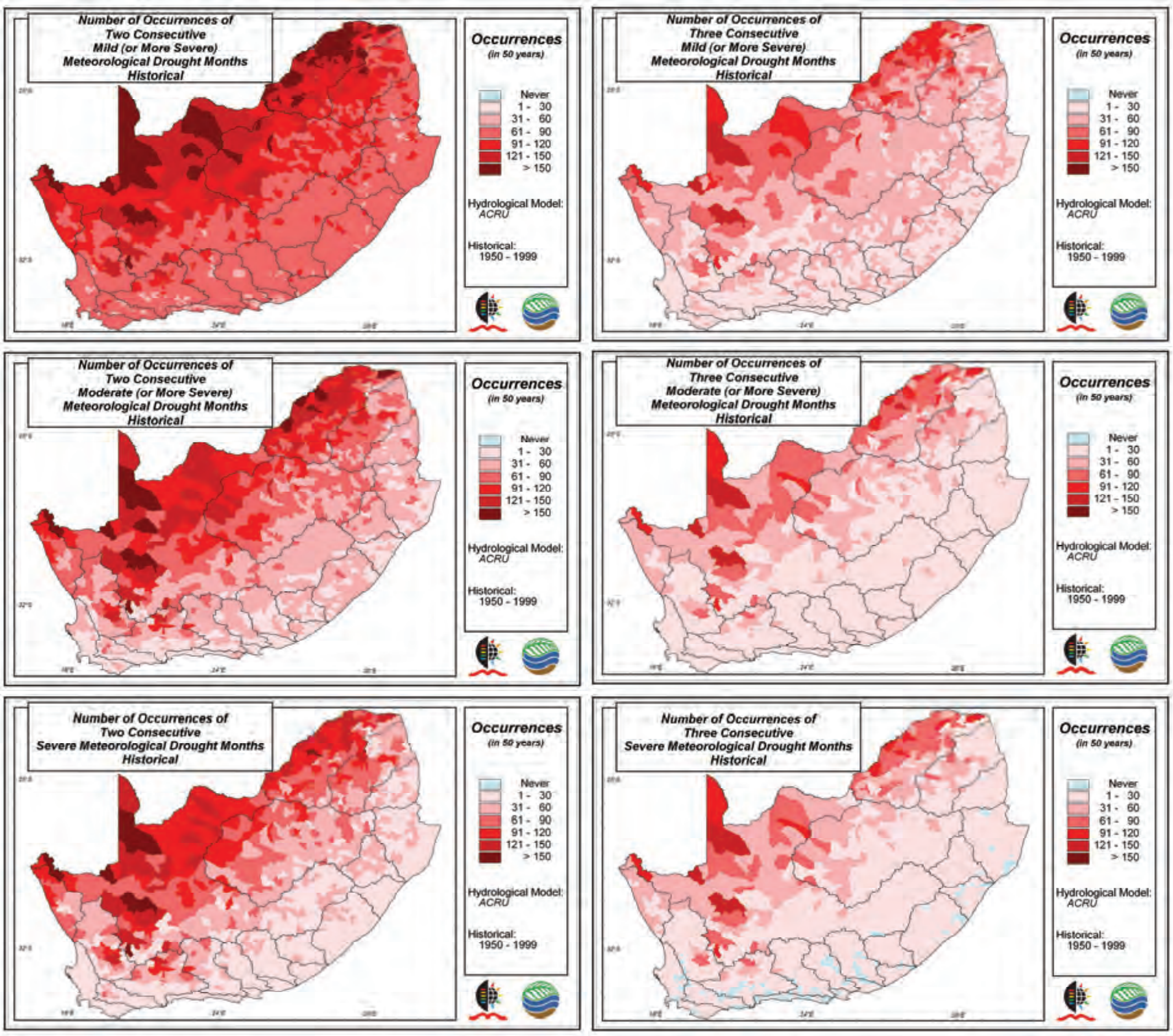

Figure 6.1.1 Number of occurrences of mild (top row), moderate (middle row) and severe (bottom row) meteorological droughts for 2 consecutive months (left column) and 3 consecutive months (right column), derived from the 50 year historical rainfall dataset from 1950 to 1999

For two consecutive years of meteorological droughts of *moderate severity* (i.e. statistically at least once in 5 years; **Figure 6.1.2** middle left), on the other hand, there are some locations in South Africa (predominantly in the semi-arid central areas) where this did not occur a single time in the 50 year historical record used. Overall, however, two consecutive years of moderate drought have been experienced 2 - 4 times over 50 years, or on average with a recurrence interval of 1 : 15 to 1 : 25 years.

Severe droughts (i.e. recurring statistically with a recurrence interval of at least 1 : 10 years) very seldom occur in two consecutive years, and where so, only in patches across South Africa and only once or twice in 50 years (**Figure 6.1.1** bottom left).

For the historical meteorological *drought analysis of three consecutive years* (**Figure 6.1.2** right column of maps) an interesting observation is that the distribution patterns on the map of 3 consecutive years of *mild drought* essentially correspond to those on the map of 2 consecutive years of moderate drought, and that the 3 year *moderate drought* map is very similar to that of the 2 consecutive year severe drought. **Figure 6.1.2** (bottom right) further illustrates that 3 consecutive years of severe meteorological drought occur very seldom in South Africa, although it must be added that a longer historical record than 50 years might yield a different conclusion.

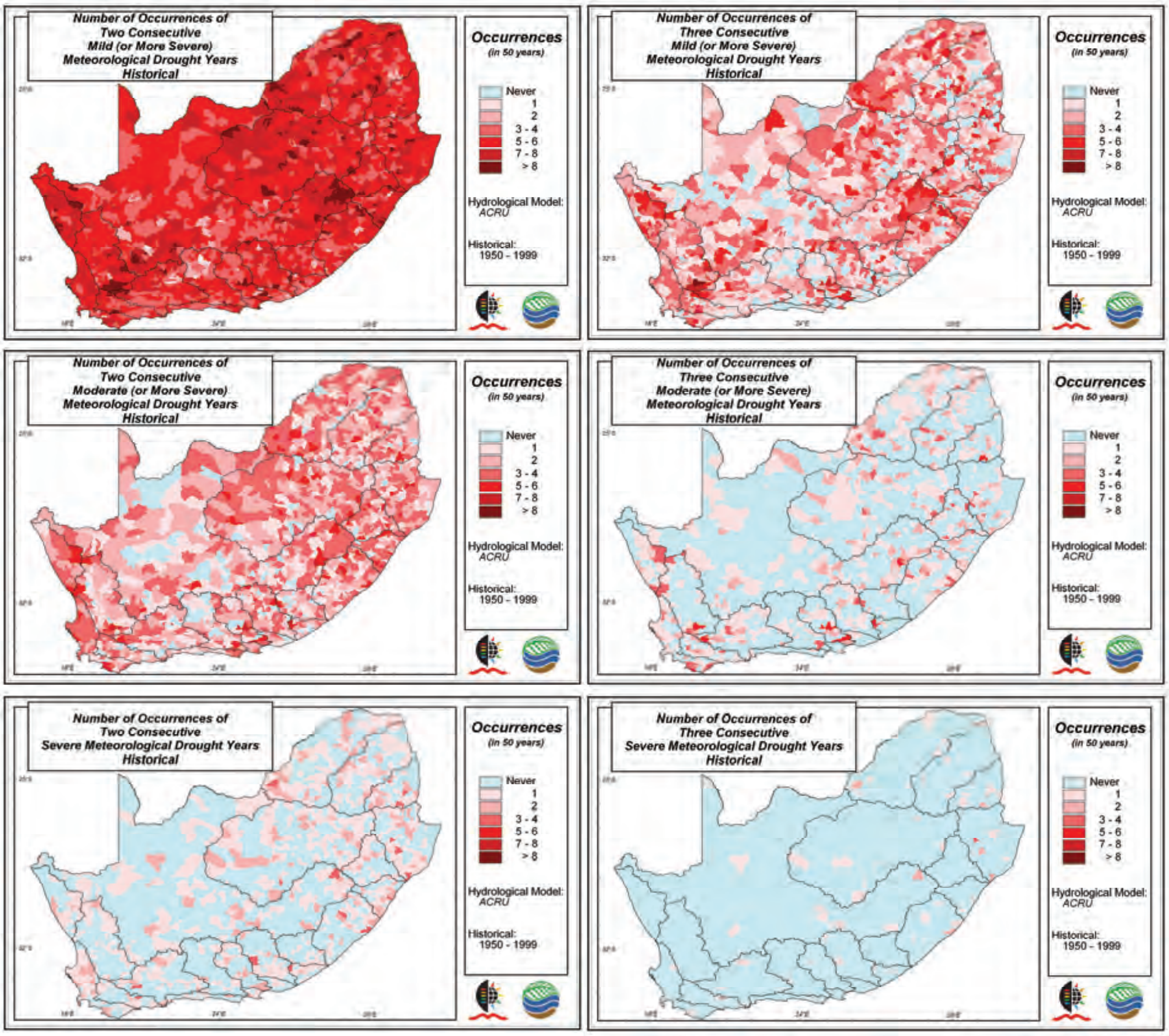

Figure 6.1.2 Number of occurrences of mild (top row), moderate (middle row) and severe (bottom row) meteorological droughts for 2 consecutive years (left column) and 3 consecutive years, derived from the 50 year historical rainfall dataset from 1950 to 1999

Ratio Changes of Future to Present Annual, Summer and Winter Season Meteorological Droughts of Different Severities, Using Output Derived from Multiple GCMs

For the assessment of projected changes in meteorological droughts under enhanced greenhouse gas conditions anticipated in future, analyses were undertaken at annual, as well as summer and winter season time periods.

The dominant feature of projected changes in *annual* meteorological droughts, as derived from multiple GCMs and shown in **Figure 6.1.3** is that, according to the methodologies used and the definitions of droughts of different severities, a *decrease* is projected over most of South Africa into the intermediate future for all three categories of drought severity. The second striking feature of anticipated changes in annual meteorological droughts shown in **Figure 6.1.3** is that in the second half of the century (in the period from the intermediate to the more distant future), a significant *increase* in especially mild and moderate droughts is projected along the west coast and, to a lesser extent, along the northern extremities of South Africa. If this increase in the latter half of this century is to materialise, there could be potentially damaging economic implications as a result of the water as well as agriculture sectors be impacted negatively.

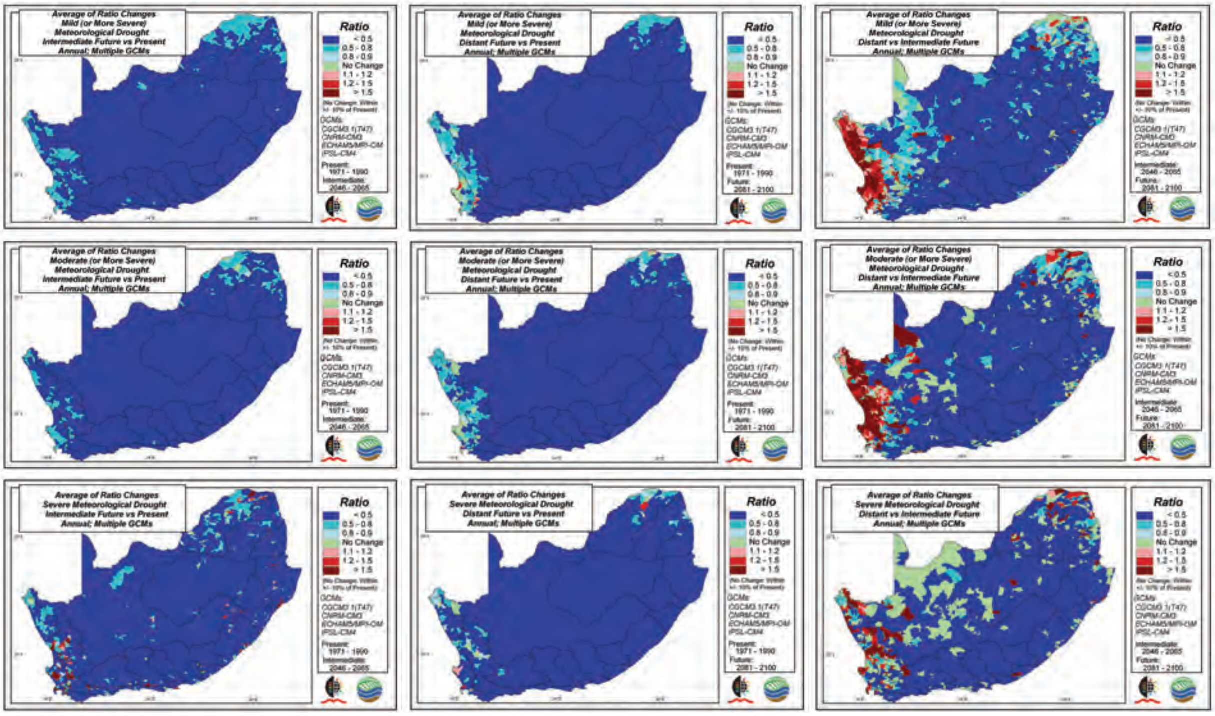

Figure 6.1.3 Ratio changes of intermediate future to present (left), more distant future to present (middle) and more distant to intermediate future (right) frequencies of annual meteorological droughts of mild (top row), moderate (middle row) and severe (bottom row) levels of severity, derived from outputs of multiple GCMs

When isolating projected changes in meteorological droughts for the s*ummer months* October to March (**Figure 6.1.4**), similar patterns to those of the annual analysis of overall decreases in droughts persist, with the exception that into the more distant future increases in moderate and severe droughts are identified from the multiple GCMs in the extreme north (in which the summer months make up the critical rainfall season) and in the southwest (its dry season). The reason for these projected increases is that in the second half of the century, i.e. during the 35 year period from the intermediate to the more distant future a significant increase in especially moderate droughts is projected to occur in the west and north of South Africa according to the multiple GCMs used (**Figure 6.1.4** right column, middle map).

When, on the other hand, only those meteorological droughts which occur in the winter months from April to September are analysed using the output from multiple GCMs (**Figure 6.1.5**), slightly different patterns of projected changes emerge in that in a ‘sea’ of projected decreases, the increases projected along the west coast of South Africa are predominantly for mild droughts and only to a lesser extent for moderate droughts (unlike summer droughts, cf. **Figure 6.1.4**)

Concluding Thoughts

Conventional thinking on changes in drought conditions in sub-Saharan Africa under climate change is that the frequency and severity of droughts (be they meteorological, agricultural or hydrological) are generally projected to increase (e.g. IPCC, 2007). This detailed analysis using daily outputs from four IPCC approved GCMs downscaled to Quinary Catchments over South Africa shows results largely at variance with that of conventional thinking in that most areas are projected to experience a reduction in meteorological droughts. What has been shown, however, is that in the second half of this century, in the period defined in this study between the intermediate future (2046 - 2065) and more distant future (2081 - 2100) substantial increases in frequencies of droughts across the range of severities are projected to be experienced along the west coast areas and, to a lesser extent, the extreme north of South Africa. This illustrates, first, the strong amplification of climate change over time (unless major greenhouse gas mitigation strategies become operational) and, secondly, that impact analyses from more GCMs and with scenarios beyond only the A2, should be used in future research. In regard to the latter, preparation of output from more GCMs and more scenarios has already commenced.

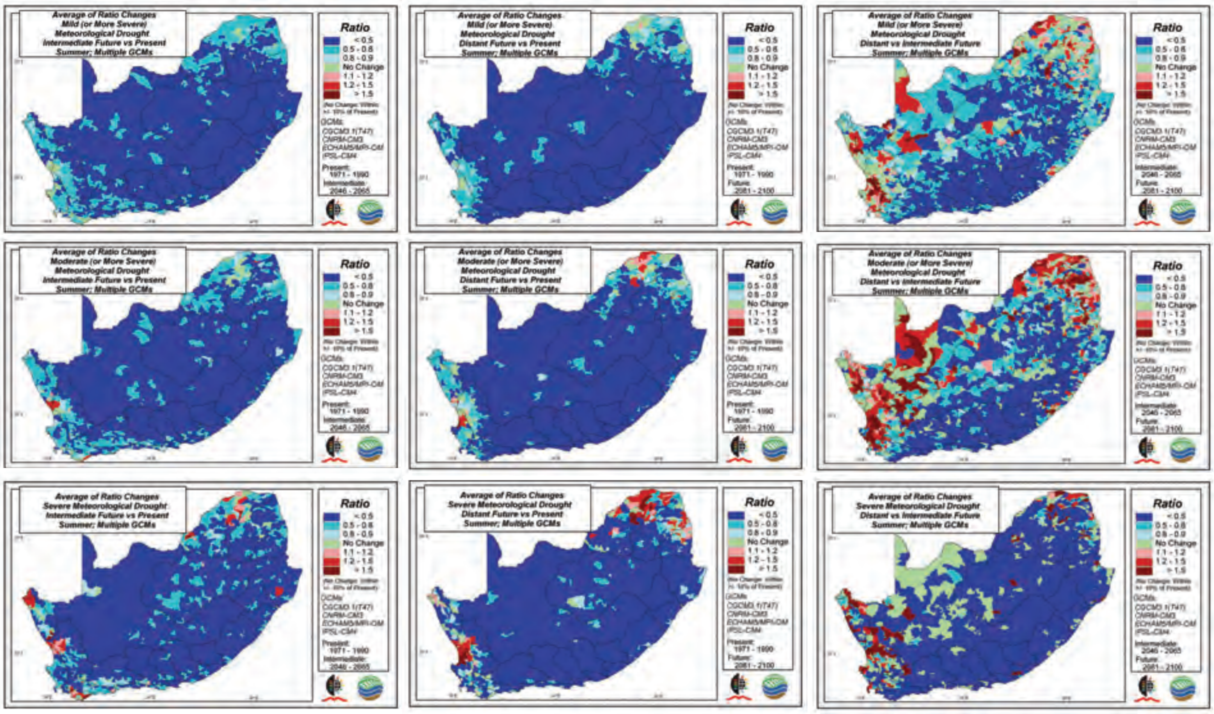

Figure 6.1.4 Ratio changes of intermediate future to present (left), more distant future to present (middle) and more distant to intermediate future (right) frequencies of summer month (October - March) meteorological droughts of mild (top row), moderate (middle row) and severe (bottom row) levels of severity, derived from outputs of multiple GCMs

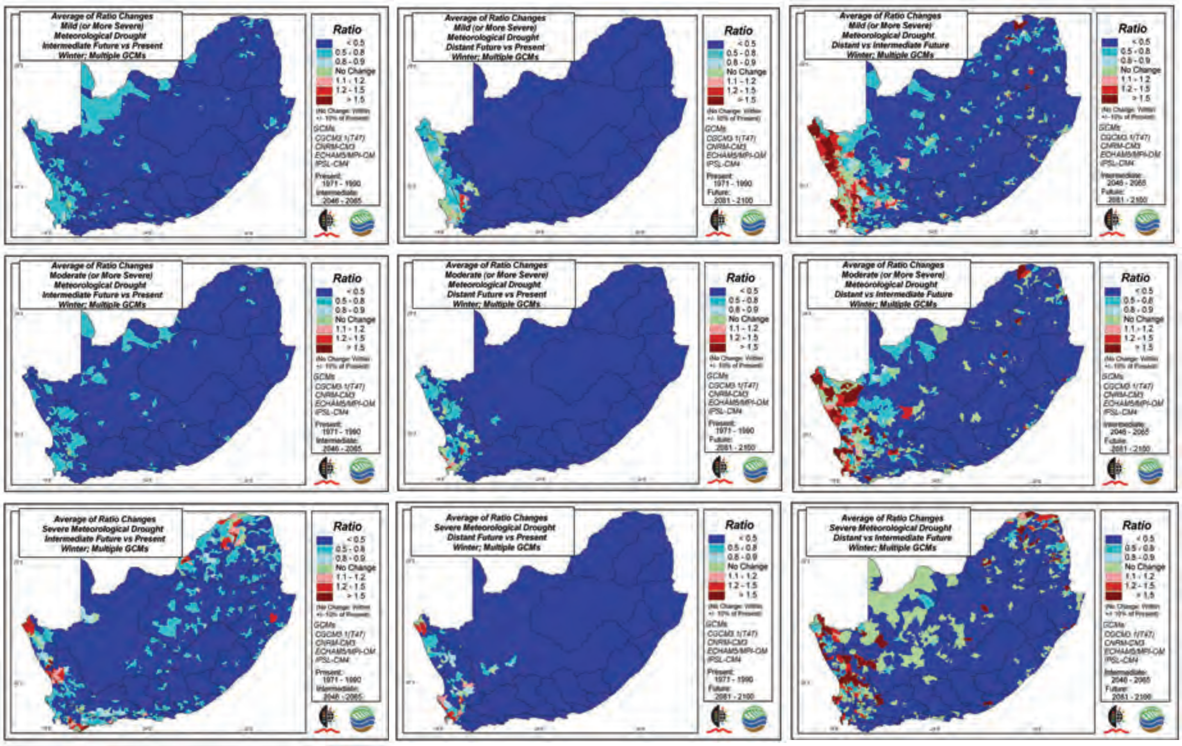

Figure 6.1.5 Ratio changes of intermediate future to present (left), more distant future to present (middle) and more distant to intermediate future (right) frequencies of winter month (April - September) meteorological droughts of mild (top row), moderate (middle row) and severe (bottom row) levels of severity, derived from outputs of multiple GCMs

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CHAPTER 6.2

CLIMATE CHANGE AND
HYDROLOGICAL DROUGHT:
A 2011 PERSPECTIVE

R.E. Schulze, D.M. Knoesen, R.P. Kunz and L.M. Bulcock

Hydrological Droughts: What are They, and How are They Different to Other Types of Drought?

This Chapter has to be read in conjunction with **Chapter 6.1** on climate change impacts on meteorological drought, because many of the basic concepts of drought addressed in that Chapter also apply to hydrological drought and not everything will be repeated here.

As already alluded to, *hydrological drought* consists of a substantial reduction in streamflows, derived from both stormflows and baseflows, in a specified area when flows are compared with long term expected conditions.

It has to be re-iterated that

- droughts are temporary phenomena from which a catchment will recover in time,
- they can be of short duration (i.e. months), up to a year in length or of multi-year duration,
- they can be of different severities, and
- can cover either extensive areas or be more local in extent.

Hydrological droughts are significantly different from either meteorological or agricultural droughts, however, with the latter two directly affecting only the specific area over which they occur, in that

- hydrological droughts can occur over a particular subcatchment, but because water cascades downstream so the accumulated effect of any drought from the entire catchment upstream of a location of concern can be felt downstream as well; furthermore,
- meteorological and agricultural droughts can be broken when relatively small amounts of rain fall whereas for a hydrological drought to be broken a threshold of rain has to fall before any significant runoff is generated; and, on the positive side,
- the onset of hydrological droughts is usually slower than those of agricultural or meteorological droughts because streamflows are made up partially of sustained baseflows which can reach a stream many months after the groundwater zone has been recharged; and
- streamflows can be stored in dams during times of high flows for release at a later stage when required, which soil moisture for plants cannot.

Methodology

As was the case with meteorological droughts, *drought duration* and *drought severity* have to be defined. For hydrological drought analyses the durations of

- historical droughts distinguished between short and longer duration droughts, where for the
  - short duration, two and three *consecutive drought months* were mapped and for the
  - longer duration, two and three *consecutive years of drought* were mapped, while for the analysis of
- impacts of climate change the durations selected were projected changes in
  - annual droughts,
  - summer season droughts (i.e. October to March) and
  - winter season droughts (i.e. April to September).

In regard to *drought severity*, the distinction in this study was again made between mild, moderate and severe droughts, where

- a period experiencing *mild* drought was defined to have occurred if that period’s streamflow was less than or equal to the 33rd percentile of that period’s series of 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)";

- a *moderate* drought was defined 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).

Further details on the methodology are elaborated upon in **Box 6.2.1**.

Box 6.2.1 Methodology for the Computation of Hydrological Drought

In order to calculate whether or not hydrological droughts are projected to occur more frequently or less frequently in the intermediate and more distant future climates, the above-mentioned thresholds for mild, moderate and severe droughts were applied to determine what magnitude would constitute a drought under present (i.e. 1971 - 1990) climatic conditions when using output derived from the each of the GCMs available in this study, *viz*. CGCM3.1(T47), CNRM-CM3, ECHAM5/MPI-OM and IPSL-CM4 (having, in the final analysis, omitted results from GISS-ER because of problems encountered in its computation of rainfall; cf. **Chapter 2.4**). The *ACRU* model (Schulze, 1995 and updates) was used for this purpose. Each of the above analyses was then also undertaken for each of the GCMs for the intermediate future (2046 - 2065) and more distant future (2081 - 2100) climate scenarios and ratio changes could between the three respective 20 year time periods could then be computed for each of the 5 838 Quinary Catchments making up South Africa. The averages of the ratio changes were then mapped in order to evaluate impacts of projected changes in hydrological droughts.

Should Hydrological Drought Analyses be Undertaken for Flows from Individual Subcatchments or for Accumulated Flows?

The fact that hydrological droughts differ from meteorological and agricultural droughts in that they may be assessed from individual subcatchments or from flows accumulated from all subcatchments upstream of a point of interest has already been alluded to. By way of example, the marked differences in flow characteristics from individual subcatchments vs. those from accumulated upstream areas are illustrated in **Figure 6.2.1**. For accumulated flows much smoother distribution patterns are evident in the map depicting lowest annual flows in 10 years (**Figure 6.2.1** top right) compared to the corresponding map from individual subcatchments (top left), while the higher flows of major rivers such as the Orange and Vaal, and to a lesser extent the Inkomati and Olifants draining towards the east or the Berg towards the northwest are clearly shown, as are the considerably lower variabilities of flows (**Figure 6.2.1** bottom right vs. bottom left), particularly of the major rivers fed by many tributaries and having their source in high rainfall mountainous areas.

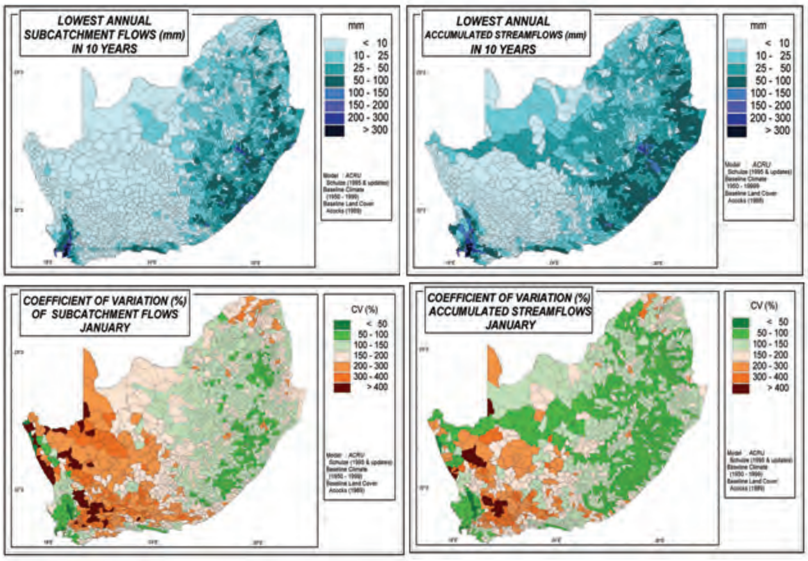

Figure 6.2.1 Flow characteristics from individual subcatchments vs. those with flows accumulated from all upstream subcatchments (Schulze, 2008)

While droughts experienced in an individual subcatchment may take on considerable significance for water demands on a local scale, for regional and national water resource planning the accumulated flows are of much greater importance. It is for this reason that the main focus in this Chapter is on drought analyses with respect to accumulated flows.

Distribution Patterns over South Africa of Frequencies of Occurrence of Two and Three Consecutive Months of Hydrological Droughts of Different Severities Derived from Baseline (Historical) Climatic Conditions

From **Figure 6.2.2**, which shows the number of occurrences of two and three consecutive months of hydrological droughts of accumulated streamflows, derived from the 50 year historical climate record with the *ACRU* model, five points are noted:

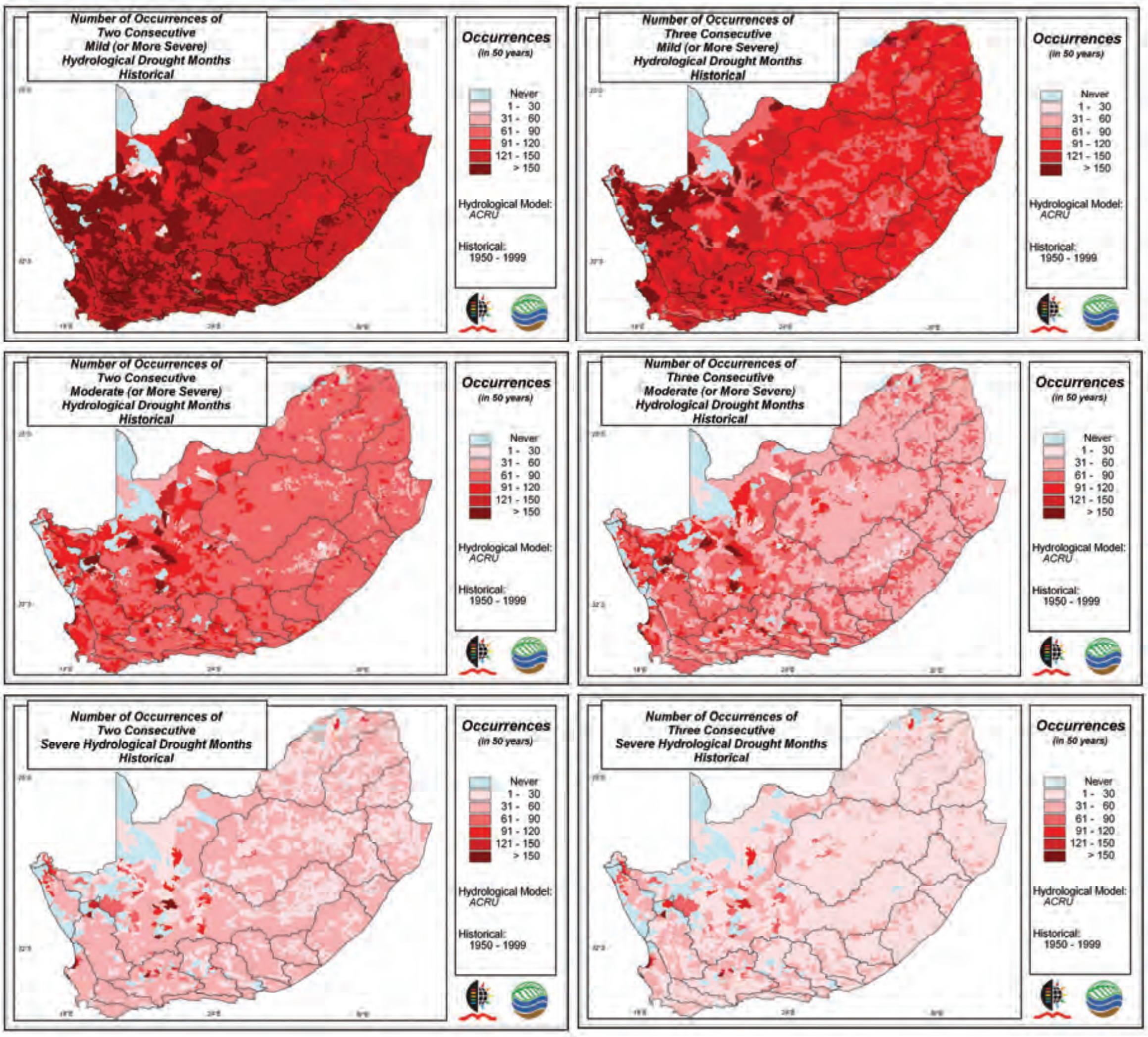

Figure 6.2.2 Number of occurrences of mild (top row), moderate (middle row) and severe (bottom row) hydrological droughts for 2 consecutive months (left column) and 3 consecutive months (right column), derived using the 50 year historical rainfall dataset from 1950 to 1999

- first, when considering 2 consecutive months of hydrological drought (**Figure 6.2.2** left column) and converting occurrences in the 50 years of simulations with historical climate records to frequencies per year, the frequencies decline from 1 - 3 per annum for *mild* droughts to < 1 - 2 for *moderate* and from once in 50 years to once a year for *severe* levels of drought;
- secondly, that 3 consecutive months of hydrological droughts (**Figure 6.2.2** right column) occur less frequently than those of 2 months' duration;

- thirdly, that hydrological droughts are experienced more frequently in the more rid west than in the wetter east, despite droughts being defined as being relative to the median streamflows experienced in an area;
- fourthly, that some areas in the hyper-arid northwest are shown as having no drought because the arid areas have runoff so seldom that drought statistics cannot be calculated; and
- fifthly, that those Quinaries with major rivers such as the Orange, Vaal, Breede, Thukela, Olifants (east) and others with their steadier flows sourced from headwaters in high rainfall areas sources in high rainfall, display lower frequencies of hydrological drought than their surrounding areas.

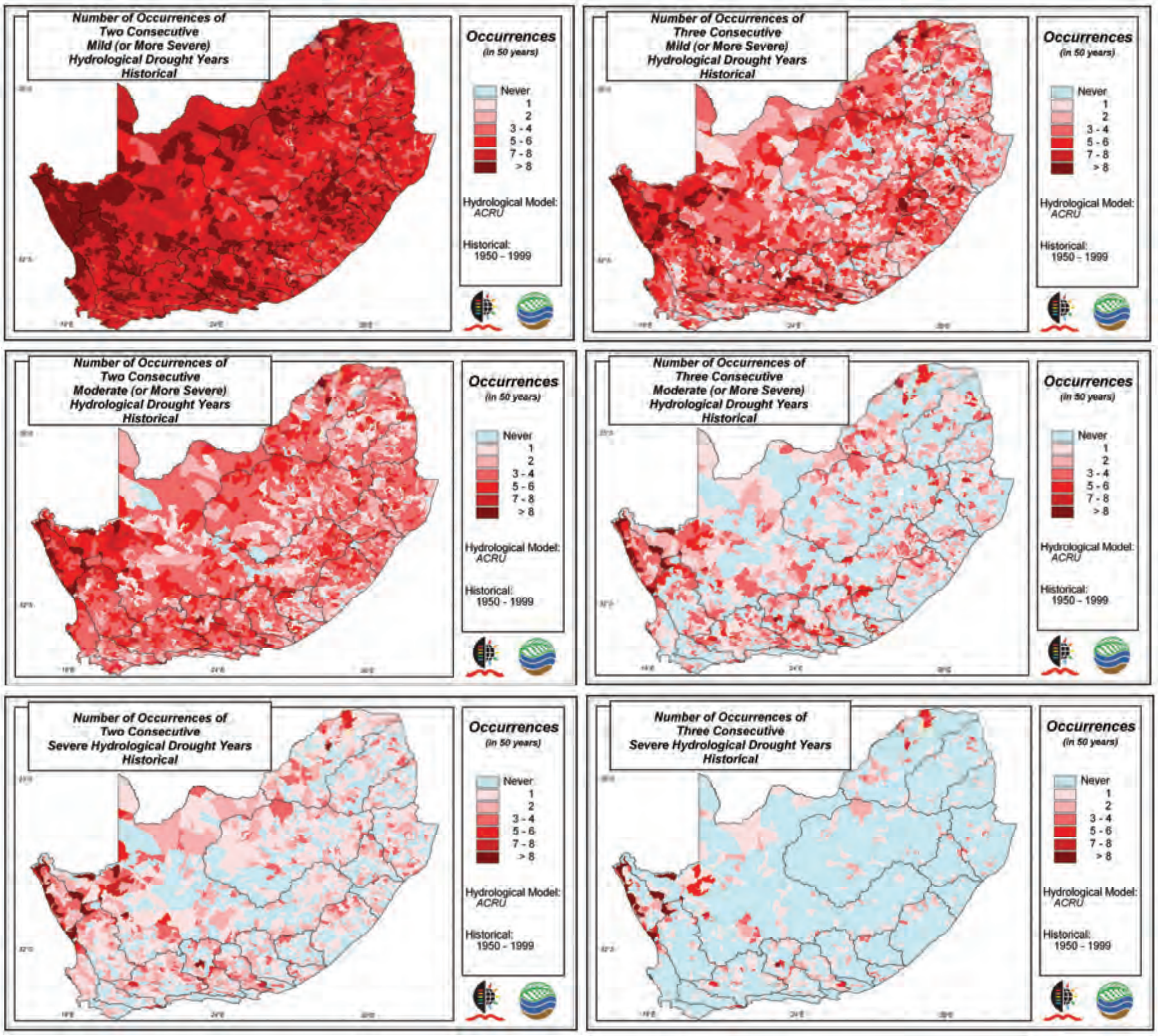

Figure 6.2.3 Number of occurrences of mild (top row), moderate (middle row) and severe (bottom row) hydrological droughts for 2 consecutive years (left column) and 3 consecutive years (right column), derived using the 50 year historical rainfall dataset from 1950 to 1999

Distribution Patterns over South Africa of Frequencies of Occurrence of Two and Three Consecutive Years of Hydrological Droughts of Different Severities Derived from Baseline (Historical) Climatic Conditions

Many large dams are designed to withstand a year's severe drought; far fewer can cope with consecutive years of drought - and least of all with three consecutive drought years or two consecutive years each experiencing a severe hydrological drought. From **Figure 6.2.3** it is seen that 2 and 3 consecutive *years* of hydrological drought occur far less frequently than 2 and 3 consecutive *months* of droughts. In the case of 2 consecutive hydrological drought years,

- *mild* droughts occur around once in 6 years in the drier west to once in 10 years in the east,

- *moderate* droughts from as infrequently as twice a century to once every 6 years,
- while 2 consecutive years of *severe* droughts have never been recorded in some areas in the 50 year period 1950 - 1999, but up to 8 times along the upper west coast.

The occurrence of 3 consecutive years of hydrological droughts is much less frequent than of 2 consecutive years. As was the case with meteorological droughts, mild 3 year droughts display similar frequencies of occurrence to moderate 2 year droughts, and moderate 3 consecutive years of droughts are similar in their distribution to 2 consecutive year severe hydrological droughts, while 3 consecutive years of severe hydrological drought has, in many parts of South Africa, never occurred in the period of record analysed, except again along the upper west coast.

Differences between Meteorological and Hydrological Drought Patterns Derived from Historical Climate Data

The clear messages from **Figure 6.2.4** (top maps) in which patterns of meteorological and hydrological droughts of the same duration (3 consecutive months) and severity (mild) are compared, is that

- hydrological droughts occur with a greater frequency their meteorological counterparts, indicating the sensitivity of runoff : rainfall relationships and the overall amplification effect of the hydrological system to rainfall;
- the amplification varies from location to location, with certain areas with a low frequency of meteorological drought exhibiting considerably higher frequencies of hydrological drought, as is the case in the southern coastal region; and
- that the degree of 'patchiness' of hydrological droughts is much greater, reflecting not only differences in precipitation patterns, but also the local influences of soil and topographic gradients.

In the bottom two maps of **Figure 6.2.4** the comparison is again between meteorological and hydrological droughts of identical duration and severity, but this time for 2 consecutive years of mild drought. Differences for longer duration droughts are somewhat more muted between the two types of drought, although there remains an amplification of meteorological droughts in the corresponding frequency of hydrological droughts.

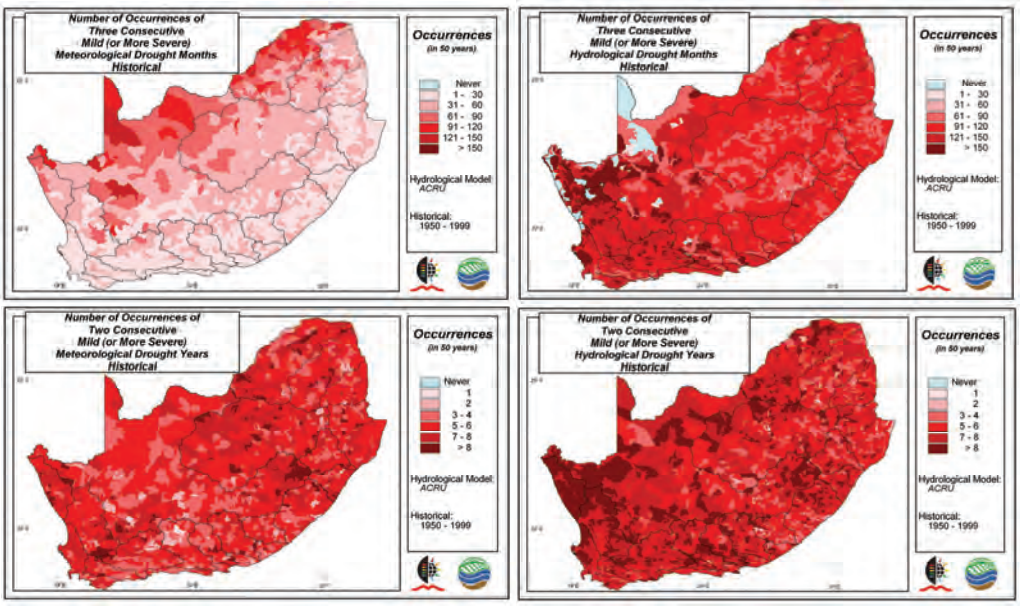

Figure 6.2.4 Comparison of 2 consecutive months (top maps) and 2 consecutive years (bottom maps) of meteorological (left column) vs. hydrological (right column) droughts of the same severity

Ratio Changes of Future to Present Annual, Summer and Winter Season Hydrological Droughts of Different Severities, Using Output Derived from Multiple GCMs

The striking features in **Figure 6.2.5** on the maps depicting averages of ratio changes of *annual* hydrological droughts derived from the multiple GCMs used in this study for mild, moderate and more severe droughts are

- the similarity between projected changes for all three levels of drought severity from the present to the intermediate future (**Figure 6.2.5** left column), the present to the more distant future (**Figure 6.2.5** middle column) and the intermediate to the more distant future (**Figure 6.2.5** middle column);
- the greater part of South Africa being projected to experience significant *reductions* in annual hydrological droughts; with, however,
- marked *increases* in annual hydrological droughts in the west, more towards the northwest up to the intermediate future and shifting towards the southwest in the more distant future;
- areas of lesser change in the north;

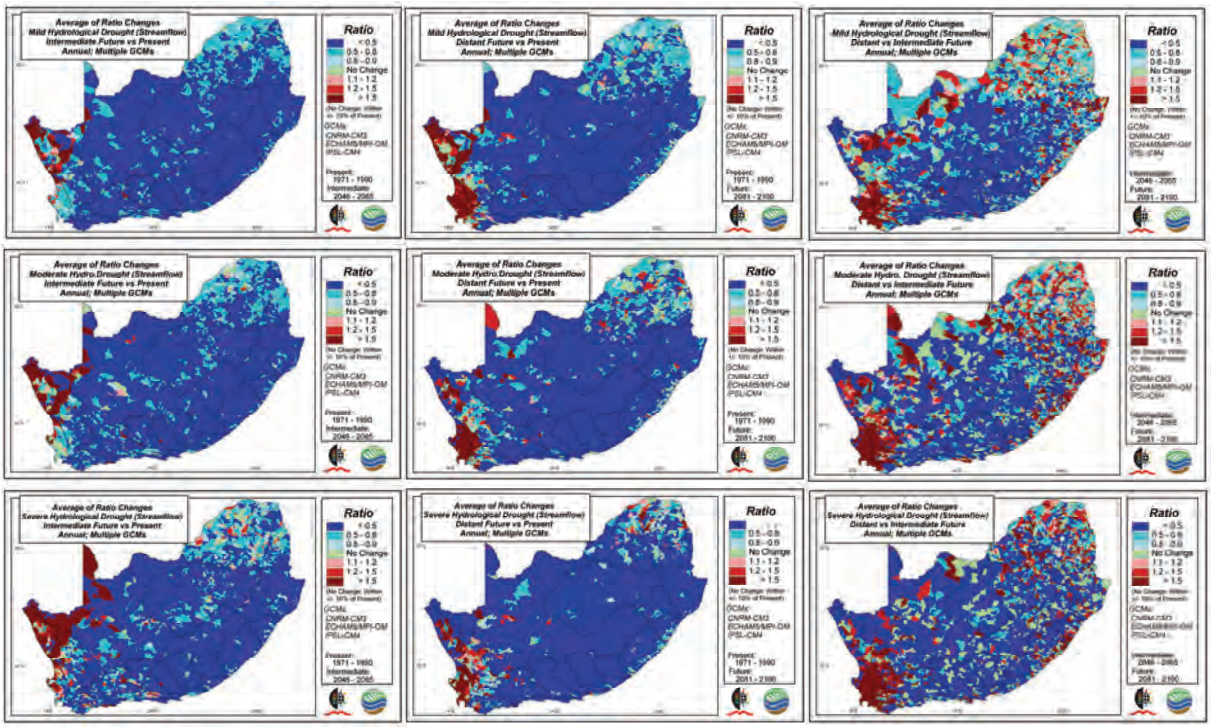

Figure 6.2.5 Ratio changes of intermediate future to present (left), more distant future to present (middle) and more distant to intermediate future (right) frequencies of annual hydrological droughts of mild (top row), moderate (middle row) and severe (bottom row) levels of severity, derived from outputs of multiple GCMs

- the geographic scatter of projected changes in annual hydrological drought occurrences in the period between the intermediate future (2046 - 2065) and the more distant future (2081 - 2100), with pockets of increases in droughts evident in the east; and
- again, the strong projected increase in annual hydrological droughts in the southwest in the latter half of this century.

The main differences between *summer season* (October to March) changes in hydrological drought patterns (**Figure 6.2.6**) and those of annual droughts above are that

- increases are projected to occur in some areas in the north in the period between the intermediate and the more distant future; and that
- increases in mild hydrological droughts are already evident in the southwest into the intermediate future.

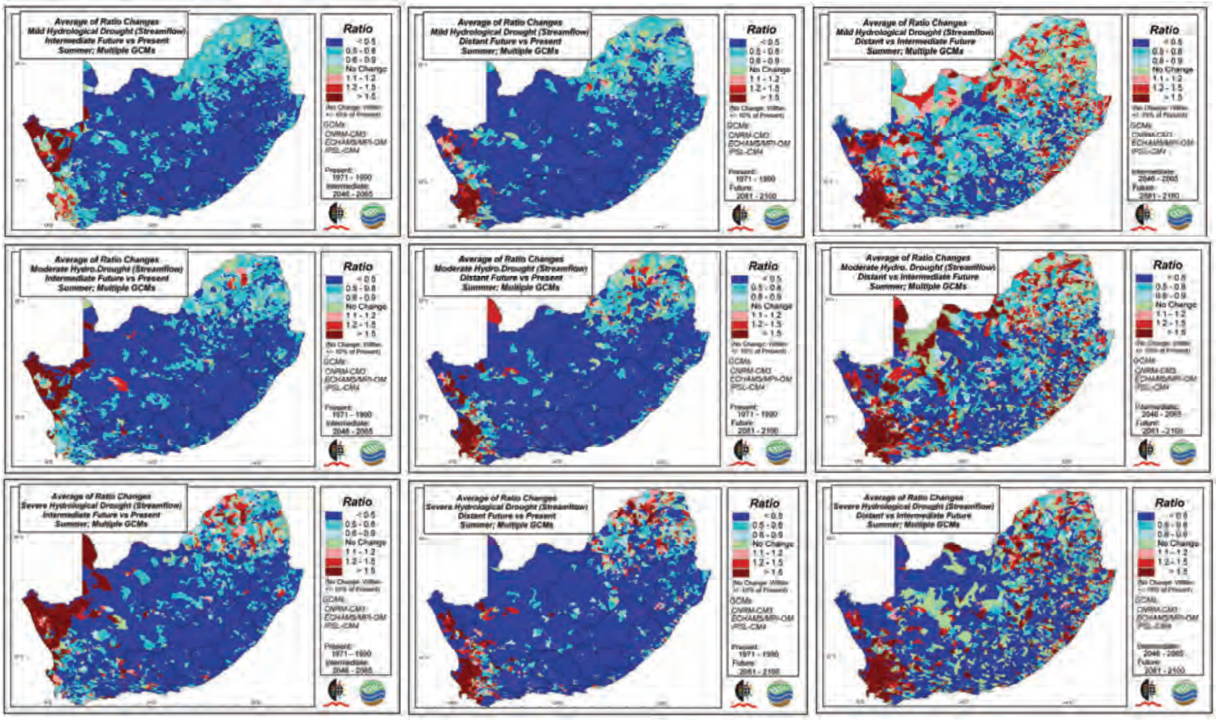

Figure 6.2.6 Ratio changes of intermediate future to present (left), more distant future to present (middle) and more distant to intermediate future (right) frequencies of summer season (October to March) hydrological droughts of mild (top row), moderate (middle row) and severe (bottom row) levels of severity, derived from outputs of multiple GCMs

There appear relatively few marked patterns of change between winter season (April to September) hydrological droughts shown in **Figure 6.2.7** and those in summer (**Figure 6.2.6**), the main being

- an intensification of drought increases in the east in the latter half of the century, albeit the patterns are still patchy; and
- a slight expansion of areas projected to experience increases in hydrological droughts in the southwest.

Are there Significant Differences in Spatial Patterns of Projected Changes in Meteorological and Hydrological Droughts with Respect to Future Management of Water Resources?

The short answer to the above question is a definite ‘yes’, as illustrated in **Figure 6.2.8**, which shows projected ratio changes averaged from output of multiple GCMs for droughts of moderate severity into the future for meteorological droughts (top maps) and hydrological droughts, distinguishing in the case of the latter between droughts computed for individual Quinary Catchments (**Figure 6.2.8** middle row) and those showing streamflows accumulated from all Quinaries upstream of any given Quinary (**Figure 6.2.8** bottom row). The message is clear that changes in hydrological droughts may, in critical areas of concern such as the southwestern regions of South Africa, show *increases* in frequencies of occurrence into the future where the meteorological droughts of the same duration and severity show *decreases* into the future.

Are there Important Differences in Spatial Patterns of Projected Changes in Hydrological Droughts between Individual Subcatchment Runoff and Accumulated Streamflows?

In answer to this question, the information in **Figure 6.2.8** again refers. In some cases changes hydrological droughts from individual subcatchments display consolidated areas of increases which the accumulated flows do not (e.g. in the west for changes from the present into the intermediated future, **Figure 6.2.8** left column, middle vs. bottom maps). In other cases, on the other hand, the opposite occurs with projected increases to accumulated flows more consolidated over an area than projected increases in the corresponding hydrological droughts from individual subcatchments (e.g. in

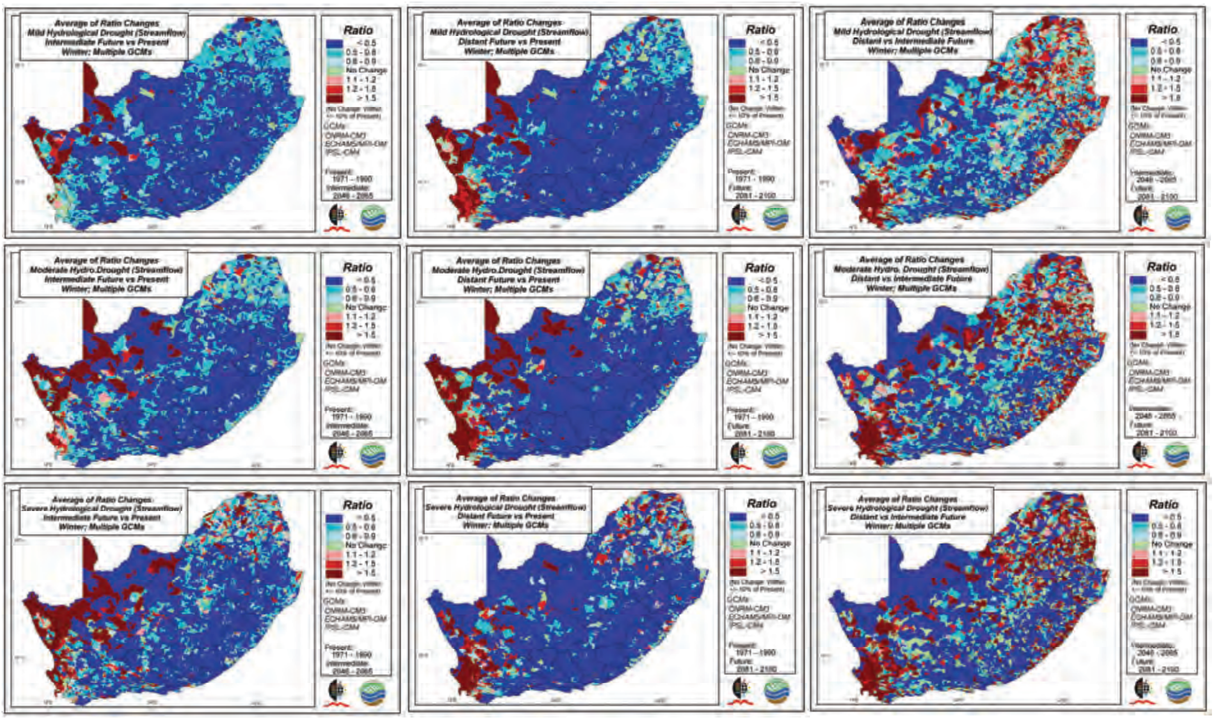

Figure 6.2.7 Ratio changes of intermediate future to present (left), more distant future to present (middle) and more distant to intermediate future (right) frequencies of winter season (April to September) hydrological droughts of mild (top row), moderate (middle row) and severe (bottom row) levels of severity, derived from outputs of multiple GCMs

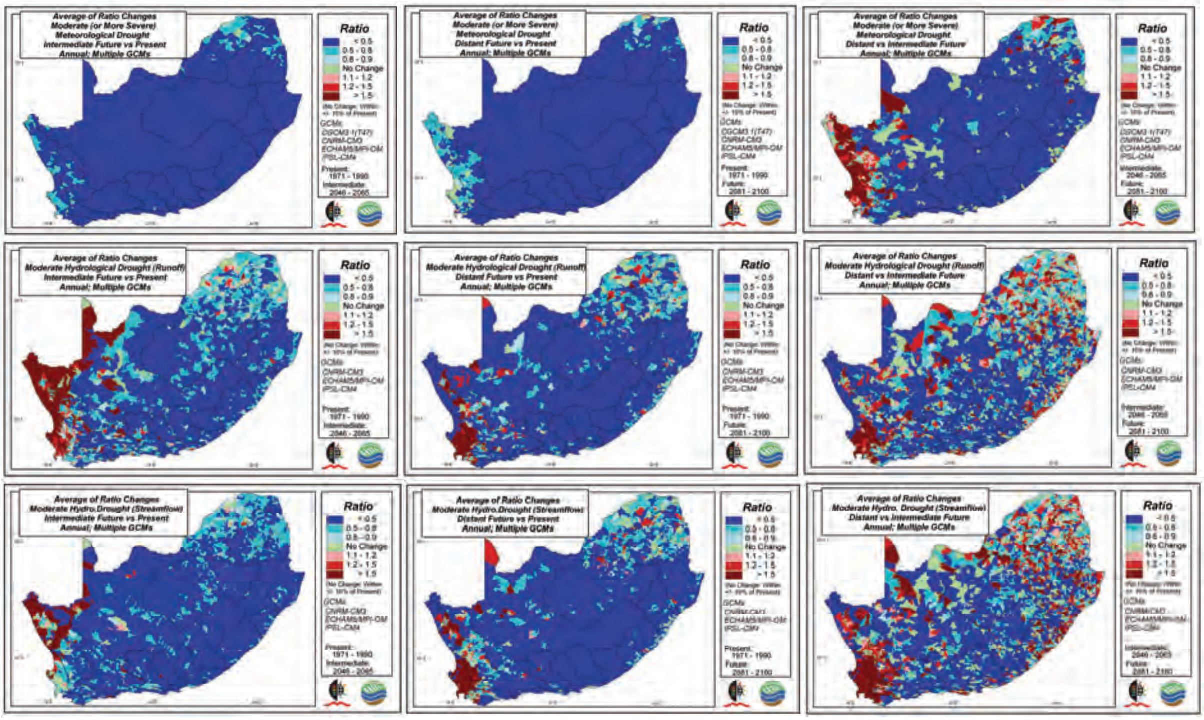

Figure 6.2.8 Ratio changes of intermediate future to present (left column), more distant future to present (middle column) and more distant to intermediate future (right column) frequencies of annual meteorological droughts of moderate severity (top row) and hydrological droughts of the same duration and severity from individual subcatchment runoff (middle row) and from accumulated streamflows (bottom row), derived from outputs of multiple GCMs

the west for changes from the intermediated into the more distant future, **Figure 6.2.8** right column, middle vs. bottom maps).

No definitive statement can thus be made in this regard, and differences therefore have to be treated on a case by case basis.

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SECTION 7

PROJECTED CHANGES TO EXTREME HYDROMETEOROLOGICAL EVENTS

CHAPTER 7.1

CLIMATE CHANGE AND
SHORT DURATION DAY DESIGN RAINFALL:
A 2011 PERSPECTIVE

D.M. Knoesen, R.E. Schulze and J.C. Smithers

Background to Design Rainfall Analysis

There are many types of hydraulic engineering and conservation structures (such as culverts, dam spillways or reticulation for drainage) which need to be designed to accommodate peak floods of a certain magnitude in order to function safely at a given level of risk. Should the structures fail, there are potential economic, environmental and societal consequences. Hence, flood frequency analysis is of great importance (Smithers and Schulze, 2003). Models of peak discharges and flood volumes, however, require inputs of so-called “extreme” rainfall that may be expected to occur only very infrequently, e.g. with recurrence intervals of 5 or 10 or 50 years, depending on the importance of the structure. Climate change, by expected “energizing” of the earth’s atmosphere through increases in temperature and resultant perturbations to rainfall regimes, including increases to rainfall variability, may lead to increases in the intensity and frequency of extreme rainfall events of both short duration (this Chapter) and long duration (**Chapter 7.2**) and, with that, associated flooding (IPCC, 2007; cf. **Chapter 7.3**). These projected increases might, consequently, have serious repercussions on the design of hydraulic structures.

Because reliable estimates of flood frequencies based on long time series of good quality observed streamflow data are seldom possible at the site of interest, rainfall based methods of flood frequency estimations therefore usually have to be resorted to. This requires a probabilistic approach to analysing rainfall for design purposes. The term “design rainfall” is then used to describe the

- *depth* (i.e. magnitude, in mm) of rainfall, for a critical
- *duration* (e.g. 5 minutes, or 1 day), which depends on the size of the catchment, for a desired
- *frequency* of recurrence (e.g. statistically once in 10 or once in 50 years, depending on the size and economic importance of the structure), commonly referred to as the return period, with this design rainfall then used to generate design flood hydrographs (Smithers and Schulze, 2003).

This analysis is commonly termed a “DDF” analysis.

Many statistical methods of deriving rainfall DDF have been used in South Africa (cf. review in Smithers and Schulze, 2003), most of them before 2000 utilising at-site design rainfall values (i.e. at a raingauge), but with post-2000 South African studies using more robust regional techniques applying L-moments (Smithers and Schulze, 2000a; 2000b; 2003).

In this Chapter short duration design rainfall, i.e. for durations < 24 hours and down to 5 minutes, is covered. An outline the methodology, first in general concept (**Box 7.1.1**) followed by the methodology used for historical records (**Box 7.1.2**) and then for GCM based climate projections (**Box 7.1.3**) is followed by an interpretation results. **Chapter 7.2** covers long duration design rainfall.

Box 7.1.1 Methodology for the Computation of Short Duration Design Rainfall: Background

In order to understand how storm intensities might change, short duration design storm magnitudes were calculated. The IPCC (2007) statement that rainfall intensities are projected to increase as a result of global warming is, however, based on a relatively simplistic assumption that intensity can be calculated by dividing the annual rainfall by the number of raindays per year. A study of trends in daily climate extremes over southern and western 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 more 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

Box 7.1.1 Methodology for the Computation of Short Duration Design Rainfall: Background (continued)

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 future to present climate scenarios, and the more distant future to present climates. Results in this section are therefore an indication of potential changes in short duration design rainfall in general.

Box 7.1.2 Methodology for Short Duration Design Rainfall Calculation for Historical Rainfall

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 in order 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.

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 seven relatively homogeneous regions identified by Smithers and Schulze (2003) and shown in **Figure 7.1.1**. The mean for the 24 hour AMS is estimated as shown in **Equation 7.1.1** from the one day mean of the AMS and regionalised 24 hour : 1 day ratios (Smithers and Schulze, 2003).

$$L\_1_{24\,hour} = L\_1_{1day}\ x\ Ratio_{24\,hour:1day} \qquad (\mathbf{7.1.1})$$

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. from 5 minutes to 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 7.1.2** for Regional Cluster 1.

Thus, knowing the mean of the AMS for the required duration, design rainfall depths are calculated using **Equation 7.1.2**.

$$DRE_{i,j} = GC_{1day.j}\ x\ L\_1_{i} \qquad (\mathbf{7.1.2})$$

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*, as estimated from the above procedures.

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

Box 7.1.2 Methodology for Short Duration Design Rainfall Calculation for Historical Rainfall (continued)

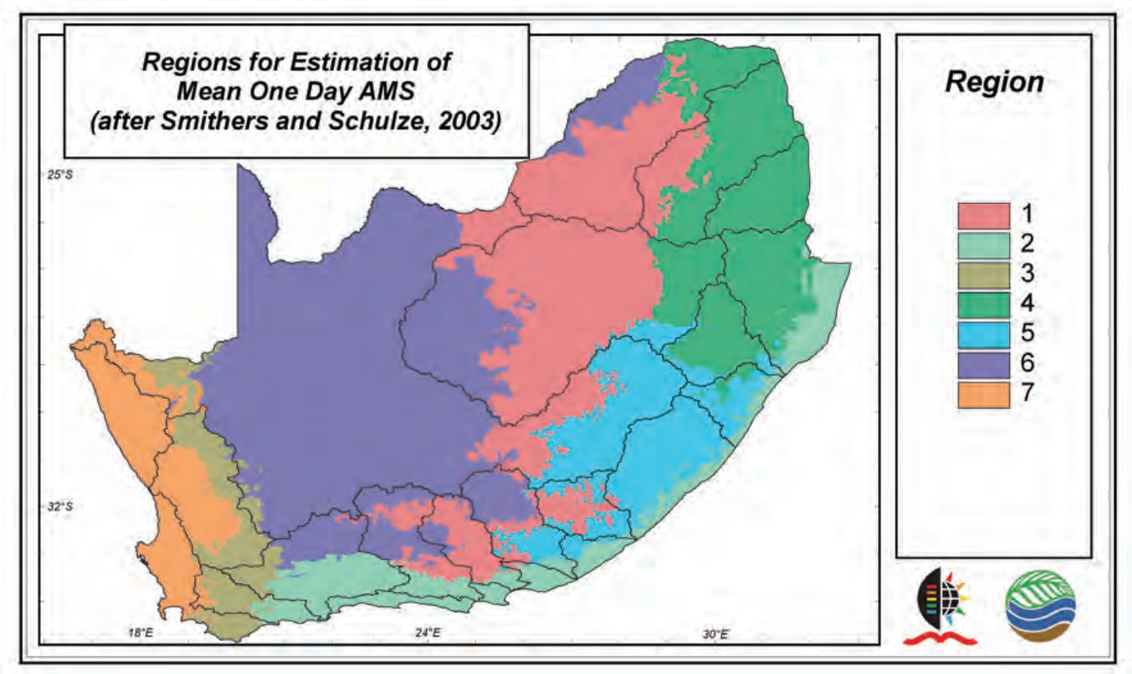

Figure 7.1.1 Relatively homogenous regions used for the estimation of the mean of the one day AMS for any location in South Africa (After Smithers and Schulze, 2003)

Box 7.1.3 Methodology for Short Duration Design Rainfall Calculation from GCM 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 of 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 7.1.2**, 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 focused 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. the 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 7.1.1**) 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.

Box 7.1.3 Methodology for Short Duration Design Rainfall Calculation from GCM Rainfall (continued)

As shown in **Figure 7.1.3**, the slopes calculated from the intermediate and future climates are similar to those calculated from the present climate, with only the derivations from 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.

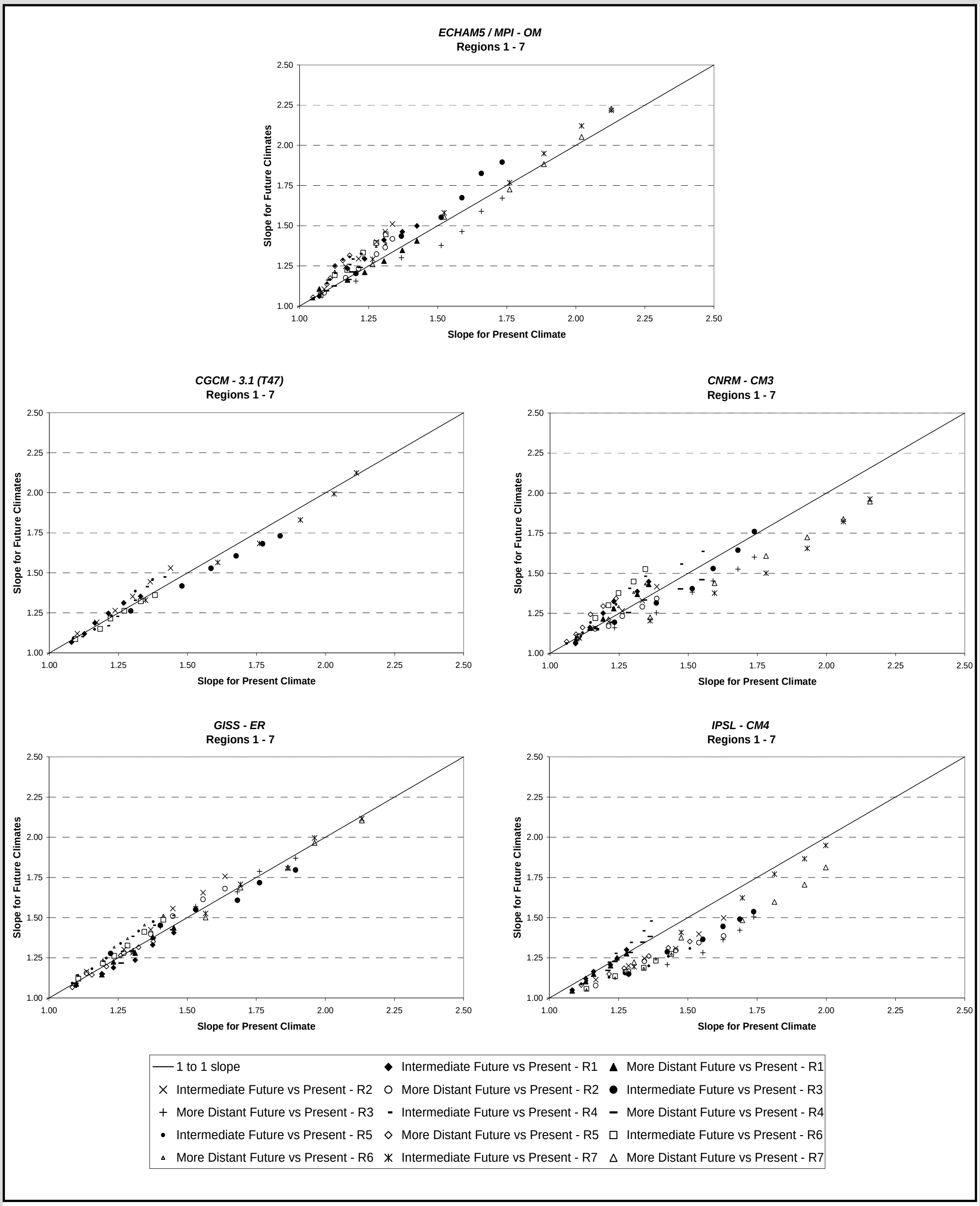

Figure 7.1.2 Example of the scaling of the AMS for a selected regional cluster (Knoesen, 2011; based on Smithers and Schulze, 2003)

Box 7.1.3 Methodology for Short Duration Design Rainfall Calculation from GCM Rainfall (continued)

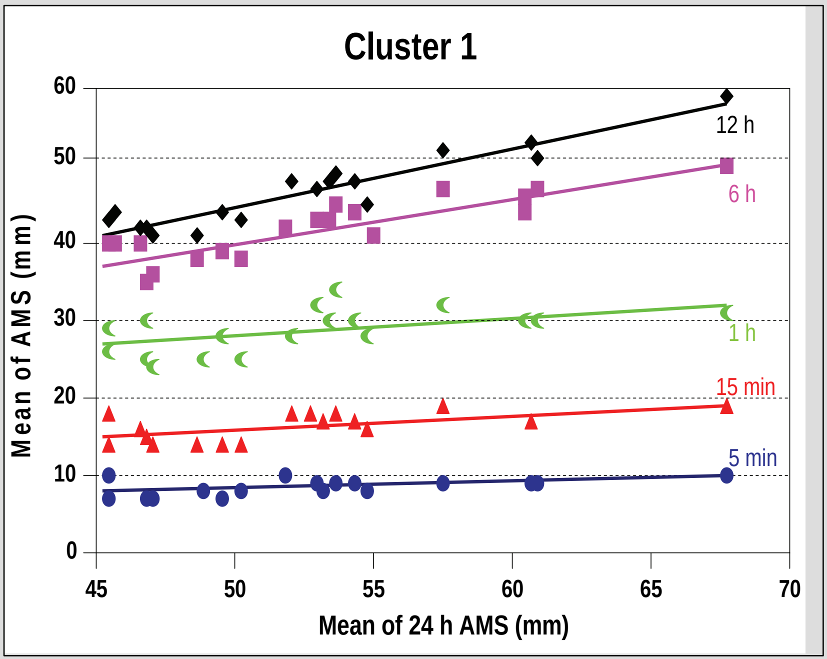

Figure 7.1.3 Comparison of intermediate future and more distant future (where applicable) scaling relationships to present climate scaling relationships for Region 1 in South Africa, calculated from GCM rainfall output

An Example of the Distribution Patterns over South Africa of Short Duration Design Rainfall under Baseline (Historical) Climatic Conditions

Because of the wide range of durations from minutes to 24 hours, and the range of return periods, only one example of short duration design rainfall is illustrated, *viz*. for the 2 year return period rainfall of 30 minutes' duration (**Figure 7.1.4**). It shows the same broad trend as annual rainfall maps with high values in the east, tapering off towards the west, but without the high values in the southwest, which generally receives low intensity fontal rainfall of long duration, even for its more extreme rains.

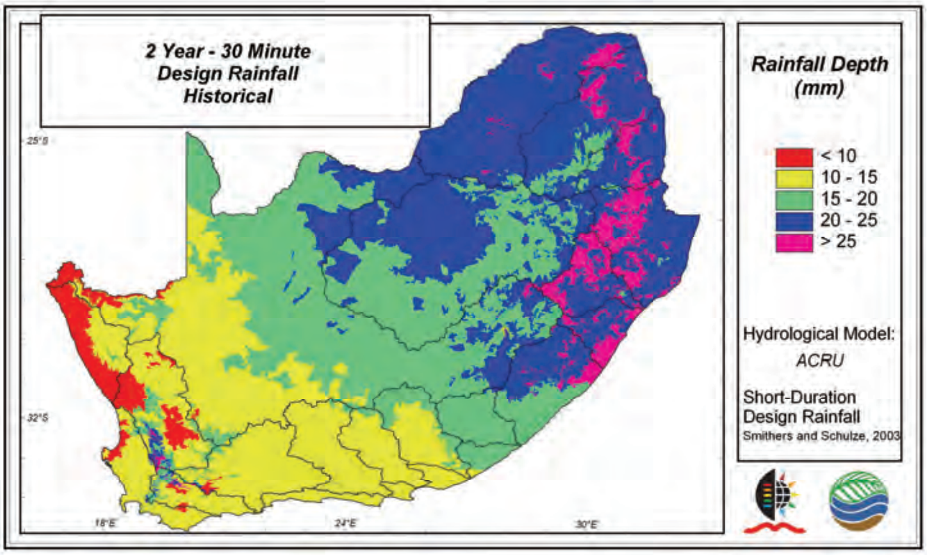

Figure 7.1.4 Distribution patterns of the 2 year return period rainfall for a 30 minute duration, for baseline (historical; 1950 - 1999) climatic conditions (Source Information: Smithers and Schulze, 2003)

Averages of Ratio Changes in Short Duration Design Rainfall under Future Climate Scenarios, Using Output from Multiple GCMs

Figure 7.1.5 (top) shows that overall across South Africa an increase up to 10 % in short duration design rainfalls may be expected by the intermediate future, with patches south of 32 °S and north of 27 °S where the models show no discernible change from the present.

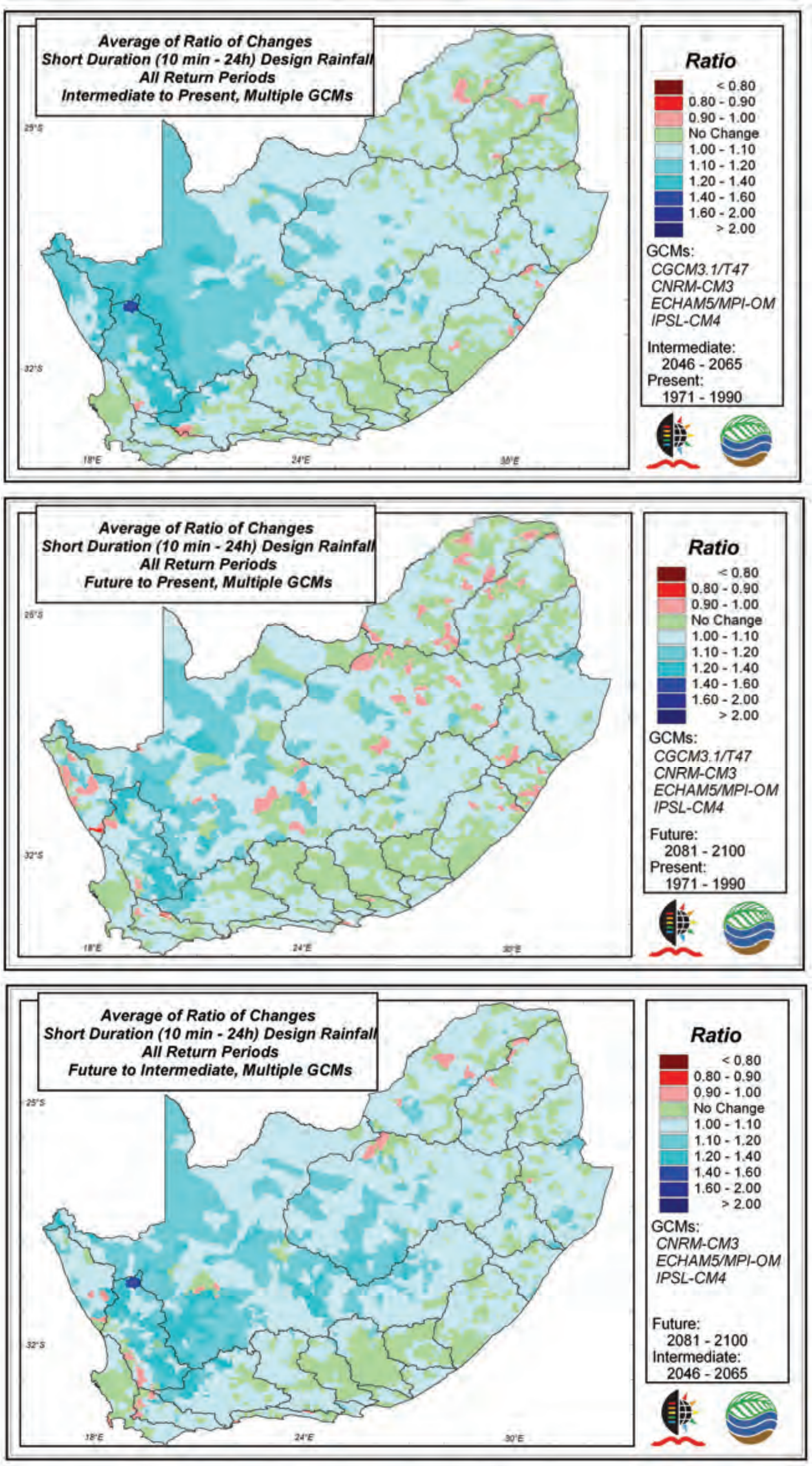

Figure 7.1.5 Averages of ratio changes in short duration design rainfall between intermediate future and present (top), more distant future and present (middle) and distant and intermediate future (bottom) climate scenarios, using outputs from multiple GCMs

Of note is the high projected change in short duration design rainfall in the area transitional between the summer and winter rainfall areas, where increases up to 40 % are projected. Changes from the present into the more distant future (**Figure 7.1.5** middle) as well as in the 3.5 decades between the intermediate and more distant future climate scenarios (**Figure 7.1.5** bottom), show similar patterns, but with the increases, where they are displayed, somewhat more muted.

These results indicate that adjustments to future hydrological designs which are based on short duration "extreme" rainfalls may already be warranted at this point in time, given that such structures have a design life of 50 years and more, and already the City Engineers' Departments of eThekwini (Durban) and Cape Town are planning on taking the above results into account in future stormwater design (Schulze *et al*., 2010a; 2010b).

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CHAPTER 7.2

CLIMATE CHANGE AND
LONG DURATION DAY DESIGN RAINFALL:
A 2011 PERSPECTIVE

R.E. Schulze, D.M. Knoesen and J.C. Smithers

Recapping Some Concepts on Design Rainfall Analysis

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. 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 term “design rainfall” is then used to describe the

- *depth* (i.e. magnitude, in mm) of rainfall, for a critical
- *duration* (e.g. of long duration such as one to seven days, which are important when considering designs on larger catchments, for multiple day flooding and for regional damage assessments), for a desired
- *frequency* of recurrence (e.g. once in 10 or in 50 years, depending on the size and economic importance of the structure, where frequency of recurrence is commonly referred to as the return period and where a return period of, say, 10 years implies a statistical probability of recurrence once in 10 years or 10 times in 100 years, and not that it will recur regularly every 10 years.

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 Chapter on long duration (one to seven days) design rainfall proceeds first with a summary of the methodology in **Box 7.3.1** (many aspects of the full methodology having been given in **Chapter 7.1**, **Box 7.1.2**. This is followed by an interpretation of historical long duration design rainfalls over South Africa for selected return periods and durations and then an assessment of projected changes in long duration design rainfall with climate change based on output from multiple GCMs.

Box 7.2.1 Methodology for the Computation of Long Duration Design Rainfall

In this study historical estimates of design rainfalls of long duration are computed using the 50 year daily rainfall datasets of the Quinary Catchments database (**Chapter 2.2**; Lumsden *et al.*, 2010; Schulze and Horan, 2010). For the climate change assessment the daily rainfalls for the present (1971 - 1990), the intermediate future (2046 - 2065) and distant future (2081 - 2100) scenarios from each of the GCMs used for this study, downscaled to Quinaries, were used. The *annual maximum series* (AMS), i.e. the largest value of each year of record of rainfall on one day, two consecutive days, three and seven consecutive days was used for further statistical analysis with the three parameter Log-Pearson Type III extreme value distribution (Kite, 1988) to determine design rainfalls for selected durations and return periods. 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 has been given in **Box 7.1.2** in **Chapter 7.1** and is not repeated here.

Distribution Patterns over South Africa of One, Three and Seven Day Design Streamflows for a Range of Return Periods under Baseline (Historical) Climatic Conditions

In order to set the scene, long duration design rainfalls are shown in **Figure 7.2.1** for the 2, 5, 10, 20, 50 and 100 year return periods, with low values in shades of dark red (< 25 mm) grading through lighter reds, light green and then light to dark blues (> 500 mm) for the highest values.

- The figure illustrates that, as expected, design rainfalls increase with duration from the one to the two, three and seven day durations while at the same time increasing with return period from the 2 to 5, 10, 20, 50 to 100 year return periods.
- For example, one day 2 year design rainfalls (**Figure 7.2.1** top left) range from < 25 mm in the arid west to > 100 mm along the east coast, while for the seven day 100 year return period a substantial area along the east coast and parts of the mountainous areas of the southwest and the Drakensberg can, on statistical average, expect rains of > 400 mm and even 500 mm to fall.

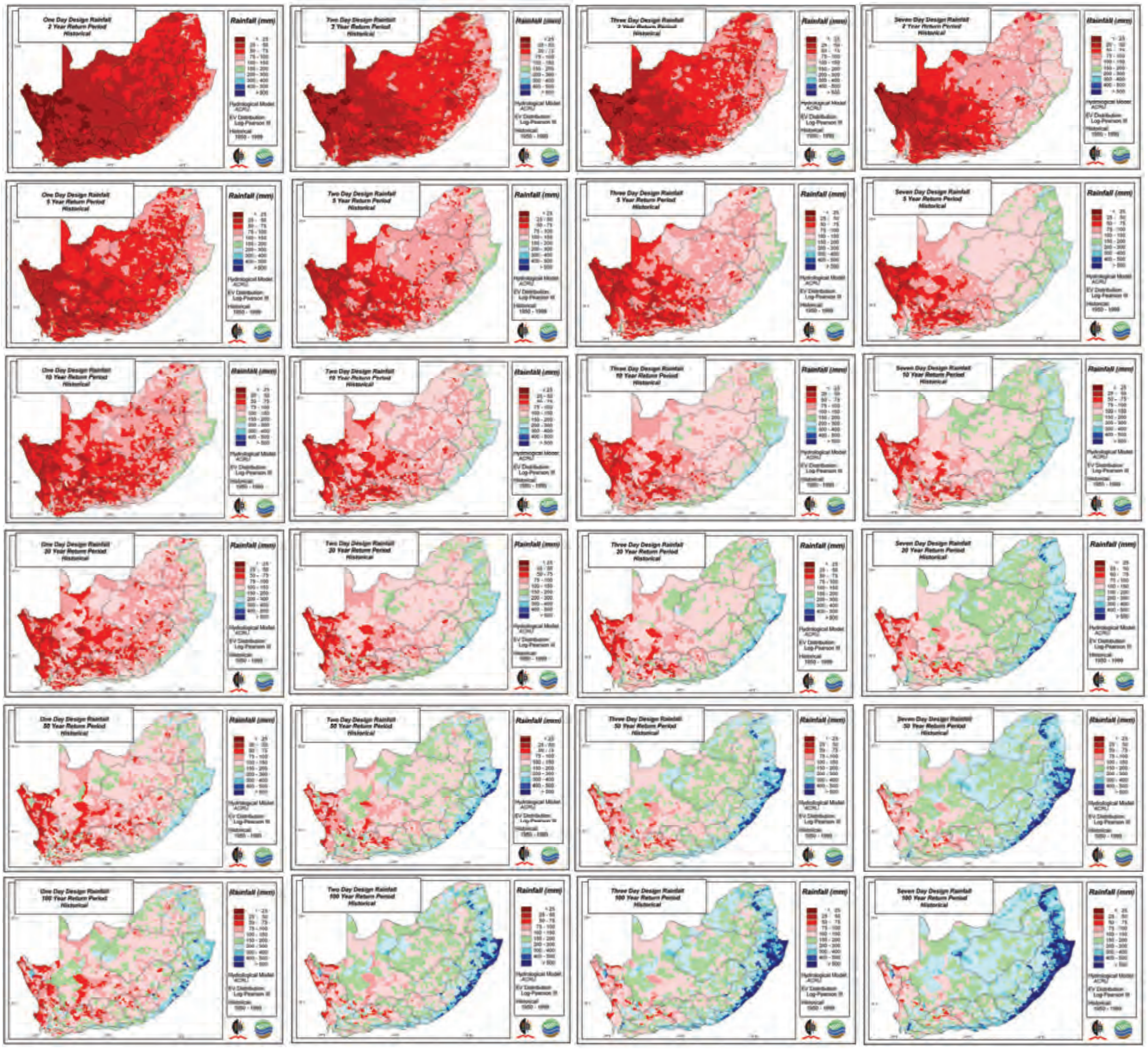

Figure 7.2.1 Design rainfalls (in mm) over South Africa for one day (left column), two day, three day and seven day durations (right column) for the 2 year return period (top row), as well as the 5, 10, 20, 50 and 100 year return period (bottom row), computed for baseline (historical; 1950 - 1999) climatic conditions

Ratio Changes of Future to Present Design Rainfalls of Long Duration with Climate Change, Using Outputs from Multiple GCMs

Averages of ratio changes of intermediate future to present one, two, three and seven day design rainfalls for the 2, 5, 10 and 20 year return periods, derived from output of multiple GCMs are shown in **Figure 7.2.2**. Note that for these assessments of changes in design rainfalls of long duration over South Africa under projected climate change conditions, only return periods up to 20 years are shown, because outputs from the multiple GCMs used in this study were only for 20 year time slices (present from 1971 -1990, intermediate future from 2046 - 2065 and more distant future from 2071 - 2100) and extrapolations of extremes beyond the length of a record tend to result in large errors.

The following main points stand out in **Figure 7.2.2**:

- The overall picture over much of South Africa is that of a 10 to 20 % increase in design rainfalls of long duration.
- For low return periods (e.g. 2 years) this increase is most pronounced in the hinterland of the west coast in the transitional area between the winter and summer rainfall regions where inconsistencies are expected as climate changes.
- Generally, also, for a given return periods (e.g. 5 years) there is an intensification of the increases in design rainfalls as the duration increases from one to seven days, indicative of higher long duration rainfall events in future climates.
- For one and two day design rainfalls there are patches especially in the northeast where decreases in design rainfalls are projected - more so for the two than the one day duration. These areas of projected decreases expand with return period.
- Also, and especially for the two day duration, the southwestern and southern Cape display decreases in design rainfalls, with these areas becoming more pronounced the higher the return period.

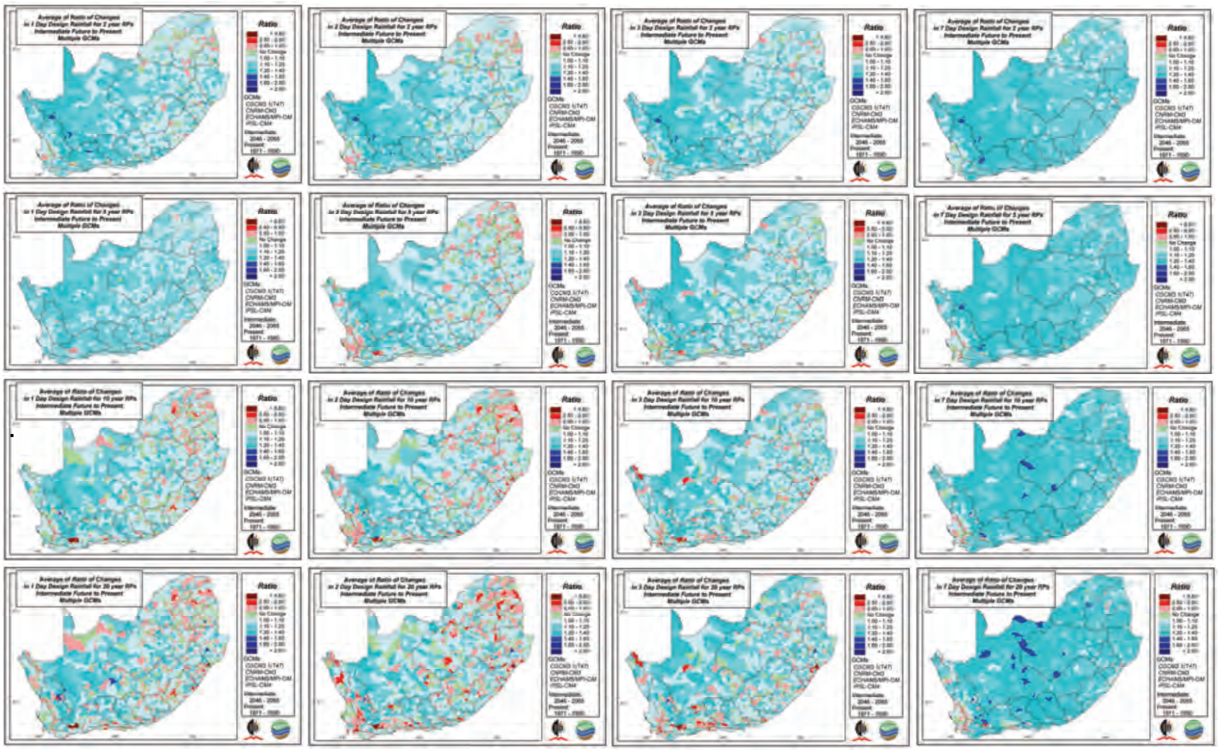

Figure 7.2.2 Averages of ratio changes of intermediate future to present one day (left column), two, three and seven day (right column) design rainfalls for the 2 year return period (top row), as well as the 5, 10 and 20 year return period (bottom row), derived from output of multiple GCMs

Ratio changes of design rainfalls of long duration between the more distant future and present are shown in **Figure 7.2.3**. While for low return periods the transitional area between the winter and summer rainfall still displays highest increases in design rainfalls, patterns of change appear more patchy than for the intermediate future, possibly because there is greater uncertainty in projections into the more distant future. Important to note is that in the more distant future the areas of projected decreases in design rainfalls become more pronounced.

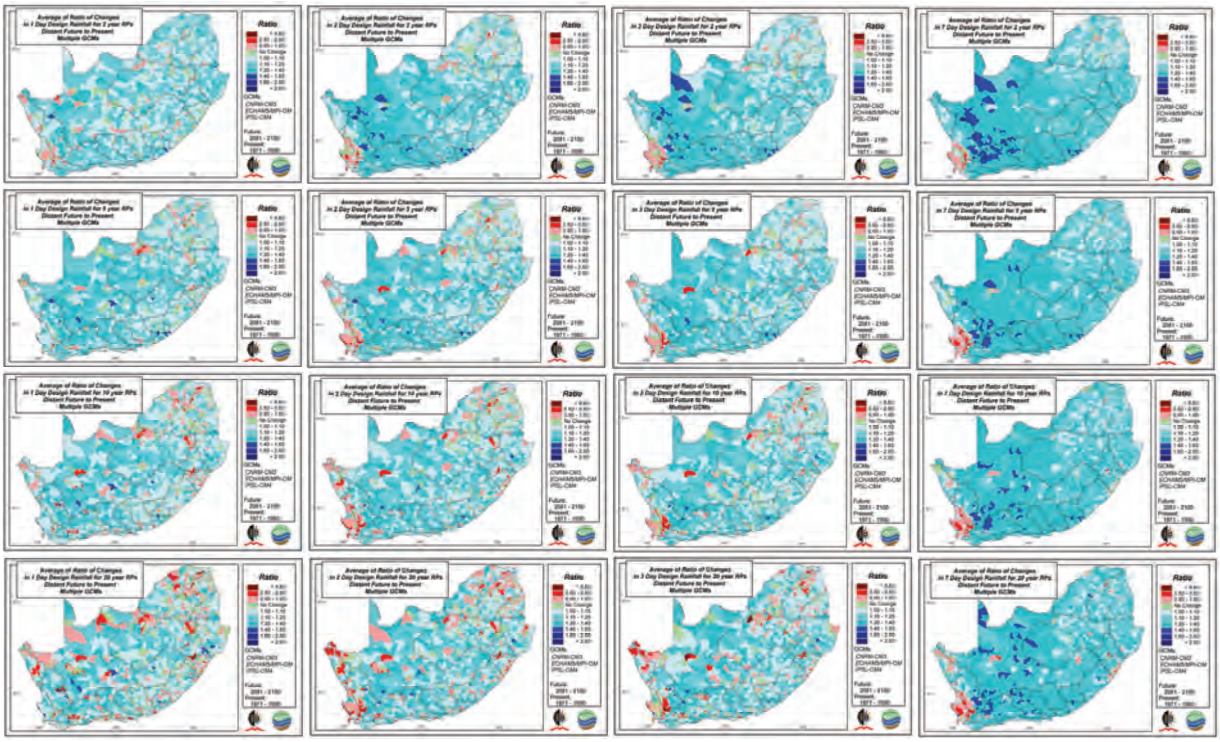

Figure 7.2.3 Averages of ratio changes of more distant future to present one day (left column), two, three and seven day (right column) design rainfalls for the 2 year return period (top row), as well as the 5, 10 and 20 year return period (bottom row), derived from output of multiple GCMs

A summary of the main differences between projected changes from output of multiple GCMs into the intermediate and more distant future climates is provided for selected durations and return periods in **Figure 7.2.4**. In this Figure comparisons can be seen for the one day 2 year return period (intermediate future top left vs. more distant future bottom left), the one day 20 year return period (second column from the left), the seven day 2 year return period changes (second column from the right) and the seven day 20 year return period changes (top right vs. bottom right).

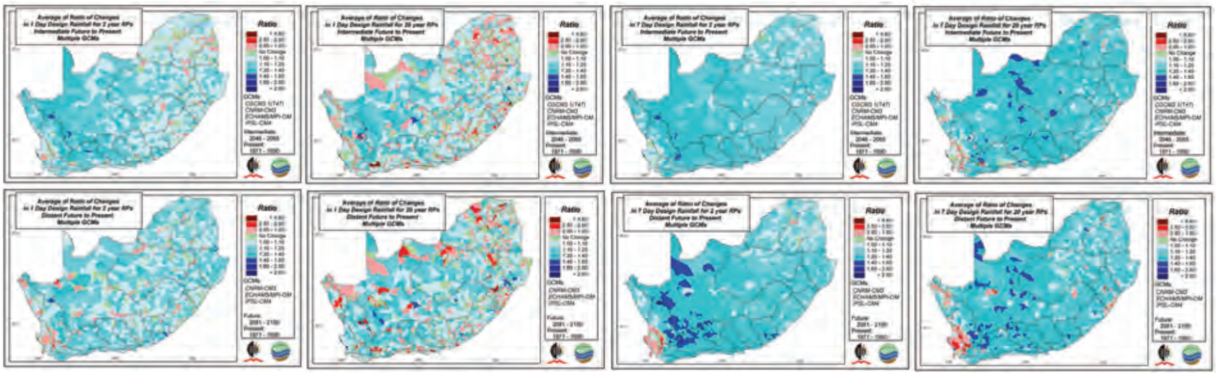

Figure 7.2.4 Comparison of averages of ratio changes for selected durations and return periods between intermediate future to present and more distant future to present design rainfalls of long duration, derived from output of multiple GCMs

In Summary

- Over much of South Africa increases in design rainfalls of long duration are projected from this analysis using outputs from multiple GCMs with the Log Pearson III extreme value distribution. The implication is that this should be considered in future designs of hydraulic structures.
- Areas transitional between the winter and summer rainfall regions of South Africa appear to be particularly sensitive to changes in design rainfall, especially for lower return periods.

- Increases tend to become more pronounced the longer the duration. The implication here is that the design of structures on large catchments for which long duration design rainfalls are critical, require additional attention in regard to climate change.
- Areas where decreases in design rainfall are shown, especially in the southwest, tend to be the same for which general decreases in annual rainfalls are projected, more so in the distant future than in the intermediate future.

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CHAPTER 7.3

CLIMATE CHANGE AND *DESIGN STREAMFLOWS:* A 2011 PERSPECTIVE

R.E. Schulze and D.M. Knoesen

Design Streamflows: Some Basic Concepts Revisited

Hydraulic engineering and conservation structures such as dams, bridges, culverts and stormwater systems need to be designed to accommodate floods of a certain magnitude and duration 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, duration and frequency of extreme rainfall events and associated flooding. 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 in South Africa 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. In this study a continuous modelling approach to flood frequency analysis has been used, whereby floods are generated using sequences of daily rainfall which are input into a daily timestep hydrological model. The term “design streamflow” is then used to describe the

- *depth* (i.e. magnitude, in m^3 or in mm equivalents) of streamflow, for a critical
- *duration* (in this study of 1, 2, 3 or 7 days’ duration, where such longer durations are important when considering designs on larger catchments, as well as for multiple day flooding and for regional damage assessments), for a desired
- *frequency* of recurrence (e.g. once in 2, or 5, 10 or 20 etc years and longer, depending on the size and economic importance of the structure), where the frequency of recurrence is commonly referred to as the return period and where a return period of, say, 20 years implies a statistical probability of recurrence once in 20 years or 5 times in 100 years, and not that it will recur regularly every 20 years.

This Chapter commences with a short summary of the methodology used in the computation of design streamflows (**Box 7.3.1**), followed by results, first of design streamflows derived by continuous modelling using historical observed climate input and thereafter with GCM derived climate values in order to assess possible changes to design floods under projected future climatic conditions.

Box 7.3.1 Summary of Methodology for the Computation of Design Streamflows

As was the case with design rainfall, the Log-Pearson Type III extreme value distribution (cf. **Chapter 7.1**) was used with the Annual Maximum Series (AMS) to compute the 1, 2, 3 and 7 day design streamflow magnitudes for the 2, 5, 10, 20, 50 and 100 year return periods. The design streamflows were simulated with daily time step *ACRU* agrohydrological model (Schulze, 1995 and updates; cf. **Chapter 2.3**) using hydrological attributes of soils (Schulze and Horan, 2008) and baseline land cover (Acocks, 1988; Schulze, 2004) from the South African Quinary Catchments Database (Schulze and Horan, 2010; Schulze *et al.*, 2010) and daily climate input of 50 years’ duration for a baseline study and the three 20 year periods for the present (1971 - 1990), intermediate future (2046 - 2065) and more distant future (2071 - 2100) for the climate change impacts study on design streamflows. The daily streamflows at each Quinary’s exit were calculated, with accumulated streamflows taken as flows cascaded downstream. From these the AMS for the different durations considered were computed at each Quinary’s exit for analysis with the Log-Pearson III extreme value distribution. Selected results from the design flood analysis are presented below.

The volume of a flood, 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 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.

Distribution Patterns over South Africa of One, Three and Seven Day Design Streamflows for a Range of Return Periods under Baseline (Historical) Climatic Conditions

Design streamflows for the 50 year historical period 1950 - 1999 are presented in mm equivalents in **Figure 7.3.1** for the selected durations of one, three and seven days and the selected return periods of 2, 10, 20 and 50 years, and then in millions of m³ in **Figure 7.3.2** for the same durations and return periods.

When expressed in mm equivalents, with dark red shading designating low values and grading through lighter reds and blues to dark blues for high values, it may seen clearly that magnitudes of design streamflows increase as return periods increase from 2 to 50 years, as would be expected (looking vertically from top to bottom), and again as would be expected the design streamflows increase as durations increase from one to seven days (horizontally left to right). Values as low as 0.5 mm equivalent make up the one day 2 year return period accumulated streamflow in the arid west, increasing up to 250 mm equivalent for the seven day design streamflow with a 50 year return period.

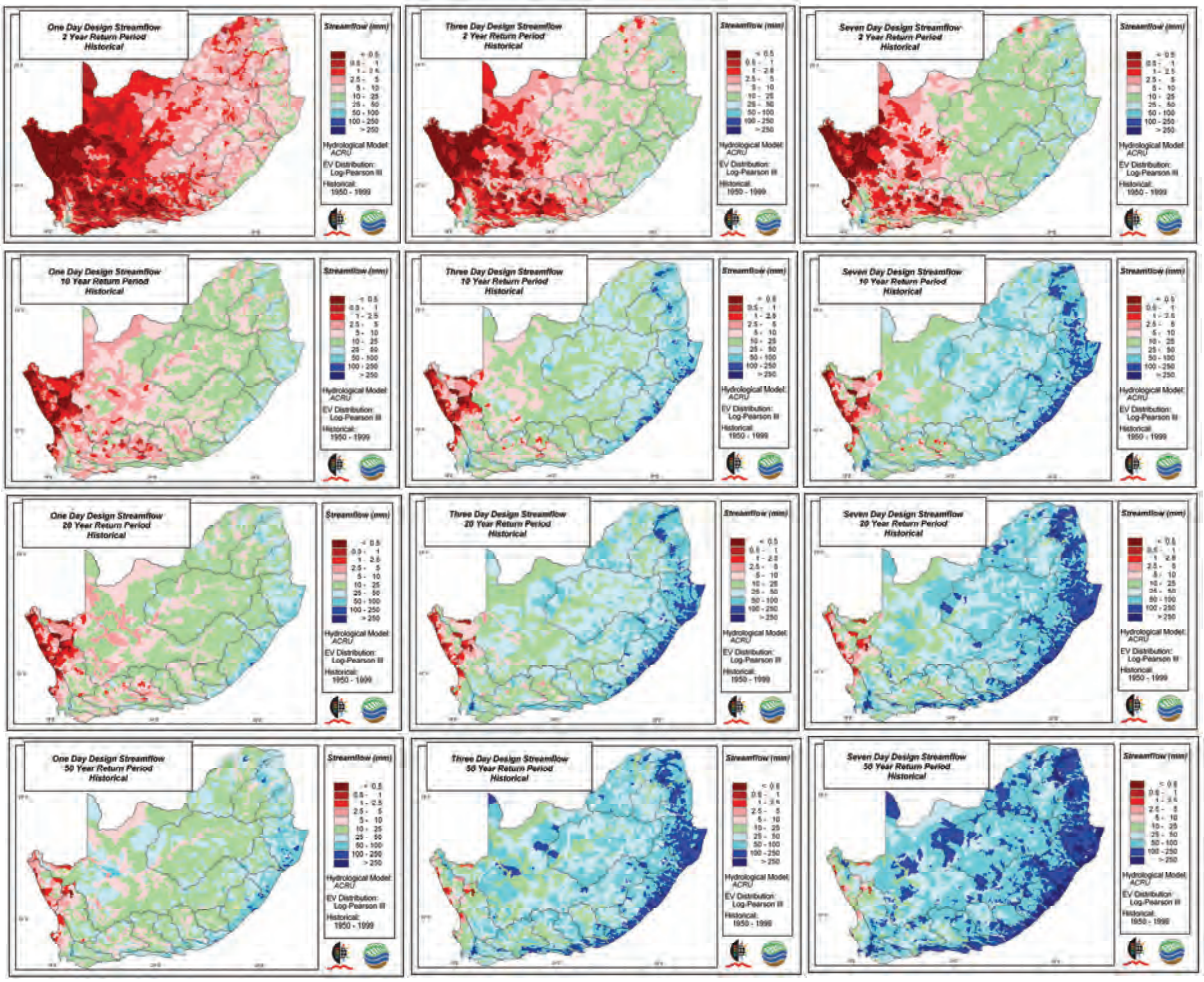

Figure 7.3.1 Design streamflows (in mm equivalents) over South Africa for one day (left column), three day (middle column) and seven day durations (right column) for the 2 year return period (top row), as well as the 10, 20 and 50 year return period (bottom row), simulated with the *ACRU* model under baseline (historical; 1950 - 1999) climatic conditions

Illustrated again by shades grading from dark reds for low values to dark blues for higher values, a very different visual picture emerges in **Figure 7.3.2** in which design streamflows are expressed in millions of m³ for the range of durations and return periods selected. What stand out very clearly are the large design flows of the mainstems of major river systems, accumulated from substantial catchment areas and with flows often generated in mountain areas where orographic influences result in substantial rainfalls. Examples of such high design flows along mainstems are the Orange, Vaal, Berg, Breede, Sundays, Fish, Kei, Thukela, Mfolosi, Komati, Sabie and Crocodile rivers.

What are deceptive in **Figure 7.3.2** are the apparently large volumes of design streamflows around the Namibia and Botswana borders and in the arid central west. These flows derive from very large Quinary Catchments (**Figure 7.3.3** left) which experience occasional large volumes of accumulated flows when expressed in m³, and with those Quinaries being largely endorheic areas with internal drainage into pans and wetlands from which water does not exit (**Figure 7.3.3** right). This endorheic characteristic has, however, not been accounted for in these simulations. Additionally, many of the design flows of smaller return periods would be lost to transmission losses from the dry alluvial channels - a process not simulated with the *ACRU* model at this stage.

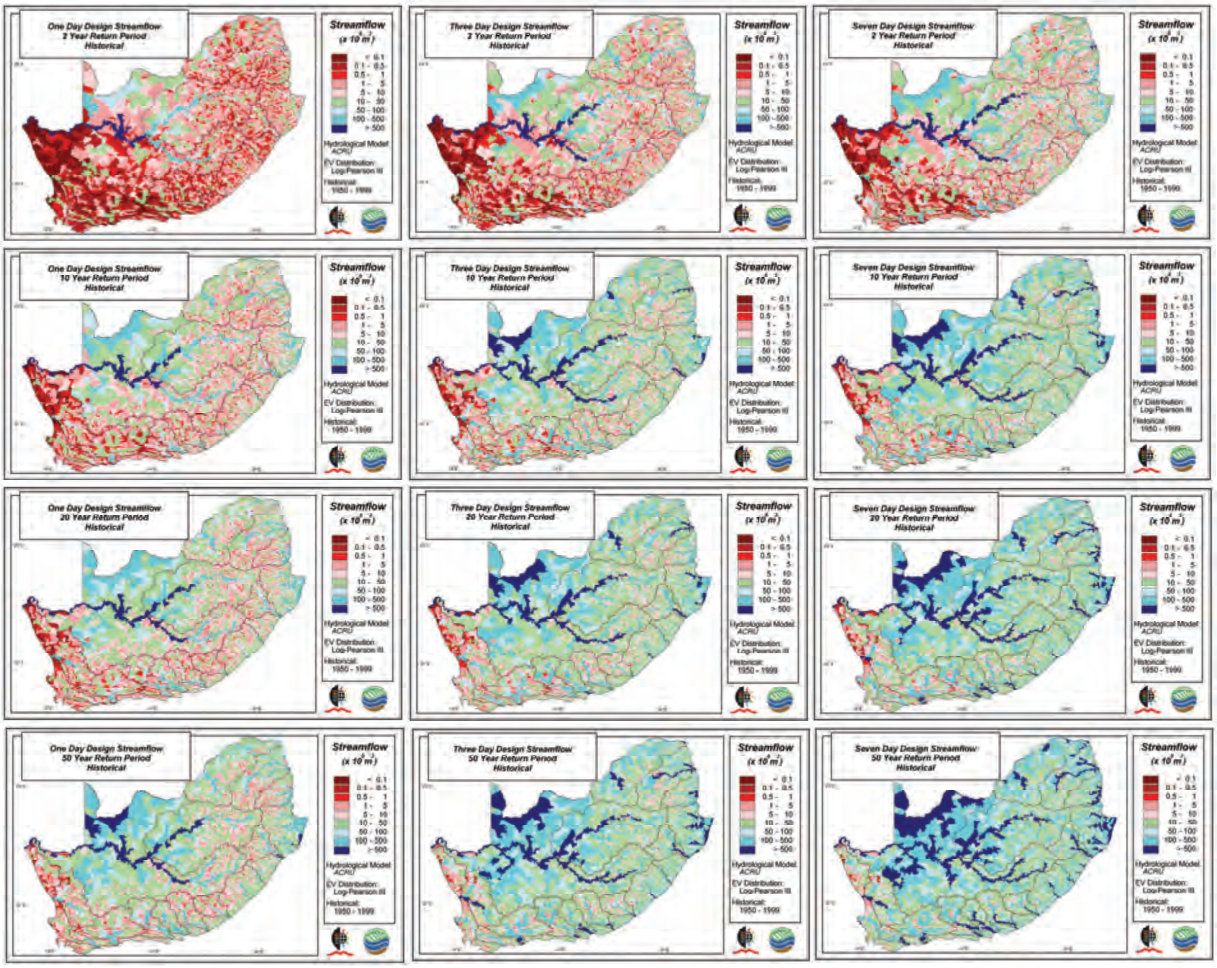

Figure 7.3.2 Design streamflows (in millions of m³) over South Africa for one day (left column), three day (middle column) and seven day durations (right column) for the 2 year return period (top row), as well as the 10, 20 and 50 year return period (bottom row), simulated with the *ACRU* model under baseline (historical; 1950 - 1999) climatic conditions

Ratio Changes of Future to Present Design Streamflows with Climate Change, Using Outputs from Multiple GCMs

For assessments of projected changes in design streamflows over South Africa with climate change, only return periods up to 20 years are shown, because outputs from the multiple GCMs used in this

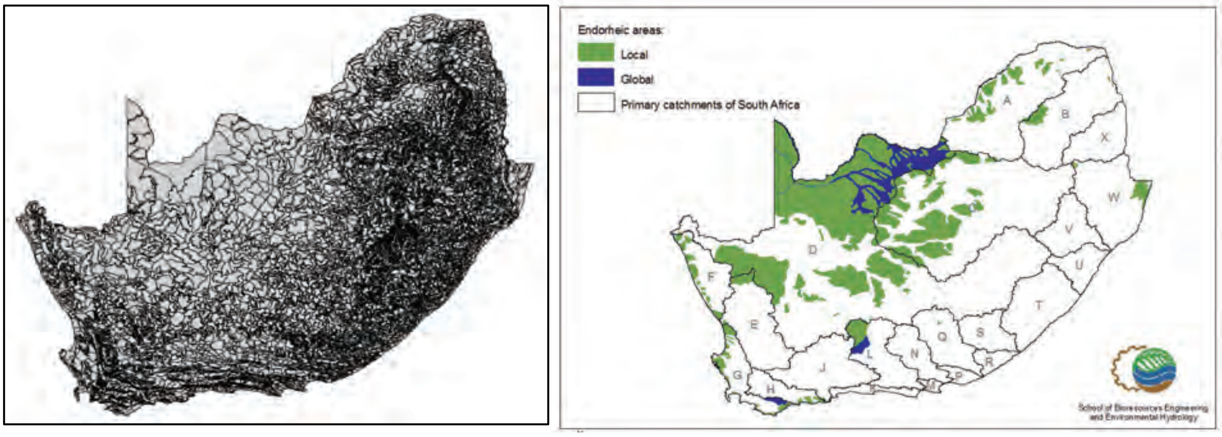

Figure 7.3.3 Quinary Catchments (left; Schulze and Horan, 2010), illustrating where the large Quinaries are located, and endorheic areas, i.e. internally drained, in South Africa (Midgley *et al*., 1994)

study were only for 20 year time slices (present from 1971 -1990, intermediate future from 2046 - 2065 and more distant future from 2071 - 2100) and extrapolations beyond the length of a record tend to result in large errors.

In **Figure 7.3.4** the projected ratio changes in design streamflows between the intermediate future and present are shown for durations of one, two, three and seven days (by row) and for 2, 5, 10 and 20 year return periods (by column). Over most (95 % +) of South Africa an increase in design streamflows is projected. For example, for the one day 2 year return period (**Figure 7.3.4** top left) this increase is 10 - 50 % (i.e. ratio changes of 1.1 to 1.5) over the eastern 2/3 of the country and 50 - 100 % in the western 1/3. The exception is the extreme southwest, where reductions in design streamflows are projected when the daily output from the multiple GCMs is used with the *ACRU* model and techniques for analysing extreme values.

The maps making up **Figure 7.3.4** highlight four issues of importance to water resource managers:

- First, as the return period increases from 2 through 5, 10 to 20 years (top to bottom sets of maps), so the increases in design streamflows are dampened and become less pronounced, irrespective of duration (i.e. irrespective of whether the one or seven day duration is evaluated).
- Secondly, the regions within South Africa where the highest increases in design stormflows are projected are the transitional areas between summer and winter rainfall regions where inconsistent weather patterns are likely to be experienced in future.
- Thirdly, and on a more local scale, as the return period increases from 2 to 20 years, so the area in the southwest where decreases in design streamflows are projected, expands.
- Fourthly, for a given return period the spatial patterns of change into the intermediate future do not vary between the one, two, three and seven day durations, i.e. the changes in design streamflow appear to be sensitive to return period, but not to duration.

Figure 7.3.5 shows the same set of design streamflow maps, but for the averages of ratio changes between the more distant future and present, derived from output of multiple GCMs as input to the *ACRU* model and then analysed with extreme value statistics. At first glance the respective maps of projected changes for the different durations and return periods look quite similar to those between the intermediate future and present. When re-packaged as in **Figure 7.3.6**, however, the following differences become apparent:

- For short durations (e.g. one day) and low return periods (e.g. 2 years)
  - the area of significant increases in design streamflows in the central-west of South Africa contracts into the more distant future, while
  - the area of decreases in design streamflows in the southwest expands (**Figure 7.3.6** top left vs. bottom left).
- For short durations (e.g. one day) and longer return periods (e.g. 20 years) there is very little difference between projected changes to design streamflows into the intermediate and more distant future periods (**Figure 7.3.6** second column, top vs. bottom maps).

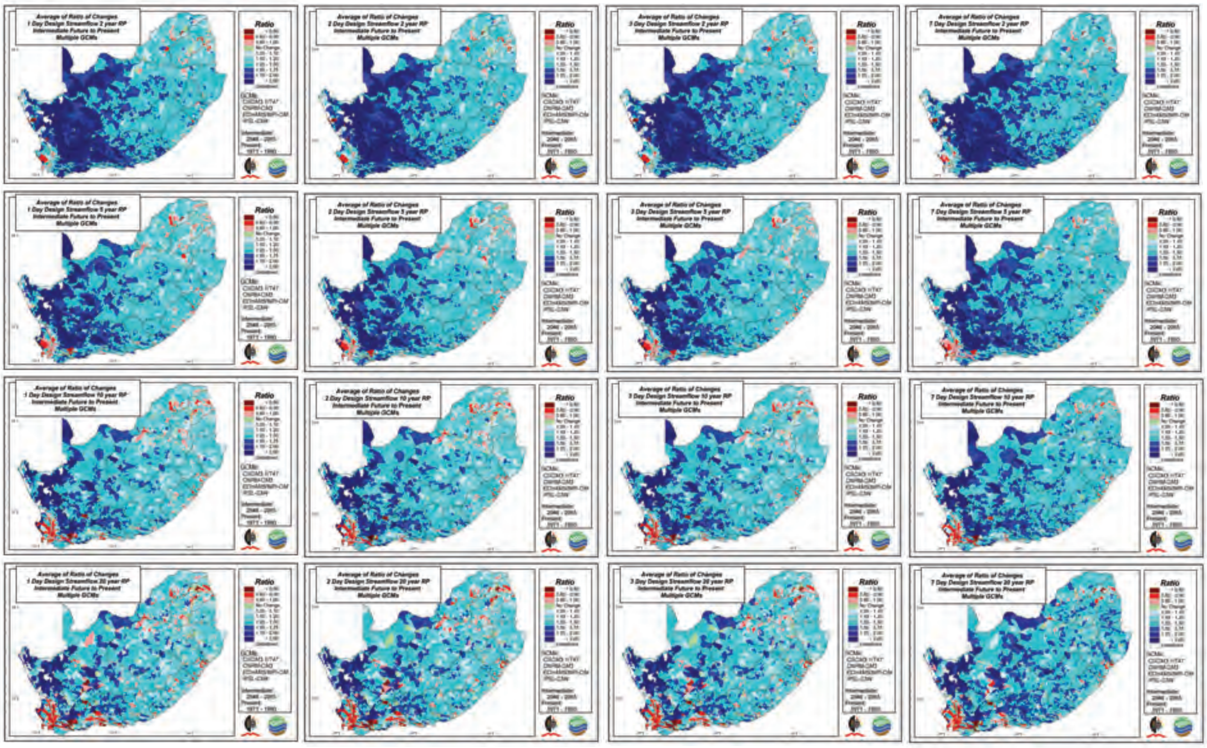

Figure 7.3.4 Averages of ratio changes of intermediate future to present one day (left column), two, three and seven day (right column) design stormflows for the 2 year return period (top row), as well as the 5, 10 and 20 year return period (bottom row), derived with the *ACRU* model from output of multiple GCMs

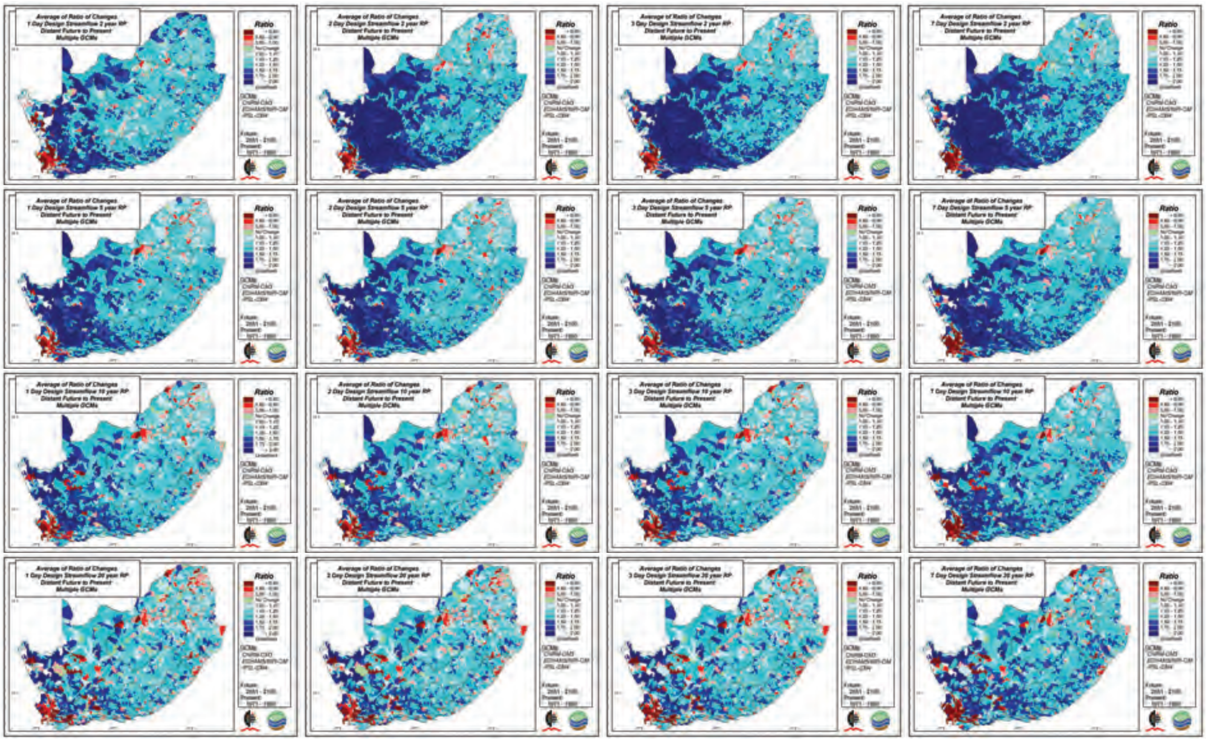

Figure 7.3.5 Averages of ratio changes of more distant future to present one day (left column), two, three and seven day (right column) design stormflows for the 2 year return period (top row), as well as the 5, 10 and 20 year return period (bottom row), derived with the *ACRU* model from output of multiple GCMs

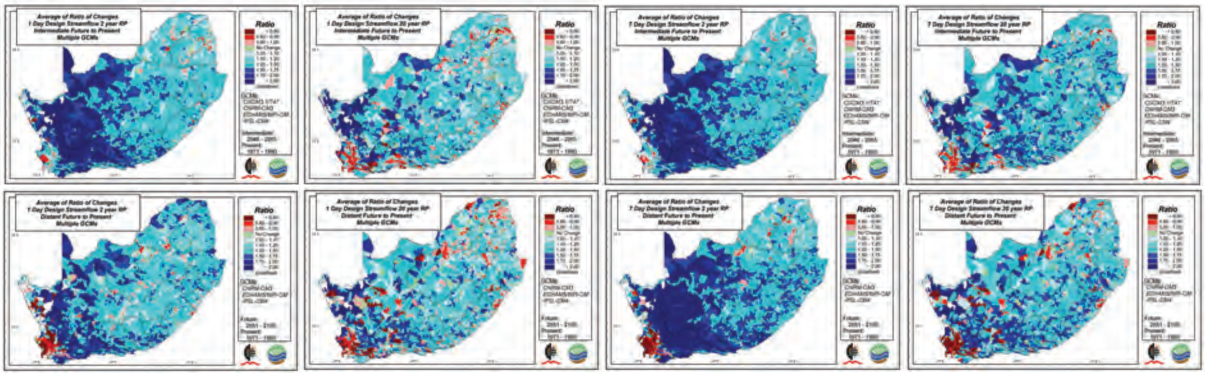

Figure 7.3.6 Comparison of averages of ratio changes for selected durations and return periods between intermediate future to present and more distant future to present design streamflows, derived with the *ACRU* model from output of multiple GCMs

- For longer durations (e.g. seven days) and low return periods (e.g. 2 years) the area of projected decreases in the southwest again shows expansion into the more distant future (**Figure 7.3.6** third column, top vs. bottom maps) while there is little difference evident for higher return periods.

Are there Significant Differences in Spatial Patterns of Projected Changes Between Design Rainfalls and Design Streamflows for the Same Durations and Return Periods?

The short answer to the above question is 'yes', with **Figure 7.3.7** showing emphatically that for the same duration and return periods between the top row of maps of design rainfalls and the bottom row of corresponding design streamflows there is significant amplification and intensification in the design streamflows into the intermediate future some 40 years from now, both where increases and where decreases are projected into the future with the multiple GCMs used in this study. For example, areas with projected increases of 10 - 20 % in design rainfall covert to increases of 20 - 75 % in design streamflows, while the projected decreases in the southwest intensify from ~ 10 % to 20 % and more.

Similar amplification of design streamflows is evident when ratio changes between the more distant future and present are projected, as illustrated in **Figure 7.3.8**, but with the projected decreases in the southwest even more pronounced between design rainfall and streamflow than for the intermediate future comparisons.

The above findings pose new challenges in engineering design, particularly for structures on large catchments where multi-day durations are critical, especially also given that hydraulic structures are constructed with design lives usually beyond 50 years.

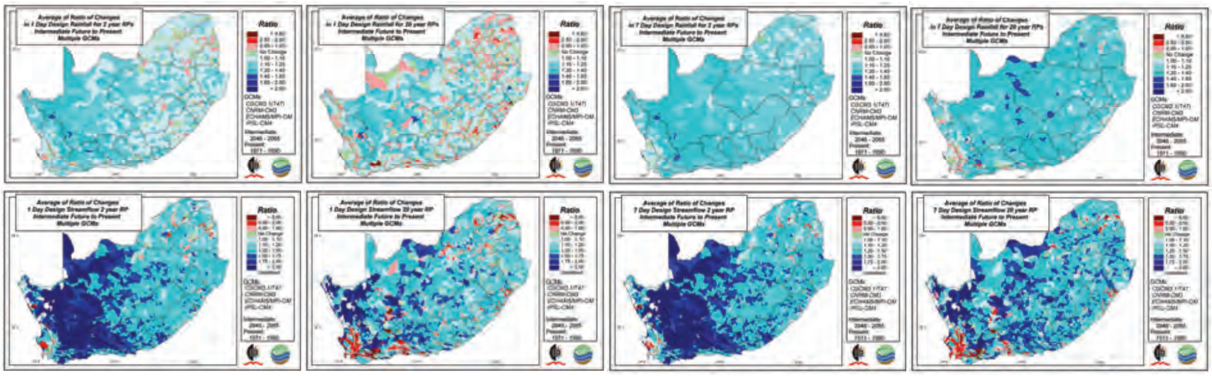

Figure 7.3.7 Comparison of averages of ratio changes from the present into the intermediate future between design rainfalls (top row) and design streamflows (bottom row) for identical durations and return periods, derived with the *ACRU* model from output of multiple GCMs

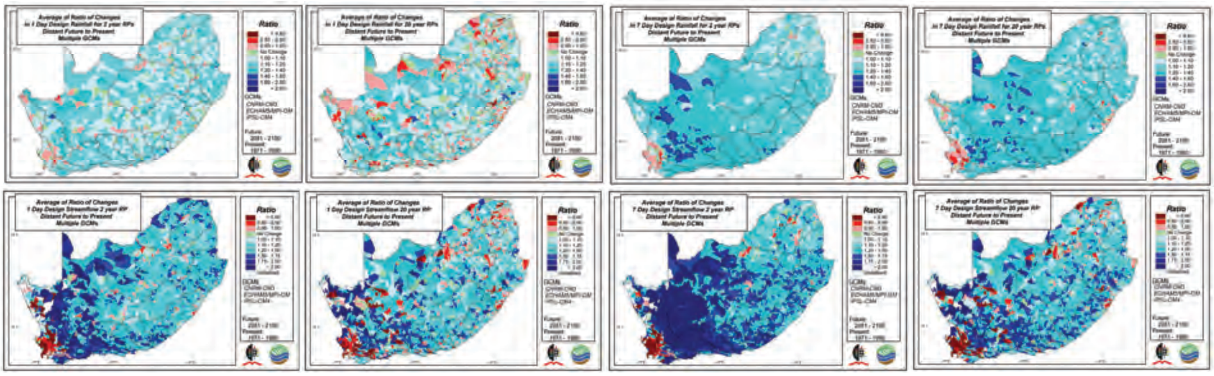

Figure 7.3.8 Comparison of averages of ratio changes from the present into the more distant future between design rainfalls (top row) and design streamflows (bottom row) for identical durations and return periods, derived with the *ACRU* model from output of multiple GCMs

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SECTION 8

PRACTICAL APPLICATIONS

CHAPTER 8.1

CLIMATE CHANGE AND
EVAPORATION FROM OPEN WATER BODIES AND WETLANDS:
A 2011 PERSPECTIVE

R.E. Schulze and L.M. Bulcock

Points of Departure

As a semi-arid country whose industrial heartlands and population concentrations are generally far distances from major sources of water, it is small wonder that over 320 storage dams have been constructed, each with full supply capacities in excess of 1 million m^3, and with a combined capacity of 32 400 million m^3, which is equivalent to 66 % of the RSA's mean annual streamflow. It is, however, the surface areas of these dams (e.g. **Photo 8.1.1**), which are often located in areas of flat topography and where evaporation rates are high, on which this Chapter focuses, for global warming is projected to increase the evaporation rates from these water surfaces significantly, leading to additional water losses in a country with already high atmospheric demand (cf. **Chapter 4.1**).

Photo 8.1.1 Bloemhof Dam: An example of the large surface area of a relatively shallow dam experiencing high evaporative losses (Photo: R. McKenzie)

An illustration of the large number of dams in the RSA with large surface areas is given in **Table 8.1.1**, in which a province by province analysis is presented of the number of dams with surface areas in excess of 1 000 ha (10 km^2), 5 000 ha (50 km^2) and 10 000 ha (100 km^2). The table shows the existence of 54 dams each with surface areas > 1 000 ha (mainly in the Free State, KwaZulu-Natal and the Eastern Cape), nine with surface areas exceeding 5 000 ha and five > 10 000 ha, the largest being Gariep Dam which covers 35 216 ha (352.16 km^2)

Analyses Undertaken on Evaporation from Open Water Bodies in South Africa

This study considers evaporative losses computed from open water surfaces beyond those of only storage reservoirs, with open water bodies here defined from the National Land Cover images (NLC, 2000) as areas consisting of dams, rivers wide enough to be identified by the NLC (i.e. wider than 100 - 200 m), wetlands and pans with water, but excluding dry pans as identified by Mucina and Rutherford (2006). The computations are explained in **Box 8.1.1**.

Table 8.1.1 Surface areas of large dams in the RSA, by province (Source: Wikipedia, 2010)

Province	> 1 000 ha	> 5 000 ha	>10 000 ha
Limpopo	3	1	-
Mpumalanga	8	1	-
North West	4	2	2
Northern Cape	3	-	-
Gauteng	1	-	-
KwaZulu-Natal	10	1	1
Free State	12	3	2
Eastern Cape	9	-	-
Western Cape	4	1	-

Box 8.1.1 Computation of Open Water Evaporation

Daily values of open water evaporation were first computed with the Penman-Monteith equation (cf. **Chapter 4.1**; Schulze and Chapman, 2008; based on Penman, 1948; Monteith, 1981; FAO, 1992). In order to then convert these values to those equivalent to reservoir evaporation they were first adjusted to A-pan equivalents by a multiplier averaging 1.24 for South Africa (range: 1.17 - 1.37, depending on location and season). To these values a multiplier to convert A-pan evaporation to that of open water bodies was applied. This multiplier was 0.70, which was determined from the mean of Chapman's (1990) month-by-month coefficients to A-pan : open water body evaporation for South Africa.

Distribution Patterns over South Africa of Annual Evaporative Losses from Open Water Bodies and Wetlands at Primary and Quinary Catchment Scales under Baseline (Historical) Climatic Conditions

In **Figure 8.1.1** (left) it is shown that in many Primary Catchments in South Africa up to 1 000s of millions of m^3 of water is evaporated annually from open water bodies and wetlands, particularly from the Primaries located in the drier interior. If one assesses these evaporative losses on a finer spatial scale of Quinaries, a somewhat different picture emerges, with **Figure 8.1.1** (right) on the one hand highlighting the many Quinaries in the drier areas devoid of any open water evaporative losses and, on the other hand, the large number of Quinaries from which 75 000 to > 500 000 m^3 are lost to the atmosphere annually. It must be reiterated again that in a semi-arid region with relatively sparse water resources these evaporative losses are significant.

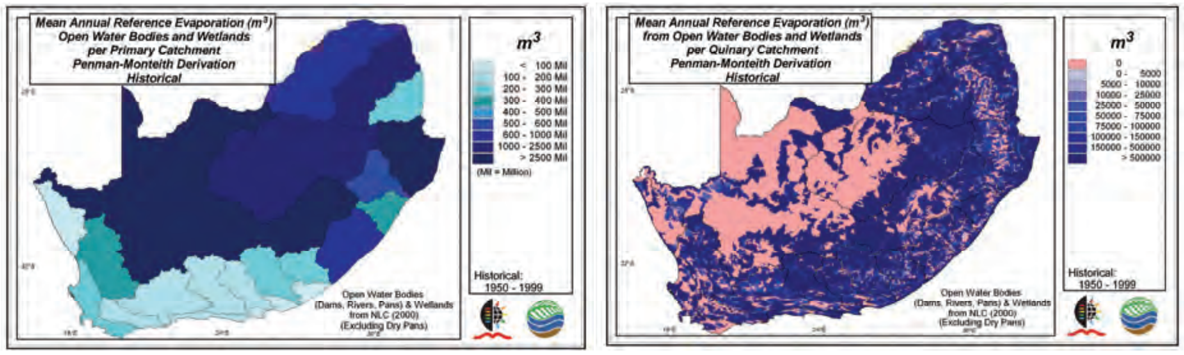


Figure 8.1.1 Mean annual evaporative losses from open water bodies and wetlands per Primary Catchment (left) and per Quinary Catchment (right)

Changes in Future to Present Annual Evaporative Losses from Open Water Bodies and Wetlands at Primary and Quinary Catchment Scales, Using Outputs from Multiple GCMs

Figure 8.1.2 shows that from Primary Catchments the *additional* evaporative losses from open water bodies and wetlands into the intermediate future (2046 - 2065) some 40 years from now (2011) range from < 10 million m^3 per annum where there are few dams to > 350 million m^3 in the Orange Catchment (**Figure 8.1.2**, top left), while at Quinary scale these additional losses translate to > 100 000 m^3 and even > 15 000 m^3 in some areas (**Figure 8.1.2**, top right). By the more distant future

(2071 - 2100; **Figure 8.1.2**, middle row) many of the Primaries show a jump in additional evaporative losses from one class interval in the legend to the next.

What is significant from the bottom row of **Figure 8.1.2**, however, is that in the relatively short period of time between the intermediate and more distant futures (2046 - 2065 vs. 2081 - 2100), i.e. only 35 years, the additional evaporative losses from open water bodies and wetlands more or less equal those of the additional losses between the present and the intermediate future (1971 - 1990) time periods, which is 75 years. This is indicative that if temperature increases continue as projected by the A2 emissions scenarios which were used in this study, an acceleration of impacts over time is to be expected.

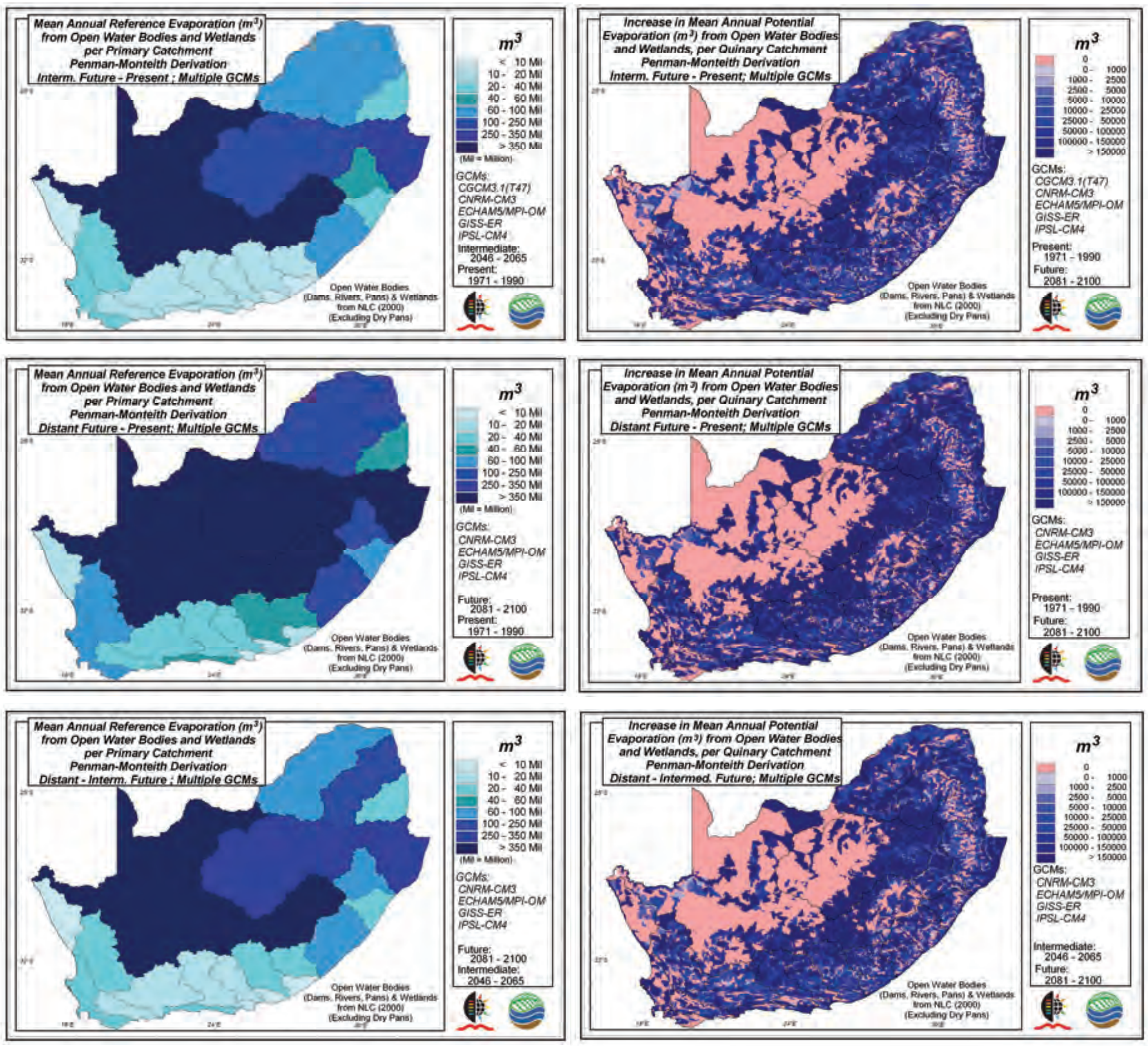
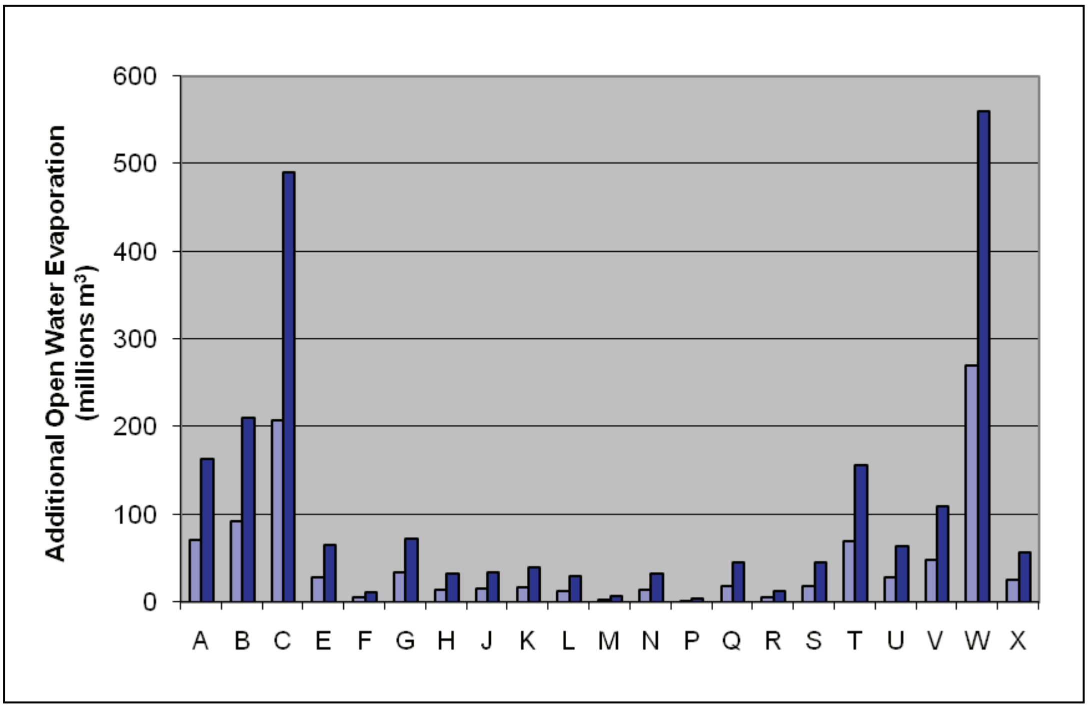


Figure 8.1.2 Changes between the intermediate future and present (top row), the more distant future and present (middle row) and the more distant and intermediate future climate scenarios (bottom row) of additional annual evaporative losses from open water bodies and wetlands from Primary Catchments (left column) and Quinary Catchments (right column), derived from output of multiple GCMs

Illustrated slightly differently, **Figure 8.1.3** (top) shows actual magnitudes of projected additional evaporative losses from open water bodies and wetlands per Primary Catchment (except the Orange), with the light blue bars indicating increases from the present to the intermediate future and the dark blue bars from the present to the more distant future. The additional projected increases for the Orange Primary Catchment are shown separately in **Figure 8.1.3** (bottom).



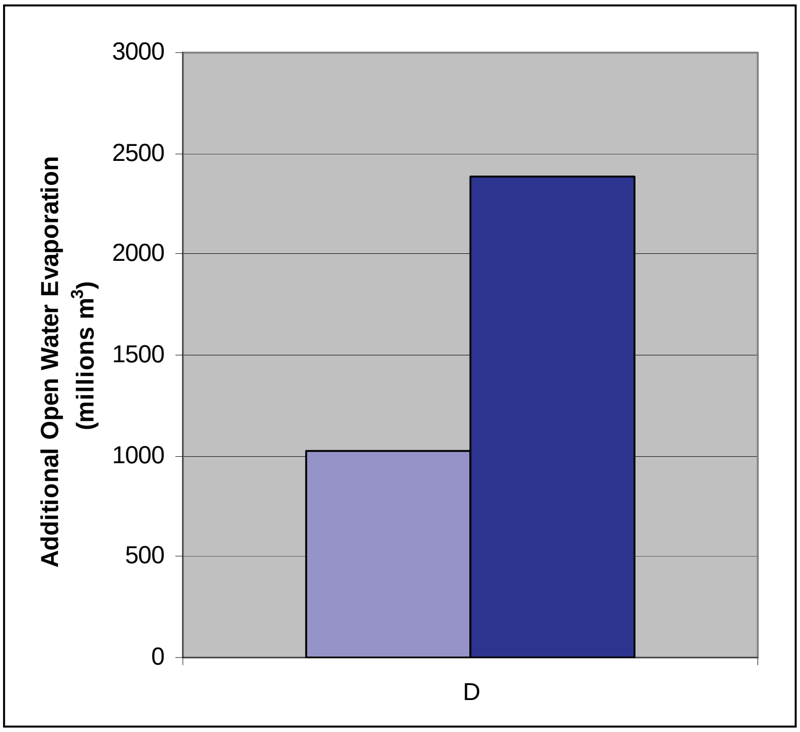


Figure 8.1.3 Changes between the intermediate future and present (light blue) and the more distant future and present (dark blue) of additional annual evaporative losses from open water bodies and wetlands from Primary Catchments other than the Orange (top) and from the Orange (bottom), derived from output of multiple GCMs

The additional losses in evaporation from open water bodies and wetlands in South Africa under future climate scenarios are very high and have implications, *inter alia*, on the availability of water, the quality of the water and on wetlands functioning.

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CHAPTER 8.2

CLIMATE CHANGE AND
NET IRRIGATION DEMANDS:
A 2011 PERSPECTIVE

R.E. Schulze and L.M. Bulcock

Setting the Scene

Large areas of South Africa experience hot and dry semi-arid climatic conditions with high evaporation rates and a low, intermittent and seasonally variable rainfall, over which optimal crop production is not possible, making the addition of plant-available water by means of irrigation necessary. It stands to reason, therefore, that irrigation contributes substantially to South Africa's agricultural production for both the local and export markets, generating 20 - 25 % of agriculture's contribution to South Africa's GDP and employing some 120 000 workers and, additionally, seasonal workers.

Before issues of climate change on net irrigation demands are discussed, an overall perspective of irrigation in South Africa is first provided, followed by some information on what mode of irrigation scheduling to apply in climate change studies, on input to the *ACRU* model for simulations and on distribution patterns of statistics of net irrigation demand over South Africa under baseline climatic conditions.

An Overall Perspective of Irrigation in South Africa

1. Historical Perspective

Reinders (2010) reports that historically, there is evidence that irrigation was applied in the Western Cape province as far back as 1797. However, the first large irrigation scheme was only established near Clanwilliam in 1912 and the trend up until the 1930s was for schemes to be developed with state aid to irrigation boards. During the depression years of the 1930s and into the 1940s the state developed various large irrigation projects largely as social upliftment schemes while from the 1950s state emphasis fell on the economic development of disadvantaged areas in the then homelands. Simultaneously, a large number of state water schemes were erected countrywide for the storage and / or transfer of water between catchment areas, in order to ensure water supplies to irrigators and other users. In parallel with state and irrigation board schemes private irrigation development took place.

In the earlier years up to the1930s, flood irrigation, with gravitational flow of water, was the primary mode of application. From the 1940s, irrigation under pressure was started and the use of sprinkler irrigation began to increase. The use of micro systems in the RSA became established only in the 1970s, as was the use of self-driven mechanised systems. By 1990 sprinkler irrigation was applied to more than half (54%), flood irrigation on one third (33%) and micro irrigation on one eighth (12%) of the irrigated surface, with preference for sprinkler irrigation to be used in higher rainfall regions and for flood irrigation in lower rainfall zones (Reinders, 2010).

2. Some Facts and Figures

- Only 19 % of the RSA's total area is suitable for surface irrigation with respect to soils and terrain criteria (FAO, 1997).
- South Africa's area under irrigation has increased steadily from 808 000 ha in 1960 (i.e. 0.66 % of the total area) to 1 000 000 ha in 1970 (0.82 %), 1 128 000 ha in 1980 (0.92 %), to 1 290 000 ha by 1990 (1.06 %), 1 354 000 ha by 1999 (1.11%; FAO, 1999; Weligamage *et al*., 2002), to 1 675 882 ha in 2007 (DWAF, 2007), which equates to ~ 1.4 % of the RSA's total area.
- The areas where irrigation is practiced in South Africa, as identified from the National Land Cover image (NLC, 2000) and expressed in km^2 per Quinary Catchment, is shown in **Figure 8.2.1**. Key areas are, *inter alia*, in the southwest, along the Orange River and the Vaal-Harts scheme.
- Irrigation uses ~ 60% of the available water in South Africa, equivalent to 7.92 X 10^6 m^3/yr (Reinders, 2010).

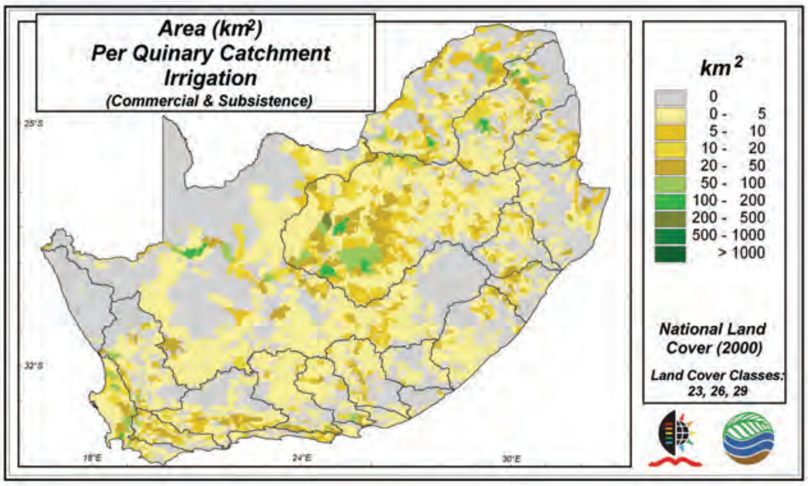

Figure 8.2.1 Areas (km^2) per Quinary Catchment under irrigation, as identified by the NLC (2000)

- Of the area registered in 2007 by the Department of Water Affairs to be under irrigation, an estimated 54.9 % is sprinkler, 14.4 % is flood, 21.8 % micro/drip irrigated, with 8.9 % unknown (Van der Stoep *et al*., 2008). Significantly, the area under micro/drip irrigation has increased from 11.8 % in 1990.
- While two decades ago the technical efficiency levels that were realistically achievable ranged from 55 - 65 % for flood irrigation, 70 - 85 % for sprinkler irrigation and 85 - 95 % for micro irrigation (Reinders, 1992), proposed new efficiency levels following recent research are 86 - 98 % for flood, 78 - 90 % for sprinkler and 85 - 95 % for micro/drip irrigation (Reinders *et al*., 2008).
- This increase in efficiencies of irrigation water use and increased water savings stems from recent advances of technologies, tools and procedures for water metering (since for > 77 % of the area under irrigation in 2007 water was pumped), reduction of canal water losses, improvements in canal water distribution, investment and cost analysis for changing to better performing drip irrigation.
- There are approximately 15 000 medium to large scale irrigation farmers (Reinders, 2010), while ~ 150 000 small scale farmers practise irrigation.
- Organisationally, irrigation in South Africa falls into three main categories, *viz*.
  - State water schemes, which at this point in time apply about 26 % of the water used for irrigation, with this percentage including 4 % small farmer schemes;
  - irrigation boards (of which there are some 300), i.e. statutory organisations to manage the storage and distribution of irrigation water to irrigators within a specific area, which use about 30 % of irrigation water; and
  - private farmer irrigators, who utilise the remaining 44 % of irrigation water (Reinders, 2010).

Irrigation Water Requirements

The irrigation requirements of plants can be determined for a period of time

- if the water consumption of the plant, i.e. transpiration, can be estimated for the period
- if the amount of water lost through evaporation from the soil surface is known
- if the amount of water from rainfall, which replenishes soil water, is known
- if it is known how much water the soil can hold in the active root zone and
- if it is known how much water can be withdrawn from the soil before plant stress sets in.

The routines for estimating irrigation requirements with the *ACRU* model (Schulze, 1995 and updates), which was used in this study, incorporate the above processes, which are summarised graphically in **Figure 8.2.2**. The model, furthermore, also considers different modes of irrigation scheduling (**Figure 8.2.3**) which may be appropriate to prevailing climatic, crop or management conditions in its daily soil water budgeting routines. In **Box 8.2.1** the components of the water budget used in the irrigation routines are summarised from Chapters 17 and 18 of the *ACRU* Theory Manual (Schulze, 1995).

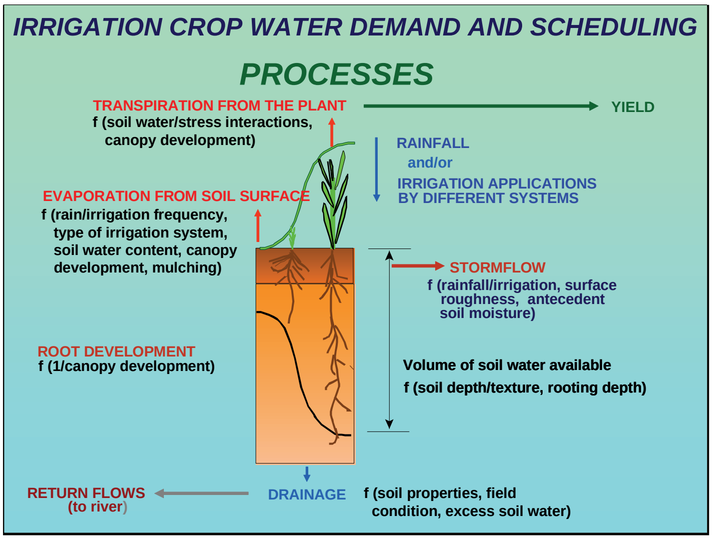

Figure 8.2.2 Schematic of the main processes of the irrigation water budget in *ACRU*

On Irrigation Scheduling

- Irrigation scheduling involves the day-to-day decisions about *when* to irrigate and *how much* to apply (**Figure 8.2.3**).
- Two important aspects of irrigation scheduling need to be considered:
  - first, there is a need to identify the most appropriate *irrigation plan* for the site, i.e. setting target soil moisture deficits (SMDs) when to irrigate, and amounts to be irrigated, depending on the plant, its growth stage, season, soil and system hardware; and
  - secondly, a means of deciding when the critical SMD has been reached needs to be identified, e.g. by water budgeting or soil water measurements.
- *Good scheduling* will apply the right quantity of water at the right time to
  - optimise production (e.g. quantity and quality of crop), and
  - minimise adverse environmental impacts (e.g. leaching), while
- *Poor scheduling* implies that either
  - under-watering can take place, i.e. too little or too late, or
  - over-watering can take place, i.e. too much or too soon.
- These aspects are also addressed in **Box 8.2.1**.

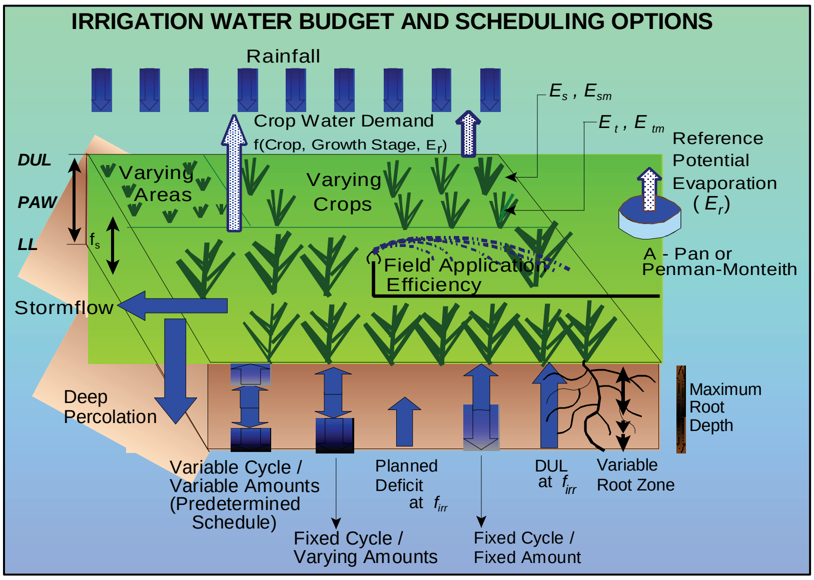

Figure 8.2.3 Schematic of the irrigation water budget in *ACRU* and scheduling options available (After Schulze, 1995 and updates)

Box 8.2.1 The Irrigation Water Budget as Represented in the *ACRU* Model

For applications of irrigation, conceptually sound, but robust, algorithms have been developed and incorporated into *ACRU* to simulate the major components of the irrigation water budget, *viz.*

- evaporation of water from the soil surface and
- transpiration from the crop, both in relation to atmospheric demand,
- available soil water with particular reference to rooting characteristics, as well as
- stormflow and
- deep percolation, with the algorithms for the latter two components given in **Chapter 8.3**..

Evaporation from the Soil Surface, E_s: General
Evaporation of soil water is a complex process, but it has been generalised into two stages. The first stage of the evaporation process is the constant rate, or the energy limiting, phase. When the soil can no longer supply water at a rate to use all the available energy for evaporation, the soil limiting, or second phase, begins.

Stage 1 Soil Water Evaporation: The Constant Rate/Energy Limited Phase
In Stage 1 of the soil water evaporation process, evaporation from the soil is limited primarily by the atmospheric demand for water above the soil surface, or reference potential evaporation E_r.

The effect of crop canopy shading on the supply of energy to the soil surface is represented by the percentage shading of the soil surface ($S_{\%}$) measured near solar noon. In *ACRU*'s irrigation routines the relationship between bare soil and the evaporation from a shaded soil is given as

$$E_s / E_{sm} = exp(-0.017 S_{g\%})$$

where
E_s = evaporation from the soil surface (mm/day),
E_{sm} = evaporation from a wet uncovered soil surface (mm/day),
$\equiv$ maximum soil water evaporation, and
$S_{g\%}$ = percentage of ground shaded, measured near solar noon.

For a fully grown crop $S_{g\%}$ depends on the crop type and the planting density. However, for most crops grown under irrigation, values for $S_{g\%}$ approach 100 % towards the end of the vegetative period. The variation in $S_{g\%}$ during the growing season is accounted for in *ACRU*'s irrigation routines by assuming a linear relationship between the rate of increase / decrease of $S_{g\%}$ and the rate of increase / decrease of the crop coefficient (K_{cm}), *viz.*

$S_{g\%}$ = 0 for $K_{cm} < 0.30$
$S_{g\%}$ = $(S_{\%mx} / (K_{cS\%mx} - 0.3)) \times (K_{cm} - 0.3)$ for $K_{cm} < K_{cs\%mx}$
$S_{g\%}$ = $S_{\%mx}$ for $K_{cm} > K_{cs\%mx}$

where
K_{cm} = crop coefficient,
$K_{cS\%mx}$ = crop coefficient when $S_{g\%}$ is at its maximum (typically at the end of the vegetative period), and
$S_{\%mx}$ = maximum per cent of ground area shaded (measured near noon and typically taken as 100 % for most irrigated crops).

Stage 2 Soil Water Evaporation: The Rapidly Declining, Soil Regulated Phase
During Stage 2 soil water evaporation, the soil begins to regulate the drying rate and evaporation decreases rapidly. Stage 2 evaporation has usually been modelled with a square root of time relation. The transition to second stage drying is assumed to occur when cumulative soil water evaporation from a defined topsoil layer reaches a soil specific upper limit threshold, U_l (mm).

The hydraulic properties of the soil play the major role in determining the amount of drying before Stage 1 evaporation ends and Stage 2 evaporation begins. In *ACRU*'s irrigation routines Stage 2 soil water evaporation proceeds as follows:

Box 8.2.1 The Irrigation Water Budget as Represented in the *ACRU* Model (continued)

$$E_s = \alpha_s . t^{0.5} - E_{s2cum}$$

where

E_s = evaporation from the soil surface (mm/day),
E_{s2cum} = cumulative Stage 2 evaporation from the soil surface (mm),
α_s = soil water transmission rate factor, and
t = days since the start of Stage 2 evaporation (day).

If any rainfall or irrigation occurs during Stage 1, the rainfall or irrigation is subtracted from the cumulative total of Stage 1 evaporation. If any rainfall or irrigation occurs during Stage 2 evaporation, E_s is calculated as follows:

$$E_s = \alpha_s t^{0.5} - E_{s2} + P_g + I_{rr} \quad \text{for } P_g + I_{rr} < E_{sl}$$
$$E_s = \alpha_s t^{0.5} - E_{s2} + P_g + Irr \quad \text{for } P_g + Irr < E_{sl}$$
$$E_s = E_{s1} \quad \text{for } P_g + Irr > E_{sl}$$

As a result $E_{s1cum} = U_l - (P_g + I_{rr})$

$U_l - (P_g + I_{rr}) < 0$

or, if $E_{s1cum} = 0$

where

P_g = precipitation (mm),
I_{rr} = irrigation (mm),
E_{s1} = potential Stage 1 soil water evaporation (mm/day),
U_l = upper limit threshold for Stage 1 evaporation (mm/day), and
E_{s1cum} = cumulative Stage 1 evaporation (mm).

During Stage 1 or 2 soil water evaporation, the amount of water available to be evaporated is that amount deemed to be available in the top 150 mm of the soil profile.

Maximum Transpiration, E_{tm}

In the irrigation routines maximum transpiration, E_{tm}, when soil water content is not limiting, is based on the concept that E_{tm} is related to the standard crop coefficient. A further refinement to this concept takes into consideration that soil surface wetness has been added, whereby E_{tm} is reduced when the soil surface is wet and increased when the soil surface is dry, according to

$$E_{tm} = \text{minimum of } (E_r \cdot K_{cmod} \text{ or } E_r - E_s) \text{ for } K_{cm} < 1.0$$

$$E_{tm} = E_r \cdot K_{cm} - E_s \qquad \text{for } K_{cm}$$

where

K_{cm} = standard crop coefficient, and
K_{cmod} = transpiration coefficient
= $(K_{cm} - 0.06) - (0.2E_s / 0.8E_r)$.

Soil Water Deficits and Transpiration

Transpiration takes place within the soil - plant - atmosphere continuum. For transpiration to proceed at potential rates, the atmospheric demand for water must be balanced by the flow of water from the soil to the plant roots and from the root surface to the leaves.

Slabbers (1980) states that in many plants leaf diffusion resistance is constant over a certain range of leaf water potential and then increases abruptly when that falls below an apparently critical value ψ^{cr}_l. This translates to transpiration, E_t, equalling maximum transpiration, E_{tm}, at ample soil water supply, until a certain fraction of the maximum available soil water is depleted. Below this threshold soil water content there is a reduction in E_t depending on the remaining available soil water and E_{tm}. Slabbers (1980) described these relationships as

Box 8.2.1 The Irrigation Water Budget as Represented in the *ACRU* Model (continued)

$$E_t = E_{tm} \qquad \text{for } \theta_{tmm} > f_s \cdot \theta_{mxmm}$$
$$E_t = E_{tm} \cdot \theta_{tmm} /(f_s \cdot \theta_{mxmm}) \qquad \text{for } \theta_{tmm} < = f_s \cdot \theta_{mxmm}$$

where

θ_{mxmm} = maximum available soil water (mm),

= (DUL - PWP)≅Root depth (mm),

DUL = drained upper limit (mm/mm),

PWP = permanent wilting point (mm/mm),

θ_{tmm} = actual soil water content (mm) at time t, and

f_s = fraction of available soil water at which a reduction in E_{tm} starts.

Slabbers (1980) derived an expression for f_s, *viz*.

$$f_s = 0.94 + 0.0026(\psi^{cr}_l / E_r$$

Values for ψ^{cr}_l, for a range of different crops, are given in (Smithers and Schulze, 1995).

Rooting Characteristics

In *ACRU*'s irrigation routines the amount of water available in the soil is determined with reference to the zone in which the majority of root activity occurs, R_z. This root zone is dynamic, accounts for root growth and is calculated by assuming a linear relationship to crop coefficients, *viz*.

$$R_z = 0.12 \qquad \text{for } K_{cm} < 0.3$$
$$R_z = 0.12 + (R_{zmx} - 0.12)(K_{cmr} - 0.3) \qquad \text{for } K_{cmr} > K_{cm} > 0.3$$
$$R_z = R_{zmx} \qquad \text{for } K_{cm} > K_{cmr}$$

where

R_z = zone in which the majority of root activity occurs (m),

R_{zmx} = maximum depth of the R_z for a fully mature crop (m), and

K_{cmr} = crop coefficient when the rooting depth reaches a maximum (normally at the end of the vegetative stage).

It is assumed that R_z plays the major role in regulating the volume of soil water available for root water uptake and that plants can extract water at potential rates from wherever it is available within this single zone, according to the constraints already described above by the various equations.

Whilst the majority of soil water uptake occurs from R_z, smaller amounts of water are taken up due to limited rooting activity in the soil below R_z, but within the maximum rooting depth, R_{mx}. Plant water uptake in the zone R_{zmx} to R_{mx} is restricted as a result of limited root - soil contact (i.e. incomplete root colonisation), but can play a role in reducing crop water stress. The supply of water from soil where rooting activity is limited is represented in *ACRU* by redistributing water from the R_{mx} zone to the R_z zone, where it is available for uptake by the plant. Water is redistributed according to gradients in water contents between the two zones. Typical initial values for the maximum rooting depths of crops R_{zmx} and R_z, are given in the *ACRU* User Manual (Smithers and Schulze, 1995 and updates)

Daily Rainfall Adjustment for Irrigation Areas

The rainfall information used in the irrigation water budget is from the identical rainfall input file as that used for the entire catchment. However, the catchment's rainfall input may not be representative of the specific location at which irrigation is being practised, and an irrigation rainfall adjustment multiplier can thus be applied to the catchment’s daily rainfall values.

Stormflow Generation and Deep Percolation and Irrigation Recharge

The algorithms for these routines are given in **Chapter 8.3**, where these two processes are discussed in detail within a climate change context.

Modes of Irrigation Scheduling in the *ACRU* Model

Modes of irrigation scheduling (cf. **Figure 8.2.3**) depend, *inter alia*, on the irrigation system (i.e. equipment), the level of management, water availability, climatic conditions, the type of crop and its stage of growth. Five modes of irrigation scheduling are available in the *ACRU* model and the mode may be changed from one to another on a month - by - month basis in the course of a year, depending on crop and climatic demand or other irrigation constraints, for example, the level of farm management.

1. Demand Mode Scheduling According to Soil Water Depletion Levels

When irrigating to avoid crop water stress, scheduling by application of water to the soil just before it has dried to a level where crop water stress sets in is considered a desirable scheduling strategy, because it involves an irrigation application only when it is necessary to prevent crop water stress (Schulze, 1984). Water requirement occurs when the depletion of water in the active root zone, R_z, has reached a critical level, in the case of sugarcane usually 50 % of the plant available water (*PAW*), i.e. $f = 0.5$. In this mode of scheduling, the soil profile is recharged to the *DUL*.

When scheduling according to soil water depletion levels (including planned deficits - see below), the interval between successive irrigation applications is variable (according to crop water use) and stored irrigation water supply is used efficiently because water is only applied when necessary. A high level of management is required for this scheduling option.

2. Demand Mode Scheduling to a Planned Deficit

In depletion level scheduling to a planned deficit the root zone soil profile is deliberately recharged by irrigation application to below the *DUL* when the soil water threshold is reached. The irrigation amount is therefore planned to leave a portion of the potential soil water store, D_a (mm), to be filled by rainfall which could occur. Assumptions in this mode of scheduling would be, *inter alia*, that irrigation is supplementary to rainfall in areas where there is a high probability of rains falling between irrigation applications. Rainfall effectiveness is then maximised and stormflow generation reduced. The potential rain water store for which water applications are reduced can be varied by local climate.

3. Irrigation with a Fixed Cycle and Fixed Amounts of Water Application

Commonly in use with centre pivot systems, a pre-selected amount of irrigation water is applied in a fixed cycle. In *ACRU* the selected cycle length is assumed to continue throughout the growing season, regardless of smaller amounts of rainfall occurring, except that the entire cycle is interrupted and restarted when rainfall on a given day exceeds a selected threshold amount, R_t. This mode of irrigation is commonly used in practice because it is easily managed.

4. Irrigation with a Fixed Cycle and Varying Amounts of Water Application

For the fixed cycle / varied application irrigation scheduling strategy, irrigation applications take place as often as the system limitations will allow, as determined by a specified irrigation cycle time, and in amounts which are limited by

- the available storage potential for water in the soil profile, which is determined according to soil water and a dynamic rooting depth, and which can be either fully or partially refilled,
- the capacity of the irrigation system, and
- the available supply of water.

This is one of the most efficient scheduling strategies and can be used to maximise the benefits of small irrigation systems. When using this scheduling option, irrigation water applications can be initiated prior to planting. These applications together with irrigation applications early in the growing season can help to refill the potential soil water store when transpiration requirements are low and a system with a limited capacity is used. This soil water is then available to supplement irrigation water applications later in the season when transpiration requirements are high. As with demand mode scheduling, the option to leave a portion of the potential soil water store to be filled by probable rainfall can be invoked.

5. Irrigating According to a Pre-Determined Schedule

Irrigating according to a pre-determined schedule is an option available to replicate a known watering regime. The dates and corresponding amounts of water applied to an irrigated field are supplied via the daily hydrometeorological data file (cf. *ACRU* User Manual).

What Mode of Irrigation Scheduling is to be Applied in Climate Change Studies?

- With the cost of water escalating, the heavy competition for the sparse water resources available in South Africa and the prospect of increased irrigation water demand with global warming, the efficient use of water through appropriate scheduling becomes an imperative.
- In a country as climatically diverse as South Africa, certain modes (i.e. methods) of irrigation scheduling may be more effective and more water use efficient in certain climatic regimes, while other modes may be more efficient in other climatic regimes.
- The day - to - day decisions about where to irrigate, or how often, and how much to apply have major implications on the source of supply of the water and on how the water resources are impacted.
- When water is stored in dams, for example, the dam levels and the frequency with which supply can no longer meet its demand are, to a large extent, dependent on amounts of irrigation applied and the irrigation frequency.
- The mode of irrigation also largely determines how high the stormflow losses and especially deep percolation losses from a field are likely to be.
- In order to compare irrigation requirements under different climatic conditions, climate variables should be the only ones to be perturbed. Therefore, the only mode of scheduling that can be considered in a climate change impacts assessment is demand irrigation, already described above, implying irrigating to avoid crop water stress and recharging the soil profile to its drained upper limit, i.e. its *DUL*.
- When scheduling according to soil water depletion levels, the interval between successive irrigation applications is variable (according to crop water use) and stored irrigation water supply is used efficiently because water is only applied when necessary. A high level of management is required when irrigation applications are scheduled according to soil water depletion levels.

It is for above reasons that demand irrigation scheduling was evaluated for South Africa under present and projected future climatic conditions, using the *daily* time step *ACRU* model (Lecler and Schulze, 1995; Schulze, 1995 and updates).

Model Inputs for Simulations of Irrigation Water Demand

In simulations of the irrigation water requirements of an all-year crop under various climatic scenarios, *net irrigation demand*, which is the irrigated water actually required and utilised by the plant in producing biomass, was simulated, rather than *gross irrigation demand* which includes conveyance and field application losses. Model inputs for these simulations are given in **Box 8.2.2**.

Box 8.2.2 Assumptions and Input to the *ACRU* Model for Simulations of Net Irrigation Water Demand

- Irrigation was applied in all 12 months of the year
  - assuming a fully grown crop with a crop (i.e. water use) coefficient of 0.8,
  - with the crop coefficient at which rooting depth reaches a maximum, and when the ground surface is fully shaded, also set at 0.8,
  - an interception loss per rainday and / or overhead irrigation application of 1.5 mm / event,
  - a coefficient of initial abstraction (i.e. an index of infiltrability) of 0.3, and
  - a tilled sandy clay loam soil of depth 0.9 m, with most of the roots in the upper 0.65 m of soil, and
  - with soil water content at
    - saturation set to 0.435 m/m, i.e. equivalent to 392 mm for a 0.9 m soil,
    - drained upper limit set to 0.260 m/m, i.e. equivalent to 234 mm, and a
    - permanent wilting point set to 0.160 m/m, i.e. equivalent to 144 mm for a 0.9 m soil.

The *ACRU* model's irrigation routines (cf. **Box 8.2.1**) were used in conjunction with the 50 year baseline (1950 - 1999) daily rainfall and daily temperature databases (Lynch, 2004; Schulze and Maharaj, 2004) at Quinary Catchments scale (cf. **Chapter 2.2**), as well as with GCM derived daily values for present (1971 - 1990), intermediate future (2046 - 2065) and more distant future (2081 - 2100) climate scenarios from multiple GCMs (cf. **Chapter 2.1**) in analyses of projected climate change impacts on net irrigation requirements over South Africa.

Note that *net irrigation demand*, which is the irrigated water actually required and utilised by the plant in producing biomass, was simulated, rather than *gross irrigation demand* which includes conveyance and field application losses.

Distribution Patterns over South Africa of Statistics of Annual Net Irrigation Demand under Baseline (Historical) Climatic Conditions

Figure 8.2.4 shows mean annual net irrigation demand over South Africa (top left), the inter-annual variability in irrigation demand (bottom left) and lowest and highest net irrigation demands in 10 years (top and bottom right), simulated for a year-round crop with the *ACRU* model under baseline (historical; 1950 - 1999) climatic conditions

Mean annual net irrigation demand over South Africa is high, ranging from < 800 mm in the wetter eastern and southern regions to > 1 600 mm in the arid northwest (**Figure 8.2.4** top left). Inter-annual variability in irrigation demand, expressed through the standard deviation, is moderate at < 100 mm/annum in the west and up to 150 mm/annum in the central north (**Figure 8.2.4** bottom left). Differences between the lowest irrigation water demands in 10 years (wet years) and the highest demands in 10 years (dry years) is only ~ 100 mm, except in the far north where it is ~ 200 mm (**Figure 8.2.4** right hand maps).

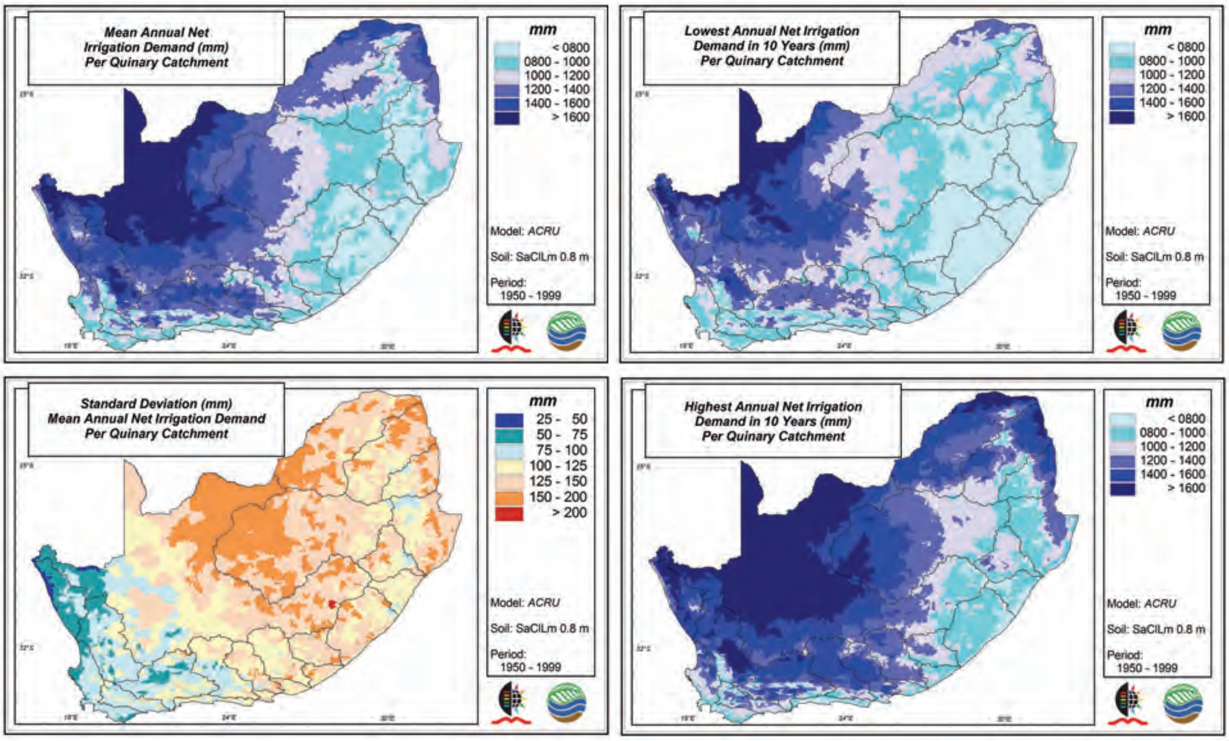

Figure 8.2.4 Mean annual net irrigation demand (top left), the inter-annual variability in irrigation demand (bottom left) and lowest and highest net irrigation demand in 10 years (top and bottom right), simulated with the *ACRU* model under baseline (historical; 1950 - 1999) climatic conditions

Medians of Changes between Future and Present Annual Net Irrigation Demand, Derived from Output from Multiple GCMs

When making projections into the future one needs to have indicators of the confidence in ones results. Because of inherent uncertainties associated with the emission scenarios that drive future changes in atmospheric composition and with the process representations in GCMs (**Chapter 2.1**), such confidence may be gained by applying statistics to outputs from multiple GCMs. One simple indicator of confidence is to map the median of modelled changes from a suite of GCMs.

From the composite results of the five GCMs used in this study, **Figure 8.2.5** (top map) shows that when compared with present day irrigation water demands, supplementary water requirements into the intermediate future (2046 - 2065) are, in fact, reduced in a significant area covering the central eastern parts of South Africa, with reductions of ~ 10 %. This indicates that in those areas the increased demand through higher temperatures, and hence enhanced evaporative demands, is more than offset by corresponding increases in rainfall. In other parts of the interior the medians of the 5 GCMs used indicate no significant change from the present, while in the drier western half and the northern quarter of the country, irrigation water demands are projected to increase by ~ 10 %.

By the more distant future (2081 - 2100) two differences emerge (**Figure 8.2.5** middle map), *viz*. that the area of reduced irrigation demand has shrunk and that in the ~ 90 % of South Africa where irrigation demands are shown to increase, the composite of the 5 GCMs indicates that these increases will be of the order of 10 - 20 % and in parts of the southwestern Cape, even > 20 %.

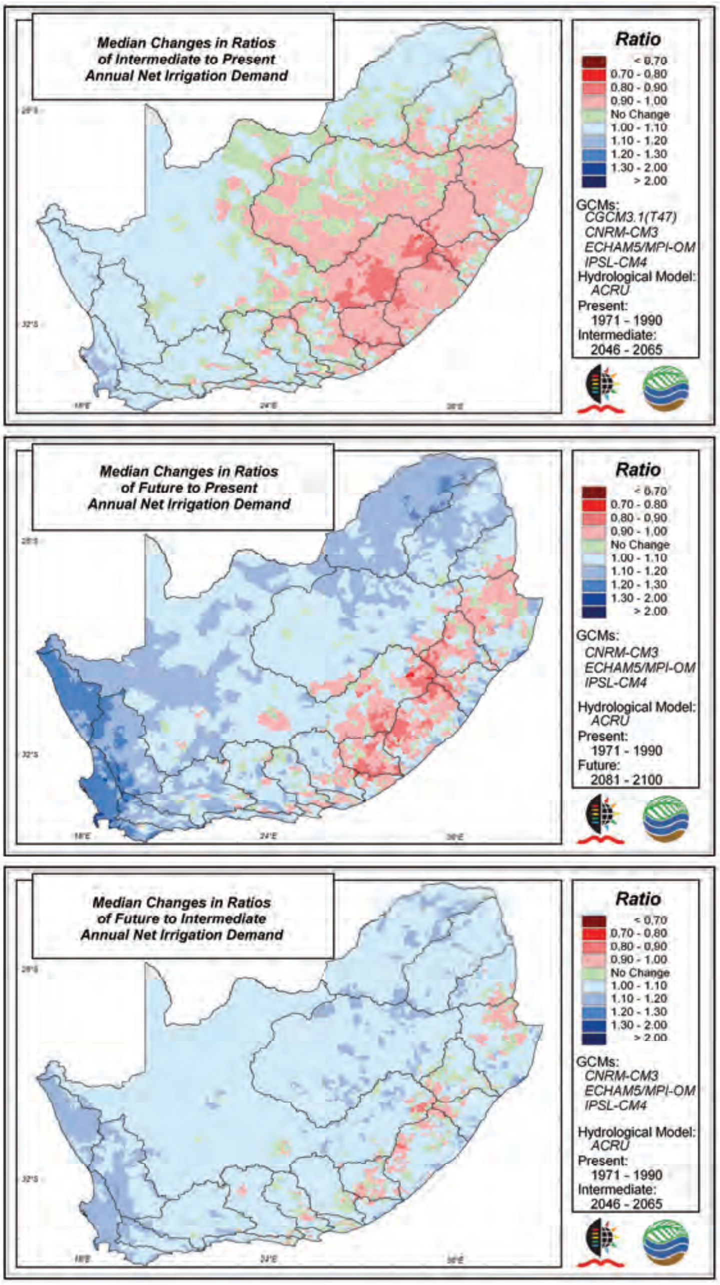

Figure 8.2.5 Median changes in ratios of intermediate future to present (top), as well as of the more distant future to present (middle) and of the more distant to intermediate future, annual net irrigation demands, computed with the *ACRU* model from output of multiple GCMs

Not only are there differences in medians of change in net irrigation requirements in average years, when the projected changes into the intermediate and more distant future climate scenarios are compared, but **Figure 8.2.6** shows that the patterns of change also differ between wet years vs. dry years. Thus, from the present into the intermediate future, the wettest year in 10 displays a significantly larger area of projected decreases than in the driest year in 10 (**Figure 8.2.6** top left vs. top right), while from the present into the more distant future both those areas of projected increases and of decreases are much more intense in the wettest year in 10 compared to the driest year in 10 (**Figure 8.2.6** middle row), with the differences between the changes into the intermediate vs. more distant future scenarios being explained largely by changes occurring in the latter half of the century (**Figure 8.2.6** bottom maps).

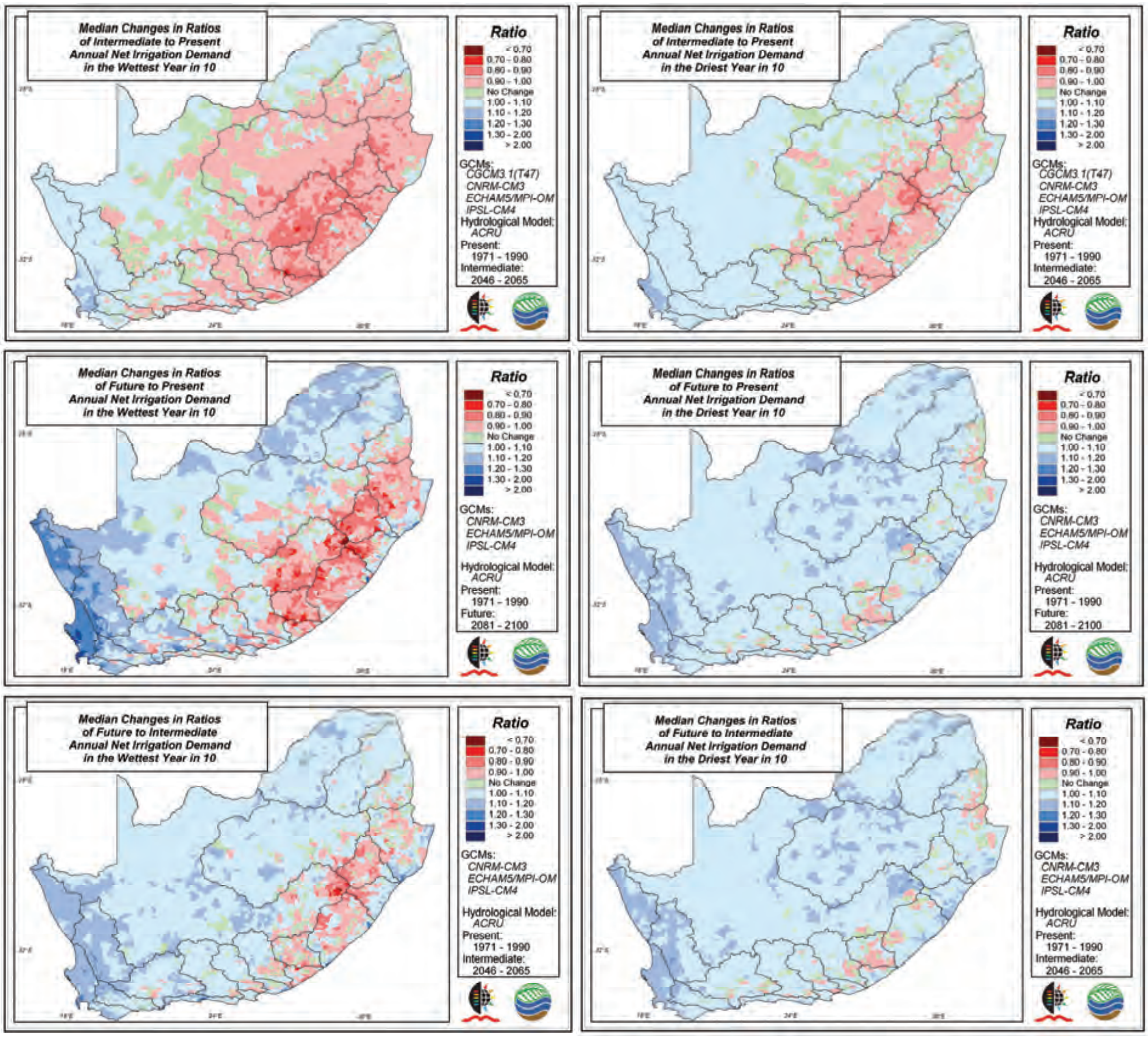

Figure 8.2.6 Median changes in ratios of intermediate future to present (top row), as well as of the more distant future to present (middle row) and of the more distant to intermediate future (bottom row) net irrigation demand in the wettest year in 10 (left column) and the driest year in 10 (right column), computed with the *ACRU* model from output of multiple GCMs

Index of Consistency of Changes in Ratios of Mean Annual Net Irrigation Demand, Computed from Multiple GCMs

In addition to providing confidence in results by assessing medians of changes from multiple GCMs, a second, and more comprehensive, indicator of confidence in results of projections of net irrigation demand is the Index of Consistency of Change (ICC), a composite statistic made up of a weighted combination of the consistency of the *direction of change* when the outputs from the GCMs are compared, with an index of the *degree of dispersion* of the changes between the outputs of the five GCMs (or four for the more distant future), with more details on this statistic given in **Chapter 2.1**.

The ICC for ratio changes in annual net irrigation demand indicates that into the intermediate future ~ 40 years hence (2046 - 2065) confidence in the projections is in the 'Very High' category in those western and northern areas of South Africa identified in the previous section as requiring the highest future additional water for irrigation (**Figure 8.2.7** left map). Confidence in projections of changes in irrigation demand decreases to the 'Low' category in some central parts of South Africa.

Into the more distant future (2081 - 2100) the ICC generated from the multiple GCMs used in this study shows that many areas which ~ 40 years previously would have projected to be in the 'Low' and 'Medium' confidence categories are now in the 'High' category, with only a band in the east displaying 'Moderate' confidence in the projected changes to net irrigation water demand.

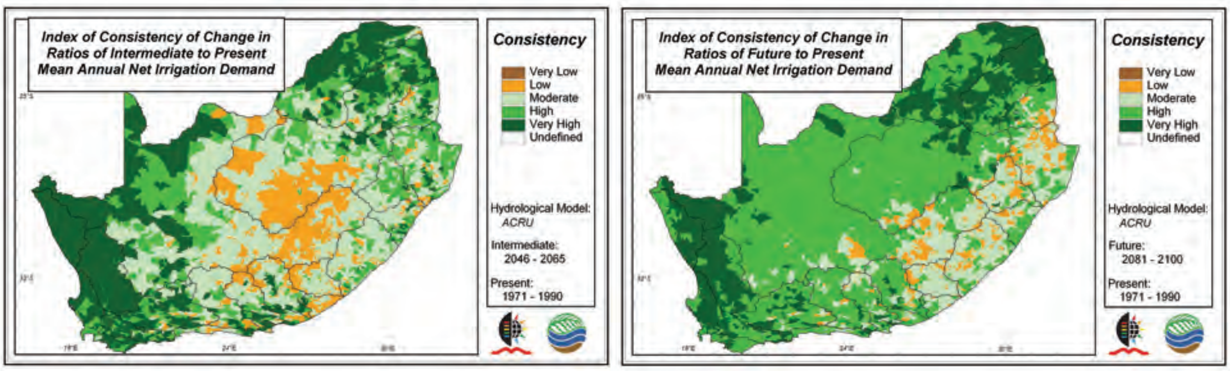

Figure 8.2.7 Index of consistency of changes in ratios of intermediate future to present (left), as well as of more distant future to present (right), mean annual net irrigation demands, computed with the *ACRU* model from output of multiple GCMs

Implications of Findings

The implications of these findings are

- *first, that there are likely to be "winners and losers" in regard to projected future net irrigation requirements, with the already drier parts of South Africa where agricultural production is very much dependent on supplementing rainfall with irrigation, requiring even more supplementary water from irrigation than at present;*
- *secondly, that projected changes display spatial differences between average, wet and dry years, adding to the complexity of managing irrigation water supply;*
- *thirdly, that in the case of projected changes in net irrigation requirements with climate change there is generally high confidence in the results presented;*
- *fourthly, that in many areas, but especially the drier west, this water cannot be sourced locally, but will need to be transferred from distant sources; and*
- *fifthly, that with higher temperatures than at present, a change-over is likely to be needed to more heat and disease tolerant crops*.

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CHAPTER 8.3

CLIMATE CHANGE AND
SURFACE WATER AND DEEP PERCOLATION LOSSES FROM IRRIGATED AREAS UNDER DEMAND IRRIGATION SCHEDULING:
A 2011 PERSPECTIVE

R.E. Schulze and L.M. Bulcock

Environmental Impacts of Irrigation on Water Resources

- A major environmental problem associated with irrigation is that of over-watering, with its downstream consequences (in addition to the costs of wasted water).
- Over-watering can have several *causes*:
  - an ineffective scheduling method, e.g.
    - over-estimating potential evaporation, i.e. the atmospheric demand, thereby increasing the frequency of irrigation applications (generally an over-estimate of 10% results in a 20% increase in volume of water applied; Hess, 1999),
    - incorrect soil moisture budgeting and / or measurements,
    - over-estimating the soil's drained upper limit (again, a 10% over-estimate can result in a 20%+ over-watering; Hess, 1999),
  - uncertainty over the amount of water applied, i.e. applying more than one thinks, resulting from poor settings / calibrations of application rates, and
  - not making best use of rainfall, which is free, when one is scheduling the irrigation applications (e.g. failing to allow for adequate storage capacity in the soil for unforeseen rain falling onto a recently irrigated field).
- *Impacts* of over-watering on water resources include
  - over-abstractions from dams or run-of-river, which not only reduces the availability of the resource downstream, but wastes money and energy, and
  - downstream return flows, since almost all the excess water applied over and above the plant's requirements is returned to the water resource through deep drainage or surface runoff, usually with the return flows being of inferior quality to the water applied, through the increased nitrate leaching in the case of deep percolation and phosphate losses in the case of surface water losses.

The following environmentally related issues also need to be considered in regard to irrigation:

- Irrigation is frequently practised in the drier parts of a country / region, where local water resources are already sparse.
- Furthermore, it is often concentrated over a relatively short period of 2 - 4 months in the year, in which case it can make a significant seasonal impact on downstream water availability.
- From a water resources perspective, most of the water abstracted for irrigation is "consumed" rather than "used" (Hess, 1999), i.e. most is not returned to the water resource as increased drainage, but is rather consumed by plants and returned to the atmosphere in the form of transpired water vapour (with this 'consumption' adding to "green" water flows).
- As indicated above already, some irrigation water losses do, however, occur in the form either of surface water losses from the irrigated fields or of deep percolation losses through the soil profile (which would constitute a use and supplement 'blue' water flows).
- Irrigation water demand is highest in dry years, when water resources are at best already stretched.
- In particular, abstractions for irrigation thus tend to exacerbate the critical low flows in watercourses during the non-rainy season.
- It should be stressed once more that, when soil is wetted beyond its drained upper limit (i.e. field capacity) and water drains from the root zone, this deep percolation water translocates nitrates in solution which will eventually be drained (either by artificial drains or by natural drainage) into local watercourses, or be percolated into the groundwater store. In either case this becomes a source of eutrophication of water bodies.

- Similarly, surface water losses (stormflows) generated from irrigated areas carry phosphates off the field by adsorption onto sediments, again potentially adding to downstream eutrophication.
- In order to minimise such environmental impacts on water resources, appropriate irrigation scheduling needs to be applied.

Surface Water Losses from Irrigated Areas

- As a result of frequent water applications to crops under irrigation, over and above those from naturally occurring rainfall events, irrigated areas can have very different soil water budgets to those of surrounding rain-fed areas.
- Therefore, the frequencies and magnitudes of surface water losses (stormflows) from irrigated areas, Q_{si}, can also be very different to those from the surrounding dryland areas.
- Under certain rainfall regimes in South Africa, and with certain modes of irrigation scheduling, this stormflow from irrigated fields can constitute a significant proportion of the water applied to those fields and add markedly to the total stormflows from a catchment area, as has been shown by Schulze and Dunsmore (1984).
- Additionally, Q_{si} can carry with it considerable loadings of phosphates in suspension from the fertilized irrigated fields, thereby contributing to eutrophication downstream.

The equations used in computations of surface water losses from irrigated fields have been presented within a wider context of overall processes, and especially the irrigation water budget, in the *ACRU* model in **Chapter 2.3**, and are therefore only summarised in **Box 8.3.1** below.

Box 8.3.1 Computations of Surface Water Losses from Irrigated Fields in the *ACRU* Model

In the *ACRU* model, surface water losses (stormflows) from irrigated areas are computed through a modified version of the SCS stormflow equation (Schulze, 1995 and updates). It is expressed in mm equivalents as

$$Q_{si} \quad = \quad (P_{ni} - I_{ai})^2 / (P_{ni} + I_{ai} + S_i) \qquad \text{for } P_{ni} > I_{ai}$$

in which

P_{ni} = net rainfall (mm) on the irrigated area, i.e. gross (measured) rainfall minus irrigation canopy interception losses,
I_{ai} = initial abstractions (mm) from the irrigated area before surface runoff (stormflow) commences, consisting mainly of that infiltration which occurs between the beginning of the rainfall event and the beginning of storm runoff, plus any depression storage,
= cS_i, with
c = coefficient of initial abstraction, and
S_i = the irrigated soil's potential maximum retention (mm), which is equated to the soil water deficit from a critical depth of soil, D_{si}.

Because of tilled soils associated with irrigated fields, a coefficient of initial abstraction, c, was set at 0.3 for irrigated lands. This coefficient does not vary from month to month as it does in dryland routines in *ACRU.* The critical depth of the soil from which stormflow can be generated, D_{si}, is set at 0.3 m for irrigation routines. All computations were based on scheduling irrigation water on demand.

It is important to note that in the *ACRU* model the actual *rate* of irrigation water applied does NOT contribute to any stormflow from the irrigated areas, on the assumption that the soil's infiltration rate would always exceed the intensity of application.

Distribution Patterns over South Africa of Mean Annual Surface Water Losses from Irrigated Areas with Demand Irrigation, under Baseline (Historical) Climatic Conditions

Mean annual surface water losses from irrigated areas under demand irrigation ranges from < 50 mm in the western 90 % of South Africa, which is characterised by lower rainfall and also less frequent consecutive days with rainfall, up to 200 mm in the high rainfall regions mainly in the east, which experience relatively high rainfall events and also more frequent consecutive days with rainfall (**Figure 8.3.1**).

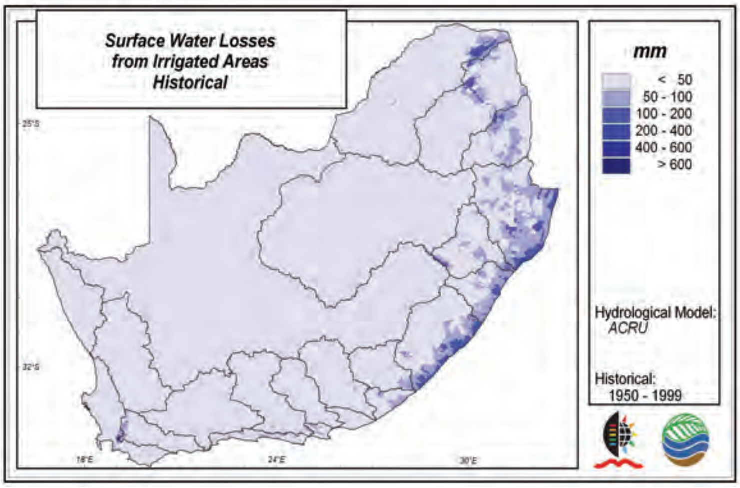

Figure 8.3.1 Mean annual surface water losses from irrigated fields over South Africa under demand irrigation

These surface water losses from irrigated fields constitute significant water and financial losses, especially also in light of already high and still increasing costs of both water and fertilizers.

Medians of Changes between Future and Present Annual Surface Water Losses from Irrigated Fields, Derived from Output from Multiple GCMs

Projections into the intermediate future (2046 - 2065) of surface water losses from demand irrigation, computed using output from multiple GCMs as input into the *ACRU* model, show increases for years of median losses from 10 % in the east to a doubling in the more arid central west, but with no marked changes from the present along the west coast (**Figure 8.3.2** top left). The changes, particularly in the central west, are marked and probably reflect changes in the overall amounts of rainfall received, the persistencies of days with rainfall and higher rainfall per rainday. Patterns for the more distant future (**Figure 8.3.2** top right) are slightly more intensified compared with those projected for the intermediate future.

However, in the driest year in 10 the patterns of change into the future are completely different (**Figure 8.3.2** middle row), with significant reductions in surface water losses in the western half of South Africa (a positive), contrasting with significant increases in the eastern half (a negative in regard to both water and fertilizer costs). Projections for the wettest year in 10 (**Figure 8.3.2** bottom row) change once more in their spatial patterns, with decreases in surface water losses foreseen along the northwest coast and increases in the remainder of the region, with a gradient from more severe surface water losses in the west to only slight increases towards the northeast in Limpopo province.

Deep Percolation Losses from Irrigated Areas

- As in the case of surface water losses from irrigated areas, a consequence of the very different soil water budgets of irrigated fields compared with those of surrounding rainfed land uses can be enhanced drainage losses by percolation of soil water beyond the irrigated crop’s root zone. These percolation losses are very different in frequencies and magnitudes to the recharge from the dryland areas because rain can fall onto an already wetted irrigated area.
- Percolation beyond the root zone can leach the often heavily fertilized irrigated fields of nitrates, thereby contributing to downstream eutrophication.
- Deep percolation can make up a significant proportion of the total irrigation water applied, as has been shown by Schulze and Dunsmore (1984), and it can therefore contribute significantly to downstream return flows.

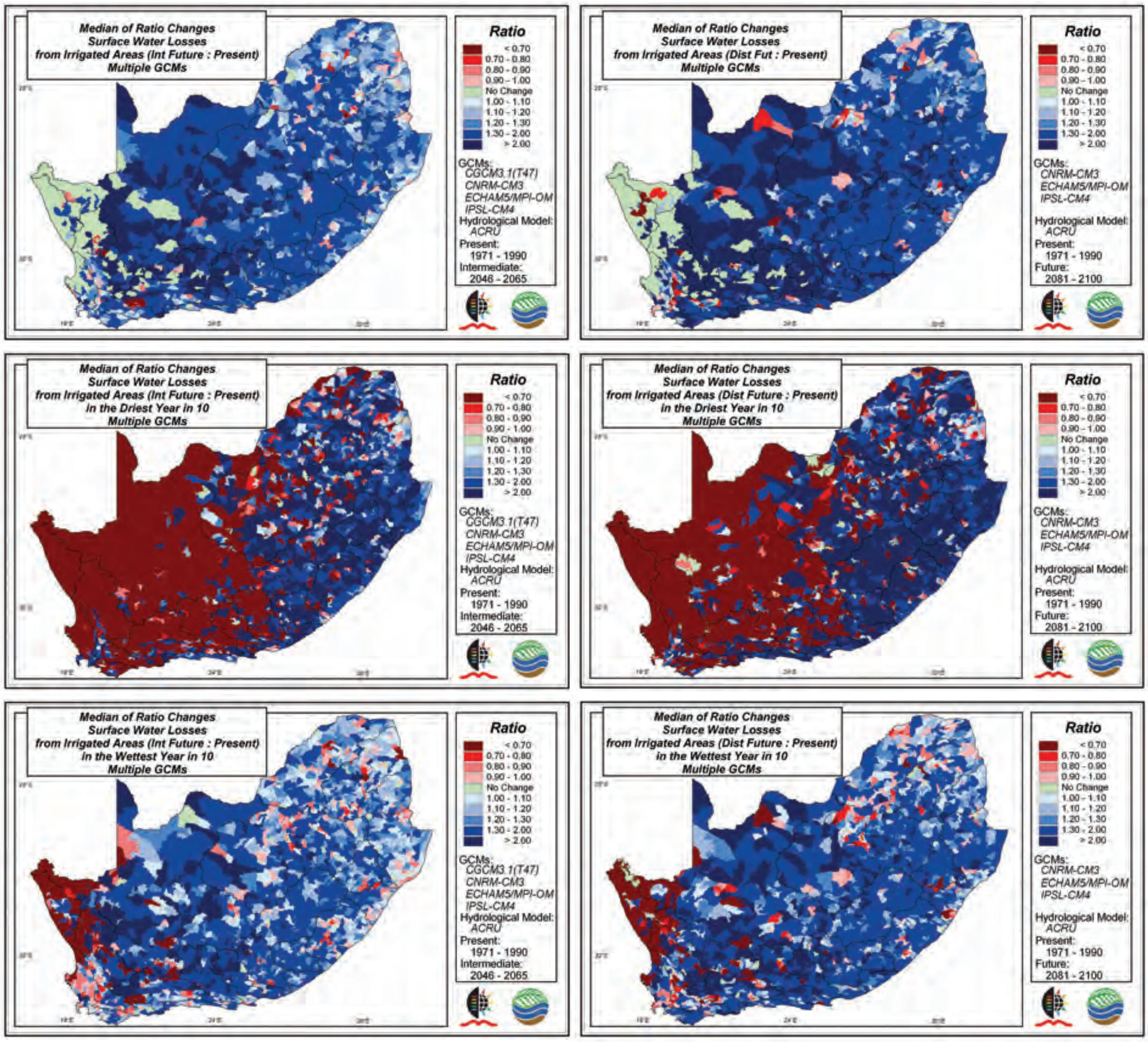

Figure 8.3.2 Medians of ratio changes in surface water losses from irrigated fields between the intermediate future and present (left column) and the more distant future and present (right column) under median year conditions (top row) as well as in the driest year in 10 (middle row) and the wettest year in 10 (bottom row)

Box 8.3.2 Computations of Deep Percolation from Irrigated Fields in the *ACRU* Model

Deep percolation from irrigated fields is initiated in the *ACRU* model (Lecler and Schulze, 1995; Schulze, 1995) as in the equation below:

$$K_{ir} = (\theta_{tmm} - \theta_{DULmm}) \cdot K_{sir} \quad \text{for } \theta_{tmm} > \theta_{DULmm}$$

where

K_{ir} = drainage of water from irrigated fields (mm/day) into the baseflow store,
K_{sir} = saturated drainage coefficient from the irrigated field,
= $(\theta_{POmm} - \theta_{DULmm})/\theta_{POmm}$
θ_{tmm} = actual soil water content (mm equivalent),
θ_{DULmm} = soil water content at drained upper limit (mm), and
θ_{POmm} = soil water content at porosity (mm).

Depending on the drainage rate, soil water in the root zone can be depleted simultaneously by transpiration, evaporation from the soil surface and by deep drainage. Recharge of the ‘surplus’ irrigated water from the catchment’s overall baseflow store is released into the streamflow downstream of the irrigated area via a decay function.

The equations relating to the initiation of deep percolation from irrigated areas are given in **Chapter 2.3** within the wider context of the overall processes encapsulated in the *ACRU* model and especially those of the irrigation water budget in *ACRU*, and are therefore only summarised again in **Box 8.3.2**. In the computations for this Chapter and maps which follow, demand irrigation scheduling was applied.

Distribution Patterns over South Africa of Mean Annual Deep Percolation Losses from Irrigated Areas with Demand Irrigation, under Baseline (Historical) Climatic Conditions

While the broad patterns of mean annual deep percolation losses show some similarities to those of surface water losses with the west at < 50mm, the area with losses exceeding 100 mm and 200 mm and more are considerably greater and extend far further inland, both in the east and in the southwest (**Figure 8.3.3**), indicating that deep percolation losses, and with that associated nitrate losses, are a major environmental concern in irrigation in South Africa, even under the relatively efficient method of irrigating only on demand.

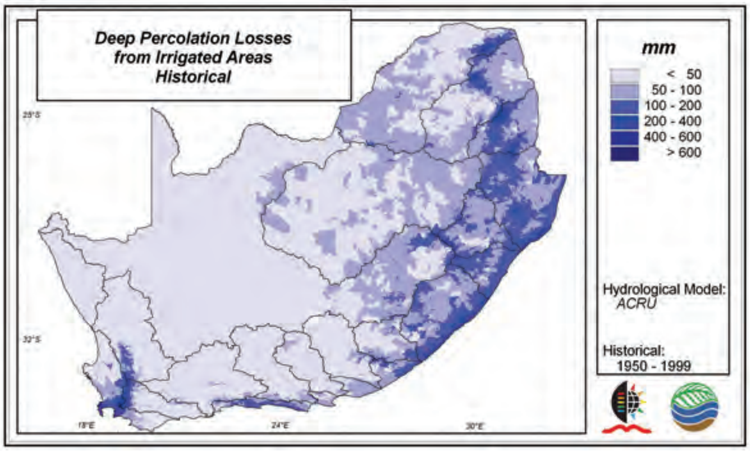

Figure 8.3.3 Mean annual deep percolation losses from irrigated fields over South Africa under demand irrigation

Medians of Changes between Future and Present Annual Deep Percolation Losses from Irrigated Fields, Based on Output from Multiple GCMs

Projections of future deep percolation losses from demand irrigation, computed using output from multiple GCMs as input into the *ACRU* model, show remarkable similarities to those of surface water losses, with increases for years of median losses (**Figure 8.3.4** top row) from 10 % in the east to a doubling in the more arid central west. One significant and positive finding is a projected decrease in deep percolation losses in the southwest, especially in the more distant future. The changes again reflect the projected changes in rainfall characteristics into the future, i.e. changes in the overall amounts of rainfall received, the persistencies of consecutive days with rainfall and higher rainfall per rainday. Patterns for the more distant future (**Figure 8.3.4** top right) are slightly intensified compared with those projected for the intermediate future (**Figure 8.3.4** top left).

Again, in the driest year in 10 the patterns of change into the future are completely different (**Figure 8.3.4** middle row), with significant reductions in deep percolation losses in the western half of South Africa (a positive), contrasting with significant increases in the eastern half (a negative in regard to both water and fertilizer costs). Projections for the wettest year in 10 (**Figure 8.3.4** bottom row) change once more in their spatial patterns, again mirroring those of surface water losses, but with decreases foreseen along the entire west coast and increases in the remainder of the region, with a gradient from more severe surface water losses in the west to only slight increases towards the northeast in Limpopo province.

Important to note is that while the ratio changes of projected deep percolation losses may be similar to those of surface water losses, the modelled deep percolation increases in median and wet years in the east carry considerably higher environmental consequences than those of surface water losses because they come off a considerably higher, and geographically more expanded, base.

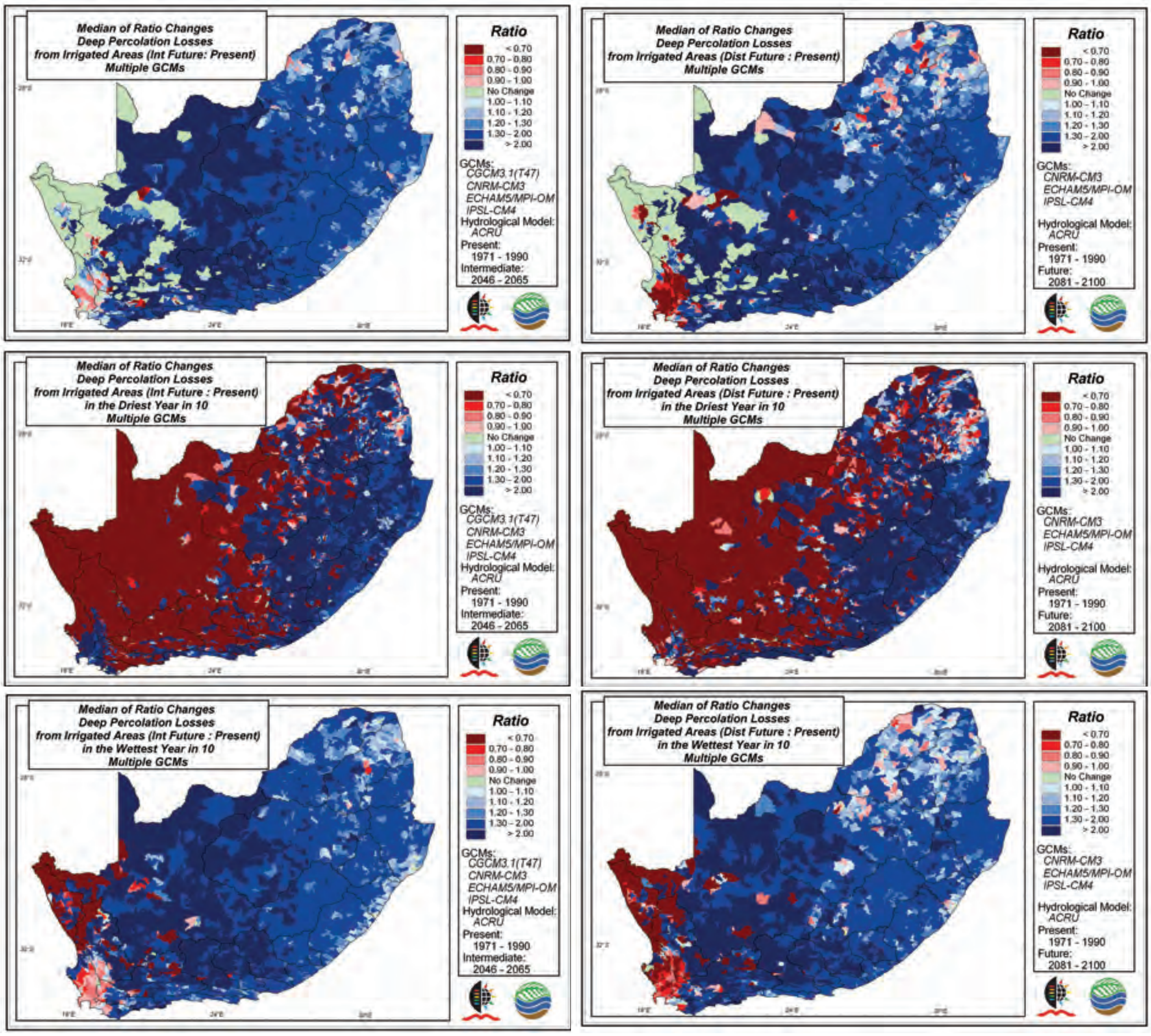

Figure 8.3.4 Medians of ratio changes in deep percolation losses from irrigated fields between the intermediate future and present (left column) and the more distant future and present (right column) under median year conditions (top row) as well as in the driest year in 10 (middle row) and the wettest year in 10 (bottom row)

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CHAPTER 8.4

CLIMATE CHANGE AND
A CASE STUDY IN RAINWATER HARVESTING:
A 2011 PERSPECTIVE

L.M. Bulcock and R.E. Schulze

Introduction

Water scarcity in countries such as South Africa places considerable strain on communities which rely directly on rainfall to sustain their livelihoods. Irregularity in timing and distribution of rainfall may leave many communities without access to water for even the most basic daily requirements. Projected changes in climate in the future may result in even greater irregularities in the availability of water for daily use. Amongst the most vulnerable are poor communities living in low income houses with little access to services and resources. Over the centuries and throughout Sub-Saharan Africa indigenous knowledge systems have adapted various ways of collecting and storing water for later use (Rockström, 2000; Mbilinyi *et al*., 2005). However, the full potential of this type of water supply has not been fully exploited in South Africa to date. It has been suggested that rainwater harvesting (RWH) could be implemented to alleviate the temporal water supply problems and to supplement the conventional water supply systems as demand increasingly grows (Mwenga Kahinda *et al*., 2005).

RWH collectively refers to all methods used to collect, store and utilise rainfall for domestic and agricultural uses (Rockström, 2000; Sutherland and Fenn, 2000). For this Chapter the focus is on collecting rainfall running off from the roof surface of a typical sub-economic house constructed through government initiatives for low income households. Such houses are frequently termed 'RDP houses' after the post-1994 Reconstruction and Development Programme. Collection of the rainwater would be in a water tank.

Rainwater yield depends largely on roof size, tank capacity and the frequency and magnitude of rainfall, but also on the daily water requirements of the household. According to the FAO, the daily per capita water requirement for basic domestic and sanitation functions is 50 litre (Gleick, 1996; Diouf, 2007). For this study an assumption of 6 people per house was made, which is slightly higher than most statistics show for urban households. However, low income households frequently have higher than average numbers of people and therefore a conservative figure was taken. RDP houses in South Africa typically have roof sizes in the range of 30 to 50 m^2, with an average around 40 m^2, as shown in **Photo 8.4.1**.

Photo 8.4.1 A typically sized RDP house in South Africa with roof area around 40 m^2

Rainwater tanks vary are available in various sizes. For the purpose of a baseline study, a medium sized tank with a capacity of 3 000 ℓ was used, as shown in **Photo 8.4.2**.

The methodology to calculate RWH under different climate scenarios is described in **Box 8.4.1**.

Photo 8.4.2 Examples of rainwater storage tanks

Box 8.4.1 Methodology Used to Calculate Rainwater Harvesting Under Different Climate Scenarios

Daily rainfall values were extracted from data files of the multiple GCMs used in this study (cf. **Chapter 2.1**) for the three 20 year periods representing the present (1971 - 1990), the intermediate future (2046 - 2065) and the more distant future (2081 - 2100) climate scenarios. An initial abstraction (i.e. loss, *Ia*) of 1 mm was assumed as a detention loss due to evaporation from, and adhesion to, the roof, and this was then subtracted from the day's rainfall. The remaining rainfall was available for collection in the 3 000 ℓ tank. The amount of water that can be harvested from the roof was then calculated as:

$$\textit{Harvested Water (l)} = \textit{(rainfall (mm) - Ia) x roof size (m}^2\textit{)}$$

Household water requirements were calculated according to FAO specifications, *viz.*

Household requirements (l) = Number of people x daily requirements per capita (l)

i.e. 300 ℓ based on 6 people at 50 ℓ per person per day. A model was set up to calculate the daily inflows into the tank from rainfall (on days when it rained more than 1 mm) and the daily abstractions for the household requirements. Assuming the rain to fall at the end of a day and after household water requirements had been abstracted from the tank, the model calculated the average number of days in a year that the tank:

- was completely empty,
- was filled completely and overflowed,
- fulfilled the daily requirements of the household (*viz*. 300 ℓ) and still had some water remaining, and
- provided some water for the daily requirement, but not enough to fulfill the total needs and was thus emptied as a result.

Availability of Household Water from Rainwater Harvesting under Present Climate Conditions

"Present climate" in the context of this study on RWH refers to computations having been performed with each of the multiple GCMs for the 20 year period 1971 - 1990, with the average of the respective results then mapped per Quinary Catchment. **Figure 8.4.1** (top left) shows that under present climate conditions a 3 000 ℓ tank serving a household of six at 50 ℓ per person per day would overflow on fewer than 50 days per annum over virtually the entire region. On the other hand, the 3 000 ℓ tank would be completely empty for over 200 days along the east coast and its hinterland, for over 250 days over much of the remaining eastern half of South Africa and for over 300 days per year in the western half of the region and in northern Limpopo (**Figure 8.4.1** top right). The 3 000 ℓ tank was simulated to be full, but not overflowing on 50 to 100 days per year in the eastern half, with the remainder at < 50 days per annum (**Figure 8.4.1** bottom left). The fourth possibility, *viz*. that of the 3 000 ℓ tank being partially full, was achieved on fewer than 50 days p.a. over most of South Africa, with small patches along the south and east coastal areas at between 50 and 100 days per year (**Figure 8.4.1** bottom right).

Given the tank and household criteria used in this case study, the eastern part of the region shows the greatest potential for RWH, with the tank being empty on fewer occasions and fulfilling the daily household water needs for more than half of the year. Certainly the western parts of South Africa would, under present climatic conditions, require a considerably larger tank to fulfil household needs of a family of six given a roof area of 40 m^2.

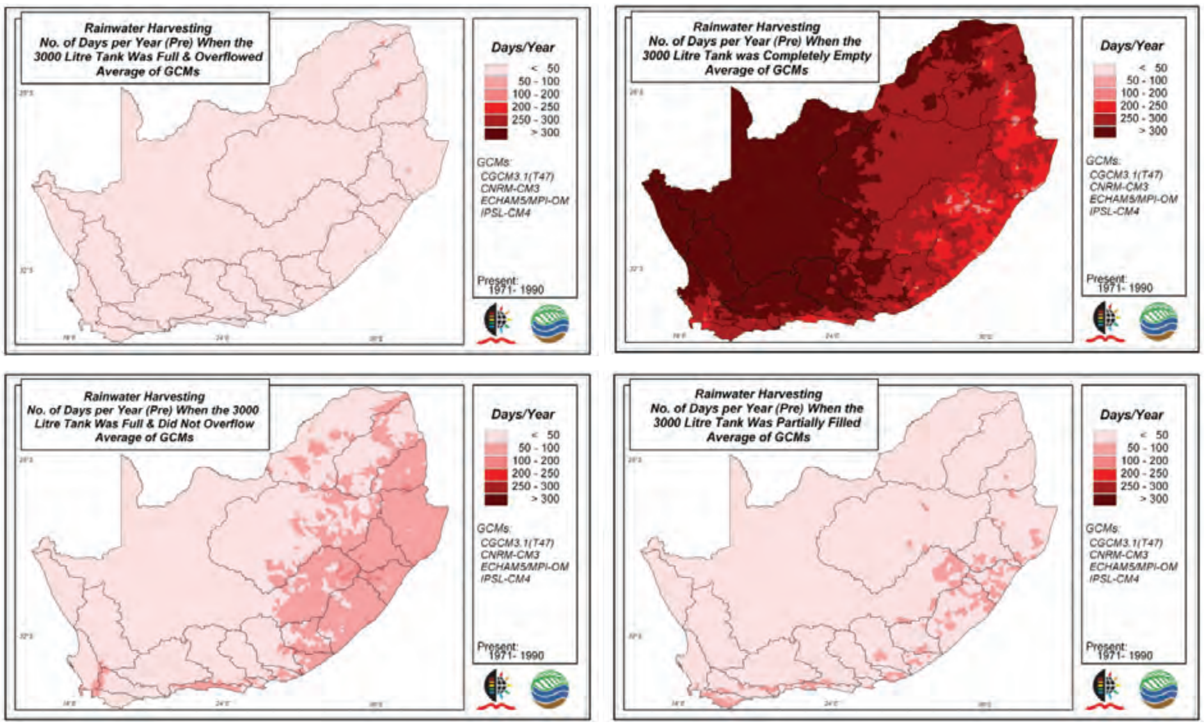

Figure 8.4.1 Rainwater harvesting potential over South Africa from a 40 m^2 roof and 3 000 ℓ tank supplying a household of 6 at 50 ℓ per person per day under present climate conditions, showing the number of days per year that the tank overflowed (top left), that it was completely empty (top right), that it could fully supply the basic water needs (bottom left) and that it could only partially fulfil the household's water needs

Ratio Changes and Absolute Changes of Future to Present Availability of Household Water from Rainwater Harvesting, Using Outputs from Multiple GCMs

The ratio of change analysis in **Figure 8.4.2** (left column) shows that under the climate change conditions into the intermediate future (2046 - 2065) projected from the multiple GCMs used, the potential for RWH generally increases across most of South Africa. The tank is projected to overflow 30 % twice more often (**Figure 8.4.2** top left), except in the southwest, and be completely empty 10 - 20 % less frequently, the exception again being the extreme southwest with fewer raindays and rainfall per rainday (**Figure 8.4.2** left column, second map). Over the majority of the country, the tank will be able to supply the daily needs of the household in full more often (**Figure 8.4.2** left column, third map), as is generally the case for the tank being able to at least partially fulfil household water needs (**Figure 8.4.2** left column, bottom map). While in relative terms the changes appear significant (left column of maps), in absolute terms when expressed as increases / decreases in days per annum, the right column of maps in **Figure 8.4.2** shows that actual days of change are quite small.

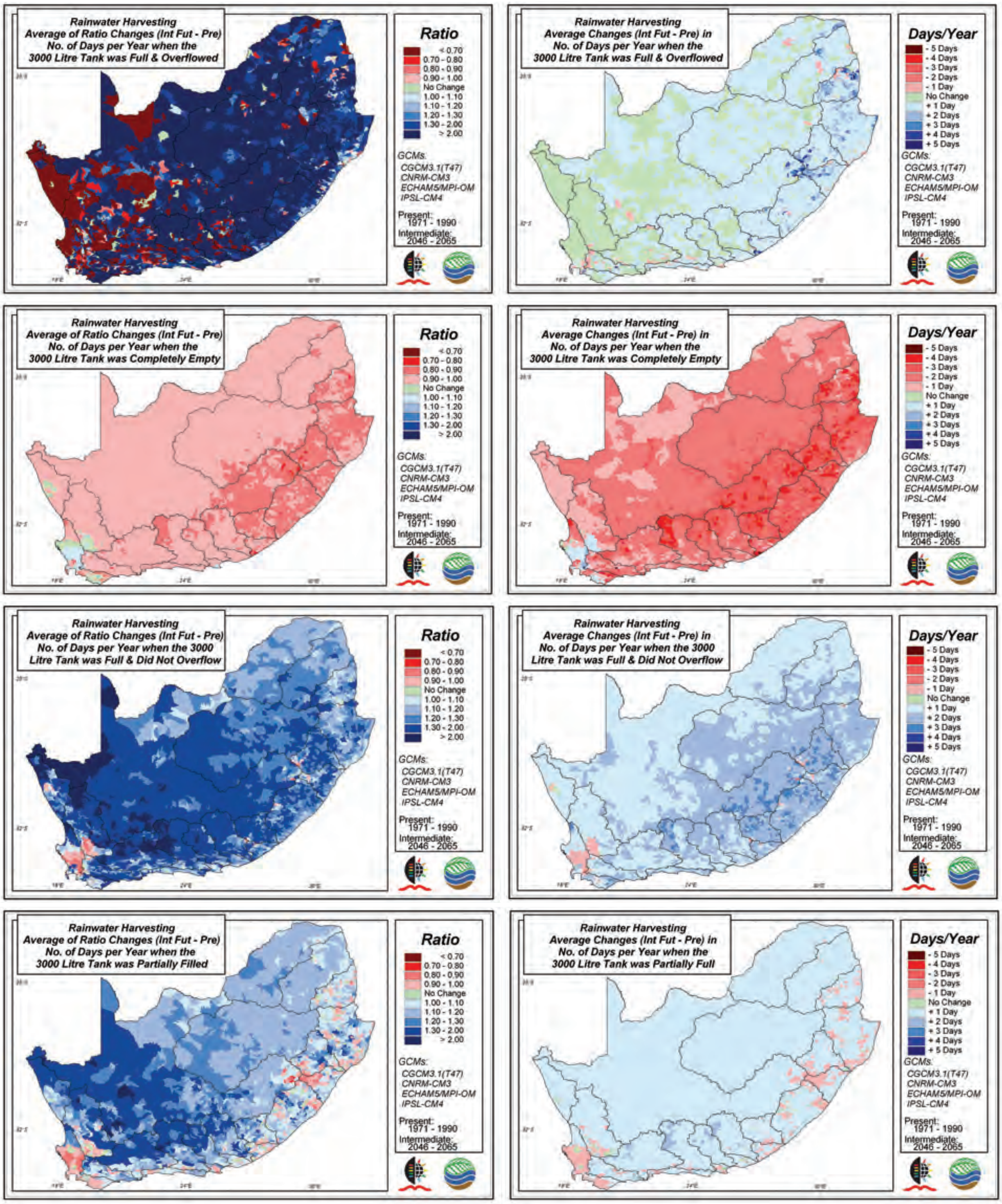

Figure 8.4.2 Averages of ratio changes (left column) and absolute changes (right column) in rainwater harvesting potential between climate conditions under intermediate future (2046 - 2065) and present (1971 - 1990) climate scenarios, derived from output of multiple GCMs

Figure 8.4.3 shows that from the present (1971 - 1990) into the more distant future climates (2071 - 2100) projections from multiple GCMs display an expansion / consolidation of areas in the west on which the tank overflowed (top left), fewer days in the east on which the tank would be empty (left column, second row), more days over most of the country on which household water needs were completely satisfied from the tank (left column, third map) and also more days on which water needs could be at least partially satisfied by rainwater harvesting (left column, bottom map). All these trends are translated into the maps of absolute changes in days per year in the right column of maps.

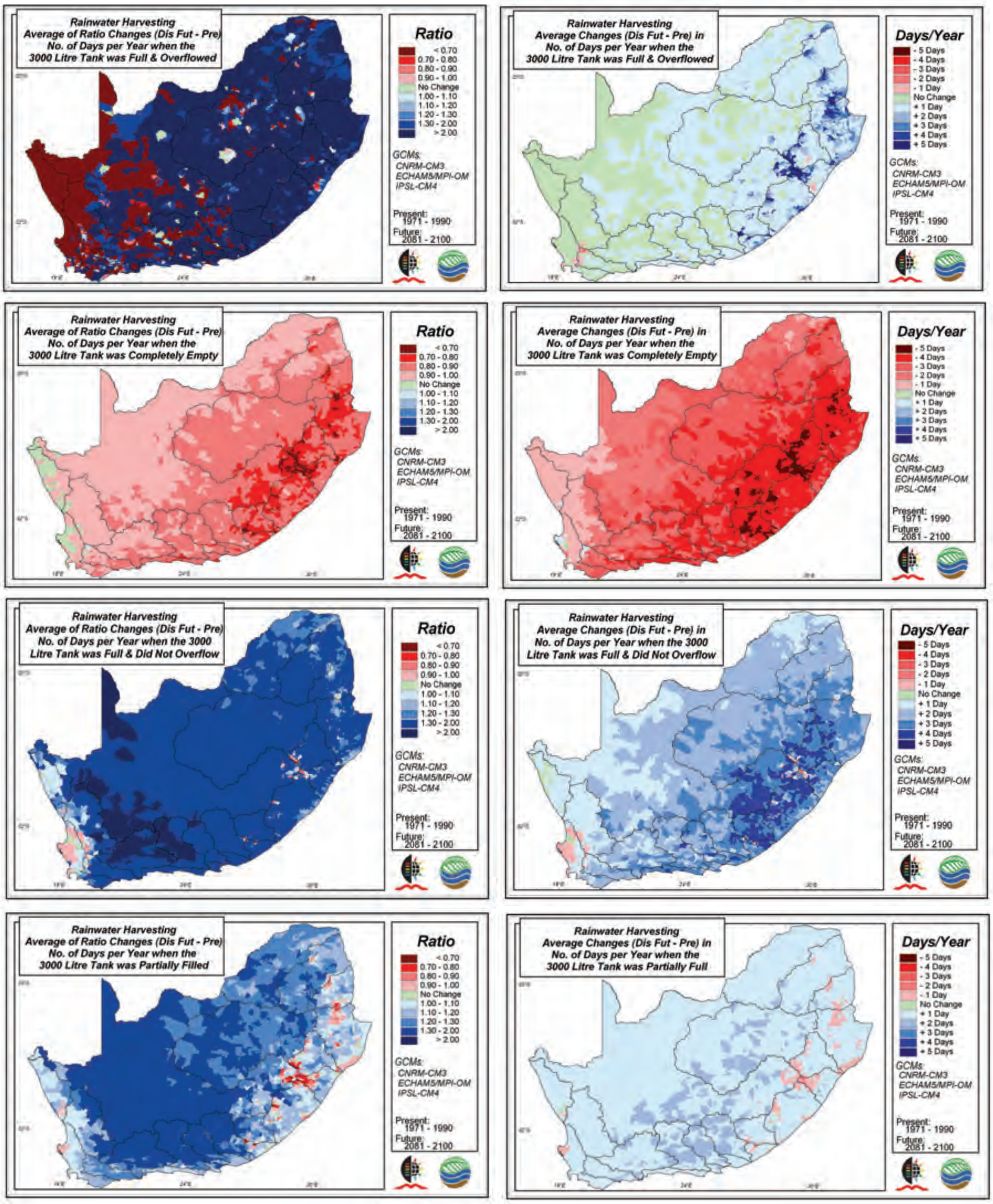

Figure 8.4.3 Averages of ratio changes (left column) and absolute changes (right column) in rainwater harvesting potential between climate conditions under more distant future (2071 - 2100) and present (1971 - 1990) climate scenarios, derived from output of multiple GCMs

To a large degree the differences in the changes between present to intermediate future (**Figure 8.4.2**) and the present to more distant future (**Figure 8.4.3**) are explained in **Figure 8.4.4** which shows the ratio changes in the relatively short 35 year period between the intermediate and distant future scenarios. While the changes in the number of days when the tank overflows (top left) decreases strongly in the west, the number of days that the tank could fully satisfy household demand also shows a marked decline in northwest (bottom left) and days on which requirements could only be partially satisfied show decreases in east and west, but increases in a broad central tract across the country (bottom right).

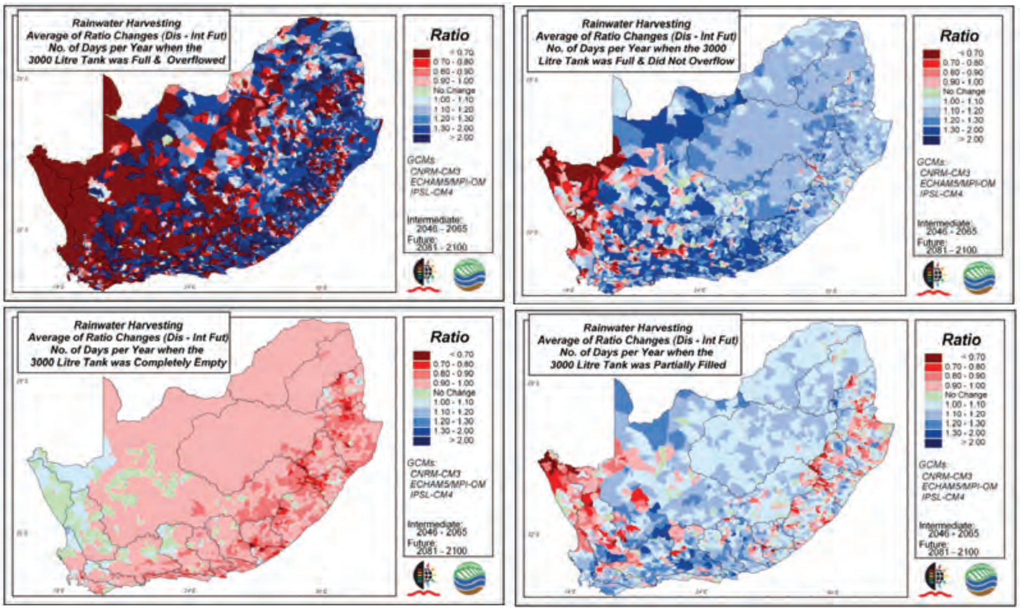

Figure 8.4.4 Averages of ratio changes in rainwater harvesting potential between climate conditions under more distant (2071 - 2100) and intermediate future (2046 - 2065) climate scenarios, derived from output of multiple GCMs

This case study has shown for the specified roof area, tank size and household size / needs, that RWH as a long term alternative water supply is not feasible along the west coast, neither under present conditions nor under conditions of projected climate change. However, most of the remainder of the country may hold potential for RWH to fulfil, or at least supplement, basic household requirements, especially under projected future climates as the tank is often full and there is even an increase in the number of times the tank overflows. It stands to reason that larger tanks may help to exploit this water supply option even more through increased collection and storage.

It is recommended that this study be expanded to assess impacts of present and future climates on a range of roof areas, household sizes and per capita water needs in order to obtain more optimum tank sizes for the different climatic regions in South Africa.

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SECTION 9

CONCLUSIONS: SUMMARY OF FINDINGS AND APPROACHES TO ADAPTATION

CHAPTER 9.1

SUMMARY OF RESULTS AND KEY FINDINGS FROM THE 2011 STUDY ON CLIMATE CHANGE AND THE WATER RELATED SECTOR IN SOUTH AFRICA

R.E. Schulze

A summary of results is given section by section and, within the technical sections, chapter by chapter by chapter, and this is followed by a summary highlighting the key hydrologically related findings.

Section 1 Background Information (Chapters 1.1 to 1.3)

- There is an overwhelming body of evidence that anthropogenically induced greenhouse gas emissions are increasing and with that global temperatures and rainfall patterns are changing, with the likelihood of significantly changing hydrological responses (**Chapter 1.1**).
- Climate change evidence has been used by the International Geosphere-Biosphere Program (IGBP, 2009) to produce a composite climate change index and this index shows the clear rise in climate change since 1980 (**Chapter 1.1**).
- With global climatic changes, changes in the South African water related sector will be inevitable, since the regional climate in South Africa is dependent on global climate, both today and in the future.
- No one knows exactly how the future global climate will develop and what the resultant consequence to South Africa's water related sector will be, but impacts could be considerable.
- Different regions of the country will likely be affected in many different ways and many knock-on effects are likely to occur.
- Given the importance of water as a constraint to development in South Africa and the importance of climate as a driver of the hydrological system, as well as the symbiotic relationships between water and agriculture, water and biodiversity, health and disaster risk management, impacts of climate change on hydrological drivers and responses in South Africa are assessed in this document, as are thoughts towards an adaptation strategy for the water sector and towards practical adaptation measures (**Chapter 1.2**).
- Because of the complexity of the country's physiography, climate and socio-economic milieu, detailed local scale analyses are needed to assess potential impacts (**Chapter 1.2**).

Section 2 Downscaling, Databases and Models

- Output from General Circulation Models (GCMs) is the most widely applied method of assessing impacts of climate change, since GCMs, despite many uncertainties associated with them, are able to simulate the most important features of the global climate (**Chapter 2.1**).
- However, because hydrological impacts occur at more local scales, outputs from the global scale GCMs have to be downscaled to an appropriate finer scale spatial resolution. For this study, this was undertaken by the University of Cape Town through empirical downscaling to the level of over 2 600 rainfall and over 400 temperature stations.
- In the various impact studies, daily rainfall as well as maximum and minimum temperature values from a 50 year historical (baseline) record (1950 - 1999) are used, as is output from five state-of-the-art GCMs, *viz.* CGCM3.1(T47), CNRM-CM3, ECHAM5/MPI-OM, GISS-ER and IPSL-CM4, in each case for three 20 year scenarios, *viz*. for
    - present climate, from 1971 - 1990, for
    - an intermediate future climate, from 2046 - 2065, and for
    - a more distant future climate, from 2081 – 2100 (**Chapter 2.1**).
- The daily climate values from these scenarios were assigned to each of 5 838 Quinary Catchments into which South Africa (in this study made up of the RSA, Lesotho and Swaziland) had been delineated (**Chapter 2.2**) and, with hydrological soils and land cover attributes added to this database, simulations could be performed with the physical - conceptual, daily time step *ACRU* agrohydrological model (**Chapter 2.3**) as well as with statistical models for extreme value analyses.

- Since overall changes in future scenarios of climate depend strongly on *which* GCMs were used, and *how many* GCMs were in the ensemble that was used, it should be noted that the five GCMs which were available for use in this study, and named above, are considered by climatologists to produce rainfall output somewhat on the wet side of the spectrum and this has to be borne in mind in interpreting any impacts in which rainfall is an input variable.
- Given the uncertainties in outputs from GCMs, a verification study was undertaken on those outputs of the five GCMs which were available to this research (**Chapter 2.4**). Outputs considered relevant to this study because they were hydrologically critical indicators were first selected. For this study these were
  - monthly means of daily maximum temperatures, represented by the values from January as the hottest month, and important in the estimation of potential evaporation;
  - monthly means of daily minimum temperatures, represented by the values from July as the coldest month, and also important in the estimation of potential evaporation;
  - the number of days per year with a rainfall of 10 mm or more, as a test to ascertain whether the downscaled GCMs could capture the significant rainfall events adequately, with 10 mm per day generally being a threshold for stormflows and sediment yields to be generated from a catchment; and
  - the number of days per year with a rainfall of 25 mm or more, as an even more stringent test to ascertain whether the downscaled GCMs could capture the hydrologically even more significant rainfall events adequately, with 25 mm per day generally resulting in a distinct hydrograph.
- The relevant values of the indicators listed above were extracted for each of the 5 838 Quinary Catchments covering South Africa from the daily output files. This was done for the overlapping period from 1971 to 1990 of historical daily rainfall and temperature data (i.e. the "observed" data) and output from the 5 GCMs available for this study (the "simulated" values). Results were shown either as scatterplots, as maps or in tabular summaries.
- By and large the verifications showed the final selection of GCMs to generate relatively good results for hydrologically critical temperature and rainfall parameters.
  - Spatial error analyses showed apparent errors in GCM output to vary by parameter and it was determined that no single GCM was the "best" for all regions within South Africa, nor for all hydrological drivers and responses.
  - Some of the apparent GCM output errors can, in fact, be attributed to errors in the historical datasets which were used as the control in the verifications. The same Quinary Catchments appear to produce outlier results with all the GCMs used, which begs the question of re-checking the historical datasets.
  - There furthermore appear to be regional biases in GCM outputs and subsequent impact studies should therefore consider regional bias corrections to temperature and rainfall output before being used with hydrological models (**Chapter 2.4**).
- However, many of these apparent errors and causes of uncertainties are considered to be largely self-cancelling and / or largely eliminated since the impacts in the chapters which follow are expressed as ratio changes between projected future and present climates, both derived from GCMs, with these projected changes then mapped as the mean or median of the results from the multiple GCMs used (**Chapter 2.4**).

Section 3 Projected Changes to First Order Climate Variables

First order variables in climate change studies include changes in CO_2 concentrations, in temperature attributes, and in rainfall characteristics. In this document only impacts of changes in temperature and rainfall were evaluated. The abbreviation IF is used for the intermediate future (2046 - 2065) and MDF for the more distant future (2071 - 2100).

Annual Temperature Statistics (Chapter 3.1)

In the hydrological cycle, temperature affects rates of evaporation from the soil, the plant and from water surfaces directly, while indirectly it affects plant growth and senescence which, in turn, influence transpiration rates. It is the one climatic variable for which there is a high degree of certainty that it will increase with global warming.

- Into the IF *annual temperatures* are projected to increase by 1.5 - 2.5 °C along the South African coast (illustrating the moderating influence of the oceans) to 3.0 - 3.5 °C in the far interior.

- By the end of the century an accelerating increase in temperatures becomes evident with projected increases between 3.0 - 5.0 °C along the coast and up to > 6.0 °C in the interior.
- Year-to-year variability of annual temperature tends to increase in the northern half of the country and decrease in the south.

January (Summer) Maximum and July (Winter) Minimum Temperatures (Chapter 3.2)

- By the IF averaged January maxima are projected to increase by 2 °C - 3 °C with essentially an east to west gradient, while July minima are set to increase by a wider range from < 2 °C to > 3 °C, but with essentially a south to north gradation.
- By the MDF the average increases range from 4 °C in the east for January maxima to > 6 °C in the northwest, while the range for July minima is once again wider with increases < 4 °C along the southwest coast to > 6 °C in the interior.
- Both January maxima and July minima display marked accelerations in increases in the latter half of the century.
- Into the IF changes in the variability of January day-time high temperatures are neither uniform in direction nor in magnitude. By the end of the century, however, very different changes in the variability of January maxima has emerged, with the central and northern interior displaying strong increases in variability (changes > 30 %), while the west coast shows strong reductions in temperature variability by up to 30 % (and more in places).
- For minimum temperatures in July (mid-winter) virtually the entire South Africa shows increases in inter-annual variability by the IF, and up to a doubling in places.

Rainfall: Background (Chapter 3.3)

In hydrology, among the individual climatic variables which influence the generation of runoff, certainly in South Africa the most important and sensitive is rainfall, as it is the fundamental driving force and pulsar input in many hydrological processes. In the South African context, limitations in water availability are frequently a restrictive factor in economic development. Focus of this Chapter is on the patterns of rainfall in time and over an area, by enquiring *how much* it rains, *where* it rains, *when* it rains, how *frequently* it rains, and what the *duration* and *intensity* of rainfall events are.

Annual Rainfall Statistics (Chapter 3.4)

It has already been alluded to that overall changes in future scenarios of climate depend strongly on *which* GCMs were used, and *how many* GCMs were in the ensemble used. Once again it should be noted that the five GCMs which were available for use in this study, *viz*. CGCM3.1(T47), CNRM-CM3, ECHAM5/MPI-OM, GISS-ER and IPSL-CM4, are considered by climatologists to produce rainfall output somewhat on the wet side of the spectrum, and this has to be borne in mind in interpreting any impacts in which rainfall is an input variable. In the course of the research it was established that the GISS-ER GCM contained errors in rainfall representation and this GCM was then omitted from further analyses in which rainfall was an input.

- Even under current climatic conditions, South Africa is regarded as a semi-arid country with ~ 20 % receiving < 200 mm per annum, 47 % < 400 mm and only ~ 9 % with a MAP in excess of 800 mm. Inter-annual variability is very high by world standards, with an inverse relationship evident between variability and the magnitude of annual rainfall.
- Projected medians of changes in MAP from the ensemble of GCMs used show an overall wetting into the intermediate future, very slight in the west and more pronounced in the east, particularly in the more mountainous areas. By the more distant future intensifications of changes in MAP become evident, with areas of decrease in the west and the increases in the east from 200 mm and up to 500 mm in the escarpment and mountainous runoff producing areas. The period of significant change in the west appears to be in the latter half of the century.
- The averaged ratio changes from multiple GCMs in the inter-annual variabilities of rainfalls show standard deviations (a measure of absolute variability) to be intensifying from the intermediate to the more distant future, with significant increases in the year-to-year variability of annual precipitation in the east (from 30 % up to a doubling), but with decreases in the west.
- The overall projected increase in rainfall variability into the future has important repercussions on the management of water resources and operations of major reservoirs as well as on the year-on-year consistency of agricultural production.

Monthly Rainfall Statistics (Chapter 3.5)

- For many water resources problems and decisions MAPs or even wet / dry season precipitation totals, be they high or low, are of relatively little consequence, because an intra-year distribution of rainfall is required. Monthly rainfall values then serve as an important tool in describing such an intra-year distribution.
- *Changes* in distribution patterns over South Africa of medians of precipitation in cardinal months, *are not uniform*, but vary markedly in
  - *direction*, in
  - *intensity*, as well as varying
  - *spatially* within South Africa in a given month,
  - *between different months of the year* for the same statistic, and
  - *between the intermediate future and the more distant future* for the same statistic, with this last-named difference suggesting an
  - *intensification and acceleration of impacts* of climate change over time.
- A recurring feature is a general *wetting trend* of varying intensity and distribution in both periods of change considered, particularly *in the east*. This wetting trend is, in general, projected to be beneficial to South Africa's water availability, but could be detrimental in regard to flood damage / erosion.
- There is a *drying trend* evident *in the west*, mainly towards the end of its rainy season. Combined with increases in temperature, repercussions on irrigation demand and water resources could thus be severe in the west.
- The GCMs used in this study also display a *drying trend in the northern areas* of South Africa in the latter half of this century, mainly in the middle and towards the end of the wet season (i.e. January, April), with projected negative impacts on water availability (and crop yields) there.
- The area which is *transitional between the summer and winter rainfall* areas in South Africa frequently displays marked relative increases in rainfall.
- The *choice of statistic* with which to assess possible changes in the variability of future climates *is crucial*, and it is suggested that the *standard deviation,* as an *indicator of absolute variability*, be used as it is not influenced by simultaneous changes in means, as is the case with the CV.
- For the period up to the intermediate future marked differences in averaged ratio changes of standard deviations are seen in the four cardinal months, as are differences in direction and intensity within a given month. January and April display a narrow coastal strip of decreased rainfall variability into the future, but with a general increase over the interior which intensifies into autumn.
- By mid-winter virtually the entire South Africa displays significant increases in the inter-annual variability of rainfall. Over much of the country this has little impact on water resources as mid-winter coincides with the dry season, but in the winter rainfall region of the southwest it does. By October, the rainy season starts for much of the country, the eastern half of South Africa and the southwest show reductions in variability, with only the semi-arid central interior displaying averaged increases in variability.

Thresholds of Daily Rainfall Amounts Exceeded (Chapter 3.6)

On days on which it rains, certain thresholds of rainfall become important, and the frequency that such thresholds are exceeded (or not) is important in climate change studies in hydrology. While 1 mm is a threshold for initial abstractions from impervious areas, under South African conditions 2 mm per day is generally accepted as exceeding plant interception and implies a threshold for actually wetting the soil. Five mm per day implies that rainfall is likely to have compensated for evaporative losses while 10 mm is often used as a lower threshold for the generation of stormflow and sediment yield, with a daily rainfall > 25 mm usually resulting in a more significant hydrograph being generated.

- Based on outputs from the multiple GCMs used, irrespective of the threshold rainfall, more days are generally projected to occur from the present into the IF, projected increases being ~ 10 % in the east and west, 10 - 20 % in the central east and 20 - 30 % in the more arid central west with, however, a weak signal of little change for the heavy rainfall days > 25 mm along the west coast.
- Into the more distant future there is a general intensification of increases in the number of days on which the various thresholds are exceeded and an expansion of areas with higher increases, except for days with high rainfalls along the vulnerable west coast, where first indications are that the numbers of days with rainfall above 25 mm is projected to decline.

- However, the 110 year time difference between the present and MDF (1971 -1990 vs. 2081 - 2100) obliterates an area of *consistent decreases* in the number of days per year with critical thresholds of rainfall being exceeded in the latter half of the century, *viz*. the west coast. When ratio changes between the IF and the MDF are assessed (i.e. 2046 - 2065 vs. 2081 - 2100), a *decrease is displayed for all threshold values analysed*, but with signs of greater intensity for the higher thresholds (> 10 and 25 mm per day), which are hydrologically more critical in that they are the runoff producing events.
- This could have major repercussions for long term water resources planning in the Western Cape province.

Section 4 Projected Changes to Second Order Climate Related Derivatives

Reference Evaporation by the Penman-Monteith Method (Chapter 4.1)

The accurate estimation of evaporation is vital in hydrology, for it is the driving force of the total amount of water which can be vaporised from open water surfaces such as dams, wetlands or river channels or be "consumed" by a plant system through the evaporation and transpiration processes. Evaporation is a particularly relevant process in South Africa, with the annual losses of 1 200 to over 2 600 mm under present conditions being highly sensitive to increases with climate change. The selected reference by which to estimate evaporation was the Penman-Monteith equation, E_{rpm}, which has become the *de facto* standard method internationally.

- A sensitivity analysis shows that in January (summer) a 2 °C temperature increase is simulated to increase E_{rpm} by ~ 3.5 % (2.9 - 3.8 %), while in winter (July) the percentage increases are even higher than in summer.
- Output from the multiple GCMs used in this study shows that by the IF an increase in annual E_{rpm} around 5 - 10 % is projected over most of South Africa, with patches increasing by > 10 %, especially along the west coast.
- By the MDF, however, the medians of the projections display annual increases of 15 - 20 % in the far interior, but 20 - 25 % along the western, southern and eastern periphery of the country.
- Projected changes in E_{rpm} are, however, neither seasonally nor spatially consistent, with the lowest increases for both the IF and for the MDF shown in mid-summer (January) and the highest increases in autumn (April), with high changes also in mid-winter (July) in the winter rainfall region.
- The implications of these projected increases in E_{rpm} could be significant to water resource managers, and in **Chapters 4.2**, **9.1** and **9.2** respectively, implications on soil water, evaporation losses from water bodies and irrigation are discussed.

Soil Water Content (Chapter 4.2)

- In hydrology, information on soil water content is vital since it determines when plant water stress sets in (and with that a reduction in transpiration losses), the need to irrigate and whether or not runoff will be generated, and how much, from a given amount of rainfall.
- Changes in soil water stress under projected future climates were expressed as medians of ratio changes of the various stress categories, derived from output of the multiple GCMs used in conjunction with the *ACRU* model.
- For conditions of *no soil water stress*, the majority of South Africa is projected to experience more such days into the IF, except in the southwest where desiccation is projected to result in plants experiencing fewer days without stress. Into the MDF over the 110 years from the present, 3/4 of the region is projected to have fewer days with no plant stress.
- For *mild stress conditions* resultant decreases into the IF are shown along the coast and especially in the Eastern Cape and Lesotho, with the remainder of the country displaying more days with mild stress. These patterns are intensified into the MDF.
- Based on the GCM projections used, days with *severe soil water stress* show a general reduction into the IF, except along the west coast where little change is projected. However, by the MDF the southwest displays more stress days while in ~ 95 % of the region a reduction in the number of days per year with severe stress is shown.
- *Stress due to waterlogging* is projected to increase markedly into the IF, except along the west coast where fewer waterlogged days are projected. These patterns intensify when changes between the MDF and the present are considered.

The implications of these findings are that in the east runoff generation is likely to be enhanced (and dryland agriculture would benefit), while the converse is projected to occur in the west. This study does show up the need for the use of output from more GCMs to come to more definite conclusions.

Section 5 Projected Changes in Hydrological Responses

Water Resources and Hydrological Challenges in South Africa within a Climate Change Context (Chapter 5.1)

The protection, development, use, conservation, management and control South Africa's water resources, as encapsulated in the aims of the RSA's National Water Act of 1998 (NWA, 1998), is for many reasons already proving very challenging. By way of a backdrop to assessing projected impacts of climate change on hydrological responses in South Africa, these challenges were grouped into the following broad themes and discussed:

- a harsh biophysical environment (including semi-aridity, the low conversion of rainfall to runoff, the high variability and sensitivity of the runoff : rainfall relationship, outlier events or years of high flows distorting the annual means of streamflows);
- the legal, administrative and governance environment, highlighting both positives and negatives;
- the present state of water resources in South Africa (emphasising the generally stressed state of water resources, complex water engineered systems, transboundary waters and aging infrastructure);
- some critical water use sectors (such as energy, agriculture, industry / mining, forestry and alien invasive plants);
- environmental issues (such as the ecological reserve); and
- the state of South Africa's water quality, also in regard to areas of future concern around issues of water quality

all of which are likely to be exacerbated by projected climate change.

Stormflow (Chapter 5.2)

Stormflow is the water generated from a specific rainfall event, either at or near the surface in a catchment, and which contributes to flows of streams within that catchment. It is largely from stormflow events that, for example, reservoirs are filled and design runoffs for selected return periods are computed, while the soil detachment process in the production of sediment yield from a catchment is highly correlated with the volume of stormflow from an event.

- Medians of changes in stormflows into the future, based on outputs from multiple GCMs, display a distinct west to east pattern for typical years, with the west coast and its hinterland showing clear reductions into the IF, which persist into the MDF.
- However, there is an abrupt shift to a band of marked projected increases in stormflows in the area which is transitional between the winter and summer rainfall regions and the more semi-arid areas, with more moderate projected increases towards the moister eastern regions.
- For the year in 10 with the lowest stormflows, the region of decreases expands eastwards to cover ~ half of South Africa, with a very abrupt transition to projected increases, while for wet years virtually the entire South Africa shows projected increases in stormflows, especially in the winter - summer rainfall transitional area.
- Year-to-year variability of stormflows, expressed through the standard deviation, shows increases across virtually the entire South Africa, with the most vulnerable area of changes in stormflows being the central west regions of the country.

Recharge into the Groundwater Store and Baseflow (Chapter 5.3)

Baseflows, i.e. the dry weather and non-rainy season runoff which are sourced from the groundwater store, take on hydrological significance in that they constitute the so-called "low flows" which sustain aquatic habitats and the dry season flows into reservoirs, as well as providing a source of water to people who have not yet been supplied with reticulated water.

- A feature of projected changes in recharge into the groundwater store from the multiple GCMs used is the very different patterns of change which emerge between median, dry and wet years.
- Characteristic of changes under median conditions into the IF is a wide band of increases in recharge stretching from northeast to southwest and covering ~ 80 % of South Africa, the areal extent of which increases into the MDF, as well as an area in the arid northwest showing no

change in recharge and a relatively small area in the extreme southwest displaying decreases in recharge, with the area of decreases expanding into the MDF, mainly as a result of a major decline in recharge projected in the 35 years between the IF and the MDF.

- The spatial patterns of projected changes in recharge are very different in the driest year in 10, with a northeast to southwest line dividing South Africa into an area of significant reductions in recharge (to < 70 % of present) on the equator-side of the line and significant increases south of that line, with this dividing line shifting in a northwesterly direction by the MDF, by which time the projections display a doubling of recharge over ~ 90 % of South Africa.
- Projected recharge in wet years display different patterns again, with a general decrease along the west coast region compared with a general increase projected across ~ 95 % of South Africa, with these patterns intensifying into the MDF as a result of projected reductions in recharge in the latter half of the century.

The implications of these projected changes in recharge into the groundwater store are important not only to the more arid parts of South Africa in which people and livestock rely heavily on groundwater as their primary source of water, but also on the sustained dry season flows from the baseflow component of streamflow which, with our current understanding of climate change from analyses of the GCMs used in this study, is projected to decrease in the southwest of South Africa, but increase elsewhere. The repercussions also have implications on the management of the ecological reserve.

Streamfows (Chapter 5.4)

The streamflow of a Quinary Catchment is derived from the stormflow and baseflow components of runoff from that Quinary and any runoff from upstream catchments.

- From the multiple GCMs used in this study large tracts of South Africa are projected to have increases in annual streamflows by ~ 20 - 30%, irrespective of whether it be a year of median flows or a year with the 1 : 10 year low or high flows.
- However, the southwestern Cape displays projected reductions in streamflows, especially in the crucial wet years when dams are filled.
- The flow reductions in the southwest are much more evident in the MDF and are projected to occur especially in the 35 years making up the time period between the IF and the MDF.
- Ratio changes in inter-annual variability of streamflows display increases in the standard deviation into the IF of around 20 to 30 % and even more, rendering the management of water resources more challenging than at present. The exception is the southwestern Cape where variability is projected to decrease, especially into the MDF.

In regard to future management of water resources, what is crucial is to identify those areas within South Africa where both the standard deviations and the CVs of annual streamflows increase, as they indicate that variability is increasing more rapidly than magnitudes of flows. Into the IF such “hotspot” areas of enhanced variability are along the west coast and the broad south to north band in the central areas of South Africa, with the west coast projected to be even worse off in regard to variability of streamflows into the MDF. Overall, results do, however, highlight the need to assess climate change impacts using output from more climate models.

Thresholds of Daily Streamflow Amounts Exceeded (Chapter 5.5)

Five critical thresholds of streamflow were identified for this climate change study, *viz*. the number of days per annum with zero flow, ≥ 0.1 mm equivalent daily flow (indicating anything above a trickle of usually baseflow, which more than compensates for any evaporative losses from the stream), ≥ 0.5 mm daily flow (indicating anything above steady streamflows), ≥ 1 mm equivalent daily flow (indicating strong flows often from stormflows and thus of relatively short duration, except in large catchments where such flows can result from a regional flood), and ≥ 2 mm equivalent daily flow (indicative of quite significant local or regional flooding).

- Results derived from multiple GCMs show that into the IF fewer days with zero flows are projected, except in the north. Into the MDF somewhat of a reversal of patterns is evident with the east central areas changing from fewer to more days with zero flows and many areas in the northeast now displaying fewer days with zero flows. These reversals may be explained by the period between the IF and MDF displaying a distinct area in the northeast of declining number of days per year with zero flows.

- Spatial patterns of ratio changes in the number of days with low flow thresholds (≥ 0.1 mm per day) to high flow thresholds (≥ 2 mm per day) are essentially similar into the IF, but with greater increases in the number of days per annum with low flow than with high flow thresholds, and with the decreases in the southwest becoming more pronounced for the high flow days.
- Into the MDF the areas in the southwest with decreases in flows above specified thresholds expands for all the thresholds evaluated, explained again by the GCMs projecting significant decreases in thresholds exceeded in the second half of the century.

The repercussions of the decreases in the number of days per year that streamflow thresholds are exceeded may become critical to water resources planners in the southwest, as the days with significant inflows into storage dams is projected to decrease according to the outputs of the GCMs used in this study.

Peak Discharge (Chapter 5.6)

The estimation of the peak flow from a flood is an important component with respect to the design of hydraulic structures such as spillways from dams or urban stormwater systems, as well as peak discharge being used in estimations of sediment yield from a catchment. Peak discharge in hydraulic design is usually expressed in m^3 per second for a specified return period, with the return period depending on design life and / or economic value of the structure.

- Projecting into the IF, maps of changes in peak discharge from the analyses from multiple GCMs show, first, a relatively clear west / east division within South Africa, with increases in peak discharges foreseen in the west and decreases in the east,
- secondly, a shrinking of the area of projected increases in peak discharge in the west as the return periods of the peak flows increase from 2 to 5, 10 and 20 years, and
- thirdly, that the highest projected increases in peak discharge appear to be in the transitional areas between the winter and summer rainfall regions, which are highly sensitive to patterns of changes in seasonal climates of the future.
- The maps depicting projected changes in peak discharge into the MDF indicate an intensification of the increases in the west and, similarly, more marked decreases in peak discharges from Quinary catchments in the east. A reason for this intensification may lie in the patterns of projected changes to peak discharge in the 35 year period between the IF and the MDF.

This study has identified that for greater confidence in the estimation of peak discharge in future studies, the lag equation used, although seemingly attractive for climate change analyses, should be re-assessed as it uses MAP not as a direct climatic variable *per se*, but rather a surrogate variable to represent, *inter alia*, above-ground biomass which is likely to change in future.

Sediment Yield (Chapter 5.7)

Soil erosion is a serious problem in southern Africa and is the result of high rainfall intensities, shallow erodible soils, limited / degraded land cover and / or substandard conservation management practices. Sediments are a potential hazard in that they can become trapped in reservoirs, thereby reducing the storage capacity and decreasing a reservoir's design life, while elevated concentrations of suspended sediments in flowing water reduce the quality of water. In this study the Modified Universal Soil Loss Equation was used to estimate sediment yields, as the components of this equation have been researched extensively for southern African conditions and it is, *inter alia*, hydrologically event-based in that it uses stormflow and peak discharge as variables.

- Averages of ratio changes of median annual sediment yields show that into the IF a general increase of 30 - 100 % is projected in the more arid west, with increases in the wetter east being somewhat less at 10 - 20 % and in places even patches of reductions are projected. These patterns of change are generally projected to persist into the MDF, except that the mountainous areas of the southwest display distinct reductions in sediment yields, which are confirmed in the 35 year period from the IF to the MDF.
- Projections of changes in sediment yields in more extreme years show similar patterns of increases for the lowest yields in 10 years. In the year in 10 with highest sediment yields the projected increases are somewhat less intense and more varied, but with the reductions in the southwest now a very distinct feature, while in the latter decades of the century more patches of reductions in sediment yields appear.

- Projected changes in standard deviations of sediment yields display a general increase in actual year-to-year variability in terms of t/ha lost, the exceptions being reductions in the mountain regions of the southwest and random patches elsewhere, with the latter decades of the century showing up more areas of actual reductions.
- Changes in the inter-annual coefficient of variation (a relative statistic) show very different patterns to those of changes in the standard deviation (an absolute measure), highlighting the value of using both for a full interpretation of changes in variability.

Section 6 Projected Changes in Meteorological and Hydrological Droughts

Meteorological Drought (Chapter 6.1)

Drought may be described as a creeping, slow on-setting natural hazard, which can manifest itself either through a lack of precipitation (*meteorological drought*), or from a lack of available soil moisture for crops (*agricultural drought*), or a reduction of streamflows below a critical threshold (*hydrological drought*), or of the amount of water stored in reservoirs, or reduced levels of groundwater compared with the long term average expected conditions. Owing to the projected increases in temperature and changes in rainfall amounts and variability in future, it is anticipated that the frequency as well as the duration and magnitude of droughts will change, either increasing or decreasing, with potentially severe economic, social and environmental implications.

For both meteorological and hydrological droughts *drought durations* in this study were assessed for 2 and 3 consecutive months and 2 and 3 consecutive years of drought, while in regard to *drought severity* a distinction has been made between *mild* drought (if it occurs on average once every three years or less frequently), *moderate* drought (occurring on average only once every five years or less frequently) and *severe* drought (occurring only once in ten years or less frequently).

- The dominant feature of projected changes in *annual* meteorological droughts, as derived from multiple GCMs, is that a *decrease* is projected over most of South Africa into the IF for all three categories of drought severity.
- The second striking feature is that in the second half of the century a significant *increase* in especially mild and moderate droughts is projected along the west coast and, to a lesser extent, along the northern extremities of South Africa. If this increase in the latter half of this century is to materialise, there could be potentially damaging economic implications as a result of the water as well as agriculture sectors being impacted negatively.
- When isolating projected changes in meteorological droughts for the s*ummer months* (October to March), similar patterns to those of the annual analysis of overall decreases in droughts persist, with the exception that into the MDF increases in moderate and severe droughts are identified from the multiple GCMs in the extreme north (in which the summer months make up the critical rainfall season) and in the southwest (its dry season). The reason for these projected increases is that in the second half of the century during the 35 year period from the IF to the MDF a significant increase in especially moderate droughts is projected to occur in the west and north of South Africa.
- On the other hand, *winter* meteorological *droughts* which occur from April to September display slightly different patterns of projected changes in that in a ‘sea’ of projected decreases, the increases projected along the west coast of South Africa are predominantly for mild droughts and only to a lesser extent for moderate droughts (unlike summer droughts).

Conventional thinking on changes in drought conditions in sub-Saharan Africa under climate change is that the frequency and severity of droughts (be they meteorological, agricultural or hydrological) are generally projected to increase. This detailed analysis using daily outputs from four IPCC approved GCMs downscaled to Quinary Catchments over South Africa shows results largely at variance with that of conventional thinking in that most areas are projected to experience a reduction in meteorological droughts. What has been shown, however, is that in the second half of this century, in the period between the IF and MDF, substantial increases in frequencies of droughts across the range of severities are projected to be experienced along the west coast areas and, to a lesser extent, the extreme north of South Africa. This illustrates, first, the strong amplification of climate change over time (unless major greenhouse gas mitigation strategies become operational) and, secondly, that impact analyses from more GCMs and with scenarios beyond only the A2, should be used in future research. In regard to the latter, preparation of output from more GCMs and more scenarios has already commenced.

Hydrological Drought (Chapter 6.2)

Hydrological drought consists of a substantial reduction in streamflows, derived from both stormflows and baseflows, in a specified area when flows are compared with long term expected conditions. Hydrological droughts are significantly different from either meteorological or agricultural droughts, however, with the latter two directly affecting only the specific area over which they occur, while water cascades downstream so that the *accumulated* effect of any drought from the entire catchment upstream of a location of concern can be felt downstream as well. Furthermore, meteorological and agricultural droughts can be broken when relatively small amounts of rain fall, whereas for a hydrological drought to be broken, a threshold of rain has to fall before any significant runoff is generated. On the positive side, the onset of hydrological droughts is usually slower than those of agricultural or meteorological droughts because streamflows are made up partially of sustained baseflows which can reach a stream many months after groundwater recharge, and streamflows can be stored in dams during times of high flows for release later, which soil moisture for plants cannot.

Comparing patterns of meteorological and hydrological droughts of the same duration (3 consecutive months) and severity (mild) for current climatic conditions shows that

- hydrological droughts occur with a greater frequency their meteorological counterparts, indicating the sensitivity of runoff : rainfall relationships and the overall amplification effect of the hydrological system to rainfall;
- the amplification varies from location to location, with certain areas which display a low frequency of meteorological drought exhibiting considerably higher frequencies of hydrological drought, and
- that the degree of ‘patchiness’ of hydrological droughts is much greater, reflecting not only differences in precipitation patterns, but also the local influences of soil and topographic gradients.
- Differences for longer duration droughts are somewhat more muted between the two types of drought, although there remains an amplification of meteorological droughts in the corresponding frequency of hydrological droughts.

The striking features of ratio changes of *annual* hydrological droughts are

- the similarity between projected changes for all three levels of drought severity from the present to the IF, the present to the MDF and the IF to the MDF;
- the greater part of South Africa being projected to experience significant *reductions* in annual hydrological droughts; with, however,
- marked *increases* in annual hydrological droughts in the west, more towards the northwest up to the IF and shifting towards the southwest in the MDF.

To the question whether significant differences were found in spatial patterns of projected changes in meteorological and hydrological droughts, and which may have important future water management repercussions, the short answer is a definite ‘yes’, in that changes in hydrological droughts may, in critical areas of concern such as the southwestern regions, show *increases* in frequencies of occurrence into the future where the meteorological droughts of the same duration and severity show *decreases* into the future.

Section 7 Projected Changes to Extreme Hydrometeorological Events

There are many types of hydraulic engineering and conservation structures which need to be designed to accommodate peak floods of a certain magnitude in order to function safely at a given level of risk. Should the structures fail, there are potential economic, environmental and societal consequences. Hence, flood frequency analysis is of great importance. The term “design hydrology” is then used to describe the

- *depth* (i.e. magnitude, in mm) of rainfall or streamflow, for a critical
- *duration* (e.g. 5 minutes, or 1 day), which depends on the size of the catchment, for a desired
- *frequency* of recurrence (e.g. statistically once in 10 or once in 50 years, depending on the size and economic importance of the structure), commonly referred to as the return period, with a design rainfall often used to generate a design flood hydrograph - an analysis commonly termed a “DDF” analysis.

Short Duration Design Rainfall (Chapter 7.1)

Using a modification of the index storm approach, together with growth curves, the short duration (i.e. 5 minutes to 24 hours) design rainfall for a given location can be estimated for a specified duration and return period.

- Overall across South Africa an increase up to 10 % in short duration design rainfalls may be expected by the IF, but with patches south of 32 °S and north of 27 °S where the models show no discernible change from the present.
- Of note is the high projected change in short duration design rainfall in the area transitional between the summer and winter rainfall areas, where increases up to 40 % are projected.

The results indicate that adjustments to future hydrological designs which are based on short duration "extreme" rainfalls may already be warranted at this point in time, given that such structures have a design life of 50 years and more, and already the City Engineers' Departments of Durban and Cape Town are planning on taking the above results into account in future stormwater drainage design.

Long Duration Design Rainfall (Chapter 7.2)

Averages of ratio changes of IF to present one, two, three and seven day design rainfalls for the 2, 5, 10 and 20 year return periods were derived from output of multiple GCMs, with annual maximum series analysed with the Log-Pearson III extreme value distribution. Only return periods up to 20 years were assessed because outputs from the GCMs used in this study were only for 20 year time slices and extrapolations of extremes beyond the length of a record tend to result in large errors. The following main points were noted:

- Over much of South Africa increases in design rainfalls of long duration of 10 - 20 % are projected from this analysis using outputs from multiple GCMs. The implication is that this should be considered in future designs of hydraulic structures.
- Areas transitional between the winter and summer rainfall regions of South Africa appear to be particularly sensitive to changes in design rainfall, especially for lower return periods.
- Areas where decreases in design rainfall are shown, especially in the southwest, tend to be the same for which general decreases in annual rainfalls are projected, more so in the MDF than in the IF.
- Increases tend to become more pronounced the longer the duration, e.g. for seven days vs. one day, indicative of higher long duration rainfall events in future climates.

The implications from this study are that the design of structures especially on large catchments for which long duration design rainfalls are critical, require additional attention in regard to projected effects of climate change.

Design Streamflows (Chapter 7.3)

Averages of ratio changes of IF and MDF to present one, two, three and seven day design streamflows for the 2, 5, 10 and 20 year return periods were derived using output of multiple GCMs with the *ACRU* model and then analysing the annual maximum series with the Log-Pearson III extreme value distribution. As was the case with rainfall, only return periods up to 20 years were assessed because outputs from the GCMs used in this study were only for 20 year time slices and extrapolations of extremes beyond the length of a record tend to result in large errors. The main findings were as follows:

- Into the IF, for over 95 % of South Africa an increase in design streamflows is projected, generally of the order of 10 - 50 % over the eastern 2/3 of the country and 50 - 100 % in the western 1/3.
- The exception is the extreme southwest, where reductions in design streamflows are projected.
- Issues of importance to water resource managers were highlighted:
  - First, as the return period increases from 2 through 5, 10 to 20 years, so the increases in design streamflows are dampened and become less pronounced, irrespective of duration.
  - Secondly, the regions within South Africa where the highest increases in design stormflows are projected are the transitional areas between summer and winter rainfall regions where inconsistent weather patterns are likely to be experienced in future.
  - Thirdly, and on a more local scale, as the return period increases from 2 to 20 years, so the area in the southwest where decreases in design streamflows are projected, expands.

  - Fourthly, for a given return period the spatial patterns of change into the IF do not vary between the one, two, three and seven day durations, i.e. the changes in design streamflow appear to be sensitive to return period, but not to duration.
- Into the MDF patterns of change display the following differences to those for the IF:
  - For short durations (e.g. one day) and low return periods (e.g. 2 years) the area of significant increases in design streamflows in the central west of South Africa contracts into the MDF, while the area of decreases in design streamflows in the southwest expands.
  - For longer durations (e.g. seven days) and low return periods (e.g. 2 years) the area of projected decreases in the southwest again shows expansion into the MDF, while there is little difference evident for higher return periods.

As to the question whether there are significant differences in spatial patterns of projected changes between design rainfalls and design streamflows for the same durations and return periods, the short answer to the above question is 'yes', with a significant amplification and intensification in the design streamflows into the IF and the MDF, both where increases and where decreases are projected into the future with the multiple GCMs used in this study.

The above findings pose new challenges in engineering design, particularly for structures on large catchments where multi-day durations are critical, especially also given that hydraulic structures are constructed with design lives usually beyond 50 years.

Section 8 Practical Applications

Evaporation from Open Water bodies and Wetlands (Chapter 8.1)

As a semi-arid country South Africa has constructed over 320 storage dams each with full supply capacities in excess of 1 million m^3. It is, however, the surface areas of these dams from which evaporation rates are high, that the focus is here, with 54 dams each with surface areas > 1 000 ha, nine with surface areas exceeding 5 000 ha and five > 10 000 ha.

The *additional* evaporative losses from open water bodies and wetlands of South Africa's Primary Catchments into the IF, over and above present day losses, range from < 10 million m^3 per annum where there are few dams in a Primary Catchment to > 350 million m^3 in the Orange Catchment. By the MDF many of the Primaries double their additional evaporative losses when compared to those into the IF.

These additional losses in evaporation from open water bodies and wetlands in South Africa under future climate scenarios are very high and have implications, inter alia, on the availability of water, the quality of the water and on wetlands functioning.

Net Irrigation Demands (Chapter 8.2)

The nearly 1.7 million ha under irrigation in the RSA contribute substantially to the country's agricultural production for both the local and export markets, generating 20 - 25 % of agriculture's contribution to South Africa's GDP and employing some 120 000 workers. In this study *net irrigation demand*, which is the supplementary irrigation water actually required and utilised by the plant in producing biomass under non-stressed conditions, was simulated with the *ACRU* model for a range of present and future climate scenarios, assuming all year round irrigation of a crop under full canopy cover and grown on a sandy clay loam soil of 0.9 m depth.

- Results from the multiple GCMs used in this study show that when compared with present day irrigation water demands, supplementary water requirements into the IF are, in fact, reduced in a significant area covering the central eastern parts of South Africa, with reductions of ~ 10 %.
- This indicates that in those particular areas the increased demand through higher temperatures, and hence enhanced evaporative demands, is more than offset by corresponding increases in rainfall.
- In other parts of the interior the medians of ratio changes indicate no significant change from the present, while in the drier western half and the northern quarter of the country irrigation water demands are projected to increase by ~ 10 %.
- By the MDF two differences emerge, *viz*. that the area of reduced irrigation demand has shrunk and that in the ~ 90 % of South Africa where irrigation demands are shown to increase, results from the multiple GCMs indicate that these increases will be of the order of 10 - 20 % and in parts of the southwest even > 20 %.

- Patterns of change also differ between years of average water demand and wet years vs. dry years. Thus, from the present into the IF the wettest year in 10 displays a significantly larger area of projected decreases than for the driest year in 10, while from the present into the MDF the areas of both projected increases and of decreases are much more sensitive in the wettest year in 10 compared to the driest year in 10.
- These differences between the changes into the IF vs. the MDF scenarios are explained largely by changes occurring in the latter half of the century.
- Using an index of consistency of change (ICC), it was shown that the confidence in the projections in annual net irrigation demand into the IF and MDF are in the ‘Very High’ category in those western and northern areas of South Africa identified as requiring the highest future additional water for irrigation.

The management implications of these findings are

- *first, that there are likely to be “winners and losers” in regard to projected future net irrigation requirements, with the already drier parts of South Africa where agricultural production is very much dependent on supplementing rainfall with irrigation, requiring even more supplementary water from irrigation than at present;*
- *secondly, that the projected changes which display spatial differences between average, wet and dry years, add to the complexity of managing irrigation water supply;*
- *thirdly, that in the case of projected changes in net irrigation requirements with climate change there is generally high confidence in the results presented;*
- *fourthly, that in many areas, but especially the drier west, this water cannot be sourced locally, but will need to be transferred from distant sources; and*
- *fifthly, that with higher temperatures than at present, a change-over is likely to be needed to more heat and disease tolerant crops*.

Surface Water and Deep Percolation Losses from Irrigated Areas under Demand Irrigation Scheduling (Chapter 8.3)

A major environmental problem associated with irrigation is that of over-watering, with its downstream consequences (in addition to the costs of wasted water) through return flows, since almost all the excess water applied over and above the plant’s requirements is returned to the water resource through deep percolation or surface runoff, usually with the return flows being of inferior quality to the water applied, through the increased nitrate leaching in the case of deep percolation and phosphate losses in the case of surface water losses. Deep percolation and surface runoff losses from irrigated lands under demand irrigation scheduling were computed with the *ACRU* model for present and for projected climate change conditions

- In regard to ***surface water losses*** from demand irrigation,
  - projections into the IF show increases for years of median losses from 10 % in the east to a doubling in the more arid central west, but with no marked changes from the present along the west coast. The changes are marked and probably reflect changes in the overall amounts of rainfall received, the persistencies of days with rainfall and higher rainfall per rainday.
  - Patterns of change for the MDF are slightly more intensified compared with those projected for the IF.
  - However, in the driest year in 10 the patterns of change into the future are completely different, with significant reductions in surface water losses in the western half of South Africa (a positive), contrasting with significant increases in the eastern half (a negative in regard to both water and fertilizer costs).
  - Projections of change for the wettest year in 10 are different once more in their spatial patterns, with decreases in surface water losses foreseen along the northwest coast and increases in the remainder of the region, with a gradient from more severe surface water losses in the west to only slight increases towards the northeast in Limpopo province.
- For ***deep percolation losses*** from demand irrigation,
  - remarkable similarities to those of surface water losses are shown for the IF, with increases for years of median losses from 10 % in the east to a doubling in the more arid central west.
  - One significant and positive finding is a projected decrease in deep percolation losses in the southwest, especially in the MDF. These changes again reflect the projected changes in rainfall characteristics into the future, i.e. changes in the overall amounts of rainfall received, the persistencies of consecutive days with rainfall and higher rainfall per rainday.
  - Patterns for the MDF are slightly intensified compared with those projected for the IF.

- Again, in the driest year in 10 the patterns of change into the future are completely different to those of an average year, with significant reductions in deep percolation losses in the western half of South Africa (a positive), contrasting with significant increases in the eastern half (a negative in regard to both water and fertilizer costs).
- Projections for the wettest year in 10 change once more in their spatial patterns, again mirroring those of surface water losses, but with decreases foreseen along the entire west coast and increases in the remainder of the region.

Important to note is that while the ratio changes of projected deep percolation losses may be similar to those of surface water losses, the modelled deep percolation increases in median and wet years in the east carry considerably higher environmental consequences than those of surface water losses because they come off a considerably higher, and geographically more expanded, base.

A Case Study in Water Harvesting (Chapter 8.4)

Rainwater harvesting (RWH) is one method of alleviating water supply problems and supplementing the conventional water supply systems as demand increasingly grows. For this case study the focus was on collecting rainfall running off from the roof surface of a typical sub-economic house constructed through government initiatives for low income households. Assumptions were for collection of rainwater from a roof of 40 m² in area into a water tank of 3 000 litre to supply a household of 6 with 50 ℓ water per day. The model developed calculated the average number of days in a year for four conditions, *viz*. that the tank was completely empty, was filled completely and overflowed, fulfilled the daily requirements of the household (*viz*. 300 ℓ) and still had some water remaining, and provided some water for the daily requirement, but not enough to fulfil the total needs of the day and was thus emptied as a result.

- A ratio of change analysis showed that under the climate change conditions into the IF the potential for RWH generally increases across most of South Africa. The tank is projected to overflow 30 % to twice more often, except in the southwest, and be completely empty 10 - 20 % less frequently, the exception again being the extreme southwest with fewer raindays and rainfall per rainday. Over the majority of the country, the tank will be able to supply the daily needs of the household in full more often, as is generally the case for the tank being able to at least partially fulfil daily household water needs.
- While in relative terms the changes into the future appear significant, in absolute terms when expressed as increases / decreases in days per annum, the actual number of days with changes are quite small.
- Into the MDF projections from multiple GCMs display an expansion / consolidation of areas in the west for days on which the tank overflowed, fewer days in the east on which the tank would be empty, more days over most of the country on which household water needs were completely satisfied from the tank and also more days on which water needs could be at least partially satisfied by RWH.
- To a large degree the differences in the changes between present to IF and the present to the MDF are explained by the ratio changes in the relatively short 35 year period between the IF and MDF scenarios.

This case study has shown for the specified roof area, tank size and household size / needs, that RWH as a long term alternative water supply is not feasible along the west coast, neither under present nor under conditions of projected climate change. However, most of the remainder of the country may hold potential for RWH to fulfil, or at least supplement, basic household requirements, especially under projected future climates as the tank is projected to often be full and there is even an increase in the number of times the tank overflows. It stands to reason that larger tanks may help to exploit this water supply option even more through increased collection and storage.

It is recommended that this study be expanded to assess impacts of present and future climates on a range of roof areas, household sizes and per capita water needs in order to obtain more optimum tank sizes for the different climatic regions in South Africa.

A Summary of Key Take-Home Messages

During this study a number of key general findings came to the fore. These are summarised below.

- There is no doubt that climate change poses new challenges to water resource managers in South Africa. The climatically determined future is certainly not all “gloom and doom, however, as some would have it, but neither do the results of this study suggest, as certain water strategists argue, that “everything is under control” in the water sector in regard to climate change.
- Some areas are likely to become “winners” for certain projected changes and new water related opportunities will arise, while other areas are likely to become “losers” in the sense that more water related stresses will be experienced. “Hotspots” of concern which were identified time and again in the assessments of impacts were the southwest of the country, the west coast and, to a lesser extent, the extreme north of South Africa (examples in **Figure 9.1.1**).

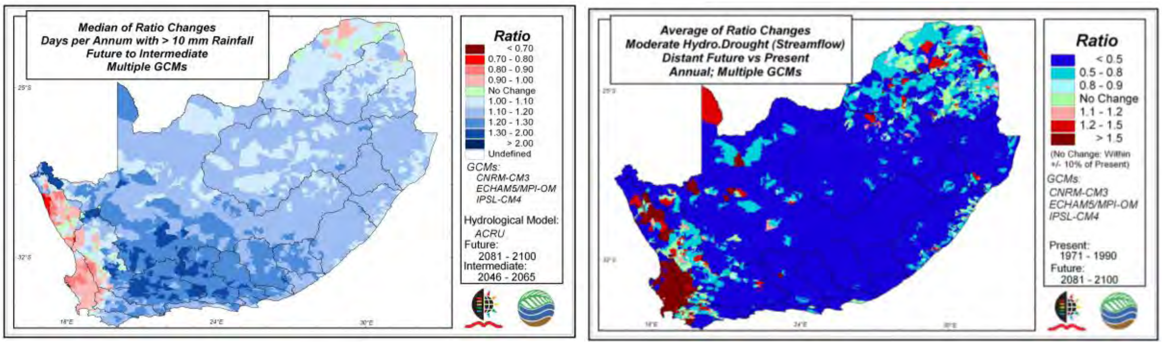

Figure 9.1.1 Examples of the southwest being a “hotspot” of concern to water resource management under conditions of projected climate change, based on output from multiple GCMs: Ratio changes between the more distant future (2071 - 2100) and the intermediate future (2046 - 2065) of days per annum with runoff producing rainfall of > 10 mm per day (left) and ratio changes between distant future and present (1971 - 1990) hydrological droughts of moderate severity (right)

- Results from analyses of ratios of change, based on output from multiple GCMs, show that patterns of change across South Africa are often projected to differ between future “average year” conditions vs. future 1 in 10 year wet or 1 in 10 year dry conditions (e.g. in the cases of stormflow, baseflow, sediment yield or net irrigation requirements). An example is given in **Figure 9.1.2**. Some changes were found to be for the positive, others were found to be potentially more detrimental, and this finding will place an added challenge to future water management.

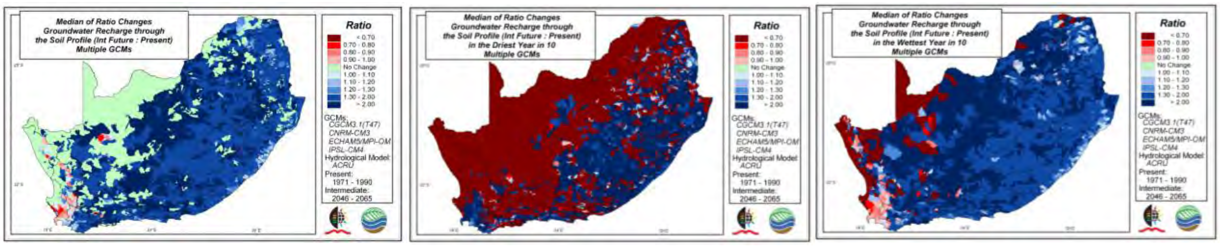

Figure 9.1.2 Example of patterns of change being different between average, dry and wet years: Medians of ratio changes of intermediate future to present recharge into the groundwater store through the soil profile in a year of median recharge (left), the year with the lowest recharge in 10 years (middle) and the year with the highest recharge in 10 years (right), derived with the *ACRU* model from output of multiple GCMs

- Another finding was that the transitional zone between the winter and summer rainfall area (**Figure 9.1.3** left) in the western interior of South Africa appears to be an area of high sensitivity and of inconsistent change (as illustrated by the low index of consistency of change between the five GCMs in **Figure 9.1.3**, middle), with frequently the highest ratios of change occurring there. This was observed, for example, in the case of projected changes to stormflows, peak discharge (**Figure 9.1.3** right) and design streamflows.

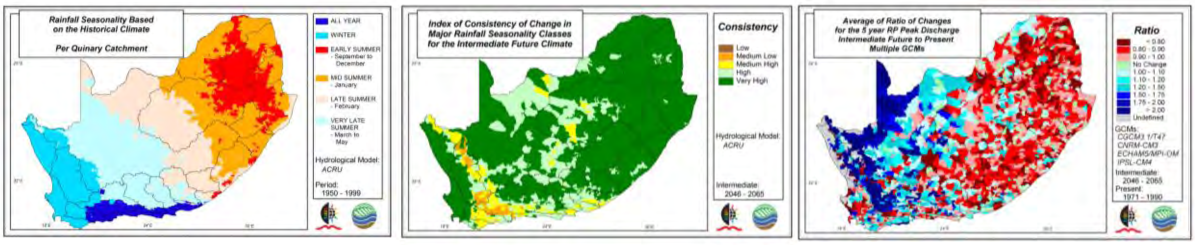

Figure 9.1.3 Example of the transitional zone between the winter and summer rainfall area (left) being an area of inconsistent change between GCMs (middle) and of high sensitivity to climate change (right)

- An intensification (both + and -), and associated expansion in area, was frequently shown for patterns of change in the relatively short period of 35 years from the intermediate future (2046 - 2065) to the more distant future (2071 - 2100), illustrating an acceleration and amplification of impacts into the second half of the century when compared with the relatively long 75 year period between the present (1971 - 1990) and the intermediate future. The high sensitivity of this later period was evident in the climate change assessments of, *inter alia*, accumulated streamflows (**Figure 9.1.4**), thresholds of streamflows exceeded, meteorological droughts, net irrigation requirements and deep percolation losses from irrigated lands.

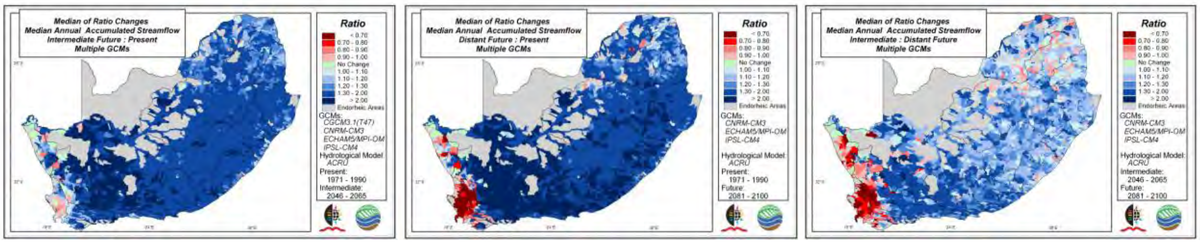

Figure 9.1.4 Example of the intensification of change in the latter part of this century by comparing ratios of change derived from multiple GCMs of median annual streamflows between the 75 year time period from the intermediate future and present (left), the 110 year period from the more distant future and present (middle) and the 35 year period between the more distant and intermediate future

- In general the results showed an increase in the year-to-year variability of hydrological responses into the future, often a quite substantial increase, especially when inter-annual variability was expressed in absolute terms by the standard deviation (e.g. **Figure 9.1.5**). The increase in variability also tended to be higher into the more distant future than between the intermediate future and present. Where both the standard deviation and the coefficient of variation (a relative indicator of variability) were shown to increase, those areas were considered to be particularly sensitive to climate change. Examples of increases in variability included changes in rainfall, to stormflows, accumulated streamflows and to sediment yields.

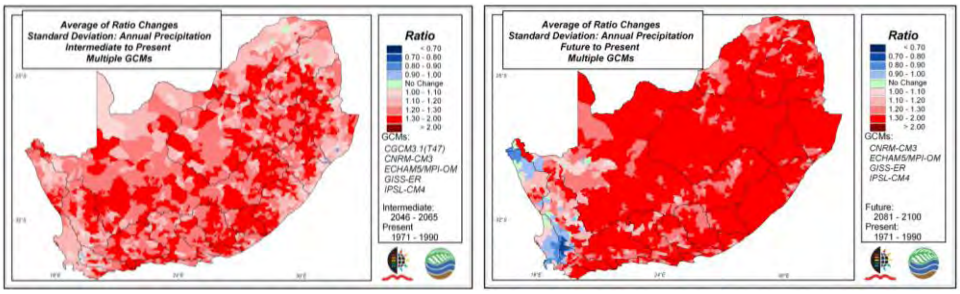

Figure 9.1.5 Example of increases in the variability of annual precipitation under projected future climates, derived from multiple GCMs, with variability increasing more into the distant future

- Patterns of change into the future of certain hydrological variables are not always smooth across South Africa. Often strong gradients of change over very short distances were shown from the analyses, sometimes even changing sign from increases to decreases over short distances. Examples were found in evaluations of changes in baseflows, stormflows and surface runoff losses from irrigated areas (**Figure 9.1.6**).

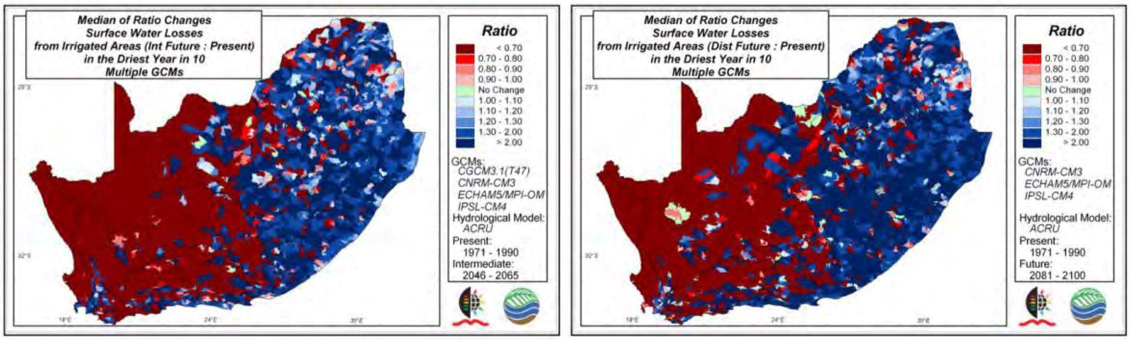

Figure 9.1.6 Example of abrupt changes with changes over short distances, including changes in sign, taken from ratio changes of surface water losses from irrigated areas between the intermediate future and present (left) and more distant future and present (right), derived with the ACRU model from output of multiple GCMs

- Some components of the hydrological system were found to be more sensitive to climate change than others, sometimes displaying a doubling or more, or a halving or more, of change into the future. Examples of highly sensitive components identified in this study were changes to baseflows, hydrological droughts and surface runoff losses from irrigated lands (**Figure 9.1.6**).
- From an engineering perspective, an important finding was that projected spatial changes to design rainfall and design streamflows vary with return period (**Figure 9.1.7**) rather than with critical duration, and this should be factored into future hydraulic designs.

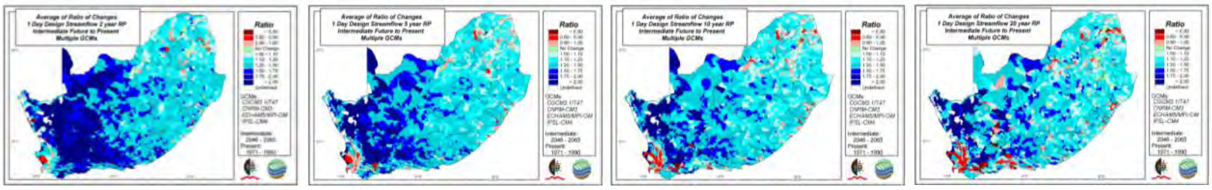

Figure 9.1.7 Averages of ratio changes of intermediate future to present one day design streamflows for the 2 year return period (left), as well as the 5, 10 and 20 year return period (right), derived with the *ACRU* model from output of multiple GCMs, illustrating that changes in design streamflows (and also design rainfall) vary with return period

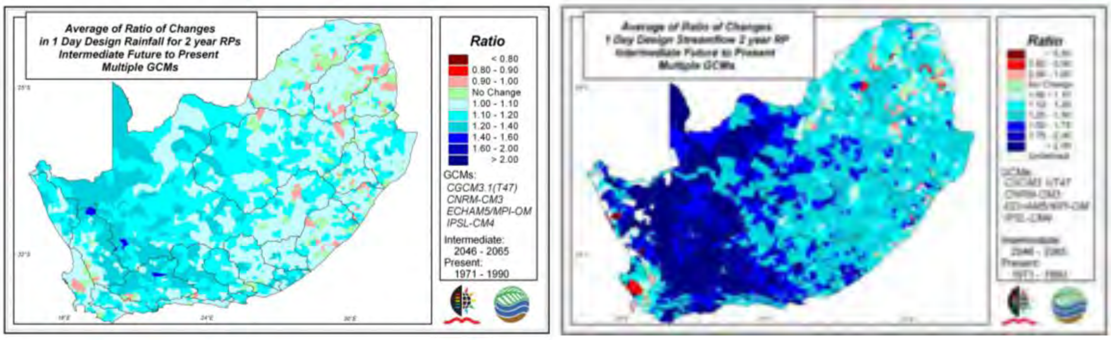

Figure 9.1.8 Comparison of averages of ratio changes from the present into the intermediate future between design rainfalls (top row) and design streamflows (bottom row) for identical durations and return periods, derived with the *ACRU* model from output of multiple GCMs, illustrating the amplification when changes in rainfall parameters are compared to equivalent changes in streamflow responses

- A strong amplification / intensification was shown when changes in rainfall parameters were compared with equivalent changes in runoff responses, highlighting again the high sensitivity of changes in rainfall in the hydrological cycle. Examples of this amplification include a comparison of hydrological drought (more sensitive) vs. meteorological drought (less sensitive) for the same duration and level of severity, as well as of design streamflows vs. design rainfall for the same duration and return period (**Figure 9.1.8**).

This study has also identified the need for assessing climate change impacts in hydrological responses from more GCMs than those used here, for a wider range of emissions scenarios and for longer periods than 20 year time slices of projected climates, in order to achieve higher confidence in results.

Citing from this Chapter of the Report

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CHAPTER 9.2

CLIMATE PROOFING THE SOUTH AFRICAN WATER RELATED SECTOR 1: THOUGHTS TOWARDS A STRATEGY FOR ADAPTATION TO CLIMATE CHANGE

R.E. Schulze

In a Nutshell: Why a Strategy for Adaptation to Climate Change Specific to the South African Water Related Sector?

Prompted by various directives and policies from government, and on the basis of

- the amplification in hydrological responses of changes in key climate attributes (especially of rainfall) in a country with an already high risk hydro-climatic environment,
- the simultaneous need for redress in regard to water and economic development,
- the symbiotic links of water quantity / quality and its distribution over space and time with
  - health,
  - terrestrial and aquatic ecosystems,
  - rural and urban communities,
  - poverty,
  - gender issues,
  - disaster risk management, and
  - agriculture,
- the trans-boundary nature of many of our rivers and
- the longevity, permanence and irreversibility of hydraulic structures,

render the in-depth understanding of the ramifications of projected climate change on the one hand, and the development of a dynamic, water related adaptation response strategy to climate change on the other, imperatives for South Africa!

This implies, *inter alia*,
- investment in South Africa's scientific capacity (including the growth of centres of expertise),
- engaging in communication between science and stakeholders,
- facilitating strong leadership by state institutions,
- working trans-nationally,
- encouraging trans-disciplinarity, and
- enabling healthy interactions between science and science, science and policy and between science and other stakeholders.

Setting the Scene for a Strategy

1. From an International Perspective
- Internationally, there is a growing recognition of the potential implications of climate change in the water related sector, with managers in many parts of the world already facing
  - more frequent and more intense drought and / or flood events,
  - decreasing water availability,
  - higher inter-annual variability of rainfall,
  - increasing evaporation from water bodies, and / or
  - increasing evapotranspiration from plants,

  with all of the above coupled to
  - population growth and growing urban water demand and
  - rising expectations of supply resulting from improved living standards (IPCC, 2007; Theesfeld *et al*., 2011).
- To ensure a sustainable supply of water into the future, not only will
  - technical innovations need to be introduced, but
  - new institutional initiatives in water governance will need to be taken.
- The global scientific community argues that projected future events require *additional* or *modified* initiatives to prevent emerging aggravation of water related problems, since over certain

thresholds of change are deemed irreversible and some catastrophic changes may become more likely (Theesfeld *et al*., 2011).

- There is, therefore, an overriding need to understand the potential impacts of climate change on water resources management, in order to begin designing strategies for adaptation. This implies, to a large extent, reducing vulnerability to the impacts of current climate variability, and taking effective measures to prevent and respond to future impacts (IPCC, 2007).
- The "art of adaptation" in water management is therefore seen as what Sadoff and Muller (2009) describe as "finding the right mix of the three I's (information, institutions and infrastructure) to achieve the desired balance between the three E's (equity, environment and economics)".
- Since water is the primary means through which climate change will impact upon people, the environment and economies, any adaptation process should include a coherent and effective management of water resources so as to achieve multiple objectives, such as
  - management and conservation of water for the provision of water services and sanitation for all,
  - efficient use of water for irrigation and food production,
  - ecological use of water for the protection of ecosystems and biodiversity,
  - improved use of water for hydropower generation,
  - strengthening coordination between water planning, land use and urban planning in order to promote sustainable economic development and
  - reduce risks to human settlements arising from extreme hydro-meteorological events (IPCC, 2007).
- A key component in this process of adaptation is to reduce the initial gap between current scientific knowledge, and decision making processes and institutions in the water community in collaboration with civil society, and what may be required in the context of a water governance under conditions of climate change.
- To close this gap, it is essential to
  - enhance society's understanding of the possible implications of climate change, and to
  - facilitate a continuous dialogue process among high-level experts, civil society organizations and decision makers in relevant institutions in the region, in order to move forward with a joint effort in adaptation which includes capacity building and institutional development (IPCC, 2007).

2. *From a South African Perspective*

Water resources, which are inextricably interlinked with land resources, are essential to the continued economic development of South Africa and to the sustainable livelihoods of its people. Because

- water shortages are already evident in many Water Management Areas (cf. **Chapter 5.1**) and
- a large proportion of South Africa's society consists of impoverished people (when compared to a relatively small middle and wealthy class), which renders them particularly vulnerable to impacts of climate change and, furthermore,
- many of the fragile ecosystems in South Africa, both terrestrial and aquatic, are implicitly or explicitly climate and water dependent,

strategies and practical plans of action to adapt to climate change through an integrated approach to land and water management are therefore urgently needed in order to establish effective resilience to the projected impacts of climate change.

The commitment to act on matters pertaining to climate change, and to shape policy informed by best-available science was recognised by the South African government in resolutions from the 2005 National Climate Change Conference (Lukey, 2009). This commitment was affirmed at the 2009 Climate Change Summit, with additional emphasis on fostering local level resilience to climate change and a participatory process to climate change policy development (Lukey, 2009). Furthermore, based on feedback from South Africa's Long Term Mitigation Scenarios (LTMS, 2007), "vulnerability and adaptation" was one of the Cabinet's broad policy direction themes, with briefs

- for South Africa to continue identifying and describing its vulnerability to climate change;
- to describe, prioritise and initiate adaptive interventions and to identify who should be driving these interventions and how they should be monitored;
- to ensure that in affected departments of state (e.g. water, agriculture, health) climate change adaptation be included as a departmental key performance area;

- that roles and responsibilities of all stakeholders, particularly organs of state in all three tiers of government, be clearly defined and articulated;
- that structures are required to ensure alignment, co-ordination and co-operation and that these be clearly defined and articulated; and
- that climate change response policies and measures be mainstreamed with existing structures of co-ordination and co-operation (Lukey, 2009).

Implementing such strategies and plans of action on adaptation will necessitate three-pronged information needs, *viz*.

- on impacts of climate change on South Africa's biophysical environment,
- on the socio-economic characteristics of various sectors or communities which may be vulnerable to climate change, and
- on the manner in which changes over time on both the above might impact on the overall vulnerability of people and ecosystems (Stuart-Hill and Schulze, 2010).

Points of Departure in the Development of a Climate Change Strategy for South Africa's Water Related Sector

1. An Obligation to Develop a National Strategy of Adaptation to Climate Change

- National strategies of adaptation (NAS) are currently being developed in many countries,
  - taking the form of strategy papers / guidelines of (mostly) proposed frameworks,
  - conforming to the precautionary principle, and
  - integrating various affected sectors (Theesfeld *et al*., 2011).
- There are numerous political and ecological drivers of this strategy, including
  - the increased perception / awareness of climate change at all decision making levels,
  - the UNFCCC obligations to take precautionary measures to adapt,
  - socio-economic concerns of not taking action,
  - the economic interests of the private sector, and
  - obligations, in South Africa, towards our Constitution, the National Water Act (NWA, 1998) and the National Water Resource Strategy (NWRS, 2004 and updates).
- Objectives of South Africa's NAS should include
  - the establishment of a transparent and structured medium-term process
  - involving all relevant actors, be they from the public or private sector or from NGOs, but
  - co-ordinated at government level across various ministries, considering furthermore
  - broader development national agendas (e.g. National Planning Commission),
  - emphasising adaptive land and water management (Theesfeld *et al*., 2011), and
  - taking due cognizance of the links between water and, for example,
    - ▫ biodiversity
    - ▫ agriculture
    - ▫ forestry
    - ▫ coastal zones
    - ▫ mountainous (water producing) regions
    - ▫ human health
    - ▫ transport
    - ▫ energy
    - ▫ tourism and
    - ▫ insurance

    in a holistic, integrative manner (adapted from Theesfeld *et al*., 2011).

2. Response to Recent Findings

Recent research published by the IPCC (2007) has updated some of the findings from previous IPCC reports in stating, *inter alia*, that

- there is new and stronger evidence than before (at very high confidence) of observed impacts of climate change on vulnerable systems such as water, with increasing levels of adverse impacts as temperatures increase; furthermore,
- there is new evidence that observed climate change is likely to have already increased the risk of certain extreme events such as floods and droughts (very high confidence), and it is more likely

than not that warming has contributed to the intensification of some tropical cyclones, with increasing levels of adverse impacts as temperatures increase; that

- the distribution of impacts and vulnerabilities is still considered to be uneven, with less-developed areas (such as large parts of South Africa) generally at greatest risk due to both higher sensitivity and lower adaptive capacity, but with evidence also that vulnerability to climate change is highly variable within countries; and that
- adaptation can significantly reduce many potentially dangerous impacts of climate change and reduce the risk of many key vulnerabilities.

3. State of Knowledge on Climate Change and Water in South Africa

- In the South African water related sector there already exists
  - a rich history of academic research (e.g. Kunz, 1994; DEAT, 2000; Perks, 2001; Tyson *et al*., 2002; Schulze, 2003; Schulze, 2005a; Knoesen *et al*., 2009; Schulze, 2010; Schulze *et al*., 2010; Stuart-Hill and Schulze, 2010; Schulze, 2011a and co-authors in the aforegoing Chapters of this Report), and
  - international collaboration in matters of climate change (e.g. active participation in the International Geosphere-Biosphere Programme, the Intergovernmental Panel on Climate Change, the Global Water Systems Project), but
  - a poorer history of converting the findings into strategies for adapting to climate change and / or to action plans.
- Water related infrastructure (e.g. dams, irrigation projects, inter-basin transfers, stormwater systems etc) in South Africa (and elsewhere) typically
  - is a long term investment with structures designed for an operational life of 50 - 100 years,
  - is very expensive,
  - is essentially irreversible, and
  - is designed to cope with currently expected extremes of floods and droughts.
- From recent hydro-climatic studies it is evident that climate change is already occurring and can be detected in South Africa (e.g. Warburton and Schulze, 2005). Climate change is no longer a matter of conjecture and it is not only an issue of something that could begin to happen only 30 - 50 years from now.
- Accounting for potential effects of climate change in South Africa's water related sector is therefore an imperative; indeed, non-consideration of potential effects of climate change should be viewed as an act of omission.
- We already live in, and already have to cope with, a high risk and generally harsh hydro-climatic environment in South Africa, which experiences high variability both over space and over time (e.g. **Chapters 3.1**, **3.2**, **3.4**, **3.5**, **5.2**, **5.3** and **5.4** of this Report).
- Any changes in rainfall, be they up or down, are amplified in changes of hydrological responses. In the case of variability from year-to-year the amplification from rainfall to runoff can be two- to five-fold (e.g. **Chapter 5.1** of this Report).
- Climate change is not going to be experienced evenly throughout the country - some areas will be "winners", other areas will be "losers" and others still are likely to become real "hotspots of concern".
- Climate change does not occur on a "clean sheet" of catchments which have not been impacted by human interventions on the land and channel components of a landscape - rather it will be superimposed onto already water stressed catchments with complex land uses, water engineered systems and a strong historical socio-political as well as economic footprint (e.g. **Chapter 5.1**).

4. What Will Need to be Considered when Climate Change Impacts are Assessed in Light of an Adaptation Strategy?

- When we assess potential impacts of climate change on the water related sector, we will need to evaluate projected changes of *critical* climate variables such as rainfall and temperature (as it manifests itself through evaporative demand) and how, in interaction with one another, they translate to changes in hydrological responses in regard to (IPCC, 2007)
  - *magnitudes of change*, i.e. how much the change is projected to be and how much impact that can have, where the magnitude of an impact is determined by
    - its scale, e.g. the area or number of people affected and
    - its intensity, i.e. the degree of damage caused, with the most widely used quantitative measures for climate impacts being
    - monetary units such as welfare, income or revenue losses,

    - costs of anticipating and adapting to certain biophysical impacts,
    - estimates of people’s willingness to pay to avoid (or accept as compensation for) certain climate impacts, or the
    - number of people affected by certain impacts such as food and water shortages, morbidity and mortality from diseases, and forced migration;
- *direction*, i.e. is it a positive or negative change, and what that implies;
- *timing*, i.e.
    - when, in the course of a year, the change is projected to occur and how that affects management decisions, or
    - whether a harmful impact is more likely to happen sooner rather than in the distant future;
- *rate*, i.e.
    - how rapidly is change projected to occur in years or decades ahead, and
    - how that affects priorities of action,
    - with adverse impacts occurring suddenly (and surprisingly) being perceived as more significant than the same impacts occurring gradually, as the potential for adaptation for both human and natural systems would be much more limited in the former case, and
    - very rapid change in a non-linear system (such as the hydrological system) possibly exacerbating other vulnerabilities (e.g. impacts on agriculture and nutrition aggravating human vulnerability to disease), particularly where such rapid change curtails the ability of systems to prevent and prepare for particular kinds of impacts;
- *location*, i.e. where will it occur first or most severely considering, inter *alia*, income, gender and age in addition to regional, national and sectoral groupings;
- *persistence and reversibility*, where impacts could become key due to persistence of, say, the emergence of near permanent drought conditions or intensified cycles of extreme flooding that were previously regarded as ‘one-off’ events;
- and, as has been shown in the various technical chapters of this Report, the
- *level of confidence / uncertainty* of projected impacts in regard to likelihood of impacts and confidence, where
    - likelihood is the probability of an outcome occurring and
    - confidence is the subjective assessment that any statement about an outcome will prove correct (cf. **Chapter 2.4** of this Report); the
- *potential for adaptation*, which differs between and within regions and sectors, and where the potential considers not only the technical feasibility of certain adaptations, but also the availability of required human resources, the costs and side-effects of adaptation, the knowledge about those adaptations, their timeliness, the (dis-)incentives for adaptation actors to actually implement them, and their compatibility with individual or cultural preferences; and the
- *importance of the system(s) at risk* in regard to the value attached to the system by different societies, be the value related to the uniqueness of a habitat or an ecosystem (e.g. the fynbos biome in South Africa), or livelihoods of many people depending crucially on the functioning of a system (IPCC, 2007).

5. Other Considerations Regarding an Adaptation Strategy for the South African Water Related Sector

- Adaptation will need to start by doing well in water related management what we ought to be doing in any event.
- Some communities and some ecosystems will be more vulnerable than others to effects of climate change, and are likely to have a lower adaptive capacity. These may require priority consideration in our adaptation strategy.
- At the end of the day practical and pragmatic adaptation is a local issue (cf. **Chapter 9.3**), but it has to take place within a broader policy framework.
- Adaptation to climate change is not a once-off event, nor is it a linear process; rather it should be seen as a process which continually needs to be re-visited.
- The capacity to adapt to climate change impacts in South Africa is a pre-condition for successful adaptation.
- With its complex social structures and juxtapositioning of first and third world economies, adaptive capacity in SA will depend on:

Experience + knowledge (scientific and indigenous) + incentives to adapt + ability to take risks + access to finance + leadership (“champions”).

- For adaptation to be effective, we need to have good observational networks of long duration and high quality hydro-climate records in order for timely detection of any shifts in climatic forcing.
- For effective adaptation we will need to understand the mechanisms and the thresholds / sensitivities ("tipping points") between drivers of environmental change and responses in the different hydro-climatic regions of South Africa.
- For adaptation to be effective, we will need flexible water management procedures in South Africa at different levels of water governance.
- Overall, the 8 "E"s of adaptation will need to drive a South African climate change adaptation strategy for the broader water related sector, *viz*.
    - *Empowering* the water related sector to adapt at all levels, through
    - *Education* at all levels,
    - *Effectiveness* in management,
    - *Engineering* skills,
    - *Environmental* consciousness,
    - *Economic* incentives,
    - *Emergency* responses from the disaster risk management sector, and
    - *Enforcement* of policies and strategies through sound governance.

Taking Cognisance of, and Understanding the Implications of, the Most Up-to-Date Scientific Findings on Impacts of Climate Change as a Springboard for an Effective Adaptation Strategy

The conceptualisation and implementation of a climate change adaptation strategy for the South African water related sector can only be effected if it is informed by the latest scientific findings. This implies

- a sound understanding and appreciation of the most up-to-date projected impacts of climate change on *hydrological responses* and hence water availability (currently contained in this Report), which may have advanced considerably and even be partially at variance with past findings (e.g. the Country Studies Report based on work a decade ago; DEAT, 2000) on which many misconceptions still rest in many official circles (cf. **Chapter 1.1**) and the media, and
- a sound appreciation (and current understanding where this is already available) on projected impacts of climate change on *water related management* in South Africa, such as water demand, water quality, transboundary waters, land use effects and the environmental reserve, to name but a few key areas.

1. Current Understanding on Projected Impacts on Hydrological Responses

The key questions here are: What is our current state of knowledge based on the most recent state-of-the-art research? What remains to be done? What are we not (yet) doing that we identify / recommend should be done? What are the key messages with respect to adaptation? What is the degree of confidence we have in these findings?

The most recent (2009 - 2011) detailed findings in regard to South Africa's water related sector (e.g. Knoesen *et al*., 2009; Lumsden *et al*., 2010; Davis, 2011; Gray, 2011; Schulze, 2011a in this report) are based on

- analyses of output from between one and five of the following General Circulation Models (GCMs), *viz*. CGCM3/T47, CNRM-CM3, ECHAM5/MPI-OM, GISS-ER and IPSL-CM4),
- empirically downscaled to climate station level (CSAG, 2008; cf. **Chapter 2.1**), and
- adjusted to the 5 838 Quinary Catchments making up the contiguous region of the RSA, Swaziland and Lesotho (Lumsden *et al*., 2010; Schulze and Horan, 2010), with
- daily values of rainfall, maximum and minimum temperatures, solar radiation and a reference potential evaporation available for
- three 20 year climate time slices, *viz*. the present (1971 - 1990), the intermediate future (2046 - 2065) and the more distant future (2081 - 2100), with
- these climate values then used as input to the daily time step and multi-purpose *ACRU* agrohydrological simulation model (Schulze, 1995; Schulze and Smithers, 2004) in order to assess projected changes in hydrological and other water related responses.

Many results are now available through this Report, but much still needs to be written up in reports/papers. Where research has already been written up, authors are listed in round ( ) brackets, where it still has to be written up in square [ ] brackets; where research is still needed, no authors have been mentioned. The examples which follow below are categorised into

- *first order* hydrological changes which include the drivers of climate change and resultant changes in streamflow patterns, and
- *second order* hydrological changes which consider extreme events and groundwater recharge.

First Order Changes

- Changes in temperature patterns
  - Magnitude (e.g. Schulze *et al*., 2005a; Schulze and Kunz, 2010a; Schulze and Kunz, 2010b; Schulze and Kunz, 2011a; 2011b in **Chapter 3.1** of this Report).
  - Variability (Schulze and Kunz, 2010a; Schulze and Kunz, 2010b; Schulze and Kunz, 2011a; 2011b in **Chapters 3.1** and **3.2** of this Report).
  - Confidence in results (Schulze and Kunz, 2010a; Schulze and Kunz, 2010b; Schulze, 2011b in **Chapter 2.4** of this Report).
- Changes in precipitation patterns
  - Magnitude (Schulze *et al*., 2005a; Knoesen *et al*., 2009; Schulze and Kunz, 2010c; 2010d; Schulze and Kunz, 2011c; 2011d in **Chapters 3.4** and **3.5** of this Report).
  - Concentration (Schulze and Kunz, 2010e).
  - Seasonal Distribution (Schulze and Kunz, 2010f).
  - Variability (Schulze and Kunz, 2010c; 2010d; Schulze and Kunz, 2011c; 2011d in **Chapters 3.4** and **3.5** of this Report).
  - Confidence in results (Schulze and Kunz, 2010c; 2010d; 2010e; Schulze, 2011b in **Chapter 2.4** of this Report).
- Changes in evaporation rates
  - Magnitude (Schulze *et al*., 2005a; Knoesen *et al*., 2009; Schulze and Kunz, 2010g; Schulze, Kunz and Bulcock, 2011a in **Chapter 4.1** of this Report; Schulze and Bulcock, 2011a in **Chapter 8.1** of this Report).
  - Confidence in results.
- Changes in streamflow patterns
  - Magnitude (Schulze *et al*., 2005a; Knoesen *et al*., 2009; Schulze and Kunz, 2011e in **Chapter 5.4** of this Report).
  - Seasonality / Shifts in timing.
  - Variability (Schulze and Kunz, 2011e in **Chapter 5.4** of this Report).
  - Exceedences of thresholds of flow (Schulze and Bulcock, 2011b in **Chapter 5.5** of this Report).
  - Confidence in results.
- Changes in flow components, drivers and fluxes
  - Stormflows (Schulze *et al*., 2005a; Schulze and Kunz, 2011f in **Chapter 5.2** of this Report).
  - Baseflows (Schulze *et al*., 2005a; Schulze, Kunz and Bulcock, 2011b in **Chapter 5.3** of this Report).
  - Blue, Green White Water Flows (Schulze *et al*., 2005a).
  - Soil Water Content (Schulze *et al*., 2005a; Schulze and Kunz, 2010i; Schulze, Kunz and Bulcock, 2011c in **Chapter 4.2** of this Report).

Second Order Changes

- Changes in magnitudes / frequencies / duration of extreme events
  - Changes in meteorological droughts (Knoesen *et al*., 2009; Schulze, Knoesen and Kunz, 2011g in **Chapter 6.1** of this Report).
  - Changes in hydrological droughts (Knoesen *et al*., 2009; Schulze, Knoesen, Kunz and Bulcock, 2011d in **Chapter 6.2** of this Report).
  - Changes in design rainfall (Schulze *et al*., 2005a; Knoesen *et al*., 2009; Knoesen, Schulze and Smithers, 2011a, 2011b in **Chapters 7.1** and **7.2** of this Report).
  - Changes in design streamflows (Knoesen *et al*., 2009; Knoesen, Schulze and Kunz, 2011 in **Chapter 7.3** of this Report).
  - Confidence in results.
- Changes in groundwater recharge
  - Magnitude (Schulze *et al*., 2005a; Schulze, Kunz and Bulcock, 2011b in **Chapter 5.3** of this Report).
  - Confidence in results.

2. *Current Understanding on Projected Impacts on Water Allocation / Demand / Use / Quality*

Climate change will affect not only water *supply*, but also the *demand* for water, with projected changes to availability, timing and assurance of water supply affecting all water user sectors, e.g. agriculture, hydropower, urban areas, water for sanitation, the poor and the environment. Changes will also affect the broader dynamics of the economy, including water scarcity, water related disasters, spatial patterns of development, structural changes in economies. Furthermore, because impacts are in the future, many uncertainties prevail, and some responses are particularly long-lived, it is timely now to focus on strengthening management, information and water infrastructure.

Issues identified as gaps, and for which confidence also has to be established in climate change studies, are discussed below, bearing in mind that in the context of climate change impacts on water allocation, demand, use and quality in this Chapter

- second order changes are considered to include those related to irrigation demands, effects of available water on different land uses and land uses on water, while
- third order changes would embrace those related, *inter alia*, to supply and demand, water quality in its various manifestations, terrestrial / aquatic ecosystems and the goods and services they render, impacts on infrastructure, integrated catchment assessments, transboundary waters and vulnerability of poorer communities.

Second Order Changes

- Changes in irrigation water demand and practices, e.g.
    - Magnitude of water demand (Schulze and Dlamini, 2005; Schulze and Kunz, 2010h; Schulze, Kunz and Bulcock, 2011e in **Chapter 8.2** of this Report).
    - Effects of different modes of scheduling on water use efficiency.
    - Environmental consequences of irrigation through losses to percolation beyond the root zone [nitrate leaching] and surface runoff [phosphate removal] (Schulze and Bulcock, 2011c in **Chapter 8.3** of this Report), and
    - Confidence in results (Schulze and Kunz, 2010h).
- Effects of changed land use patterns on water availability and production, e.g.
    - Plantation forestry,
    - Land degradation,
    - Land reform,
    - Land use management such as conservation and tillage practices, and
    - Alien invasive species in both riparian and upslope locations.
- Effects of changed water availability on land use patterns, e.g.
    - Shifts in cropping patterns and yields in regard to food security (Schulze, 2010) and biofuels, and
    - Intensification or extensification of land uses.

Third Order Changes

- Changes in water demand and supply, e.g.
    - Urban, i.e. municipal, domestic (formal and informal residential), industrial, and
    - Rural, including settlements, tourism, recreational or agricultural.
- Changes in water rights and allocation mechanisms in the face of not only the National Water Act (NWA, 1998), but also the realities of climate change, biofuel production and national as well as local food security.
- Changes in dynamics of water quality responses and their consequences in regard to
    - Physical water quality, i.e. sediment yield (Schulze *et al*., 2005a; Knoesen *et al*., 2009; Schulze, Knoesen and Kunz, 2010a, 2011f in **Chapter 5.7** of this Report).
    - Chemical water quality, i.e. eutrophication through nitrate leaching and phosphorous wash-off.
    - Biological water quality, e.g. faecal coliform such as *E. coli*.
    - Water temperature (Barichievy, Schulze and Kunz, 2010a; Barichievy and Schulze, 2010) in light of aquatic habitat changes and animal / human health, with
    - Consequences on purification costs, and
    - Consequences on human health through
        - ▫ *Water-borne diseases* which result from the contamination of water by human or animal faeces, or by urine infected by pathogenic viruses or bacteria, in which case the disease is transmitted directly when the water is drunk or used in the preparation of food,

        - *Water-washed diseases* which result from inadequate personal hygiene because of scarcity or inaccessibility of water and which include many water-borne diseases as well as typhus,
        - *Water-based diseases*, i.e. those arising from parasites that use an intermediate host that lives in or near water (e.g. guinea worm),
        - *Water-related diseases*, i.e. those diseases borne by insect vectors, which have habitats in or near water (e.g. malaria), and / or
        - *Water-dispersed diseases* which are infections, whose agents proliferate in fresh water and enter the human body through the respiratory tract (e.g. Legionella).
- Impacts on terrestrial and aquatic ecosystems, including changes in
    - Water related ecosystems goods and services (Scott-Shaw and Schulze, 2009; Scott-Shaw, 2011),
    - Environmental integrity,
    - Baselines against which to assess impacts,
    - Wetlands responses and functioning (Gray, 2011),
    - Estuary responses and functioning (Davis and Schulze, 2009; Davis, 2011),
    - Impacts of increased water temperatures (Barichievy *et al*., 2010a; Barichievy and Schulze, 2010), or
    - Changes to Indicators of Hydrological Alteration (Barichievy *et al*., 2010b).
- A re-think on water storage, including natural, man-made and virtual storage;
- Impacts on infrastructure in regard to
    - Hydraulic design (Schulze, Knoesen, Kunz and van Niekerk, 2010b; 2010c),
    - Dam safety, and
    - Infrastructure maintenance.
- Integrated Catchment Studies, with installed modelling systems (IMSs) particularly on stressed and vulnerable catchments, examples of IMSs being the
    - Berg / Breede System (Lumsden *et al*., forthcoming),
    - Mbuluzi (Schulze and Dlamini, 2005),
    - Mngeni Catchment (Gillham and Summerton, 2009; Summerton and Schulze, 2009; Warburton *et al*., 2011), or
    - Thukela (Schulze *et al*., 2005b).
- Potential conflicts over shared rivers, i.e.
    - Rivers as international boundaries, and
    - Rivers discharging to, or from, South Africa's neighbouring countries (e.g. Schulze and Dlamini, 2005), with possible
    - Changes needed to international agreements.
- Vulnerability of the poor
    - In urban areas, e.g. living in flood prone riparian areas,
    - In rural areas, e.g. availability of potable water, and including
    - Climate forced in-migration from other countries or rural to urban migration, or
    - Water Poverty Index studies (e.g. Dlamini and Schulze, 2005); and
- A focus on mountainous areas
    - which are South Africa's runoff producing areas ('water towers'),
    - are sensitive / vulnerable to climate change, but
    - have under-represented hydro-climatic networks (e.g. Warburton and Schulze, 2005), and
    - poorly understood future changes in vertical gradients affecting precipitation and runoff.

Taking Cognisance of, and Understanding the Implications of, Other Constraints and Gaps in Developing an Effective Adaptation Strategy

In addition to compelling reasons given in the aforegoing sections which outline the need for a climate change adaptation strategy for the South African water related sector and which provide an overview on what has already been achieved in this country in regard to the physical basis of hydrological responses and climate change, and what still needs to be done in the field of water management, some real world constraints and gaps are identified. These include the following:

- *Policy Constraints* revolve primarily around South Africa to date (mid-2011) urgently requiring the completion of an adaptation policy and action plan specific to the water related sector, some principal components of which should include that

  - its present water resources, water related vulnerabilities and its water needs be fully understood, well documented and up-to-date;
  - adaptation in the water sector take place within legal and policy frameworks which display government's commitment to adapt on an international level, a national level and on a water sector level;
  - an adaptive approach to integrated management be followed;
  - the development principle be adhered to, bearing in mind that in South Africa the poor and marginalized groups are most vulnerable, that
  - adaptation is an integral part of development and that
  - climate change is but one of several drivers of global change;
  - the principle be followed that greater resilience today implies more effective adaptation tomorrow;
  - that sound water governance is an imperative;
  - stakeholder participation be an important principle;
  - sectoral integration be promoted since the water related sector is intimately interwoven with agriculture, forestry, health, spatial planning, as well as coastal zone and disaster risk management;
  - adaptation be practised at appropriately fine spatial scales;
  - uncertainties be addressed;
  - climate change information be communicated and disseminated relevantly; that
  - appropriate budgets be set aside for adaptation; and that
  - a balance be found between structural and non-structural adaptation measures.

  The points listed above are elaborated upon in some detail later in this Chapter.
- *Capacity Constraints* of those involved in research, management, as well as in the effective operation of water resources infrastructure (e.g. municipal employees operating waste water treatment plants) revolve around constraints within universities as well as parastatals and, particularly, that the relevant national as well as provincial and local departments do not have enough dedicated and sustained water related research and understanding in regard to climate change and water.
- *Physical Constraints* include that very few suitable sites for future dams are left in South Africa.
- *Developmental Constraints* have to do with our lack of understanding of the interactions of climate change being superimposed on operational catchments with already existing land uses, urban areas, dams, mines, roads etc and what the feed-forwards and feed-backs might be.
- *Economic Constraints* focus on the high cost of new water infrastructure to cope with possible added effects of climate change, and of maintaining acceptable levels of water quality under future warmer climates and expanding / maintaining hydro-climatic networks, especially in hydrologically sensitive areas.

Therefore, accounting for, and adapting to, potential effects of climate change in South Africa's water related sector are imperatives - indeed, non-consideration of potential effects of climate change in, for example, updates of the National Water Resource Strategy, and adaptation on the country's water sector should be viewed as an act of omission.

On Clarification of Terms and Concepts Used Frequently in this Document

Different user communities often interpret terms and concepts related to climate change differently. This section therefore serves to clarify some key terms in the context that they are used in this Chapter. Where not specifically referenced, information has been gleaned from IPCC (2001), Schulze (2003; 2005b), IPCC (2007) and Theesfeld *et al*. (2011).

1. Climate Change and Climate Variability: Two Concepts Often Confused

- *Climate change*, in IPCC usage, refers to any change in climate over time, whether due to natural variability or as a result of human activity (IPCC, 2007). This usage differs from that of the United Nations Framework Convention on Climate Change (UNFCCC, 2007), which more comprehensively defines climate change as a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.
  - Climate change is considered to be irreversible and permanent, where a trend over time (either positive or negative) of means and deviations from the mean as well as other higher order statistics is superimposed over naturally occurring variability.

  - The time scale of climate change is decades to centuries and the trend is more likely to occur in steps than linearly over time.
- *Climate variability* (CV), on the other hand, signifies any deviation from the long-term expected value. It is an entirely natural phenomenon, is reversible and non-permanent. An example would be the droughts in southern Africa associated with the El Niño. CV has time scales from
  - diurnal (within the course of a day, e.g. time of occurrence of convective thunderstorms), to
  - daily (i.e. variations from one day to the next), to
  - intra-seasonal (e.g. monthly CVs), to
  - inter-annual (e.g. year-to-year variability), and
  - decadal (e.g. consecutive wet years or dry years).

2. Climate Scenarios, Climate Projections and Climate Predictions: Three Concepts Equally Often Confused

- *Climate scenarios* are projections following on from a set of basic 'what if' assumptions which can evolve in multiple directions and, strictly speaking, cannot be predicted. In climate change studies they can take several forms:
  - First, and nowadays most commonly applied, are *scenarios from GCM output* based on one of the A1, A2, B1 or B2 emission scenarios (Nakićenović and Swart, 2000) bearing in mind (UKCIP, 2003) that
    - ▫ uncertainties exist within each of the four scenarios, with each having their own explicit assumptions on greenhouse gas emissions dependent on technology, politics, economics and type of development, and associated probabilities, that
    - ▫ no one scenario is "a more likely future", or a "best guess", that
    - ▫ uncertainties occur due to differences between GCMs, each of which represents certain processes differently and imperfectly, with no GCM being the "best" (cf. **Chapter 2.4**), and
    - ▫ "best" in agriculture (or any other sector) not necessarily being the "best" in terms of hydrology, and that
    - ▫ uncertainties associated with changes in precipitation (the main "driver" of hydrological responses) are greater than uncertainties in temperature, that
    - ▫ uncertainty is greater in regard to magnitudes of change than direction, and
    - ▫ greater for changes in variability and extremes than for means, while
    - ▫ uncertainties associated with downscaling from global to hydrologically relevant local scales, be it by empirical / statistical techniques or by dynamic methods, remain a source of concern.
  - Secondly, scenarios can take the form of *simple incremental scenarios*, which in effect are sensitivity type analyses of plausible changes in climate such as
    - ▫ increases in temperature by +1 ^{o}C, or +2 ^{o}C, or +3 ^{o}C, or
    - ▫ changes in precipitation by -10 %, or -20 %, or +10 %, or +20 %, or
    - ▫ enhancements of atmospheric CO_2 concentrations to 1.5 times pre-industrial revolution values, or to an effective doubling of CO_2, or to specific concentrations (in ppmv),
    - ▫ with changes made by small, but realistic / plausible, increments from a baseline, and
    - ▫ changes made initially to single variables and later to multiple variables,

    and with the usefulness of such sensitivity analysis being that one can
    - ▫ *gauge* likely *impacts*,
    - ▫ determine *critical thresholds* of change (when does the system "flip"?),
    - ▫ determine *when* change becomes significant,
    - ▫ determine *where* change is significant, and
    - ▫ determine *which* driver is more significant than others, thereby determining the *sensitivity* of the "exposure unit" (UKCIP, 2003).
  - Thirdly, and nowadays no longer used frequently, are scenarios of *climate analogues*, i.e. using present-day examples of extreme years (e.g. a hot, dry year) as analogues for projected common occurrences of a plausible future climate.
    - ▫ Note that while climate analogues are based on historically observed climate records,
    - ▫ it should be appreciated that analogue years may differ from future climate scenarios.
- *Climate projections* are projections of the responses of the climate system to emission or concentration scenarios of *greenhouse gases* and *aerosols*, or *radiative forcing* scenarios, which are based on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realised, and are therefore subject to substantial uncertainty (IPCC, 2007).

  - Climate projections are usually based on simulations by Global Climate Models, also known as General Circulation Models (GCMs).
  - Projections are not predictions in the sense that the quality of a projection, and therefore the likelihood that it will occur, cannot be firmly determined.
- A *climate prediction* is a forecast of what will happen in future. It can be a
  - deterministic forecast ('tomorrow it will be raining'), or a
  - probabilistic forecast ('there will be a more than average change that tomorrow it will rain').
  - -- The predictability of a phenomenon can be defined as the degree to which its evolution can be deduced from the known initial conditions and the known evolution of factors that affect the phenomenon. It thus depends significantly upon the spatial and temporal scales of the phenomenon.

3. Climate Change Impacts

Climate change impacts are the *consequences* of climate change on any natural and human system and, depending on the consideration of adaptation, one can distinguish between potential impacts and residual impacts, where

- *Potential Impacts* imply all impacts that may occur given a projected change in climate, without considering adaptation, while
- *Residual Impacts* are the impacts of climate change that would occur after adaptation.

4. Mainstreaming Climate Change

- *Mainstreaming*, in the climate change context, refers to integration of climate change vulnerabilities or adaptation into some aspect of related government policy such as water management, disaster preparedness and emergency planning or land-use planning (Agrawala, 2005: IPCC, 2007).
- Actions that promote the mainstreaming of climate change adaptation include
  - integration of climate information into environmental data sets,
  - preparing climate change related vulnerability or hazard assessments,
  - factoring climate change into broad development strategies, as well as into
  - macro policies and / or sector policies,
  - institutional or organisational structures, or
  - development project design and implementation (Huq *et al*., 2003).
- By implementing mainstreaming initiatives, it is argued that adaptation to climate change will become part of, or will be consistent with, other well established programmes, particularly sustainable development planning, but that mainstreaming needs to encompass a broader set of measures to reduce vulnerability than has thus far been the case (IPCC, 2007).
- Mainstreaming initiatives have been classified in the development planning literature at various levels (IPCC, 2007):
  - At the international level, mainstreaming of climate change can occur through policy formulation, project approval and country-level implementation of projects funded by international organisations.
  - At the regional level mainstreaming assesses the likely impacts of climate change on key economic sectors such as water, agriculture or human health, while
  - At the community level responses may also be defined.

5. Vulnerability

- *Vulnerability* to climate change is the degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change, including climate variability and extremes.
- It is a measure of a system's susceptibility to the type (e.g. drought), the magnitude (e.g. how bad will it be) and the rate (how quickly will it set in) of climate change, and it therefore depends on what the system (e.g. a poor community, or an estuary) is exposed to (e.g. flooding), what it is sensitive to (e.g. sustained inundation of at least 2 days), and whether it has the capacity to adapt to climate change.
- Vulnerability can thus be
  - a relative property to a potential event (e.g. an occasional flood), or
  - a constant stress that increases over time (e.g. more water-borne diseases).
- Vulnerability need not always be a negative property; indeed, it may lead to beneficial development.

- The term vulnerability, in the IPCC literature, may refer to
  - the vulnerable system itself (e.g. a riparian zone adjacent to a river),
  - the impact to this system (e.g. prone to flooding),
  - or to the mechanism causing these impacts (e.g. a higher frequency of tropical cyclones under climate change).
- Assessment of key vulnerabilities involves not only
  - substantial scientific uncertainties, but also
  - value judgements.
- It requires consideration of the response of
  - biophysical and socio-economic systems to changes in climatic conditions over time (e.g. more floods), and
  - non-climatic conditions over time (e.g. changes in population, economy or technology),
  - important non-climatic developments that affect adaptive capacity (e.g. a civil war),
  - the potential for effective adaptation across regions, sectors and social groupings,
  - value judgements about the acceptability of potential risks, and
  - potential adaptation and mitigation measures.
- To achieve transparency in such complex assessments, scientists and analysts need to provide a ‘traceable account’ of all relevant assumptions (Moss and Schneider, 2000).

6. On Exposure, Sensitivity and Resilience

- *Exposure* is the extent (i.e. the nature and degree) to which a climate-sensitive sector (e.g. water) is in contact with / exposed to significant climatic variations (e.g. of rainfall).
- *Sensitivity*, on the other hand, is the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli.
- Effectively it is the magnitude of change in a response (e.g. runoff) to a change in the driver of that response (e.g. rainfall).
- The effect (IPCC, 2007) may be
  - direct (e.g. a change in evaporation in response to a change in the mean, range, or variability of temperature), or
  - indirect (e.g. damages caused by an increase in the frequency of coastal flooding due to sea level rise),

  and the response to an event or exposure can be
  - positive, i.e. direct (e.g. as rainfall increases, so does runoff), or
  - negative, i.e. inverse (e.g. as evaporation from the soil surface increases between rainfall events, so the runoff from a certain amount of rainfall will decrease).
- *Resilience* may be defined as the ability to absorb disturbances and recover from them - in colloquial English also implying the “bounce-back-ability”.
  - An example would be the capacity of a system (e.g. a dam) to absorb (e.g. a flood), and recover from a hazardous event (e.g. a drought).
  - Resilience therefore implies that there are thresholds which, when exceeded, result in a system being vulnerable.

7. On Adaptation and Related Concepts

- *Adaptation*, from various sources within the IPCC (2007) literature, may be defined as actual adjustments in natural or human systems, or changes in decision environments, in response to actual or expected climatic stimuli or their effects, which could moderate harm and which might therefore ultimately enhance resilience or reduce vulnerability to observed or expected changes in climate, or exploit beneficial opportunities.
- The UNFCCC (2007) definition in some ways expands somewhat on the above, with adaptation being *“a process through which societies make themselves better able to cope with an uncertain future. Adapting to climate change entails taking the right measures to reduce the negative effects of climate change (or exploit the positive ones) by making the appropriate adjustments and changes”*.
- Various *types of adaptation* can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation:
  - *Anticipatory Adaptation* is adaptation that takes place before impacts of climate change are observed. It is also referred to as proactive adaptation.
  - *Autonomous Adaptation* is adaptation that does not constitute a conscious response to climatic stimuli, but is triggered by ecological changes in natural systems and by market or welfare changes in human systems. This is also referred to as spontaneous adaptation.

  - *Planned Adaptation* is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state.
  - *Private Adaptation* is initiated and implemented by individuals, households or private companies, usually in the actor's rational self-interest.
  - *Public Adaptation* is initiated and implemented by governments at all levels and is usually directed at collective needs.
  - *Reactive Adaptation* takes place after impacts of climate change have been observed. Reactive approaches are seen as inefficient and not always successful.
- As alluded to above already, the drivers of adaptation differ as a function of the administrative setting. According to Theesfeld *et al*. (2011).
- Adaptation at "higher" levels (e.g. central government) tends to be planned and is driven by
  - planned institutional adaptation,
  - meeting in-country environmental policy targets,
  - meeting international obligations and commitments (e.g. to UNFCCC), and
  - co-ordination across agencies with climate change agendas.
- Adaptation at higher levels is, as a rule, thus
  - intentional
  - anticipatory
  - pro-active
  - long term and
  - strategic.
- At "lower" levels (e.g. local government) adaptation tends to be *autonomous* and is driven by
  - hydroclimatic drivers such as experiences of floods and droughts
  - with often rules and procedures put in place to facilitate technical coping solutions
  - with a mix of climate and non-climate factors and
  - with bottom-up initiatives by NGOs and / or local media and
  - blending indigenous experience / knowledge with anticipated change.
- Adaptation at lower levels thus tends to be more
  - spontaneous
  - reactive
  - short term and
  - practical.
- A distinction needs to be made between *adaptive management vs adaptive governance*, where
  - adaptive management is more about the operational aspects of water allocation, while
  - adaptive governance refers to the making of rules (e.g. assigning water rights, handling trade-offs, centralised vs decentralised water management).
- Adaptation practices can be differentiated along several dimensions (IPCC, 2007), for example,
  - by spatial scale (local, regional, national);
  - by sector (water resources, agriculture, tourism, public health, and so on);
  - by type of action (physical, technological, investment, regulatory, market);
  - by actor (national or local government, international donors, private sector, NGOs, local communities and individuals);
  - by climatic zone (dryland, floodplains, mountains, etc);
  - by baseline income / development level of the systems in which they are implemented (least-developed countries, middle income countries, and developed countries); or
  - by some combination of these and other categories.
- From a temporal perspective, adaptation to climate risks can be viewed at three levels, including responses to:
  - current variability (which also reflects learning from past adaptations to historical climates);
  - observed medium and long-term trends in climate; and
  - anticipatory planning in response to model-based scenarios of long-term climate change.

  The responses across the three levels are often intertwined, and indeed might form a continuum.

8. Adaptive Capacity

- Closely related to the concept of adaptation *per se* is that of the capacity to adapt, usually termed adaptive capacity. From Brooks and Adger (2005) and the IPCC (2007) it may be defined as the ability or potential of a system to respond successfully (i.e. adjust in both behaviour and in resources and technologies) to climate change (including climate variability and extremes), to moderate potential damages (by changing exposure or sensitivity), to take advantage of opportunities, or to cope with the consequences of impacts (by recovering or maintaining welfare / system function in the face of climatic change) and to profit from new opportunities (assuming climate change affects agents differentially).

- Systems with high adaptive capacity are able to reconfigure themselves more easily after a shock due to an extreme event than systems with a low adaptive capacity.
- The presence of adaptive capacity has been shown to be a necessary condition for the design and implementation of effective adaptation strategies so as to reduce the likelihood and the magnitude of harmful outcomes resulting from climate change (Brooks and Adger, 2005).
- Research on vulnerability and adaptive capacity shows clearly that some dimensions of adaptive capacity are generic, while others are specific to particular climate change impacts.
  - Generic indicators include factors such as education, income and health.
  - Specific indicators to a particular impact, such as drought or floods, may relate to institutions, knowledge and technology (e.g. Yohe and Tol, 2002; Brooks *et al*., 2005).
- Technology can potentially play an important role in adapting to climate change, with engineering solutions representing some of the options that can lead to improved outcomes and increased coping under conditions of climate change.
- Adaptive capacity is influenced not only by economic development and technology, but also by social factors such as human capital and governance structures (e.g. Brooks and Adger, 2005).
- Adaptive capacity is uneven across societies, and while national-level indicators of vulnerability and adaptive capacity may be used by climate change negotiators, practitioners, and decision makers in determining policies and allocating priorities for funding and interventions, the usefulness of indicators of generic adaptive capacity and the robustness of the results is not entirely convincing (e.g. Yohe and Tol, 2002; Brooks *et al*., 2005).
- Adaptive capacity is unevenly distributed and highly differentiated within nations due to multiple processes (stresses) of change interacting to influence vulnerability and shape outcomes from climate change (e.g. Ziervogel *et al*., 2006).
- Social and economic processes determine the distribution of adaptive capacity, which can be highly heterogeneous within a society or locality, and for individuals and communities it is differentiated by age, class, gender, health and social status.
- Adaptive capacity can change over time, because it may be enhanced or constrained or eroded by factors such as regulations or economic policies determined at the regional or national level that either limit or enhance the freedom of individuals and communities to act, or that make certain potential adaptation strategies either viable or unviable, including violent conflict or the spread of infectious diseases or urbanisation or even trade liberalization (IPCC, 2007).

Guiding Principles for an Adaptation Strategy

The core challenge of adaptation in South Africa is water security for its people, i.e. when managing water to proactively ensure the ability to harness water’s social and productive forces and to control water’s destructive forces. As such, any adaptation strategy has to balance the three “E”s, *viz*. environment, economy and equity, by the dictum “some, for all, for ever”.

The cornerstones of this adaptation strategy are expressed through 18 guiding principles which, while described separately, are not mutually exclusive.

1. Principle 1: An Adaptation Strategy for the South African Water Sector can only be Successfully Implemented if the Current State of its Hydro-Climate, its Water Resources, its Water Related Vulnerabilities and its Water Needs are Fully Understood, Well Documented and Up-to-Date

- Any projection on water management into the future, with and without accounting for potential impacts of climate change, has to be founded on high quality and up-to-date baseline, or reference, data and information.
- The regular updates of, *inter alia*, the DWA’s National Water Resource Strategy, its Internal Strategic Perspectives (ISPs), specialist consulting reports on catchments and the WARMS database, as well quality controlled, readily accessible and up-to date climate, streamflow, water quality, land use and demographic databases therefore become an imperative to successful planning and adaptation.
- The onus is on relevant national, provincial and local government departments as well as on parastatals and other research organisations such as universities and their funding agencies to ensure state-of-the-art data and information.

2. *Principle 2: Adaptation in the Water Sector has to Take Place Within Legal and Policy Frameworks which Display Government's Commitment to Adapt*

- Much of the adaptation planning literature emphasises the role of governments, but also recognises the constraints that they face in implementing adaptation actions at other scales (Few *et al*., 2007).
- While there are few examples of successful mainstreaming of climate change risk into development planning (IPCC, 2007), government plays a crucial role in establishing legal and policy frameworks which guide day-day priorities of water managers and will encourage adaptation to climate change by managers in the public and private sectors, including private individuals (Stern, 2007).
- Strong government commitment, leadership and willingness to achieve adaptation to climate change also makes roles and responsibilities for the implementation of adaptation strategies at lower levels more understandable (Smit and Pilvosova, 2001).
- Governments do, however, face major constraints when developing adaptation strategies for climate change, and Agrawala and van Aalst (2005) have identified the following five major constraints, *viz*.
  - obtaining relevant climate information for development-related decisions,
  - uncertainty of climate information, especially in regard to climate projections into the future,
  - compartmentalisation within government departments,
  - segmentation and other barriers within development - cooperation agencies, and
  - trade-offs between climate change and other development objectives.
- There is, however, strong government commitment to adaptation to climate change evident in South Africa through legal and policy frameworks both of a generic nature, at both international and national levels, as well as commitment of a more water sector specific nature.

On an International Level

- United Nations Framework Convention on Climate Change (UNFCCC)
  The South African government ratified the UNFCCC in August 1997 and the UNFCCC's Kyoto Protocol in July 2002 (Green, 2008). The erstwhile DEAT, now incorporated into DWEA, coordinates actions and ensures compliance with such international obligations related to climate change on behalf of the government.

On a National Level

- The Constitution of South Africa
  A point of departure to South Africa's commitment adaptation to climate change in the water sector may be taken as the South African Constitution (RSA, 1996), in which it is enunciated that everyone has the right to access "sufficient…water". Furthermore, it is stated that everyone is provided with the right "to an environment that is not harmful to their health or well-being"; and "to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures […] while promoting justifiable economic and social development" (RSA, 1996).
- National Committee on Climate Change (NCCC)
  The NCCC, with representatives from relevant government departments (including water) and from business and industry, mining, labour, community based organisations and NGOs, acts as an advisory body to DEAT.
- Government Committee on Climate Change (GCCC)
  More recently the GCCC was established to allow representatives of government to caucus internally and present a front (Green, 2008).
- National Climate Change Response Strategy (NCCRS)
  The NCCRS was developed by DEAT in 2004 and revised / updated in 2011, *inter alia*, to support national and sustainable development in light of climate change, develop adaptation strategies (with water resource management and contingency planning one of the key sectors), and to ensure that international obligations to the UNFCCC are met, that climate change issues are provided for in South African legislation, that there is an effective and integrated programme of climate change research in South Africa and that there is best possible access to available climate change funding.
- National Long-Term Mitigation Scenarios (LTMS)
  As an extension of the NCCRS, DEAT initiated the development of the LTMS (Midgley *et al*. 2007), to which there was a major contribution on the water sector (Schulze *et al*., 2007).

On a Water Sector Level

- The National Water (NWA) Act of South Africa of 1998

  In being mandated with protecting, utilising, developing, conserving, managing and controlling South Africa's water resources through, *inter alia*,
  - demand management (e.g. promoting sustainable, beneficial and efficient water use; satisfying basic human needs both at present and in the future; ensuring equitable access to water; socio-economic development into the future), as well as
  - environmental management (e.g. reduction of water pollution and degradation; protection of ecosystems)
  - crisis management (e.g. promoting dam safety; managing floods and droughts) and
  - political management (e.g. redressing past inequities; meeting international water obligations)

    all of which are implicated by climate change, the NWA (1998) clearly declares its commitment, explicitly or implicitly, to adaptation to future climatic conditions through Integrated Water Resource Management (Schulze, 2008; Stuart-Hill and Schulze, 2010).
- The National Water Resource Strategy (NWRS)

  The NWRS (2004), mandated by the NCCRS to give sufficient consideration for future climate change in the water sector, does so, albeit with a "relatively soft and cautious approach" (Boardley and Schulze, 2005) highlighting uncertainties and inadequacies of the (then; 2004) existing science of the day for climatic shifts throughout South Africa by stating, *inter alia*, that it was "prudent, however, to anticipate the possibility of climate change and to take this into consideration in the development of catchment management strategies", that "a balance (would) have to be sought between preparedness and overreaction, to prevent valuable resources being wasted" and that climate change impacts on the water sector would need to be "formally re-assessed with each five-yearly review of the National Water Resource Strategy over the long term" (NWRS, 2004: 50)
- The Water for Growth and Development Framework (WfGD)

  The WfGD Framework (2009; Version 7), in representing the DWA's commitment to water security for the people, the economy and the environment for now and in the future, and in presenting a comprehensive and collective response to the manifold water challenges facing South Africa, identifies climate change as an accepted threat to the sustainability of South Africa's water supplies, highlighting the quantification of potential impacts, its associated uncertainties, the fact that this complicates planning and the importance of DWA's participation in, contribution to, and support of ongoing research as well as monitoring of the effects of climate change on the sub-region (and beyond). The critical role of climate change adaptation in relation to DWA planning processes is highlighted by emphasising that all scenario planning must factor in projected future impacts of climate change which, in turn, requires research to be disseminated within the DWA, and water sector in general in order to inform policy formulation. The Framework also identifies climate change to present specific challenges of a practical nature. While in its latest available iteration (March 2009) at the time of writing (July 2011) it is not yet providing an entirely "mature" overview of climate change impacts over South Africa, the WfGD Framework nevertheless to date contains one of the most comprehensive official and public water-related documentation on climate change and lays the foundation for a water sector climate change strategy for South Africa.

3. Principle 3: The Adaptive Approach to Integrated Management

While the importance of widespread impacts of climate change on the water sector is clearly acknowledged by scientists, it is policy makers and water managers that will need to recognise that changes in attitude towards water management, and adoption of new approaches, will be required to successfully adapt to the impacts and challenges associated with climate change (Ludwig *et al*., 2009).

In summary, adaptive management

- is a structured process for improving management policies and practices by systemic learning from outcomes of implemented strategies and by taking into account changes in external factors;
- explicitly recognising uncertainties and complexities and
- requiring integrated system design to build and sustain enabling structural conditions.

In regard to adaptive water management and climate change in South Africa the following elements identified by Aerts and Droogers (2009) will be key:

- Flexibility and robustness: Because one is dealing with uncertainty in future water management, those management strategies and infrastructures (especially large scale and irreversible) which display high levels of flexibility, or robustness, are most likely to contribute to both resilience and adaptive capacity as climatic proofing mechanisms, considering the wide range of future scenarios under which alternative solutions are evaluated (Aerts *et al*., 2008b).
- Cross-sectoral cooperation: More attention will need to be given to related sectors, notably finance and insurance, regional economic development, livelihoods and spatial planning, with water management not only focusing on managing the probability of events, but also on reducing its consequences.
- The ability to learn: As change proceeds, the ability to learn by drawing on experiences (in addition to analysis) in the formulation of new strategies (rather than merely 'reinventing the wheel') is central to the ability to adapt. This implies a need to develop educational approaches for climate and water specialists that are capable of evolving as new information and perspectives emerge. Stakeholder involvement within participatory processes is also seen as key to stimulating adaptive capacity (Pahl-Wostl *et al*., 2007).
- Governance: The ability of systems and populations to recognize change and to respond to it are central to adaptive capacity. This is as much about the institutional structures and effective governance as it is about the structural or technical flexibility of the water system (Aerts *et al*., 2008a).

4. Principle 4: The Environmental Dimension

The transformation and destruction of aquatic and terrestrial ecosystems, as well as the over-exploitation and pollution of surface and groundwater resources are major problems to overcome in order to ensure sustainable use of water resources in southern Africa. It is important to conserve these resources, and to this end it is necessary to conserve the integrity of the hydrological cycle, recognising it as a basic condition to implement efficient and effective climate change adaptation strategies.

The impacts caused by climate change on the natural dynamics of ecosystems and watersheds pose new challenges to be faced by the water community, which cannot be served if the environmental dimension of the problem and the care of critical ecosystems for the hydrological cycle are ignored.

This involves the preparation of development plans in accordance with the limits imposed by nature and emphasises issues such as ecological - land management systems, the implementation of environmental flow rates, restoration of ecosystems and maintenance of their natural dynamics.

In designing adaptation strategies in water to address the conditions expected as a result of climate change, it is important to consider environmental criteria as encapsulated directly and indirectly in, *inter alia*, the NWA (1998) and the NWRS (2004 and updates) and articulated by Miralles-Wilhelm *et al*. (2010), *viz*.

- Conserving the key ecosystems for the water cycle, which implies:
  - undertaking and strengthening measures to ensure that priority land-based and aquatic ecosystems, which are associated with the maintenance of the hydrological cycle, are no longer being altered and destroyed;
  - harmonising agricultural development with environmental policies; and
  - extracting only water that is available in natural ecosystems as surplus to that required for their proper functioning, for other uses.
- This requires the consideration of:
  - balancing the extraction of water resources in terms of the renewal capacity of water bodies, the latter defined based on scientifically sound and appropriate information, ensuring sustained future water availability of acceptable quality;
  - considering ecological aspects of the water balance from the design phase of large water projects, including irrigation, energy and tourism, and not after deciding on their construction;
  - carrying out strategic environmental evaluations in all water resources projects;
  - implementing adjustments to the water resources management measures by considering the minimum flow necessary to maintain ecosystem functions; and
  - improving methodologies for monitoring and regulatory tools of such measures, so that they fulfill environmental, social and economic objectives;

- defining the environmental flow as a variable to be considered depending on the need to support the resilience of an ecosystem; and
- considering the environmental flow rate not just for it being used / needed by ecosystems, but as an absolutely essential and legitimate condition, and
- considering that their definition can only be achieved through participatory and inclusive processes, creating awareness on the importance of water and how to use it in a more efficient and rational manner, always taking into account the institutional and social processes involved in the overall management of ecosystems and their resources (Miralles-Wilhelm *et al*., 2010).

5. Principle 5: Equity, Poverty and Gender Considerations

It is now widely recognised that the impacts of climate change across South Africa generally fall disproportionately on those regions and social groups that are less able to cope with them. In this sense, the vulnerability to extreme weather and climate phenomena is directly related to levels of development and more particularly to the conditions of poverty and marginalisation. Similarly, it is important to emphasise that it is expected that climate change will continue to undermine development efforts throughout the southern African region and that there is a possibility that it could further exacerbate poverty. Therefore, there is a pressing need for water resources managers to understand the differential burden that climate variability and change impose on the poorest and most marginalised populations of the region, and proceed to design and implement water-based adaptation measures to help reduce the vulnerability of these populations. The management and development of water resources in the region will only meet the challenges of water security and development objectives through a comprehensive long-term adaptation strategy (Miralles-Wilhelm *et al*., 2010). This strategy clearly has to support the overall objectives of re-distribution and poverty alleviation in order to reduce vulnerability. This requires taking a number of relevant measures, such as:

- including explicit criteria of equity and poverty alleviation in the process of policy design and implementation;
- developing and implementing methodologies to properly assess and mitigate social impacts;
- developing risk and vulnerability maps using an inclusive and participatory approach;
- conducting climate change risk and vulnerability mapping in an inclusive and participatory fashion;
- relocating settlements that have established in risky areas;
- linking efforts on adaptation to other areas of social development policy, and
-

generating the political will to address these priorities (Miralles-Wilhelm *et al*., 2010).

6. Principle 6: Continuing the Ongoing Process of Institutional Capacity Development for Water-Based Adaptation to Climate Change

A key strategic principle in the process of water-based adaptation to climate change is ensuring that the sound policies in place in South Africa, as well as responding to climate change impacts in water resources, also determine the rules of participation and allocation of roles and responsibilities in the process. These policies should also create the right incentives and environment for their successful implementation, and should enable the promotion of shared responsibility between society and government in their design and in the plans of action for implementing water-based climate change adaptation measures.

This requires strong stakeholder participation in the policy formulation. The strategies identified through such a policy dialogue process therefore have to complement “top-down” approaches with “bottom-up” ones, from the following lines of action:

- creating regional and sub-regional bodies to strengthen partners for integrated hydro-climatic risk management;
- clearly defining the role of local governments / municipalities in the process of adaptation to climate change in order to help them to strengthen capacities, establish the rules and channel local investments into any planned adaptation measures;
- creating institutions which specialise in risk management of a cross-sectoral nature by employing professional staff, having a long-term vision and a high ranking in the public sector hierarchy within South Africa;

- increasing the participation of the environmental sector in hydro-meteorological risk management and in the different levels of government;
- appreciating that the vulnerability of systems is determined by local conditions and the degree of exposure to climate risks, thus making it essential to also strengthen land management actions, both rural and urban, in order to prevent the poorest being located in the most vulnerable marginal areas, which are the least protected against droughts and floods;
- strengthening institutions in the implementation of legal systems;
- strengthening management tools and environmental regulation to ensure the implementation of the strategies articulated for achieving water security;
- establishing transparency and accountability in the use of financial resources by the institutions involved in prevention, mitigation and emergency response;
- building and strengthening the interface between scientific knowledge and public policy;
- establishing multi-sectoral collaboration between water authorities and responsible communities, and considering the community management of water as a key element in the care of catchments and aquifers;
- creating synergies between water policies which are related to climate change and water and other environmental sector policies, as well as with other social and economic sectors; and
- integrating (i.e. mainstreaming) adaptation to climate change options into other current policies (Miralles-Wilhelm *et al*., 2010).

7. Principle 7: The Development Principle

Adapting to current climate variability is already sensible in an economic development context, given the direct and certain evidence of the adverse impacts of such phenomena. Adapting to climate change in South Africa must therefore be addressed in a broader spatial and economic development context, by recognising that climate change is an added challenge and stressor to balancing water demands and supply for sustained economic development, reducing poverty, redressing past inequities and preventing further environmental degradation. As such, it has to be stressed again that

- the poor and marginalised groups in South Africa are more vulnerable than most other communities,
- adaptation to climate change is an integral part of development, and should not be in conflict with it, and that therefore
- adaptation in South Africa's water sector has to be seen as being synergistic with national development priorities including, for example, achieving the Millennium Development Goals and the goals set by the National Planning Commission, by remembering again that
- climate change is but one of several drivers of global change, along with others such as population and economic growth.

8. Principle 8: Climate Change, Adaptation and Resilience

Given that resilience may be defined as the ability to absorb disturbances and recover from them (in colloquial English also implying the "bounce-back-ability"), that it therefore implies that there are thresholds which, when exceeded, result in a system being vulnerable, it is seen as imperative that building greater resilience today to ongoing climate variability and future climate change calls for adaptation to start now by addressing existing problems in South Africa's land and water management, for example, by

- focusing on the adaptive capacity for livelihoods and ecosystem maintenance, and
- adopting "no regrets" and forward-looking investments for both hard and soft adaptation measures in the water sector, as well as planning responses that go beyond just short-term responses to current climate variability, which may include
  - increased water use efficiency,
  - increased water storage capacity, and / or
  - intensification and diversification in agriculture.

9. Principle 9: Adaptation Implies Sound Governance

- The ability of systems and populations to recognise change and to respond to it are central to adaptive capacity. This is as much about the effectiveness of the agency / institution effecting the implementation of adaptive strategies as it is about the structural / technical flexibility of the water system *per se* when under stress (Aerts and Droogers, 2009).

- Strengthening South African water (and associated land) management institutions is thus crucial to effective adaptation and must build on principles of
  - transparency,
  - participation of civil society,
  - gender equality,
  - subsidiarity, and
  - decentralisation.
- This includes
  - development of a comprehensive, integrated framework
  - approaches where bottom-up meets top-down; from community to transboundary considerations and
  - adaptation being mainstreamed in dynamic national, catchment and local governance systems.
- Governance for effective adaptation to climate change in South Africa needs to strongly consider being polycentric (in contrast to being a monocentric or hierarchical system), in which governance consists of different centres of management and control ranging from small to medium and large scale democratic units with each able to exercise considerable independence to make and enforce adaptation rules within a circumscribed scope of authority for a specific geographical area (Ostrom, 2001), either with general authorities or with specialised authorities for specific tasks (Hooghe and Marks, 2003).
- Polycentric governance offers a flexible system that promotes experiments within small scale units (Ostrom, 2005) and has a good capacity to cope with external shocks (Ostrom, 2001).
- It nevertheless risks being inefficient if there is fragmentation or duplication of authority, thus necessitating
  - coordination and collaboration between the different spheres of authority to be effective and
  - requiring cross-boundary integrators (Roberts and King, 1996), i.e. individuals or collectives who connect centres, levels and sectors (Möllenkamp and Kastens, 2009).
- In the South African context polycentric governance of adaptation actions re. climate change will thus have to independently and in coordinated collaboration involve role players such as
  - the Department of Water Affairs (DWA) at national government level, as custodian of the country's water resources and the regulator within the water sector,
  - water service authorities (WSAs) which, at local government level, are the municipalities that have the executive authority to provide water services to end users within their areas of jurisdiction, and
  - water service providers (WSPs), organisations which on a regional scale have contracts with WSAs or other WSPs to sell water to and / or accept wastewater from that authority or provider for the purposes of treatment (Gillham and Summerton, 2009).
- Other issues of governance are discussed in the 'Participation Principle' below.

10. Principle 10: The Importance of Wide Participation in Developing an Adaptation Strategy

Being a complex problem, climate change poses new challenges for the management and development of water resources. Close coordination is therefore a necessity, not only between the national, provincial and local tiers of government, and with Water Management Areas / Catchment Management Agencies, but also between the wide range of other relevant stakeholders ranging from grassroots communities, to civil society organisations, and from research and development centres, international agencies and development banks.

This need for coordination, collaboration and participation in the face of climate change has to consolidate practices in governance (in addition to those addressed under the 'Governance Principle' above) and social organisation such as multi-level and cooperative governance, being used in various public policy sectors relevant to the issue, in this instance the broader water and related sectors. Miralles-Wilhelm *et al*. (2010) include the following forms of governance in this regard:

- support for the coordination and collaboration between relevant stakeholders in the climate change adaptation process;
- seeking coherence in the definition of goals and synergies in sectoral and inter-sectoral policy actions regarding adaptation to climate change, with water with its many links to other sectors playing a leading role;
- ensuring that social participation is not only for informational purposes, but to cause and articulate collective action;

- having each agency perform its task in a coordinated fashion with the various levels of government;
- facilitating 'vertical integration' between the different tiers of government (national, provincial and local), implying close coordination between them, accompanied by an appropriate and clear distribution of differentiated responsibilities and the development of commensurable capacities to meet these responsibilities; and
- facilitating 'horizontal integration' with various social stakeholders, through the creation and organisation of different institutional arrangements and social participation mechanisms, such as public - private partnerships, cooperative regimes and public policy and technical cooperation networks / coalitions and others (Miralles-Wilhelm *et al*., 2010).

Participation from the very beginning of non-governmental stakeholders (and of civil society in general) will be vital and instructional in effecting climate change policy and adaptation development / implementation by organs of the state as it

- may affect the stakeholders directly
- facilitates legitimacy of decisions by creating a sense of belonging
- enhances the achievement of goals (Newig, 2007)
- helps to widen the range of interests to be included in adaptive processes (e.g. ecosystem services or risks (Lebel *et al*., 2009) and
- establishes the basis for learning processes and creative adaptation solutions (Folke *et al*., 2005).

In order to generate an increased awareness and social participation based on information and knowledge of water-based adaptation to climate change, shying away from scaremongering and catastrophic visions, a regional communication plan should be implemented that establishes the method of dissemination and promotion of specialised and state-of-the-art information, generally concentrated in the hands of climate change specialists, bearing in mind the special place of water in climate change, but also that water related issues are but one of the many issues directly affected by the processes of global warming (Miralles-Wilhelm *et al*., 2010).

11. Principle 11: The Principle of Sectoral Integration

- As alluded to several times already, the water sector is intimately interwoven with the agriculture, forestry, health, spatial planning, coastal zone and disaster management sectors.
- Because of these interactions, the institutional response of the water sector in South Africa thus requires sectoral integration in adaptation strategies / policies for climate change, requiring institutional arrangements of similar policy issues to be synergistic and adjusted to each other (Burton *et al*., 2002; Stern, 2007) in order to address and coordinate emergent problems effectively (Pahl-Wostl, 2005) and to avoid mal-adjustment (whereby a positive adaptation in one sector has negative repercussions in another sector).
- Inter-sectoral integration also implies paying close attention to related sectors, notably finance and insurance, regional economic development and livelihoods (Aerts and Droogers, 2009).

12. Principle 12: Increasing Capacity on Climate Change Issues

Climate change worldwide, and in particular in developing countries such as South Africa, poses the challenge of training a new generation of experts and decision makers who are capable of dealing with complex problems from the perspective of inter-disciplinarity, multi-disciplinarity and planning under contexts of uncertainty and risk. For this purpose, the following strategies and actions are proposed (Miralles-Wilhelm *et al*., 2010):

- *Formally Mainstreaming Issues on Climate Change and Adaptation to Climate Change into Curricula for the Broader Water Community*
  - A vitally important challenge is to formally mainstream water-based issues on climate change and adaptation to climate change in academic curricula at all levels of education from primary school to universities.
  - Programmes should be implemented and study plans should be coordinated at all educational levels within South Africa, on the basis of objectively developed curricular activities, weighing up their impact in the educational market and ensuring that mixed messages and emotional mis-information on climate change be prevented. This should be done in consultation with top climate change scientists with expertise across the range of climate change science.

  - These scientists should also design and carry out substantial training programmes on climate change as a key element in educating a new breed of water professionals.
  - The challenge and opportunity is to train individuals with capacities that allow them to communicate broadly and to face complex problems related not only with climate change and its related concepts (e.g. mitigation, vulnerability and adaptation), but within a sustainable development framework.
  - At the same time, given the complex nature of water-based adaptation to climate change and that it requires multi-disciplinary and inter-disciplinary approaches, educational and professional training models in the water community (academic, training and continuing education) need to be transformed to stress the principles and practices of multi-disciplinarity and inter-disciplinarity.
- *Support for research and knowledge generation on climate change*
  - Similarly, sustained, long-term support for research and knowledge generation on the causes and effects of climate change is important, complementing them with research and studies derived from the social processes of resilience and adaptation.
  - In this regard further initiatives such as those by the Water Research Commission and the Department of Science and Technology should be encouraged.

13. Principle 13: Adaptation Needs to be Implemented at a Detailed Spatial Resolution

- Climate change is not going to be experienced evenly throughout the country - some areas will be “winners”, other areas will be “losers” and others still will be real “hotspots of concern”.
- Adaptation is a local rather than a national issue, and for socio-economic and other reasons communities adjacent to one another within the same biophysical zone may have to adapt in very different ways to changes in, for example, the following (with relevant Chapters contained in this Report and others also given):

- Flash floods	Ch 5.6, 7.1
- Regional floods	Ch 7.2, 7.3
- Agricultural droughts	Ch 4.2, 6.1, 6.2, 8.2
- Hydrological droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
- Heat waves	See Schulze and Kunz (2010j)
- Surface water supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
- Groundwater supply	Ch 5.2
- Water Quality, re. Sediments	Ch 5.7
- Water Quality, re. Chemical (N, P)	Ch 8.3
- Water Quality, re. Biological (*E. coli*)	Not addressed in this Report
- Water Temperature	See Barichievy and Schulze (2010)
- Design Precipitation	Ch 7.1, 7.2
- Design Hydrology	Ch 5.6, 7.3
- Storm Surges	Not addressed in this Report
- Sea Level Rise	Not addressed in this Report

- Furthermore, as is illustrated by way of practical examples in **Chapter 9.3**, within the South African water related sector, adaptation concerns and plans of action may be different between
  - National water planners (e.g. DWA),
  - Regional water planners (e.g. CMAs),
  - Bulk water suppliers (e.g. Umgeni Water),
  - Water user associations / Irrigation boards (e.g. Pongola Irrigation Board),
  - Municipalities,
  - Disaster risk management,
  - Rainfed agriculture, including livestock activities,
  - Irrigated agriculture, the
  - Insurance industry, the
  - Road transport sector, the
  - Thermal electric power industry (e.g. Eskom),
  - Hydro-electric power,
  - Poor rural communities,
  - Informal urban communities,
  - Individual households,
  - Aquatic ecosystems (e.g. estuaries, wetlands, environmental flows), and / or
  - Terrestrial ecosystems (e.g. biodiversity, buffers)

- Adaptation, at the end of the day, will thus have to be effected at all levels, i.e. at project level, for communities, within cities, in hydro-climatically as well as socio-economically homogeneous zones within catchments, between catchments, nationally, and even across international borders (Lenton, 2009).
- The choice of spatial scale at which impacts are examined and broad adaptation actions be implemented is therefore crucial, and for South African water related climate change studies the Quinary Catchments, which are relatively small, homogeneous hydrological response zones, and of which 5 838 have been delineated within the RSA, Lesotho and Swaziland (cf. **Chapter 2.2**), has been used in this Report.

14. *Principle 14: The Information Principle: Obtaining Relevant Information*

- The operational management of water resources systems consists of a trade-off between the safe supply of water for the demands of society and the need to cope with risk of failure linked to climate variability.
- For the professional water resources manager in South Africa, water management involves the regulation, control, allocation, distribution and efficient use of existing supplies of water, such as in irrigation, power cooling, municipalities and industries; and the provision of water for in-stream uses such as environmental flows, hydro-electric power and recreation.
- Additionally, all levels of government, the private sector and individual stakeholders, including farmers, are routinely engaged in managing water, with those who pay for its delivery and treatment also being responsible for its efficient use and conservation (van Beek, 2009). Technically, therefore, every individual who uses water is a water manager, from the water resource professional to the woman in the village who draws water from a spring for her own household, and all those in-between listed under ***Principle 13***.
- Climate change will affect all of the above water managers such that they will need to adapt in managing their resource sustainably in future, as detailed in **Chapter 9.3**.
- If adaptation is to be guided by sound science, then information on climate change and its projected impacts on South Africa's water sector has to be sufficient, up-to-date, reliable, and be communicated adequately and timely.
- A major imperative in South Africa will need to be active collaboration between end users / decision makers such as the DWA, CMAs, WUAs or municipalities with universities and other research institutions.
- The information must be provided and improved right down to the level of local adaptation (e.g. at Quinary Catchments level) and be suitable for best management practices.
- Information must be considered a public good to be shared / exchanged at all levels (Lenton, 2009).
- Information on the state of knowledge on climate change, our improved understanding of its causes and consequences, filling of information gaps and dealing with uncertainties related to climate change should be achieved 'by open, shared information sources that … facilitate integration' (Pahl-Wostl, 2005).
- Levels and types of information need to be communicated in a manner tailored to the audience (cf. ***Principle 16***). Thus, for example,
  - maps with technical information such as ratios of change or showing risk or uncertainty may be useful tools for communication and encouraging exchange between the scientists and competent authorities, as well as between authorities and other actors (Pahl-Wostl, 2007), while
  - local and / or indigenous knowledge may be necessary for other audiences.
- Information should include that concerning both the
  - Physical science basis of climate change, and the
  - Water resource management basis related to climate change.
- *The Physical Science Basis* should include
  - First order impacts such as changes in
    - temperature patterns (magnitudes, variability, rates, confidence in results);
    - precipitation patterns (magnitudes, seasonal distribution, variability, confidence in results);
    - evaporation rates; and in
    - streamflow patterns (magnitude, seasonality, shifts in timing, variability, exceedences of thresholds, confidence in results); as well as
  - Second order impacts such as changes in
    - magnitudes / frequencies / durations of extreme rainfall events;
    - drought frequencies and durations;

    - design hydrology (including confidence in results); and in
    - groundwater recharge.
- *The Water Resource Management Basis* should include climate change effects on
  - water supply as well as demand, the timing and assurance of water affecting various water user sectors such as agriculture, hydro-power, urban areas, water for sanitation, the poor and the environment, effects on the broader dynamics of the economy, including water scarcity, water related disasters, spatial patterns of development and structural changes in economies, with adaptation implying that these dynamics can be managed (Lenton, 2009).
  - Because climate change impacts are set to occur in the future, uncertainties prevail (cf. ***Principle 15***), and some consequences are particularly long-lived. This makes it timely to now focus on strengthening management, information and infrastructure.
  - Second order impacts in regard to water resource management would include
    - changes in irrigation demand (e.g. magnitude) and environmental consequences such as losses to percolation and runoff;
    - effects of changed land use and land management patterns on water production and downstream availability (e.g. effects of plantation forestry, land degradation, land reform, or land use management such as conservation and tillage practices, alien invasive species); and
    - effects of changed water availability on land use patterns (e.g. shifts in cropping patterns and yields in regard to food security, intensification or extensification of land uses); while
  - Third order impacts would include changes in
    - water demand and supply in urban (domestic, industrial) and rural (recreation, agricultural) settings;
    - changes in water rights and allocation mechanisms in the face of new realities;
    - changes in the dynamics of water quality responses and their consequences re. physical water quality (sediment yield), chemical water quality (N, P, eutrophication), biological water quality (*E. coli*), water temperature, purification costs and human health (waterborne diseases);
    - impacts on aquatic ecosystems (e.g. ecosystems goods and services related to water, environmental integrity, changing hydrological baselines against which the ecological reserve is assessed, wetlands and estuaries, water temperatures or changes to Indicators of Hydrological Alteration);
    - rethinking water storage (re. natural, man-made and virtual water);
    - impacts on infrastructure (e.g. hydraulic design, dam safety, infrastructure maintenance);
    - potential conflicts over shared rivers (with rivers as international boundaries and rivers discharging to, or from, other countries, as well as changes to international agreements);
    - vulnerability of the poor (e.g. in urban areas when living on / near floodplains or in rural areas where rivers are their source of water); and a
    - focus on mountainous areas in South Africa (which are the runoff producing areas, are sensitive / vulnerable to climate change, but are poorly understood with under-represented hydro-climatic networks and changes in vertical gradients affecting precipitation and runoff).

15. Principle 15: Adaptation under Conditions of Uncertainty

- Uncertainty is nothing new to practitioners in the water sector. For decades engineers in South Africa (and elsewhere) have been making safe designs on, for example, optimum storage capacities of dams, their emergency spillways or urban stormwater systems using as key inputs into their models climate datasets of relatively short length from sparse networks, with the data not always fully quality controlled, and frequently not factoring in satisfactorily the non-stationarity of hydrological responses over time due to future upstream land use development or (especially) channel changes.
- However, the inherent uncertain future in regard to long term changes in politics, population, economics, land use and / or technology poses major new challenges to hydrological design and the management of the water resource.
- For water managers in South Africa (and elsewhere) who are seeking to identify effective interventions in the water system, climate change thus presents another layer of complex conditions superimposed on the already uncertain future.
- The uncertainties in hydrological and water quality responses to changing climate make concrete water management strategies and measures for daily operational water management difficult to develop.

- Planned, proactive adaptation ideally requires knowledge of unknown future developments. However, it is conceptually difficult to plan fully for the changes in climate induced risk associated with changes to key climate drivers under future conditions since projections at decadal timescales have to deal with the "noise" of year-on-year and within-year climate variability with the "signal" of climate change trends superimposed on this "noise". This, in combination with other non-linear interactions emanating from widely ranging projections of greenhouse gas emissions, and hence of inconsistent large scale climate projections (which, due to linkages can amplify, delay, dampen or transform disturbances of the hydrological regime) and which, because of further uncertainties associated with downscaling, can result in a lack of accuracy and confidence in projections at the regional and local scales at which water resources decisions are made (cf. **Chapter 2.1**).
- The above factors make definitive statements on adaptation difficult.
- Moreover, the relatively short series of historical hydrological data in South Africa can no longer be assumed to be stationary and can no longer therefore represent conditions.
- Research, some more generic and some uniquely South African, will therefore be needed to reduce levels of uncertainty wherever possible.
- It is the role of *climate scientists* to reduce uncertainties in climate projections and in downscaling results to local scales for use by water scientists.
- The role of the *water scientists* is to reduce uncertainties in
  - the hydrological (and other) models we use, for example, by
    - applying daily as against monthly time step models, since climate projections are now provided at daily (and even sub-daily) time steps, or
    - using and improving process-based rather than calibration-based models, as calibrated model parameter values based on present day climate, streamflow and land use conditions may no longer be valid under future conditions, or
    - ensuring that land use and channel influences are captured conceptually correctly in models and are modelled explicitly rather than implicitly,
  - requesting from climate scientists that downscaled climate values be provided at the catchment scale at which hydrological modelling is done and water resources decisions are made (e.g. at Quinary Catchment scale), rather than in raster format,
  - performing climate change impacts simulations with the most up-to-date multiple climate models run with multiple emissions scenarios in order to ensure a wide envelope of results,
  - identifying how uncertainties in climate drivers (e.g. rainfall, evaporation), and hence in hydrological responses (e.g. streamflows, floods, droughts, water quality), will vary in different sub-regions of South Africa,
  - identifying hydrological "hotspots" of concern which may require priority status in adaptation actions,
  - assessing the relative roles of climate change impacts vs. those of land use and how the two may interact dynamically, and
  - addressing climate change issues on operational catchments with already complex infrastructure in place rather than assuming catchments to be under natural conditions.
- In summary, we should not be "hiding behind" climate change uncertainties as an excuse to remaining with the status quo in decision making; rather, we should be working towards reducing any uncertainties in our field of expertise.

16. Principle 16: The Communication Principle: Communicating and Disseminating the Information Relevantly

- One of the major challenges of climate change is the difficulty in communication.
- There is, on the one hand, the need to construct (and then adhere to) a common language that facilitates the exchange between the various scientific disciplines, and between the scientific and economic and social disciplines that play a role one way or another in the climate change issue.
- Another challenge is the lack of easily understandable and consensual concepts to explain climate change to the public-at-large, through different dissemination and promotion mechanisms, and the development of concepts that allow any affected interested stakeholders and decision makers to understand the climate change situation, its causes and long-term implications.
- The IPCC (2007) stresses, *inter alia*, that the cultural diversity of the peoples making up a country (such as South Africa) should be recognised and that their participation be strengthened by understanding how the communication on climate change is framed and that it affects social participation. This further challenges the relationship between the scientific communicator and

the public-at-large. These should be priority aspects on the climate agenda of the water resources sector in the short term.

- In a practical example from the water sector, Theesfeld *et al*. (2011) suggest that awareness of climate change and responsible communication of the latest scientific findings (both the positive and negative) should be effected through existing structures such as Water User Associations,
  - clarifying the potential impacts on the landscape water regime by providing relevant information,
  - developing and testing local adaptive measures and solutions,
  - empowering the WUA to take strong adaptive measures themselves, including the development of action plans and regional strategies,
  - gathering ideas / opinions of all relevant stakeholders in civil society,
  - setting up, for example, thematic sub-groups (e.g. on forestry, water, irrigated agriculture etc) to look at sector related initiatives,
  - setting local level near-term goals (e.g. water conservation, water stewardship practices) and longer-term goals (such as local IWRM plans),
  - adopting goals of IWRM, and
  - identifying mal-adaptive practices.
- On a broader front and in regard to higher level communication in South Africa, the following are considered important:
- *Communication at the International Level*
  Ensuring South African water sector representation in, regular attendance at, contribution to, taking positions in, and benefiting from, scientific and strategic international climate change forums related directly or indirectly to water, such as
  - the United Nations Framework Convention on Climate Change (UNFCCC)
  - the Intergovernmental Panel on Climate Change (IPCC)
  - the International Geosphere-Biosphere Programme (IGBP)
  - the NEPAD climate change sector…etc.
- *Communication at the National Level*
  Ensuring water sector representation in, regular attendance at, contribution to, taking positions in, and benefiting from, scientific and strategic national climate change forums related directly or indirectly to water, such as
  - the South African Scientific Committee on Climate Change
  - the Government Committee for Climate Change
  - the Department of Science and Technology's Grand Challenge on Global Change…etc.
- *Communication at Water Sector Level*
  A climate change response and adaptation strategy has to ensure that the gap in the South African water sector between the climate change researchers (who intuit / produce new results - in their specialist terminology), policy makers (who interpret the new findings - in their own language) and practitioners (who integrate / apply the results - with their specific terms of expression) has to be closed by making certain communication is not
  - lost *before* translation,
    - ▫ where researchers are producing results and even answers, but they may be purely theoretical or the questions are not the ones policy makers and / or practitioners consider relevant or find useful;
  - lost *in* translation,
    - ▫ where the researchers are producing answers needed, but the policy makers / practitioners are not aware of the research, or do not understand the answers; and
  - lost *after* translation,
    - ▫ where relevant, accessible results are available, but they are not used by policy makers / practitioners (Payne, 2009).

17. Principle 17: Adaptation Implies Economics and Financing

- Given the magnitude of potential impacts of climate change in southern Africa and the required financial (and other) resources for adaptation, it is necessary to optimise the use of available resources.
- However, the literature on adaptation costs and benefits remains quite limited and fragmented in terms of sectoral and regional coverage (IPCC, 2007). Adaptation costs are usually expressed in monetary terms, while benefits are typically quantified in terms of avoided climate impacts, and expressed in monetary as well as non-monetary terms (e.g. changes in available water, welfare or population exposed to risk).

- In order to promote social and economic development in southern Africa, it is not sufficient to only consider the efficient use of financial resources for adaptation projects, but also to incorporate prioritisation criteria of social cost-benefit analysis.
- However, it is necessary for there to be an enabling social, economic and environmental scheme which aims at promoting payment for environmental services and compensation for negative environmental externalities to mitigation as well as to eliminate “damaging” subsidies (which might induce the waste of water and energy).
- While many impacts of climate change may only be experienced several decades from now, to ensure a comprehensive response strategy to climate change, the financing for adaptation in the water sector needs to go beyond purely reactive emergency responses into a long-term financing challenge, which extends beyond short term cycles or fixed legislative / reporting periods such as the 5 year cycle of the National Water Resource Strategy.
- The cost of inaction, and the economic and social benefits of adaptation actions, both therefore call for increased and innovative financing, particularly targeted towards the most vulnerable, exposed communities.
- This call builds on the premise that today’s investments in water security should be viewed as financing towards sustainable development that simultaneously delivers adaptation benefits (Lenton, 2009).
- Such resources refer not only to financial and labour resources (Burton *et al*., 1998), but also to professional, technical and, particularly, political support (Allman *et al*., 2004).
- The economics of climate change adaptation must therefore utilise the full range of financing options, using a broad set of private and public financial instruments.

18. Principle 18: Balancing Technological and Structural vs Non-Structural Methods of Adaptation

Adaptation to climate change in the water related sector will need to be a balance between structural and non-structural adaptation measures. A strict separation between these two categories is not straightforward, however, as technological adaptation measures often fall between the two. Thoughts on structural and non-structural measures are given below, but these are then followed by a summary of an adaptation approach being tested for the South African water sector and which is elaborated upon in **Chapter 9.3**.

- *Some Thoughts on Structural Adaptation Measures*
  - A priority for South and southern Africa is a diagnosis of the capabilities of existing and planned water resources infrastructure to respond to the needs posed by climate change, and to channel the necessary resources so that this infrastructure can meet the objectives of water security, with special attention to the most vulnerable populations and ecosystems.
  - The challenge of developing infrastructure for water-based climate change adaptation is to focus its conception, design and construction to complement these environmental services, thereby enhancing the resilience of water systems and the preservation of the hydrological cycle.
  - Another challenge related to new water infrastructure is the need to design it in such a way that it is “resistant” to climate change in that it continues to meet its objectives under the influence of climate change and variability of water.
- *Some Thoughts on Non-Structural Adaptation Measures*
  - New approaches for dealing with future uncertainties in water management include the development of flood insurance and general risk management approaches that specifically address the probability of certain future trends (e.g. Gleick, 2003). These are gaining increasing attention in water management.
  - Other non-structural measures such as demand management, agricultural conservation practices, pricing, regulation and relocation may provide important contributions to water safety and water services in terms of gross quantities of water supply, but not necessarily in terms of system reliability.
  - Furthermore, from the social sciences the concept of adaptive water management has been introduced, which aims at more institutional flexibility (Pahl-Wostl *et al*., 2007).
- *An Approach to Adaptation Measures in the Water Related Sector Being Tested in South Africa*
  - In **Chapter 9.3** the following adaptation measures which are considered appropriate for South Africa are elaborated upon for different components of the water sector:

1. ***Technological and Structural***
   - Storage and Reticulation (Surface Water; Groundwater; System Maintenance; Rainwater Harvesting; Water Re-use / Recycling)
   - Water Quality and Quantity Monitoring Systems
   - Desalination
   - Flood / Storm Surge Control (Structures)
   - Early Warning Systems (Near Real-Time; Medium-Term; Long-Term)
   - Communication of Forecasts to End Users
   - Operations / System Improvements (Reservoir Operations Rules; Retrofitting Existing Structures; Irrigation Scheduling; Wastewater Treatment Works; Sanitation)
   - Water Demand Management
   - Indigenous Coping Strategies
   - Precipitation Enhancement
2. ***Knowledge / Skills / Participation***
   - Research and Development (Efficient Technologies; Upgrading of Climate Models; Improvement of Forecast Skill / Dissemination; Development of Drought Resistant Crops)
   - Development of Risk Maps / Floodlines
   - Communication, Training, Dissemination (Awareness Creation at Higher Decision Making Level; Awareness Creation at Operational Level; Training at Middle Management Level; Training at Local Level; Knowledge Management to Influence Decision Making)
   - Participatory Approach in Decision-Making (Establishment of Interdepartmental Learning Platforms; Establishment of an Integrated Communication System; Creation of Ongoing Learning and Communication Platforms between Main Water Users)
3. ***Policy Instruments***
   - International Conventions (e.g. Kyoto Protocol; UNFCCC; Biodiversity)
   - International Water Agreements
   - International Trade
   - National Water Master Plans (National Water Act of 1998; Water Services Act of 1997; National Water Resource Strategy of 2004, 2011; Water for Growth and Development Framework of 2009; Catchment Management Strategies; Estuary Management Plans)
   - Other National Master Plans (National Environmental Management Act; Conservation of Agricultural Resources Act; Integrated Development Plans)
   - Provincial Strategies (Provincial Growth and Development Strategies; Provincial Water Reconciliation Strategies)
   - Local Strategies (Municipal Bye-Laws)
   - Disaster Management Policies / Action Plans
4. ***Risk Sharing / Spreading***
   - Private Sector Strategies (Insurance [primary insurers; re-insurance; micro-insurance]; Banks [development; private; micro-lenders])
   - Public Sector Strategies (Drought Relief; Flood Relief)
5. ***Change of Use / Activity / Location***
   - Land Use Measures (Conservation Structures; Adaptive Spatial Planning; Tillage Practices; Use of Organic Fertilizers; Alien Invasive Clearing Activities)
   - Crop Changes
   - Resettlement
   - Maintenance or Re-establishment of Natural Capital (e.g. wetlands, estuaries)

- *The Choice and the Mix*

  The permutations for coping with, and adapting to, the uncertainties of climate change and variability are wide-ranging - both in the number of strategies and in the combinations of management measures that comprise a strategy (van Beek, 2009). The choice of portfolios of measures in South Africa will vary from locality to locality depending, *inter alia*, on the consequences of not adapting, the degree of social risk tolerance, as well as the complexity of the problem.

Concluding Thoughts

A fundamental aspect of adaptation to climate change for South Africa's water related sector is an appropriate strategy based on a public participation approach. This approach should be founded on a combination of being informed by state-of-the-art climate model output used with hydrological and water resources models to determine vulnerability and projected future impacts of climate change, with clear and strong rules on participation / responsibility in the process, including how best to structure incentives so that they can support successful policy implementation. Such an approach will allow adaptation strategies and actions to be developed for South Africa, which at the same time facilitate the greater participation of all stakeholders in water resources development and management to ensure the success of their implementation in coping better with climate change. This involves adopting transparency and accountability schemes in the use of financial resources, which need to be optimised given the magnitude of the task at hand and the limited funds available.

Similarly, it has to be underscored that the availability of water resources is a prerequisite for the further and sustained development of South Africa, and that even without considering the impacts of climate change many areas within the country are already suffering from some degree of being affected in terms of the quantity or quality of water resources (cf. **Chapter 5.1**). This situation is having a negative impact on any further development, and as a result, the long-term economic well-being of South Africa.

It is self-evident that, owing to the complex nature of the problem, there are no one-size-fits-all solutions for adaptation to climate change in South Africa. Measures implemented in one region or one water use sector within South Africa with a certain degree of success may or may not have the same impact in different environmental, social and economic conditions. Some practical options on adaptation for water related decision makers ranging from national level planners to individual households are therefore evaluated in **Chapter 9.3**.

In order for an adaptation strategy for South Africa to be effective as a framework for practical adaptation, it is necessary for climate and water scientists involved in climate change research to reach out beyond water technocrats and experts, to those stakeholders who are out of the mainstream "water box". The stakeholders that should be involved include representatives of central and local governments, legislators, experts from other related sectors such as the environment, agriculture, forestry and energy, to name but a few, the financial community, and society-at-large. At the same time as climate change constitutes a challenge to the entire country and a threat to parts of South Africa, it also provides us with a unique opportunity to strengthen the management of our precious resource - water.

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CHAPTER 9.3

CLIMATE PROOFING THE SOUTH AFRICAN WATER SECTOR 2: AN INITIAL STUDY ON PRACTICAL SUGGESTIONS FOR ADAPTATION TO CLIMATE CHANGE

R.E. Schulze

Setting the Scene

In South Africa's Second National Communication under the United Nations Framework Convention on Climate Change (DEA, 2010) it is stated that there is a growing body of evidence which suggests that climate change could have important consequences on the hydrological cycle and in South Arica this could include

- the operation of infrastructure associated with water storage and movement,
- flow regulation and distribution, with
- impacts on the provision of safe water and sanitation, and
- supply for irrigation and industrial usage.
- For example, in densely populated cities, the occurrence of more frequent and intense rainfall could overload the capacity of stormwater drainage systems and wastewater treatment facilities.
- Also, increases in sea level in coastal areas could lead to the salinisation of water sources provided by coastal aquifers.
- Similarly, increased runoff and flooding endanger hundreds of villages located in areas of high risk.
- Changes in river flows may also have a direct impact on hydropower generation, with a reduction of water for hydropower generation, or increased variability in river flows, reducing the stability and reliability of power supply, with consequent effects on the economy.
- Soil erosion due to increased rainfall amounts and / or intensity, land degradation and land use changes can affect the livelihoods of rural communities living off agriculture, and lead to sedimentation in reservoirs, affecting the operation of multi-purpose facilities and the sustainability of watersheds.
- Furthermore, the extreme variability and / or reduction of water sources could increase rural migration to peri-urban areas and, more generally,
- exceed the functional limits of the infrastructure and institutional capacities to manage water systems in all sectors and even beyond the borders of our countries.
- This situation, combined with increased competition among users over limited water resources could lead to mistrust between users, increasing the potential for conflicts (DEA, 2010).

Changes in response to climate and management activities themselves include not only the infrastructure and technology, but also the institutions that govern water use within sectors (e.g. water rates), between sectors (e.g. water markets), and even across international borders (e.g. watershed boundary agreements and the recognition of virtual water), and more general governance systems, which must also evolve to address climate change (DEA, 2010). Strong statements such as those above are a motivation to re-visit some further needs for assessing projected impacts of climate change on the South African water related sector in light of having to adapt to anticipated future climate scenarios.

In this Chapter the focus is on practical approaches to adaptation to climate change for the South African water related sector.

Re-Visiting the Needs for a Comprehensive Study on Climate Change and the South African Water Related Sector

South Africa's water resources, which are already subjected to high hydro-climatic variability both over space and over time, are a key constraint to the country's continued economic development and the sustainable livelihoods of its people. Because

- water is arguably the primary medium through which early (and subsequent) climate change impacts will be felt by people, ecosystems and economies,
- a large proportion of South Africa's population is impoverished (thus rendering them particularly vulnerable to impacts of climate change), and
- many of the fragile ecosystems in South Africa (both terrestrial and aquatic) are implicitly or explicitly water dependent,
- strategies and plans of action to adapt to climate change through an integrated approach to land and water management are therefore urgently needed in order to establish effective resilience to the projected impacts of climate change.

To the above needs to be added that

- water-related infrastructure (e.g. dams, irrigation projects, inter-basin transfers, stormwater drains etc) is typically a long term investment with a design life of 50 - 100 years, very expensive, essentially irreversible once constructed and is designed to cope with currently (but not necessarily future) expected extremes of floods and droughts, that
- any changes in rainfall, be they up or down, are amplified in changes of hydrological responses (in the case of year-to-year variability the amplification from rainfall to runoff can be 2 - 5 fold),
- climate change is not going to be experienced evenly throughout the country, with some areas "winners", other areas "losers" and others still are likely to become real "hotspots of concern", and that
- climate change does not occur on a "clean sheet" of virgin catchments not yet impacted upon by human interventions on the land and in the channel, but will rather be superimposed onto already water stressed catchments with complex land uses, water engineered systems and a strong socio-political as well as economic historical footprint.

These arguments are compelling in striving to formulate practical ways and means of adaptation in the water related sector. As a point of departure to outlining practical adaptation measures, however, a brief review of the state of progress in climate change research on the South African water sector, including findings from this study, is first given.

Looking Back - State of Progress by 2010

Considerable research progress was made during the first decade of this century in addressing issues of climate change on the South African water sector (e.g. Schulze and Perks, 2000; Schulze, 2003; Dlamini and Schulze, 2005; Schulze, 2005; Schulze *et al*., 2005; Knoesen *et al*., 2009; Lumsden *et al*., 2009; Barichievy *et al*., 2010a, 2010b; Schulze 2010). This research focussed primarily on biophysical aspects, and frequently used outputs from only a single GCM, e.g. C-CAM in the case of Schulze *et al*. (2005) or ECHAM5/MPI-OM in the case of Barichievy *et al*. (2010a; b) and Knoesen *et al*. (2009). It was only in research with a predominantly agricultural focus (Schulze, 2010) that drivers and responses were addressed in detail by way of output from multiple GCMs.

Looking at the Present - New Findings from this Research

Research in this project included an assessment of daily outputs from multiple GCMs, downscaled to the 5 838 Quinary Catchments making the region defined as South Africa, with the GCM outputs from three time periods of present and projected future climates used either in direct analyses or as input to the daily time step *ACRU* model (Schulze, 1995 and updates) for hydrological assessments of the impacts of climate change. Results include those of

- *First Order Impacts* such as projected changes in temperature patterns (magnitude, variability) and in precipitation patterns (magnitude, intra- and inter-annual variability, exceedences of thresholds), as well as of
- *Second Order Impacts* such as projected changes in evaporation rates and in soil moisture status,
- *Projected Changes in Hydrological Responses* covered projected changes in streamflow patterns (magnitude, variability, exceedences of thresholds), and changes in flow components, drivers and fluxes (e.g. of stormflows and baseflows), as well as projected
- *Changes in Droughts* in regard to different durations and severities of meteorological as well as hydrological droughts,

- *Changes in Design Hydrology* with respect to projected changes magnitudes, frequencies and durations of extreme events (i.e. in short and long duration design rainfall, peak discharge and streamflows), and those to do with more
- *Practical Applications* such as projected changes in net irrigation requirements and their environmental consequences and in water available for rainwater harvesting.

During this study a number of key general findings which are considered important in an adaptation chapter came to the fore. These are elaborated upon in **Chapter 9.1**, but are summarised below.

- The first is that while there is no doubt that climate change poses new challenges to water resource managers in South Africa, the climatically determined future is certainly not all "gloom and doom as some would have it, but neither do the results of this study suggest, as others argue, that "everything is under control" in the water sector in regard to climate change.
- Some areas are likely to become "winners" for certain projected changes and new water related opportunities will arise, while other areas are likely to become "losers" in the sense that more water related stresses will be experienced. "Hotspots" of concern which were identified time and again in the assessments of impacts were the southwest of the country, the west coast and, to a lesser extent, the extreme north of South Africa.
- Results from analyses of ratios of change, based on output from multiple GCMs, show that patterns of change across South Africa are often projected to differ between future "average year" conditions vs. future 1 in 10 year wet or 1 in 10 year dry conditions. Some changes were found to be for the positive, others were found to be potentially more detrimental, and this finding will place an added challenge to future water management.
- Another finding was that the transitional zone between the winter and summer rainfall area in the western interior of South Africa appears to be an area of high sensitivity and of inconsistent change, with frequently the highest ratios of change occurring there
- An intensification (both + and -), and associated expansion in area, was frequently shown for patterns of change in the relatively short period of 35 years from the intermediate future (2046 - 2065) to the more distant future (2071 - 2100), illustrating an acceleration and amplification of impacts into the second half of the century when compared with the relatively long 75 year period between the present (1971 - 1990) and the intermediate future.
- In general, the results showed an increase in the year-to-year variability of hydrological responses into the future, often a quite substantial increase. The increase in variability also tended to be higher into the more distant future than between the intermediate future and present.
- Patterns of projected change into the future of certain hydrological variables are not always smooth across South Africa. Often strong gradients of change over very short distances were shown from the analyses, sometimes even changing sign from increases to decreases over short distances.
- Some components of the hydrological system were found to be more sensitive to climate change than others, sometimes displaying a doubling or more, or a halving or more, of change into the future.
- From an engineering perspective, an important finding was that projected spatial changes to design rainfall and design streamflows vary with return period rather than with critical duration, and this should be factored into future hydraulic designs.
- A strong amplification / intensification was shown when changes in rainfall parameters were compared with equivalent changes in runoff responses, highlighting again the high sensitivity of changes in rainfall in the hydrological cycle. Examples of this amplification include a comparison of hydrological drought (more sensitive) vs. meteorological drought (less sensitive) for the same duration and level of severity, as well as of design streamflows vs. design rainfall for the same duration and return period.

These findings form the scientific basis for practical approaches on adaptation in South Africa's water related sector, with these approaches outlined in sections which follow later in this Chapter. As a lead-in to those sections, however, some frequently asked generic questions on adaptation to climate change and water management are addressed.

Challenges of Adaptation to Climate Change in the Water Related Sector

1. Who Manages Our Water and What do They Manage?

For the professional water resources manager, water management involves the regulation, control, allocation, distribution and efficient use of existing supplies of water for off-stream uses such as irrigation, power cooling, municipalities and industries, as well as to the development of new supplies, control of floods and the provision of water for in-stream uses such as hydro-electric power, recreation and environmental flows (Appleton *et al*., 2003; Schulze, 2005).

All levels of government, as well as the private sector and individual stakeholders, are routinely engaged in the management of water. Hence, technically, every individual who uses water is a water manager, from the water resource professional to the woman in the individual household or community who draws water from a spring or river. Those who pay for its delivery and treatment are also responsible for its efficient use and conservation. Nevertheless, water managers typically are considered to be those people who are formally trained and involved in some institutionally organised component of water development, delivery or regulation, and who have responsibility and accountability for the decisions that are made (Appleton *et al*., 2003; Schulze, 2005).

For the purposes of this discussion, all users, including farmers, are considered to be water managers. In terms of water resources systems, both the large-scale, mostly technical systems, and the small-scale rural systems (including rainfed agriculture) are taken into account. Addressing the adaptation options that farmers in the lesser-developed countries have is particularly critical, owing to the direct impacts climate variability and change could have on their livelihoods.

Water managers have to deal with a host of interlinked and integrated issues (**Figure 9.3.1**), ranging from supply, quality, allocation and distribution; equity with respect to present and future generations, as well as resource vulnerability and reliability, sustainable use, biological diversity and ecological integrity (Schulze, 2005).

For many water managers in developing countries, vulnerability to future climate changes may seem to be a far-away problem. Certainly, many argue for focusing on current pressing issues related to population growth, economic underdevelopment, HIV / AIDS and lack of investment in water infrastructure, rather than on climate change (Reid *et al*., 2005). To some water managers, dealing with natural climate variability and climate-related hazards such as droughts and floods has always been a part of their routine concerns. For them, taking climate change into account does not mean adding any new “tricks” to their present practices for coping with climate extremes. What they do have to recognise is that climate variability is projected to increase and future weather is likely to be more extreme more frequently.

2. Are Adaptation Practices in Place Yet for Coping with Future Climates?

In many countries sound practices of adapting to climate change have been identified in the past decade; in many other countries plans of action re. climate proofing are not yet in place, let alone have strategies on adaptation in the water sector been formulated. Effective management of climate risks, under both present and projected future conditions, calls for a holistic approach linking technological, social and economic development with the protection of natural ecosystems (**Figure 9.3.1**) and with dependable projections of future climatic conditions. There is a need to mobilise expertise across a range of disciplines to provide the knowledge and methods necessary to assess the climate risk connected with rural and urban water management, and to develop adaptive strategies that can respond to emerging climate fluctuations and help to reduce adverse impacts. The process involves making connections between the continuum from short (days) to medium-term (weeks to months) and longer-term (seasons) climate forecasts to decadal scale climate change, focusing on climate-related hazards and the planning, design, operation, maintenance, and rehabilitation of water-related infrastructure to cope with projected future conditions.

3. What Balances Therefore Need to be Established?

Establishing balances between consumptive use, environmental needs, subsidiary functions such as flood control, and the ill-defined costs and benefits of climatic impacts on fisheries, aquatic ecosystems, scenery and recreation, is technically complex and subject to a high level of uncertainty

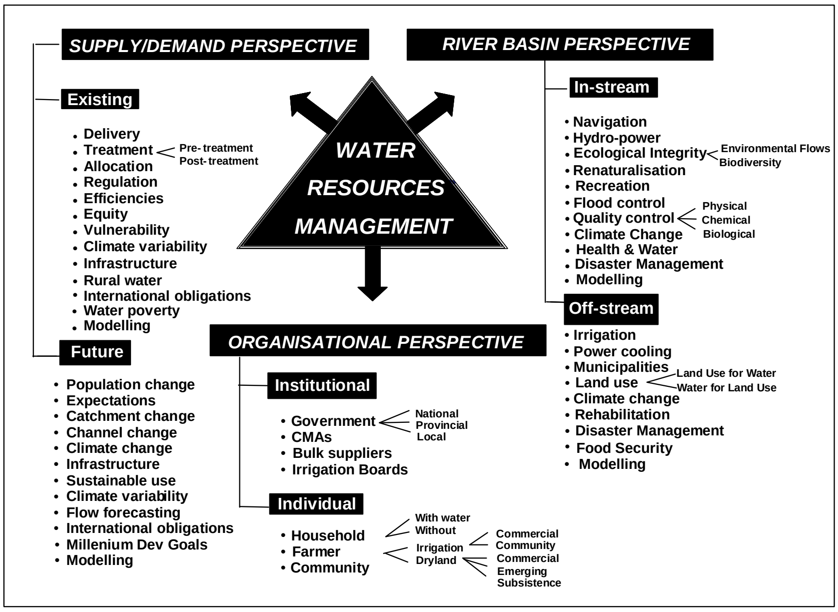

Figure 9.3.1 The interlinked nature of water resources management (Schulze, 2005)

(Appleton *et al*., 2003). It requires difficult decisions involving the interests of various sectors of the economy, the community and the environment. By taking a pro-active approach, water managers can pre-empt and avoid water crises whenever possible and devise effective responses to crises when they occur. To date, most water managers have adopted a static rather than adaptive approach to setting operating policies. This risk-averse behaviour is often encouraged by the constraints imposed by the political and institutional arrangements and societal expectations. However, increasing demand for water from finite sources will progressively lead to decisions that are more responsive to predicted and forecast climatic conditions and involve a higher degree of uncertainty and risk - as part of the balances which need to be established (Appleton *et al*., 2003).

4. Should the Uncertainties which Remain in Regard to Potential Impacts of Climate Change on Water Resources be Seen as a Challenge or a Hindrance?

Uncertainties still abound around the question of climate change, and these have been addressed in various contexts in **Chapters 2.1** and **2.4**. From an adaptation perspective, these uncertainties start with emission scenarios of greenhouse gases, with further uncertainties revolving around the sensitivity of the global climate to enhanced emission. The uncertainties are then seen by many to "explode" at each successive level, e.g. on regional changes, climate variability, then on biophysical impacts and eventually of resultant socio-economic impacts.

Uncertainties include questions on

- what is "noise" (i.e. natural variability) vs what is already a clear "signal" (i.e. trend) in an already variable climate, or
- the different GCMs at present still not giving identical signals, and certainly giving varying magnitudes of change in certain parts of South Africa, especially on hydrologically critical rainfall parameters, and not yet with high degrees of accuracy on changes at local scale, although these uncertainties are gradually being reduced (Hewitson *et al*., 2005).

More specifically, in hydrology there are further uncertainties, which revolve around

- stochasticity, i.e. the inherent unknowable randomness, for example, of rainfall;
- ignorance, i.e. imperfect knowledge of hydrological system dynamics; and
- spatial upscaling issues, i.e. upscaling of process representations
  - from points where measurements are made, to
  - homogeneous landscape elements such as the "patch" in ecology, or the hydrological response unit (HRU) or Quinary Catchment in hydrology, to
  - the 3-dimensional representation of a hillslope or small catchment, and, equally,
- climatic downscaling issues of GCM information to the finer scales

  - at which hydrological models operate, which is usually at the daily (and even sub-daily) time step and at the Quinary or even sub-Quinary spatial scale, or
  - at which local topographic forcing by mountains may become a key driver to the frequencies and amounts of rainfall, or to temperature lapse rates.

All of these uncertainties should be seen as a challenge to the research community, whose scientific brief is to reduce the uncertainties, and not to present them as a hindrance behind which decision makers can then hide through inaction in regard to adaptation.

5. Nevertheless, there are Sound Reasons to Adopt at Minimum a "No-Regrets" Approach

In regard to issues on climate change and hydrology it may be argued that

- hydrological and hydraulic design is, at best, still an approximation only, with safety factors already built in, or that
- South Africa (and Africa as a whole) has more pressing water problems than those related to climate change, or that
- impacts of
  - the water and engineered landscape (e.g. of irrigation, channel modifications, water storages / releases or water diversions / inter-basin transfers) are generally greater than those of
  - land use changes (e.g. afforestation or urbanisation) which, in turn, may be greater than those resulting from
  - climate change (Schulze, 2004),

  with the latter the subject of a current (August 2011) investigation by Warburton (2011).

However, any impacts of climate change are "superimposed" upon all other water problems and become an additional, overarching stressor. Currently, there are no management options that are uniquely suited for adaptation to climate change that would be measurably different to those already employed for coping with contemporary climate variability (Schulze, 2003). The only substantive difference is whether one adopts

- a more conventional and incremental *no regrets approach*, where no regrets measures are those whose benefits equal or exceed their cost to society, i.e. measures worth doing anyway whether or not climate change poses additional pressures, or whether one adopts
- the more anticipatory *precautionary principle*, i.e. a process through which stakeholders influence and share control over development initiatives and the decision and resources which affect them by taking account explicitly of climate change, and where the precautionary principle is a process which can improve the quality, effectiveness and sustainability of projects and strengthen ownership and commitment of government and stakeholders.

Despite the uncertainties which abound, there are sound reasons to adopt at minimum a no-regrets approach to potential hydrological impacts of climate change, but more ideally opt for the more pre-emptive participatory principle, because of factors already mentioned elsewhere, but including that

- hydrological structures
  - have long lead times,
  - are often designed for lifespans of 50 - 200 years,
  - are very expensive and essentially irreversible investments, which
  - are designed to operate close to their design limits in times of major floods or droughts;

  furthermore, the
- hydrological system amplifies any changes in climate, particularly of rainfall, implying that the assumption of climatic stationarity, used in current hydrological design, is invalidated;
- the public expects efficient, robust designs to function into a future which may include climate change; and
- decision makers need to justify their decisions on water structures *now*, and for *local* hydroclimatic conditions, and cannot stall decisions until more certainty is available on climate change (Schulze, 2003).

To ignore projected impacts of climate change on hydrological responses is, therefore, done at peril, and a *practical approach* to adaptation is needed in the water related sector, which goes beyond having strategies for adaptation as outlined in **Chapter 9.2**.

Towards a Practical Approach to Adaptation to Climate Change in the South African Water Related Sector

The approach adopted here is to

- identify the major categories in which adaptive capacity can be enhanced, of important
- sectors within the broader water related community in South Africa which are likely to be impacted, and then to
- identify what the various sectors would have to be coping with, and adapting to, in regard to projected
  - changes in the drivers of the hydrological system (e.g. in temperature, evaporation and / or rainfall characteristics) and
  - changes in the responses of the hydrological system (e.g. in streamflow, or droughts, or irrigation requirements)

1. Enhancing Adaptive Capacity

Following Appleton *et al*. (2003) and Schulze (2005), five major categories of enhancing adaptive capacity were identified, *viz*. those relating to

- technological and structural issues,
- knowledge, skills and participation,
- policy instruments,
- risk sharing and risk spreading, and to adaptation around changes in
- uses of land, activities on the land and the location of activities.

Each of the five major categories was then divided into sub-categories which were considered relevant to the South African water related sector and these were, in turn, further sub-divided for consideration in climate change adaptation practices, as shown in the breakdown below.

- *Technological and Structural*
  - Storage and Reticulation
    - Surface Water
      - Large Reservoirs
      - Small Reservoirs
    - Groundwater
      - Artificial Recharge
      - Borehole Drilling
      - Sand Dams
    - System Maintenance
      - Supply Leakage Control
      - Irrigation Equipment Maintenance
      - Irrigation Canal Leakage / Losses
    - Rainwater Harvesting
    - Water Re-use / Recycling
  - Water Quality and Quantity Monitoring Systems
  - Desalination
  - Flood / Storm Surge Control
    - Structures (i.e. Dams, spillways, stormwater systems, levees, sand bags, wave breaks, vegetative planting)
  - Early Warning Systems
    - Near Real-Time (Hours to one day)
    - Short-Term (Days to weeks)
    - Medium-Term (Month to season)
    - Long-Term (Years to decades)
  - Communication of Forecasts to End Users
    - Awareness Creation at Higher Decision Making Level
    - Awareness Creation at Operational Level (e.g. Municipal wastewater treatment, i.e. WWT)
    - Training at Middle Management Level
    - Training at Local Level (e.g. Municipal WWT operators)
  - Operations / System Improvements
    - Reservoir Operating Rules

        - Retrofitting Existing Structures
        - Irrigation Scheduling
        - Wastewater Treatment Works
        - Sanitation
    - Water Demand Management
    - Indigenous Coping Strategies
    - Precipitation Enhancement
- *Knowledge / Skills / Participation*
    - Research and Development
        - Efficient Technologies
        - Upgrading of Climate Models
            - Improvements to Downscaling / RCM
            - Fine Scale Information Provision Relevant to Local Water Managers
        - Improve Forecast Skill / Dissemination
        - Development of Drought Resistant Crops
    - Development of Risk Maps / Floodlines
    - Communication, Training, Dissemination
        - Awareness Creation at Higher Decision Making Level
        - Awareness Creation at Operational Level (e.g. Municipal wastewater treatment, i.e. WWT)
        - Training at Middle Management Level
        - Training at Local Level (e.g. Municipal WWT operators)
        - Knowledge Management to Influence Decision Making (e.g. Synthesising; re-assessing; sectorising)
    - Participatory Approach in Decision-Making
        - Establishment of Inter-Departmental Learning Platforms (e.g. Task teams)
        - Establishment of an Integrated Communication System (Trends, priorities, activities, risks)
        - Creation of Ongoing Learning and Communication Platforms between Main Water Users (e.g. WRC Reference Group meetings)
- *Policy Instruments*
    - International Conventions (e.g. UNFCCC)
    - International Water Agreements
    - International Trade
    - National Water Master Plans
        - National Water Act of 1998
        - Water Services Act of 1997
        - National Water Resource Strategy of 2004 and of 2011 (Unpublished at the time of printing)
        - Water for Growth and Development Framework of 2009
        - Catchment Management Strategies (CMS)
        - Estuary Management Plans
    - Other National Master Plans
        - National Environmental Management Act (NEMA)
        - Conservation of Agricultural Resources Act (CARA)
        - Integrated Development Plans (IDPs)
    - Provincial Strategies
        - Provincial Growth and Development Strategies (PGDS)
        - Provincial Water Reconciliation Strategies
    - Local Strategies
        - Municipal Bye-Laws
    - Disaster Management Policies / Action Plans
- *Risk Sharing / Spreading*
    - Private Sector Strategies
        - Insurance
            - Primary Insurers
            - Re-Insurance
            - Micro-Insurance
        - Banks
            - Development

            - ∊ Private
            - ∊ Micro-Lenders
        - ▫ Stock Exchange
    - Public Sector Strategies
        - ▫ Drought Relief by Government
        - ▫ Flood Relief by Government
- *Change of Use / Activity / Location*
    - Land Use Measures
        - ▫ Conservation Structures
        - ▫ Adaptive Spatial Planning
        - ▫ Tillage Practices
        - ▫ Use of Organic (instead of chemical) Fertilizers
        - ▫ Alien Invasive Clearing Activities
    - Crop Changes
    - Resettlement
    - Maintenance or Re-establishment of Natural Capital (e.g. Wetlands, estuaries, buffers etc)

2. *Impacted Sectors*

Many water related sectors and institutions in South Africa are likely to be impacted upon by climate change, and in this initial investigation the following 17 were identified:

- National Water Planners (e.g. Department of Water Affairs, DWA)
- Regional Water Planners (e.g. Catchment Management Agencies, CMAs)
- Bulk Water Suppliers (e.g. Umgeni Water)
- Water User Associations / Irrigation Boards (e.g. Pongola Irrigation Board)
- Municipalities
- Disaster Risk Management
- Rainfed Agriculture, including Livestock Activities
- Irrigated Agriculture
- Insurance Industry
- Road Transport Sector
- Thermal Electric Power Industry (e.g. Eskom)
- Hydro-Electric Power
- Poor Rural Communities
- Informal Urban Communities
- Individual Households
- Aquatic Ecosystems (e.g. Estuaries, wetlands, buffers, environmental flows)
- Terrestrial Ecosystems (e.g. Biodiversity, land degradation, fire, alien invasive plants)

3. *Coping with / Adapting to Changes in Drivers and Responses*

The above sectors making up the wider water community in South Africa and those who manage water will need to cope with, and adapt to, a range of changes which are foreseen to climate drivers and the hydrological responses to the changes of those drivers. Anticipated changes to the following are considered in this initial study, noting that this list below is not exhaustive and that the distinction between what are considered drivers and what are seen a responses is not always clear-cut. References to Chapters in this Report and to other Reports on where to find some information on projected impacts in South Africa also provided.

a. *Drivers: Changes in…*

- Enhanced Evaporation — Ch 4.1, 4.2, 8.1

  [This is the evaporation from open water bodies and from the soil-plant system over and above that of present climatic conditions. Chapters referred to under enhanced evaporation cover projected changes to reference potential evaporation, to soil water content and to additional evaporation from open water bodies]
- Heat Waves — See Schulze and Kunz (2010; Ch 3.4)

  [Heat waves are defined as 3 consecutive days with maximum temperatures exceeding 30 °C on each day and extreme heat waves have 3 consecutive days each exceeding 35 °C]
- Water Temperature — See Barichievy *et al*. (2010a; Ch 13 and 14)

  [Water temperature is computed for each day and for each Quinary Catchment from a maximum air temperature related empirical equation developed in South Africa, and then combined with the computed water temperature from any upstream Catchment, assuming perfect mixing of the waters]

- Thresholds of Rainfall Exceeded Ch 3.6
  [Number of days per year with daily rainfall exceeding hydrologically critical amounts, e.g. 10 mm or 25 mm]
- Design Precipitation - Short Duration (5 min - 24 h) Ch 7.1
  [The rainfall expected statistically only once in 2 or 5 or 10 or 20 years for a period of time ranging from anything between 5 minutes and 24 hours, and used in the sizing / design of, for example, stormwater systems]
- Design Precipitation - Long Duration (1 - 7 days) Ch 7.2
  [The rainfall expected statistically only once in 2 or 5 or 10 or 20 years falling over a period of time ranging from one day to seven consecutive days and used, for example, in regional flood analyses or in the spillway design of dams on large catchments]

b. Responses: Changes in…

- Soil Moisture Ch 4.2
  [Water content in the soil profile, the amount of which determines whether a plant experiences no water stress, mild stress or severe stress because of a lack of soil water, or stress to plants when the soil becomes waterlogged]
- Groundwater Recharge Ch 5.3
  [Recharge emanates from soil water percolating through the soil profile of a landscape under wet conditions and beyond the root zone of plants into the groundwater zone, to recharge the groundwater and also become available for slow release into the stream as baseflow]
- Thresholds of Streamflows Exceeded Ch 5.5
  [Number of days per year with daily streamflows, accumulated from all upstream catchments, exceeding hydrologically critical amounts, including no flow or significant amounts of high flows]
- Flash Floods Ch 5.6, 7.1
  [These are severe floods over a short period of time and usually over a small catchment area only, frequently the result of severe convective activity from thunderstorms with high intensity rainfall. Chapters referred to under flash floods cover projected changes in peak discharge per Quinary Catchment and in short duration (5 min and up to 24 h) design rainfall]
- Regional Floods Ch 5.2, 5.4, 7.3
  [These are floods with high waters occurring over several days and covering substantial areas, usually in the 1000s of km^2, inundating areas around the channel system, and resulting from widespread rains over a period of several consecutive days with considerable amounts of rain falling on already wet catchments. Chapters referred to under regional floods cover projected changes to 1 : 10 year stormflows from individual Quinaries, 1: 10 year accumulated streamflows from all upstream catchments and design streamflows for a range of durations from one to seven days and for a range of return period from 2 to 20 years]
- Design Streamflow Volumes Ch 7.3
  [The streamflow at a location accumulated from all upstream catchments which is expected statistically only once in 2 or 5 or 10 or 20 years and experienced over a period of time ranging from one day to seven consecutive days and used, for example, in the spillway design of dams on large catchments]
- Design Peak Discharge Ch 5.6
  [The peak discharge on a given day, in m^3/s, at the exit of a Quinary Catchment which is expected statistically only once in 2 or 5 or 10 or 20 years and used, for example, in the spillway design of dams]
- Agricultural Droughts Ch 4.2, 6.1, 6.2, 8.2
  [These are droughts of different severities such as mild (worst in 3 years or less frequently), moderate (worst in 5 years or less frequently) or severe (worst in 10 years or less frequently), which are experienced over a period of either months or years, in which soil moisture deficits result in crop yield losses of different severities. Chapters referred to under agricultural droughts cover projected changes to soil water content, changes to frequencies of meteorological and hydrological droughts for a range of durations and severities as well as changes to net irrigation requirements]
- Hydrological Droughts Ch 5.5, 6.1, 6.2, 8.1, 8.2
  [These are droughts of different severities such as mild (worst in 3 years or less frequently), moderate (worst in 5 years or less frequently) or severe (worst in 10 years or less frequently), which are experienced over a period of either months or years, in which accumulated streamflows at a location within a catchment are below the expected and which may result in water shortages or curtailments / rationing being applied. Chapters referred to under hydrological droughts cover projected changes to the number of times per year that thresholds of specified streamflows are exceeded, changes to frequencies of meteorological and hydrological droughts for a range of durations and severities as well as changes to net irrigation requirements]
- Surface Water Supply Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
  [Water available from streams in a catchment and made up of accumulated stormflows and baseflows from all areas upstream of the point of interest. Chapters referred to under surface water supply cover projected changes to stormflows from individual Quinaries, accumulated streamflows from all upstream catchments, changes to meteorological and hydrological droughts of a range of durations and severities as well as the additional water evaporated from open water bodies in South Africa]

- Transboundary Flows (Quantity and quality) Ch 5.4, 5.5, 5.7, 6.2, 7.2, 7.3, 8.1, 8.2, 8.3
  [Flows emanating *from* another country and entering South Africa, e.g. the Orange-Senqu from Lesotho, or flows from South Africa exiting *into* another country, e.g. the Sabie or Olifants flowing into Mozambique, or rivers *shared* between South Africa and another country through a common border, e.g. the Limpopo with Zimbabwe or the Orange with Namibia. Chapters referred to under transboundary flows cover projected changes to accumulated streamflows, to the number of times per year that thresholds of specified streamflows are exceeded, to sediment yield, hydrological droughts, changes to long duration design rainfalls and streamflows, as well as to projected changes in net irrigation demand and in percolation and runoff losses from irrigated areas]
- Groundwater Supply Not addressed in this Report
  [Water supplied by abstractions from a subterranean source, e.g. deep aquifers, which is not connected to a stream]
- Water Quality - Sediments Ch 5.7
  [Deterioration of water quality as a result of turbid waters and high silt content resulting from a sediment load emanating from the landscape component of a catchment, with the main causes being related to flow events off the catchment, and dependent also on soil, slope, vegetative cover above as well as on the ground and land management practices]
- Water Quality - Chemical Ch 8.3
  [Deterioration of water quality as a result of, *inter alia*, point source pollutants or non-point source pollutants from agricultural chemicals, metals from mining, acid atmospheric deposits, to the detriment of the aquatic habitat and downstream water users]
- Water Quality - Biological Not addressed in this Report
  [Deterioration of water quality as a result, *inter alia*, of pathogens and organics from urban and rural areas, often from *sewage effluent discharges* into non-existent or dysfunctional wastewater treatment plants in many of the formal and informal urban areas, frequently manifested as excessively high *E. coli* concentrations in rivers and stored water, and with often severe health consequences]
- Environmental Flows See Barichievy *et al*. (2010b; Ch 12)
  [Environmental flows are minimum flow requirements in river reaches to sustain aquatic habitats in regard to typical magnitudes, frequencies, durations, timing and rates of change of flows in a river reach]
- Storm Surges Not addressed in this Report
  [Storm surges are a coastal / near coastal phenomenon in which water surges upstream into estuaries and river channels, resulting in the widening of river banks or allowing rivers to expand sideways, with implications on river bank infrastructure]
- Sea Level Rise Not addressed in this Report
  [Sea level rise at between 1.5 and 7.0 mm/a as a result of expansion of oceanic waters due to higher temperatures and melting ice masses can have hydrological consequences *inter alia* through sea water intrusion into coastal freshwater lenses and soil salinisation]

Modus Operandi

The 17 tables developed below are self-standing as in practice each of the different sectors considered here are likely to evaluate their sector-specific table by itself, without cross-reference to tables on other sectors. For this reason also, each of the tables (which are of different lengths) starts on a separate page. It is anticipated that individual sectors will debate and elaborate on the contents of their specific table and that in follow-up workshops the tables will be amended, expanded and improved upon. At this juncture no explanations are given as to which drivers and responses have been included in a specific table; this is likely to happen at sector-specific workshops at a later stage. Cross-reference is also made in the third column to Chapters from this Report in which more information can be gleaned and impacts maps obtained, as well as to some other sources of information. These cross-references are not exhaustive and would be added to in future.

Water Related Sector Adaptation 1: National Water Planners (e.g. Department of Water Affairs)

Table 9.3.1 Adaptation recommendations for the National Water Planning Sector

ENHANCING ADAPTIVE CAPACITY TECHNOLOGICAL AND STRUCTURAL	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES TO SCHULZE (2011)
• Storage and Reticulation		
- Surface water		
▫ Large Reservoirs	• Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Storm Surges	Not in Report
	Transboundary Flows	Ch 5.4, 5.5, 5.7, 6.2, 7.3, 8.2, 8.3
	Environmental Flows	See Barichievy *et al*. (2010b)
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Threshold Streamflows	Ch 5.5
• Early Warning Systems		
- Short-Term (Days to Weeks)	• Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
- Medium-Term (Month to Season)	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
	Regional Floods	Ch 7.2, 7.3
- Long-Term (Years to Decades)	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
• Operations / System Improvements		
- Reservoir Operations Rules	• Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	DDF - Peak Discharge	Ch 5.6
	DDF - Streamflows	Ch 7.3
	Water Temperature	See Barichievy *et al*. (2010a)
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
• Water Demand Management	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
	Water Quality - All	Ch 5.7, 8.3
KNOWLEDGE / SKILLS / PARTICIPATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Research and Development		
- Efficient Technologies	• All	
- Upgrading of Climate Models	• All	
▫ Improvements to Downscaling / RCMs	• All	
- Improvement of Forecast Skill / Dissemination	• All	
• Development of Risk Maps / Floodlines	• Regional Floods	Ch 7.2, 7.3
	Flash Floods	Ch 5.6, 7.1
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	7.2
	DDF - Discharge	5.6
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
• Communication / Training / Dissemination		
- Awareness Creation at Higher-Decision Making Level	• All	
• Participatory Approach in Decision-Making		
- Establishment of Inter-Departmental Learning Platforms	• All	
- Establishment of Integrated Communication Systems	• All	

POLICY INSTRUMENTS	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES
• International Conventions (e.g. UNFCCC)	• All	
• International Water Agreements		
• National Water Master Plans		
- National Water Act of 1998	• All	
- National Water Resource Strategy	• All	
• Other National Master Plans		
- National Environmental Management Act	• Environmental Flows	See Barichievy *et al*. (2010b)
- Conservation of Agricultural Resources Act	• Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
• Disaster Management Policies / Plans	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 5.2, 5.4, 7.3
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
RISK SHARING / SPREADING	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Private Sector Strategies		
- Banks		
▫ Development	• All	
CHANGE OF USE / ACTIVITY / LOCATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Land Use Measures		
- Adaptive Spatial Planning	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Streamflows	Ch 7.3
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report

Water Related Sector Adaptation 2: Regional Water Planners / Managers (e.g. Catchment Management Agencies)

Table 9.3.2 Adaptation recommendations for Regional Water Planners (CMAs, Provincial Governments)

ENHANCING ADAPTIVE CAPACITY TECHNOLOGICAL AND STRUCTURAL	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES TO SCHULZE (2011)
• Storage and Reticulation		
- Surface water		
▫ Large Reservoirs	• Regional Floods	Ch 7.2, 7.3
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Transboundary Flows	Ch 5.4, 5.5, 5.7, 6.2, 7.3, 8.2, 8.3
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	DDF - Streamflows	Ch 7.3
	Threshold Streamflows	Ch 5.5
	Enhanced Evaporation	Ch 4.1, 42, 8.1
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
	Water Temperature	See Barichievy *et al*. (2010a)
	Storm Surges	Not in Report
▫ Small Reservoirs	• Flash Floods	Ch 5.6, 7.1
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Threshold Streamflows	Ch 5.5
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
	Water Temperature	See Barichievy *et al*. (2010a)
	DDF - Rainfall : Short	Ch 7.1
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
- Groundwater		
▫ Artificial Recharge	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Groundwater Recharge	Ch 5.3
▫ Borehole Drilling	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Groundwater Recharge	Ch 5.3
▫ Sand Dams	• Flash Floods	Ch 5.6, 7.1
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Groundwater Supply	Not in Report
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
- Water Re-use / Recycling	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
• Flood / Storm Surge Control		
- Structures (e.g. Dams, spillways, stormwater systems, levees, wave breaks, vegetation)	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
• Early Warning Systems		
- Short-Term (Days to Weeks)	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	DDF - Rainfall : Long	Ch 7.2
	DDF - Peak Discharge	Ch 5.6
	DDF - Streamflows	Ch 7.3
	Environmental Flows	See Barichievy *et al*. (2010b)
	Water Quality - Seds	Ch 5.7
- Medium-Term (Month to Season)	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Supply	Not in Report
	Environmental Flows	See Barichievy *et al*. (2010b)
- Long-Term (Years to Decades)	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Supply	Not in Report

• Communication of Forecasts to End Users	• Flash Floods Regional Floods Hydrological Droughts Agricultural Droughts Storm Surges	Ch 5.6, 7.1 Ch 7.2, 7.3 Ch 5.5, 6.1, 6.2, 8.1, 8.2 Ch 4.2, 6.1, 6.2, 8.2 Not in Report
• Water Quality and Quantity Monitoring Systems	• All	
• Operations / System Improvements		
- Reservoir Operations Rules	• Flash Floods Regional Floods Agricultural Droughts Hydrological Droughts DDF - Rainfall : Short DDF - Rainfall : Long DDF - Streamflows DDF - Peak Discharge Surface Water Supply	Ch 5.6, 7.1 Ch 7.2, 7.3 Ch 4.2, 6.1, 6.2, 8.2 Ch 5.5, 6.1, 6.2, 8.1, 8.2 Ch 7.1 Ch 7.2 Ch 7.3 Ch 5.6 Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
- Retrofitting Existing Structures	• Flash Floods Regional Floods Sea Level Rise Storm Surges Surface Water Supply Groundwater Recharge	Ch 5.6, 7.1 Ch 7.2, 7.3 Not in Report Not in Report Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4 Ch 5.3
• Water Demand Management	• Agricultural Droughts Hydrological Droughts Environmental Flows Sea Level Rise Surface Water Supply Groundwater Recharge Water Quality - Seds Water Quality - Chem	Ch 4.2, 6.1, 6.2, 8.2 Ch 5.5, 6.1, 6.2, 8.1, 8.2 See Barichievy *et al*. (2010b) Not in Report Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4 Ch 5.3 Ch 5.7 Ch 8.3
KNOWLEDGE / SKILLS / PARTICIPATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Research and Development		
- Efficient Technologies	• All	
- Upgrading of Climate Models		
▫ Improvements to Downscaling / RCMs	• All	
▫ Fine Scale Information Provision Relevant to Local Water Managers	• All	
- Improvement of Forecast Skill / Dissemination	• All	
• Development of Risk Maps / Floodlines	• Flash Floods Regional Floods Hydrological Droughts Sea Level Rise Storm Surges	Ch 5.6, 7.1 Ch 7.2, 7.3 Ch 5.5, 6.1, 6.2, 8.1, 8.2 Not in Report Not in Report
• Communication / Training / Dissemination		
- Awareness Creation at Higher Decision Making Level	• All	
- Awareness Creation at Operational Level	• All	
• Participatory Approach in Decision-Making		
- Establishment of Interdepartmental Learning Platforms (e.g. Task teams)	• All	
- Establishment of an Integrated Communication System (Trends, priorities, activities, risks)	• All	
- Creation of Ongoing Learning and Communication Platforms between Main Water Users	• All	
POLICY INSTRUMENTS	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• International Water Agreements	• All	
• National Water Master Plans		
- National Water Act of 1998	• All	
- National Water Resource Strategy of 2004, 2011	• All	
- Catchment Management Strategies (CMS)	• All	
- Estuary Management Plans	• All	
• Provincial Strategies		
- Provincial Growth and Development Strategies	• All	
- Provincial Water Reconciliation Strategies	• All	
• Disaster Management Policies / Plans	• All	
RISK SHARING / SPREADING	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Private Sector Strategies		
- Banks		
▫ Development	• All	
CHANGE OF USE / ACTIVITY / LOCATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Land Use Measures		

- Adaptive Spatial Planning	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Streamflows	Ch 7.3
	Environmental Flows	See Barichievy *et al*. (2010b)
	Surface Water Supply	Surface Water Supply
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
- Alien Invasive Clearing Activities	• Surface Water Supply	Surface Water Supply
• Maintaining or Re-establishment of Natural Capital (e.g. wetlands, buffers etc)		
	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 5.2, 5.4, 7.3
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report

Water Related Sector Adaptation 3: Bulk Water Suppliers (e.g. Umgeni Water)

Table 9.3.3 Adaptation recommendations for Bulk Water Suppliers

ENHANCING ADAPTIVE CAPACITY TECHNOLOGICAL AND STRUCTURAL	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES TO SCHULZE (2011)
• Storage and Reticulation		
- Surface water		
▫ Large Reservoirs	• Regional Floods	Ch 7.2, 7.3
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Threshold Streamflows	Ch 5.5
	Water Temperature	See Barichievy *et al*. (2010a)
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Storm Surges	Not in Report
▫ Small Reservoirs	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	DDF - Rainfall: Short	Ch 7.1
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Threshold Streamflows	Ch 5.5
	Water Temperature	See Barichievy *et al*. (2010a)
- Groundwater		
▫ Artificial Recharge	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Groundwater Recharge	Ch 5.3
▫ Borehole Drilling	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Groundwater Recharge	Ch 5.3
▫ Sand Dams	• Flash Floods	Ch 5.6, 7.1
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
- System Maintenance		
▫ Supply Leakage Control	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Water Quality - Chem	Ch 8.3
- Rainwater Harvesting	• Rainfall Thresholds	Ch 3.6
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
- Water Re-use / Recycling	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
• Desalination	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
• Early Warning Systems		
- Near Real-Time (Hours to Days)	• Flash Floods	Ch 5.6, 7.1
	DDF - Rainfall: Short	Ch 7.2
	DDF - Peak Discharge	Ch 5.6
	Regional Floods	Ch 7.2, 7.3
	Environmental Flows	See Barichievy *et al*. (2010b)
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
- Short-Term (Days to Weeks)	• Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	
- Medium-Term (Month to Season)	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1

	Environmental Flows	See Barichievy *et al*. (2010b)
- Long-Term (Years to Decades)	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
• Communication of Forecasts to End Users	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Storm Surges	Not in Report
• Water Quality and Quality Monitoring Systems	• All	
• Operations / System Improvements		
- Reservoir Operations Rules	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	DDF - Stormflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Water Temperature	See Barichievy *et al*. (2010a)
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
- Retrofitting Existing Structures	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Peak Discharge	Ch 5.6
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Supply	Not in Report
• Water Demand Management	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Sea Level Rise	Not in Report
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
	Water Quality - Chem	Ch8.3
KNOWLEDGE / SKILLS / PARTICIPATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Research and Development		
- Efficient Technologies	• All	
- Upgrading of Climate Models		
▫ Improvements to Downscaling / RCMs	• All	
▫ Fine Scale Information Provision Relevant to Local Water Managers	• All	
- Improvement of Forecast Skill / Dissemination	• All	
• Communications, Training and Dissemination		
- Awareness Creation at Higher Decision-Making Level	• All	
- Training at Middle Management	• All	
• Participatory Approach in Decision-Making		
- Establishment of an Integrated Communication System (trends, priorities, activities, risks)	• All	
- Creation of Ongoing Learning and Communication Platforms between Main Water Users	• All	
POLICY INSTRUMENTS	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• International Conventions (e.g. UNFCCC)	• All	
• International Water Agreements	• All	
• National Water Master Plans		
- National Water Act of 1998	• All	
- National Water Research Strategy	• All	
• Provincial Strategies		
- Provincial Growth and Development Strategies	• All	
- Provincial Reconciliation Plans	• All	
• Disaster Management Policies / Plans	• All	
RISK SHARING / SPREADING	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Private Sector Strategies		
- Stock Exchange	• All	
CHANGE OF USE / ACTIVITY / LOCATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Land Use Measures		
- Adaptive Spatial Planning	• Flash Floods	Ch 5.6, 7.1

	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Environmental Flows	See Barichievy *et al*. (2010b)
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
• Resettlement	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Water Quality - Biol	Not in Report
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report

Water Related Sector Adaptation 4: Water User Associations / Irrigation Boards (e.g. Pongola Irrigation Board)

Table 9.3.4 Adaptation recommendations for Water User Associations / Irrigation Boards

ENHANCING ADAPTIVE CAPACITY TECHNOLOGICAL AND STRUCTURAL	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES TO SCHULZE (2011)
• Storage and Reticulation		
- Surface water		
▫ Large Reservoirs	• Regional Floods	Ch 7.2, 7.3
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	DDF - Streamflows	Ch 7.3
	Threshold Streamflows	Ch 5.5
	Enhanced Evaporation	Ch 4.1, 42, 8.1
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
	Water Temperature	See Barichievy *et al*. (2010a)
▫ Small Reservoirs	• Flash Floods	Ch 5.6, 7.1
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Threshold Streamflows	Ch 5.5
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
	Water Temperature	See Barichievy *et al*. (2010a)
	DDF - Rainfall : Short	Ch 7.1
	DDF - Stormflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
- Groundwater		
▫ Artificial Recharge	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Groundwater Recharge	Ch 5.3
	Groundwater Supply	Not in Report
▫ Borehole Drilling	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Groundwater Recharge	Ch 5.3
	Groundwater Supply	Not in Report
▫ Sand Dams	• Flash Floods	Ch 5.6, 7.1
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Groundwater Supply	Not in Report
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
- Water Re-use / Recycling	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
• Flood / Storm Surge Control		
- Structures (e.g. Dams, spillways, stormwater systems, levees, wave breaks, vegetation)	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
• Early Warning Systems		
- Short-Term (Days to Weeks)	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
	Environmental Flows	See Barichievy *et al*. (2010b)
	Water Quality - Seds	Ch 5.7
- Medium-Term (Month to Season)	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Supply	Not in Report
	Environmental Flows	See Barichievy *et al*. (2010b)
- Long-Term (Years to Decades)	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Supply	Not in Report
• Communication of Forecasts to End Users	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2

	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
	Storm Surges	Not in Report
• Water Quality and Quantity Monitoring Systems	• All	
• Operations / System Improvements		
- Reservoir Operations Rules	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
- Retrofitting Existing Structures	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
• Water Demand Management	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Environmental Flows	See Barichievy *et al.* (2010b)
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
KNOWLEDGE / SKILLS / PARTICIPATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Research and Development		
- Efficient Technologies	• All	
- Upgrading of Climate Models		
▫ Improvements to Downscaling / RCMs	• All	
▫ Fine Scale Information Provision Relevant to Local Water Managers	• All	
- Improvement of Forecast Skill / Dissemination	• All	
• Development of Risk Maps / Floodlines	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
• Communication / Training / Dissemination		
- Awareness Creation at Higher Decision Making Level	• All	
- Awareness Creation at Operational Level	• All	
• Participatory Approach in Decision-Making		
- Establishment of Interdepartmental Learning Platforms (e.g. Task teams)	• All	
- Establishment of an Integrated Communication System (Trends, priorities, activities, risks)	• All	
- Creation of Ongoing Learning and Communication Platforms between Main Water Users	• All	
POLICY INSTRUMENTS	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• National Water Master Plans		
- National Water Act of 1998	• All	
- National Water Resource Strategy of 2004, 2011	• All	
- Catchment Management Strategies	• All	
- River Management Plans	• All	
• Provincial Strategies		
- Provincial Growth and Development Strategies	• All	
- Provincial Water Reconciliation Strategies	• All	
• Local Strategies		
- Municipal Bye-Laws	• All	
• Disaster Management Policies / Plans	• All	
RISK SHARING / SPREADING	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Private Sector Strategies		
- Banks		
▫ Development	• All	
CHANGE OF USE / ACTIVITY / LOCATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Land Use Measures		
- Adaptive Spatial Planning	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Long	Ch 7.2

	DDF - Streamflows	Ch 7.3
	Environmental Flows	See Barichievy *et al*. (2010b)
	Surface Water Supply	Surface Water Supply
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
- Alien Invasive Clearing Activities	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
• Maintaining or Re-establishment of Natural Capital (e.g. wetlands, buffers etc)	• Flash Floods	Ch 5.6, 7.1
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Regional Floods	Ch 5.2, 5.4, 7.3
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report

Water Related Sector Adaptation 5: Municipalities

Table 9.3.5 Adaptation recommendations for Municipalities

ENHANCING ADAPTIVE CAPACITY TECHNOLOGICAL AND STRUCTURAL	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES TO SCHULZE (2011)
• Storage and Reticulation		
- Surface water		
▫ Large Reservoirs	• Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Water Temperature	See Barichievy *et al*. (2010a)
	DDF - Stormflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
	Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Storm Surges	Not in Report
▫ Small Reservoirs	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	DDF - Rainfall: Short	Ch 7.1
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Threshold Streamflows	Ch 5.5
	Water Temperature	See Barichievy *et al*. (2010a)
- Groundwater		
▫ Artificial Recharge	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Groundwater Recharge	Ch 5.3
▫ Borehole Drilling	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Groundwater Recharge	Ch 5.3
▫ Sand Dams	• Flash Floods	Ch 5.6, 7.1
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Groundwater Supply	Not in Report
- System Maintenance		
▫ Supply Leakage Control	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Water Quality - Chem	Ch 8.3
- Rainwater Harvesting	• Rainfall Thresholds	Ch 3.6
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
- Water Re-use / Recycling	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Supply	Not in Report
• Desalination	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
• Flood / Storm Surge Control		
- Structures (e.g. Dams, spillways, stormwater systems, levees, wave breaks, vegetation)	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
• Early Warning Systems		
- Near Real-Time (Hours to Days)		
	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Stormflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
- Short-Term (Days to Weeks)	• Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Streamflow Thresholds	Ch 5.5
	Water Quality - Chem	Ch 8.3

	Water Quality - Biol	Not in Report
- Medium-Term (Month to Season)	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
- Long-Term (Years to Decades)	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Supply	Not in Report
• Communication of Forecasts to End Users		
- Awareness Creation at Operational Level	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
- Training at Local Level	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 5.2, 5.4, 7.3
	Storm Surges	Not in Report
• Water Quality and Quantity Monitoring Systems	• All	
• Operations / System Improvements	• Flash Floods	Ch 5.6, 7.1
- Reservoir Operations Rules	Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Environmental Flows	See Barichievy *et al.* (2010b)
- Retrofitting Existing Structures	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
• Water Demand Management	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
KNOWLEDGE / SKILLS / PARTICIPATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Research and Development		
- Efficient Technologies	• All	
- Upgrading of Climate Models		
▫ Fine Scale Information Provision Relevant to Local Water Managers	• All	
- Improvement of Forecast Skill / Dissemination	• All	
• Communication / Training / Dissemination		
- Awareness Creation at Operations Level (e.g. Senior Municipal Officials re. budget allocation and future special planning)	• All	
- Training at Middle Management Level	• All	
- Training at Local Level (e.g. Municipal WWT operators)	• All	
• Participatory Approach in Decision-Making		
- Establishment of Inter-Departmental Learning Platforms	• All	
- Establishment of Integrated Communications Systems	• All	
- Creation of Ongoing Learning and Communication Platforms between Main Water Users	• All	
POLICY INSTRUMENTS	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• National Water Master Plans		
- National Water Act of 1998	• All	
- National Water Resource Strategy	• All	
- Water Services Act of 1997	• All	
- Catchment Management Strategies	• All	
- River Management Plans	• All	
• Other National Strategies		
- Integrated Development Plans	• All	
• Provincial Strategies		
- Provincial Growth and Development Strategies	• All	
• Local Strategies		
- Municipal Bye-Laws	• All	

• Disaster Management Policies / Plans	• All	
RISK SHARING / SPREADING	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Private Sector Strategies		
- Insurance		
▫ Re-Insurance	• Regional Floods	Ch 7.2, 7.3
	Flash Floods	Ch 5.6, 7.1
CHANGE OF USE / ACTIVITY / LOCATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Land Use Measures		
- Conservation Structures	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Streamflows	Ch 7/3
	DDF - Peak Discharge	Ch 5.6
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
- Adaptive Spatial Planning	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflow	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
- Alien Invasive Clearing Activities	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
• Resettlement	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 5.2, 5.4, 7.3
	Rainfall Thresholds	Ch 3.6
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
• Maintaining or Re-establishment of Natural Capital (e.g. wetlands, buffers etc)	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 5.2, 5.4, 7.3
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report

Water Related Sector Adaptation 6: Disaster Risk Management

Table 9.3.6 Adaptation recommendations for Disaster Risk Management

ENHANCING ADAPTIVE CAPACITY TECHNOLOGICAL AND STRUCTURAL	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES TO SCHULZE (2011)
• Storage and Reticulation		
- Surface water		
▫ Large Reservoirs	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Threshold Streamflows	Ch 5.5
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Storm Surges	Not in Report
▫ Small Reservoirs	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	DDF - Rainfall: Short	Ch 7.1
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Threshold Rainfall	Ch 3.6
	Threshold Streamflows	Ch 5.5
- Groundwater		
▫ Artificial Recharge	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Groundwater Recharge	Ch 5.3
• Flood / Storm Surge Control		
- Structures (e.g. Dams, spillways, stormwater systems, levees, wave breaks, vegetation)	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Storm Surges	Not in Report
• Early Warning Systems		
- Near Real-Time (Hours to Days)	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Threshold Streamflows	Ch 5.5
	Soil Moisture	Ch 4.2
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
- Short-Term (Days to Weeks)	• Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Flash Floods	Ch 5.6, 7.1
	Threshold Streamflows	Ch 5.5
	Soil Moisture	Ch 4.2
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
- Medium-Term (Month to Season)	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
• Communication of Forecasts to End Users	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Threshold Streamflows	Ch 5.5
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
	Storm Surges	Not in Report
• Operations / System Improvements		
- Reservoir Operations Rules	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Threshold Streamflows	Ch 5.5
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2

- Retrofitting Existing Structures	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
• Precipitation Enhancement	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
KNOWLEDGE / SKILLS / PARTICIPATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Research and Development		
- Efficient Technologies	• All	
- Upgrading of Climate Models	• All	
▫ Improvements to Downscaling / RCMs	• All	
▫ Fine Scale Information Provision Relevant to Local Water Managers	• All	
- Improvement of Forecast Skill / Dissemination	• All	
• Development of Risk Maps / Floodlines	• Flash Floods	Ch 5.5, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
• Communication, Training, Dissemination		
- Awareness Creation at Operational Level	• All	Not in Report
- Training at Middle Management Level	• All	Not in Report
- Training at Local Level	• All	Not in Report
• Participatory Approach in Decision-Making		
- Establishment of an Integrated Communication System	• All	Not in Report
- Creation of Ongoing Learning and Communication Platforms	• All	Not in Report
POLICY INSTRUMENTS	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• International Water Agreements	• All	
• International Trade	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
• National Water Master Plans		
- National Water Act of 1998	• All	
- National Water Resource Strategy	• All	
• Disaster Management Policies / Plans	• All	
RISK SHARING / SPREADING	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Private Sector Strategies		
- Insurance		
▫ Primary Insurers	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Regional Floods	Ch 7.2, 7.3
	Flash Floods	Ch 5.6, 7.1
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Stormflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
▫ Re-Insurance	• Regional Floods	Ch 7.2, 7.3
	Flash Floods	Ch 5.6, 7.1
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Stormflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
▫ Micro-Insurance	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
- Banks		
▫ Development		
▫ Private	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Regional Floods	Ch 7.2, 7.3

	Flash Floods	Ch 5.6, 7.1
▫ Micro-Lenders	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3

CHANGE OF USE / ACTIVITY / LOCATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Land Use Measures		
- Adaptive Spatial Planning	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
- Alien Invasive Plant Clearance	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
• Maintenance & Re-establishment of Natural Capital (Buffer zones, wetlands etc.)	• Threshold Streamflows	Ch 5.5
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report

Water Related Sector Adaptation 7: Rainfed Agriculture, Including Livestock Activities

Table 9.3.7 Adaptation recommendations for Dryland Agriculture, including Livestock Activities

ENHANCING ADAPTIVE CAPACITY TECHNOLOGICAL AND STRUCTURAL	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES TO SCHULZE (2011)
• Storage and Reticulation		
- Surface water		
▫ Small Reservoirs	• Flash Floods	Ch 5.6, 7.1
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	DDF - Rainfall: Short	Ch 7.1
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Threshold Streamflows	Ch 5.5
	Water Temperature	See Barichievy *et al.* (2010a)
	Water Quality - Sed	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
- Groundwater		
▫ Borehole Drilling	• Hydrological Drought	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Drought	Ch 4.2, 6.1, 6.2, 8.2
	Groundwater Recharge	Ch 5.3
▫ Sand Dams	• Flash Floods	Ch 5.6, 7.1
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Groundwater Supply	Not in Report
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Threshold Streamflows	Ch 5.5
• Rainwater Harvesting	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Threshold Rainfalls	Ch 3.6
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
• Flood / Storm Surge Control		
- Structures (e.g. Dams, spillways, stormwater systems, levees, wave breaks, vegetation)	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Sea Level Rise	Not in Report
• Early Warning Systems	Storm Surges	Not in Report
- Near Real-Time (Hours to Days)		
	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Soil Moisture	Ch 4.2
	Threshold Rainfalls	Ch 3.6
- Short-Term (Days to Weeks)	Threshold Streamflows	Ch 5.5
	• Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Heat Waves	See Schulze and Kunz (2010)
	Threshold Rainfalls	Ch 3.6
- Medium-Term (Month to Season)	Threshold Streamflows	Ch 5.5
	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
- Long-Term (Years to Decades)	Groundwater Recharge	Ch 5.3
	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
• Communication of Forecasts to End Users	Groundwater Recharge	Ch 5.3
	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Heat Waves	See Schulze and Kunz (2010)
	Threshold Rainfalls	Ch 3.6
	Soil Moisture	Ch 4.2
• Indigenous Coping Strategies	Storm Surges	Not in Report
	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
• Precipitation Enhancement	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
KNOWLEDGE / SKILLS / PARTICIPATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**

• Research and Development		
- Efficient Technologies	• Agricultural Droughts Regional Floods	Ch 4.2, 6.1, 6.2, 8.2 Ch 7.2, 7.3
- Upgrading of Climate Models		
▫ Fine Scale Information Provision Relevant to Local Water Managers	• Agricultural Droughts DDF - Rainfall: Short Heat Waves	Ch 4.2, 6.1, 6.2, 8.2 Ch 7.1 See Schulze and Kunz (2010)
- Improvement of Forecast Skill / Dissemination	• Agricultural Droughts Regional Floods Heat Waves Soil Moisture Threshold Rainfalls	Ch 4.2, 6.1, 6.2, 8.2 Ch 7.2, 7.3 See Schulze and Kunz (2010) Ch 4.2 Ch 3.6
- Development of Drought Resistant Crops	• Agricultural Droughts Heat Waves Soil Moisture	Ch 4.2, 6.1, 6.2, 8.2 See Schulze and Kunz (2010) Ch 4.2
• Communication, Training, Dissemination		
- Awareness Creation at Operational Level	• Agricultural Droughts Regional Floods Heat Waves Soil Moisture	Ch 4.2, 6.1, 6.2, 8.2 Ch 7.2, 7.3 See Schulze and Kunz (2010) Ch 4.2
- Training at Local Level	• Agricultural Droughts Regional Floods Heat Waves Soil Moisture	Ch 4.2, 6.1, 6.2, 8.2 Ch 7.2, 7.3 See Schulze and Kunz (2010) Ch 4.2
• Participatory Approach in Decision-Making		
- Creation of Ongoing Learning and Communication Platforms	• Agricultural Droughts Regional Floods Heat Waves Soil Moisture	Ch 4.2, 6.1, 6.2, 8.2 Ch 7.2, 7.3 See Schulze and Kunz (2010) Ch 4.2
POLICY INSTRUMENTS	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• International Trade	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
• Other National Strategies		
- National Environmental Management Plan	• All	
- Conservation of Agricultural Resources Act	• All	
RISK SHARING / SPREADING	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Private Sector Strategies		
- Insurance		
▫ Primary Insurers	• Agricultural Droughts Hydrological Droughts Regional Floods Flash Floods	Ch 4.2, 6.1, 6.2, 8.2 Ch 5.5, 6.1, 6.2, 8.1, 8.2 Ch 7.2, 7.3 Ch 5.6, 7.1
▫ Micro-Insurance	• Flash Floods Regional Floods Agricultural Droughts	Ch 5.6, 7.1 Ch 7.2, 7.3 Ch 4.2, 6.1, 6.2, 8.2
- Banks		
▫ Private	• Agricultural Droughts DDF - Rainfall: Short DDF - Streamflows DDF - Peak Discharge Heat Waves Regional Floods Flash Floods	Ch 4.2, 6.1, 6.2, 8.2 Ch 7.1 Ch 7.3 Ch 5.6 See Schulze and Kunz (2010) Ch 7.2, 7.3 Ch 5.6, 7.1
▫ Micro-Lenders	• Agricultural Droughts Flash Floods Regional Floods	Ch 4.2, 6.1, 6.2, 8.2 Ch 5.6, 7.1 Ch 7.2, 7.3
CHANGE OF USE / ACTIVITY / LOCATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Land Use Measures		
- Conservation Structures	• DDF - Rainfall: Short DDF - Streamflows DDF - Peak Discharge Flash Floods Regional Floods Storm Surges Agricultural Droughts	Ch 7.1 Ch 7.3 Ch 5.6 Ch 5.6, 7.1 Ch 7.2, 7.3 Not in Report Ch 4.2, 6.1, 6.2, 8.2
- Adaptive Spatial Planning	• Flash Floods Regional Floods Water Quality - Seds Water Quality - Chem Sea Level Rise Storm Surges	Ch 5.6, 7.1 Ch 7.2, 7.3 Ch 5.7 Ch 8.3 Not in Report Not in Report
- Tillage Practices	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2

	Heat Waves	See Schulze and Kunz (2010)
	Thresholds - Rainfall	Ch 3.6
	Soil Moisture	Ch 4.2
- Use of Organic (instead of chemical) Fertilizers	• Soil Moisture	Ch 4.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
- Alien Invasive Clearing Activities	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
• Crop Change	• Heat Waves	See Schulze and Kunz (2010)
	Threshold Rainfalls	Ch 3.6
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
• Resettlement	• Threshold Rainfalls	Ch 3.6
	Soil Moisture	Ch 4.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Regional Floods	Ch 7.2, 7.3

Water Related Sector Adaptation 8: Irrigated Agriculture

Table 9.3.8 Adaptation recommendations for Irrigated Agriculture

ENHANCING ADAPTIVE CAPACITY TECHNOLOGICAL AND STRUCTURAL	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES TO SCHULZE (2011)
• Storage and Reticulation		
- Surface water		
▫ Large Reservoirs	• Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Enhanced Evaporation	Ch 4.2
	Water Temperature	See Barichievy *et al*. (2010a)
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
▫ Small Reservoirs	• Flash Floods	Ch 5.6, 7.1
	DDF - Rainfall: Short	Ch 7.1
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Water Temperature	See Barichievy *et al*. (2010a)
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
- Groundwater		
▫ Artificial Recharge	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Groundwater Recharge	Ch 5.3
	Groundwater Supply	Not in Report
▫ Borehole Drilling	• Groundwater Supply	Not in Report
	Groundwater Recharge	Ch 5.3
- System Maintenance		
▫ Irrigation Equipment Maintenance	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
▫ Irrigation Canal Leakage / Losses	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Water Temperature	See Barichievy *et al*. (2010a)
• Water Quality and Quantity Monitoring Systems	• All	
• Early Warning Systems		
- Short-Term (Days to Weeks)	• Heat Waves	See Schulze and Kunz (2010)
	Threshold Rainfalls	Ch 3.6
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
- Medium-Term (Month to Season)	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
- Communication of Forecasts to End Users	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Heat Waves	See Schulze and Kunz (2010)
	Threshold Rainfalls	Ch 3.6
• Operations / System Improvements		
- Reservoir Operations Rules	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Temperature	See Barichievy *et al*. (2010a)
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
- Irrigation Scheduling	• Threshold Rainfalls	Ch 3.6
	Soil Moisture	Ch 4.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
• Precipitation Enhancement	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2

KNOWLEDGE / SKILLS / PARTICIPATION	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES
• Research and Development		
- Efficient Technologies	• All	
- Upgrading of Climate Models		
▫ Fine Scale Information Provision Relevant to Local Water Managers	• All	
- Improvement of Forecast Skill / Dissemination	• All	
- Development of Drought Resistant Crops	• Heat Waves	See Schulze and Kunz (2010)
	Soil Moisture	Ch 4.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
• Communication / Training / Dissemination		
- Awareness Creation at Operational Level	• Heat Waves	See Schulze and Kunz (2010)
	Soil Moisture	Ch 4.2
	Threshold Rainfalls	Ch 3.6
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
• Participatory Approach in Decision-Making	Heat Waves	See Schulze (2010)
- Creation of Ongoing Learning and Communication Platforms	• All	

POLICY INSTRUMENTS	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES
• International Water Agreements	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
• International Trade	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
• National Water Master Plans		
- National Water Resource Strategy of 2004, 2011	• All	
- Catchment Management Strategy	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Water Quality - Seds	Ch 5.7
	Water Quality -Chem	Ch 8.3
• Other National Strategies		
- National Environmental Management Plan	• All	
- Conservation of Agricultural Resources Act	• All	

RISK SHARING / SPREADING	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES
• Private Sector Strategies		
- Insurance		
▫ Primary Insurers	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
▫ Micro-Insurance	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
- Banks		
▫ Development	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
▫ Private	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3

CHANGE OF USE / ACTIVITY / LOCATION	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES
• Land Use Measures		
- Conservation Structures	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Streamflows	Ch 7.3
	Threshold Rainfalls	Ch 3.6
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
- Adaptive Spatial Planning	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
- Tillage Practices	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Soil Moisture	Ch 4.2
- Use of Organic (instead of chemical) Fertilizers	• Soil Moisture	Ch 4.2
• Crop Change	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Heat Waves	See Schulze and Kunz (2010)
	Soil Moisture	Ch 4.2

Water Related Sector Adaptation 9: Insurance Industry

Table 9.3.9 Adaptation recommendations for the Insurance Industry

ENHANCING ADAPTIVE CAPACITY TECHNOLOGICAL AND STRUCTURAL	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES TO SCHULZE (2011)
• Early Warning Systems		
- Near Real-Time (Hours to Days)	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Heat Waves	See Schulze and Kunz (2010)
	Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
- Short-Term (Days to Weeks)	• Regional Floods	Ch 7.2, 7.3
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Heat Waves	See Schulze and Kunz (2010)
	Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
- Medium-Term (Month to Season)	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
- Long-Term (Years to Decades)	• Regional Floods	Ch 7.2, 7.3
• Communication of Forecasts to End Users	• Flash Floods	Ch 5.6, 7.1
	Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
	Heat Waves	See Schulze and Kunz (2010)
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Peak Discharge	Ch 5.6
	Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
• Operations / System Improvements		
- Retrofitting Existing Structures	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
- Precipitation Enhancement	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
KNOWLEDGE / SKILLS / PARTICIPATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCE**
• Research and Development		
- Efficient Technologies	• All	
- Upgrading Climate Models		
▫ Fine Scale Information Provision Relevant to Local Water Managers	• All	
- Improvement of Forecast Skill / Dissemination	• All	
• Development of Risk Maps / Floodlines	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
• Communication. Training , Dissemination		
- Awareness Creation at Higher Decision-Making Level	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Heat Waves	See Schulze and Kunz (2010)
POLICY INSTRUMENTS	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Disaster Management Policies / Plans	• All	
RISK SHARING / SPREADING	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**

• Private Sector Strategies		
- Insurance		
▫ Primary Insurers	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
▫ Re-Insurance	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
▫ Micro-Insurance	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Agriciultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
CHANGE OF USE / ACTIVITY / LOCATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Land Use Measures		
- Conservation Structures	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Storm Surges	Not in Report
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2

Water Related Sector Adaptation 10: Road Transport Sector

Table 9.3.10 Adaptation recommendations for the Road Transport Sector

ENHANCING ADAPTIVE CAPACITY TECHNOLOGICAL AND STRUCTURAL	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES TO SCHULZE (2011)
• Flood / Storm Surge Control		
- Structures (i.e. Levees, Sand Bags, Wave Breaks, Planting)	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
• Early Warning Systems		
- Near Real-Time (Hours to Days)	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
- Short-Term (Days to Weeks)	• Flash Floods	Ch 7.2, 7.3
	Regional Floods	Ch 5.6, 7.1
	Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
- Long-Term (Years to Decades)	• Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
• Communication of Forecasts to End Users	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Storm Surges	Not in Report
	Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5

KNOWLEDGE / SKILLS / PARTICIPATION	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES
• Research and Development		
- Improvement of Forecast Skill / Dissemination	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Storm Surges	Not in Report
• Development of Risk Maps / Floodlines	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Sea Level Rise	Not in Report
	Storm surges	Not in Report
• Communication / Training / Dissemination		
- Awareness Creation at Higher Decision-Making Level	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
- Awareness Creation at Operational Level	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
	Sea Level Rise	Not in Report

	Storm Surges	Not in Report
• Participatory Approach in Decision-Making		
- Establishment of an Integrated Communication System	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
POLICY INSTRUMENTS	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Disaster Management Policies / Plans	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
RISK SHARING / SPREADING	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Private Sector Strategies		
- Insurance		
▫ Primary Insurers	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Threshold Rainfalls	Ch 5.6
	Threshold Streamflows	Ch 3.6
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
▫ Re-Insurance	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
CHANGE OF USE / ACTIVITY / LOCATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Land Use Measures		
- Adaptive Spatial Planning	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
• Resettlement	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Sea Level Rise	Not in Report

Water Related Sector Adaptation 11: Thermal Electric Power Industry (e.g. Eskom)

Table 9.3.11 Adaptation recommendations for the Thermal Electric Power Industry

ENHANCING ADAPTIVE CAPACITY TECHNOLOGICAL AND STRUCTURAL	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES TO SCHULZE (2011)
• Storage and Reticulation		
- Surface water		
▫ Large Reservoirs	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Threshold Streamflows	Ch 5.5
	DDF - Streamflows	Ch 7.3
• Early Warning Systems	DDF - Peak Discharge	Ch 5.6
- Near Real-Time (Hours to Days)	• DDF - Rainfall: Short	Ch 7.1
	Flash Floods	Ch 5.6, 7.1
	Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
	Soil Moisture	Ch 4.2
	Regional Floods	Ch 7.1, 7.2
- Short-Term (Days to Weeks)	• DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
	Soil Moisture	Ch 4.2
	Regional Floods	Ch 7.1, 7.2
	Hydrological Droughts	Ch 7.1, 7.2
- Medium-Term (Month to Season)	• Hydrological Droughts	Ch 7.2, 7.3
	Surface Water Supply	Ch 5.5, 6.1, 6.2, 8.1, 8.2
- Long-Term (Years to Decades)	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
• Communication of Forecasts to End Users	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	Threshold Rainfalls	Ch 3.6
	Soil Moisture	Ch 4.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Storm Surges	Not in Report
• Operations / System Improvements		
- Reservoir Operations Rules	• Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Threshold Streamflows	Ch 5.5
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
KNOWLEDGE / SKILLS / PARTICIPATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Research and Development		
- Efficient Technologies	• All	
- Upgrading of Climate Models	• All	
▫ Improvements to Downscaling / RCMs	• All	
▫ Fine Scale Information Provision Relevant to Local Water Managers	• All	
- Improvement of Forecast Skill / Dissemination	• All	
• Communication, Training, Dissemination		
- Awareness Creation at Higher Decision-Making Level	• All	
- Awareness Creation at Operational Level	• All	
• Participatory Approach in Decision-Making		
- Establishment of Interdepartmental Learning Platforms (e.g. task teams)	• All	
- Establishment of an Integrated Communication System (trends, priorities, activities, risks)	• All	
- Creation of Ongoing Learning and Communication Platforms	• All	
POLICY INSTRUMENTS	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• National Water Master Plans		
- National Water Act of 1998	• All	
- National Water Resource Strategy of 2004, 2011	• All	
• Disaster Management Policies / Plans	• All	
RISK SHARING / SPREADING	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Private Sector Strategies		
- Banks		

▫ Development	• All	
• Public Sector Strategies	• All	
CHANGE OF USE / ACTIVITY / LOCATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Land Use Measures		
- Adaptive Spatial Planning	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Soil Moisture	Ch 4.2
	DDF - Rainfall: Short	Ch 7.1
	Sea Level rise	Not in Report
	Storm Surges	Not in Report
• Resettlement	• Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Soil Moisture	Ch 4.2
	Storm Surges	Not in Report
	Sea Level Rise	Not in Report
	Water Quality - Seds	Ch 5.7

Water Related Sector Adaptation 12: Hydro-Electric Power Industry

Table 9.3.12 Adaptation recommendations for the Hydro-Electric Power Industry

ENHANCING ADAPTIVE CAPACITY TECHNOLOGICAL AND STRUCTURAL	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES TO SCHULZE (2011)
• Storage and Reticulation		
- Surface water		
▫ Large Reservoirs	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Threshold Streamflows	Ch 5.5
• Early Warning Systems		
- Near Real-Time (Hours to Days)	• Regional Floods	Ch 7.2, 7.3
	Water Quality - Seds	Ch 5.7
- Short-Term (Days to Weeks)	• DDF - Rainfall: Long	Ch 7.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Water Quality: Seds	Ch 5.7
	Threshold Streamflows	Ch 5.5
- Medium-Term (Month to Season)	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
- Long-Term (Years to Decades)	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
• Communication of Forecasts to End Users	• Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Storm Surges	Not in Report
• Operations / System Improvements		
- Reservoir Operations Rules	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Threshold Streamflows	Ch 5.5
	Water Quality - Seds	Ch 5.7
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
KNOWLEDGE / SKILLS / PARTICIPATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Research and Development		
- Efficient Technologies	• All	
- Upgrading of Climate Models	• All	
▫ Improvements to Downscaling / RCMs	• All	
▫ Fine Scale Information Provision Relevant to Local Water Managers		
- Improvement of Forecast Skill / Dissemination	• All	
• Participatory Approach in Decision-Making	• All	
POLICY INSTRUMENTS	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• National Water Master Plans		
- National Water Act of 1998	• All	
- Nation Water Resource Strategy of 2004, 2011	• All	
• Disaster Management Policies / Plans	• All	
RISK SHARING / SPREADING	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Private Sector Strategies		
- Banks		
▫ Development	• All	
CHANGE OF USE / ACTIVITY / LOCATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Land Use Measures		
- Adaptive Spatial Planning	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
• Resettlement	• Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	DDF - Stormflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6

Water Related Sector Adaptation 13: Poor Rural Communities

Table 9.3.13 Adaptation recommendations for Poor Rural Communities

ENHANCING ADAPTIVE CAPACITY TECHNOLOGY AND STRUCTURES	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES TO SCHULZE (2011)
• Storage and Reticulation		
- Surface water		
▫ Small Reservoirs	• Flash Floods	Ch 5.6, 7.1
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Enhanced Evaporation	Ch 4.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
- Groundwater		
▫ Borehole Drilling	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Groundwater Recharge	Ch 5.3
	Groundwater Supply	Not in Report
• Rainwater Harvesting	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Threshold Rainfalls	Ch 3.6
	Soil Moisture	Ch 4.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
• Early Warning Systems		
- Short-Term (Days to Weeks)	• Heat Waves	See Schulze and Kunz (2010)
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Soil Moisture	Ch 4.2
	Threshold Rainfalls	Ch 3.6
- Medium-Term (Month to Season)	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
	Groundwater Supply	Not in Report
	Threshold Rainfalls	Ch 3.6
	Soil Moisture	Ch 4.2
• Indigenous Coping Strategies	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Soil Moisture	Ch 4.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Storm Surges	Not in Report
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
KNOWLEDGE / SKILLS / PARTICIPATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Research and Development		
- Development of Drought Resistant Crops	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Soil Moisture	Ch 4.2
• Participatory Approach in Decision-Making	• All	
POLICY INSTRUMENTS	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Other National Master Plans		
- Conservation of Agricultural Resources Act	• All	
- Integrated Development Plans	• All	
RISK SHARING / SPREADING	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Private Sector Strategies		
- Insurance		
▫ Micro-Insurance	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Heat Waves	See Schulze and Kunz (2010)
	Threshold Rainfalls	Ch 3.6
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
- Banks		
▫ Micro-Lenders	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Heat Waves	See Schulze and Kunz (2010)
	Threshold Rainfalls	Ch 3.6
	Soil Moisture	Ch 4.2
	Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3

CHANGE OF USE / ACTIVITY / LOCATION	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES
• Land Use Measures		
- Conservation Structures	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Storm Surges	Not in Report
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
- Tillage Practices	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Soil Moisture	Ch 4.2
• Crop Change	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Soil Moisture	Ch 4.2
• Resettlement	• Regional Floods	Ch 7.2, 7.3
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Sea Level Rise	Not in Report
	Water Quality - Biol	Not in Report

Water Related Sector Adaptation 14: Informal Urban Communities

Table 9.3.14 Adaptation recommendations for Informal Urban Communities

ENHANCING ADAPTIVE CAPACITY TECHNOLOGICAL AND STRUCTURAL	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES TO SCHULZE (2011)
• Storage and Reticulation		
- Surface water		
▫ Large Reservoirs	• Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
- Groundwater		
▫ Borehole Drilling	• Groundwater Storage	Not in Report
	Groundwater Recharge	Ch 5.3
	Water Quality -Chem	Ch 8.3
- System Maintenance		
▫ Supply Leakage Control	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
- Rainwater Harvesting	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Threshold Rainfalls	Ch 3.6
- Water Re-use / Recycling	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
• Water Quality and Quantity Monitoring Systems	• All	
• Flood / Storm Surge Control		
- Structures (e.g. Dams, spillways, stormwater systems, levees, wave breaks, vegetation)	• Threshold Streamflows	Ch 5.5
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
• Early Warning Systems		
- Near Real-Time (Hours to Days)	• Flash Floods	Ch 5.6, 7.1
	Threshold Streamflows	Ch 5.5
	Soil Moisture	Ch 4.2
	DDF - Rainfall: Short	Ch 7.1
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
- Short-Term (Days to Weeks)	• Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
- Medium-Term (Month to Season)	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
• Communication of Forecasts to End Users		
- Awareness Creation at Higher Decision Making Level	• All	
- Training at Local Level (e.g. Municipal WWT operators)	• All	
• Operations / System Improvements		
- Retrofitting Existing Structures	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
- Irrigation Scheduling	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
• Water Demand Management	• All	
• Indigenous Coping Strategies	• All	
KNOWLEDGE / SKILLS / PARTICIPATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Research and Development		
- Efficient Technologies	• All	
- Upgrading of Climate Models		
▫ Fine Scale Information Provision Relevant to Local Water Managers	• All	
- Improvement of Forecast Skill / Dissemination	• Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
	Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 5.2, 5.4, 7.3
• Development of Risk Maps / Floodlines	• DDF - Streamflows	Ch 7.3
• Communication, Training, Dissemination	DDF - Peak Discharge	Ch 5.6
- Awareness Creation at Higher Decision Making Level	• All	
- Awareness Creation at Operational Level (e.g. Municipal WWT)	• All	
- Training at Middle Management Level	• All	
- Training at Local Level (e.g. Municipal WWT operators)	• All	

• Participatory Approach in Decision-Making		
- Creations of Ongoing Learning and Communication Platforms btw. Main Water Users (e.g. WRC Reference Group meetings)	• All	
POLICY INSTRUMENTS	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• National Water Master Plans		
- Water Services Act of 1997	• All	
- National Water Resource Strategy of 2004, 2011	• All	
- Water for Growth and Development Framework of 2009	• All	
- Catchment Management Strategies	• All	
• Other National Master Plans		
- Integrated Development Plans (IDPs)	• All	
• Provincial Strategies		
- Provincial Growth and Development Strategies	• All	
- Provincial Water Reconciliation Strategies	• All	
• Local Strategies		
- Municipal Bye-Laws	• All	
• Disaster Management Policies / Plans	• All	
RISK SHARING / SPREADING	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Private Sector Strategies		
- Insurance		
- Micro-Insurance	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 5.2, 5.4, 7.3
	Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
- Banks		
▫ Development	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
CHANGE OF USE / ACTIVITY / LOCATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Land Use Measures		
- Adaptive Spatial Planning	• All	
• Resettlement	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 5.2, 5.4, 7.3
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6

Water Related Sector Adaptation 15: Individual Households

Table 9.3.15 Adaptation recommendations for Individual Households

ENHANCING ADAPTIVE CAPACITY TECHNOLOGICAL AND STRUCTURAL	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES TO SCHULZE (2011)
• Storage and Reticulation		
- Surface Water		
▫ Small Reservoirs	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Threshold Streamflows	Ch 5.5
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
- Groundwater		
▫ Borehole Drilling	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Groundwater Recharge	Ch 5.3
	Groundwater Supply	Not in Report
- Rainwater Harvesting	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Threshold Rainfalls	Ch 3.6
	Soil Moisture	Ch 4.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
• Early Warning Systems		
- Near Real-Time (Hours to Days)	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Threshold Rainfalls	Ch 3.6
	Soil Moisture	Ch 4.2
- Short-Term (Days to Weeks)	• Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Threshold Rainfalls	Ch 3.6
- Medium-Term (Month to Season)	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
	Groundwater Supply	Not in Report
- Long-Term (Years to Decades)	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Groundwater Recharge	Ch 5.3
	Groundwater Supply	Not in Report
• Communication of Forecasts to End Users	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Threshold Rainfalls	Ch 3.6
	Threshold Streamflows	Ch 5.5
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
• Indigenous Coping Strategies	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Soil Moisture	Ch 4.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
KNOWLEDGE / SKILLS / PARTICIPATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Research and Development		
- Improve Forecast Skill / Dissemination	• All	
- Development of Drought Resistant Crops	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Soil Moisture	Ch 4.2
• Participatory Approach in Decision-Making	• All	
POLICY INSTRUMENTS	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Disaster Management Policies / Plans	• All	
RISK SHARING / SPREADING	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Private Sector Strategies		
- Insurance		
▫ Primary Insurers	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Regional Floods	Ch 7.2, 7.3
	Flash Floods	Ch 5.6, 7.1

▫ Micro-Insurance	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
- Banks		
▫ Private	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Regional Floods	Ch 7.2, 7.3
	Flash Floods	Ch 5.6, 7.1
▫ Micro-Lenders	• Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
CHANGE OF USE / ACTIVITY / LOCATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Resettlement	• Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Water Quality	Ch 5.7, 8.3

Water Related Sector Adaptation 16: Aquatic Ecosystems (e.g. Estuaries, wetlands, buffers, environmental flows)

Table 9.3.16 Adaptation recommendations for Aquatic Ecosystems

ENHANCING ADAPTIVE CAPACITY TECHNOLOGICAL AND STRUCTURAL	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES TO SCHULZE (2011)
• Storage and Reticulation		
- Surface water		
▫ Large Reservoirs	• Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Water Temperature	See Barichievy *et al*. (2010a)
	Threshold Streamflows	Ch 5.5
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
	Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Environmental Flows	See Barichievy *et al*. (2010b)
	Storm Surges	Not in Report
▫ Small Reservoirs	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Enhanced Evaporation	Ch 4.1, 4.2, 8.1
	Threshold Streamflows	Ch 5.5
	Water Temperature	See Barichievy *et al*. (2010a)
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
- Groundwater		
▫ Sand Dams	• Flash Floods	Ch 5.6, 7.1
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
- Water Re-use / Recycling	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Water Temperature	See Barichievy *et al*. (2010a)
	Water Quality - Chem	Ch 8.3
• Flood / Storm Surge Control		
- Structures (e.g. Dams, spillways, stormwater systems, levees, wave breaks, vegetation)	• Environmental Flows	See Barichievy *et al*. (2010b)
	Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
• Early Warning Systems		
- Near Real-Time (Hours to Days)	• Environmental Flows	See Barichievy *et al*. (2010b)
	Water Temperature	See Barichievy *et al*. (2010a)
	Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Threshold Streamflows	Ch 5.5
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
- Short-Term (Days to Weeks)	• Environmental Flows	See Barichievy *et al*. (2010b)
	Water Temperature	See Barichievy *et al*. (2010a)
	Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Threshold Streamflows	Ch 5.5
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
- Medium-Term (Month to Season)	• Environmental Flows	See Barichievy *et al*. (2010b)
	Water Temperature	See Barichievy *et al*. (2010a)
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4

	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
- Long-Term (Years to Decades)	• Environmental Flows	See Barichievy *et al*. (2010b)
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Threshold Streamflows	Ch 5.5
	Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
• Communication of Forecasts to End Users		
- Awareness Creation at Higher Decision Making Level	• Environmental Flows	See Barichievy *et al*. (2010b)
	Water Temperature	See Barichievy *et al*. (2010a)
	Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 5.2, 5.4, 7.3
	Storm Surges	Not in Report
	Threshold Streamflows	Ch 5.5
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
- Awareness Creation at Operational Level	• All	
- Training at Local Level	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Environmental Flows	See Barichievy *et al*. (2010b)
	Water Temperature	See Barichievy *et al*. (2010a)
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Threshold Streamflows	Ch 5.5
• Water Quality and Quantity Monitoring Systems	• All	
• Operations / System Improvements		
- Reservoir Operations Rules	• Environmental Flows	See Barichievy *et al*. (2010b)
	Water Temperature	See Barichievy *et al*. (2010a)
	Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 5.2, 5.4, 7.3
	Threshold Streamflows	Ch 5.5
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
• Water Demand Management	• Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
	Environmental Flows	See Barichievy *et al*. (2010b)

KNOWLEDGE / SKILLS / PARTICIPATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Research and Development		
- Upgrading of Climate Models		
▫ Fine Scale Information Provision Relevant to Local Water Managers	• All	
- Improvement of Forecast Skill / Dissemination	• All	
• Communication / Training / Dissemination		
- Awareness Creation at Higher Decision Making Level	• All	
- Awareness Creation at Operations Level (e.g. Senior Municipal Officials (re. budget allocation and future special planning)	• All	
- Training at Middle Management Level	• All	
- Training at Local Level (e.g. Municipal WWT operators)	• All	
• Participatory Approach in Decision-Making		
- Establishment of Inter-Departmental Learning Platforms	• All	
- Establishment of Integrated Communications Systems	• All	
- Creation of Ongoing Learning and Communication Platforms between Main Water Users	• All	

POLICY INSTRUMENTS	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES
• International Conventions (e.g. RAMSAR)	• All	
• International Agreements	• Environmental Flows	See Barichievy *et al*. (2010b)
• National Water Master Plans		
- National Water Act of 1998	• Environmental Flows	See Barichievy *et al*. (2010b)
- National Water Resource Strategy	• Environmental Flows	See Barichievy *et al*. (2010b)
- Water for Growth and Development Framework of 2009	• Environmental Flows	See Barichievy *et al*. (2010b)
- Catchment Management Strategies	• Environmental Flows	See Barichievy *et al*. (2010b)
- River Management Plans	• Environmental Flows	See Barichievy *et al*. (2010b)
	Water Temperature	See Barichievy *et al*. (2010a)
- Estuary Management Plans	• Environmental Flows	See Barichievy *et al*. (2010b)
• Other National Strategies	• Environmental Flows	See Barichievy *et al*. (2010b)
- National Environmental Management Act	• All	
- Integrated Development Plans		
• Provincial Strategies	• All	
- Provincial Water Reconciliation Strategies		
• Local Strategies	• All	
- Municipal Bye-Laws	• All	
• Disaster Management Policies / Plans		
RISK SHARING / SPREADING	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
CHANGE OF USE / ACTIVITY / LOCATION	**ADAPTING TO CHANGES IN . . .**	**CROSS REFERENCES**
• Land Use Measures		
- Conservation Structures	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Streamflows	Ch 7/3
	DDF - Peak Discharge	Ch 5.6
	Storm Surges	Not in Report
- Adaptive Spatial Planning	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflow	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Threshold Streamflows	Ch 5.5
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Environmental Flows	See Barichievy *et al*. (2010b)
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
- Alien Invasive Clearing Activities	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
• Resettlement	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 5.2, 5.4, 7.3
	Rainfall Thresholds	Ch 3.6
	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
• Maintaining or Re-establishment of Natural Capital (e.g. wetlands, buffers etc)	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 5.2, 5.4, 7.3
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report

Water Related Sector Adaptation 17: Terrestrial Ecosystems (e.g. Biodiversity, land degradation, fire, alien invasives)

Table 9.3.17 Adaptation recommendations for Terrestrial Ecosystems

ENHANCING ADAPTIVE CAPACITY TECHNOLOGICAL AND STRUCTURAL	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES TO SCHULZE (2011)
• Storage and Reticulation		
- Surface water		
▫ Large Reservoirs	• Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
	Regional Floods	Ch 7.2, 7.3
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
▫ Small Reservoirs	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Threshold Streamflows	Ch 5.5
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
• Water Quality and Quantity Monitoring Systems	• All	
• Early Warning Systems		
- Near Real-Time (Hours to Days)	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	Threshold Streamflows	Ch 5.5
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
- Short-Term (Days to Weeks)	• Environmental Flows	See Barichievy *et al*. (2010b)
	Regional Floods	Ch 7.2, 7.3
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Threshold Streamflows	Ch 5.5
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
- Medium-Term (Month to Season)	• Environmental Flows	See Barichievy *et al*. (2010b
	Threshold Streamflows	Ch 5.5
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Agricultural Droughts	Ch 4.2, 6.1, 6.2, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
- Long-Term (Years to Decades)	• Environmental Flows	See Barichievy *et al*. (2010b)
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Threshold Streamflows	Ch 5.5
	Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 7.2, 7.3
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflows	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Hydrological Droughts	Ch 5.5, 6.1, 6.2, 8.1, 8.2
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report
• Communication of Forecasts to End Users		
- Awareness Creation at Higher Decision Making Level	• Environmental Flows	See Barichievy *et al*. (2010b)
	Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 5.2, 5.4, 7.3
	Threshold Streamflows	Ch 5.5
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report

- Awareness Creation at Operational Level	• All	
- Training at Local Level	• Flash Floods Regional Floods Hydrological Droughts Environmental Flows Surface Water Supply Threshold Streamflows Water Quality - Seds Water Quality - Chem Water Quality - Biol	Ch 5.6, 7.1 Ch 7.2, 7.3 Ch 5.5, 6.1, 6.2, 8.1, 8.2 See Barichievy *et al*. (2010b) Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4 Ch 5.5 Ch 5.7 Ch 8.3 Not in Report
• Water Quality and Quantity Monitoring Systems	• All	
• Water Demand Management	• Hydrological Droughts Threshold Streamflows Surface Water Supply Water Quality - Chem Water Quality - Biol Environmental Flows	Ch 5.5, 6.1, 6.2, 8.1, 8.2 Ch 5.5 Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4 Ch 8.3 Not in Report See Barichievy *et al*. (2010b)

KNOWLEDGE / SKILLS / PARTICIPATION	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES
• Research and Development		
- Upgrading of Climate Models		
▫ Fine Scale Information Provision Relevant to Local Water Managers	• All	
- Improvement of Forecast Skill / Dissemination	• All	
• Communication / Training / Dissemination		
- Awareness Creation at Higher Decision Making Level	• All	
- Awareness Creation at Operations Level (e.g. Senior Municipal Officials (re. budget allocation and future special planning)	• All	
- Training at Middle Management Level	• All	
- Training at Local Level (e.g. Municipal WWT operators)	• All	
• Participatory Approach in Decision-Making		
- Establishment of Inter-Departmental Learning Platforms	• All	
- Establishment of Integrated Communications Systems	• All	
- Creation of Ongoing Learning and Communication Platforms between Main Water Users	• All	

POLICY INSTRUMENTS	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES
• International Conventions (Biodiversity Convention)	• All	
• International Agreements	• All	
• National Water Master Plans		
- National Water Act of 1998	• All	
- National Water Resource Strategy	• All	
- Water for Growth and Development Framework of 2009	• All	
- Catchment Management Strategies	• All	
- River Management Plans	• All	
- Estuary Management Plans	• All	
• Other National Strategies		
- National Environmental Management Act	• All	
- Conservation of Agricultural Resources Act	• All	
- Integrated Development Plans	• All	
• Provincial Strategies		
- Provincial Water Reconciliation Strategies	• All	
• Local Strategies		
- Municipal Bye-Laws	• All	
• Disaster Management Policies / Plans	• All	

RISK SHARING / SPREADING	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES

CHANGE OF USE / ACTIVITY / LOCATION	ADAPTING TO CHANGES IN . . .	CROSS REFERENCES
• Land Use Measures		
- Conservation Structures	• Flash Floods Regional Floods DDF - Rainfall: Short DDF - Streamflows DDF - Peak Discharge	Ch 5.6, 7.1 Ch 7.2, 7.3 Ch 7.1 Ch 7/3 Ch 5.6
- Adaptive Spatial Planning	• Flash Floods Regional Floods	Ch 5.6, 7.1 Ch 7.2, 7.3

	DDF - Rainfall: Short	Ch 7.1
	DDF - Rainfall: Long	Ch 7.2
	DDF - Streamflow	Ch 7.3
	DDF - Peak Discharge	Ch 5.6
	Threshold Streamflows	Ch 5.5
	Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Environmental Flows	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Sea Level Rise	Not in Report
	Storm Surges	Not in Report
- Alien Invasive Clearing Activities	• Surface Water Supply	Ch 5.2, 5.4, 6.1, 6.2, 8.1, 8.4
	Threshold Streamflows	Ch 5.5
• Maintaining or Re-establishment of Natural Capital (e.g. wetlands, buffers etc)	• Flash Floods	Ch 5.6, 7.1
	Regional Floods	Ch 5.2, 5.4, 7.3
	Threshold Streamflows	Ch 5.5
	Water Quality - Seds	Ch 5.7
	Water Quality - Chem	Ch 8.3
	Water Quality - Biol	Not in Report

Some Additional Thoughts on Adaptation in the South African Water Sector from the Second National Communication to the UNFCCC

In addition to the information contained in the tables above, the following nine bulleted comments on adaptation are extracted, with only slight modifications, from South Africa's Second National Communication to the United Nations Framework Convention on Climate Change (DEA, 2010), for which the author was co-responsible for compiling the water section:

- In, specially, the western and central parts of South Africa water service providers will need greater water storage to buffer the projected higher variability of future rainfall regimes. Currently South Africa has fairly low levels of *per capita* storage and it has typically relied on large and medium sized dams supplied by surface runoff. Dams are projected to become more vulnerable to losses due to enhanced evaporation, siltation and contamination from algal blooms and water suppliers will need to diversify their water storage strategies.
- Most water stored naturally in catchments is stored in aquifers underground, therefore groundwater can provide an important buffer against more uncertain rainfall in the future. It is estimated that mean annual recharge to groundwater is ~ two thirds that of river runoff at 30 000 million m^3 (DWAF, 2005). However, there is more than seven times the volume of groundwater stored in aquifers (~ 235, 000 million m^3) than surface water stored in major dams (DWAF, 2005). The DWA is already developing a National Groundwater Strategy and plans to enable water service providers to diversify the water mix by using more groundwater (DWEA, 2009).
- Groundwater plays a critical role in rural development as a robust resource with buffered storage and distributed occurrence. It allows local control and uses a range of off-grid energy (solar, wind, hand pumps etc) and has been identified for increased use by DWA. The storage of groundwater can be enhanced using managed aquifer recharge. The DWA is now encouraging municipalities to set up managed recharge schemes as part of their long term integrated water resource planning.
- Water sensitive urban design has been pioneered in some semi-arid cities elsewhere in the world as a means of capturing water within the urban landscape and minimising pollution, erosion and disturbance resources. This ensures that stormwater is treated as a valuable water resource and not simply discharged to rivers or the sea. The City of Cape Town has already put a policy in place to enable water sensitive urban design.
- Land use zoning in the future may need to take greater account of water resource impacts. Buffer zones around rivers could be required to mitigate increased erosion and runoff and protect water quality in rivers and wetlands. Groundwater protection zones may be required in areas where groundwater recharge is vulnerable to the impacts of development of on-site sanitation, land-fills or petrol tanks. Agricultural best practice to reduce contamination and soil erosion will need to be implemented in areas increasingly vulnerable to floods. Industrial and mining environmental management of potential contaminants will need to become a priority.
- Municipal wastewater treatment plants will require stricter enforcement of effluent standards and significant investment in aging infrastructure. This process has begun with the roll-out of DWA's 'Green Drop' campaign which supports improved effluence compliance (e.g. DWA, 2011). Furthermore it is important that municipal employees operating the plants are well trained and have a good understanding of the importance of their jobs with regard to ensuring high standards.
- With its strong policies and laws to protect water resources and ensure their efficient and equitable use, for example, the Water Service Act (1997), the National Water Act (1998), the National Water Resource Strategy (NWRS, 2004 and updates) and the Water for Growth and Development Framework (WfGD, 2009), South Africa has the potential to lead the continent in adapting to climate change. However, the water sector is characterised by capacity constraints, inadequate funding, a reliance on ageing bulk infrastructure and erratic water quality, especially in smaller municipalities and rural areas.
- Climate change adds one more layer of uncertainty to the already challenged water sector. Whilst scientists' ability to project long term changes remains imperfect, in many areas we know enough to prioritise risks and put adaptation measures in place.
- With both drying and wetting projected over South Africa, the first measure necessary to conserve the country's water resources is water demand management (WDM) in order to use most efficiently and productively the limited water there is. While WDM is a management approach for the water sector and water in which the efficient use of existing supplies is emphasised, through policy as well as ethical, educational, economic as well as technical means

rather than developing new water resources, in several municipalities WDM is no longer considered a possible option, but is rather seen as a necessity that must be implemented with immediate effect. In line with this, the DWA has put WDM high up on its agenda and regards municipalities as the key implementers of WDM and water conservation programmes.

Looking into the Future - Perceived Research Gaps to Enhance Adaptation to Climate Change in South Africa’s Water Related Sector

Climate change will affect not only water *supply*, but also the *demand* for water, with projected changes to availability, timing and assurance of water supply affecting all water related user sectors, e.g. agriculture, hydropower, urban areas, water for sanitation, the poor and the environment. Changes will also affect the broader dynamics of the economy, including water scarcity, water related disasters, spatial patterns of development, structural changes in economies. Furthermore, because impacts are in the future, many uncertainties prevail, and some responses are particularly long-lived, it is timely now to focus on strengthening management, information and water infrastructure.

Issues identified as gaps, and for which confidence also has to be established in climate change studies, are discussed below, bearing in mind that in the context of climate change, the impacts are on water allocation, demand, use and quality. In regard to terminology used,

- second order changes are considered to include those related to irrigation demands, effects of available water on different land uses and land uses on water, while
- third order changes would embrace those related, *inter alia*, to supply and demand, water quality in its various manifestations, terrestrial / aquatic ecosystems and the goods and services they render, impacts on infrastructure, integrated catchment assessments, transboundary waters and vulnerability of poorer communities.

1. Perceived Gaps in Second Order Changes

These include

- Changes in irrigation water demand and practices (e.g. more detail on magnitudes of water demand, effects of different modes of scheduling on water use efficiency, more detail on environmental consequences of irrigation through losses to percolation beyond the root zone and surface runoff, and confidence in results);
- Effects of changed land use patterns on water availability and production (e.g. of plantation forestry, land degradation, land reform, land use management such as conservation and tillage practices, and removal of alien invasive species in both riparian and upslope locations);
- Effects of changed water availability on land use patterns (e.g. shifts in cropping patterns and yields in regard to food security and biofuels, and effects of the intensification or extensification of land uses).

2. Perceived Gaps in Third Order Changes

These include

- Changes in water demand and supply (e.g. in urban areas with respect to municipal, formal and informal residential and industrial supply and demand, as well as in rural areas in regard to settlements, tourism, recreational or agricultural supply and demand);
- Changes in water rights and allocation mechanisms in the face of not only the National Water Act of 1998), but also the realities of climate change, biofuel production and national as well as local food security;
- Changes in dynamics of water quality responses and their consequences in regard to physical water quality (i.e. more process understanding on sediment yield), to chemical water quality (e.g. on eutrophication through nitrate leaching and phosphorous wash-off) and to biological water quality (e.g. on faecal coliform such as *E. coli*), in addition to changes in water temperature (in light of aquatic habitat changes and animal / human health), with consequences on purification costs and consequences on human health (through water-borne diseases, water-washed diseases, water-based diseases, water-related diseases and water-dispersed diseases);
- Impacts on terrestrial and aquatic ecosystems, including changes in water related ecosystems goods and services, environmental integrity, changing baselines against which to assess

impacts, wetlands responses and functioning, estuary responses and functioning, impacts of increased water temperatures, or changes to Indicators of Hydrological Alteration);

- A re-think on water storage, including natural, man-made and virtual storage;
- Impacts on infrastructure in regard to hydraulic design, dam safety, and infrastructure maintenance;
- Integrated Catchment Studies, with installed modelling systems (IMSs) particularly on stressed and vulnerable catchments;
- Potential conflicts over shared rivers (i.e. rivers as international boundaries, and rivers discharging to, or from, South Africa's neighbouring countries, with possible changes needed to international agreements;
- Vulnerability of the poor in urban areas (e.g. living in flood prone riparian areas), in rural areas (re. availability of potable water), and including climate forced in-migration from other countries to South Africa, or climate-driven rural to urban migration, or Water Poverty Index studies); and
- A focus on mountainous areas, which are South Africa's runoff producing areas ('water towers'), are sensitive / vulnerable to climate change, but have under-represented hydro-climatic networks, and poorly understood future changes in vertical gradients affecting precipitation and runoff.

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