LONG TERM ADAPTATION SCENARIOS

TOGETHER DEVELOPING ADAPTATION RESPONSES FOR FUTURE CLIMATES

DISASTER RISK REDUCTION AND MANAGEMENT

environmental affairs
Department:
Environmental Affairs
REPUBLIC OF SOUTH AFRICA

giz

On behalf of:
Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety
of the Federal Republic of Germany

SANBI
Biodiversity for Life

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LONG-TERM ADAPTATION SCENARIOS
FLAGSHIP RESEARCH PROGRAMME (LTAS)

CLIMATE CHANGE ADAPTATION PERSPECTIVES FOR DISASTER RISK REDUCTION AND MANAGEMENT IN SOUTH AFRICA

PROVISIONAL MODELLING OF DROUGHT, FLOOD AND SEA LEVEL RISE IMPACTS AND A DESCRIPTION OF ADAPTATION RESPONSES

LTAS Phase II, Technical Report (no. 3 of 7)

The project is part of the International Climate Initiative (ICI), which is supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

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LIST OF ABBREVIATIONS

ACRU	Agricultural Catchments Research Unit Model
AEP	annual exceedance probability
AMF	annual maximum flood
AMFP	annual maximum flow peak
CFD	cumulative frequency distributions
CMIP3	Coupled Model Intercomparison Project3
CORMIX	Cornell Mixing Zone Model
CSAG	Climate Systems Analysis Group (University of Cape Town)
CSIR CCAM	Council for Scientific and Industrial Research Conformal-cubic Atmospheric Model
CSIR	Centre for Scientific and Industrial Research
DEA	Department of Environmental Affairs
DEM	digital elevation model
DRRM	disaster risk reduction and management
DWA	Department of Water Affairs
EMC	environmental management class
EWR	ecological water requirement
GCM	global circulation model
GEV	general extreme value (distribution)
GF0	Geophysical Fluid Dynamics Laboratory Coupled Model, version 2.0 (GFDL-CM2.0)
GFI	Geophysical Fluid Dynamics Laboratory Coupled Model version 2.1 (GFDL-CM2.1)
GIS	geographic information system
GIZ	Gesellschaft für Internationale Zusammenarbeit
GSM	Max Planck Institute for Meteorology ECHAM5/MPI-Ocean coupled climate model
HAT	highest astronomical tide
HFD	hybrid frequency distribution
IAP	invasive alien plants
IGSM	integrated global systems model
IPCC	Intergovernmental Panel on Climate Change
IPSS	infrastructure planning system support
JPV	joint-peak-volume
LIS	Level I Stabilization
LM	local municipality

LN	log-normal (distribution)
LTAS	Long Term Adaptation Scenarios
MAMF	mean annual maximum flood
MAP	mean annual precipitation
MAR	mean annual runoff
MIR	Model for Interdisciplinary Research on Climate, medium resolution (MIROC3.2-medres)
MIT IGSM	Massachusetts Institute of Technology Integrated Global System Model
MPI	Max Planck Institute for Meteorology ECHAM5/MPI-Ocean coupled climate model
MSL	mean sea level
NCCRP	National Climate Change Response White Paper
NGI	national geospatial information
NWRS	National Water Resources Strategy
PFA	probabilistic flood analysis
RCP	relative concentration pathways
RI	rainfall intensity
RI	recurrence interval
RSA	Republic of South Africa
SANBI	South African National Biodiversity Institute
SANCOLD	South African National Committee on Large Dams
SANRAL	South African National Roads Agency Limited
SFR	stream flow reduction
UCE	Unconstrained Emissions
UKM	United Kingdom Met Office, Hadley Centre coupled model, version 3 (UKMO-HadCM3)
WCWSS	Western Cape water supply system
WMA	water management area
WR2005	Water Resources 2005
WR90	Water Resources 1990
WRC	Water Research Commission
WRYM	Water Resources Yield Model
WSAM	Water Situation Assessment Model
WSUD	water sensitive urban design

ACKNOWLEDGEMENTS

The Long-Term Adaptation Flagship Research Programme (LTAS) responds to the South African National Climate Change Response White Paper by undertaking climate change adaptation research and scenario planning for South Africa and the Southern African sub-region. The Department of Environmental Affairs (DEA) is leading the process in collaboration with technical research partner the South African National Biodiversity Institute (SANBI) as well as technical and financial assistance from the Gesellschaft für Internationale Zusammenarbeit (GIZ).

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REPORT OVERVIEW

This report provides initial quantitative estimates of risks related to extreme events based on a provisional model of potential impacts under a range of possible climate futures to inform adaptation scenarios for the disaster risk reduction and management (DRRM) sector of South Africa including droughts, floods, sediment and sea level rise that complements other LTAS reports. A mixture of empirical and biophysical modelling techniques have been employed to give a first indication of potential risks associated with floods, droughts, sediment loads and sea level rise during the course of this century under a selection of available climate models.

Section 1 gives a brief background and introduction to the study.

Section 2 presents an overview of the general methodologies applied in this study including a brief discussion of the climate scenarios used (2.1), and the approach to provisional modelling of these climate change impacts on droughts (2.2), floods (2.3), sediment loads (2.4) and sea level rise (2.5).

The results are then presented in **Section 3** with respect to the potential impacts of relevance for disaster risk in South Africa. The impacts on the frequency, severity and duration of droughts are discussed in Section 3.1 including meteorological, hydrological, agricultural, and water supply droughts. Spatial and temporal impacts of climate change on flood magnitudes are discussed in Section 3.2. These results are also interpreted in terms of the potential increase in flooding risks for key infrastructure across the country including bridges, dams and power transmission line river crossings. The potential impacts of climate change in terms of total sediment yields are discussed in Section 3.4 and interpreted in terms of the potential impact on reduced storage capacity of dams. The results of the analysis of areas at risk from future sea level rise and the potential economic impacts in terms of municipal infrastructure, private real estate and tourism are described in Section 3.5.

A brief discussion of potential adaptation options for droughts, floods, sediment and sea level rise is given in **Section 4**. This includes a short summary of some cross-cutting and "no regrets" options.

Recommendations for further research, the need for more regional downscaling, issue specific studies, and the refinement and modelling of specific adaptation options are given in **Section 5**.

Finally, **Section 6** presents some general conclusions and recommendations for the way forward.

EXECUTIVE SUMMARY

The possibility of increased disaster risk is considered to be one of the most concerning and potentially costly impacts of future climate change in South Africa and globally. Understanding these risks and identifying key areas of concern is critical for developing suitable and sustainable adaptation policies and scenarios. This study provides initial quantitative estimates of risks related to extreme events based on provisional modelling of potential impacts including droughts, floods, sediment loads and sea level rise under a range of possible climate futures. It aims to inform adaptation scenarios for South Africa's disaster risk reduction and management (DRRM) sector and complement other studies in the LTAS programme.

The study employs a mixture of empirical and biophysical modelling techniques to give a first indication of potential risks associated with floods, droughts, sediment loads and sea level rise during the course of this century under a selection of available climate models. While it provides a general overview of the potential risk, a detailed analysis of the specific risks associated with climate change impacts on disasters and in specific areas of the country requires finer scale modelling and additional research and analysis of potential impacts from a wider range of climate models. Some recommendations for further work required are given based on the results of this study.

A critical aspect of this study was to link changes in specific hazards, for example floods, droughts and sediment loads, to specific infrastructure such as roads, dams, power lines and bridges. These are directly relevant to the DRRM community and are also relevant in terms of consideration for future design standards.

A consistent message from the analysis of drought-related risks over the medium and long term indicates increased water supply limitations in the Western Cape and potential for increased availability of water resources to Gauteng and the Vaal system. In general the results suggest that the current well-developed and integrated water supply system in South Africa provides resilience to a wide range of climate variability and climate change uncertainty. However, a more detailed regional analysis is required to assess drought risks at a finer spatial scale, particularly focusing on the vulnerable stand-alone systems where the potential for increased integration and diversification of resources should be investigated as a potential adaptation option. The risks of extreme drought due to increased natural climate variability, such as shorter El Niño cycles also needs to be investigated further.

Analysis of future flood risk shows consistent increases across most parts of the country, but particularly in KwaZulu-Natal, the Eastern Cape, Limpopo, and the southern Cape. However, the regional distribution of risks is not consistent between various model projections. Linking the potential increased flooding risk with the location of current key infrastructure shows the potential for "high" or "very high" impacts on the current flood design standards for more than 30% of bridges (road and rail), 19% of dams and 29% of ESKOM transmission line river crossings across the country by mid-century.

Analysis of the potential climate change impacts on increased sediment yields shows only limited impact as a result of increasing flood frequencies, with future changes in land cover and land use potentially of greater significance. Further research is required to investigate the direct impact of climate change on land cover and the sensitivity to erosion and soil loss across the country. While the overall impact on the total sediment yield from a selection of 95 dam catchments across the country may have been small, there were significant impacts for some individual dams in certain parts of the country. Adaptation responses using effective land management and ecosystem-based approaches are therefore indicated as having high potential effectiveness for reducing sediment impacts and increased flood risks.

Analysis of the potential impacts of sea-level rise showed that on a national scale the potential economic impacts are likely to be relatively small given that South Africa does not have large areas of low-lying land or developments on large deltas, but that the potential impacts at the local scale could be quite significant, particularly for coastal metropolitan areas such as Cape Town, Durban and Port Elizabeth. Of particular concern is the potential impact on the coastal tourism sector. Ports are considered to be less vulnerable as they would be relatively easy to upgrade, although future research should focus on small harbours and coastal communities with more limited resources for adaptation.

The demarcation and enforcement of coastal set-back lines that take into consideration potential for increased sea level rise and local storm surges are considered to be the most appropriate adaptation option for coastal communities. Similarly enforcement of zoning regulations and exclusion of development within current and future flood prone areas is considered to be the most appropriate no regrets adaptation option for future increases in flood risk. Where necessary, more detailed analysis is required for specific areas of concern or critical municipal and national infrastructure.

Although the specific impacts of individual adaptation options were not modelled in this study, the results were used to provide recommendations for suitable options. These included a number of adaptation options that would be applicable to multiple aspects of disaster risk reduction including droughts, floods and sea level rise that should be considered as no regrets options as they would also be applicable under multiple climate futures (both wetting and drying) and would increase resilience to multiple threats including increased flood risk or erosion and sediment yields. They also tended to represent best practice options that should be pursued irrespective of the additional risk associated with future climate change and could be implemented at national level and generally across the country. More detailed regional analysis and modelling is required to investigate specific adaptation options for individual locations or key areas of concern for infrastructure assets as part of future research.

1. INTRODUCTION

1.1 Modelling in support of disaster risk reduction in South Africa

The possibility of increased disaster risk is considered to be one of the most concerning and potentially costly impacts of future climate change in South Africa and globally. Understanding these risks and identifying key areas of concern is critical for developing suitable and sustainable adaptation policies and scenarios. This study provides initial quantitative estimates of risks related to extreme events. These are based on provisional modelling of potential impacts including droughts, floods, sediment loads and sea level rise under a range of possible climate futures. It aims to inform adaptation scenarios for the disaster risk reduction and management (DRRM) sector of South Africa under a range of possible climate futures and to complement other studies in the LTAS programme.

Given the limited time available for the study, a mixture of empirical and biophysical modelling techniques were employed to give a first indication of potential risks associated with flood, droughts, sediment loads and sea level rise during the course of the century.

Recommendations are also made for further work required for the analysis of existing information as well as additional modelling and analysis of information from the most recent regional climate models.

1.2. Linking potential impacts to specific infrastructure

A critical aspect of this study was to link changes in specific hazards, such as floods, droughts and sediment loads, to specific infrastructure such as roads, dams, power transmission lines and bridges. These are directly relevant to the DRRM community and are also relevant in terms of consideration for future design standards.

This study, however, only represents a high-level overview of potential impacts. Further studies are required to focus in on particular areas of risk or specific infrastructure assets that require more detailed modelling of both hydrological and hydraulic aspects relating to potential increasing flood risk. In addition this study has considered the potential impacts of only a limited number of climate models. Consideration of the potential impacts under additional climate models is required as well as a more generic approach to assessing the sensitivity of specific infrastructure assets to future uncertainty.

1.3. Adaptation options and recommendations

The modelling of potential increases in drought, floods, sediment and sea level rise risk in South Africa provides insight into potential adaptation options and recommendations for policy, future downscaling and more detailed regional assessments in particular areas of concern. Many of the recommended adaptation options are considered to be no regrets options as they are consistent with best practice and would be applicable under any future climate scenario. These include improved monitoring, long term, risk-based integrated planning, enhancement of natural systems, decentralisation and diversification of options and general social development and flexible, responsive institutions and systems.

As with any model, modelling is simply a tool to assist in planning for the future. A model will never be able to accurately predict the future and at best remains a simplification of the real world situation and the complexity of natural and human systems. The insights provided by this study must be considered in the context of other initiatives in the LTAS process to initiate robust adaptation options, and planning to improve resilience and potentially mitigate some of the more negative impacts of climate change.

2. METHODOLOGY

2.1. Climate futures for South Africa

Two sets of climate change information were used in this study that represent a range of potential impacts that are consistent with the four general climate futures for six different hydro-climatic regions of South Africa derived through the LTAS process and summarised in Figure 1.

The two future climate change data sets used in this study were:

- A hybrid frequency distribution (HFD) of multiple climate models derived from the Massachusetts Institute of Technology Integrated Global System Model (MIT IGSM).
- Five dynamically downscaled regional climate models derived from the Council for Scientific and Industrial Research Conformal-cubic Atmospheric Model (CSIR CCAM) model.

2.1.1. *Hybrid frequency distribution of climate change impacts*

TThe first set of climate change information results from consideration of a HFD of the range of possible climate futures for the globe (Schlosser et al. 2012). These HFDs are generated through the numerical hybridisation of zonal trends derived from the MIT IGSM (Sokolov et al. 2009) with a set of pattern kernels of regional climate change from the global circulation models (GCMs) of the International Panel on Climate Change (IPCC) 4th Assessment Report (AR4).

The IGSM ensembles produce a range of climate outcomes under an unconstrained emissions (UCE) pathway (Sokolov et al. 2009) as well as a range of global climate policies (Webster et al. 2011). This study presents results for the UCE case and a best case greenhouse gas stabilisation scenario in which an equivalent CO_2 concentration of ~480 ppm is achieved by the end of the century – referred to as the "Level 1 stabilization" (L1S) policy in Webster et al. (2011).

This hybridisation approach is based on 400 realisations of the IGSM model and was applied to 17 of the available GCMs that were found to have a constant latitudinal zonal pattern. The result is a total of 6 800 possible climate

Scenario	Limpopo/ Olifants/Inkomati	Pongola-Umzimkulu	Vaal	Orange	Mzimvubu-Tsitsikamma	Breede-Gouritz/ Berg
1: warmer/ wetter	↑ spring and summer	↑ spring	↑ spring and summer	↑ in all seasons	↑ in all seasons	↓ autumn, ↑ winter and spring
2: warmer/ drier	↓ summer, spring and autumn	↓ spring and strongly ↓ summer and autumn	↓ summer and spring and strongly ↓ autumn	↓ summer, autumn and spring	↓ in all seasons, strongly ↓ summer and autumn	↓ in all seasons, strongly ↓ in the west
3: hotter/ wetter	Strongly ↑ spring and summer	Strongly ↑ spring	↑ spring and summer	↑ in all seasons	Strongly ↑ in all seasons	↓ autumn, ↑ winter and spring
4: hotter/ drier	Strongly ↓ summer, spring and autumn	↓ spring and strongly ↓ summer and autumn	↓ summer and spring and strongly ↓ autumn	↓ summer, autumn and spring	↓ all seasons, strongly ↓ in summer and autumn	↓ all seasons, strongly ↓ in the west

Figure 1: Summary of possible climate future derived for six hydro-climatic zones in South Africa as part of Phase 1 of the Long Term Adaptation Scenarios (LTAS) programme.

futures. The 6 800 scenarios were reduced to a more manageable set of 367 climate futures for each of the two emission scenarios using a process of quadrature thinning which maintains the statistical structure of the original full set of scenarios (Arndt et al. 2011).

The resulting HFDs of precipitation and temperature impacts were used to derive a time series of monthly catchment runoff for all quaternary catchments in South Africa for the period 2000 to 2050. This information was used to inform the risks of reduced runoff at catchment scale and in terms of the ability to supply water to the system supplying key sectors in South Africa as part of a parallel study to investigate the potential economic impacts of climate change on the national economy (Cullis et al. 2014; DEA 2014).

This information was also used to make initial estimates of the potential impacts of reduced precipitation on dry-land crop yields and to inform a semi-empirical analysis of potential impacts on flood frequency based on the relationship between mean annual runoff (MAR) and annual flood maxima derived from historical flood peak data in the joint peak-volume (JPV) flood methodology (Görgens 2007).

2.1.2. Dynamically downscaled regional climate models

The second set of climate information used was derived from a time series of daily precipitation and temperature information obtained from five dynamically downscaled regional climate models produced by the CSIR for the LTAS programme (Engelbrecht et al. 2011). The five models considered were all derived from the Coupled Model Intercomparison Project 3 (CMIP3) suite of global climate models and are representative of the A2 Special Report on Emissions Scenarios (SRES) (IPCC 2000) derived from the following individual GCM models:

- Geophysical Fluid Dynamics Laboratory Coupled Model, version 2.0 (GFDL-CM2.0) (GF0)
- Geophysical Fluid Dynamics Laboratory Coupled Model version 2.1 (GFDL-CM2.1) (GF1)
- Max Planck Institute for Meteorology ECHAM5/MPI-Ocean coupled climate model (MPI)
- United Kingdom Met Office, Hadley Centre coupled model, version 3 (UKMO-HadCM3) (UKM)
- Model for Interdisciplinary Research on Climate, medium resolution (MIROC3.2-medres) (MIR)

As these scenarios are all based on the A2 family of emissions scenarios characterised by regionally oriented economic development in the IPCC's Special Report on Emissions Scenarios (IPCC 2000), they are therefore representative of high global carbon emissions and therefore result in "hotter" climate futures as defined by the four generalised LTAS climate futures for South Africa (DEA 2013). In general the CSIR regional downscaled climate models are considered to be more representative of a drying future for South Africa; however, as the results of this study indicate that very much depends on what time horizon you are considering and which spatial location you are interested in. Although generally considered to be dryer, all the models show some areas of drying and some areas of increased wetting across the country, although these locations are often vary for the different models.

The time series of daily precipitation and temperature information obtained from these models was then used to generate a time series of average daily rainfall and catchment runoff for all quinary catchments in South Africa from 1962 to 2100 using the Agricultural Catchments Research Unit (ACRU) model, as described in Appendix A. This information was used to investigate the potential changes in annual flood frequencies under the different climate models as well as the number and severity of drought years to the end of the century.

2.2. Modelling potential drought impacts

Unlike floods, which are a short term extreme event that can happen almost at any time and with very little warning, droughts are a longer term hazard that may take months or even years to manifest. Drought is also a relative concept with humans and ecological systems adapted to natural variability in rainfall and water availability. The causes of drought are many and include both natural and anthropogenic factors.

Wilhite and Glantz (1985) define four general types of drought:

- **Meteorological drought** is defined usually on the basis of the degree of dryness, normally in terms of reduced precipitation, in comparison to some "normal" or long term average amount.
- **Hydrological drought** is associated with the effects of periods of precipitation (including snowfall) shortfalls on surface or subsurface water supply (namely, streamflow, reservoir and lake levels and groundwater) also relative to the long term expected conditions.
- **Agricultural drought** links various characteristics of meteorological (or hydrological) drought to agricultural impacts, focusing on precipitation shortages during critical periods specific to particular crop types, differences between actual and potential evapotranspiration, soil water deficits, reduced groundwater or reservoir levels, and so forth.
- **Socioeconomic or water supply drought** associates the supply and demand of some economic good (including water) with elements of meteorological, hydrological, and agricultural drought. It differs from the aforementioned types of drought because its occurrence depends on the time and space processes of supply and demand to identify or classify droughts.

Each type of drought has different characteristics and the magnitude and severity of the drought impact are also important as well as the relative recurrence interval (RI). In this study we undertake some initial analysis of the likely spatial and temporal variability in flood frequency and severity to the end of 2100.

2.2.1. Meteorological and hydrological drought

Potential changes in meteorological (precipitation) and hydrological (streamflow) droughts were modelled using both the HFD climate scenarios and the five regionally downscaled climate models.

The monthly time series for the HFD scenarios were used to model the relative change in the mean annual precipitation and runoff at secondary catchment scale for the period 2040 to 2050 under both UCE and LIS climate scenarios relative to the base scenario for the period 1990 to 2000.

The daily time series for the five regional climate change models was used to examine change in the number of years of total annual rainfall below critical thresholds for mild, moderate and severe drought, for the period 1990 to 2100 relative to the historical period (1962 to 1990).

For this analysis the daily time series values were aggregated up to annual precipitation and runoff values for each quinary catchment. A mild drought year was defined as a year with 33% of the average annual precipitation or runoff for the historical period 1962 to 1990. A moderate drought was defined as a year with 20% of the average for the base period, and a severe drought year was defined as a year with 10% of the average annual precipitation or runoff for the base period. These results were used to investigate the potential changes in both the number of drought years under the five different climate models as well as the duration of drought events and the spatial and temporal variability to 2100.

Separately, changes in the criteria for defining a drought event were also investigated using a thirty year moving window on the annual precipitation and runoff to determine the threshold values used to determine a mild (33%), moderate (20%) and severe (10%) drought over time.

2.2.2. *Agricultural drought*

Potential impacts on agricultural drought were not investigated in detail in this study although potential impacts on dry-land crop yields were calculated using the HFD climate scenarios based on empirical relationships between water supply and annual crop yields. These impacts were determined for the LTAS economic impacts study (Cullis et al. 2014; DEA. 2014) and are summarised as an initial indication of the impact of reduced precipitation on national dry-land crop yields for the period 2040 to 2050.

2.2.3. *Water supply (social) drought*

Potential impacts of the HFD climate scenarios were modelled in terms of the likely changes in the average water supply to key sectors of urban, irrigation and bulk industry for all water management areas in South Africa. The potential impact on hydropower generation was modelled using a monthly simulation model for South Africa and the change in the average annual water supply over a ten year period was assessed for the period 2040 to 2050. These models were used in a parallel study for the LTAS to investigate the potential impacts of climate change on the national economy (Cullis et al. 2014; DEA 2014). Details of the models, including key assumptions, are described in the report for this study.

Changes in catchment runoff were modelled using the Pitman rainfall runoff model (Pitman 1973) and changes in the average water supply were modelled using the Water Resources Yield Model (WRYM) The WRYM was configured for the entire country on a secondary catchment scale (including catchments within Lesotho and Swaziland) based on a generic modelling unit shown in Figure 2.

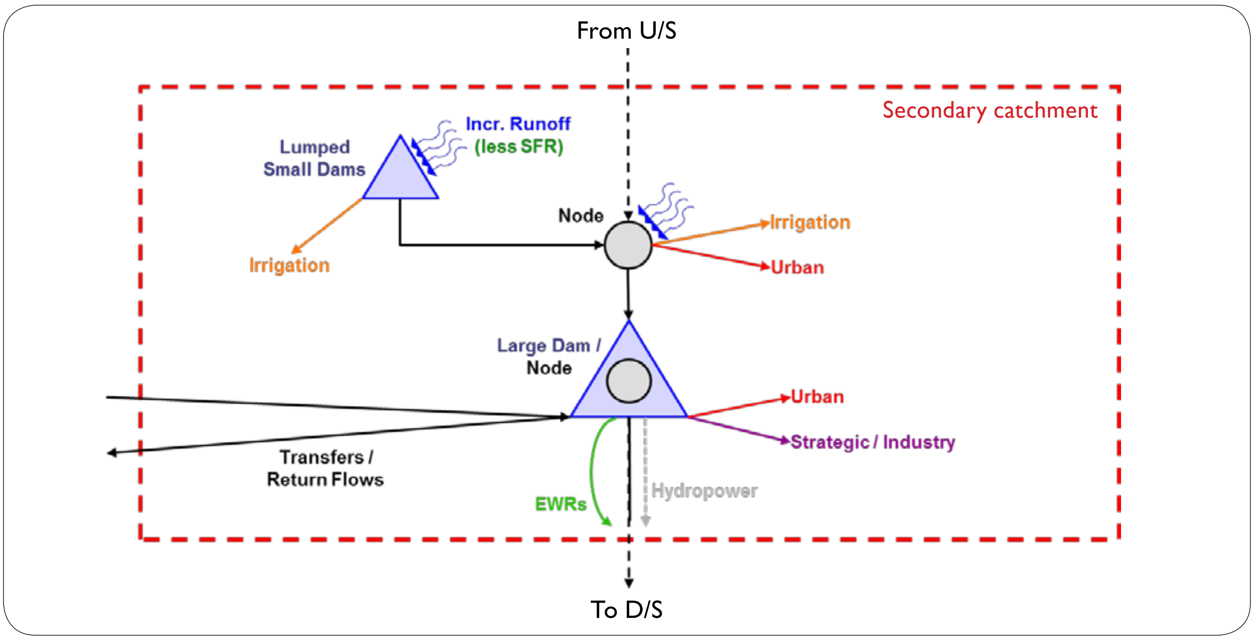


Figure 2: Generic modelling unit used for configuring the WRYM (Drawn by authors)

Each modelling unit includes the following basic elements:

- Runoff from the catchment in question.
- Precipitation on and evaporation from the exposed surface area of dams.
- Large dams which, for the purposes of this study, were defined as those with a storage capacity greater than 50 million m^3/a.
- All other dams which were lumped into a single representative dam (or "dummy dam"), defined with physical characteristics such that its modelled impact would be comparable to that of the combined effect of the individual dams that it represents.
- Transfers into and out of the catchment.
- Projected water requirements of all water users located within the catchment, including (i) irrigation; (ii) urban (including light industry); and (iii) strategic, heavy industry and mining water requirements which, for the purposes of this study, were combined and referred to as "bulk" water users. Each water user type (such as irrigation) was modelled using a single WRYM element (abstraction channel), configured to represent the total requirement of all individual users of the user type in question.
- The impact on runoff of stream flow reductions (SFRs) including commercial forestry and invasive alien plans (IAPs).
- Ecological water requirements (EWRs) located at the outlet of each secondary catchment.

Individual modelling units were configured at secondary catchment scale and interconnected for the entire country resulting in a high level representative national system model as shown in Figure 3.

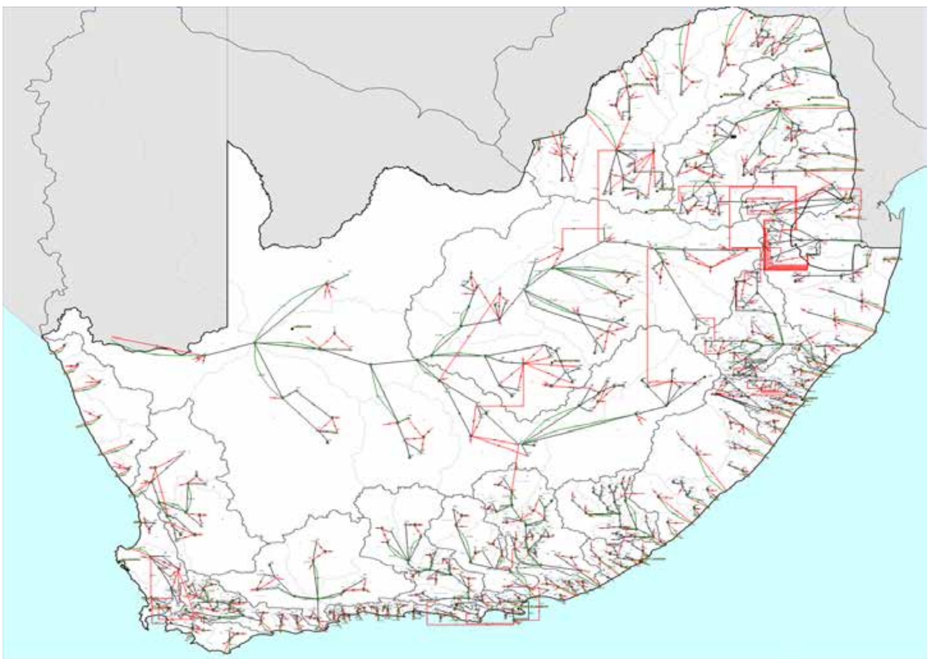


Figure 3: Schematic diagram of the national WRYM system model (Drawn by authors)

In its current format the national configuration of the WRYM consists of approximately:

- 148 secondary catchment modelling units.
- 80 large dams.
- 190 dummy dams.
- 300 water requirement abstraction channels.
- 150 EWRs.
- 1 000 system channel links (rivers, inter-basin transfers, and other system components).

Each secondary catchment was configured at a similar level of detail, generally with a single large dam and one dummy dam and three individual demand channels, although in the case of certain catchments further refinements were required. This was generally to account for the presence of multiple large dams, the inter-connectivity between system elements and the physical location of large water users which may affect their access to specific water resources within the catchment. A typical example is the Mooi-Mgeni River System as shown in Figure 4.

It is important to note that given the level of aggregation required for this study it is not possible to correctly capture the detailed operations of individual systems. Although the national configuration of the WRYM is highly detailed, as shown in Figure 4, it is still a gross simplification of the true complexity of the water resources systems in South Africa. Hence outputs from the model will most likely differ from similar outputs obtained from more detailed individual system models at a local scale, particularly in terms of local system operating rules and allocation priorities.

The objective of this study was, however, to provide a first-order picture of the potential impacts of climate change scenarios at water management area (WMA) and at national scale relative to a base scenario without climate change impacts, rather than to achieve accuracy in absolute terms for water resources planning purposes.

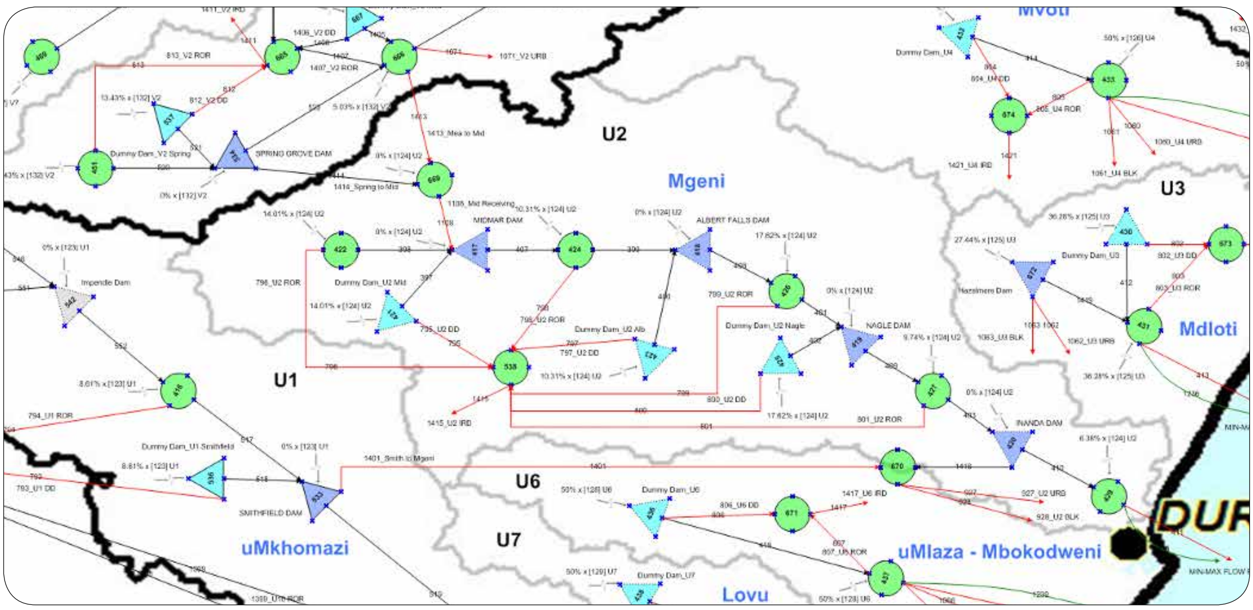


Figure 4: Details of a portion of the national WRYM system model (Mooi-Mgeni River System) (Drawn by authors)

The results from the model configured for this study are therefore considered to be of adequate accuracy for the purposes of this study and could potentially be used for other high level strategic planning purposes. It is, however, recommended that more detailed modelling of the potential impacts on individual systems be undertaken as part of future research using the results from this study as a guide, particularly in the large systems such as the Vaal and the Western Cape systems.

2.3. Modelling potential flooding impacts

For this stage of the study the investigation into the potential impacts of climate change on floods was restricted to flood peaks, therefore we omitted attention to impacts on flood volumes or flood hydrographs. Furthermore, given the study's focus on potential infrastructure risk due to climate change, our flood impact investigation focused on the typical recurrence interval (RI) flood peaks that are used in various infrastructure design methodologies.

The approaches employed to examine potential impacts of climate change on floods varied according to considerations of catchment scale, as well as with recognition of two different available sources of information on potential climate change-related changes (hereafter called deltas) to runoff across southern Africa. The two sources referred to here are the climate change-related runoff deltas generated for a range of climate futures and various emission scenarios through the following approaches:

(i) the HFD approach, based on the Pitman monthly model, outlined in Section 2.2.3 of this report

(ii) the ACRU daily modelling approach, detailed in Appendix B of this report.

The scale or area of a catchment for which a design flood peak is to be calculated determines what methodology would be appropriate. In this study secondary and quaternary catchments were regarded as representing the medium to large catchment scale, while quinary catchments represented the small catchment scale, respectively. (It should be noted that median quinary, quaternary and secondary catchment sizes are about 130 km^2, 430 km^2 and 3 320 km^2 respectively.)

2.3.1. *Joint peak-volume methodology using HFD climate futuress*

The joint peak-volume (JPV) design flood methodology, detailed in Görgens (2007), comprises regionalised non-dimensional probabilistic flood peak determination equations for South Africa that need to be given dimension by applying the mean annual maximum flood peak (MAMF) at the site of interest. The JPV methodology also presents regionalised equations for estimating the mean annual maximum flood peak at any site of interest, based on physical upstream catchment descriptors: area, slope, naturalised mean annual runoff (MAR) and flood region. The form of these equations is as follows:

$$\text{MAMF } (m^3/s) = A + B.\ln(\text{Area}) + C.\text{Slope} + D.\ln(\text{MAR}) + E.\text{Flood Region Number}$$

Six regionalised equations were available – three each for the so-called K-Region and Veld Type approaches, respectively.

The MAR deltas at the exit points of all quaternary and secondary catchments for 367 HFD climate futures (by mid-century) were imported from the HFD study (Cullis et al 2014) and individually applied to the naturalised Pitman model MARs for corresponding catchments. The MAMFs at each of these sites were then calculated for all the climate futures by means of the aforementioned regionalised equations, using the catchment descriptors applicable for all quaternary and secondary catchments. This exercise was conducted for both the UCE and LIS emission scenarios. The calculated recurrence interval flood peaks under the JPV methodology are directly dependent on the MAMFs. Therefore, the RI floods at a site have identical deltas to the MAMF at that site.

Unfortunately, the value of the results of this exercise was marred by unavoidable peculiarities caused by the empirical nature of the aforementioned regionalised equations. The natural logarithm form of the MAR term in the equations causes flood peak deltas always to be smaller than the corresponding MAR deltas for delta values larger than zero and to be larger than the corresponding MAR deltas for the converse. As such apparently uniform biases of flood peak deltas with respect to their corresponding MAR deltas due to climate change are mere artefacts of the regionalised equations. Therefore we decided to abandon this particular set of analyses.

For the record, the results of the JPV exercise for secondary catchments are presented graphically in Appendix B. The marked (but artificial) differences in the spatial distributions of delta quantiles between the two "flood region" approaches are clearly evident. The apparent contraction of the range of the quantiles evident in the LIS scenario graphs merely reflects a similar contraction in the range of the corresponding MAR quantiles.

2.3.2. *The ACRU modelling approach using five regionally downscaled climate models*

In order to evaluate the dynamic nature of potential flood risks to infrastructure due to climate change during the course of the century, annual maximum daily flows (hereafter called "annual maximum floods") were extracted from the ACRU-simulated daily streamflow sequences described in Appendix A, representing the five climate futures and covering the hydrological years from October 1961 to September 2099. The flood values were determined at quinary, quaternary and secondary scales.

Given the focus of this study on dynamically-changing flood risks resulting from ongoing climate change, the probabilistic flood analyses (PFAs) were conducted on forward-rolling 30-year windows of annual maximum floods, shifting one year at a time. A window period of 30 years was seen as arguably the maximum sample size for a PFA to be tolerably free of significant non-stationarity effects due to climate change. Furthermore, in order to ameliorate disrupting effects on PFA statistical parameters of intermittent extreme outliers in specific windows, RI floods calculated from the forward-rolling window-based sequences had to be smoothed by a 10-year moving average.

As individual PFAs had to be conducted for about 8 000 quinary, quaternary and secondary catchments and for about 100 individual 30-year windows for each of the five climate futures, the choice of a suitable probability distribution for the RI flood analyses was dictated by the availability of software that would allow the PFA process to be fully automated. The SciPy package was deemed suitable for such automation. It offered two probability distributions that are generally used for PFAs in South Africa, namely the General Extreme Value (GEV) and the Log-Normal (LN) distribution.

The GEV-distribution was initially preferred for this study, because it was originally specifically developed to provide for a very wide range of skewness parameter values in annual maximum flood peak samples. However, the parameter-fitting sub-routines in the package were found to be highly unstable in the case of the GEV-distribution component and in many instances produced absurd RI flood values. The LN-distribution component, on the other hand, produced reasonable RI flood values for the vast majority of the 30-year rolling windows. Therefore, all the PFAs in this section of the study were based on the LN-distribution.

2.4. Modelling potential sedimentation impacts

The report Sediment yield prediction for South Africa: 2010 Edition (Msadala et al. 2010) includes a sediment-related database (for GIS applications) for all reservoirs for which the Department of Water Affairs (DWA) had done physical sediment surveys and for which secure estimates of their catchments' long-term sediment yield had been made (142 reservoirs in total). The report also presents empirical regionalised equations for the calculation of potential long-term sediment yield values for six homogeneous regions which cover about 65% of the land area of South Africa, Lesotho and Swaziland. The format of these six equations is as follows:

$$Qs = C.(Q10^{P1}).(S^{P2}).(R^{P3}).(A^{P4}).(E^{P5})$$

where *Qs* = sediment load (t/a); *C* = regression constant; *Q10* = 1:10 year RI flood (m^3/s); *S* = average river slope; *R* = river network density; *A* = effective catchment area; *E* = weighted erosion hazard class according to sub-catchment areas; *P1-5* = power values determined by regression.

The ten sediment yield regions defined for South Africa and the ten erosion hazard classes are shown in Figure 5 (Msadla et al. 2010). The empirical equations are not applicable in regions 3, 6, 9 and 10.

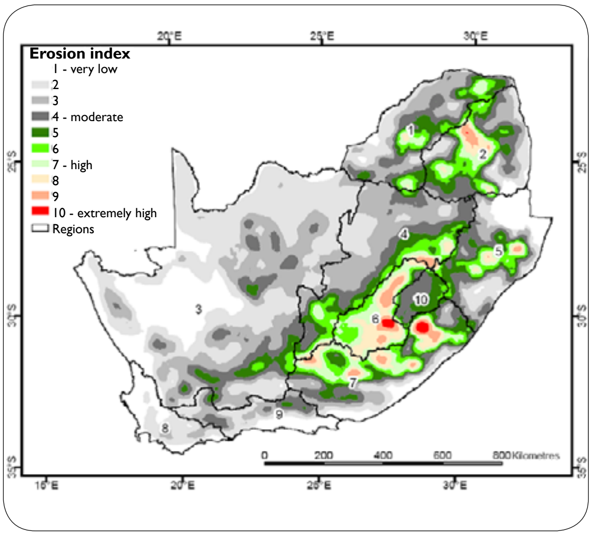


Figure 5: Sediment regions and erosion hazard classes for South Africa (Msadala et al (2010))

The Q10 term in these equations was the key for efficient estimation of changes to long-term sediment yields for the five different climate scenarios outlined earlier, under an assumption that the essence of the above equations will not change under climate change. The PFAs performed on the ACRU-simulated annual maximum floods (described in Section 2.2.3), provided Q10 values for 30-year moving windows for the five scenarios at quinary catchment scale for the whole country. The quinaries that contain the individual reservoirs specified in Msadala et al. (2010) were identified by means of GIS and the corresponding Q10 values were abstracted from the ACRU PFA outputs.

The dynamically-changing Q10s under the five scenarios were applied to the base sediment yield equation for each reservoir according to the following formulation:

$$Qs_{changed} = Qs_{base}.(Q10_{changed}/Q10_{base})^{P1}$$

The assumption here was that climate change would not significantly change the C, S, R, A and E terms in the sediment yield equation. Application of this equation produced dynamically-changing sediment yield values at the 142 reservoir sites for the five scenarios which were then further manipulated for calculation of reservoir sediment storage loss risk estimates. Only the dams located in sediment regions 1, 2, 4, 5, 7 and 8 could be modelled as the empirical equations are not applicable in the other regions.

2.5. Modelling potential sea-level rise impacts

2.5.1. Sea level rise trends in South Africa

South Africa has a topographically diverse and dynamic coastline and the influences of local tide, bathymetry, wave run-up and wave set-up currently dominate the influence of eustatic rise. This, however, is expected to change by the end of the 21st century when regionally determined mean sea-level rise will be the definitive influence.

Assessments of the rate of sea-level rise along the 2 798 kilometres of coastline rely on tide gauges (not satellite records), and data are often too patchy to make robust analysis of trends possible. In 2009, Mather et al. collated a wide set of tide gauge readings to report that sea-levels along South Africa's west coast were rising at 0.42 millimetres per annum, while those along the east coast of the country were rising at 3.55 millimetres per annum, and that levels along the south-western and southern Cape coast were rising at 1.57 millimetres per annum.

Earlier work by Searson & Brundrit (1995) relied on a decade of readings in Simon's Bay (west coast) to suggest that sea-levels in that region (south-west coast) were rising at 2 centimetres per decade. In both studies the duration of the time series was sub-optimal. The available data from both Mather et al. and Searson & Brundrit, however, suggest that sea-level rise along much of the South African coastline is similar to, or slightly above, the global mean.

2.5.2. *Regional studies of potential sea-level rise impacts*

At least six region specific studies of sea-level rise impact, some of them drawing on each other, have been conducted in South Africa. A review of these studies on potential impacts and adaptation options for future sea-level rise along the South Africa coastline is presented in Appendix C. The studies include:

- Developing country study by the Wold Bank (Dasgupta et al. 2007)
- The City of Cape Town (Brundrit & Cartwright 2012)
- Eden District Municipality (Umvoto 2010)
- KwaZulu Natal and eThekwini Municipality (Mather 2007; Mather et al. 2009, Palmer et al. 2011)
- Overberg Municipality (WC DEA&DP)
- Provisional economic impact assessment of sea level rise for National Treasury (Cullis et al. 2013).

These regional impact studies provide valuable insight into the potential impacts of sea level rise and further development of the methodologies used is required and extension of the studies to other areas along the South African coastline. A consistent approach to regional and local impact assessments is required as these are very difficult to model at national scale and ultimately require local solutions.

2.5.3. *First order modelling of potential national impacts of sea-level rise*

The objective of this study, however, was a first order estimate of the potential impact at national scale. The focus of the study is on identifying existing low-lying areas that may be at risk of different sea level rise scenarios and the associated potential economic impact. Given the limited scope of the study, the modelling is based primarily on available topographic information and does not account for local coastal conditions (namely, no detailed wave modelling or modelling of coastal dynamics). Local level studies incorporating these elements are required to provide a more detailed assessment of the potential impacts and adaptation options for sea level rise. These more detailed local and regional studies should be undertaken along similar lines to work done in Cape Town, the Western Cape and Kwazulu-Natal.

The potential impacts of sea-level rise were investigated based on a review of previous studies in South Africa, and on a provisional estimate of the amount of land currently located below specified elevation thresholds derived from available survey and topographic information for South Africa. Similar studies around the world have been based on the 90 m shuttle digital elevation model (DEM). The topography resulting from this model, is however of such a coarse resolution that it is only relevant in countries with very large low lying areas including deltas. In general South Africa does not have such large areas of low-lying land and so more detailed topographic information is required.

Considerable effort was required to obtain a realistic estimate of the topography of the coastline below 5.5 m and this was complicated by the fact that there is currently no available geographic information system (GIS) shapefile of either the zero elevation (namely at mean sea level (MSL)) or the current highest astronomical tide (HAT). For this study a coastline DEM for South Africa was derived from the National Geospatial Information (NGI) 5 m and 20 m contours, spot heights and break lines. ArcGIS models were developed using Model Builder and Python scripts to generate the various levels. The approximate areas below a specified elevation level were extracted using map algebra and converted into polygons. The areas were then intersected with local municipality (LM) boundaries and cadastral boundaries (erven and farm portions) to determine the total area at risk below each elevation level and the percentage of the total area for each local municipality. Summary reports where generated for each of the levels per local municipality broken down between erven and farm portions to identify the most at risk local municipalities and to inform the initial estimate of the economic risk for the country.

Estimates of the potential for future sea level rise as well as additional swash run up were made for a high (1 metre by 2100) and a low (0.5 metre by 2100) scenario compiled using general observations and a review of previous studies on potential sea level rise in South Africa and globally. These estimates were then intersected with the elevation model as well as cadastral information defining the boundaries of private properties (erven) and farms (farm portion) as well as local municipality areas to determine the total area impacted at each elevation threshold.

An economic model was then developed to make a first order estimate of the potential impacts of sea level rise on (1) private property, (2) municipal infrastructure, and (3) tourism. Full details of the background to existing studies on the potential impacts of sea level rise in South Africa and the assumptions and approach to determine the potential economic impacts are given in Appendix C.

It is important to note that no detailed coastal and wave modelling was undertaken for this study given the limited time available and the need for a simple national assessment of potential impacts. Nor was an attempt made to accurately identify individual properties or municipal infrastructure at risk given the resolution of the study. Modelling of local coastal impacts that takes into account the potential for future sea level rise is required to obtain more detailed information and risk assessments. This should be undertaken in some of the critical areas of risk identified in this initial overview study.

3. CLIMATE CHANGE IMPACTS OF RELEVANCE TO DRRM

3.1. Water Resource Units for South Africa

The results of the provisional modelling of potential climate change impacts for disaster risk reduction and described in the following sections with reference the currently defined water resources units of South Africa. These consist of the original nineteen water management areas (WMA) and twenty one primary catchments numbered from A to X as shown in Figure 6. Each primary catchment is further divided into a number of secondary tertiary and quaternary catchments. The catchments have also been grouped into six hydro-climatic regions as defined in the DWA Climate Change strategy.

3.2. Potential drought impacts

3.2.1. Impacts on occurrence and severity of drought events from regional downscaled models

The impact of future climate change on the frequency, duration and severity of drought events in terms of both annual rainfall and total annual cumulative streamflow for six representative catchments around South Africa based on the GF0 regionally downscaled climate model are given in Figure 6 and Figure 7 respectively. The severity

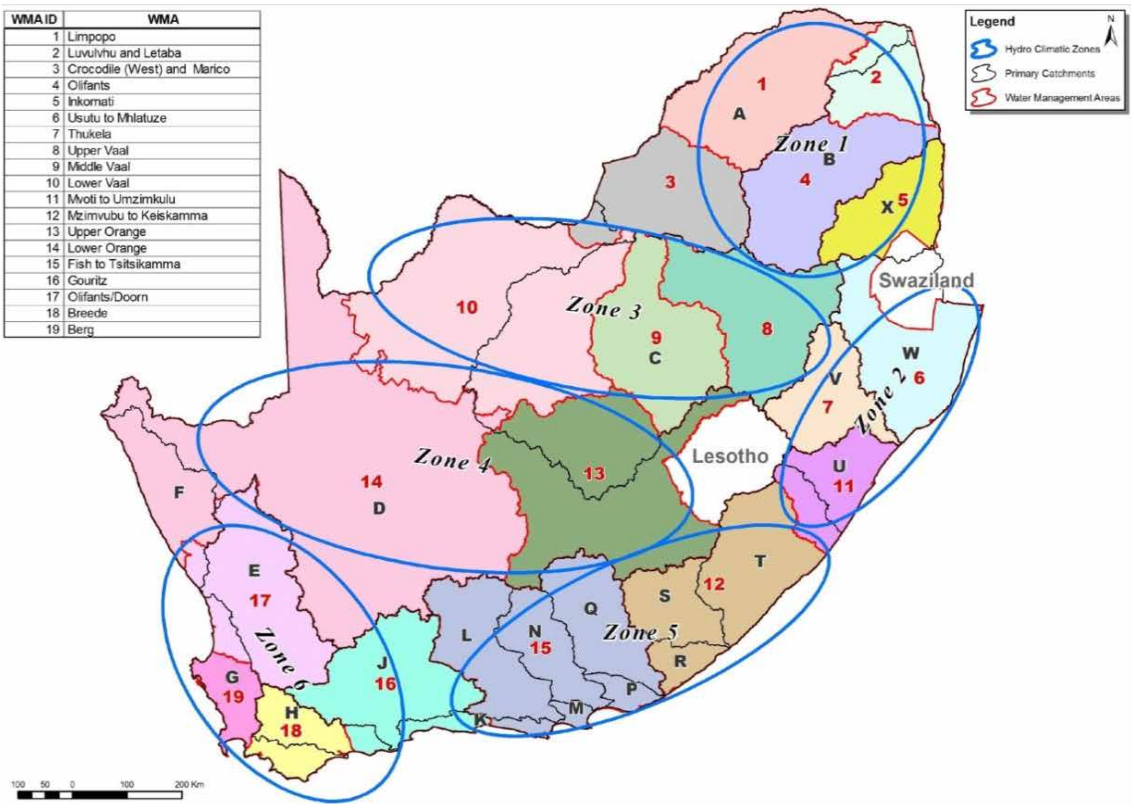
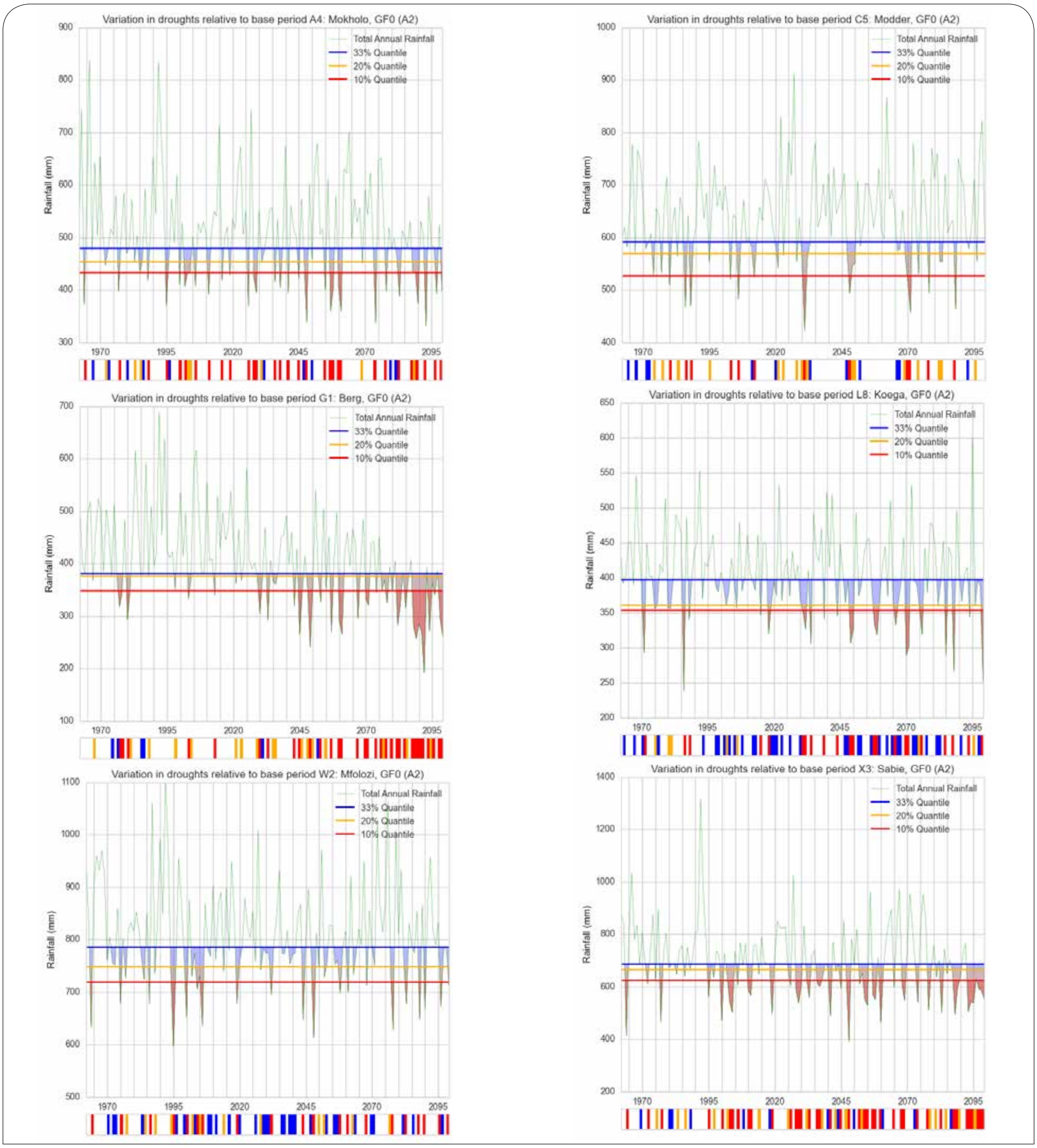


Figure 6: Map of South Africa showing the name and location of the nineteen water management areas, primary catchments and the grouping of catchments into six general hydro-climatic zones.


Variation in droughts relative to base period A4: Mokholo, GF0 (A2)
Variation in droughts relative to base period C5: Modder, GF0 (A2)
Variation in droughts relative to base period G1: Berg, GF0 (A2)
Variation in droughts relative to base period L8: Koega, GF0 (A2)
Variation in droughts relative to base period W2: Mfolozi, GF0 (A2)
Variation in droughts relative to base period X3: Sabie, GF0 (A2)
Total Annual Rainfall
33% Quantile
20% Quantile
10% Quantile
Rainfall (mm)
1970
1995
2020
2045
2070
2095

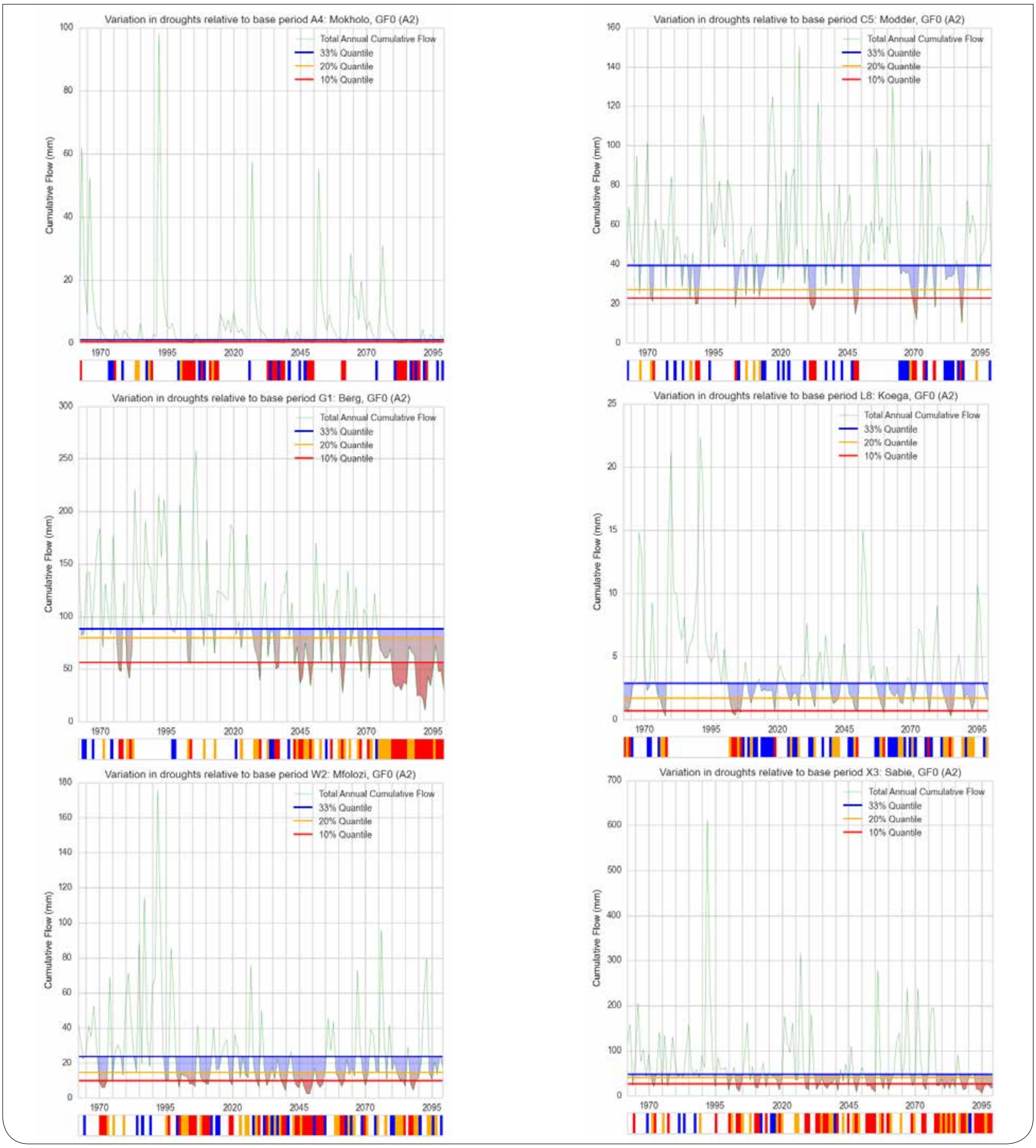


Figure 7: Change in the frequency, severity and duration of hydrological droughts for six representative catchments across South Africa based on the annual cumulative flow at the outlet for the period 1962 to 2100 using the dynamically downscaled GF0 model for the A2 SRES scenario.

of drought is determined based on the 33% (mild), 20% (moderate) and 10% (severe) quantiles of the mean annual precipitation (meteorological drought) or runoff (hydrological drought) for the period 1962 to 1990.

Similar figures for the four other climate models are included in Appendix D.

The results show a significant increase in the frequency and duration of droughts particularly in the Berg River catchment which is representative of the expected conditions in the winter rainfall regions of the country (namely the south-western Cape). The impact, however, appears to occur only in the second half of the century. While not as severe as the Berg River, the risk of increasing droughts in the Sabie River appears to occur earlier with an apparent increase in drought impacts starting as early as 2000.

The potential impact on hydrological (streamflow) droughts, shown in Figure 7, appears to be more acute than for meteorological (precipitation) droughts, shown in Figure 6, with hydrological drought effects appearing to last longer and to be less responsive to annual fluctuations. In the Berg River for example, there appears to be a continuous state of severe hydrological drought from about 2070, despite less severe impacts in terms of meteorological droughts during this period. In effect, while there might be a few wet years to break the meteorological drought, this does not translate into sufficient increases in runoff to break the hydrological drought periods that can last for many years.

This is particularly important when considering the different impacts. Crop yields can be severely affected by a single drought year, but can recover quickly if the drought is broken even by a single good year (or season). Water resources systems however respond much more slowly and it takes a number of years for the impacts of droughts to be felt. For example the critical period for a number of our large dams could be up to seven years, while for smaller dams it could be two or three years. These dams also take a number of years to recover from a drought period and so a single wet year does not necessarily break the drought, as it might for agricultural systems.

It is important to note that the definition of drought is a relative concept. Hence as rainfall and streamflow potentially decrease in the future, the definition of drought conditions should change accordingly, particularly if adaptation measures are put in place that respond to these changing conditions. An example of how the thresholds for drought definitions might change is given in Figure 8 for the Berg River. Similar figures for the other catchments and the different climate models are given in Appendix E.

This example highlights the importance of monitoring and early warning in order to prepare for changes in drought frequencies and to put in place measures necessary to cope with the changing climate.

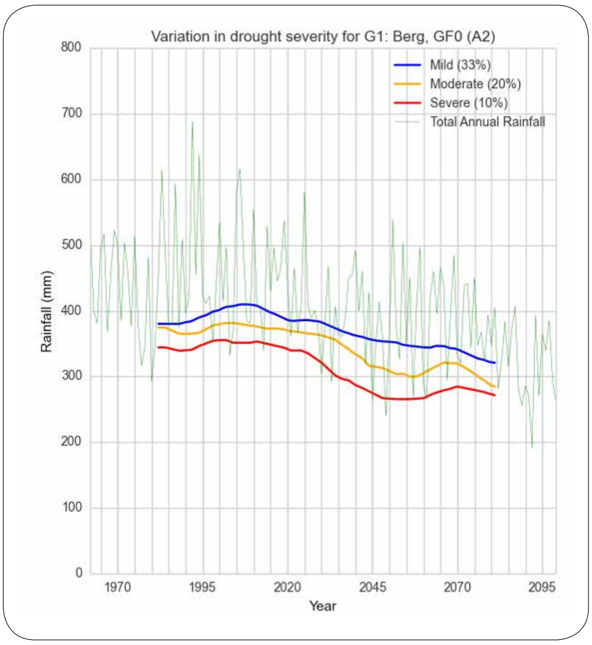


Figure 8: Variation in the thresholds for definition of drought severity over time in the Berg River catchment.

3.2.2. *HFD impacts on mean annual runoff by 2050*

Estimated change in the mean annual runoff (MAR) by 2050 for all secondary catchments based on the HFD analysis of the UCE scenarios (which is comparable to the hotter LTAS climate future) is shown in Figure 9. Although not truly representative of potential changes in hydrological drought frequency or severity, these results do give an indication of the range of potential impacts across the country that is much broader than an indication based on a selection of a limited number of downscaled models.

This figure shows a wide range of potential impacts as well as significant spatial variations in impact. In particular these results show a reduction in streamflow for the western half of the country (D to K) and in particular the south-western Cape catchments (F, G and H) where all the climate models show a likely reduction in stream flow. In contrast there are some very large potential increases in runoff for the east coast (Q to W) which could result in increased flooding risks. The average across the whole country, however, shows little change as the potential increases balance the potential reductions.

3.2.3. *Links to potential shortfalls in future water supply*

The potential impacts of climate change on future water supply were quantified in terms of the change in the percentage of the average annual demand for each of the three sectors (urban, bulk and agriculture) that could be supplied over the last ten years of the simulation (2040 to 2050) under each of the climate scenarios relative to the base scenario. The HFD of the average change in the proportion of the average annual demand that can be supplied relative to the base for each sector is given in Figure 10.

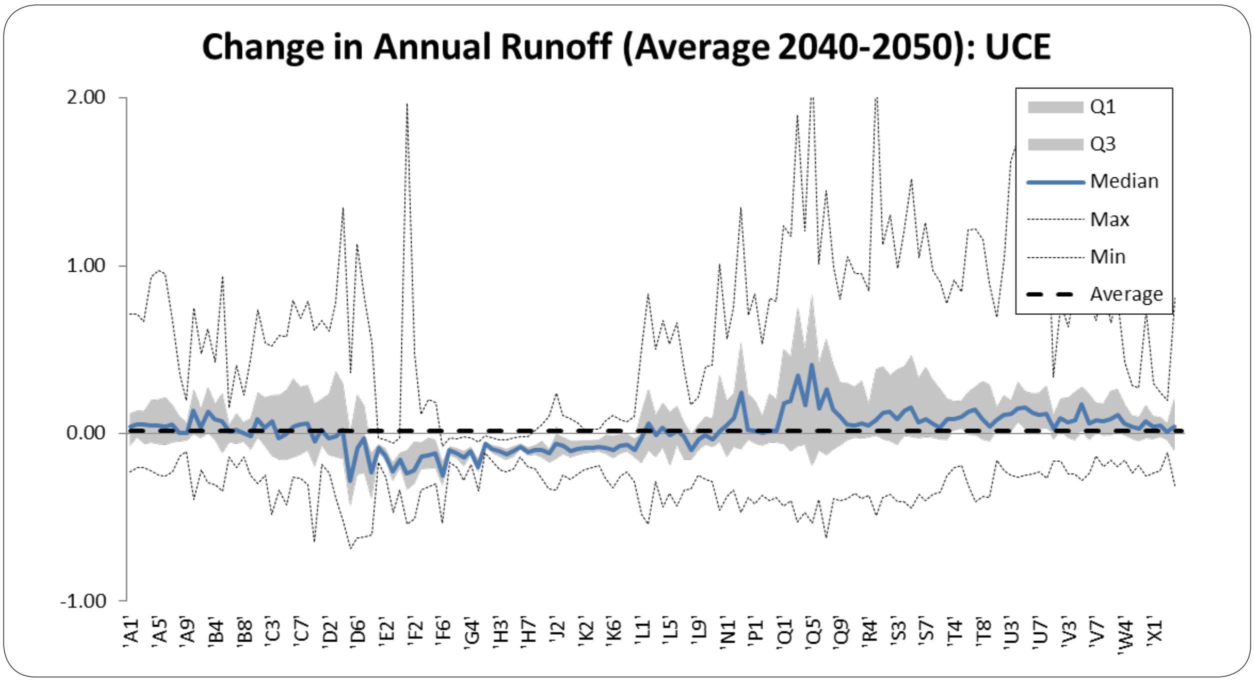


Figure 9: Range of potential impacts of climate change on the average annual catchment runoff for all secondary catchments for the period 2040 to 2050 due to the UCE scenario relative to the base scenario. The locations of primary catchments A to X are shown in Figure 6.

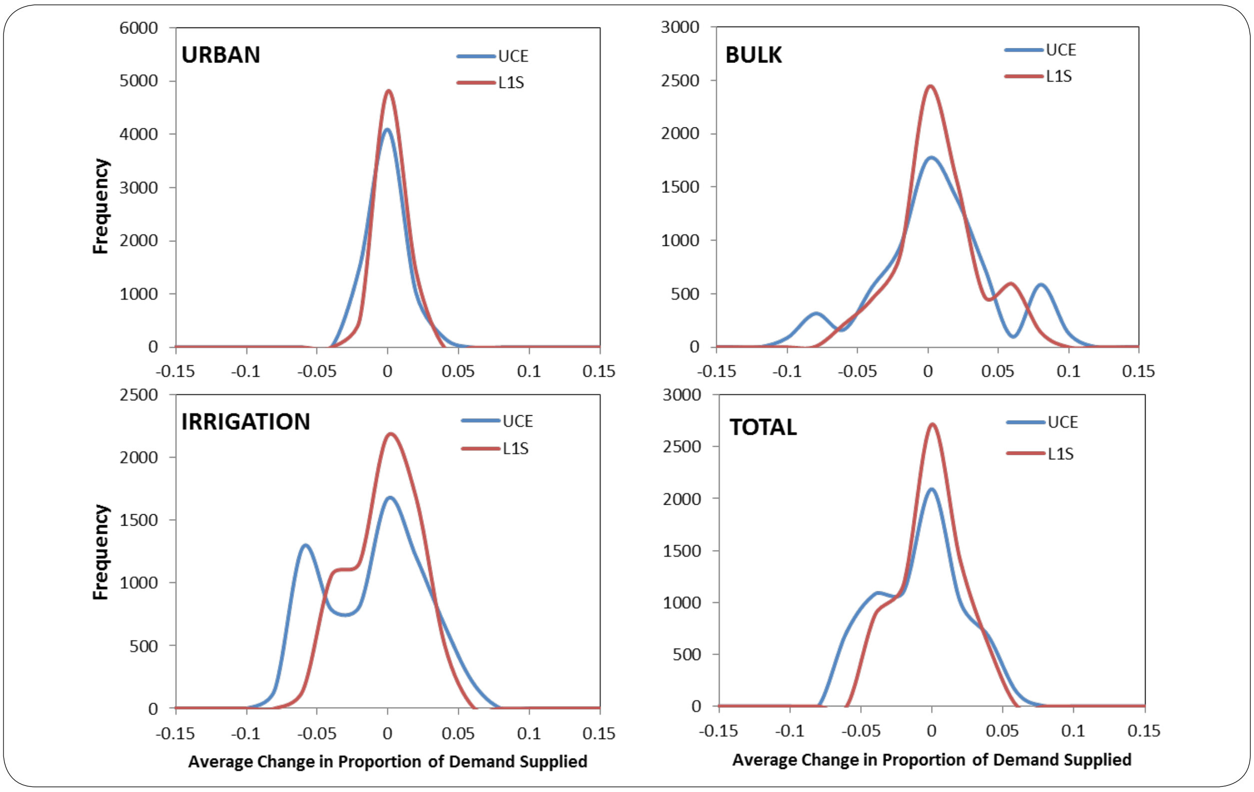


Figure 10: Hybrid frequency distribution of the change in the proportion of the average annual demand for the whole country and from different sectors that can be met under different climate scenarios over the period 2040 to 2050.

These results show a narrow range of impacts in terms of urban supply with very little difference between the UCE and LIS scenarios. In both cases the mode is at zero although the median impact of the model scenarios is around a 1% reduction. Under both scenarios there is less than a 5% change in the ability to supply the average annual demand by 2050, indicating a resilient water supply system.

There is a greater range of potential impacts in the ability to supply both the bulk industry demands and the irrigation demands. Under the UCE scenario the median impact in terms of the ability to supply the average annual demand is only a 1.5% reduction but with the possibility of up to a 9% reduction under the hotter, dryer future climate scenarios. Under the LIS scenario this risk is reduced with the maximum impact being reduced to a reduction of 6.7% of the average annual demand. The impact on supply to bulk industry is similar to that for irrigation, but there is a greater possibility of increased supply under the UCE scenario due to increases in runoff in the areas of greatest bulk industrial demand (namely in Gauteng and the north eastern part of the country).

Despite the apparently limited impact in terms of the ability to supply future demands at national level, there is potential for very significant impacts at regional level.

Figure 11 presents the estimated total average annual demand for each sector in each of the 19 WMAs by 2050 (top) and the average percentage of this annual demand for the period 2040 to 2050 that can be supplied under

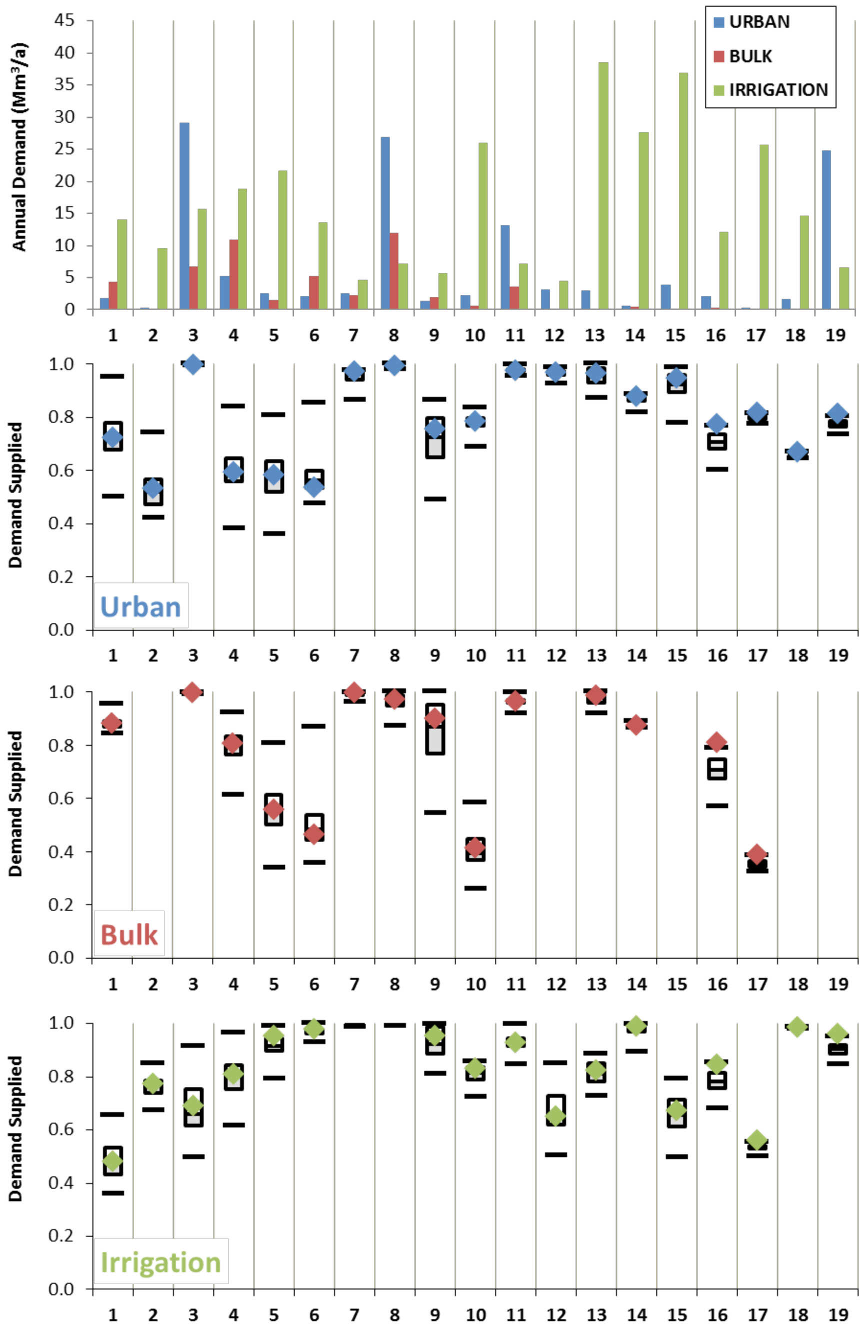


Figure 11: Average annual water demand (top) for the 19 WMAs for the period 2040 to 2050 and the proportion of demand that can be supplied under the base scenario (symbols) and models representing the minimum, 25th, median, 75th percentile and maximum impact under the UCE scenario for different sectors.

the base scenario and under the UCE scenario for the three industry sectors; urban, bulk and irrigation. In each plot the symbol represents the percentage of the average annual demand that can be supplied under the base scenario in each WMA while the box plots show the median and the inter-quartile range and the bars show the maximum and minimum model results.

The results show that there is very little impact on the ability to supply the major urban centres of South Africa. These are in WMA 3 (Crocodile West) and WMA 8 (Upper Vaal) for Gauteng, WMA 11 (Mvoti to Mzimkulu) for Durban and WMA 19 (Berg) for Cape Town. In fact there may even be the potential for increased supply to Gauteng due to increased precipitation over Lesotho following the construction of the Polihale Dam, which is included in the model. Cape Town is already experiencing water stress and this is the only major centre where there is a very strong probability of a decrease in supply under a future climate, although this impact is partially mitigated by the highly integrated nature of the Western Cape Water Supply System (WCWSS). It is important to note that these impacts are also only in terms of the average annual water supply and do not indicate the potential impact during critical periods, when the impacts of a future dryer climate are likely to be more significant in terms of the level of assurance of supply and the overall system yield.

The potential impacts on the water supply to bulk industry and irrigation tend to show an equal likelihood of both increases and reductions in the ability to supply future demands under different climate futures with the median impact being very similar to the current base scenario. The most vulnerable area showing the greatest potential for a significant reduction in the ability to meet future demands, appears to be the Gouritz WMA (WMA 16) in the southern Cape, although if some of the drier scenarios are realised either on average or during future dry periods then there are likely to be significant impacts across all sectors and across all regions.

It is important to note that this study looked at the impact on average water supply reliability over a ten year period towards the end of a fifty year simulation. It was not intended as a detailed study of the potential impacts of climate change on the long term yield and reliability of individual systems such as the Vaal or the Western Cape systems. Detailed modelling of potential climate change impacts on the long term yields of individual systems, particularly those identified as at risk should be undertaken as part of future research and modelling of potential adaptation options.

Some modelling of individual systems was undertaken for the DWA's Climate Change Strategy (DWA 2012) and is described in the LTAS Phase 1 report on potential water resources impacts and adaptation options including the WCWSS, the Inkomati system, the Umzimvubu River and De Aar. There have also been a number of other modelling studies looking at potential impacts of climate change on long term (1:50 year RI) yield from individual systems. These include a review of the potential impacts on the future water supply options to Polokwane (Cullis et al. 2011), impacts on yields from a selection of major dams around the country (Gerber et al. 2011), and an assessment of the potential impact on the Umgeni system (De Jager & Summerton 2012) as well as an assessment of the relative impacts of climate change uncertainty in terms of other model uncertainty (Mantel et al. 2012). The methods, approaches and findings of these previous modelling studies should be considered when planning further studies in specific regions of concern in future adaptation work.

3.3. Potential flood impacts

3.3.1. *Changes in daily rainfall intensity and annual flood peaks*

Spatial variability

The results of the analysis of potential relative changes in both rainfall intensity (RI) and annual flood peaks using the daily precipitation and runoff values derived from the ACRU model outputs of the five regionally downscaled climate models indicate significant spatial variation in the potential impacts across the country. Figure 11 presents the most extreme changes in the 1:10 year RI annual maximum daily rainfall between 2045 and 2100 under the different climate models. The 1:10 year RI case was chosen as a suitable indicator of extreme daily rainfall changes, given that its estimation is generally relatively insensitive to the choice of probability distribution. The following outcomes are particularly striking:

- All five climate models indicate that significant increases in extreme daily rainfall intensity (>25% increase) are not likely over the majority of the country.
- There is little correspondence among the climate models regarding the locations of potential extreme daily rainfall and the likely areas of concern vary under different climate models, even though they all share the same emissions scenario (SRES A2).

Figure 12 presents the most extreme changes in the 1:10 year RI annual maximum cumulative daily flow between 2045 and 2100. The following outcomes are particularly striking:

- While these results show similar spatial variability in the areas experiencing either increasing or decreasing flooding risk for the maximum daily rainfall, *the magnitudes of these impacts are much greater for runoff* (reflecting the non-linear relationship between rainfall and runoff). For example the maximum impact on changes in daily rainfall intensity is an approximately 80% increase over the base period, while the corresponding impacts on streamflow represent a threefold increase.
- *In multiple climate model outcomes (GF0, GF1, MIR), the Eastern Cape Province and the Limpopo Province are the regions where significant increases in extreme floods are indicated.*
- *All five climate model outcomes indicate significant increases in extreme floods in portions of the Western Cape Province but none of these locations overlap.*

The reason for choosing the most extreme changes to represent the spatial distribution of potential impacts under different climate models is highlighted by the temporal variations of potential impacts under different climate scenarios and for different parts of the country – demonstrated in the following sub-section.

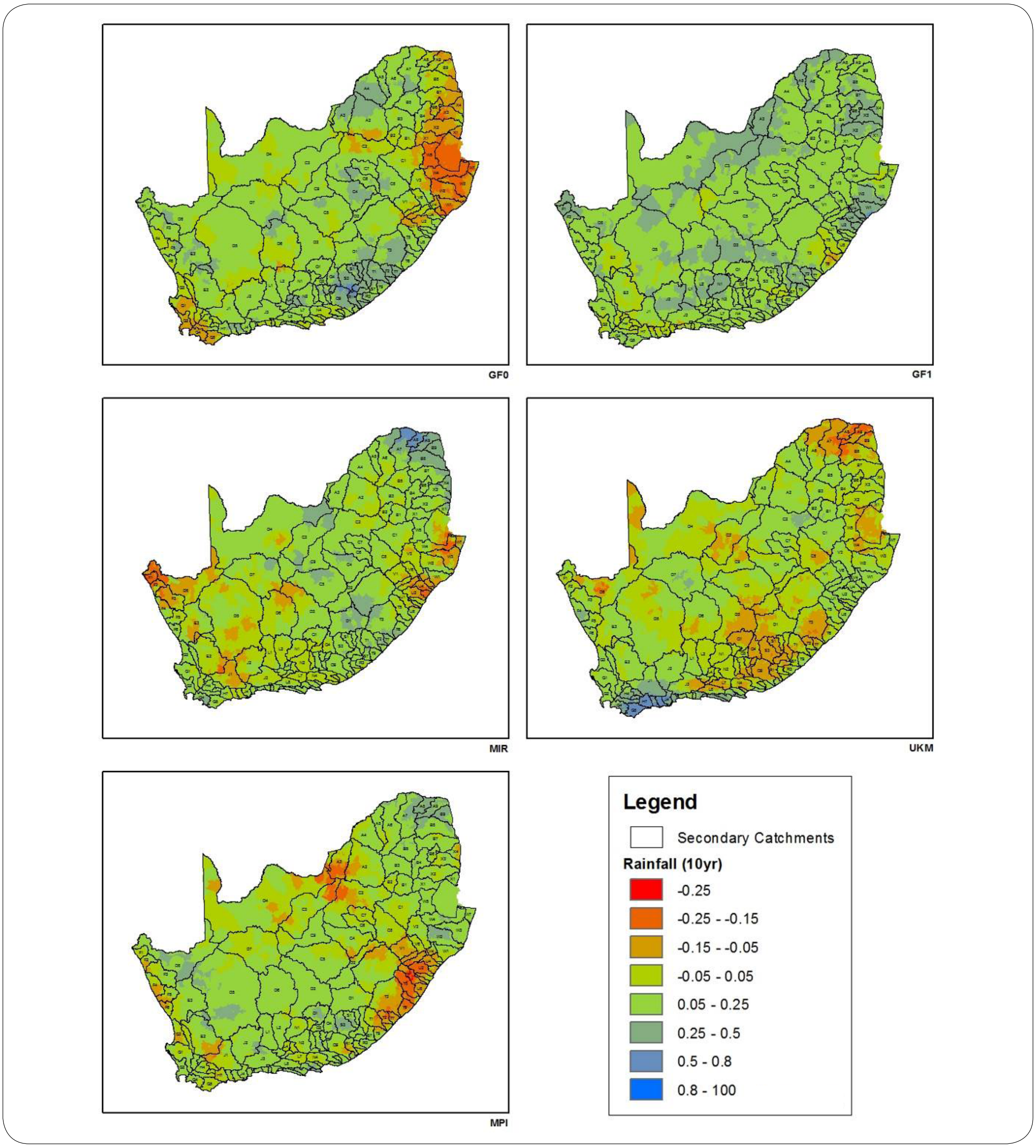


Figure 12: Most extreme impact of climate change on the 1:10 RI maximum annual daily rainfall over the period 2045 to 2100 relative to the historical period for five climate models. Values given are the relative change in the simulated maximum daily rainfall for the future period to the current day.

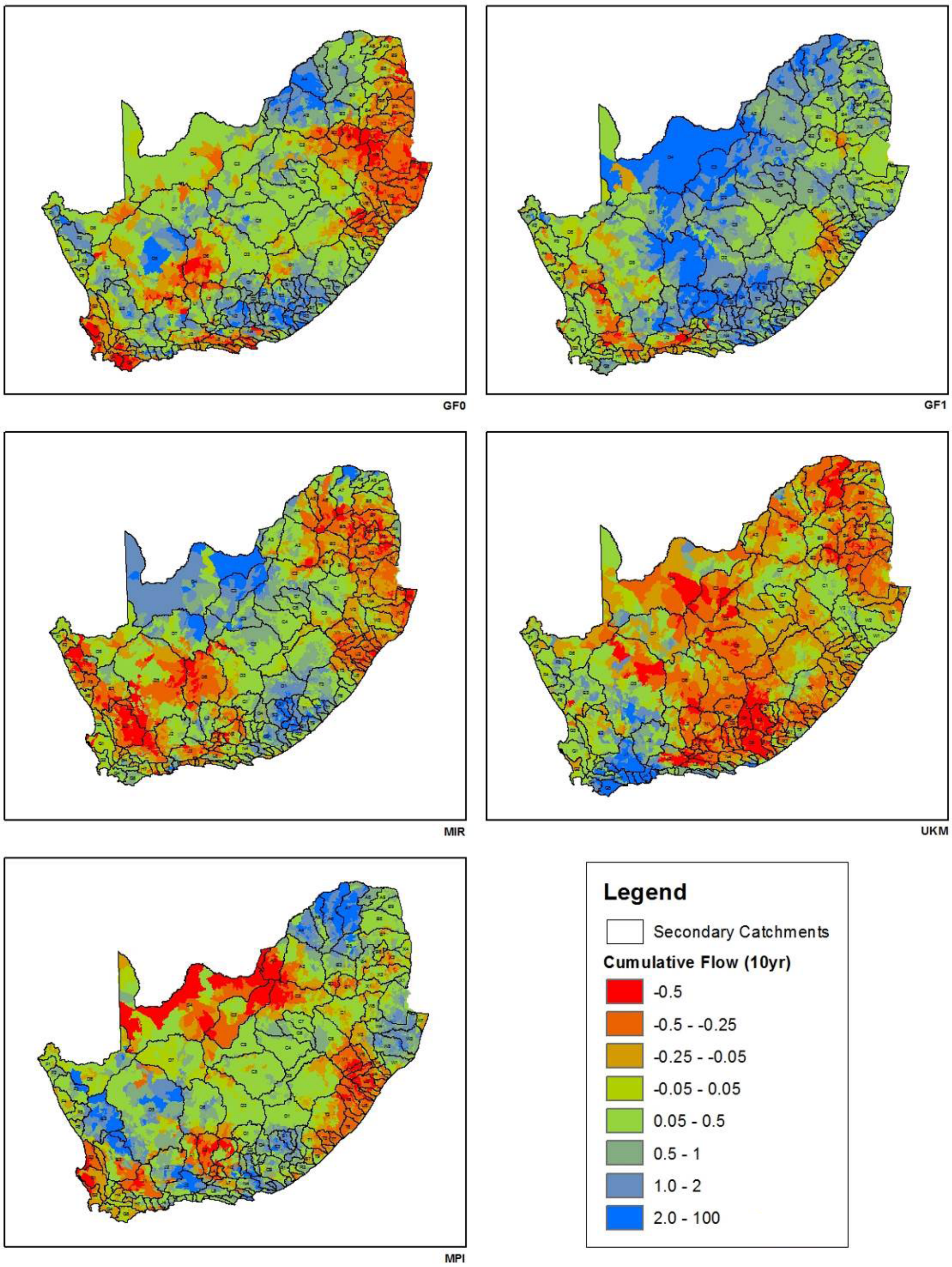


Figure 13: Most extreme impact of climate change on the 1:10 RI maximum annual daily cumulative runoff over the period 2045 to 2100 relative to the historical period for five climate models. Values given are the relative change in the simulated maximum daily rainfall for the future period to the current day for the five climate models used.

Temporal variability

The dynamic nature of the relative changes to RI annual maximum daily rainfall and RI floods during the course of the century is illustrated in Figure 14 which shows the temporal change in the 1:10 year RI maximum daily cumulative streamflow for six representative catchments across South Africa. These RI floods were derived by log-normal probabilistic analysis, using thirty year forward-rolling windows of annual maximum daily runoff over the period 1962 to 2100 for the five different climate models.

The rainfall changes are the weighted averages of the corresponding values over all the quinaries in each selected secondary catchment while the cumulative streamflow impacts are derived from the quinary catchment at the outlet of the secondary catchment.

Appendix F presents additional figures that show the temporal variation of a range of RI floods for the different models for these six representative catchments.

The following outcomes are particularly striking:

- Some climate models indicate significantly increased flood risks before mid-century, but with the risk actually diminishing in the second half of the century. Other models indicate significantly increased flood risks only in the latter part of the century. These "flip-flop" characteristics potentially pose a severe dilemma for climate change adaptation planning, with disaster risk reduction initiatives having to attempt to stay synchronised with these flip-flop patterns in different parts of the country.

- The outcomes of all five of the climate models correspond with regard to relatively low impacts (positive or negative) in both the Modder (C5 secondary) and the Berg (G1 secondary) catchments.

- The most volatile trajectories of temporal relative change in 1:10 year RI floods during the century are those for the Mokholo (A4 secondary) and the Koega (L8 secondary) catchments.

- Many of the trajectories of temporal change in the range of RI floods presented in Appendix F indicate that, at any point in time during the century, the relative changes in the higher recurrence interval extreme rainfalls and floods are significantly more extreme than the relative changes in the equivalent lower recurrence interval cases – for both positive and negative changes. In general, the 1:2 year RI rainfall and flood trajectories of relative changes are much more benign than the often volatile 1:100 year RI trajectories for equivalent cases. This indication is both surprising and worrying. Surprising, because general wisdom has hitherto been that climate change would impact small to medium RI rainfall and floods relatively more than the more extreme RI events, such as the 1:100 year case. Worrying, because the design costs and safety of large infrastructure (bridges, power line crossings, dam spillways) are invariably highly sensitive to the magnitude of the more extreme floods (see Sub-section 3.2.2).

(NB: It should be noted that it is also possible that in certain cases the log-normal probability distribution chosen for this study might not be the optimal distribution, which might partially contribute to this outcome.)

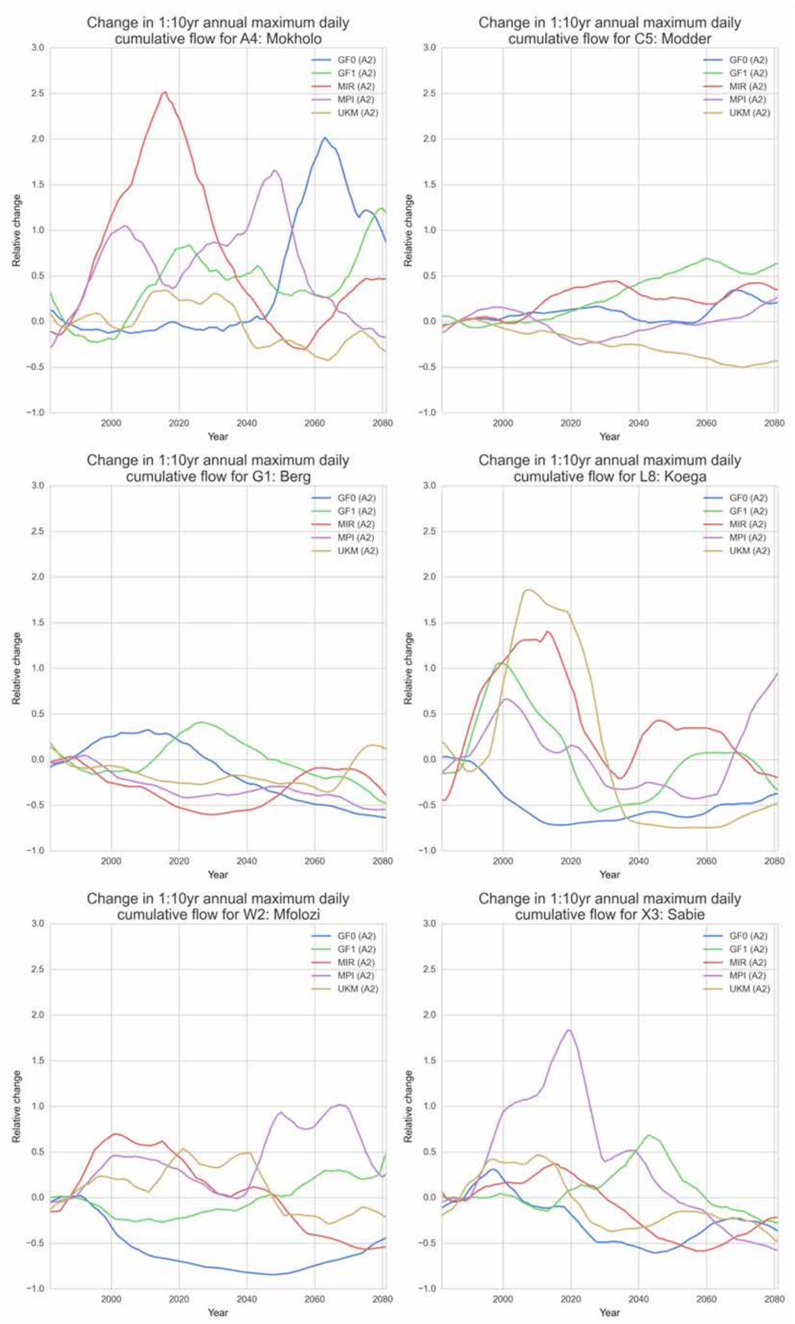


Figure 14: Temporal changes in the 1:10 year RI annual maximum floods for six representative catchments across South Africa under five different climate models.

3.3.2. *Comparison of spatial and temporal changes in floods and droughts*

Figure 15 shows a comparison of the spatial and temporal variability in potential changes in flood magnitude and droughts for all quaternary catchments for the GF1 model. Similar figures for the other climate models as well as for changes in annual maximum daily rainfall are given in Appendix G.

The following initial observations are derived from these figures:

- There are significant differences between catchments as well as temporal variability that make planning for future changes in either floods or droughts particularly challenging.
- Areas and periods of particularly severe flooding tend not to coincide with periods or locations of increased droughts.
- It is also clear that there are no periods when the whole country is either experiencing severe flooding or severe drought. This provides opportunities for mitigation of potential impacts through regional cooperation and integration.

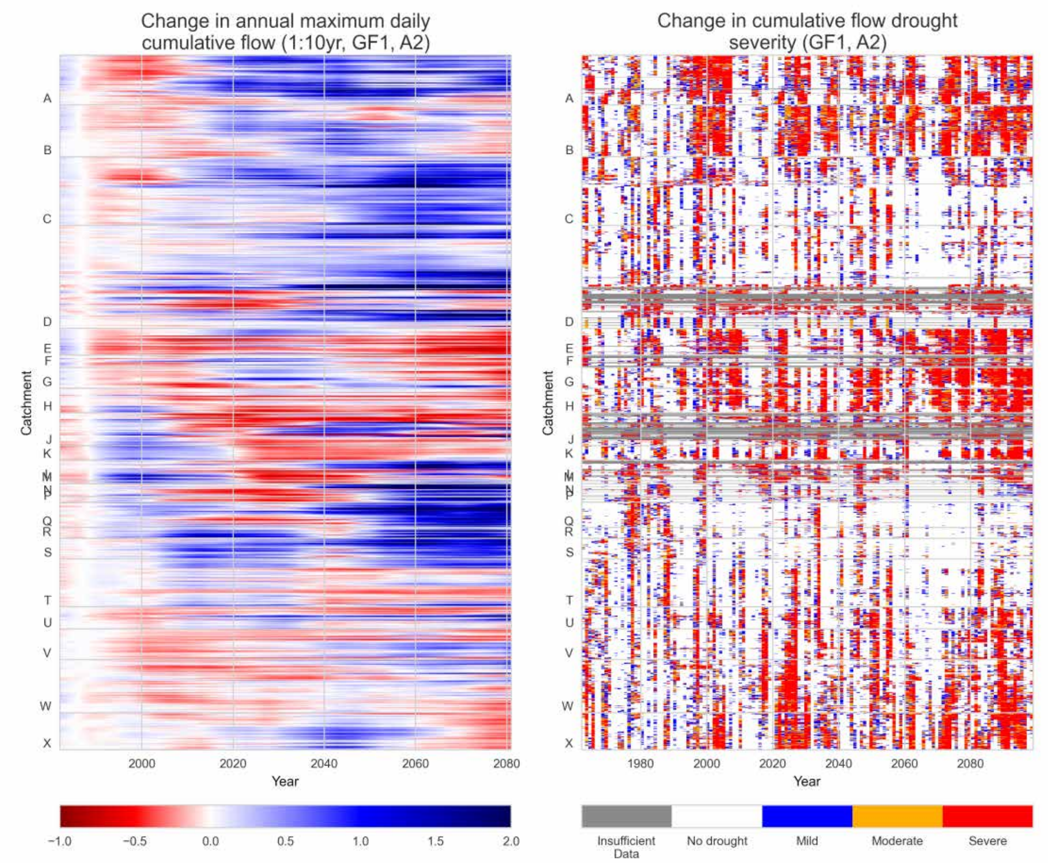


Figure 15: Spatial and temporal comparison of changes in flood magnitude and drought frequency for all catchments across South Africa (GF1 model, A2)

3.3.3. Increasing flood risk for key infrastructure

The relative changes in the 1:100 year annual maximum flood (AMF) at more than 17 000 locations of existing key infrastructure – dams, bridges and power line crossings – were averaged from the outcomes of the five climate models for two time horizons, 2050 and 2100. The dam locations were extracted from the DWA Dam Safety database. The bridge locations were extracted from the SANRAL database. The power line locations were extracted from the SA Explorer GIS database and intersected with 1 in 500 000 rivers from DWA. Figure 16 presents the resulting cumulative frequency distributions (CFDs).

The following aspects of Figure 16 are particularly striking:

- About 50% of infrastructure locations included in this analysis are projected to potentially experience reduced design flood risk by both 2050 and 2100. The vast majority of the flood risk reduction locations fall in the -50% to 0% range for both time horizons. However, it bears noting that the exact constitution of the sample of infrastructure locations with reduced flood risk differs markedly for the two time horizons, given the fluctuating trajectories of relative flood risk changes for different parts of the country presented in Figure 14.
- These flip-flop characteristics potentially pose a severe dilemma for climate change adaptation planning, with disaster risk reduction initiatives having to attempt to stay synchronised with these flip-flop patterns in different parts of the country.
- An increase in design flood risk of 50% or more would generally be regarded as fully catastrophic for infrastructure security. Figure 16 indicates that the proportion of such direly threatened infrastructure

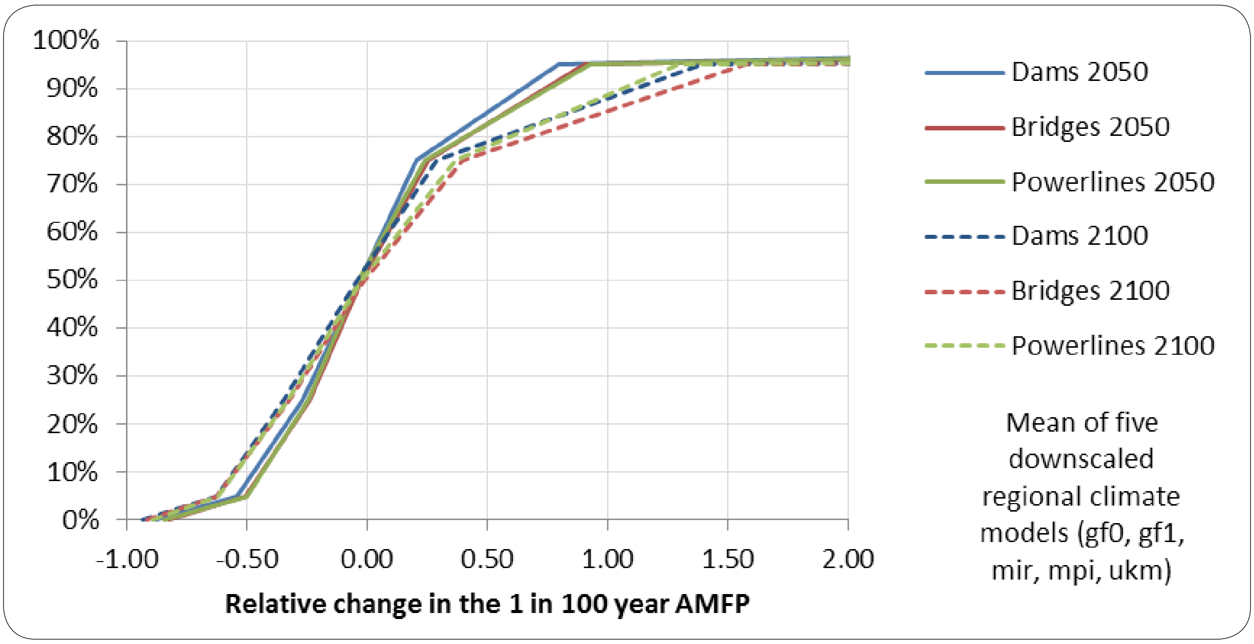


Figure 16: Cumulative frequency distributions of the relative changes in the 1 in 100 year annual maximum flood peak (AMFP) key infrastructure across South Africa by 2050 and 2100 compared to the historical period (representing the average impacts of five climate models).(Authors' compilation)

locations are projected to potentially increase during the second half of the century from about 16% to about 22%. *This poses a very serious risk to society and the national economy.*

The four flood risk categories ranging from low to very high presented in Table 1 allow a more nuanced analysis of increased design flood risks per infrastructure type. These numbers are based on the averages of the outcomes of the five climate models. We focus these outcomes specifically on the 2050 time horizon, as that date is conceivable as an extreme bound for current infrastructure planning.

The locations of infrastructure facing high or very high potential flood risk increases in the next half century are presented in Figure 17 for the climate model (GF1), which gives the largest flood risk increases.

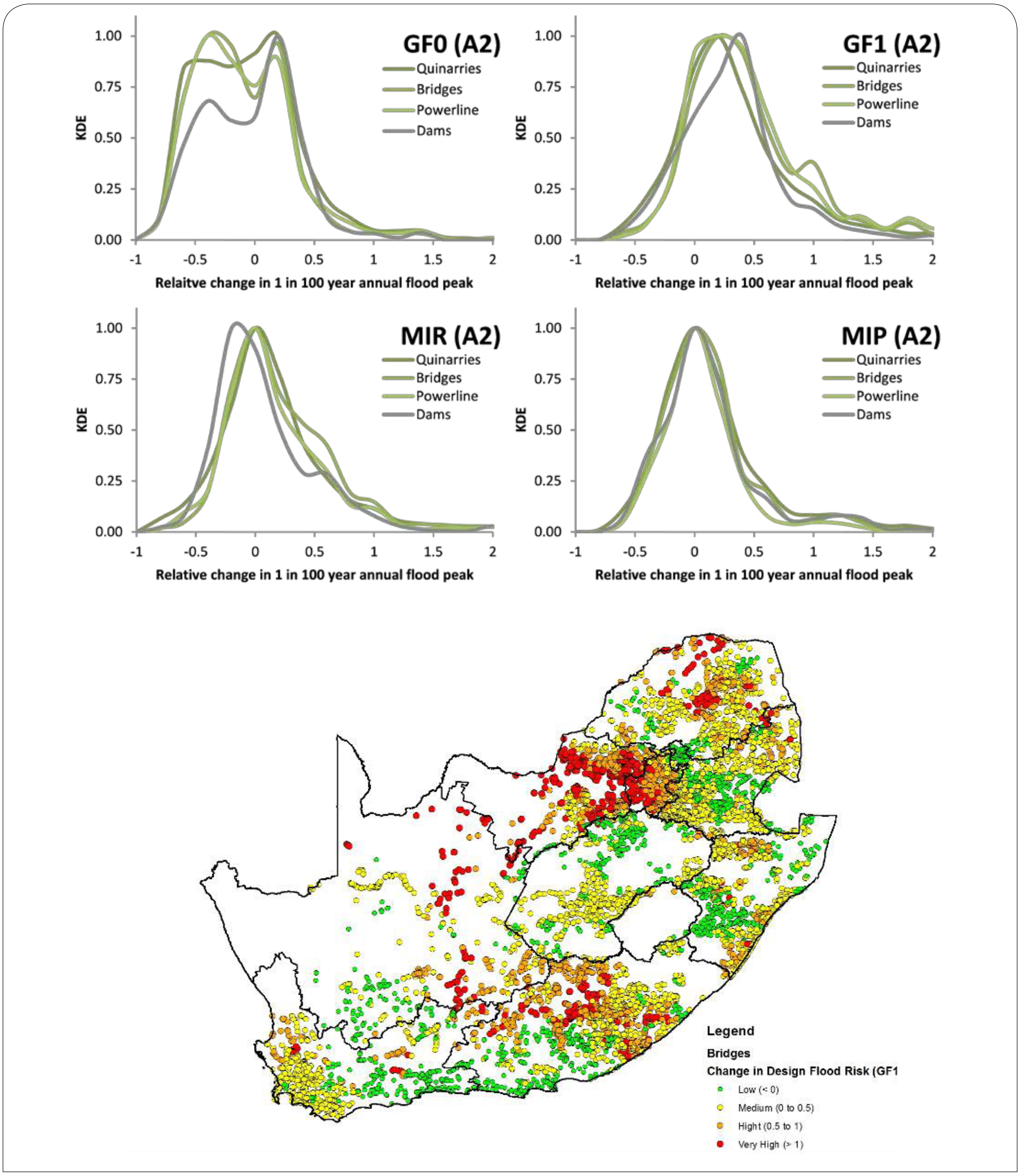
The number of impacted bridges in terms of increasing flood risk in each province is given in Figure 18.

Table 1: Number of structures (bridges, dams and power line crossings) with projected flood risk increases by 2050 relative to the current design flood magnitude (1:100 year RI).

Risk Catagories	Change in Q_{100} by 2050	Bridges		Dams		Powerlines	
		Count	%	Count	%	Count	%
0 Low	< 0	2271	25	1502	30	850	26
1 Medium	0 to 0.5	4264	46	2515	51	1477	45
2 High	0.5 to 1	1808	20	673	14	557	17
3 Very High	> 1	882	10	237	5	379	12
TOTAL		**9225**		**4927**		**3263**	

The following aspects of Table 1 are particularly striking:

- Almost 2 700 bridges (30%) on the SANRAL database are projected to potentially experience high to very high flood risk increases by mid-century.
- More than 900 dams (19%) on the DWA Dam Safety database are projected to potentially experience high to very high flood risk increases by mid-century.
- Almost 900 power line crossings (29%) on the SA Explorer GIS database are projected to potentially experience high to very high flood risk increases by mid-century.
- As stated earlier the total number of these threatened infrastructure components are projected to potentially increase towards the end of the century, but with a different mix to that which existed at 2050. These flip-flop characteristics potentially pose a severe dilemma for climate change adaptation planning, with disaster risk reduction initiatives having to attempt to stay synchronised with these flip-flop patterns in different parts of the country.


GF0 (A2)
Quinarries
Bridges
Powerline
Dams
KDE
1.00
0.75
0.50
0.25
0.00
-1
-0.5
0
0.5
1
1.5
2
Relaitve change in 1 in 100 year annual flood peak
GF1 (A2)
Quinarries
Bridges
Powerline
Dams
Relative change in 1 in 100 year annual flood peak
MIR (A2)
Quinarries
Bridges
Powerline
Dams
Relative change in 1 in 100 year annual flood peak
MIP (A2)
Quinarries
Bridges
Powerline
Dams
Relative change in 1 in 100 year annual flood peak
Legend
Bridges
Change in Design Flood Risk (GF1
Low (< 0)
Medium (0 to 0.5)
Hight (0.5 to 1)
Very High (> 1)

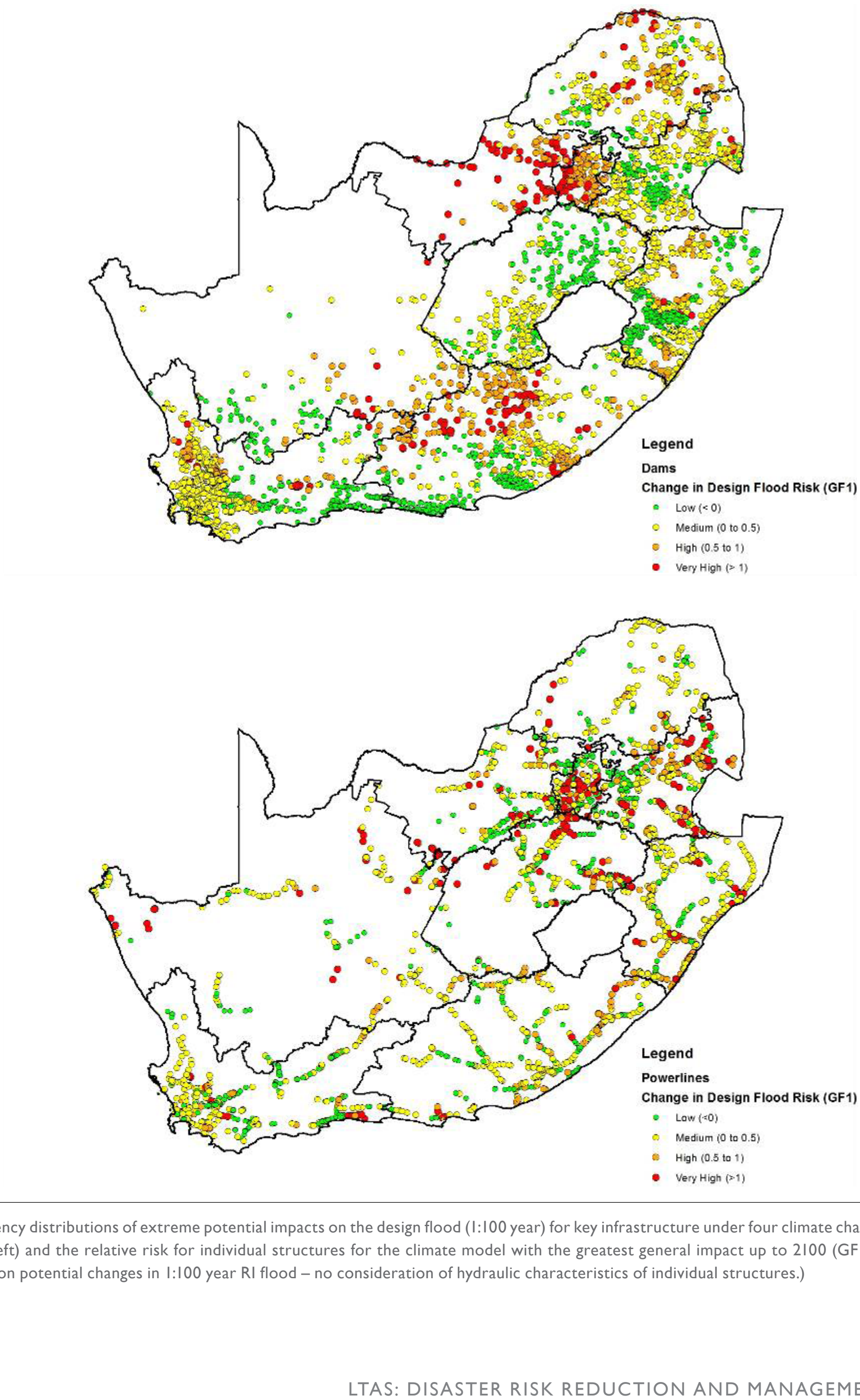


Figure 17: Frequency distributions of extreme potential impacts on the design flood (1:100 year) for key infrastructure under four climate change models (top, left) and the relative risk for individual structures for the climate model with the greatest general impact up to 2100 (GF1). (Analysis based on potential changes in 1:100 year RI flood – no consideration of hydraulic characteristics of individual structures.)

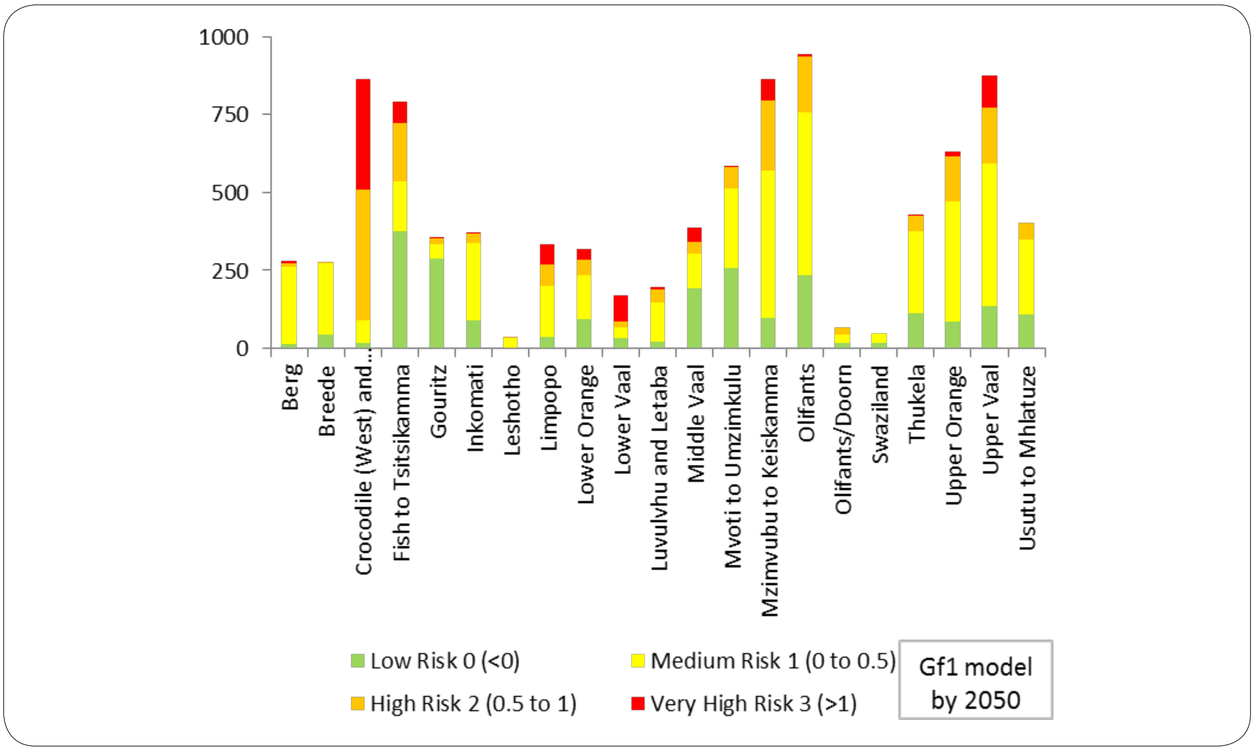


Figure 18: Number of bridges in each WMA in each risk class defined in terms of the maximum relative increase in the 1:100 year design flood by 2050 for the GF1 climate model.

The following spatial patterns of extreme design flood-related infrastructure risks by 2100 as per the GF1 climate model, presented in Figures 17 and 18, are particularly striking:

- **Bridges**: The highest general concentrations of bridges at risk by significant potential design flood increases are projected for the Gauteng, North-West and Limpopo Provinces in that order. When viewed on a WMA basis, Figure 17 illustrates that the Crocodile (West)/Marico is the WMA with the highest number of bridges with significantly increased design flood risk.
- **Dams**: The highest general concentrations of dams at risk by significant potential design flood increases are projected for the Gauteng and North-West Provinces, with the Limpopo and Eastern Cape Provinces a distant joint third.
- **Powerline crossings**: The highest general concentrations of power line crossings at risk by significant potential design flood increases are projected for the Gauteng, Mpumalanga, KwaZulu-Natal and Eastern Cape Provinces, in that order.

3.4. Potential sedimentation impacts

3.4.1. Changes in potential sediment yields

As outlined in Section 2.4 the relative changes in the annual sediment yields for 95 dam catchments around South Africa were based on the projected relative changes in the 1:10 year RI annual maximum daily flow using the empirical sediment yield equations derived for South Africa by Msadala et al. (2010). Figure 19 presents the frequency distributions of relative changes in the mean annual sediment yied for the 95 dam catchments for three overlapping fifty year windows.

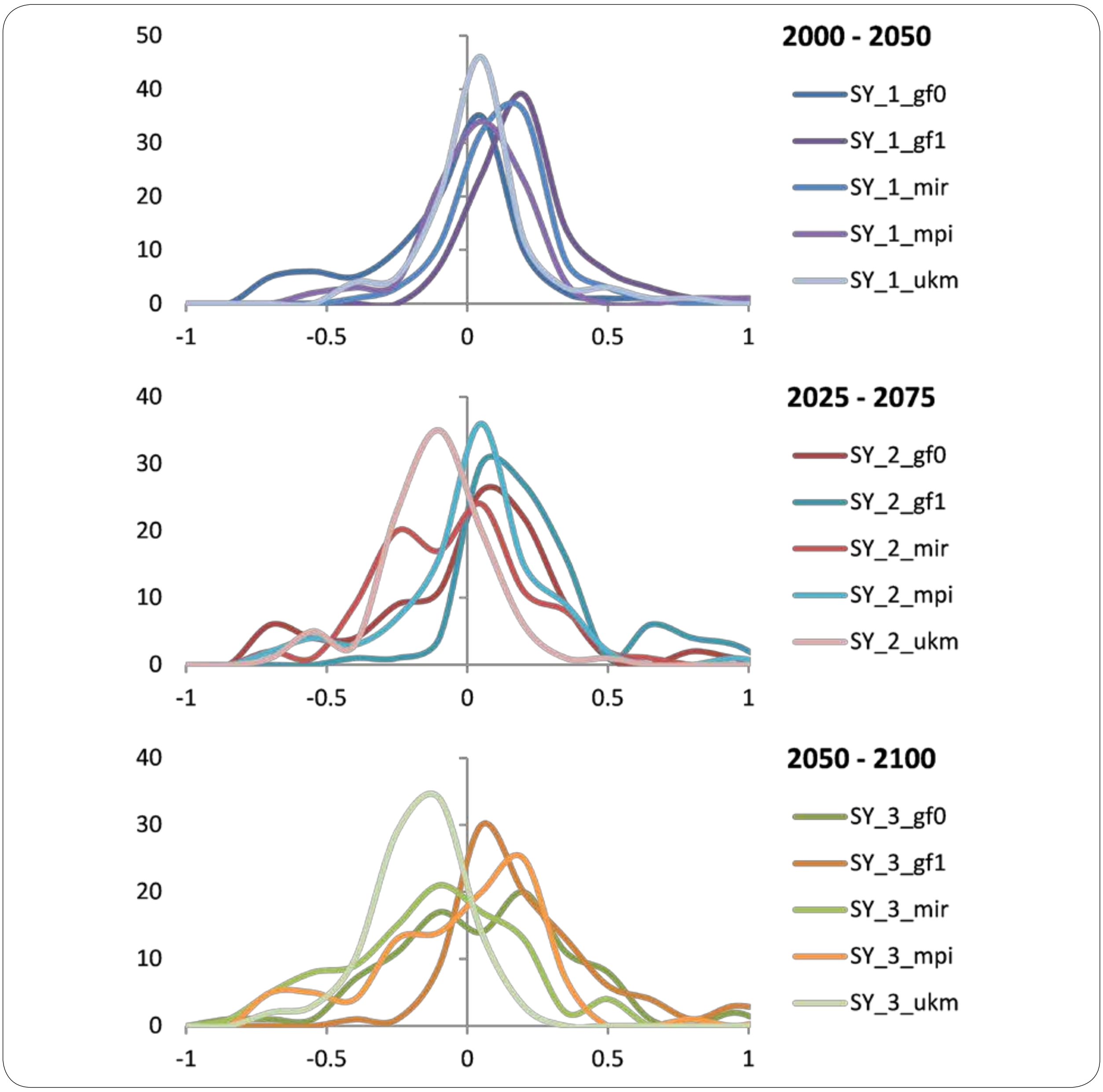


Figure 19: Relative change in the annual sediment yields for 95 dam catchments around South Africa based on the relative change in the 1:10 year RI annual maximum daily flow derived from a probabilistic analysis over three overlapping fifty year periods under the five climate models.

The following aspects of these results are particularly striking:

- The results for all five climate models indicate that for the first fifty year window the majority of dams are projected to be subject to increased sedimentation (positive modus value in all cases).
- By the time of the third fifty year window the relatively tight clustering of the frequency distributions of the first window has been replaced by markedly different distributions related to the five climate models.
- The frequency distributions for the third window show an increased number of dam catchments with extreme relative changes (>50% or <50%) in mean annual sediment yield.
- The frequency distributions for the third window indicate an increased number of dam catchments with diminished mean annual sediment yield.

3.4.2. *Impacts on future reservoir storage capacity*

Figure 20 shows how climate change might have an impact on future reservoir storage capacity in South Africa based on the analysis of the 95 dams located across the country. The results show that despite the potential for wide ranging impact on the annual sediment yields (described above) there is not much impact in terms of the potential for additional loss of storage capacity under the different climate models. This might be because the sediment impacts are not as significant in the areas where there are large dams, but rather in areas of smaller dams. Hence while there appears to be a limited impact on the total reservoir storage there are likely to be very significant impacts on individual dams, particularly smaller dams in areas of high erosion potential overlaid with increases in flood flows.

It is also important to note that the exponents used to determine the changes in sediment yield are relatively small (ranging from -0.25 to 1.31) which means that sediment yield is not necessarily that sensitive to changes in runoff. It is well known that sediment loads are very sensitive to other factors, including land use change, which may also be adversely impacted by climate change.

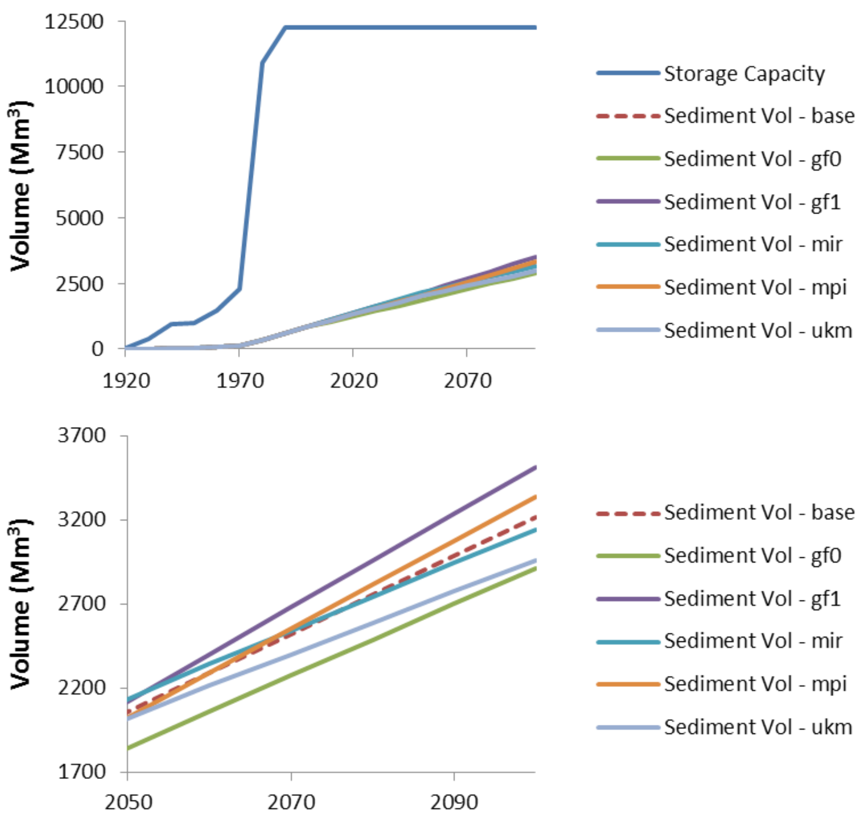


Figure 20: Potential impact of changes in sediment yield for a selection of 95 dams around the country as a function of changes in the 1:100 RI maximum annual daily streamflow (Q10) under five dynamically downscaled regional climate models out to 2100, relative to the historical annual sediment loads.

3.5. Potential sea-level rise impacts

The total area of land estimated to be below 5.5 m of elevation, the upper bound of land potentially impacted by sea level rise, tidal fluctuations and increased storm surges by the end of the century, was estimated to be around 2 130 km^2. This represents only a very small percentage (0.17%) of the total land mass of South Africa (≈ 1.2 million km^2). The affected proportion is even smaller once the land that is already affected by tidal flux and swash is excluded. Of the impacted area approximately 1 742 km^2 was found to be surveyed land, consisting of 228 km^2 defined as erven (namely urban) and 1 515 km^2 defined as farm portions (namely rural). The difference between the total local municipality (LM) area and the combined total of the urban and farm portion areas represents unsurveyed land. This could include existing coastal buffers as well as transport corridors, open space, or unsurveyed state land. This analysis does not include potential impacts on inhabited islands including Robben Island or Marion and Gough islands in the Southern Ocean that are part of South Africa.

Figure 21 shows the amount of land in each coastal local municipality estimated to be below 5.5 m above the current mean sea level (MSL) elevation. In terms of total

LM area, the municipalities with the largest amounts of land under 5.5 m are the Big 5 False Bay (19% of total LM area), Mtubatuba (14% of total LM area), and Cape Agulhas (5% of total LM area). In terms of urban areas impacted, the most significant are uMhlatuze (50km^2), City of Cape Town (45km^2) and eThekwein (25km^2). As a percentage of urban areas impacted, however the greatest impact is for the Berg River LM (29%).

The estimated areas below 5.5 m for all coastal municipalities (total LM area, erven and farm portion areas) are given in Table 2 as well as the relative percentage of the total area in each municipality. It is important to note that these results are based on national contour line estimates and not detailed local surveys or modelling of local coastal dynamics. The results therefore do not necessarily account for adaptation behaviour, including raised land, sea walls or other defences.

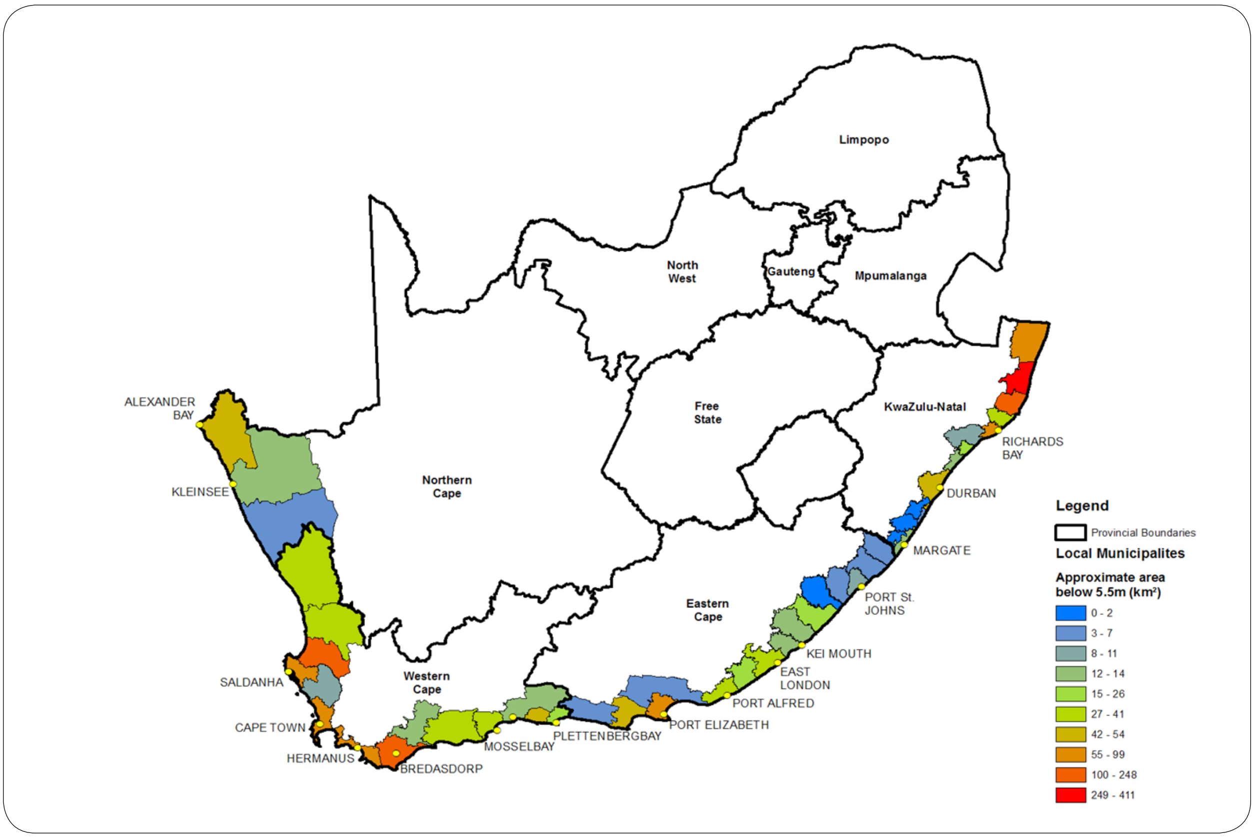


Figure 21: Approximate area of coastal local municipalities below 5.5 m elevation above current mean sea level (MSL).

Table 2: Estimated area of coastal municipalities below 5.5m elevation above current mean sea level (MSL). The top five municipalities in terms of impacted area are indicated by the shading of the rank value starting with the most impacted.

Local Municipality	Area below 5.5 m (km²)						Total Area of LM (km²)			Percentage Area Below 5.5 m		
	LM	Rank	Erven	Rank	Farm	Rank	LM	Erven	Farm	LM	Erven	Farm
Bergrivier	142	4	8	7	118	4	4414	29	4360	3%	29%	3%
Bitou	20	24	2	19	15	23	996	16	928	2%	10%	2%
Buffalo City	29	21	2	18	18	18	2539	469	1939	1%	0%	1%
Cape Agulhas	176	3	6	9	164	3	3476	142	3426	5%	10%	5%
Cederberg	36	17	2	16	32	9	8015	142	7912	0%	2%	0%
City of Cape Town	68	10	45	2	15	22	2475	142	1493	3%	6%	1%
eThekwini	54	12	25	3	19	17	2295	142	1559	2%	3%	1%
Ezingoleni	0	46	0	33	9	46	648	0	640	0%	26%	0%
George	12	30	3	11	6	31	5196	147	4909	0%	2%	0%
Great Kei	12	32	1	26	7	29	1740	36	1717	1%	2%	0%
Hessequa	30	20	1	20	17	19	5746	139	5691	1%	1%	0%
Hibiscus Coast	14	26	3	10	4	36	841	108	699	2%	3%	1%
Kamiesberg	5	40	0	29	1	43	14238	104	14603	0%	0%	0%
King Sabata Dalindyebo	2	43	0	43	1	41	3030	639	1592	0%	0%	0%
Knysna	54	11	9	6	21	16	1114	79	993	5%	12%	2%
Kouga	52	13	3	12	36	7	2680	106	2522	2%	3%	1%
Kou-Kamma	7	36	0	41	1	42	3611	0	3546	0%	0%	0%
KwaDukuza	13	29	1	22	8	28	737	109	635	2%	1%	1%
Mandeni	22	23	0	38	10	26	546	13	524	4%	0%	2%
Matzikama	36	16	22	5	16	20	13011	910	12046	0%	2%	0%
Mbhashe	18	25	0	41	14	24	3179	0	1949	1%	0%	1%
Mbizana	6	38	0	41	3	37	2418	0	2405	0%	0%	0%
Mfolozi	33	19	0	36	26	14	1213	2	1193	3%	0%	2%
Mnquma	13	28	0	31	6	30	3275	614	1255	0%	0%	0%
Mossel Bay	35	18	2	17	26	13	2018	57	1933	2%	3%	1%
Mtubatuba	248	2	0	32	235	2	1780	32	1630	14%	0%	14%
Nama Khoi	14	27	0	37	10	25	18003	1816	16208	0%	0%	0%
Ndlambe	41	15	3	13	28	10	1846	140	1691	2%	2%	2%
Nelson Mandela Bay	68	9	23	4	35	8	1968	656	1233	3%	4%	3%
Ngqushwa	26	22	2	15	16	21	2249	99	2054	1%	2%	1%
Ngquza Hill	4	41	0	41	2	40	2464	0	2447	0%	0%	0%
Nyandeni	4	42	0	41	3	39	2478	0	2443	0%	0%	0%
Overstrand	72	7	2	14	39	6	1723	108	1711	4%	2%	2%
Port St Johns	11	33	1	24	5	32	1292	91	1192	1%	1%	0%
Richtersveld	52	14	0	28	21	15	9755	12	8886	1%	3%	0%
Saldanha Bay	68	8	7	8	55	5	2050	94	1892	3%	8%	3%
Sundays River Valley	6	39	0	30	4	34	6005	11	5991	0%	2%	0%
Swartland	10	34	0	27	9	27	3715	106	3581	0%	0%	0%
Swellendam	12	31	1	23	4	35	3835	163	3673	0%	1%	0%
The Big 5 False Bay	411	1	0	39	405	1	2186	6	2152	19%	0%	19%
Theewaterskloof	0	47	0	41	0	47	3232	0	0	0%	0%	0%
Umdoni	7	37	1	25	3	38	252	31	223	3%	3%	1%
Umhlabuyalingana	74	6	0	41	27	12	4055	0	3941	2%	0%	1%
uMhlathuze	99	5	50	1	27	11	798	254	453	12%	20%	6%
uMlalazi	10	35	1	21	5	33	2215	35	2173	0%	4%	0%
Umzumbe	1	44	0	35	0	45	1259	0	1179	0%	2%	0%
Vulamehlo	0	45	0	40	0	44	960	0	959	0%	0%	0%
Grand Total	**2130**		**228**		**1515**		**163569**	**8925**	**146179**	**1%**	**3%**	**1%**

The estimated national economic impacts of potential sea level rise are given in Table 3. These indicate a potential total cost of between R50.5 and R169 billion by 2050 with the most significant impact in terms of loss of private real estate. Although these costs are significant it is important to note that they are accrued over a 50 year period and on an annual basis are therefore only between R1 and R3 billion which is a relatively small percentage of the national gross domestic product (GDP), but very significant at the local scale. By 2100 the estimated cost will be between R228 and R428 billion (2010 prices) which if discounted at 6% gives a net present value of sea-level rise to South Africa of R43 to R79 billion. The estimates imply that on an annual basis sea-level rise could cost South Africa the equivalent of between 0.07 to 0.13% of 2013 GDP.

Table 3: Summary of national sea-level rise costs for 2010–2100 under two scenarios (2010 prices, billion).

	Low (0.5m eustatic rise by 2100)	High (1m eustatic rise by 2100)
Public Infrastructure	R32.6 B	R66.0 B
Private Real Estate	R150.4 B	R270.4 B
Tourism	R45.9 B	R91.8 B
TOTAL	R228.87 B	R428.17 B

By way of comparison a 2013 Treasury study (Cullis et al. 2013) projected the cost of South Africa's sea level rise to 2050 and put the total cost at between R50.5 and R169.0 billion. A similar study for the City of Cape Town (Cartwright et al. 2008), based on a set of assumptions that was limited by the available data on property values and public infrastructure, estimated the risk cost of sea level rise impacts related to storm surge risk in Cape Town to be between R4.9 and R20.2 billion for scenarios 1 and 2 respectively over the ensuing 25 years to 2035 as shown in Table 4.

Table 4: Value of sea-level rise risk for three different storm surge scenarios for Cape Town (Cartwright, 2008)

	Assumed prob. of occurring in the next 25 years	Value of real estate at risk	Value of tourism revenue at risk	Value of public infrastructure at risk			Total potential cost to the city	Value of the risk to the city
				Storm water	Roads	Electricity		
Scenario 1 - 2.5 m	0.95	R3,255 B	R750 M	R167.3 M	R900 M	R 94.8 M	R5,167 B	R4,908 B
Scenario 2 - 4.5 m	0.85	R19,459 B	R1.44 B	R408.25 M	R2,197 B	R230,2 M	R23,734 B	R20,174 B
Scenario 3 - 6.5 m	0.20	R44,460 B	R3.60 B	R635.80 M	R5,702 B	R358,6 M	R54,756 B	R10,951 B

4. CLIMATE CHANGE ADAPTATION RESPONSES AND POLICY RECOMMENDATIONS

4.1. Adaptation options for increased drought risk

Droughts are considered to be **long-term, slow-onset or creeping disasters** and as such adaptation options should be focused on more **long-term systemic and structural changes** rather than short-term physical or engineering solutions. That does not however detract from the fact that drought adaptation options still need to be put in place as soon as possible, particularly in areas identified as high risk.

The results of the modelling study have shown that South Africa generally has a well-planned and integrated water supply system, which provides a certain level of resilience to potential climate change impacts on the larger water supply systems. Adaptation options require the use of a **standardised set of climate models** as well as a **standardised approach** for incorporating climate change (and other uncertainties) into the existing water resources planning methods for individual systems across the country. These studies could then decide on appropriate physical adaptation options such as increased storage capacity or additional interbasin transfer schemes within each system.

In addition to developing a standard approach to incorporating climate change impacts into existing water resources studies for the major systems, particular attention should be placed on investigating the potential impact on **smaller and less integrated systems** (in DWA terminology these are "all towns" or "stand-alone schemes") and determining appropriate adaptation options. These systems are considered to be the most vulnerable to potential climate change impacts and adaptation options would consist of changes to improve integration and diversification of water supply sources.

Continued **monitoring, seasonal forecasting** and drought **early warning systems** are critical for drought adaptation and require further development, research and maintenance. In addition improved **drought planning**, including drought resistant seed varieties, food stock piles, and support for farmers and rural households, is required so that these can be put in place in advance of forecast impending disasters.

Other **drought risk reduction measures** are also important. These include **restoration of critical ecological systems** such as restoring of natural systems, removal of invasive alien plants, rehabilitation of wetlands, as well as consideration for improved **water use efficiency** and **alternative sources and improved storage capacity**, although as has been stated earlier, simply building more dams does not necessarily improve resilience under a drying climate as they end up storing hot air (see Cullis et al. 2011).

Drought adaptation also requires **continual adjustment of what is "normal"** based on continued monitoring and evaluation and structural changes to local economies, crop types and farming practices. As the results from this study have shown, changes to the threshold definitions for droughts would change over time and these should be considered well in advance as they require time to be realised.

Drought adaptation requires **rethinking concepts of food security** and **food sovereignty**. The results of this study have shown potential for significant impacts on dry land crop yields from existing staple crops such as wheat and maize, particularly under a drying future. Some of these impacts can be offset by increased irrigation demand and water use efficiency, but ultimately it may require consideration of alternative sources, including importation or, alternatively, fundamental changes in diets.

4.2. Adaptation options for increased flood risk

Floods are very immediate hazards and as the results from this study have shown there could be significant increases in flood risks in many parts of the country, even within the next few decades. As with adaptation options for droughts, adaptation options for reducing future flood risk need to be **holistic** and require institutional changes, as well as both soft and hard engineering solutions.

Catchment management, improved **land care** practices as part of ecosystem based adaptation approaches and enforcement of **zoning regulations** are critical adaptation options for increased flood risk. They are, however, also components of best practice and represent **no regrets options** that should be immediately implemented across the country and would be necessary, irrespective of the direction of future climate change impacts. In this regard there should be increased support for the DEA's Working for Water, and Working for Wetlands programmes, including a NRM land user incentives programme as well as enhanced land care and catchment management at local and district municipality levels.

Adaption options also include changes to **design standards**. These include regulatory requirements for **water sensitive urban design** (WSUD) and increased on-site **storm water retention** and flood mitigation measures. On a national scale the results of this study have shown that a review of current **design standards for key infrastructure**, including bridges, dams, and flood lines, for sustainable urban design and the placement of critical infrastructure such as power lines, treatment plants and sub-stations, is sorely required.

Changes in design standards are a long-term adaptation measure. A more immediate requirement is for **improved maintenance of existing infrastructure**. Often significant flood damage results from even small increases in flood risk if there has been insufficient clearing of storm water drains or proper operation and maintenance of roads or other municipal infrastructure. As this study has shown it is likely that there will be significant increases in flood risk for many parts of the country and it is therefore even more **critical that routine maintenance is done at local level** to maintain existing design standards.

This study has looked at the likely impacts of climate change on rainfall intensity and catchment runoff. As mentioned previously, additional impacts of **land use changes** have not been considered, but are critical in determining future flood and disaster risks. Similarly, changes in **storm water retention and flood mitigation** have also not been considered. These could provide additional resilience and mitigation of increased future flood risks. At local level, increased flood retention should be addressed through improved urban design, but at a larger scale the potential to operate large dams with a specific flood control role needs to be considered. Most dams in South Africa are currently operated for the primary purpose of improved assurance of water supply. The results from this study suggest that in parts of the country with particularly significant increases in flood risk the potential for additional **flood operating rules** should be considered. This, however, requires careful study of the trade-offs between potential changes in flood risk, against potential changes in drought risk and requires more detailed system or dam-specific analysis and consideration of a wider range of future climate models.

4.3. Adaptation options for reducing negative sedimentation impact

The key adaptation focus for reducing potential sediment impacts should be on improved **land care and catchment management as part of ecosystem based adaptation approaches**, including appropriate farming and forestry practices such as the rehabilitation of dongas, the rehabilitation and re-vegetation of degraded lands, the enforcement of buffer strips and set-back lines, and the rehabilitation of wetlands and natural flood-plains. "Hard" engineering solutions, such as sand bypass systems, additional treatment capacity or dredging of reservoirs are possible, but are generally more expensive and less reliable than improved catchment management which aims to mitigate the risk at source.

This study has shown that, while there is the potential for increases in sediment loads due to climate change, these are not particularly significant, as the empirical factor relating changes in the sediment yield to changes in the 1:10 year RI flood event is relatively small. Other factors, including **land cover and catchment management practices** which determine the erosion potential in the contributing catchment, are considered to be more significant in determining the potential sediment yields. Further research, however is required to determine the potential climate change impacts on these factors.

The results from this study can be used as a first estimate to incorporate **additional uncertainty in sediment loads into design and operating procedures** for water resources infrastructure, including dams and treatment plants. In these cases, however, **routine maintenance** is critical and considered to be a no regrets option irrespective of the existing uncertainty in determining future climate change impacts.

4.4. Adaptation options for sea-level rise impacts

Economic impact assessments tend to be based on the assumption that no preventive measures will be taken. In a stylised sense, sea level rise adaptation measures can be classified as those that would make sense even in the absence of sea level rise, but where implemented will reduce sea level rise risk, and those that are explicitly focused on reducing sea level rise risk, which include both hard and soft (or biological) engineering solutions as well as social and institutional interventions.

While climate change adaptation must address potential impacts resulting from eustatic rise, consideration must also be given to potential increases in violent storms and hurricanes. Currently, however, there is insufficient data to show that this is occurring in South Africa. Many of the adaptation options, however, would also be appropriate for increased storm intensities and frequencies.

4.4.1. No-regrets approaches

Some of the most effective sea level rise adaptation options involve systemic interventions that reduce exposure to multiple risks, including sea level rise. Options in this category are typically classified as no-or low regret in that they deliver multiple benefits (not necessarily related to sea level rise) or involve little additional cost. Such options include:

- not reclaiming further land from the sea
- no further degradation of coastal wetlands and estuaries
- Protecting dune cordons
- integrating sea level rise scenarios into future planning decisions
- incorporating sea-level rise risks in disaster management strategies
- maintaining coastal storm-water infrastructure
- decentralising strategic services infrastructure.

Whilst the no regrets options outlined above are uncontroversial in their scope and should be, and in many cases already are being, pursued as part of South Africa's ongoing development, adaptation to sea level rise will also require targeted interventions aimed at managing specific aspects of the risk. These interventions involve new investment, new approaches and in most instances some form of trade-off or cost – they are additional to business as usual.

4.4.2. Infrastructure options

Hard engineering techniques – seawalls, groynes, detached breakwaters, and revetments – have historically provided a first recourse for coastal engineers in South Africa. Physical sea defences are typically costly, often result in unforeseen adverse consequences and do not provide absolute guarantees against inundation and storm surges. They do, however, provide developers with a false sense of confidence with which to pursue coastal construction, some of which is complicit in exacerbating the risk. In spite of this, infrastructural sea defences continue to be used in specific contexts – most notably where it is prohibitively expensive to relocate infrastructure or settlements. The key to success with all physical sea defences is that they be based on an intimate understanding of near-shore processes including currents, dune mobility, species migration and wave action.

4.4.3. Biological options

Biological responses to sea level rise rely on vegetation and existing ecosystem buffers and are often categorised as ecosystem based adaptation. These include dune rehabilitation, estuary and wetland rehabilitation and maintenance of kelp beds. Biological options, like infrastructural options, are difficult to implement well and as with infrastructural options they seldom provide an absolute solution to sea level rise risk. They are, however, typically cheaper and more labour intensive than infrastructural options and pose less risk of adverse consequences. Crucially, biological responses tend to leave the option of complementary social and infrastructural options open, whilst infrastructural options often comprise a last resort. Particularly where sea level rise risk is being exacerbated by degraded ecological buffers, biological interventions can be highly effective.

4.4.4. Socio-institutional responses

Climate change adaptation is increasingly being seen as a social and institutional change process (Downing and Dyszynski 2011). Socio-institutional responses do not preclude physical and biological responses; indeed the success of physical and biological approaches is in many ways dependent on a supportive institutional environment (Cartwright et al. 2013). Most institutional responses to sea level rise risk focus on increasing the capacity of people, legislation and agencies to cope with the problem as a means of reducing risk. Identifying vulnerability, communicating risk, implementing coastal set-back lines, early warning systems and insurance market corrections are all considered as potential social and institutional adaptation responses for reducing sea level risk and vulnerability in South Africa.

On the issue of implementing coastal set-back lines, South Africa's Integrated Coastal Management Act, Act No. 24 of 2008 (ICMA) makes set-back lines a legal requirement. The ICMA defines a set-back as a "… line determined by an MEC[1] in accordance with section 25 [of the ICMA] in order to demarcate an area within which development will be prohibited or controlled in order to achieve the objectives of this Act or coastal management objectives;" (DEA 2008:18) and speaks to the need to retain the coast as a shared and common asset, to retain the aesthetic and heritage value of the coast and to protect coastal biodiversity. As these are intended as long term demarcations the setting of coastal set-back lines should adopt a precautionary principal and take into account potential future sea level rise impacts.

1 MEC: Member of the Executive Council. The executive council is the cabinet of the provincial government.

In the context of sea level rise risk coastal set-back zones are, "Frankly just good planning" (Mather 2007) and can be justified against the cost of foregone development by their ability to mitigate the costs of dealing with sea level rise damage. In a cost-benefit study of climate change adaptation options in eThekwini Municipality, the implementation of a coastal set-back line emerged as among the top-three (out of 48) in terms of cost-benefit under a range of scenarios (Mather 2007).

4.5. Summary of adaptation responses for South Africa under future climates

The recommendations for adaptation options show a number of **cross-cutting issues** for mitigation of increasing drought, floods and sediment loads that are **applicable across a range of climate futures** and therefore represent **no regrets options** that should be implemented. These include:

- Continuous monitoring and drought/flood early warning systems.
- Improved land care, catchment management and water sensitive urban design.
- Enforcement of current zoning practices to reduce the number of people in flood-risk areas.
- Routine maintenance and correct operation of existing infrastructure
- Integrated design and planning that takes into account climate risks and change uncertainty.
- Improved safety nets and diversification of livelihoods for particularly vulnerable groups.

These no regrets options tend to be institutional in nature rather than requiring hard engineering solutions.

In specific cases adaptation should consider engineering solutions (both soft and hard), but unlike changes in land care and catchment management or climate change mitigation, these solutions tend to address the symptoms and not the cause of increased disaster risks. It is important therefore that adaptation addresses **all aspects of the risk equation**, including improved resilience and capacity.

Under a **drying future** (either nationally or in specific regions of the country) adaptation should include a review of the resilience of existing water supply systems with a particular focus on **improved integration and diversification** of the current stand-alone water resources systems. Future **food security** and **food sovereignty** also require increased integration and diversification at national and regional (SADC-wide) scale and these should be considered as potential adaptation options.

Under a **wetting future**, adaption options need to include a review of **current flood risk and design standards**, changes to urban **flood retention** and **flood mitigation** works, focus on water sensitive design of municipal infrastructure and changes to the operating rules of large dams with an increased flood control role. The latter requires consideration of the trade-off with increasing drought risks.

For sea level rise the most appropriate adaptation option is **managed retreat through the demarcation and enforcement of coastal set-back lines** that incorporate future sea level rise. In certain situations hard engineering solutions could be considered, but care must be taken that these solutions do not simply move the problem onto somewhere else where the impacts may be just as significant, if not more substantial.

5. FUTURE RESEARCH NEEDS, FUTURE ADAPTATION WORK AND DOWNSCALING

The results from this study have shown that there are significant spatial variations in the potential impacts as well as the adaptation options under different climate models across the country. It is therefore almost impossible to develop a national-scale strategy for implementation of adaptation responses to the increased risks under future climate change; therefore, **further local and regional studies are critically required**.

It is essential that the initial analysis undertaken here is used to inform more detailed assessments at regional level in order to identify appropriate risks and responses. For example, a consistent approach needs to be developed to incorporate climate change impacts into the **DWA reconciliation studies** for individual bulk water supply systems as well as the more vulnerable stand-alone systems.

Separately, the DWA needs to consider whether specific **flood operating rules** (for example, draw-down of dams prior to the onset of the flood season) should be considered in particular regions of the country.

The value of **ecosystem based adaptation measures** has been highlighted across all aspects of disaster risk in this study (droughts, floods, sediment and sea level rise). These approaches therefore represent a critical no regrets and multi-objective adaptation response that should be investigated further.

It is even more critical that potential flooding impacts be considered at **local level**. This study has provided an overview of potential impacts in terms of changes in the magnitude of design flood estimates, but more **detailed hydrological and hydraulic analysis** is required to investigate the specific risk and adaptation options for individual critical infrastructure, ecosystems, and human settlements.

This study has shown that it may be necessary to consider **reviewing existing design standards**. The responsibility for a review of these design standards should be designated to the relevant authority, for example:

- SANRAL and Transnet to review road- and rail-bridge design standards
- DWA/WRC to review dam safety design floods and potential for flood control
- Eskom to identify and review increased flood risks for critical power line crossings.

These results have shown that there are potentially significant increases in drought risks in certain parts of the country that could impact on regional economies as well as **national food security**. A more detailed analysis of **potential drought impacts on the agricultural sector** is required, as well as consideration of appropriate potential adaptation options, including **more regional (SADC-wide) integration**.

The models used in this study to investigate changes in flood risk are based on a selection of the original Coupled Model Intercomparison Project3 (CMIP3) global climate models that have been downscaled by the CSIR and further downscaled at quinary catchment level for use in the ACRU runoff model. Through the LTAS process (as well as the global Cornell Mixing Zone Model (CORMIX) initiative) an **updated set of CMIP5 regional climate models** is now available from both the CSIR and CSAG. It is critical that these models be further downscaled to generate a time-series of **daily streamflows** (using the ACRU model) for additional flood, drought and sediment impact analyses.

A **combination of the HFD and regionally downscaled climate models** should also be considered, as this would provide a wider range of potential impacts, but with increased resolution at a local level from the regional models.

The ACRU configurations used in this study were based on natural land cover types and so do not reflect the impact of **changes in land cover**, either as a result of human impacts or indirectly due to climate change. The sensitivity of changes in flood risks and sediment yields to these land use changes and the potential for climate change to drive these changes, needs further investigation. Of particular concern are major land cover changes such as bush encroachment of grassland areas and increased spread of invasive alien plants.

6. CONCLUSION

There is a general consensus for future warming across all parts of South Africa. The potential magnitude of this warming will vary across the country. The critical question is whether this will result in a hotter future, associated with a business-as-usual global situation of continued carbon intensive development, or only a warmer world resulting from global cooperation and reduced carbon dependence. Under both futures there is potential for wetting and drying scenarios both nationally and for specific regions within the country. Associated with this uncertainty is uncertainty in the potential impacts across the country in terms of future floods, droughts, sediment yields and sea level rise risks.

This study has undertaken an initial assessment of these potential risks though modelling of potential impacts of a selection of regionally downscaled climate models and a hybrid frequency distribution (HFD) of global climate models in support of developing adaptation scenarios for disaster risk reduction as part of the Long Term Adaptation Scenarios Research Flagship Programme (LTAS) in South Africa. The results show significant spatial and temporal variations in the potential impacts under the different climate models.

A consistent message from the HFD analysis is for increased drought and water supply risks in the Western Cape and potential for increased water resources availability to Gauteng and the Vaal system. In general the results suggest that the various highly developed and integrated water supply systems in South Africa provide resilience to climate change uncertainty, but that more detailed regional analysis is required – particularly focusing on the stand-alone systems, where the potential for increased integration and diversification of resources should be investigated as a potential adaptation option.

Analysis of the potential increases in flood risk using daily rainfall and streamflow outcomes of a selection of downscaled climate scenarios (A2 scenarios from the CSIR), show consistently increased flooding risks in parts of the country, including KwaZulu-Natal, the Eastern Cape, Limpopo, and the southern Cape, but not necessarily in all areas under the same climate model. Linking the potential increased flooding risk with the location of current key infrastructure shows the potential for high or very high impacts on the current design flood standards for more than 30% of bridges (road and rail), 19% of dams and 29% of ESKOM transmission line crossings across the country by mid-century.

Analysis of the potential climate change impacts shows the potential for increased sediment yields as a result of increasing flood frequency. Currently available empirical models, however, show only limited sensitivity, with potential changes in land cover and land use potentially of greater significance for increased sediment yields. Further research is required to investigate the impact of climate change directly on land cover and sensitivity to erosion and soil loss across the country. While the overall impact on the total sediment yield from a selection of 95 dam catchments across the country may have been small, there were significant impacts for some individual dams in certain parts of the country.

Analysis of the potential impacts of sea level rise showed that on a national scale the potential economic impacts were relatively small, given that South Africa does not have large areas of low-lying land or development on large deltas, but that the potential impacts at local scale could be quite significant. Of particular concern was the potential impact on the coastal tourism sector.

Although the specific impacts of individual adaptation options were not modelled in this study, the biophysical modelling results were used to provide recommendations for suitable adaptation options. These included a number of cross-cutting options that should be considered as no regrets options, as they would be applicable under multiple climate futures (both wetting and drying) and would increase resilience to multiple threats, including increased flood risk, erosion and sediment yield. They also tended to represent best practice options that should be pursued irrespective of the additional risk associated with future climate change. They could also be implemented at national level and generally across the country.

More detailed regional analysis and modelling is required to investigate specific adaptation options for individual locations or key areas of concern about infrastructure assets as part of future research.

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APPENDICES

Appendix A

On model selection, downscaling and bias correction of GCM output for design of hydrological applications, with emphasis on the CSIR GCMs. Report prepared by Prof. Roland Schulze.

Appendix B

Representative results using the HFD and JPV methodology to determine the potential impacts of climate change on annual flood peaks as a function of changes in mean annual runoff (MAR).

Appendix C

Modelling the potential economic impacts of sea level rise for South Africa. Report prepared by Anton Cartwright of Econologic.

Appendix D

Additional figures showing potential climate change impacts on frequency, severity and duration of droughts in six representative catchments across South Africa based on five regionally downscaled future climate models (GF0, GF1, MIR, MPI, UKM).

Appendix E

Additional figures showing potential climate change impacts on the threshold values for definition of mild (33% of the mean annual rainfall), moderate (20%) and severe (10%) meteorological droughts in six representative catchments under five regionally downscaled climate models.

Appendix F

Additional figures showing potential climate change impacts on the frequency, duration and severity of meteorological and hydrological droughts and the 1 in 10 year recurrence interval (annual exceedance probability (AEP) = 0.1) annual maximum rainfall and cumulative streamflow for all quaternary catchments across South Africa based on five regionally downscaled climate models from 1962 to 2100.

Appendix G

Additional figures that show the temporal variation of a range of recurrence interval (RI) floods and for the five different climate models for these six representative catchments till 2100.

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