LONG TERM ADAPTATION SCENARIOS

TOGETHER DEVELOPING ADAPTATION RESPONSES FOR FUTURE CLIMATES

ECONOMICS

environmental affairs
Department:
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giz

On behalf of:
Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety
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SANBI
Biodiversity for Life

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LONG-TERM ADAPTATION SCENARIOS FLAGSHIP RESEARCH PROGRAMME (LTAS)

THE ECONOMICS OF ADAPTATION TO FUTURE CLIMATES IN SOUTH AFRICA

AN INTEGRATED BIOPHYSICAL AND ECONOMIC ANALYSIS

LTAS Phase II, Technical Report (no. 6 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

ARC	Agricultural Research Council
CCAM	Conformal-Cubic Atmospheric Model
CGE	computabl general equilibrium (model)
CMIP3	Coupled Models Intercomparison Project Phase 3
CMIP5	Coupled Models Intercomparison Project Phase 5
CRU	Climate Reporting Unit
CSAG	Climate Systems Analysis Group
CSIR	Council for Scientific and Industrial Research
CU	University of Colorado
DAFF	Department of Agriculture, Forestry and Fisheries
DEA	Department of Environmental Affairs
DfID	Department for International Development
DUCC	development under climate change
DWA	Department of Water Affairs
EMC	Ecological Management Class
EPP	Employment Promotion Programme
EWR	ecological water requirements
GCM	global circulation model
GDP	gross domestic product
GIZ	Gesellschaft für Internationale Zusammenarbeit
GVA	gross value added
HFD	hybrid frequency distribution
IAM	integrated assessment model
IAP	invasive alien plants
IBT	inter-basin transfer

ICLICS	Institute of Climate and Civil Systems
IFPRI	Institute for Food and Policy Research
IGSM	Integrated Global System Model
IPCC	Intergovernmental Panel on Climate Change
IPSS	Infrastructure Planning System Support
IRRDEM	Irrigation Demand Model
L1S	level 1 stabilisation
LHWP	Lesotho Highlands Water Project
LTAS	Long Term Adaptation Scenarios
MAC	municipal adaptation cluster
MAP	mean annual precipitation
MAR	mean annual runoff
MIT	Massachusetts Institute of Technology
NCCRP	National Climate Change Response White Paper
NPV	net present value
NT	National Treasury
NWRS	National Water Resource Strategy
PET	potential evapotranspiration
RCM	regional climate model
RCP	representative concentration pathway
RSA	Republic of South Africa
SACRED	Systematic Assessment of Climate Resilient Development (framework)
SAM	social accounting matrix
SANBI	South African National Biodiversity Institute
SANCOLD	South African National Committee on Large Dams

SANRAL	South African National Roads Agency Limited
SFR	streamflow reduction
SPATSIM	spatial and time series information modelling
UCE	unconstrained emissions
UNU-WIDER	United Nations University – World Institute for Development Economics Research
WAA	water availability assessment
WARMS	Water Authorisation and Registration Management System
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 System Assessment Model (DWA database)

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REPORT OVERVIEW

The objective of this study is to develop an appropriate modelling framework and to provide a first order estimate of the potential macroeconomic impacts of future climate change on the South African economy by 2050. An integrated modelling framework has been used to estimate the potential impacts of multiple climate futures on water supply and demand for different sectors, irrigated and dryland crop impacts, and road infrastructure costs. These biophysical impacts are linked to a dynamic computable general equilibrium (CGE) model and translated into economic impacts in the context of world commodity prices that are affected by the same set of climate scenarios. The primary objective is to determine economic impacts at national scale, although sub-national analysis is possible and is considered at catchment scale as are economic impacts at water management area (WMA) scale.

The water and economic model simulates how resources are optimally reallocated in response to future climates, in effect representing autonomous adaptation responses. While the model assumes that adaptation through such altered resource allocation is autonomous, in reality the reallocation of resources would involve at least some policy intervention to facilitate it. Although alternative development and adaptation scenarios are not specifically modelled, the results of this study are used to provide recommendations on critical areas of concern, and to derive a number of key adaptation messages for which potential response actions are given. Recommendations are given for regional downscaling of potential impacts under future phases of the Longterm Adapation Scenarios Flagship Research Programme (LTAS) and other areas requiring further research.

Section 1 of the report gives a brief overview of potential economic impacts of future climate change.

Section 2 describes the general integrated assessment modelling framework with a brief description of the individual component models used and some of the key assumptions and simplifications required in both the biophysical and economic assessment of potential climate change impacts in South Africa.

The potential climate futures under the two mitigation scenarios, unconstrained emissions (UCE) and level 1 stabilisation (L1S) are described in **Section 3**. These are also evaluated in the context of the currently available South African regional downscaled climate models and the general LTAS climate futures of "hotter" and "warmer", "wetter" and "drier" as well as a number of South African regionally downscaled climate models. Further work, currently underway, will apply these regional downscaled climate models to the same integrated modelling framework to assess if the biophysical and economic impacts differ from the hybrid frequency distribution (HFD) results given here.

Results of biophysical and economic impacts are presented in **Section 4** and **Section 5** respectively.

Key messages on impacts and adaptation derived from the model results are presented in **Section 6**.

Section 7 describes future research needs including recommendations for further regional downscaling.

The final section of the report, **Section 8**, presents a general conclusion.

EXECUTIVE SUMMARY

This study represents the first attempt at an integrated approach to modelling the potential impacts of climate change on the national economy of South Africa via a number of, but not necessarily all, impact channels. The study focuses primarily on national economic impacts by 2050 under a wide range of potential climate futures using a computable general equilibrium (CGE) model of the South African economy, and at sub-national scale to investigate potential regional impacts at the level of the 19 individual water management areas (WMA). The CGE model is supported by a national scale water supply system model configured at the secondary catchment level, and incorporating all the major dams and inter-basin transfer systems, a dryland crop model, and an impacts assessment model for roads infrastructure at national and provincial scale.

This study identifies some critical **areas of concern in terms of future climate change impacts and adaptation,** such as the **potential water supply impacts in the western and southern Cape,** the **significant risk to road infrastructure across the country, increases in irrigation demand** and the potential **reduction in crop yields from staple crops** such as maize and wheat. Overall the economic impact is found to be **most significant at a regional, namely sub-national, scale and for specific sectors such as dryland agriculture.** Although there are many **negative impacts** identified there are also **potential positive benefits** in some sectors and in some areas of the country.

While the annual impact on gross domestic product (GDP) and GDP growth was found to be relatively low as a percentage, the net present value (NPV) of the cumulative impact on GDP by 2050 is highly variable, ranging from **losses of R930 billion to gains of R310 billion (real 2007 rand), with 96% of the climate scenarios showing overall losses. These losses result primarily from the potential impacts on dryland agriculture and on roads infrastructure. The median loss in NPV under the unconstrained emissions (UCE) or "hotter" scenario is approximately R259 billion by 2050. At more than 10% of 2007 GDP, this is sizeable and should motivate for action in terms of both mitigation and consideration and funding of potential adaptation scenarios.**

The study also provides some insights into potential impacts on the nature of **future employment** and **inequality**, although the results are not conclusive and **further research is required**.

The results from this study highlight the significance of **endogenous adaptation (namely individual market related responses to climate change) in providing resilience to future climate change. These results** should be used to **identify key enabling mechanisms** to support endogenous adaptation and **not to limit the potential for individuals to respond to a changing climate. This would potentially result in the most efficient use of the available resources including water, land, labour and capital and allow adaptation irrespective of the nature and direction of change.**

Some recommendations for **future research** are derived, in particular the need for more detailed **regional and sector-specific modelling** of potential climate change impacts and adaptation options, as well as developing **standardised approaches to incorporating climate change into existing infrastructure and water resources planning and other national or regional planning studies.**

While this study has modelled the potential biophysical and economic impacts of a wide range of potential climate change impacts, only a single baseline development scenario was considered and **alternative development and adaptation options were not modelled.** Nonetheless, the model structure is well suited to modelling these alternative future scenarios and the model results are used to derive a number of conclusions on the requirements and potential impacts of alternative development and adaptation options. Key points derived from this study and informed by discussions at various national stakeholder workshops during the LTAS process include:

1. **Addressing current development needs in a way that** leads to a more robust and flexible society is an excellent form of adaptation, but must include protection for **natural systems.**
2. **Adaptation and mitigation together** are required to address the risks of climate change.
3. The capacity to **shift productive resources** from relatively unfavoured to relatively more favoured sectors/regions provides resilience and potentially mitigates future impacts.
4. Adaptation requires **investments now** that will pay **benefits in the future.**
5. Adaptation will require us to **rethink/redefine our current design and regulatory standards** in diverse areas such as roads, bridges, buildings, and land using planning and zoning.
6. There will be **winners as well as losers due to climate change,** certainly in relative terms. A key challenge is to find ways to benefit from the potential opportunities and mitigate losses.
7. **Vulnerable communities,** such as those which are dependent on dryland agriculture or a single water supply source or transport link, are more likely to be severely impacted by climate change.
8. **Economic impacts are likely to be most significant at sub-national and sector-based level.**
9. Adaptation requires us to **rethink concepts of national food security and food sovereignty.**
10. **Well planned and integrated water supply infrastructure** can increase resilience under future climate change uncertainty (and other development/ land cover/model uncertainties), but building more dams or inter-basin transfers (IBTs) is not necessarily an appropriate response.
11. **Adaptation in the water and transport sectors has additional costs** including the early implementation of more costly and energy intensive water supply options (for example, desalination) and increased pumping through IBT schemes or higher upfront construction costs for roads.

This study considers two future global emissions scenarios that are consistent with potential climate futures for South Africa determined during the LTAS. Firstly an **unconstrained emissions scenario (UCE)** is considered which is consistent with the more extreme "hot" LTAS climate future where global policies to reduce emissions fail to materialise. Secondly **a level 1 stabilisation scenario (L1S)** is considered, which is consistent with the "warmer" LTAS climate futures in which aggressive emissions policies are successful, thereby reducing the potential for future warming, but with global temperatures still increasing due to the legacy of current greenhouse gas emissions. In addition the climate futures contain both "wetter" and "drier" scenarios completing the full coverage of potential LTAS climate futures for South Africa.

For each emissions scenario, 6 800 possible climate futures were extracted from the Integrated Global System Model (IGSM) developed at the Massachusetts Institute of Technology (MIT). These climate futures represent 400 realisations of the outputs from 17 of the 22 global circulation models (GCMs) and hence capture the full range of plausible climate futures for South Africa. The range of potential climate futures are used to derive a hybrid frequency distribution (HFD) of possible climate futures that provide some measure of probability to future climate change scenarios across the country, which is critical for risk-based decision making. The results are described at both regional (catchment and water management area) and national scale.

This HFD analysis is also shown to encompass the **range of potential impacts** derived from statistically and dynamically downscaled **regional climate models** from both the University of Cape Town (UCT) Climate Systems Analysis Group (CSAG) and the Council for Scientific and Industrial Research (CSIR) respectively, that were also developed during phase 1 of the LTAS.

Despite a wide range of potential impacts on precipitation and runoff across the country, the results of the water supply model show that the impacts on the **main urban and industrial centres in Gauteng appear to be minimal and could even be positive.** This is due to the integrated nature of the Vaal system, the planned development of the Polihale Dam as part of the Lesotho Highlands Water Project (LHWP) and the fact that many of the global climate scenarios show potential wetting over the eastern half of the country including Lesotho and the upper Vaal River catchments.

In contrast, however the results **for all models predict a reduction in streamflow in the Western Cape including the Berg River catchment with a potential negative impact on future water supplies to Cape Town and for agriculture in the Western Cape.** The potential for a constrained future water supply may result in a **reallocation of water** from agriculture to urban and industrial demands in the region with knock on impacts for both the regional and national economy.

The greatest consistently negative impact on future water supply is in the Gouritz Water Management Area (WMA) where urban and bulk water supply are dependent on smaller and less integrated local resources and the climate models predict likely future drying. Similarly, in other areas of the country, while the median results show only limited impact, there are **still many future scenarios that show significant impacts,** both positive and negative on the future water supply to all sectors, particularly in areas dependent on a single local water supply source and not necessarily supported by the large-scale water transfer schemes that mitigate potential impacts in other areas.

This reduction in the buffer of water availability in the **Berg and Gouritz WMAs and under certain drier climate scenarios in other parts of the country is likely to result in increased vulnerability** to climate variability even by 2050. This requires further research and more detailed analysis of potential **regional impacts,** and of alternative development and adaptation scenarios.

In addition it is important to note that the results are based on changes in the **average annual water supply by 2050, and do not represent potential impacts of increased frequency of dry periods or multiple year droughts that could potentially impact on the long term yield of a system.** In addition the water supply model **does not take into account the potential negative impacts of increased flooding** under a wetter climate future that may well offset any potential benefits for supply.

In terms of **alternative mitigation scenarios,** the results of the water supply model show little difference in the median impact on the average annual streamflow or ability to supply future water demands between the UCE and LIS scenarios. The **risk of extreme impacts,** however, both in terms of potential flooding under the "wetter" scenarios and potential reduction in water supply and droughts under the "drier" scenarios are reduced under the LIS climate scenario.

The largest impact of mitigation is on future irrigation demands which are likely to increase

under all scenarios, but more so under the UCE scenario due to higher temperatures.

There are **significant advantages to mitigation** in terms of reducing future irrigation demands, the impact on dryland crops, and the potential costs of future impacts on road infrastructure, where mitigation is shown to have similar benefits to adaptation over the long term.

The results for the agricultural sector show a **general increase in irrigation demands** based on existing crop types and management practices due to increased evaporative demand across the country. These impacts vary across the country, with increases in some areas, notably the east coast and KwaZulu-Natal, potentially being offset by increases in precipitation. Overall, the median impact on the total average annual irrigation demand across the country under the UCE scenario is an increase of about 6.3%, but with some models showing a total increase of up to 12% across the country, and with some individual catchments showing possible increases of up to 25% under very dry scenarios. It is possible, however, recalling the 2050 time frame, that this level of increase can be addressed through **improved irrigation practices and the development of new crop varieties,** although there is a cost associated with these adaptation options that must be considered and ongoing research is required.

The potential impacts on dryland crop yields are mixed with some crops even showing a potential increase in yields due to regional variations in precipitation, while others show a general reduction in potential yields. **Of most concern is the likely reduction in the total average annual yields from maize and wheat of around 3.5% and 4.3% respectively for the median impact scenario by 2050.** There is, however, a very wide range of potential impacts from a worst-case **reduction of 25% in the total average annual maize yield** to a possible increase of 10% under some very wet scenarios. **All future climate scenarios show some level of reduction in wheat yields from the Western Cape catchments due to a consistent reduction in future average annual precipitation in this region.**

The study of potential impacts on **roads infrastructure** shows significant advantages in implementing adaptation options for the repair and rehabilitation of the existing roads network, particularly in the **second half of the century when the costs for no adaptation overtake the costs for adaptation.** By the end of the century the median annual additional costs for road rehabilitation and repair will be approximately R19 billion under the UCE "no-adapt" scenario, but only R6 billion under the LIS "no-adapt" scenario and R4 billion under the "adapt" scenario for both UCE and LIS. **The greatest total economic impacts are in the Eastern Cape due to the large number of roads in this province.** Given that the average design life of a major road is 30 years, it is important that adaptation measures are implemented sooner rather than later as it will take time to roll over the entire roads inventory.

The results from the individual impact channels (water, agriculture, roads) provide inputs to the economic model. **The total impact of climate change on real GDP is found to range between -3.8% and 0.3% for the UCE scenario, although results indicate that, for the very large majority of climate futures, the impact on total GDP will be negative.** The median result shows that by 2050, South Africa's real GDP level will be about **1.5% lower than in the baseline scenario. This translates into a 0.03 percentage point decline in the average annual real GDP growth rate. However, the net present value (NPV) of the cumulative impact of the median UCE scenario up until 2050 is a loss to the economy of around R259 billon (real 2007 rand) or 10% of GDP, and the impacts from individual drier and wetter models range from losses of R930 billion to gains of R310 billion.**

Employment growth is, both in the economic model used for the analysis and in reality, vastly more sensitive to labour market policies and institutions. Consequently, the potential **impacts of climate change, at least at national scale, were found to be overshadowed by these other uncertainties.** It is clear, however, that a more **flexible and diverse labour market is likely to provide resilience under future climate and other uncertainties** as it allows for the **movement of labour and other resources (land, water and capital) between regions and between sectors that are more or less impacted by climate change.** This requires further research as a critical adaptation mechanism.

From the perspective of **overall GDP growth,** the impacts of climate change may be quite **small at national level.** However, when looking more closely at the **spatial and sectoral impacts,** there are cases where **the impacts, particularly on agriculture, become large and highly variable across climate futures.** Focusing on agriculture, there are three key findings from the **regional analysis** that have implications for potential future development scenarios and adaptation options.

The first is the **large variability in results, especially in areas with high poverty rates.** The dependence of many of these regions on dryland agriculture makes them **particularly susceptible to changes in temperature and precipitation.** The wide variation in agricultural value added means that the outlook for these types of workers is uncertain, which could exacerbate the degree of poverty in these areas. One such region is KwaZulu-Natal (water management areas 6, 7, and 11), which has the second highest poverty rate and in which the impact of climate change is highly variable depending on the climate future.

The second salient result is the **impact of climate change on agriculturally important areas, such as the Vaal region** (water management areas 8, 9 and 10). The Vaal region is a major domestic producer of summer cereals, winter cereals, and oilseeds, and accounts for about one quarter of national agricultural value added. In water management areas 8 and 9, more than 55% of climate futures indicate that agricultural value added deteriorates by more than 10%, and about 23% of climate futures suggest this deterioration exceeds 20%. This could have sizeable impacts on national agricultural production, and additional implications for food security.

Thirdly, the results identify regions with almost **universally negative impacts on agriculture.** These include the Olifants/Doorn (WMA 17) and the Berg (WMA 19) catchments in the Western Cape. **These areas are important domestic producers of winter cereals, deciduous fruits, viticulture and vegetables.** Deciduous fruit is a high value commodity and, as over 60% of it is exported, an important agricultural export commodity. The same is true for wine and grapes. More than 99% of climate futures show deteriorating agricultural value added in water management area 17, and more than 96% of climate futures indicate lower agricultural value added in water management area 19.

Given the high variations in results, particularly in agriculture, **there is no doubt that some households will suffer as a consequence of climate change, while others may gain.** The full implications of these changes for the distribution of income are only roughly captured in the existing modelling framework, which finds no major shifts in the overall distribution of income as a consequence of climate change.

It is also important to note that there is a large amount of **endogenous adaptation** within the economic model that highlights the importance of considering the overall structure of the economy. The economic model assumes that resources including water, labour, land and capital can move between sectors and, in the case of capital, between regions. **This allows individuals to respond to different climate stressors and seek out the**

most efficient use of resources. The overall result is to limit the potential economic impacts of climate change. In reality, however, such movements may be more restricted in South Africa limiting the potential for endogenous adaptation.

An important aspect to adaptation is to identify inflexibilities in the South African economy that may prevent or drastically slow this endogenous adaptation. From the perspective of overall GDP and aggregate sectors, climate change appears highly likely to unfold in a context of economic growth, at least to 2050. In this context, resource allocation adjustments in response to climate change appear likely to mainly take the form of reductions or increases in growth rates across sectors or regions rather than actual shrinkage. These adjustments, however, accumulate significantly over time.

Finally, considerable effort has been expended in the LTAS process to construct and then integrate models that reflect South African realities. Nevertheless, as with any modelling effort, the suite of integrated models employed here contain shortfalls and oversimplifications. The models are not South Africa. The crucial value that the models offer is to structure thinking in a rigorous way in order to achieve insights that would be difficult to obtain in their absence.

In future, the framework employed can, no doubt, be improved. As climate change seems unlikely to disappear, this will not be the last opportunity to investigate potential economic impacts. The modelling framework developed for this study should be used as a platform for future analysis with continual refinements where required, and to target specific issues or regional areas of concern given the uncertainty of future climates and impacts.

1. INTRODUCTION

The consequences of climate change are generally manifested through a series of impact channels that cover all aspects of society and economic development (IPCC 2007). A study by the World Bank entitled The Cost to Developing Countries of Adapting to Climate Change (World Bank 2010a) concluded that the cost between 2010 and 2050 of adapting to an approximately 2 °C warmer world by 2050 is in the **range of $75 billion to $100 billion a year.** While this represents a significant cost it is a relatively small percentage of total GDP and of the same order of magnitude as the amount of foreign aid that developed countries now give developing countries each year. Consideration of GDP impacts also does not address potential impacts on inequality and livelihoods, particularly of vulnerable groups.

Four key lessons stand out from the results of the above study that are applicable in South Africa:

- Adaptation to a 2 °C warmer world will be costly but manageable, as it represents a relatively small percentage of GDP and is equivalent to current foreign aid contributions.
- The world cannot afford to neglect mitigation as mitigation addresses the root cause of climate change, while adaptation only reduces the symptoms and decreases the impact/risk.
- Development is imperative as the best form of adaptation, but it must take a new form.
- Uncertainties are still large, both in terms of future climate and future development scenarios, so robust and flexible policies and further research are both needed.

A limited number of studies have attempted to quantify the economic consequences of climate change in South Africa. Many of these focus on the impact on the agriculture sector, using econometric approaches to determine the impact of climate and other variables on net farm revenues (see, for example, Gbetibouo & Hassan 2005; Turpie & Visser 2012; Blignaut et al. 2009). These studies find that climate change generally has a negative impact on the agriculture sector, primarily as a result of higher temperatures.

Turpie et al. (2002) provides preliminary estimates of the economic cost of unmitigated climate change to biodiversity, agricultural systems, infrastructure and human health. The study highlights considerable losses in tourism and existence value attached to biodiversity, as well as a lower value of the subsistence use of forest resources. Moreover, sizeable losses stem from mortality and morbidity impacts from higher malaria risks.

These studies, however, fall short of capturing the macroeconomic impacts of climate change, and may omit the agricultural impact on other activities, income and spending, as well as other key sectors like roads. To our knowledge there are no studies that have taken an integrated modelling approach that incorporates biophysical and economic impacts of climate change in South Africa.

The objective of this study is to undertake a risk-based assessment of the potential macroeconomic impacts of future climate change on the South African economy using an integrated assessment model (IAM) of potential biophysical impacts of key impact channels, and a dynamic computable general equilibrium (CGE) model to simulate the economy-wide impacts from 2010 to 2050 under a number of possible future climate scenarios. This report is based primarily on the modelling results of a UNU-WIDER study undertaken for National Treasury in support of the assessment of the potential economic impacts of climate change in South Africa (Cullis et al. 2015). The future climate scenarios include both "warmer" and "hotter", and "wetter" and "dryer" scenarios that are in line with the anticipated four possible climate futures derived as part of the Long Term Adaptation Scenarios Flagship Research Programme (LTAS). The results of this study should be used to inform discussions around potential alternative future development and adaptation scenarios as part of the LTAS programme and ultimately contribute to the third national communication on climate change to the Intergovernmental Panel on Climate Change (IPCC) as well as future national and regional development planning for South Africa.

2. METHODOLOGY

2.1. Integrated modelling framework

The general modelling framework for translating climate change impacts to economic impacts is shown in **Figure 1**. This general framework has been implemented for a similar assessment of the potential economic impacts of climate change in Mozambique (Arndt et al. 2011), Vietnam (UNU-WIDER 2012) and the Zambezi River Basin (Schlosser & Strzepek 2013) and is generally referred to as the Systematic Assessment of Climate Resilient Development (SACRED) framework. The focus of this study is on the biophysical modelling of the three primary impact channels shown in **Figure 1**, namely (i) water supply and water use (including urban, industrial and agricultural); (ii) roads; and (iii) coastal infrastructure. These impacts are then integrated through a dynamic computable general equilibrium (CGE) model at national and sub-national, namely water management area, (WMA) level (Thurlow 2008).

The strength of the modelling framework is that it is generic and individual models can be selected to fill each of the boxes in the framework. Where possible models currently used in South Africa have been used and adapted where necessary for the specific objectives of this study. The following sections provide a brief description of the models used in each of the components of the framework.

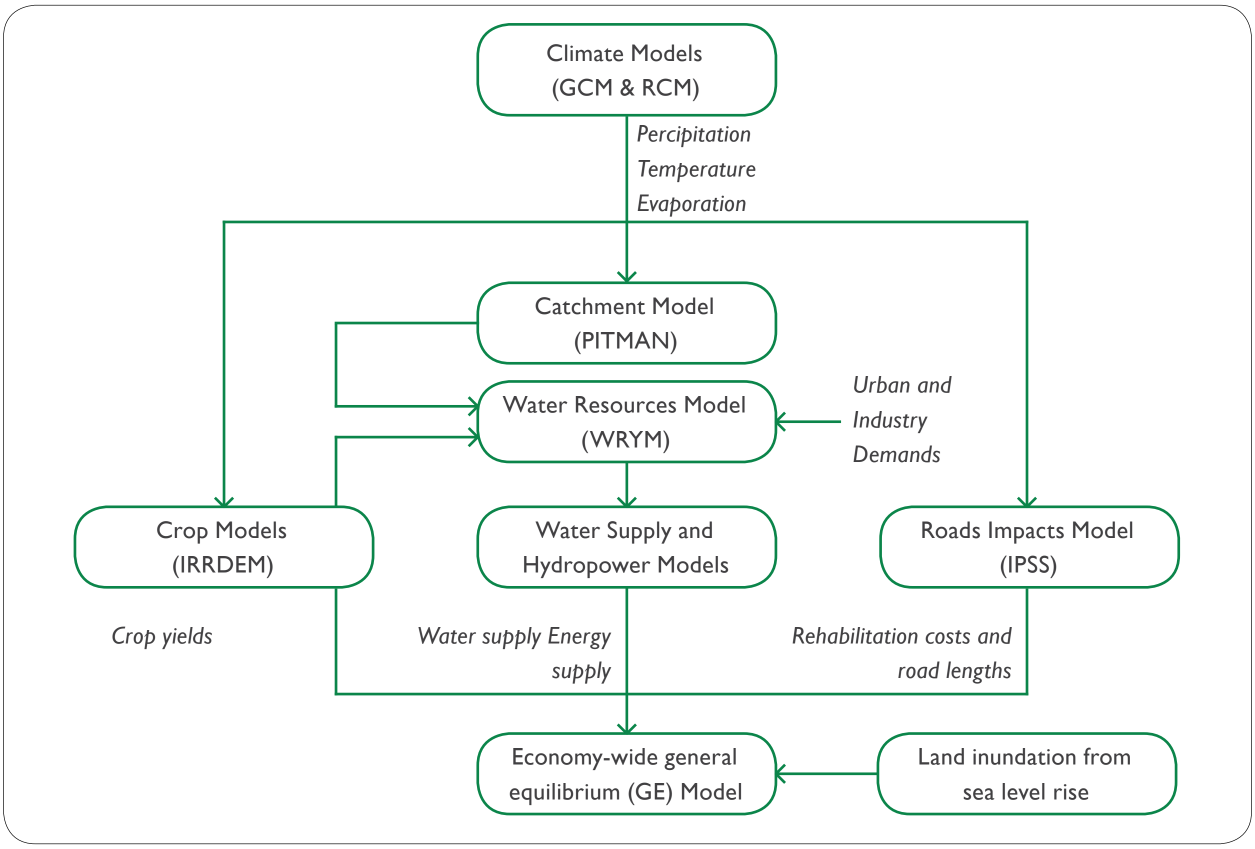


Figure 1: Integrated modelling framework.

2.2. Future climate change impacts

2.2.1. Hybrid frequency distribution of potential climate change impacts

The climate change impacts used in this study result from consideration of a hybrid frequency distribution (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 Massachusetts Institute of Technology (MIT) Integrated Global System Model (IGSM) (Sokolov et al. 2009) with a set of pattern kernels of regional climate change from the global circulation models (GCMs) of the Intergovernmental Panel on Climate Change (IPCC) Fourth 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 under a range of global climate policies (Webster et al. 2012). We present 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 stabilisation (L1S) policy in Webster et al. (2012).

This hybridisation approach is based on 400 realisations of the IGSM model and applied to 17 of the available GCMs that were found to have a constant latitudinal zonal pattern. This results in a total of 6 800 possible climate futures. The 6 800 scenarios were reduced to a more manageable set of 367 climate futures for each of two emission scenarios using a process of quadrature thinning which maintains the statistical structure of the original full set of scenarios (Arndt et al. 2006).

Outputs from the HFDs were used to develop a time series of absolute changes (in degrees or mm) in the average monthly temperature and precipitation for each quaternary catchment across South Africa for the period 2010 to 2050. Temperature and precipitation impacts were also used to determine possible changes in monthly evaporation using the modified Hargreaves equation (Hargreaves 2003). The absolute changes were then applied to a baseline scenario to generate monthly time series information at quaternary catchment scale. The baseline scenario used was monthly precipitation and evaporation data for all quaternary catchments for the period 1950 to 2000 available from the WR2005 database (Middleton & Bailey 2008) as shown in **Figure 2**.

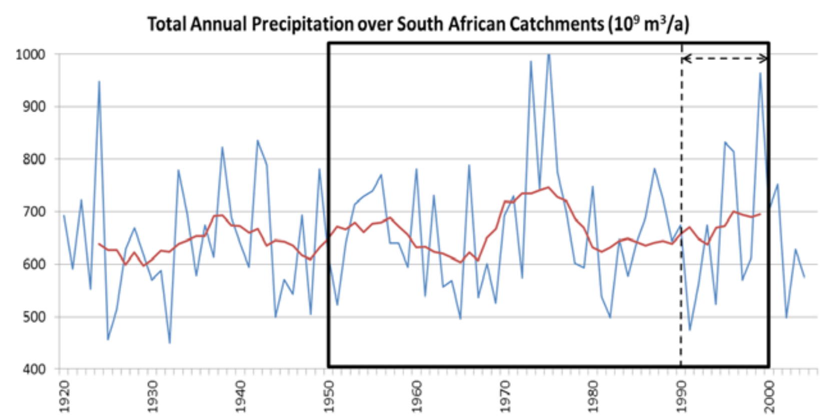


Figure 2: Total annual precipitation over South African catchments (109m3/a) showing the period 1950 to 2000 used as the base scenario for simulation of the climate change impacts from 2000 to 2050. Also indicated is the last ten year period used to determine the potential impacts by mid-century (WR2005 database).

As an initial estimate we assume that the baseline climate scenario for the period 2000 to 2050 is similar to that experienced for the period 1950 to 2000. The baseline scenario assumes that future weather patterns will retain the characteristics of historical climate variability. The purpose of the baseline scenario is not to predict future weather patterns but to provide a counterfactual for the climate change scenarios. A clear limitation of using only a single baseline climate scenario is that it does not fully account for current climate variability and this needs to be addressed in future studies.

A time-series of future climate scenarios is developed relative to the assumed baseline and then run through the systems of integrated biophysical impact models and the economic model to simulate the potential development over the next fifty years in response to the future climate change impacts. For comparison of scenarios, the average change in a selection of key indicators (precipitation, streamflow, water supply, GDP, and so on) are determined relative to the base scenario over the last ten years of the simulation (namely for the period 2040 to 2050 as shown in **Figure 2**).

The use of a large ensemble of multi-model outputs such as that generated using the IGSM and the HFD approach allows for a risk-based approach to considering potential climate change impacts rather than focusing on the detailed modelling of a few scenarios (Schlosser 2012).

2.2.2. *Future climate scenarios for the long term adaptation scenarios programme*

The HFD approach is consistent with the four general climate futures resulting from LTAS phase 1. The four LTAS climate futures are derived from an interpretation of a range of regional and global climate model predictions for South Africa and are described in terms of global scenarios as:

1. **Warmer (<3° C above 1961-2000) and wetter** with greater frequency of extreme rainfall
2. **Warmer (<3° C above 1961-2000) and drier** with an increase in the frequency of drought events and somewhat greater frequency of extreme rainfall events.
3. **Hotter (>3° C above 1961-2000) and wetter** with substantially greater frequency of extreme rainfall events.
4. **Hotter (<3° C above 1961-2000) and drier** with a substantial increase in the frequency of drought events and somewhat greater frequency of extreme rainfall events.

The warmer and hotter futures are also considered to be consistent with global mitigation scenarios, with the hotter future resulting from business as usual and a continued high dependence on fossil fuels, while the warmer scenario results from increased global cooperation, increased mitigation and a more sustainable future but recognising that some future warming is inevitable.

Figure 3 shows the regional variability of the LTAS climate futures in terms of precipitation.

The UCE and the LIS mitigation scenarios represent the hotter, more carbonised, and warmer, less carbonised, futures of the generalised LTAS future climate scenarios respectively. The HFD scenarios include a range of both wetter and drier scenarios that are consistent with and cover a wider range of potential climate futures for South Africa as identified through the LTAS process (DEA 2013). The HFD approach therefore represents a comprehensive range of future scenarios and the results can be interpreted at multiple scales for the four general LTAS climate futures.

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 3: Summary of possible impacts of climate change on precipitation across six hydro-climatic zones in South Africa under four possible climate futures identified as part of phase 1 of the Long Term Adaptation Scenarios Programme (LTAS) (DEA 2013).

2.2.3. Regional downscaled climate scenarios for South Africa

Although the HFD scenarios are considered to represent the range of possible climate futures identified during LTAS phase 1, the results are also compared with a number of regionally downscaled climate scenarios for South Africa. These represent results of both phases of the Coupled Models Intercomparison Project phase 3 and 5 (CMIP3 and CMIP5) global circulation models subject to both statistical downscaling by the Climate Systems Analysis Group (CSAG) at the University of Cape Town (UCT), and dynamic downscaling using the conformal-cubic atmospheric model (CCAM) by the Council for Industrial and Scientific Research (CSIR). A total of 31 regional downscaled climate models consisting of CMIP3 and CMIP5 results as well as representative concentration pathways (RCPs) 4.5 and 8.5 emission scenarios were considered for comparison with the results of the HFD analysis.

Results of the comparison of the HFD scenarios with the regional downscaled scenarios are presented in section 3 in terms of the main climate drivers in six hydro-climatic zones across South Africa, and in terms of water supply impacts at WMA level in **Section 4.3.3**.

2.3. Catchment runoff model

South Africa is divided into a number of primary, secondary, tertiary and quaternary catchments. There are over 1 500 quaternary catchments with an average catchment size of 573 km^2. The Pitman model (Pitman 1973) was used to determine a time series of monthly catchment runoff for all quaternary catchments in South Africa for both UCE and LIS emission scenarios using the existing calibrated parameters from the Water Resources 1990 (WR90) database (Midgley et al. 1994) and for the period 2000 to 2050 using the historical precipitation and evaporation data for the period 1950 to 2000 as the base scenario.

The Pitman model has become one of the most widely used monthly time-step rainfall-runoff models within southern Africa (Hughes et al. 2006) and is still the basis for current models used for all water resources planning studies in South Africa (Pitman et al. 2006). The Pitman model is a calibrated monthly model which is suitable for water resources planning, but not for investigations of potential flooding impacts or land use change impacts. The Pitman model was used because calibrated parameter values were already available for all catchments in South Africa (Midgely et al. 1994).

2.4. Water supply model

The Department of Water Affairs (DWA) currently runs a number of detailed water resources system models for all the major water supply systems in the country. These are highly complex systems reflecting the complex nature and high level of infrastructure development in terms of dams, canals, tunnels, pipelines and inter-basin transfers in South Africa. These models are used to regularly review existing operating rules and to plan for future water resources development schemes.

Currently there is no single model of the overall water supply system for the whole country that can be used for strategic planning studies at national scale as was required for this study. For this reason a national configuration of the Water Resources Yield Model (WRYM) was developed specially for this study based on secondary catchment scale modelling units. The WRYM was selected as it is still the primary water resources modelling tool used by the DWA for systems analysis in South Africa.

2.4.1. Water resources yield model configuration

The Water Resources Yield Model (WRYM) was configured for the entire country on a secondary catchment scale (including catchments in Lesotho and Swaziland) based on a generic modelling unit shown in **Figure 4**.

Each modelling unit includes the following basic elements:

- Inflows from upstream nodes (From U/S) and outflows to downstream nodes (To D/S)
- Runoff from the catchment in question (Incr. Runoff).
- 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 m3/a (Large Dam).
- All other dams which were lumped into a single representative dam (or dummy dam), defined with physical characteristics making its modelled impact comparable to the combined effect of the individual dams it represents (Lumped Small Dams).
- Transfers and return flows 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 requirements of all individual users of the user type in question.
- The impact on runoff of streamflow reductions (SFRs) including commercial forestry and invasive alien plans (IAPs).
- Ecological water requirements (EWRs) located at the outlet of each secondary catchment.

Using the above approach individual modelling units were configured at secondary catchment scale for the whole of South Africa and interconnected for the entire country resulting in a representative national system model as shown in **Figure 5**.

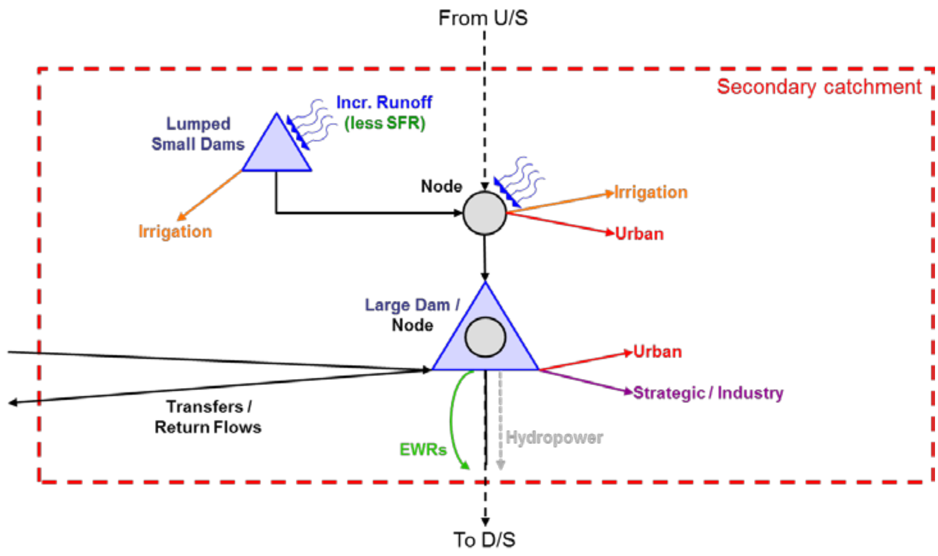


Figure 4: Generic modelling unit used for configuration of the WRYM

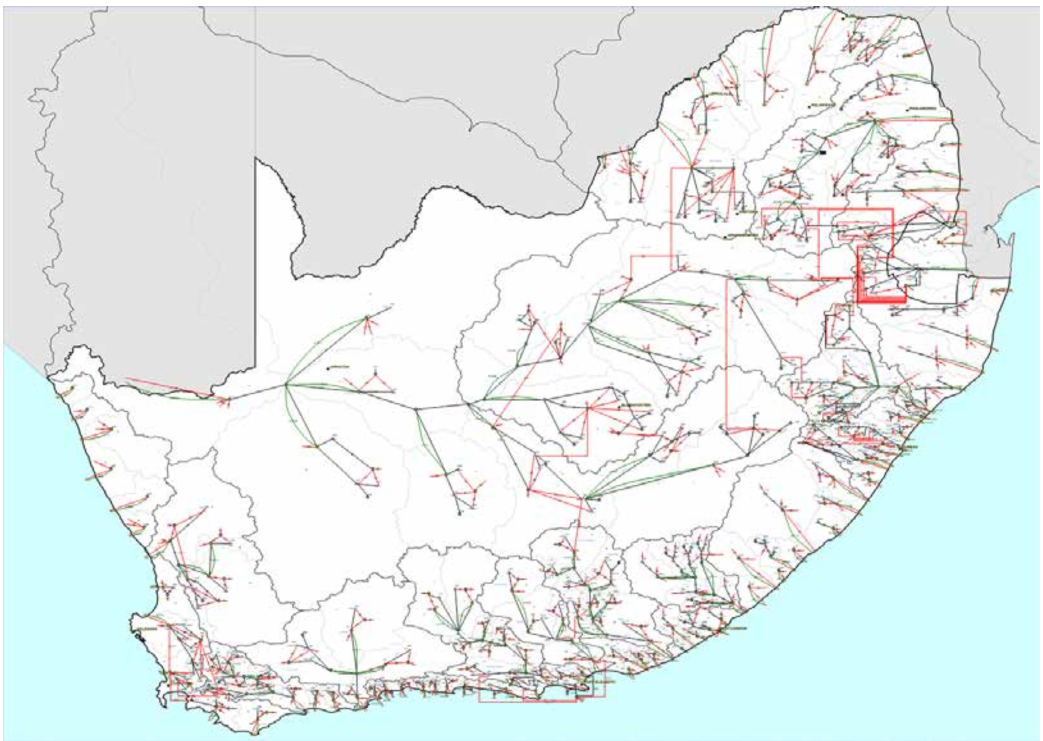


Figure 5: Schematic diagram of the national WRYM system model

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
- 1000 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 general 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 6**.

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 6 it is still a gross simplification of the true complexity of the water resources system in South Africa. Hence outputs from the model will most likely differ from similar outputs obtained from more detailed individual system models at local scale, particularly in terms of local system operating rules and allocation priorities.

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

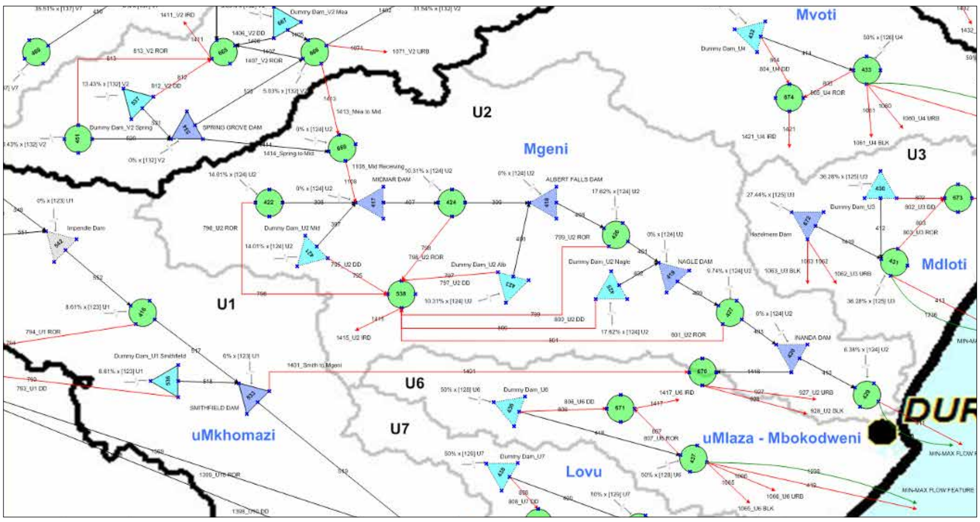


Figure 6: Details of a portion of the national WRYM system model (Mooi-Mgeni River System).

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 recommended, however, that more detailed modelling of the potential impacts on individual systems be undertaken through 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.

2.4.2. *Catchment runoff*

Outputs from the Pitman model (Pitman 1973) used to analyse the potential impacts of climate change on catchment runoff (described above) were used as the inputs to the WRYM. The time series of monthly runoff values generated at quaternary catchment scale were aggregated at secondary catchment scale taking into account potential channel losses which were varied as a function of relative changes in evaporation potential.

2.4.3. *Irrigation demands*

The impacts of climate change on irrigation demands were also determined using a simple water supply deficit model (Irrigation Demand Model (IRRDEM)) based on average monthly crop factors, changes in monthly precipitation and A-pan evaporation as currently used for water resources planning studies in South Africa (Pitman et al. 2006).

Current day crop areas and crop type distributions were used to estimate the future impact on irrigation demand based on the assumption that the DWA was unlikely to increase allocations to agriculture (DWAF 2004a). Hence any required increases in yields from irrigated agriculture, or to offset the potential impacts of climate change, must come from improved efficiencies of water use.

2.4.4. *Urban water demands*

Future demands for direct and indirect urban consumption were modelled based on the UN-median population growth estimate for South Africa and current estimates of per capita direct and indirect consumption from the DWA's Water System Assessment Model (WSAM) database (**Figure 7**). Any additional increases in per capita demands due to improvements in water supply and development were assumed to be met through reductions in the percentage of water lost through the distribution system and other inefficiencies which have been estimated to be around 30% on average across the country with some systems having 50% losses.

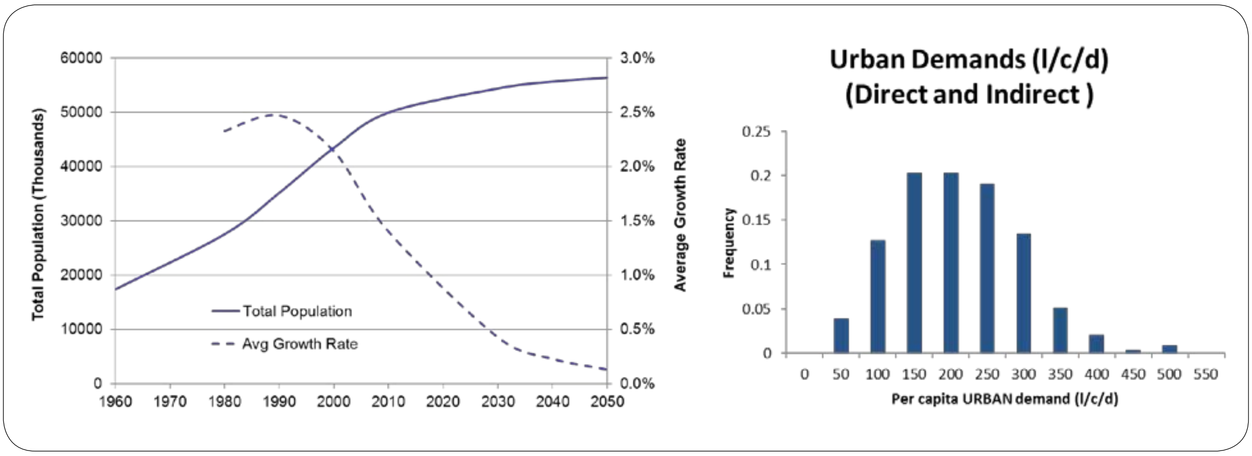


Figure 7: Future South African population growth (left) and the current distribution of average daily per capita demand (l/c/d) for direct and indirect urban water requirements for South Africa (WSAM database)

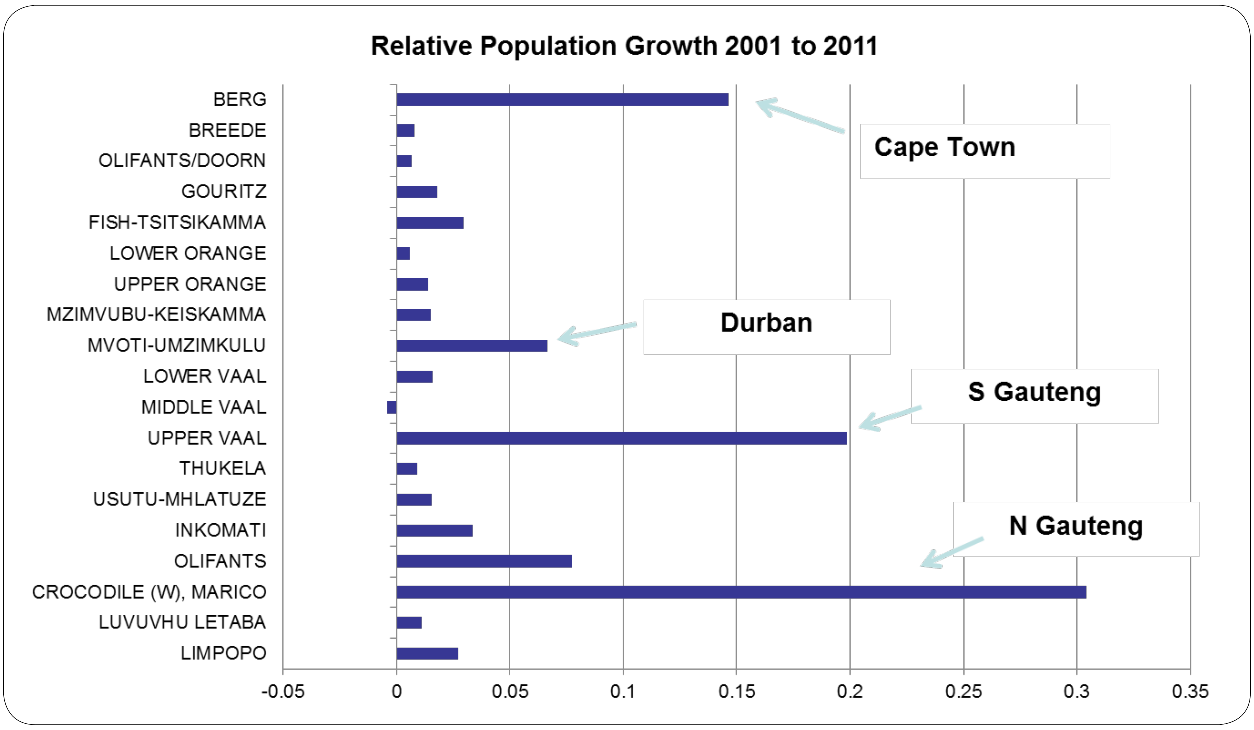


Figure 8: Relative population growth for individual water management areas (WMA) in South Africa based on comparison of the 2001 and 2011 national census regional population estimates.

To account for internal migration and variations in regional population growth rates, the future growth in population was also distributed across the country based on an analysis of the relative growth in population in the different quaternary catchments derived from a comparison of the 2011 and 2001 national population census, which reveals significant migration towards the main urban centres of Cape Town, Gauteng and Durban (**Figure 8**).

2.4.5. Bulk water demands

The estimate of annual bulk water requirements for each quaternary catchment in South Africa contained in the WSAM database was used. These demands were then increased at 1% per year out to 2050 to allow for future economic growth. It was assumed that an increase in economic growth in excess of 1% per year would have to be met without significant increases in the bulk water demand. However, in the Lephalale area in the North West Province (located in secondary catchment A4) modelled bulk water requirements were revised to account for anticipated future developments in the region associated with the commissioning of Eskom's Medupi power station, other planned power stations and a significant anticipated increase in coal and other mining activities in the area.

2.4.6. Forestry and invasive alien plants

Streamflow reductions due to commercial forestry and IAPs are also incorporated into the water resources yield model. The original Scott curves (Scott & Smith 1997) were used for predicting the percentage reduction in streamflows due to commercial forestry and IAPs. Commercial forestry was assumed to be represented by pines under optimal growing conditions with an average rotation of 10 years, and thus a 55% reduction in streamflow. Similarly, IAPs were assumed to be represented by pines under sub-optimal growing conditions with an average rotation of 15 years, with a streamflow reduction of 17% as for previous estimates of the potential impact of IAPs on water supply (Cullis et al. 2007). In additions to these assumptions, average densities of 100% and 25% were assumed for forestry and IAPs respectively.

These are considered to be conservative estimates of the potential reduction in streamflow due to both commercial forestry and IAPs, particularly under future climates with increasing temperatures and $C0_2$ concentrations that could result in significant increases in woody biomass. In the case of IAPs, the potential for significant increases in invasion due to poor management or climate shifts could also occur and should be considered in future research.

2.4.7. *Large dams and dummy dams*

Large dams, which were defined as those with a storage capacity greater than 50 million m^3 were modelled as individual elements in the national WRYM model. This included both existing and known major schemes that are likely to be implemented within the next 25 to 30 years. Dam characteristics information, including full supply, dead storage and bottom levels, as well as elevation-storage capacity-surface area relationships, were obtained from a variety of sources including:

- Existing WRYM model configurations, particularly those developed for recent DWA water availability assessment (WAA) and reconciliation strategy studies.
- The South African Dam Safety Database developed by the DWA Dam Safety Office.
- The SANCOLD database of medium and large dams.

All other registered dams were modelled as a single dummy dam per secondary catchment based on:

- The total storage capacity and surface area of small dams provided in the WR2005 database, aggregated up to either the secondary catchment level or to the incremental catchment area upstream of modelled major dams, as appropriate.
- An assumed linear area-capacity relationship.
- The assumption that 50% of catchment runoff is generated upstream of dummy dams.

2.4.8. *Evaporation from dams*

The WRYM accounts for evaporation losses from dams by including average monthly lake evaporation rates as part of the dam and reservoir characteristics in the model. In order to account for the impact of lake evaporation under each of the climate change scenarios, the system was modelled using the baseline evaporation for each dam and the precipitation time series were adjusted by subtracting, on a monthly basis, the difference in baseline evaporation and evaporation for the climate change scenario in question. This resulted in time series of climate change based net precipitation, namely the result of the combined impact of changing monthly precipitation and evaporation values for each dam.

2.4.9. *Ecological water requirements*

Ecological water requirements (EWRs) for the main dams were determined at the outlet of all secondary catchments using the desktop model in the spatial and time series information modelling (SPATSIM) framework (Hughes 2004). The selected ecological management class (EMC) was based on the current class listed in the WSAM database for the quaternary catchment located at the outlet of the secondary catchment in question.

2.4.10. Inter-basin transfers

Inter-basin transfer schemes, including known major schemes that are likely to be implemented within the next 25 to 30 years, were modelled based on information from:

- Existing WRYM model configurations, particularly those developed for recent DWA water availability assessment (WAA) and reconciliation strategy studies.
- The water authorisation and registration management system (WARMS) inter-basin transfer table, which includes a description, the source and recipient quaternary catchments, the end user (if applicable) and the maximum transfer capacity.

It should be noted that smaller schemes were excluded from the analysis, as well as those that occur within a single secondary catchment, since the national model was configured at a secondary catchment level. Consideration of these smaller dams and transfer schemes would be important in more detailed analysis of the potential climate change impacts at regional or local scale.

2.4.11. System operating rules

Generic operating rules were adopted for modelling the water resources within each secondary catchment and details for this are provided in the following sub-sections. The operating rules were implemented using the WRYM penalty structure functionality.

The following general priority of supply to water users was adopted (from highest to lowest priority):

- Ecological water requirements (EWRs)
- Bulk water users
- Urban water users
- Irrigation

The utilisation of water sources within a secondary catchment was prioritised on the basis that downstream sources are used before upstream sources (for example, a major dam at the bottom of the catchment is used before an upstream one) as this approach generally minimises spills resulting in higher overall system yields. Furthermore, dams were modelled to draw down entirely before utilisation of the next source of water. This approach was adopted in preference to more practical ones (such as dual drawdown of dams or subjecting water users to restrictions under severe drought conditions) in order to assess the absolute supply potential of the systems in question. Finally, it should be noted that EWRs were assumed to be supplied first from incremental runoff and spills (if available) and then by releases from major dams. Small dams were assumed not to make releases to supply EWRs.

In certain cases operating rules were customised to improve the modelled behaviour of the model for the system in question. This was particularly important for the larger systems in the country (such as the integrated Vaal River system) and relates mostly to the operation of inter-basin transfer schemes, the priority of water source utilisation and, in the case of the Vaal Dam, releases made to the downstream Vaal Barrage for water quality purposes.

2.5. Hydropower potential

Hydropower in South Africa is predominantly a secondary water use, where power is generated from releases of water from dams to supply users downstream. There are some smaller schemes built primarily for hydropower, but the larger schemes in the country, such as those at the Gariep and Vanderkloof dams are part of multi-purpose schemes where hydropower is a secondary benefit. There are a number of pump-storage schemes around the country, but they are operated in a closed system.

To quantify the potential impacts of climate change on hydropower generation and potential at national scale the most significant existing and planned hydropower schemes in the country were used to assess impacts. This included the two schemes on the Orange River, namely at the Vanderkloof and Gariep dams, as well as an earmarked scheme at Hartbeespoort Dam. Many other smaller schemes in the country that are important locally, are not significant for South Africa's power generation capacity as hydropower only constitutes a small portion of total energy production.

2.6. Dry-land crop yields

The impacts of climate change on dryland crop yields are determined based on empirical relationships between annual water availability and crop yields for the major field crops currently cultivated in South Africa as shown in **Figure 9**. These empirical relationships were developed by Thurlow (2008) using data from the Agricultural Research Council (ARC) using the following equation:

$$Y_i = \beta_{0i} + \beta_{1i} W_i + \beta_{2i} W$$

where Y_i: Output of crop type i per hectare of land (kg)

W: Annual amount of water used to produce this level of output (mm)

β_{0i}, β_{1i}, β_{2i}: Empirically derived coefficients for crop type i.

In the same way that increases in evaporation have an impact on irrigation demand it was important to consider the potential impact of increases in evaporative demand on dryland crops. As a first order estimate, we assumed that any increase (or decrease) in evaporation resulted in a similar increase in the water supply to achieve the same yield for the base scenario. Hence the empirical relationship between water supply and crop yield was adjusted as follows:

$$Y_i = \beta_{0i} + \beta_{1i} \left(\frac{W}{\Delta E}\right) + \beta_{2i} \left(\frac{W}{\Delta E}\right)^2$$

where ΔE: the ratio of the monthly evaporation for the given climate scenario to the monthly evaporation for the base scenario.

This revised crop yield equation was used to determine a first order estimate of the annual yield for the nine selected dryland crop types for each secondary catchment for the base scenario and all possible climate futures produced by the HFD model for the UCE and LIS scenarios.

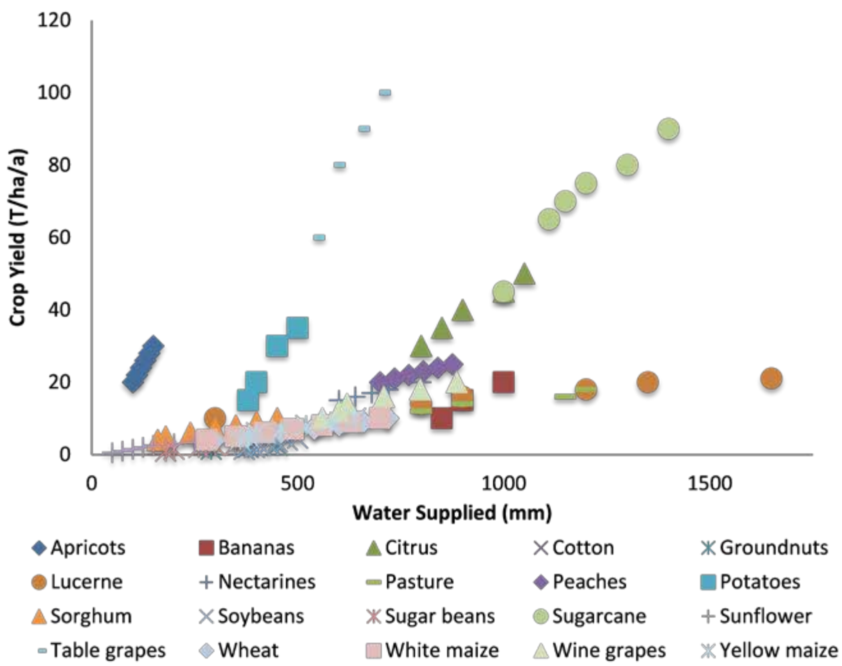


Figure 9: Empirical relationships between water supply and crop yields (after Thurlow 2008)

Other potential impacts of climate change on dryland crop yields such as direct temperature impacts including heating and chill units, flooding impacts, potential waterlogging or increased CO_2 fertilisation are not considered in this simple empirical model. Ignored also are the potential benefits from new and more resilient crop types, improved irrigation and agricultural practices or the expansion of existing crop types to new areas that become suitable for cultivation under future climate scenarios – although some allowance for efficiency gains is made in the economic model.

2.7. Roads impact model

The potential climate change impacts on roads infrastructure costs for South Africa was determined using the Integrated Planning System Support (IPSS) model developed by the Institute of Climate and Civil Systems (iCliCS) based in Boulder Colorado, USA (Chinowsky et al. 2011). The IPSS model is based on an engineering approach and the consideration of a proactive adaptation (adapt) and a reactive no adaptation (no adapt) scenario subject to potential climate change impacts on key stressor functions including temperature, precipitation and extreme events (flooding) (**Table 1**).

The adapt analysis assumes perfect foresight with respect to climate change impacts and a policy that applies these forward-looking climate projections to upgrade new roads as they are rebuilt and maintained. The adapt approach focuses on adjusting road design to improve resilience to climatic impacts. The no adapt analysis assumes no adaptation changes are put in place. Roads

Table 1: General scenario assumptions and impacts and adaptation responses for different road types

	No-adaption Scenario	Adaptation Scenario
	General scenario assumptions	
Planning	Assumes no adaptation changes are put in place.	Assumes foresight with respect to climate change.
Design standards	Roads are rebuilt according to existing design standards.	Applies these forward-looking climate projections to upgrade new roads as they are rebuilt and maintained.
Costs	The costs incurred are from increased maintenance necessary to retain the design life of the original road as degradation of the road infrastructure occurs from climate change stressors.	Incurs up-front costs to adapt a road to mitigate future damages that are projected from increases in precipitation or temperature.
	Impacts and adaption responses	
Paved roads	Increased rutting and cracking due to temperature impacts. Increased washout and drainage infrastructure damages due to changes in precipitation and flooding impacts. Reduced lifetime and increased replacement costs.	Upgrade asphalt binder (temperature increase). Increase drainage capacity. Design period life maintained.
Gravel roads	Increased maintenance costs from damages due to changes in precipitation.	Increase sub-base layers Increase drainage capacity Increase grading frequency Design period life maintained

are rebuilt according to previous baseline standards. The costs incurred are from increased maintenance necessary to retain the design life of the original road as degradation of the road infrastructure occurs from climate change stressors.

Inputs to the IPSS model include:

1. Existing **road inventory** for different road classes
2. **Road construction and rehabilitation costs** for the different road classes
3. Different **climate change scenario impacts** on temperature, precipitation and flooding.

2.7.1. South African road inventory

Information on the current road stock for each province in South Africa was obtained from MapIT, who provide information for use in GPS units. These were validated using information on the national roads inventory supplied by the South African National Roads Agency (SANRAL). The roads inventory was classified as paved or gravel, and as primary, secondary or tertiary road as follows:

- **Primary:** to provide mobility in the national context, usually over long distances, and designed for relatively high speeds and minimum interference by through traffic (typically national roads and routes).
- **Secondary:** to provide mobility in the regional context, shorter travel distances and more moderate speeds (typically provincial roads).
- **Tertiary:** intended to provide access to properties and link them to the higher order roads (typically municipal roads and streets).

A map showing the current road network and the grids used to calculate the climate change impact is shown in **Figure 10**. The total length of roads in South Africa was estimated to be just over 600 000 km. More than half of this is gravel roads as shown in **Figure 11**. The most roads are located in the Eastern Cape (±100 000 km) as shown in **Figure 12** consisting mostly of gravel roads. In contrast almost 90% of the roads in Gauteng and almost 50% in the Western Cape are paved roads.

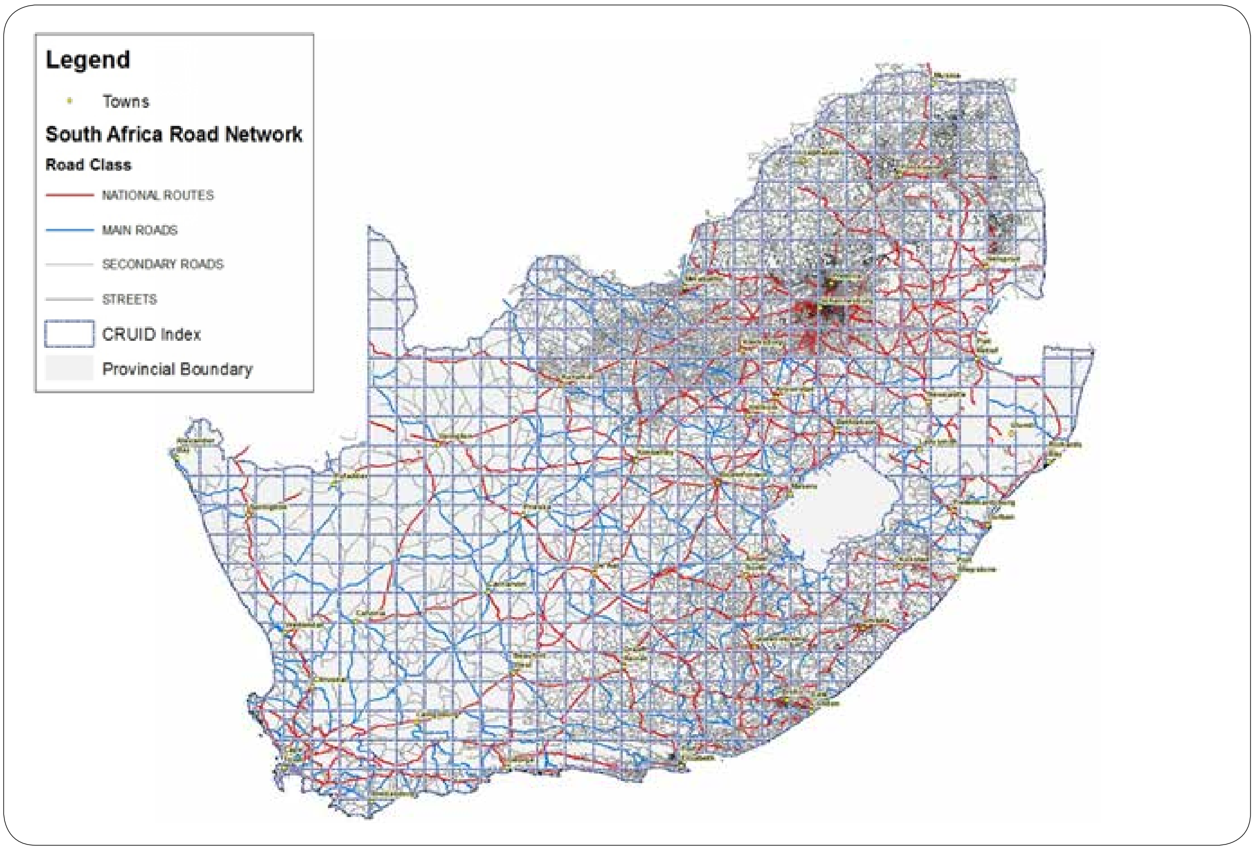
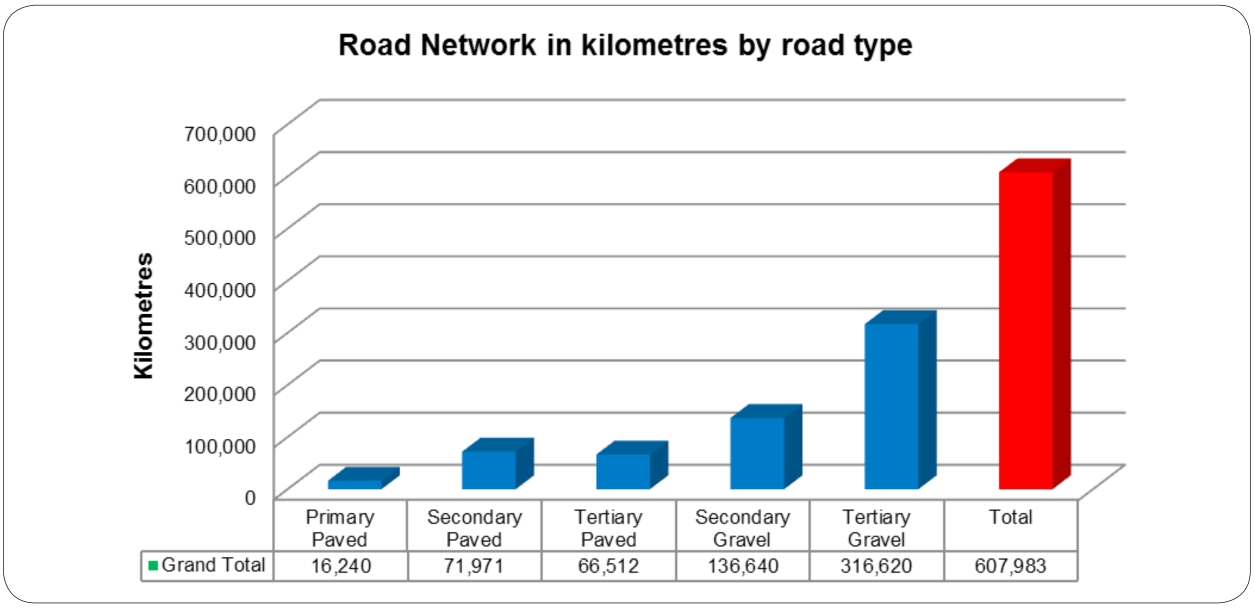
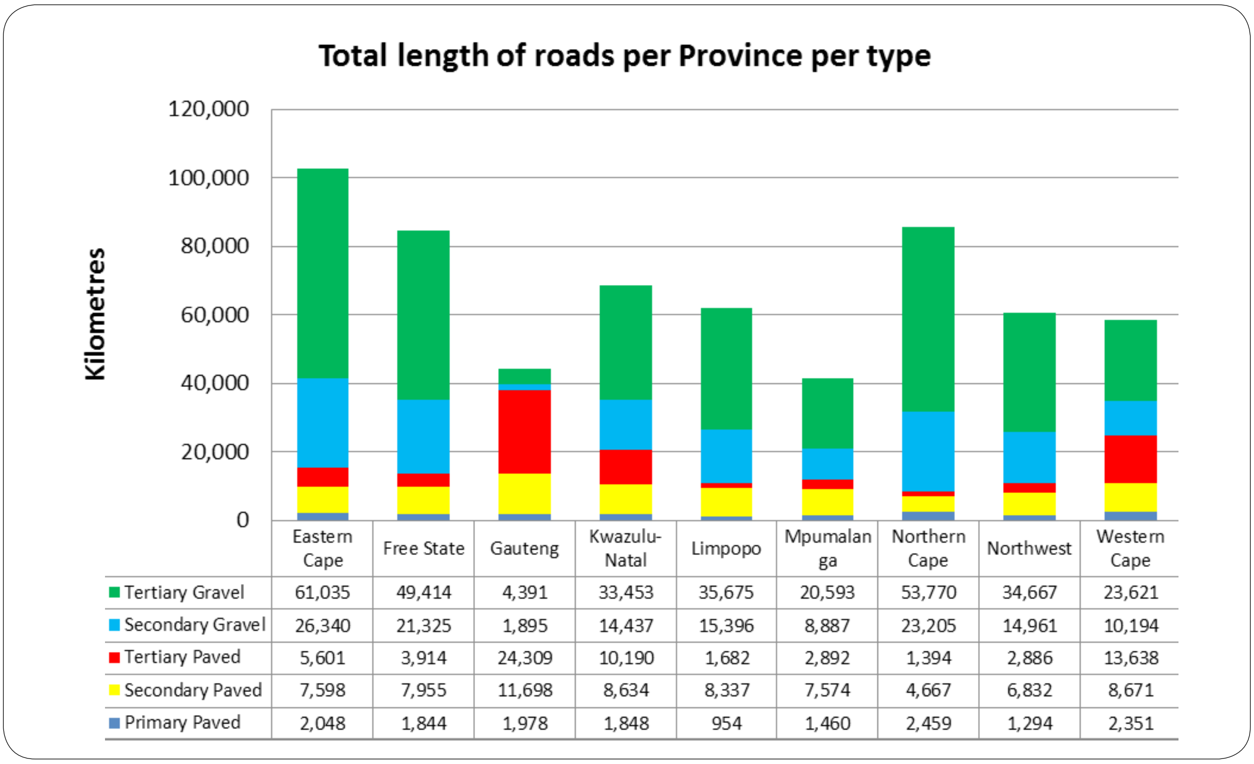


Figure 10: South African road network and the grid of Climate Reporting Units (CRU) (MapIT: SANRAL)



	Primary Paved	Secondary Paved	Tertiary Paved	Secondary Gravel	Tertiary Gravel	Total
Grand Total	16,240	71,971	66,512	136,640	316,620	607,983

Figure 11: Total length of road type in South Africa (MapIT; SANRAL)



	Eastern Cape	Free State	Gauteng	Kwazulu-Natal	Limpopo	Mpumalanga	Northern Cape	Northwest	Western Cape
Tertiary Gravel	61,035	49,414	4,391	33,453	35,675	20,593	53,770	34,667	23,621
Secondary Gravel	26,340	21,325	1,895	14,437	15,396	8,887	23,205	14,961	10,194
Tertiary Paved	5,601	3,914	24,309	10,190	1,682	2,892	1,394	2,886	13,638
Secondary Paved	7,598	7,955	11,698	8,634	8,337	7,574	4,667	6,832	8,671
Primary Paved	2,048	1,844	1,978	1,848	954	1,460	2,459	1,294	2,351

Figure 12: Total length of road type per province (MapIT; SANRAL)

2.7.2. *South Africa road construction and maintenance costs*

Six variables for costs are considered in the model. These require determining the unit cost per kilometre for the construction, maintenance and upgrading of the different road types. These cost considerations are shown graphically in **Figure 13** and are described briefly below:

A - Base cost for building a new road to current design standards for current climate – the cost per kilometre of the construction of a new road (this also applies to rehabilitation).

B - Adaptation cost for upgrading road to future climate – based on adaptation cost applied at the end of the road's lifespan – this is extra cost incurred due to projected increase/decrease in temperature/ precipitation.

C - Adapted roads rebuild costs – cost premium for rehabilitating a road that was previously adapted.

D - Rehabilitation of a flood damage road – the cost per kilometre of repairing a road damaged by a flood.

E - Maintenance costs – the cost per kilometre of maintaining a gravel road only; calculated as a percentage of construction cost.

F - Maintenance savings.

Base construction costs were developed per kilometre of road length for different road types according to the standard typical cross sections for the various road categories used in South Africa (primary, secondary and tertiary) and current construction estimates for materials and labour. Each category has different typical road widths and pavement structure standards. These costs are referred to as the unit costs and each of the other variable costs described above are determined as a proportion of the base cost for construction of a new road. The resulting unit costs for the construction of different road types in South Africa based on current climate are given in **Figure 14**.

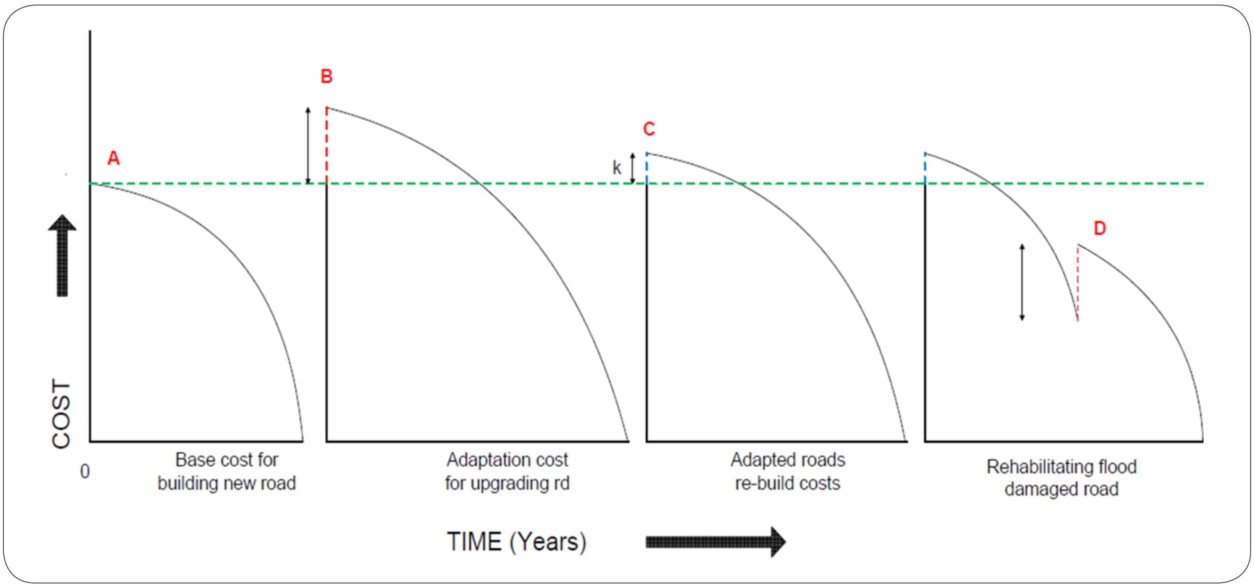


Figure 13: Illustration of costing variables for different scenarios described above (this study)

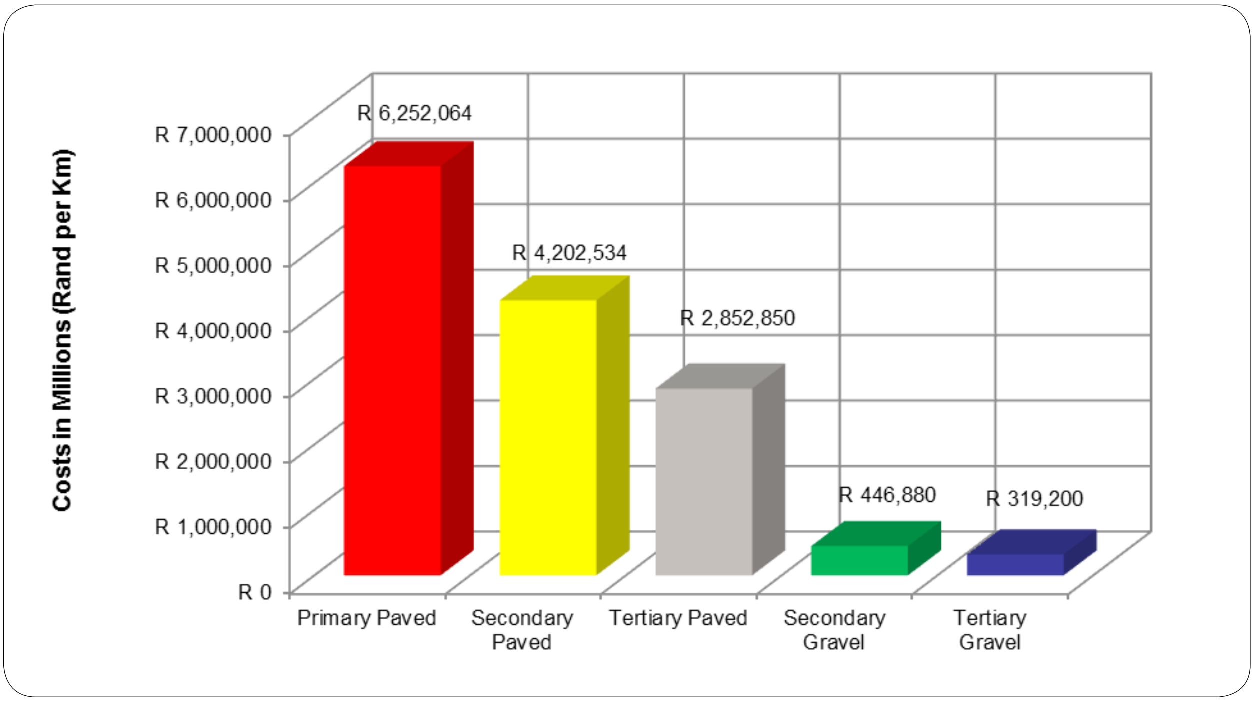


Figure 14: Typical road construction cost in South Africa (this study)

2.8. Economy-wide CGE model

The impacts of climate change as determined through the modelling processes outlined above (sections 2.3–2.7) are integrated through a dynamic computable general equilibrium model (CGE) developed for South Africa (Thurlow 2008). Economy-wide models of this type are appropriate for evaluating how climate change may affect the economy. They are detailed models which contain information that describes the structure of the economy, and the industries and institutions it comprises. They also incorporate the decision-making behaviour of participants in activity, commodity, investment and factor markets, and take into account economy-wide constraints. The model allows economic agents to respond to changes in relative prices according to various elasticities of substitution. This permits several analyses, including how climate scenarios transmit through the economy, how they impact the structure and performance of the economy, and how different participants respond.

The model is unique in that it uses water and agricultural production as primary drivers of economic impacts which make it particularly well suited to assessing the potential impacts of climate change. In addition the model produces outputs at both national level and at the scale of the individual 19 WMAs which makes it suitable for analysis of regional impacts given the spatial variability in climate change impacts. The model includes different sectors of the economy and distinguishes between rural and urban households as well as separate government sectors (**Figure 15**). Outputs from the model include employment, income and GDP at individual sector level and at both regional (WMA) and national scale.

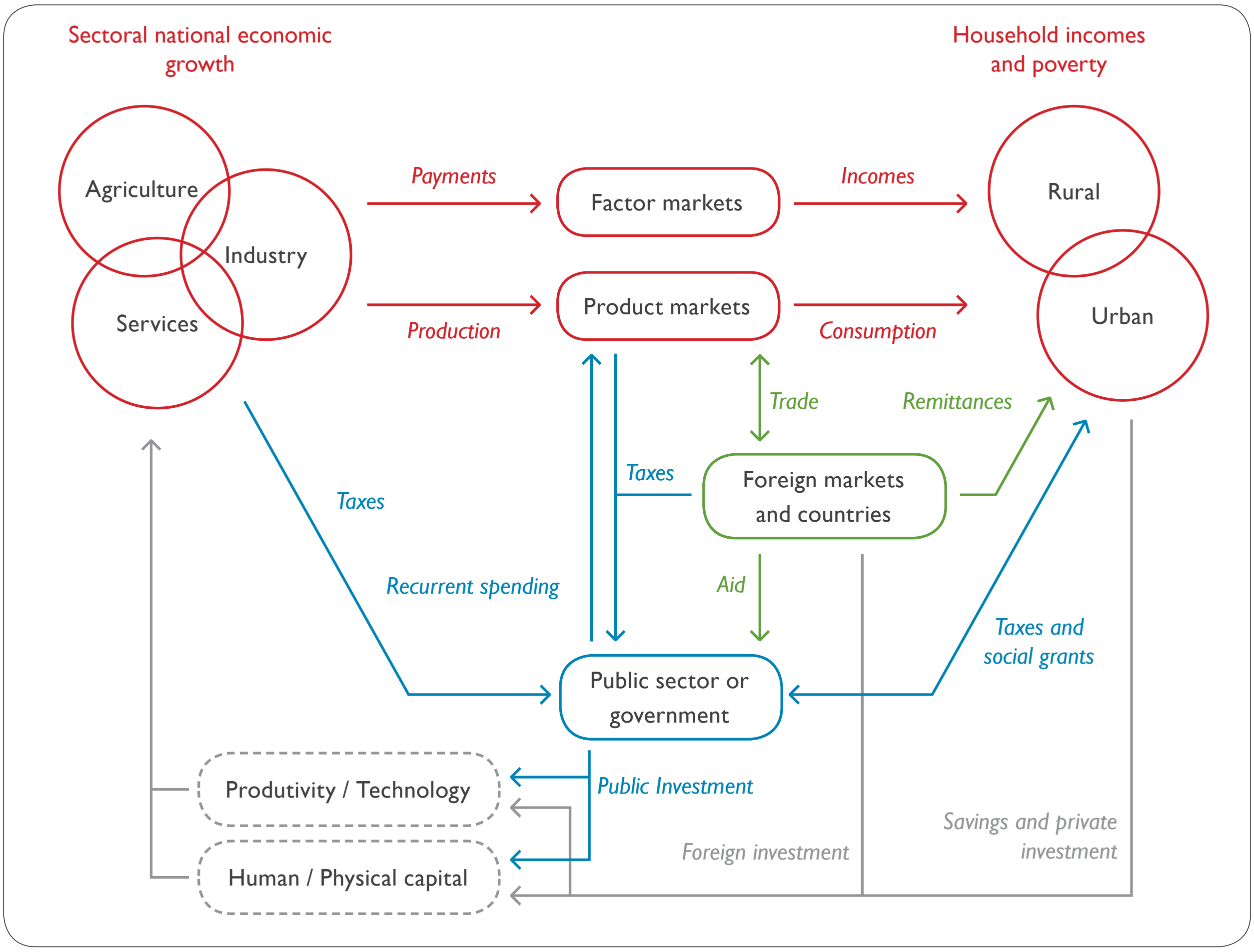


Figure 15: Schematic of the integrated general equilibrium model for the South African economy

The recursive dynamic nature of the model allows structural changes to the economy to accumulate over time. The model is updated in each period using the solution values of the preceding period. For example, capital investment is affected by income and savings outcomes. To the extent that climate change is expected to influence these outcomes, it is well suited to incorporate these effects.

The model is informed by data from a 2002 social accounting matrix (SAM), as well as the 2000/2005 water accounts. The SAM contains 26 types of activities, including 11 agricultural sub-sectors, five of which are further divided by whether cultivation is dryland or irrigated. The activities are distributed across each of South Africa's 19 WMAs. Seven factors of production are identified, and are also disaggregated by region. The factors include three labour categories (unskilled, skilled and highly-skilled), capital, land, agricultural water, and domestic water. The regional and sectoral disaggregation provides relevant detail on the spatial and industrial characteristics of the economy, and will affect model results. The model is calibrated to reproduce the base-year values in the SAM.

The model assumes a balanced closure for investment and government expenditure in which their shares of total absorption (C+I+G) remain constant. Government savings are assumed to be flexible, while foreign savings are considered fixed. The exchange rate is assumed to be flexible. A "putty-clay" formulation is applied to capital in that new investment can be directed to any sector (investment is positively related to the sector specific capital rental rate and the size of the sector) while the existing stock of capital is immobile or fixed within the sector.

An important assumption in the model is that labour is assumed to be fully employed and mobile across sectors. Agricultural and domestic water and land are also assumed to be fully employed and fully mobile within a WMA but immobile across WMA boundaries. In addition the reallocation of water across WMAs is handled in the water resource modelling (WRYM). The economy-wide model takes the supply of available water as fixed, after accounting for increased demand due to, for example, the effects of higher temperatures on crop irrigation demand.

The assumption that resources including water, labour and capital can move freely within the economic models is critical in terms of interpreting the final results as this allows for a high degree of endogenous adaptation to climate change impacts. In particular, this results in the movement of resources from an area such as dryland agriculture that is negatively impacted by climate change to another sector such as the services sector that is less impacted by climate change.

While this represents an ideal situation, as it results in the most efficient use of resources, it is not necessarily representative of the true nature of the South African economy were such movements are often highly restricted. The model therefore provides an indication of the optimal solution and response to future climate change impacts and careful interpretation of these results is required in order to extract key messages and to make recommendations on appropriate adaptation scenarios. Further investigations into flexible water, capital, labour and economic systems as an adaptation option is required, as well as consideration of potential interventions that could facilitate endogenous adaptation. These interventions need to be identified and strengthened.

3. POSSIBLE CLIMATE FUTURES

As described in the previous section, the climate futures used are based on a large number of climate futures (6 800) derived from the MIT Integrated Global System Model (IGSM) (Sokolov et al. 2009; Webster et al. 2012) which are used to generate hybrid frequency distributions (HFDs) of possible climate change impacts under two mitigation scenarios: the unconstrained emissions scenario (UCE) and a level 1 stabilisation (L1S) scenario (Schlosser et al. 2012). These represent different levels of global cooperation on climate change mitigation and alternative global scenarios.

As part of the LTAS phase 1, South African regional downscaled climate models were prepared, including both statistical (empirical) downscaled models from the Climate Systems Analysis Group (CSAG) at the University of Cape Town (UCT) (Hewitson & Crane 2006) and dynamic downscaled models from the Council for Scientific and Industrial Research (CSIR) (Engelbrecht et al. 2011). The outputs from these regional climate models were based on the A2 and B1 climate scenarios from the Coupled Models Intercomparison Project Phase 3 (CMIP3) suite of global climate models, and the CMIP5 suite of global climate models for representative concentration pathways (RCPs) 4.5 and 8.5. These models were used to inform the description of four general LTAS climate futures and possible regional impacts shown in **Figure 16**.

The HFD scenarios represent the full range of LTAS climate futures, summarised in **Figure 16** according to six hydro-climatic zones in South Africa. The UCE HFD scenarios represent the hotter futures resulting from a highly carbonised world with no mitigation and the L1S HFD scenarios represent the warmer futures resulting from successful global cooperation and mitigation efforts and a less fossil fuel dependent world. Both the UCE and L1S HFD scenarios include a range of potential precipitation impacts that result in both wetter and drier futures that are in many cases more extreme than future scenarios predicted by South African regional downscaled climate models. Potential impacts under the different LTAS scenarios at both national and regional levels can therefore be determined by considering the range of future scenarios modelled using the HFDs.

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 16: Summary of possible impacts of climate change on precipitation across six hydro-climatic zones in South Africa under four possible climate futures identified as part of phase 1 of the LTAS programme (DEA 2013).

To confirm that the HFD scenarios are consistent with results of regional downscaled models, a total of 31 regional climate models were obtained from LTAS phase 1 and compared to the HFDs. The outputs from the HFDs and the LTAS scenarios are compared in terms of the change in average annual temperature (**Figure 18**) and average annual precipitation (**Figure 22**) over the last ten years of the simulation (namely for the period 2040 to 2050) relative to the base scenario. The results are presented grouped according to the six hydro-climatic zones shown in Figure 17 that were defined by the DWA in its climate change strategy (DWA 2013) and used to define the four LTAS climate futures.

A comparison of the HFD and regional climate model results are presented in the following sections in terms of temperature and precipitation impacts. Further research, currently underway, will continue this analysis of the regional climate models in terms of water supply and economic impacts.

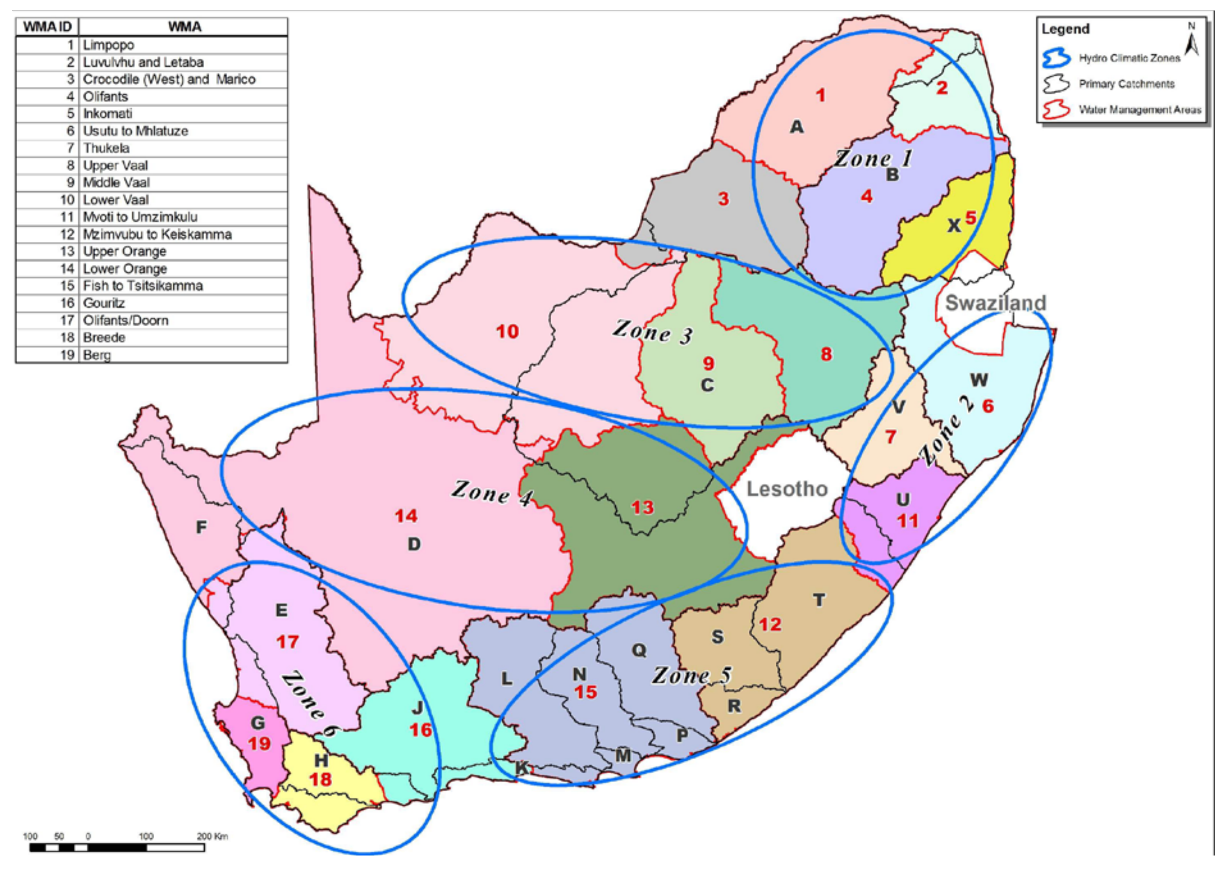


Figure 17: Map showing the six general hydro–climatic zones defined by the DWA (DWA 2013) and used for the summary of HFDs and comparison with outputs from regional climate models. The primary catchment letters and water management area (WMA) numbers are also show as a reference for later results.

3.1. Temperature impacts

The median impact of the UCE climate scenarios shows an increase in the average annual temperature across South Africa of between 1.5 and 2˚C by mid-century (2050) as shown in Figure 18 and the median impact of the LIS scenario is an increase of around 1˚C by 2050. In addition the spread of possible temperature increases is much greater under the UCE scenarios than the LIS scenarios reaching an average increase in annual temperature of up to 3˚C. This shows the significant benefits of mitigation in reducing the potential risks of future temperature increases.

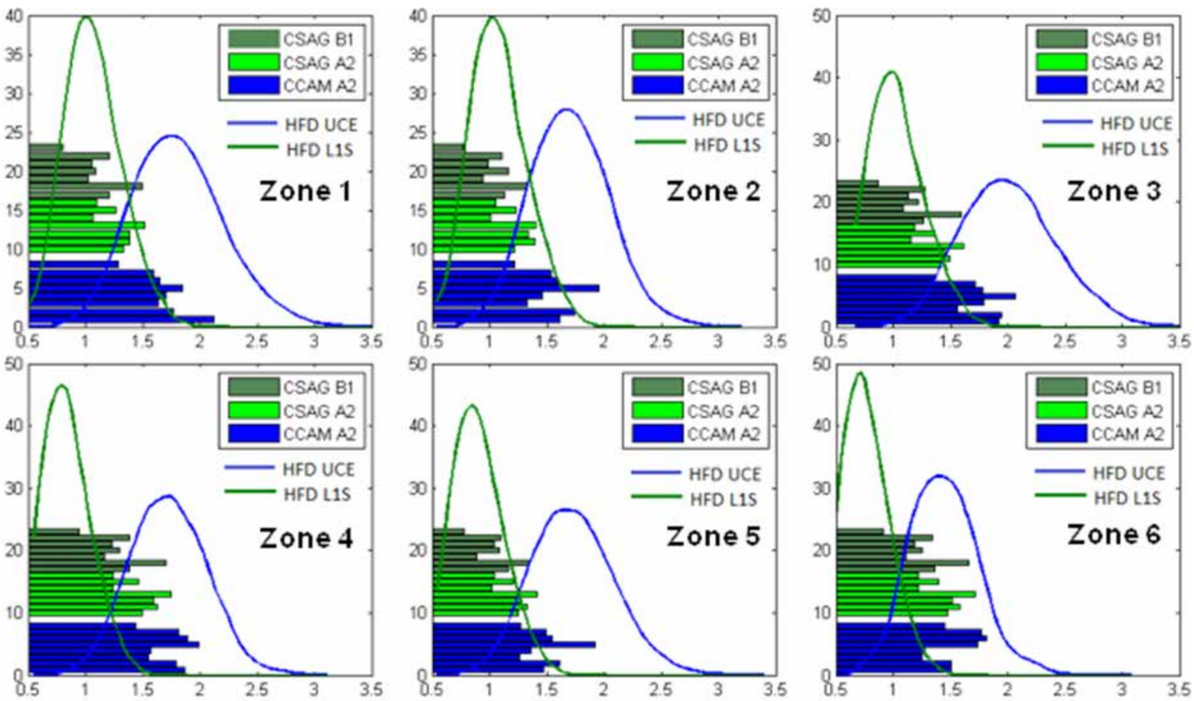


Figure 18: Increase in average annual temperature in ˚C for the period 2040–2050 as compared to the period 1990 to 2000 for the six hydro-climatic zones of South Africa. Comparison of HFD outputs from all global climate models with outputs from 14 statistically downscaled regional climate models.

The impacts on average annual temperature for a selection of the regional downscaled climate models are plotted in Figure 18 and show slightly higher average temperature increases for the CCAM A2 scenarios than for the CSAG A2 and B1 scenarios, but with a maximum impact of only 2 ˚C on average annual temperature by 2050. The outputs from the CCAM A2 scenarios are generally consistent with the median values for the HFDs of the LIS scenarios. In contrast the CSAG A2 scenarios plot in the range of the 25th percentile for the LIS HFDs. The range of potential impacts for the HFD scenarios, however, is much greater showing the need for consideration of more extreme scenarios.

3.2. Precipitation Impacts

The potential impacts on precipitation are much more uncertain than for temperature and vary more significantly between models and across the country. The hybrid frequency distributions (HFDs) of the average annual change in the total national precipitation volume by 2050 for the UCE and LIS climate scenarios are shown in **Figure 19**. The results show a wide range of potential impacts, both positive and negative, that is slightly greater for the UCE scenarios than for the LIS scenarios. **The UCE scenario impacts range from -12.5% change to +20.6% with a median impact of a 1.9% reduction in the average annual total precipitation by 2050.** The LIS scenario results in a slightly lower median impact of a 1.2% reduction in precipitation and a range of possible impacts from -9.4% to +15%.

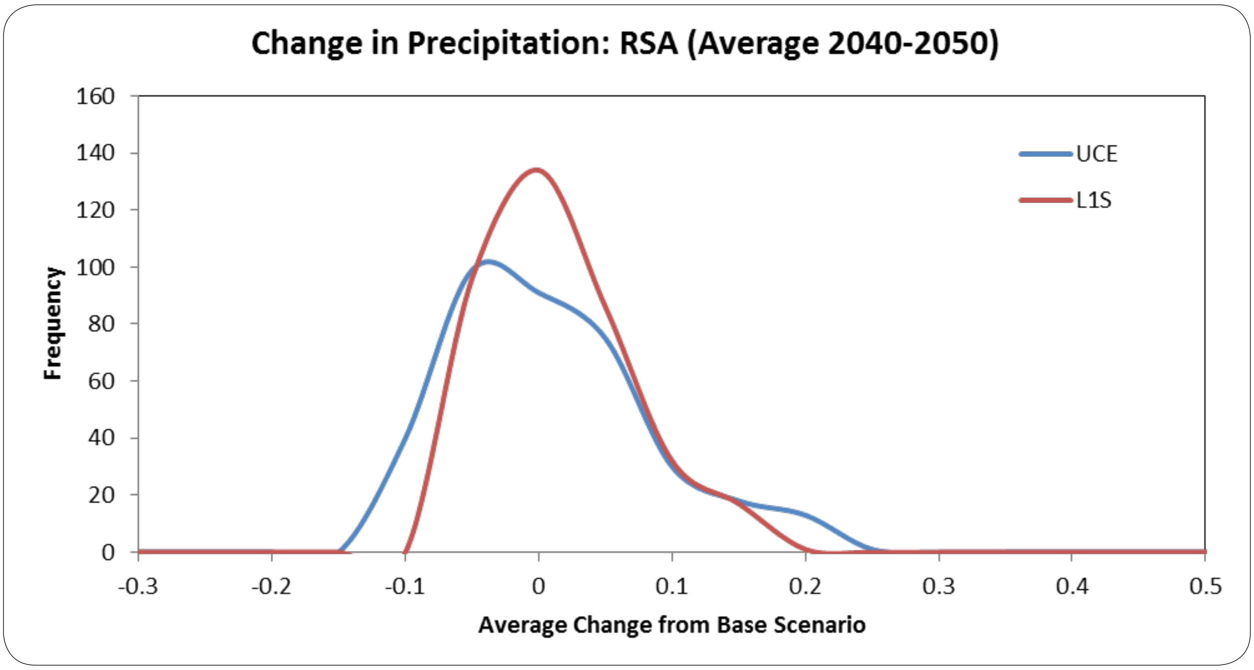


Figure 19: Hybrid frequency distributions (HFDs) of the average change in national annual precipitation over South Africa for the UCE and LIS scenarios for the period 2040 to 2050 relative to the base period.

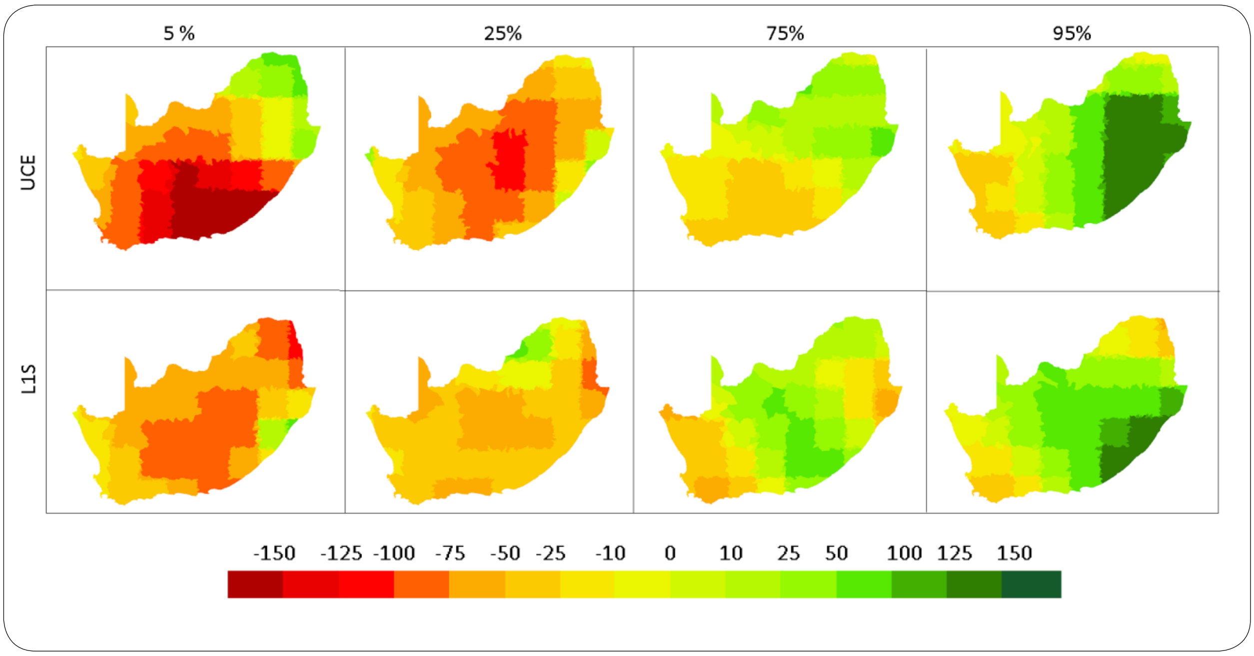


Figure 20: Change in the average annual precipitation (2040 to 2050) across the country for individual models representing the 5th, 25th, 75th and 95th percentile under the UCE and LIS scenarios.

In addition to the wide range of potential impacts due to different climate scenarios, there is also significant spatial variation across the country. The change in the average annual precipitation by 2050 across the country for specific models used in the HFD analysis that represent different percentile impacts under the UCE and LIS climate scenarios are shown in **Figure 20**.

The ratio of potential impacts under the UCE scenario relative to the base scenario in each secondary catchment scenario is shown in **Figure 21**. The solid blue line indicates the median impact of all the climate scenarios and the shaded and dotted lines show the range of potential impacts. The heavy dashed line indicates a reduction of about 3.6% in the median impact on the average annual precipitation for all secondary catchments across the country and the grey areas and the dotted lines show the inter-quartile and full range respectively of potential impacts.

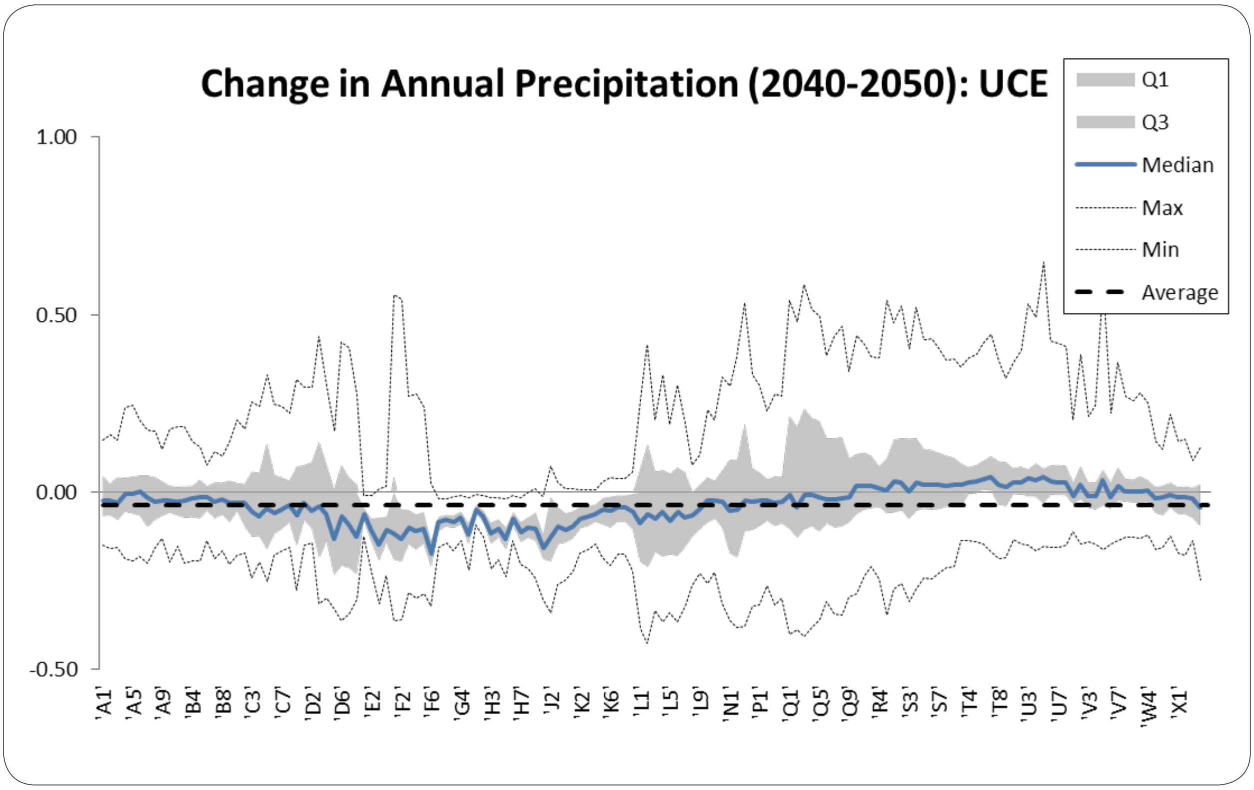


Figure 21: Range of potential impacts on the change in average annual precipitation for the period 2040 to 2050 in each secondary catchment of South Africa under the UCE climate scenario.

Despite a wide range of uncertainty across much of the country there is a clear indication of a reduction in precipitation across most of the country with all climate scenarios showing reduced precipitation in the F, G and H secondaries which are located in the south-west of the country including the west coast, the Berg River and the Breede River catchments. In contrast the catchments in the east of the country (T and U) show a general increase in average annual precipitation, but even here about a quarter of the scenarios show a decrease in the average annual precipitation.

The HFDs for the UCE estimate of the change in the average annual precipitation for the six hydro-climatic zones are given in **Figure 22**, along with the corresponding outputs from the regional downscaled CMIP3 and CMIP5 climate models (CSAG and CCAM) for South Africa (DEA 2013).

The results show that the HFD scenarios cover the full range of the potential impacts under the regional climate models with similar median impacts and general conclusions of future climate change scenarios for the majority of hydro-climatic zones across South Africa. The added benefit of the HFDs are that they show a wider range of potential impacts and hence possible climate risk, but also give some indication of probability to future precipitation and temperature impacts.

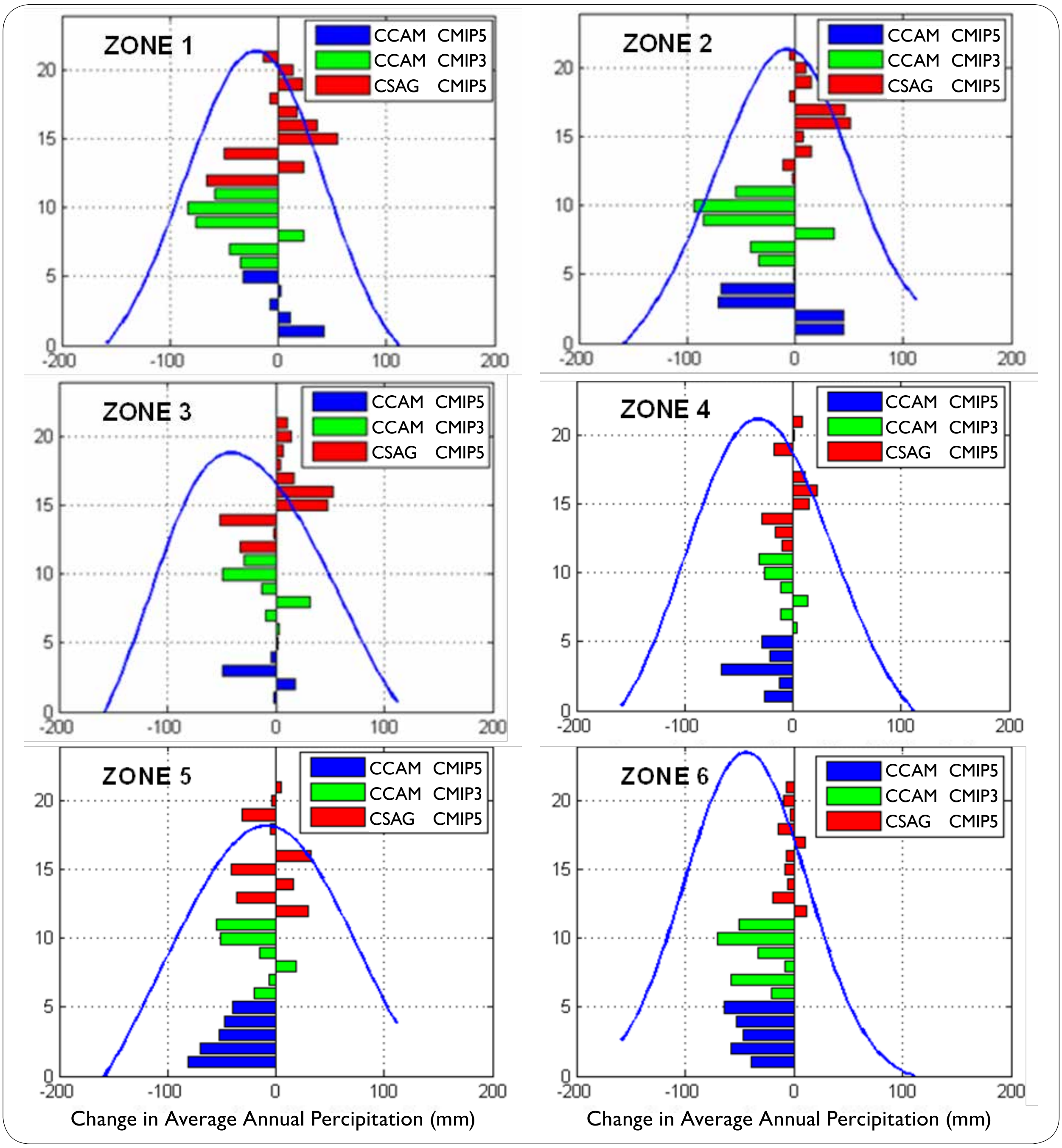


Figure 22: Potential increase in average annual precipitation in mm/year for the period 2040–2050 for the six hydro-climatic zones. Comparison of the hybrid frequency distribution (HFD) of UCE scenarios from the IGSM model with outputs from a number of statistically (CSAG) and dynamically (CCAM) downscaled regional climate models for South Africa

For zones 1, 2 and 5 the mode of the HFD is close to zero change, but with a slightly greater probability of drying than wetting scenarios. For zones 3 and 6, the mode of the HFD is about a 50 mm reduction in the average annual precipitation by 2050, while for Zone 4 it is about a 25 mm reduction. Even in these zones, however, there are a number of models showing the potential for increased precipitation. The maximum impact in all zones is about a 150 mm reduction in mean annual precipitation (MAP).

For zones 1, 2 and 3 the regional climate models show equal likelihood of both increases or decreases in the average annual precipitation with up to 100 mm reduction in zones 1 and 2, and up to about 50 mm reduction in Zone 3. An equal number of models show a possible increase of up to 50 mm. In this respect the results from the regional models are consistent with the HFD results, but the HFD results show the potential for an even greater possibility of impacts both positive and negative. They therefore represent a wider range of potential climate change risks in these zones.

For zones 4, 5 and 6 the CCAM models all show significant drying, while the CSAG models show reduced impacts, with an equal number of models showing both positive and negative impacts. In Zone 6 the CCAM models all show similar impacts around the mode of the HFD scenarios, while the CSAG models show very little change in the average annual precipitation for the Western Cape.

Similarly for Zone 4, the Orange River catchment, the mode of the HFD scenarios shows a reduction in the average annual precipitation consistent with the predicted impacts from the CCAM models. As with all zones, however, the HFD scenarios show a much wider range of potential impacts including a number of models that show the potential for increases in precipitation. This is consistent with the CSAG model results that also show some possibility for increases in precipitation in this zone.

In Zone 5, the Eastern Cape, the HFD results are more consistent with the CSAG models showing the potential for both increases and decreases in precipitation with a mode of around zero change. This zone represents the transition between the winter rainfall regions of the south-western Cape and the summer rainfall regions of the KwaZulu-Natal coastline and is probably the area of greatest uncertainty in terms of future climate scenarios. The CCAM CMIP5 results show consistent drying for this region.

An important conclusion from this comparison is that analysis of the results from the HFD scenarios can be considered to encompass the potential impacts of the regional downscaled models, with some additional potential for more extreme impacts, particularly in terms of both wetter and drier climate scenarios. This is important for assessing potential adaptation options as it would be important to consider a wider range of potential impacts given persistent uncertainty and risk.

Further work currently underway will look to apply the individual CMIP5 regional downscaled models (CCAM and CSAG) to the same integrated modelling framework to investigate how these might differ in terms of biophysical and economic impacts and where the regional climate models fall short in terms of the range of potential impacts from the HFD results.

Despite this, the potential to use the regional downscaled models to provide the pattern kernels necessary to distribute the results of the IGSM model across South Africa should be considered in future studies as this would combine the best of the HFD and regional downscaling approaches.

3.3. Evaporation impacts

In terms of the impacts of climate change on water resources and crop yields, the potential increase in evaporation is more directly relevant than increases in average annual temperature alone. Potential evaporation is calculated using the modified Hargreaves equation which calculates changes in potential evapotranspiration (PET) as a function of temperature and precipitation while accounting for other factors such as cloud cover, humidity and wind (Hargreaves & Allan 2003).

The spatial variation in the change in the average annual evaporation potential at secondary catchment scale under the UCE climate scenario by 2050 across the country is shown in **Figure 23**. The solid blue line shows the median impact of all the climate models while the heavy dashed line shows the national average increase in the average annual evaporation of 4.7% across the country and the grey areas and the dotted lines show the inter-quartile and full range respectively of potential impacts.

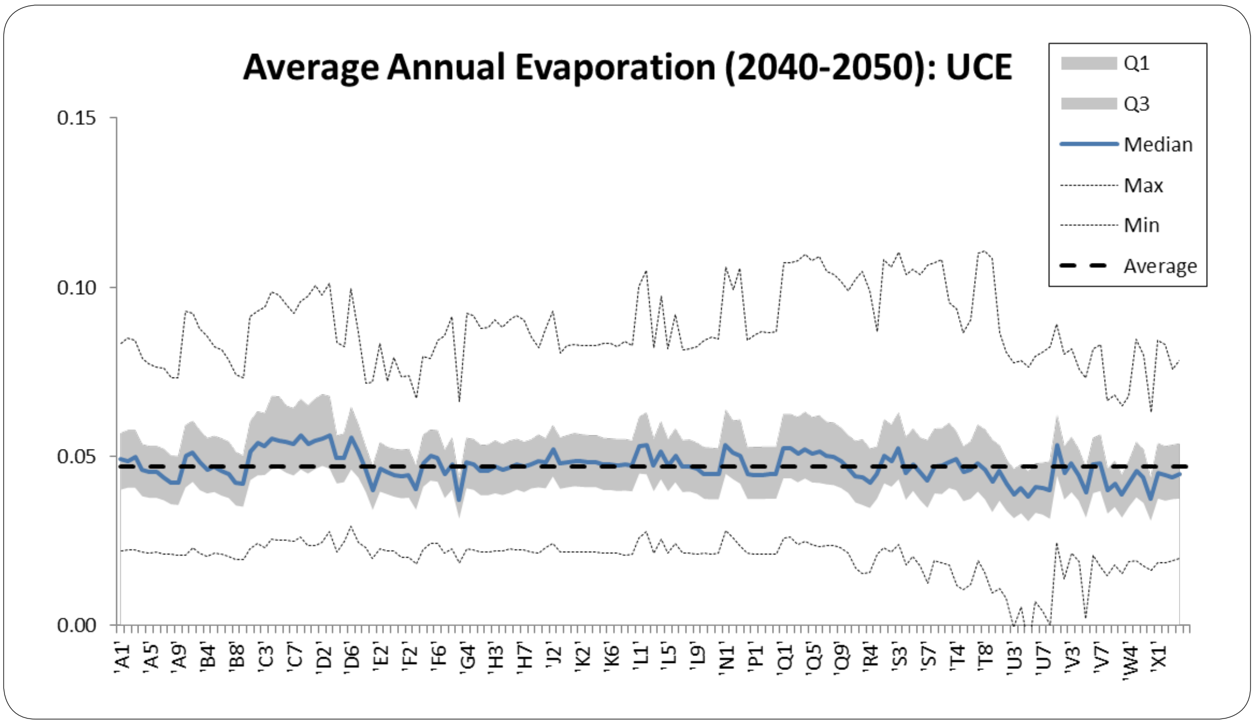


Figure 23: Range of potential impacts on average annual evaporation for all secondary catchments in South Africa under the UCE climate scenarios over the period 2040 to 2050.

The results show a relatively consistent impact across the country of a median increase of about 5%. The highest median impacts appear to be in the north of the country (C and D) while the lowest impacts are for the secondary catchments along the east coast (U, V and W). The range of uncertainty indicates the potential for increases up to 10% over the base for some models.

4. BIOPHYSICAL IMPACTS UNDER FUTURE CLIMATES

The results of the integrated assessment model (IAM) of the potential biophysical and economic impacts of climate change under the different climate scenarios (UCE and LIS) are described in terms of:

- Surface water catchment runoff
- Irrigation demands
- Water supply
- Hydropower potential
- Dryland crop yields
- Roads infrastructure costs
- National and sub-national (WMA) economic impacts.

4.1. Surface water catchment runoff

A comparison of HFD results for the change in the national average annual catchment runoff for the whole of South Africa resulting from the UCE and LIS climate scenarios relative to the base scenario for the period 2040 to 2050 is given in **Figure 24**. The results show that the median impact of the UCE scenario is an increase in the annual catchment runoff over the whole country of 4.4% over the baseline, while the median impact of the LIS scenario is an increase in the total catchment runoff of only 2.6%. For both scenarios there is a wide range of potential impacts. The risk of extreme impacts at both ends of the spectrum is slightly reduced under the LIS climate scenario. For the UCE scenarios the potential impacts on total catchment runoff range from a 13% reduction to a 48% increase, while under the LIS scenario the range is markedly smaller from a 10% reduction to a 30% increase.

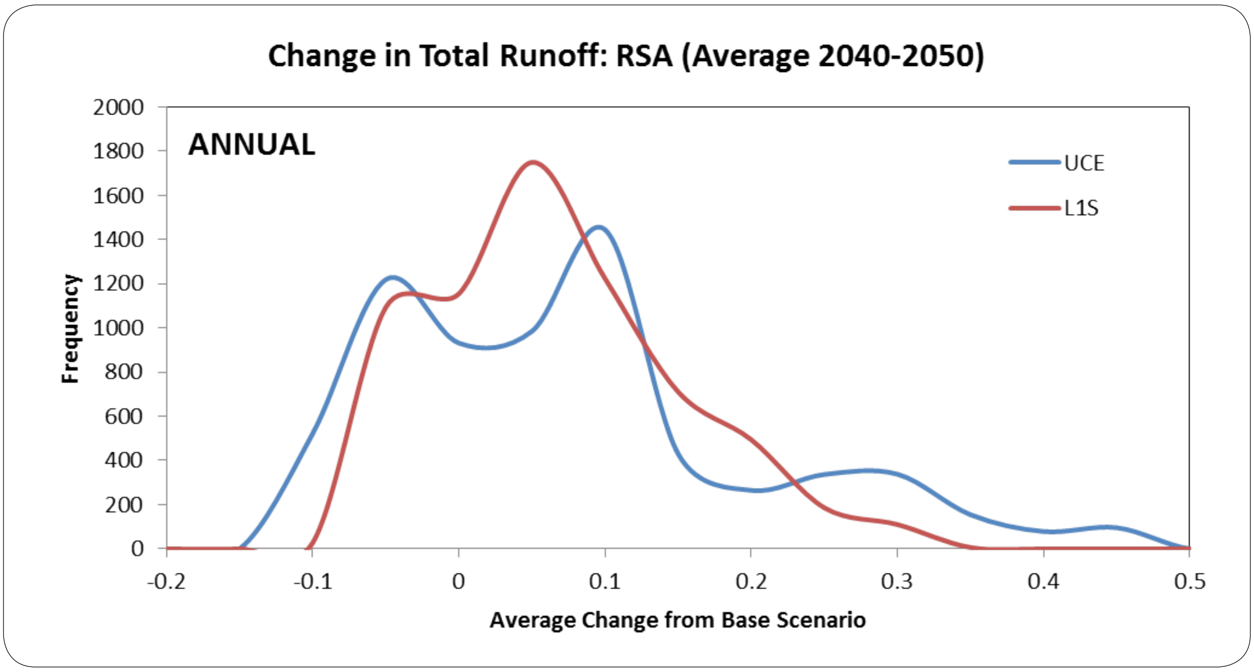


Figure 24: Hybrid frequency distributions (HFDs) of the impacts of the UCE and LIS climate scenarios on the national average annual catchment runoff for the period 2040–2050 relative to the base scenario.

The variation in the impact on the annual runoff for different secondary catchments across the country is shown in **Figure 25**. 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 reduction in streamflow. 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.

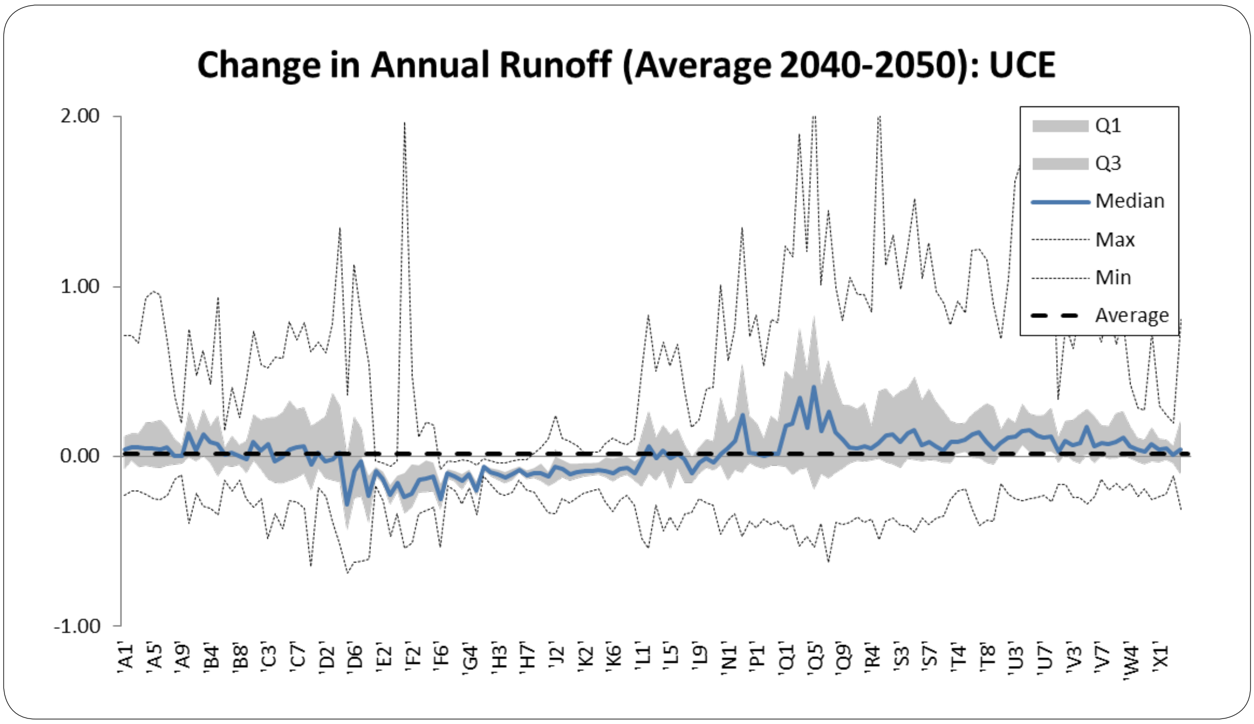


Figure 25: Range of potential impacts of climate change on the average annual catchment runoff for all secondary catchments for the period 2040–2050 due to the UCE scenario relative to the base scenario.

The impact of the LIS scenario in terms of reducing the potential risk for both large increases in catchment runoff and large reductions in catchment runoff becomes more obvious at the secondary catchment scale (**Figure 26**). While some models show a potential doubling in annual runoff in selected secondary catchments in the eastern half of the country, under the LIS scenario the additional risk is only half, but still shows possible increases of up to 100% of the base scenario.

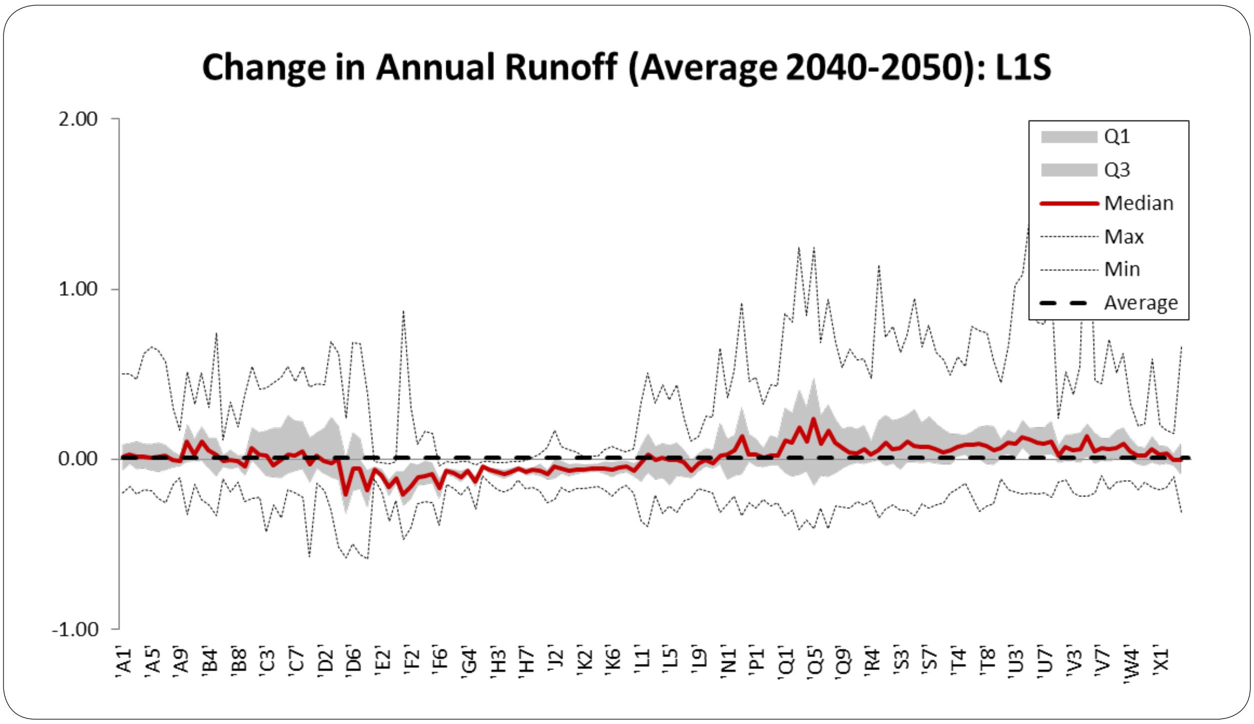
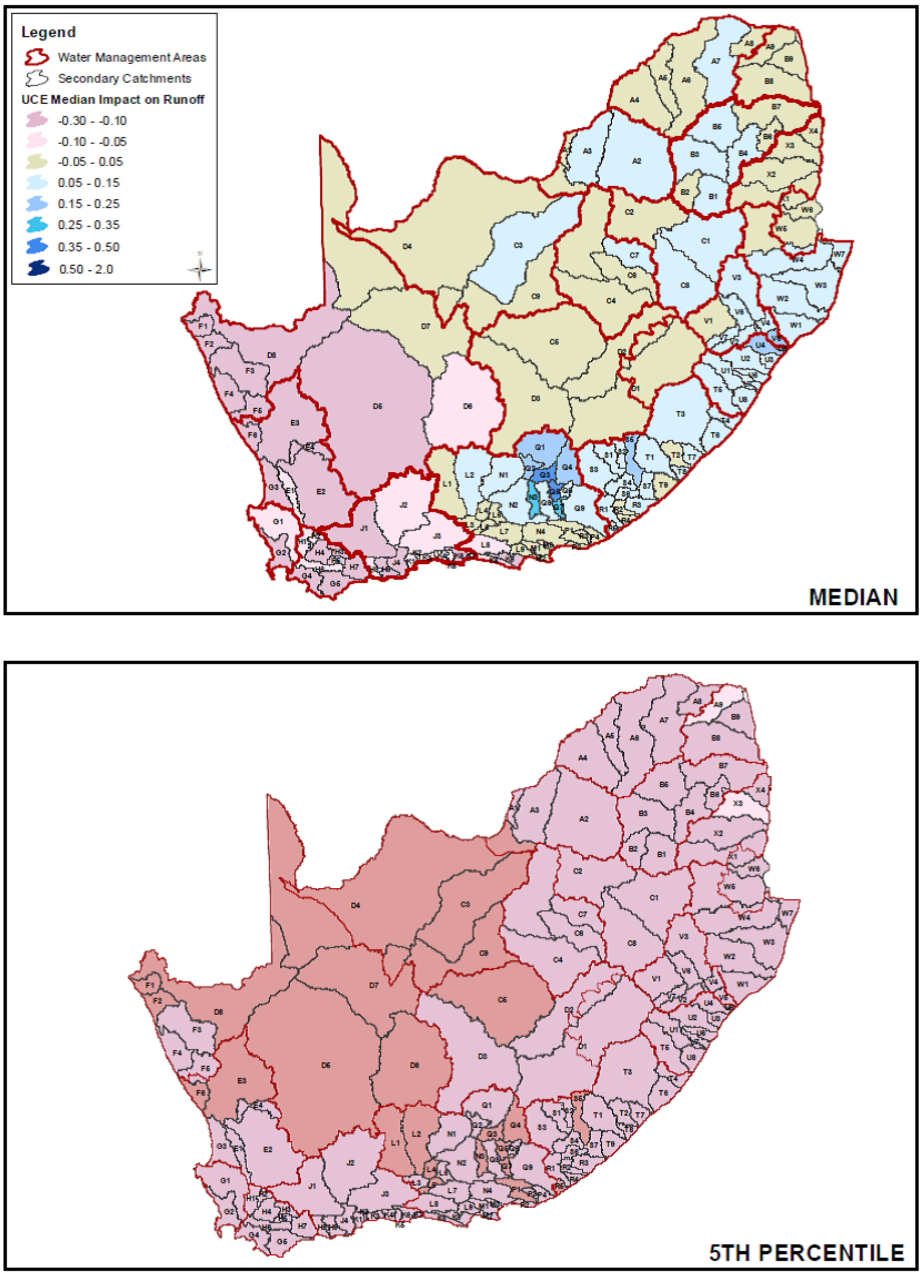


Figure 26: Range of potential impacts of climate change on the average annual catchment runoff for all secondary catchments for the period 2040–2050 due to the L1S scenario relative to the base scenario.

The spatial variations in the projected change in the median, 5th and 95th percentile of annual catchment runoff by 2050 at secondary catchment scale across the country are shown in **Figure 27**. These results show that even under a very wet scenario there is still drying in the Western Cape.



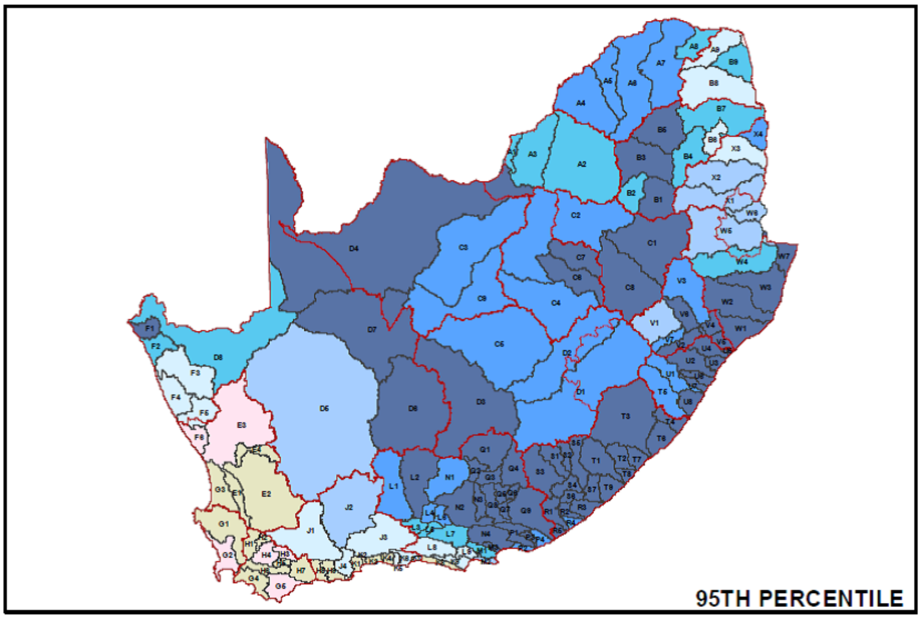


Figure 27: Median, 5th percentile and 95th percentile impact on the average annual catchment runoff at secondary catchment scale under for the UCE scenario for the period 2040–2050 across South Africa.

A time-series of impacts from six secondary catchments is shown in figures 29 to 34, along with the impacts on the average monthly runoff for the period 2040–2050. The six catchments selected are representative of each of the six hydro-climatic regions of South Africa as shown in **Figure 28**.

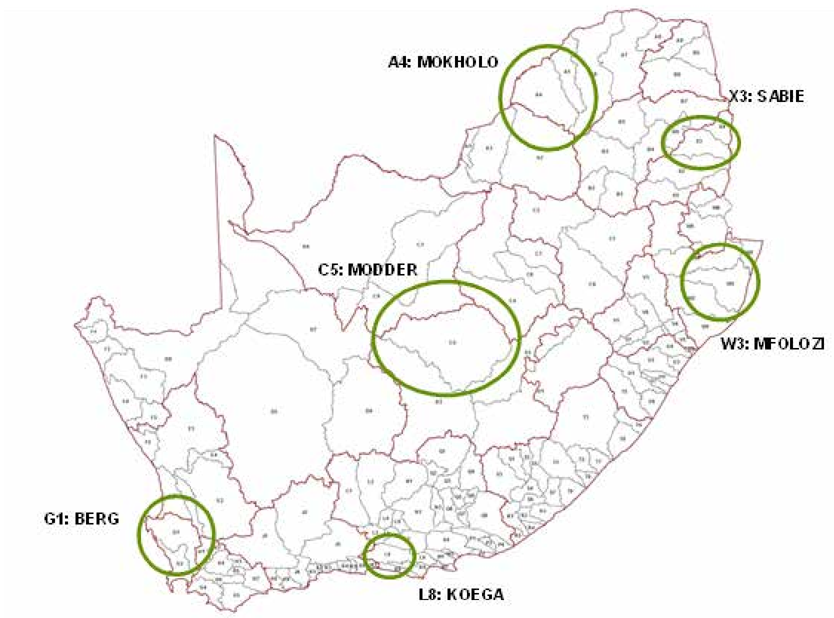


Figure 28: Representative catchments for six hydro-climatic zones in South Africa.

The following general observations can be made based on these results

A4: Mokholo River (**Figure 29**): Even distribution of increases and decreases in annual precipitation with the impact being most significant in the early part of the wet season (December and January).

C5: Modder River (**Figure 30**): A general drying with only a few scenarios showing the potential for increases in annual runoff with the potential impacts relatively evenly spread during the year.

G1: Berg River (**Figure 31**): All models show drying. The proportional impacts are relatively consistent during the year, but the magnitude of the impact is greatest during the winter rainy season.

L8: Koega River (**Figure 32**): A roughly equal possibility of wetting and drying with the median showing close to zero change in the annual streamflow. The wettest scenarios show the greatest impact in April.

W3: Mfolozi River (**Figure 33**): A greater possibility of wetting than drying, but still some dry scenarios. The greatest impact is in January showing a potential shift in the early period of the high flow season.

X3: Sabi River (**Figure 34**): Possibility for increased runoff outside current variability with the greatest impact during the wetter months (December and January).

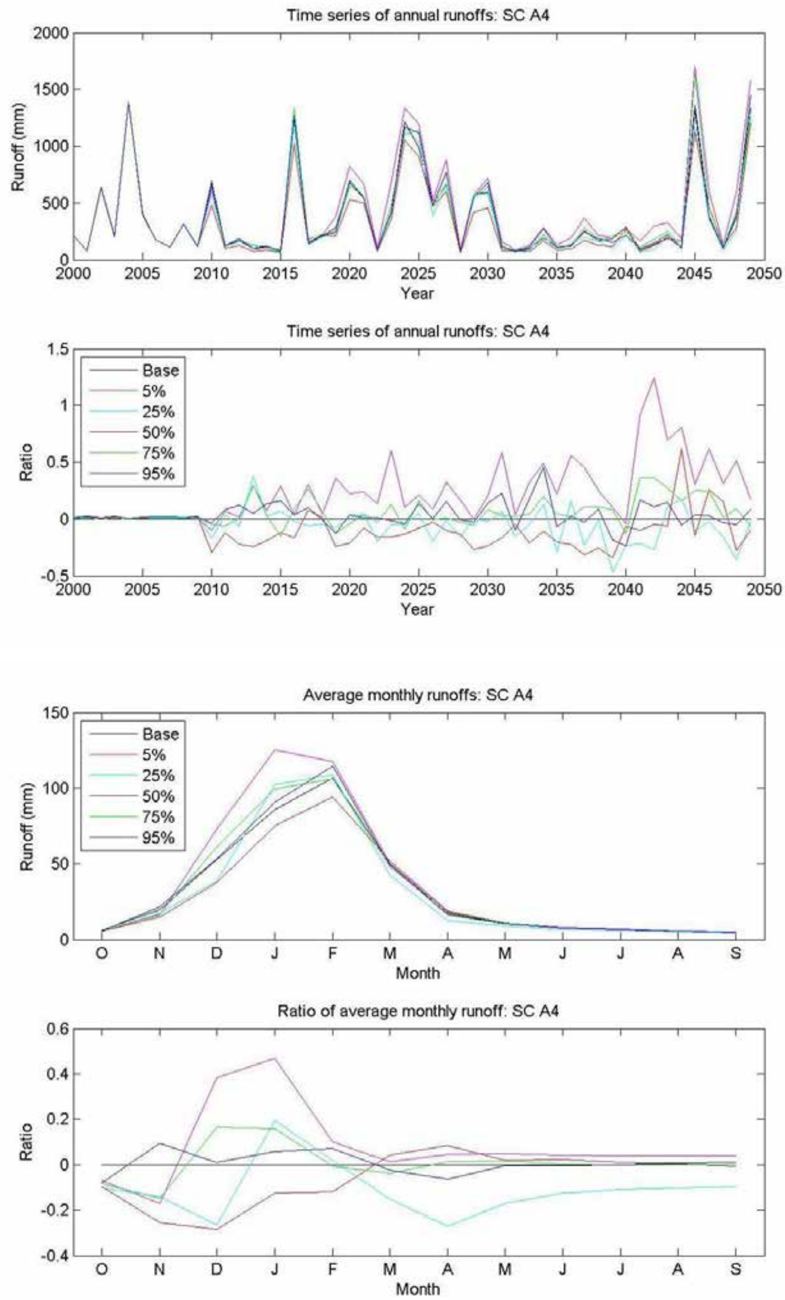


Figure 29: Catchment A4: Mokholo River, impact of the UCE scenarios on the time series of average annual flow for 2000–2050 (top) and the average monthly flows for 2040–2050.

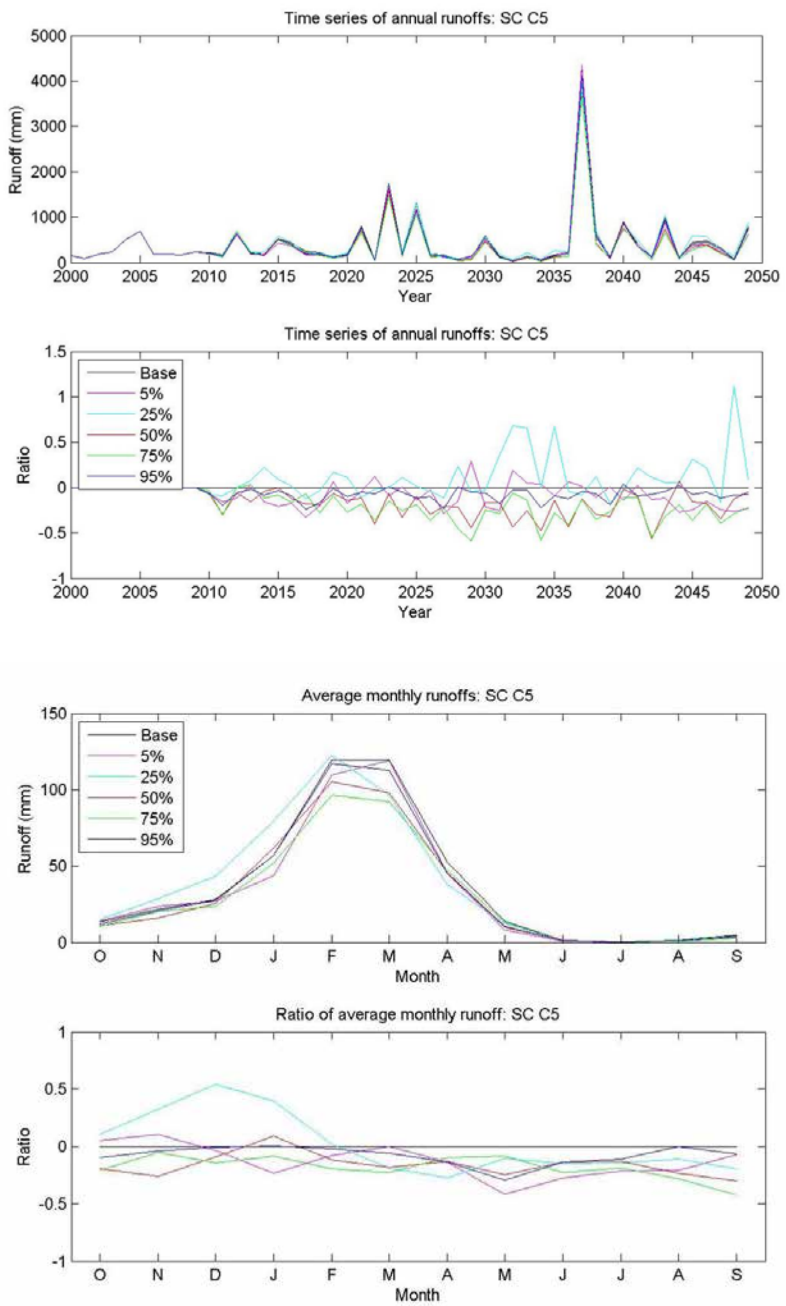


Figure 30: Catchment C5: Modder River, impact of the UCE scenarios on the time series of average annual flow for 2000–2050 (top) and the average monthly flows for 2040–2050.

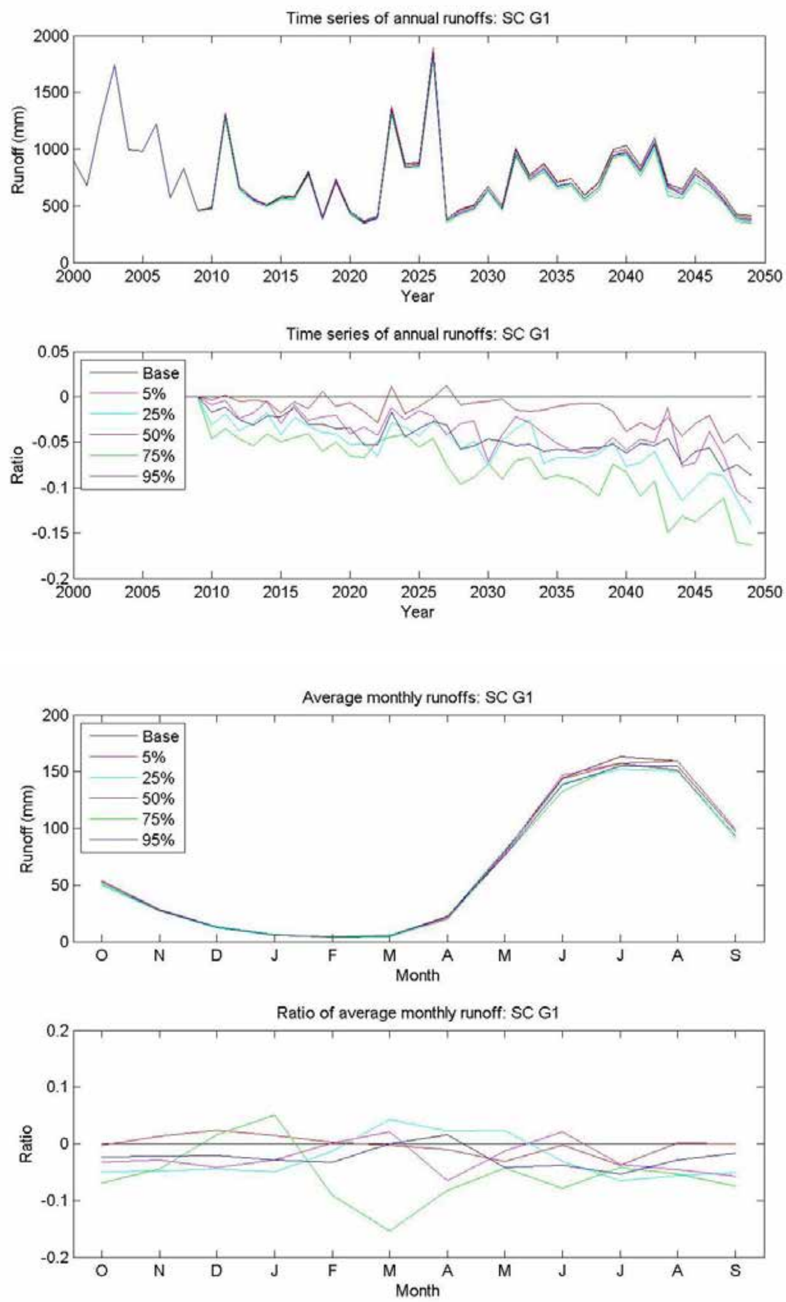


Figure 31: Catchment G1: Berg River, impact of the UCE scenarios on the time series of average annual flow for 2000–2050 (top) and the average monthly flows for 2040–2050.

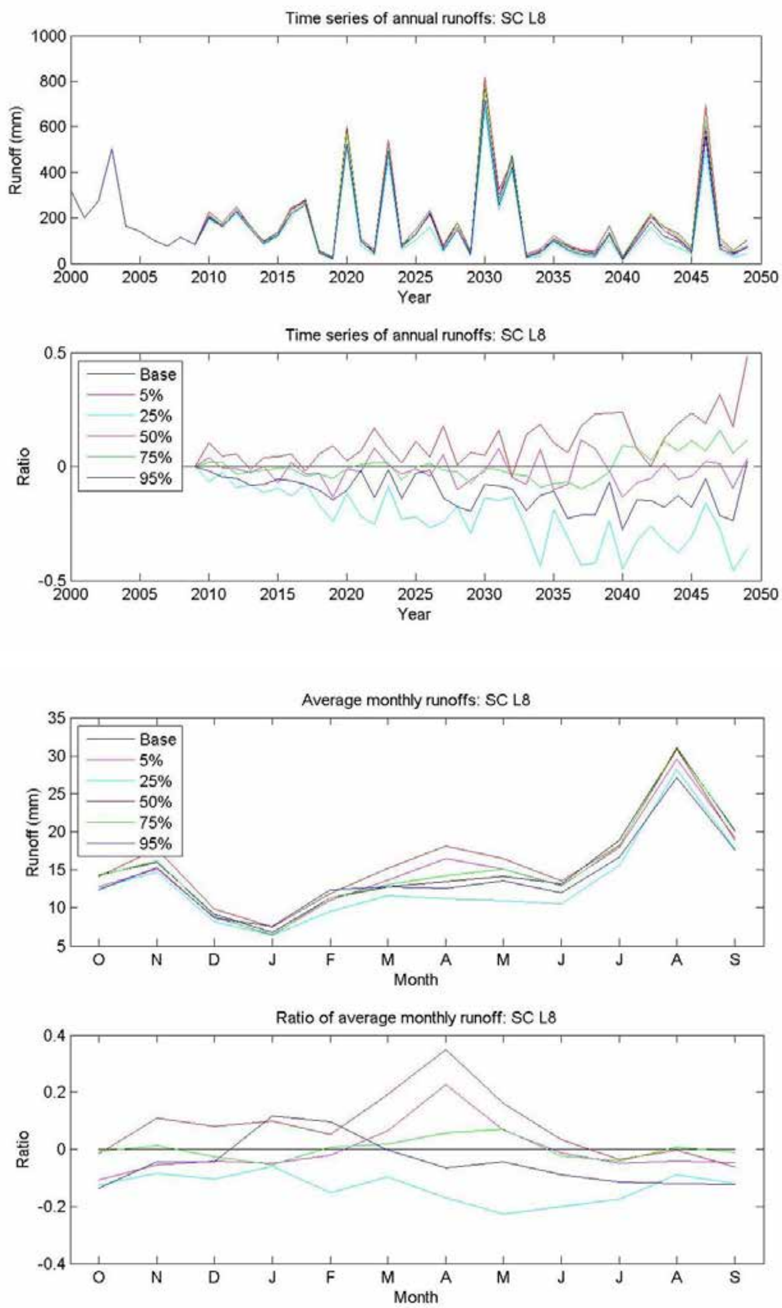


Figure 32: Catchment L8: Koega River, impact of the UCE scenarios on the time series of average annual flow for 2000–2050 (top) and the average monthly flows for 2040–2050.

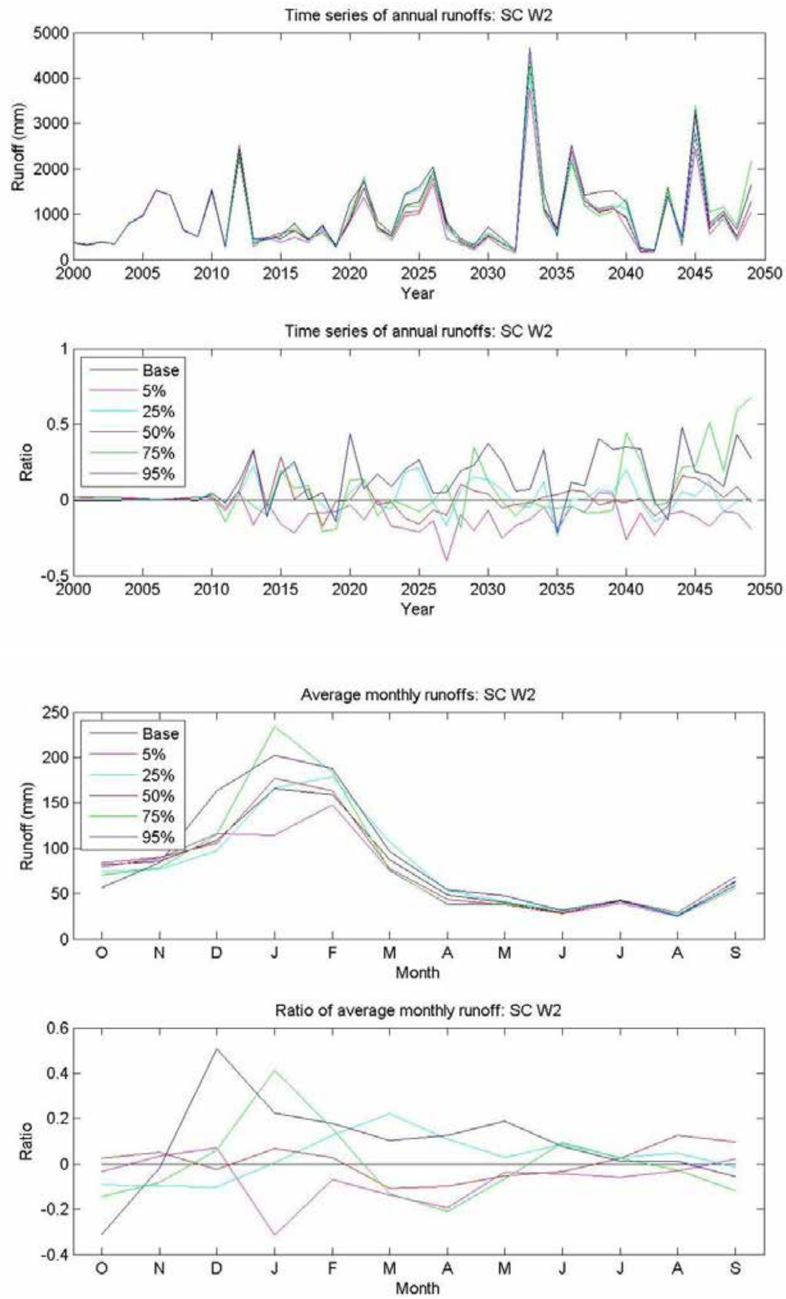


Figure 33: Catchment W2: Mfolozi River, impact of the UCE scenarios on the time series of average annual flow for 2000–2050 (top) and the average monthly flows for the period 2040–2050.

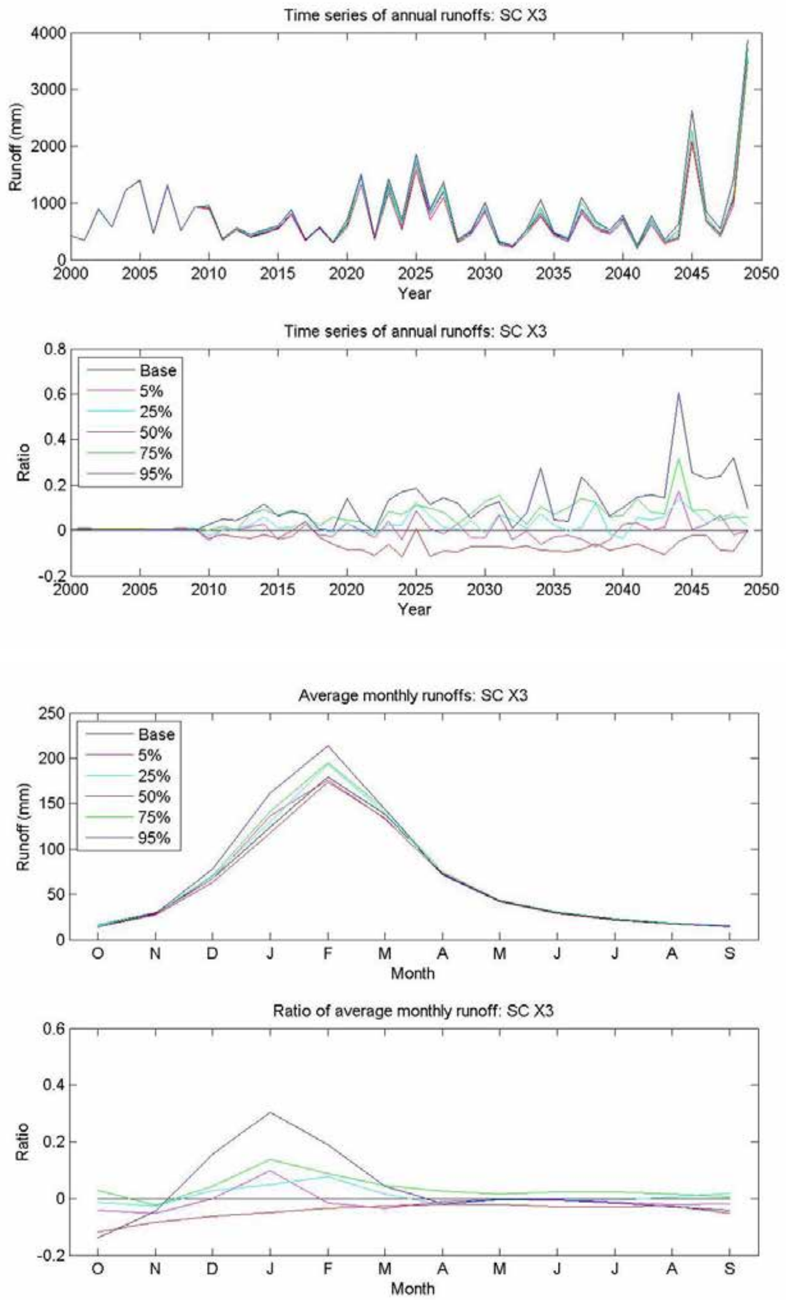


Figure 34: Catchment X3: Sabie River, impact of the UCE scenarios on the time series of average annual flow for 2000–2050 (top) and the average monthly flows for 2040–2050.

4.2. Irrigation demands

The estimated impact of the UCE and L1S climate scenarios on the average annual irrigation demand for the country by 2050 is given in **Figure 35**. Under almost all scenarios irrigation demand is likely to increase in the future due to increases in temperature and evaporation. The UCE scenarios result in a very wide spread of possible impacts with some models showing more than 12% increase in the total average annual irrigation demand. The median increase for the UCE scenario is approximately +6.3%.

Total irrigation demands are reduced under the L1S scenario with the median impact being only an increase of about 3.6% across the whole country. The maximum expected increase under the L1S scenario is 8.6% and some models even show the potential for a slight reduction in the total irrigation demand of about 1.2% where increased precipitation offsets the increased evaporative demand.

As agriculture accounts for around 60% of the total water demand in the country this potential increase is likely to have a significant impact on overall water demand, particularly in drier parts of the country.

The impacts of climate change on irrigation demand do vary across the country (**Figure 36**) but, as temperature is expected to increase relatively uniformly across the country, there is little change in the median impact on irrigation demand in the different secondary catchments. The average median impact across secondary catchments is 6.4% ± 1.9%. There is, however, a wider range of possible impacts in the eastern part of the country (S to V secondary catchments) due to the wider range of potential impacts on precipitation in this part of the country for different climate models. Some models even predict a reduction in irrigation demand of greater than 25% due to increased precipitation.

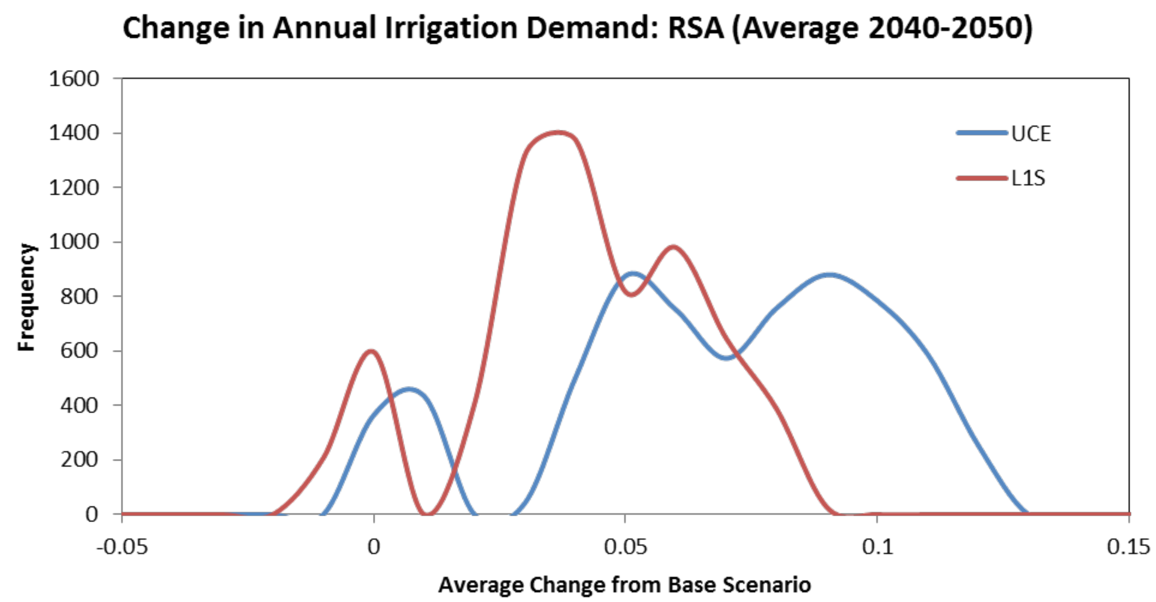


Figure 35: Hybrid frequency distributions (HFDs) of the impacts of the UCE and L1S global climate scenarios on the total national average annual irrigation demand for the period 2040–2050 relative to the base scenario based on the current crop mix and estimate of total irrigated area in each quaternary catchment.

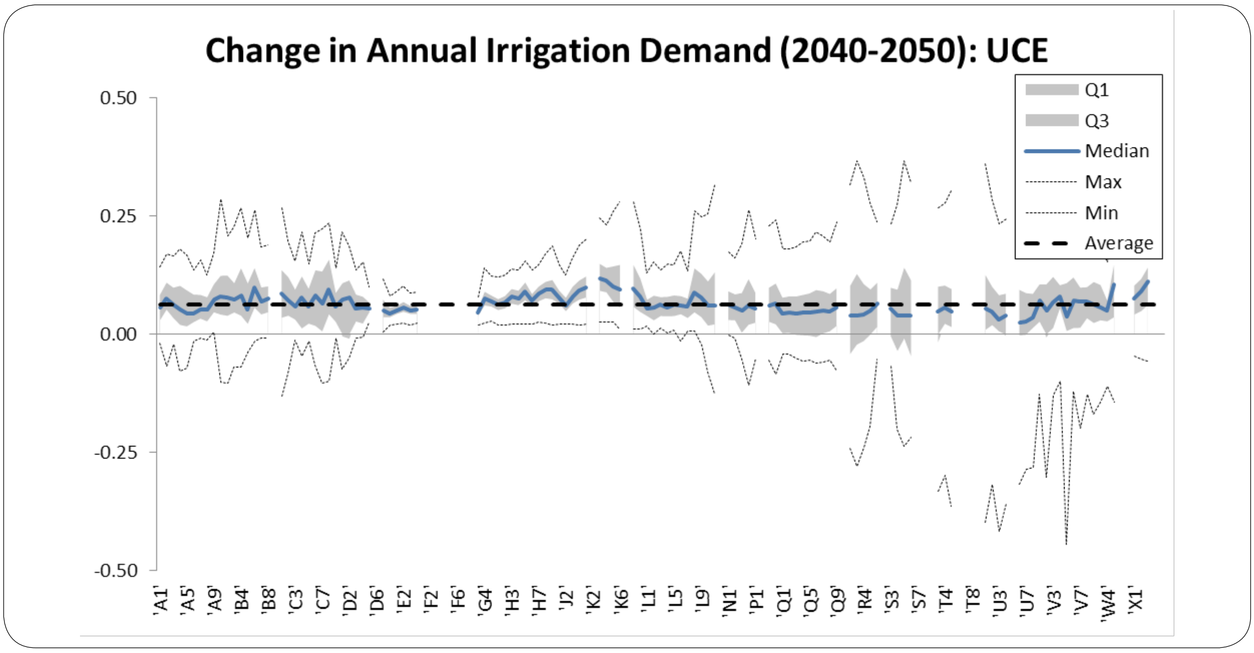


Figure 36: Range of potential impacts of climate change on the average annual irrigation demand for all secondary catchments for the period 2040–2050 due to the UCE scenario relative to the base scenario.

4.3. Water supply impacts

The results of the water supply model show a wide range of potential impacts at regional scale and for different sectors across the country, but a relatively limited impact at national scale. This can be attributed to the nature of water resource planning in South Africa and the resulting highly integrated water resources infrastructure and distribution system at national scale that allows water to be transferred between different regions of the country in response to variable climate impacts.

Figure 37 shows the 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 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 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 under the UCE scenario.

The results show that there is little impact on the ability to supply to the major urban centres and economic hubs of South Africa, with the exception of Cape Town located in WMA 19 (Berg). The other major urban areas are Gauteng in WMA 3 (Crocodile West) and WMA 8 (Upper Vaal), and Durban in WMA 11 (Mvoti to Mzimkulu). These areas are indicated by high urban demands in **Figure 37**. There may even be the potential for increased availability of water for Gauteng as a number of scenarios show increased precipitation over Lesotho under a wetter future scenario. This is due to the number of inter-basin transfers from Lesotho to Gauteng, and the construction of the Polihale Dam in Lesotho, which is included in the water supply model and will significantly increase the yield of the Vaal System.

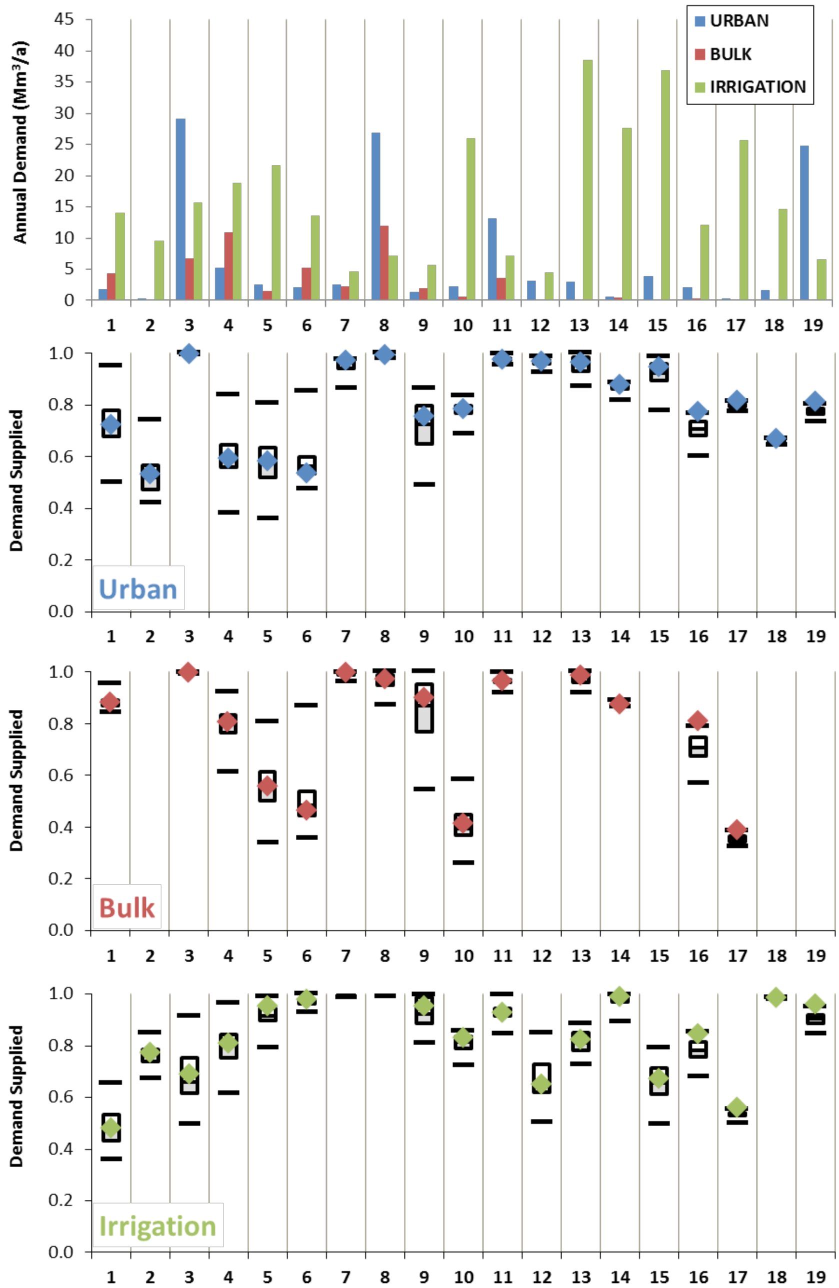


Figure 37: Average annual water demand (top) for the 19 WMAs for the period 2040–2050 and the proportion of demand that can be supplied under the base scenario (symbols) and models representing the minimum, 25th, median, 75th percentile and maximum impact under the UCE climate scenario for different water use sectors. A key to the individual WMA names and locations is given in **Figure 17** on **page 43**.

Cape Town, supplied by the Berg River WMA (WMA 19), is the only major centre where there is a very strong probability of a decrease in supply under all future climates. This impact however is partially mitigated due to the highly integrated nature of the Western Cape Water Supply System (WCWSS). The greatest impact is in the Gouritz WMA (WMA 16) where urban and bulk water supply depend on smaller and less integrated local resources and the climate models predict likely future drying.

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, namely showing the greatest potential for a significant reduction in the ability to meet future demands across all possible climate futures, is 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 of the country.

The potential impacts of climate change on total water supply at national level 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 (2040–2050) under each of the climate scenarios relative to the base scenario. The HFD of the change in the proportion of the total average annual demand that can be supplied relative to the base scenario for each water use sector (urban, irrigation and bulk) as well as total supply is given in **Figure 38**.

These results show a narrow range of impacts in terms of urban water 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 total average annual demand across the country by 2050. This indicates a potentially resilient water supply system particularly for the major urban centres

There is a greater range of potential impacts on the ability to supply both the bulk industry demands and the irrigation demands than for urban water supply. Under the UCE scenario the median impact in terms of the ability to supply the total average annual irrigation demand is only a 1.5% reduction but with the possibility of up to a 9% reduction under the hotter, drier future climate scenarios. Under the LIS scenario this risk is reduced with the maximum impact being reduced to a reduction of only 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).

It is, however, important to note that these potential impacts have been analysed 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 drier climate are likely to be more significant in terms of the level of assurance of supply and the overall system yield. As with the impacts on the total average annual water supply to the country, the impact during critical periods is most likely to be greater at regional scale than at national scale with less integrated systems reliant on a single water resource (namely not able to access water from another region or alternative supply source such as groundwater) being most vulnerable. This will also tend to be in the more rural areas and for small towns and small-scale irrigation schemes.

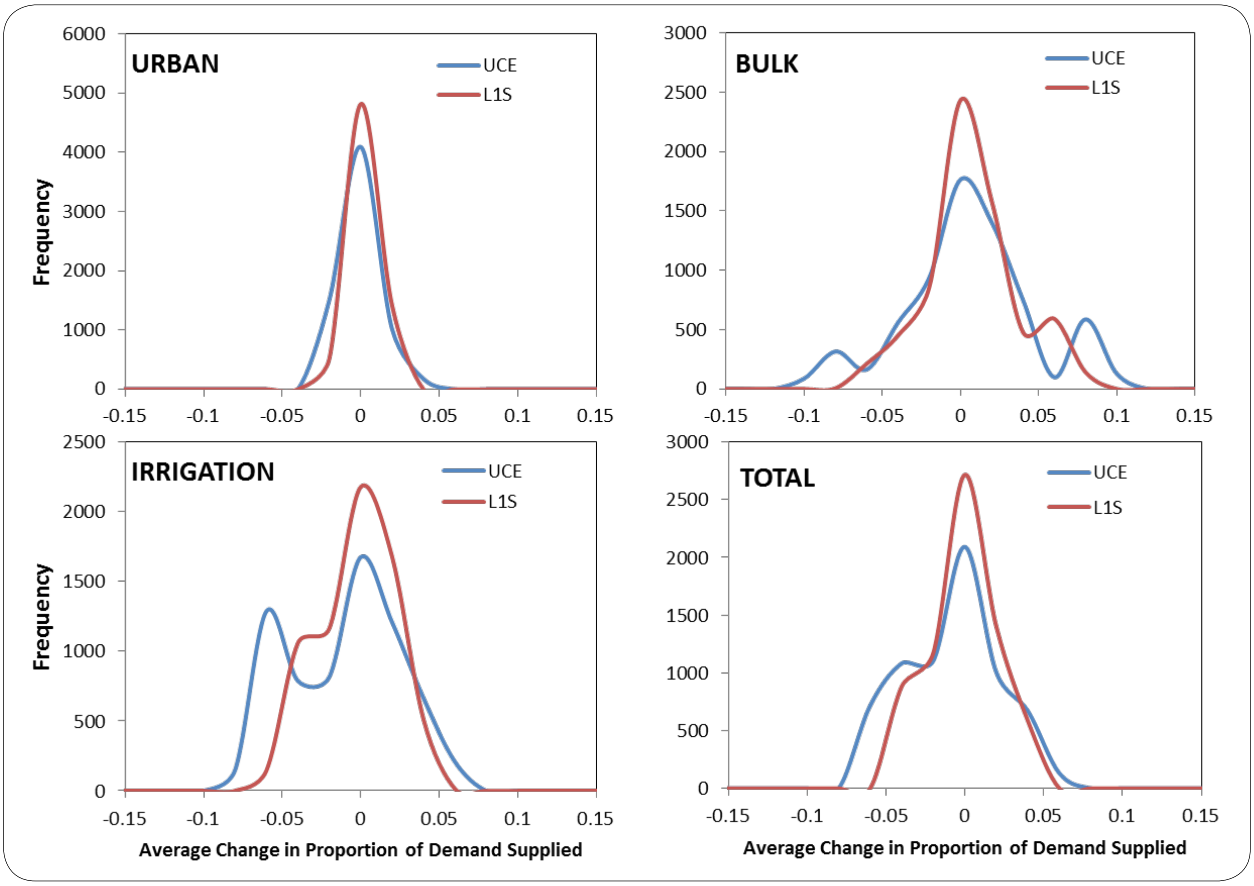


Figure 38: Hybrid frequency distribution of the change in the proportion of the average annual demand for the whole country and for different sectors that can be met under different climate scenarios over the period 2040–2050.

4.4. Hydropower potential

Hydropower is not a significant contributor to power production in South Africa. Eskom produces hydropower at the Gariep and Vanderkloof dams on the Orange River and at a number of pump-storage schemes. There are also a few smaller hydropower dams and plans to retrofit some existing dams, for example the Hartbeespoort Dam, with turbines to generate additional hydropower potential. None of these dams, however, are operated specifically as hydropower dams and hydropower is rather a by-product generated when releases are made for other downstream users including irrigation demands.

Using the HFD UCE and LIS climate scenarios, the results from an initial assessment of the likely impacts on the potential hydropower production at the Vanderkloof Dam and the planned hydropower station at Hartbeespoort Dam are given in **Figure 39**. These results show significant differences for hydropower potential across the country that should be considered when planning to build new dams or adding hydropower capability to existing DWA owned and other dams. There appears, however, to be little difference between the UCE and LIS scenarios as a result of some mitigation of variability in flow due to the available storage capacity and limited change in the median impacts under both scenarios.

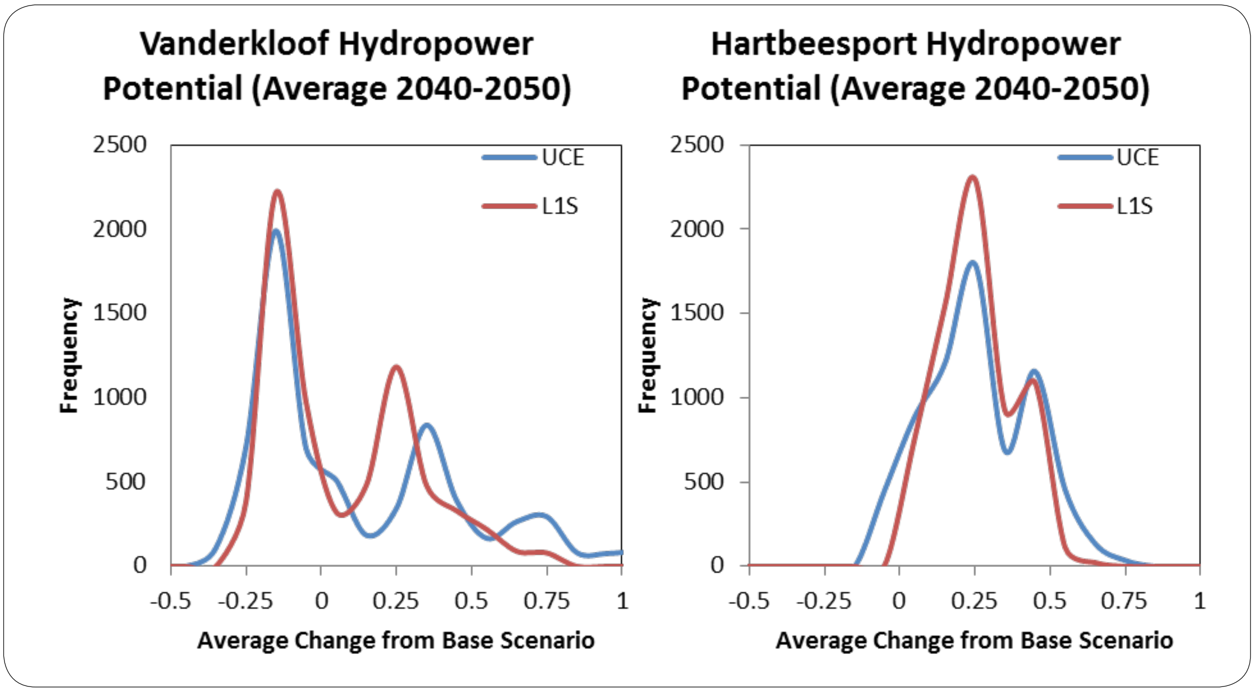


Figure 39: Hybrid frequency distribution (HFD) of the change in the potential average annual hydropower production for the Vanderkloof and Hartbeespoort dams for the UCE and L1S climate scenarios.

The results show a general reduction in the hydropower potential from the Vanderkloof Dam, currently the largest hydropower dam in South Africa, with a median impact of a reduction of 4.9% in the average annual hydropower potential for the UCE scenario. There are however some models showing a potential positive impact on hydropower even up to a 75% increase. The results for the L1S scenario appear to be very similar to the UCE scenario with only a very slight reduction in the range of potential impacts.

The HFD for the Hartbeespoort Dam however shows a likely positive impact on hydropower potential due to increased runoff under future climate change scenarios.

The median impact under the UCE scenario is a 19% increase in the average annual hydropower potential by 2050.

Although these results are derived from a limited assessment of potential hydropower generation, and may be limited by daily flow variations, the turbine capacity and the potential risk of increased flooding the results suggest that certain dams could have increased hydropower potential under certain future climate scenarios in some parts of the country and the DWA should consider incorporating hydropower turbines into existing and future dams to increase alternative energy sources.

4.5. Dry-land crop yields

The impact of the potential climate futures developed from the HFD model for the UCE and LIS scenarios are determined for the current distribution of nine major rain fed crop types. These are maize, sorghum, wheat, sunflower, groundnut, soybean, lucerne, sugarcane and cotton. The frequency distributions of the potential impacts on the yield of these dryland crops are given in **Figure 40**.

The results of the analysis show a very wide range of possible impacts on the average annual yield of dryland crops by 2050 under the UCE scenario. Most concerning is the potential for significant declines in the average annual yields of maize and wheat, two staple food crops, by 2050. The impact on maize yields ranges from a reduction in the total yield for the country of -25% to a potential increase of 10%.

The median impact on total maize yields for the country under the UCE scenario is, however, a reduction of only around 3.5% and only a slightly less reduced impact of 3% under the LIS scenario by 2050. The potential impact on the total average annual wheat yield is similar to that of maize with the median impact for the UCE scenario being a decrease of around 4.3%. The range of potential impacts however is quite large, from -20% to +10%. The potential benefits of mitigation are quite clear for wheat, with the median impact for the LIS scenario being reduced to only -1.8% and a clear shift in the range of potential impacts with a reduced risk of potentially large reductions (below -10%) in the total yield.

The potential impact of climate change on the mean annual maize and wheat yields in each secondary catchment across the country by 2050 is given in **Figure 41**. The figure shows the median impact of the UCE and LIS climate scenarios representing the hot and warm LTAS scenarios respectively as well as the upper and lower quartile impacts representing the wetter and drier climate models. The results for both maize and wheat show the median impact to be negative across all catchments. There is some mitigation in the impacts under the LIS scenario but, consistent with the national results, this is relatively small and the median impact is still negative.

The primary maize growing areas of the country include catchments A (Limpopo), B (Olifants) and C (Upper Vaal) in **Figure 41**. In these areas the average impact is -7% with a lower quartile (drier scenarios) of -14% and an upper quartile impact (wetter scenarios) showing no change. The impacts are much less (median impact of -2.5%) for catchments R and S in the Eastern Cape suggesting that these areas may be favoured for reducing the risk of future climate change on future maize yields. Under the wetter scenarios these catchments show a 7% (upper quartile), to 32% (maximum) increase.

The primary wheat growing areas of the country are in the Western Cape, catchments G (Berg) and H (Breede) in **Figure 41**. The median impact under the UCE scenario in these catchments is around -14% with even the upper quartile results (wet scenarios) showing an 11% reduction in the annual yields.

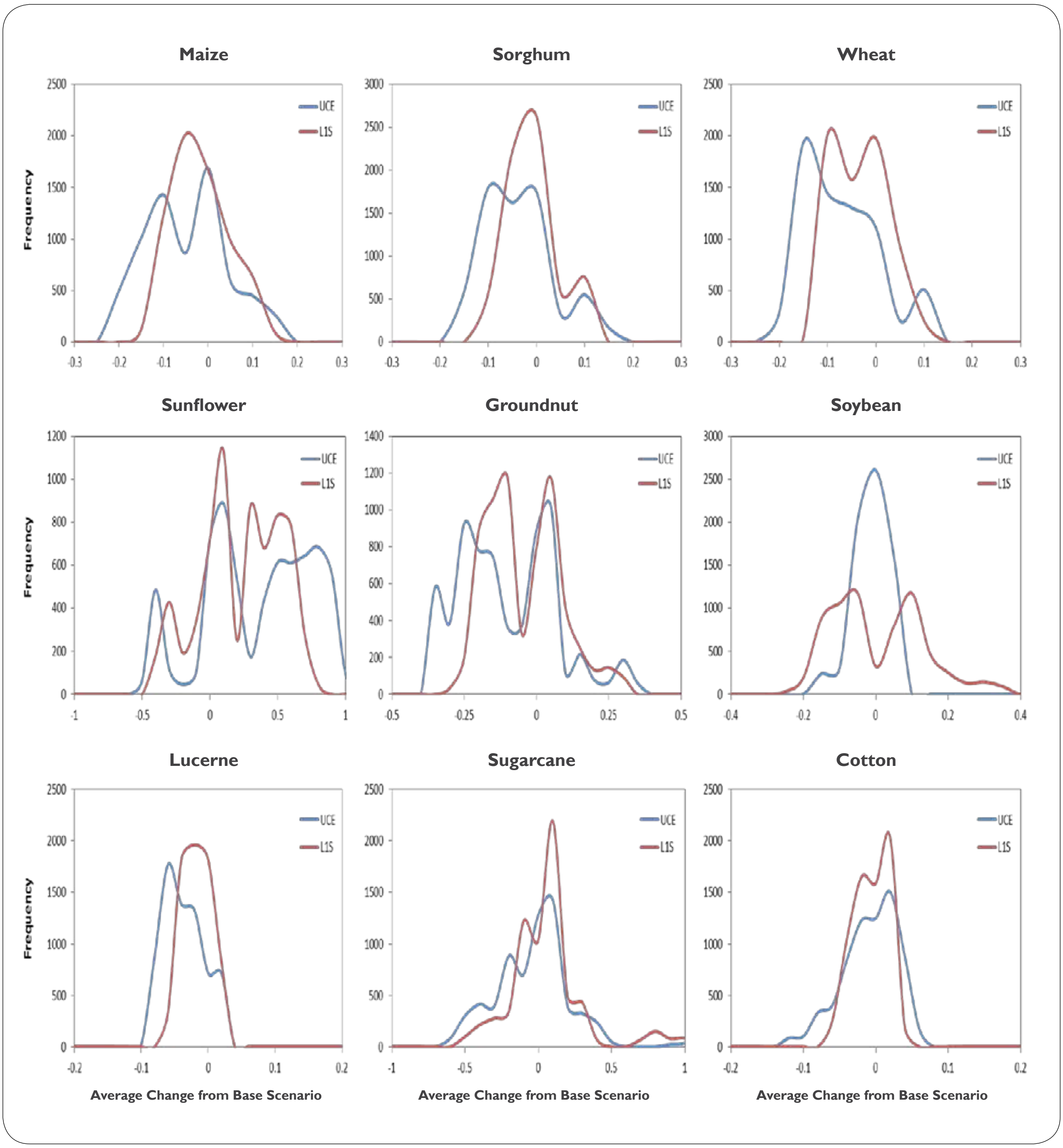
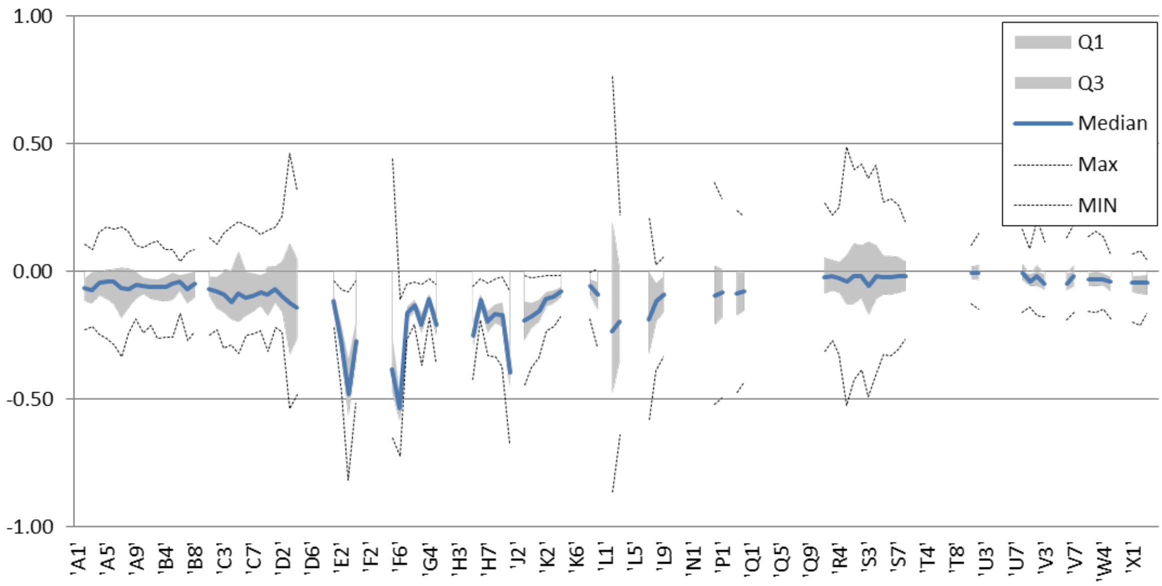
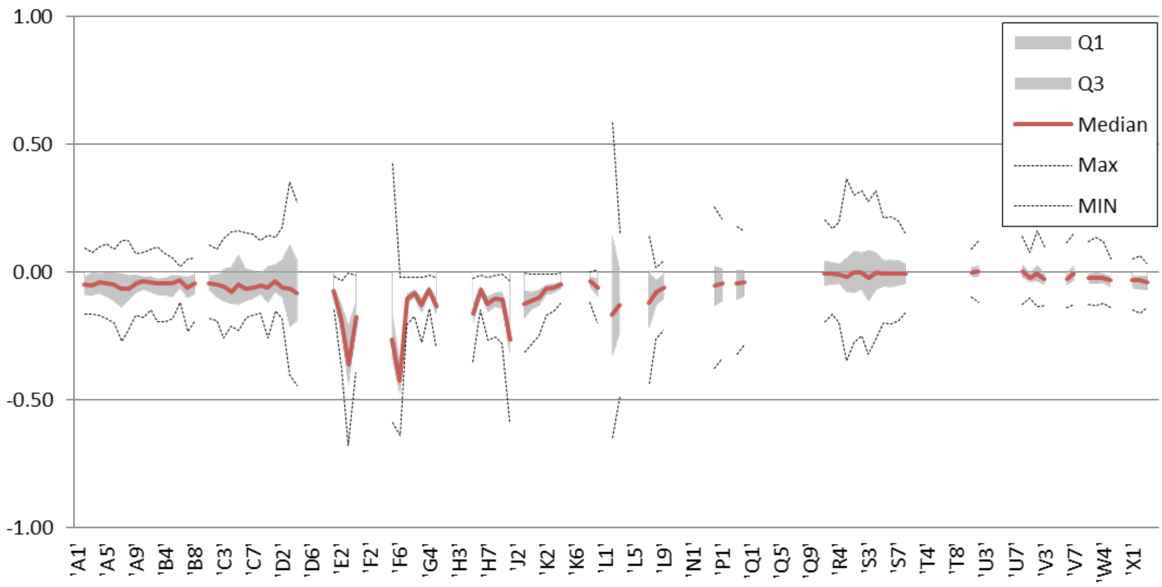


Figure 40: Hybrid frequency distribution of combined impact of changes in precipitation and evaporation on the average annual dryland crop yields under the UCE and LIS climate scenarios for South Africa for the period 2040–2050 relative to the baseline scenario.

Change in Dry-land Maize Yield (2040-2050): UCE



Change in Dry-land Maize Yield (2040-2050): L1S



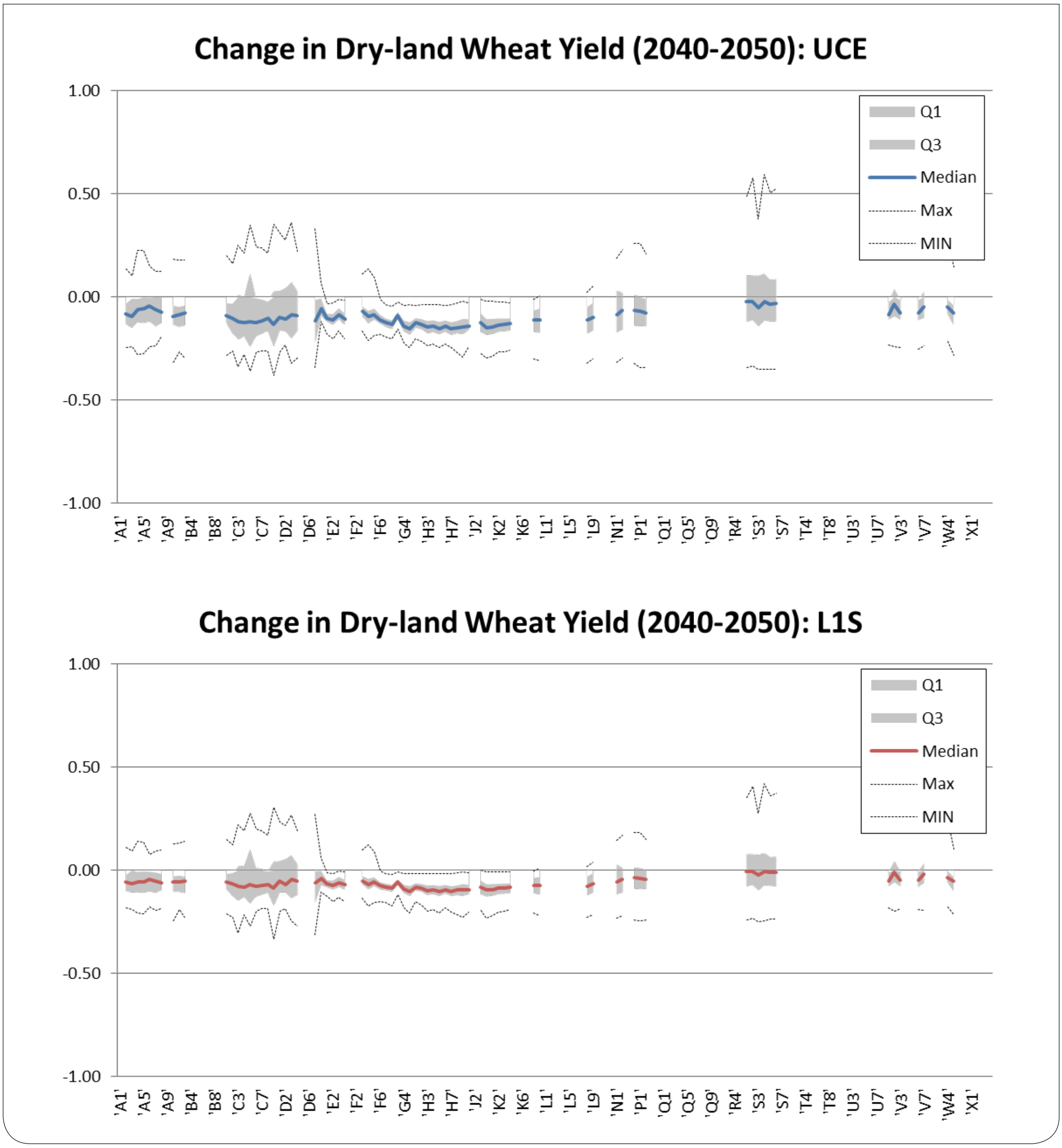
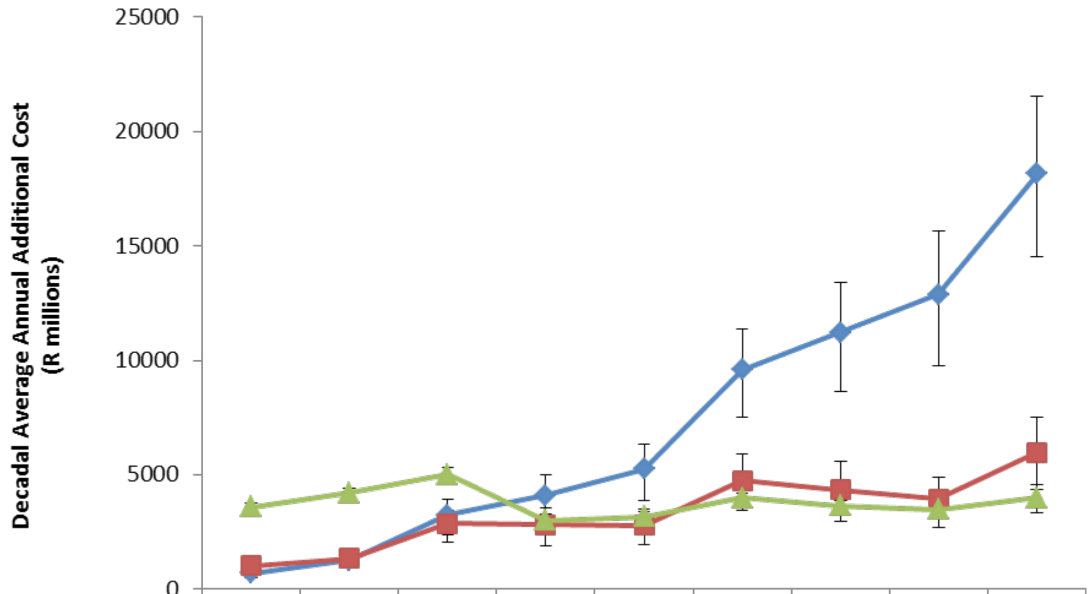


Figure 41: Median impact and the range of potential impacts of climate change on the average annual crop yield for dryland maize (left) and wheat (right) for all secondary catchments for the period 2040 to 2050 due to the UCE and L1S future climate scenarios. The x-axis shows the change in the average annual yields relative to the base scenario.

4.6. Roads infrastructure impacts

A time series of potential additional costs for the adapt and no adapt scenarios is given in **Figure 42**. These costs represent the median impact cost from the range of possible climate scenarios and give the decadal average annual additional cost for maintenance of all road types across the country. The results show that by the end of the century the annual additional costs for road rehabilitation and repair will be approximately R19 billion more for the UCE no adapt scenario, but only R6 billion for the LIS no-adapt scenario and R4 billion for the UCE and LIS adapt scenarios. Note that the UCE and LIS adapt scenarios result in the same impact as they are both based on knowledge of the future climate, irrespective of what this is, and thus result in the same optimal solution.



	2020	2030	2040	2050	2060	2070	2080	2090	2100
UCE No Adapt	708	1263	3236	4109	5266	9583	11215	12891	18152
L1S No Adapt	1023	1349	2873	2832	2788	4748	4358	3944	5983
UCE/L1S Adapt	3599	4202	5021	3012	3174	4010	3649	3480	3991

Figure 42: Median decadal average annual additional costs (R millions) on the roads infrastructure of South Africa for the adapt and no-adapt management scenarios under the UCE and LIS climate scenarios. Whiskers represent one standard deviation in the results for individual climate models.

The results suggest significant benefits for both mitigation and adaptation. Initially, however, the costs for adaptation are significantly greater than for the no-adapt scenario. By 2050, however, the benefits of adaptation start to be realised as the costs for the no-adaptation scenario increase, while the costs for adaptation reduce and stabilise once all roads have been upgraded or replaced. The benefits from mitigation (namely by following the LIS scenario) even without adaptation also start to be realised from about 2040 onwards. By 2010 there is a very significant difference between the UCE and the LIS scenarios, but with the adapt scenario resulting in the lowest overall cost noting that the adapt solution is the same for the UCE and L1S mitigation scenarios. This would suggest that greatest benefits would be derived from a combination of mitigation and adaptation. Mitigation however requires global agreements and mitigation on a global scale. Adaptation, however, is something that can be addressed at national and even regional level which gives more control and certainty to the potential benefits.

The initial cost for the adapt scenario relative to the no adapt scenario is approximately R3 billion per year. This represents approximately 7% of the approved total roads budget of R42 billion for the financial year 2013/14. The cost for adaptation is therefore relatively small. By mid-century the additional investment in adapted infrastructure is more than recovered as the annual cost of the no adapt scenario is double that of the adapt scenario by 2050.

Given that it will take at least 30 years for a full turnover in the roads inventory, based on the current estimated lifetime for paved roads, it is imperative that an adaptation policy is implemented sooner rather than later in South Africa. This will ensure that the benefits are felt in the second half of the century when climate change impacts start to become really significant.

The range of outputs from the different impacts and adaptation scenarios on the average annual additional cost for rehabilitation and repair by 2050 and 2100 are given in **Figure 43**. These results show that the median additional costs for the rehabilitation and maintenance of the existing roads network using current design standards and assumptions will total R94 billion by 2100. There is, however a wide range of possible outcomes with some models predicting a cumulative impact cost of up to R 140 billion by 2100. Even under the adapt scenario there is still likely to be a significant cost impact resulting from future climate change. This impact, however, is half of the no-adapt scenario with a median cumulative impact cost by 2100 of R46 billion. These results highlight the importance of considering the potential climate change impacts on the roads infrastructure for South Africa

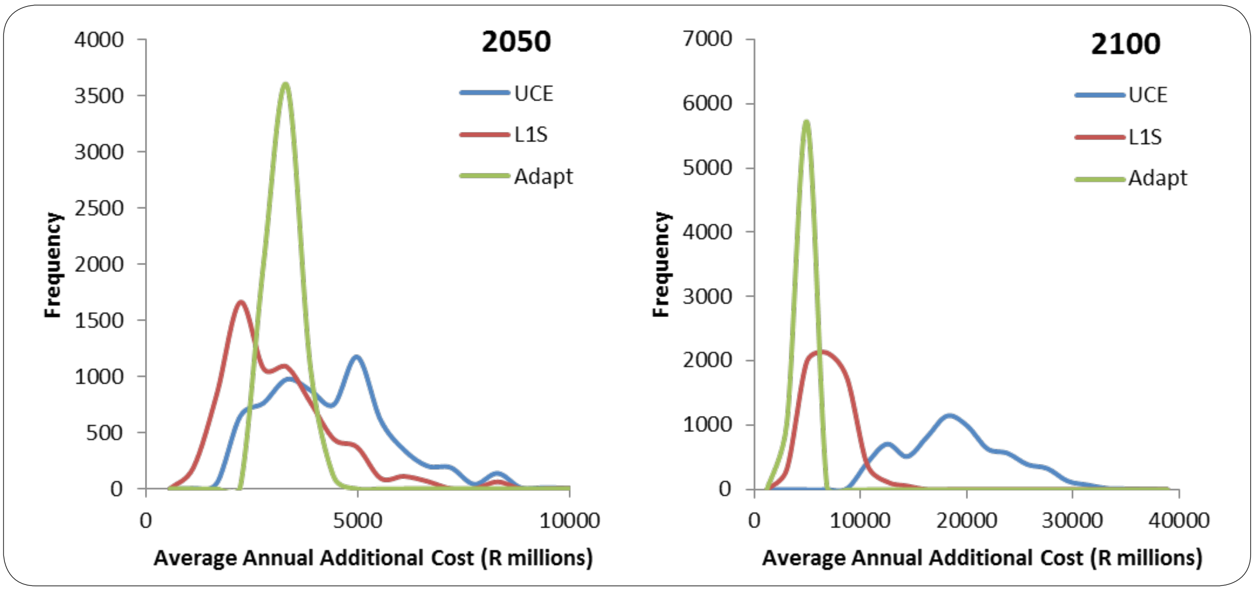
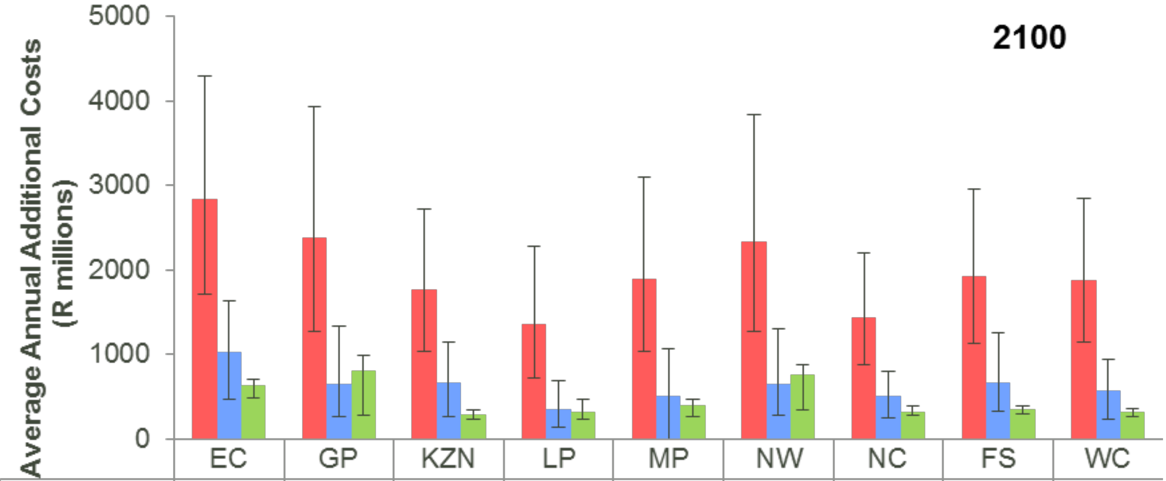


Figure 43: Range of potential impacts of future climate change scenarios on the decadal average annual additional costs for roads infrastructure in South Africa by 2050 and 2100 under the adapt and no adapt management scenarios.

The variation in the potential impact of climate change on road maintenance costs for the different provinces by 2100 is shown in **Figure 44**. The greatest cost impact of the no-adapt option under the UCE climate scenario is in the Eastern Cape which has the largest total road network. The second most significant impact is in Gauteng, which has the smallest total road network but the highest percentage of primary paved roads which are much more expensive than gravel roads to maintain under a hotter and potentially wetter future.



	EC	GP	KZN	LP	MP	NW	NC	FS	WC
UCE	2833	2385	1769	1368	1889	2339	1442	1921	1882
L1S	1038	659	664	358	510	658	509	673	575
UCE Adapt	633	806	288	316	396	755	324	354	329

Figure 44: Average annual additional costs for the final decade of the century (2095–2105) by province for the UCE and LIS no adapt scenarios and the UCE adapt scenarios. Values shown are the median of the HFD climate scenarios with whiskers representing the range of potential impacts from the 5th to the 95th percentile of the modelled scenarios.

The results given in **Figure 44** also show the significant benefit of either mitigation (namely under the LIS mitigation scenario) or adaptation to climate change with both options resulting in similar reductions in the additional maintenance costs across the country. In some provinces, however, it would appear that mitigation is marginally more beneficial than adaptation (Gauteng and North West), while in the other provinces adaptation appears more beneficial than mitigation. Ideally however there should be a combination of both mitigation and adaptation to achieve the greatest benefits and best possible maintenance of the road network.

5. POTENTIAL ECONOMIC IMPACTS UNDER FUTURE CLIMATES

The analysis of potential economic impacts proceeds by imposing the climate shocks via a number of biophysical impact channels discussed in preceding sections on an economy-wide model of South Africa. The model employed belongs to a class of models called computable general equilibrium (CGE) models. The particular model employed for this analysis contains very substantial regional and sectoral detail for South Africa (Thurlow 2008). Some of the key model assumptions are described in **Section 2.8**.

The most critical assumption in the model is that labour is assumed to be fully employed and mobile across sectors as this allows for substantial endogenous adaptation to climate change that may not be possible in reality. Agricultural and domestic water and land are also assumed to be fully employed and fully mobile within a WMA but immobile across WMAs. The modelling results suggest that this is a critical assumption as it allows for a certain level of autonomous adaptation to future climate shocks.

The analysis of potential economic impacts focuses on three key impact channels identified by LTAS, namely transport, particularly roads; water availability for irrigation, municipal and industrial uses; and yield impacts on dryland agriculture. These scenarios are labelled Roads, Irrigation, and Total. The scenarios present cumulative impacts. The alternative scenarios cannot be analysed in isolation as the cumulative impacts are not the same as the sum of the individual sector impacts due to the highly integrated nature of the economy and the economic model. The first scenario, Roads, considers only impacts on transport infrastructure. The second scenario, Irrigation, adds the implications for water resources to the Roads scenarios. The final scenario, Total, adds implications for dry-land agriculture to the Irrigation scenario. Hence, the final scenario, Total, contains all three impact channels.

The primary objective of the study was to investigate potential impacts at national level in terms of major economic drivers such as GDP and employment. The model structure, however, allows for a high degree of regional and sector specific analysis that provides further insight into potential regional impacts and inequalities in terms of potential winners and losers under future climate scenarios.

The results of the simulation of potential economic impacts are described below in terms of:

1. Overall growth of GPD and economic structure
2. Net present value of climate change impacts
3. Climate change impacts on the structure of employment
4. Potential impacts on inequality
5. Regional variations in climate change economic impacts.

5.1. Overall growth, GDP and economic structure

The total impact of climate change on the level of real GDP is found to range between -3.8% and 0.3%, although results indicate that, for the very large majority of climate futures, the impact on total GDP will be negative. This is shown in Figure 45 which illustrates the impact of the Roads, Irrigation and Total scenarios on aggregate real GDP at factor cost relative to a no climate change baseline by about 2050. Although a relatively small percentage, this is still a very large number in terms of economic impacts, and it will have a significant impact on the ability to maintain economic growth in the future.

The overall GDP impact also masks significant differences in the regional and sector specific impacts that are discussed in section 5.5, as well as potential impacts on inequality discussed in Section 5.4.

The median result shows that by 2050, South Africa's real GDP level will be about 1.5% lower than in the World Price scenario.[1] This translates into a 0.03% decline in average annual real GDP growth over the period 2011 to 2050.[2] The decline in GDP is primarily driven by the impact of Roads (estimated to be between -2.6% and -0.1% with a median of -0.8%) and dry-land agricultural productivity. Insufficient water availability in some scenarios has only a small negative impact on real GDP at national scale, although there are potentially significant impacts at regional scale. This occurs because South Africa's extensive water transfer system ensures that, in most climate scenarios, and for the main economic hubs (such as Gauteng), the share of water demand met remains relatively unchanged when compared to a no climate change baseline and there is even potential for increased supply under certain wetter future climate scenarios. The water transfer system is particularly effective in meeting urban and bulk industrial demand as well as for the major irrigation schemes across the country.

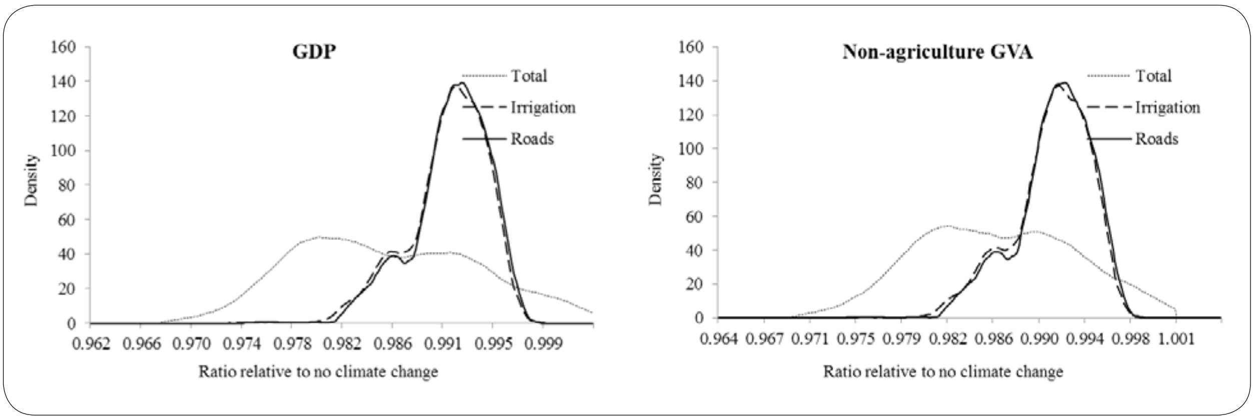


Figure 45: Impacts on average annual GDP and non-agricultural GVA under the UCE climate projections by 2050 for the Roads, Irrigation, and Total impact scenarios. The figures show the kernel density of the relative change in the average annual value for the period 2040–2050 for each of the 367 individual UCE climate scenarios relative to the historic base scenario without climate change.

1 The World Price is, for a given category of goods, the amount in rands paid by South Africa to obtain the foreign currency necessary to purchase the volume of imports of that good. Note that categories are broad, hence, units are arbitrary. For example, we import agriculture but this is composed of wheat, corn, meat, fruit etc. Weight is meaningless. Nevertheless, the unit price used is very analogous to a known price such as a barrel of oil. The price reflects a basket of goods rather than a single commodity.

2 In other words, if the no climate change growth rate were 4.5% from 2011 to 2050, the growth rate with climate change would be about 4.47% on average.

In the Roads scenario, the need for increased road maintenance raises the cost of maintaining the same road network system, hence pulling funds away from other productivity enhancing investments by government. This has a negative impact on the productivity of all sectors. The analysis of the roads impacts shows that if adaptation measure were to take place, the frequency and hence cost of road maintenance would decrease substantially, particularly in the longer term.

The inclusion of dryland agricultural productivity impacts broadens the range of possible outcomes significantly relative to the other scenarios. This highlights the sensitivity of dryland agricultural production to changes in precipitation and temperature. Furthermore, it is important to highlight that impacts on productivity in dryland agriculture are not restricted to the agricultural sector. In the case of non-agricultural gross value added (GVA), the median impact worsens to -1.4% from -0.9% in the Irrigation scenario. A direct link between agriculture and non-agriculture resides in value added processing (for example, fruits to fruit juice and wheat to flour).

The economy-wide model endogenously allocates factors of production to alternative uses in accordance with productivity and prices. If prices are unchanged, resources will tend to flow towards relatively high productivity sectors. However, domestic prices may not remain constant (as many domestic prices are not fixed by world market prices). If, for a given agricultural commodity, climate change reduces dryland agricultural productivity by 10% but the sales price to producers rises by 20% as a result of constrained domestic supply, then producers have incentives to allocate resources towards the production of this commodity even though productivity is lower as a consequence of climate change. This particular endogenous adaptation, ceteris paribus, reduces real GDP as resources are shifted from relatively high productivity to relatively low productivity sectors. This sort of resource transfer can be expected in sectors that are lightly traded internationally, where prices, as a consequence, are not strongly linked to world markets. Opposite flows also occur, especially for products strongly anchored in world markets such as wheat. In almost 30% of the climate futures, the non-agriculture sector in the Total scenario expands relative to the results from the Irrigation scenario implying a movement of resources away from agriculture and towards non-agriculture.

Figure 46 illustrates the impact of the scenarios on agricultural GVA. The rise in road maintenance costs and loss in total factor productivity (TFP) stemming from the Roads scenario reduces the level of GVA in agriculture by between 0.2 and 2.1%. Adding in the impact of Irrigation marginally worsens this result with the median decreasing by 0.07 percentage points. Under these scenarios the range of possible outcomes are small with the median impact on agricultural GVA estimated at -0.9%. Including the impact on dryland agriculture broadens the possible impacts of climate change.

In the Total scenario, which includes agriculture, the range of possible results expands substantially. The results show that agricultural GVA could rise by up to 4.7% and decline by as much as 9%. The increase in variation highlights the uncertainty regarding the impact on dryland agriculture, particularly in the Vaal and Pongola to Mzimkulu regions which experience a wide range of possible temperature and precipitation changes (see **Section 3.1.2**). These areas largely produce cereals and sugarcane and account for 39.3% and 41.6% of dryland agricultural GVA respectively and 23.2% and 27.5% of total agricultural GVA.

While the impacts on GVA in agriculture as a whole are broad, the implications within the agricultural sector tend to be even more pronounced. For example, a very important endogenous adaptation channel involves relative expansion and decline of dryland and irrigated agriculture. **Figure 46** illustrates that the change in dryland agricultural GVA is very broad ranging between -58.7% and 22.1%. Consistent with average negative impacts on dryland crop productivity and net real

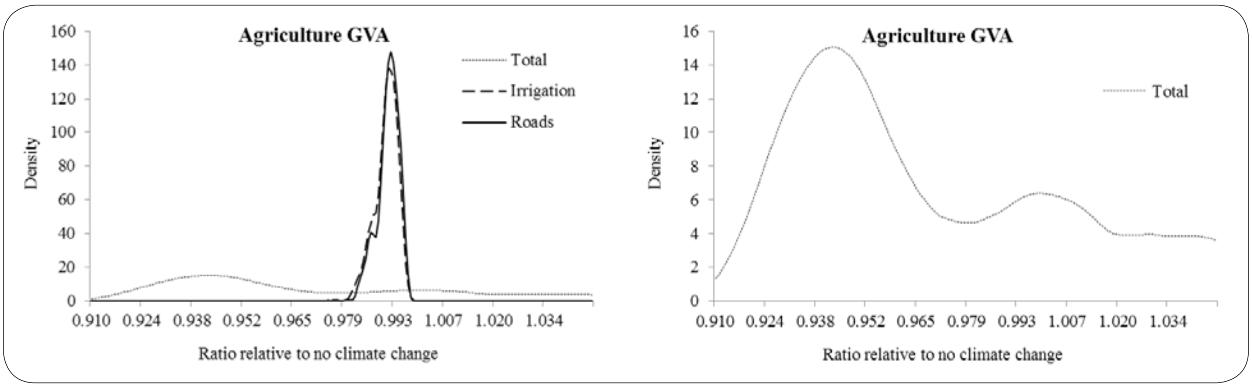


Figure 46: Climate change impact on agricultural GVA across scenarios. The figures show the kernel density of the relative change in the average annual value for the period 2040–2050 for each of the 367 individual UCE climate scenarios relative to the historic base scenario without climate change.

resource movements away from dryland agriculture on average, the median impact is estimated at -20.3%.

As might be expected, movement in irrigated agriculture is in the opposite direction. Real value added in irrigated agriculture is expected to increase, sometimes substantially, as resources move away from dryland production and towards irrigated production. Hence, as productivity in dryland agriculture declines, the relative attractiveness of irrigated agriculture increases. Overall,

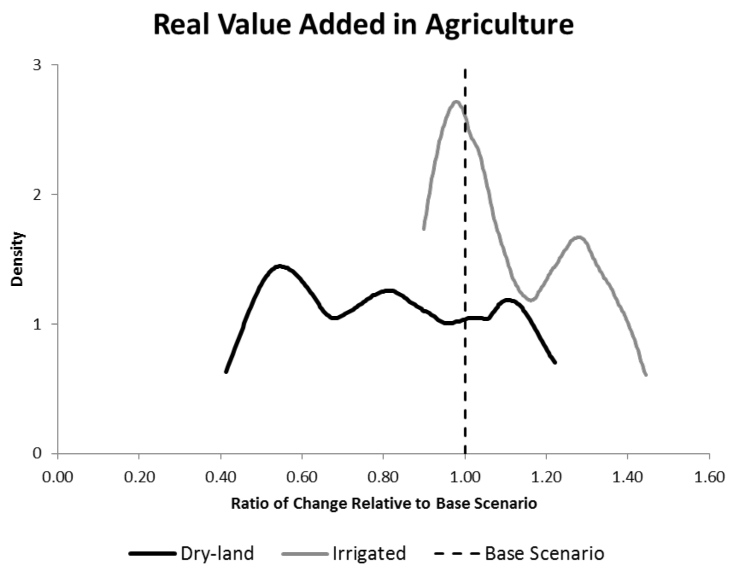


Figure 47: Impact on value added in dryland agriculture and irrigated agriculture. The figure shows the kernel density of the relative change in the average annual value for the period 2040–2050 for each of the 367 individual UCE climate scenarios relative to the historic base scenario without climate change.

the model points to an ability to expand (or contract) the irrigated agricultural area as an important endogenous adaptation channel. It is important to note, however, that the economy-wide model, as currently constructed, may overstate the ease with which resources can flow between irrigated and dryland agricultural production as this provides flexibility in the endogenous adaptation options under future climate scenarios that may not exist in reality. More constrained possibilities for reallocation would reduce the magnitudes of the shifts depicted in Figure 46. However, even with higher costs associated with these reallocations, the qualitative result of shifts between dryland and irrigated agriculture as an important endogenous adaptation channel would be expected to remain.

5.2. Net present value of climate change impacts

While the implications for the average annual growth rate of GDP are small, these reductions are consistent and they accumulate over time. Consequently, in terms of net present value (NPV) of losses, the total value of GDP losses induced by climate change is noteworthy. The NPV of GDP losses, calculated as the discounted difference between the GDP of the climate scenarios and that of the World Price scenario, are presented in **Figure 48**. The losses are presented in rands in 2007 prices using a discount rate of 5% as this is the base year for data used in the economic model.

Total discounted GDP losses in the Roads scenario range between R10.5 billion and R386 billion for all climate futures, with a median loss of about R102 billion. Including the Irrigation impact, this range extends to between R19 billion and R407 billion, with a marginally higher median loss of about R109 billion. In the Total scenario, the impact on GDP is much more variable, ranging from losses of R651 billion to gains of R217 billion, although 96% of climates show losses, which tend to be more severe than in the Irrigation scenario.

The median loss is approximately R259 billion which, at more than 10% of 2007 GDP, is sizeable.

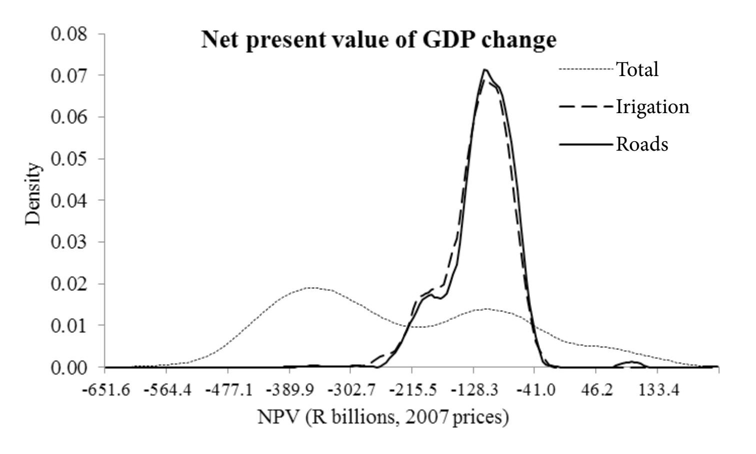


Figure 48: NPV of GDP losses due to climate change for different scenarios by 2050. The figure shows the kernel density of the change in the average annual value for the period 2040–2050 for each of the 367 individual UCE climate scenarios relative to the historic base scenario.

Figure 49 shows GDP losses by decade in the final scenario. As might be expected, the estimated impact on GDP becomes more negative and the distribution wider in successive decades. In the 2010s, the GDP losses are well contained and largely centred on zero. As time progresses, these losses become much stronger and the variance larger. This shows that, even with losses discounted to 2007, the impact of climate change in later decades is sizeable. The likelihood of positive NPV outcomes also falls dramatically, from 22% in the 2010s to 4% in the 2040s.

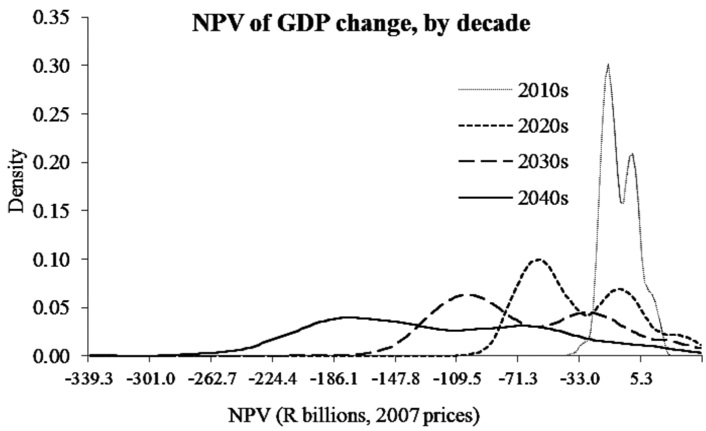


Figure 49: Net present value of GDP impacts of climate change for future decades. The figure shows the kernel density of the change in the average annual value for each decade for each of the 367 individual UCE climate scenarios relative to the historic base scenario.

In sum, a window of opportunity exists to prepare to confront the challenges posed by climate change. In two or three decades time, the challenges posed by climate change are likely to be much more profound, especially in the absence of global mitigation policy, with very real consequences for the national economy as well as significant regional variability and potential inequality impacts.

5.3. Climate change impacts on employment opportunities

Overall employment levels and trends are clearly of interest in the South African context. This is particularly true for unskilled labour where unemployment rates are high. Nevertheless, as we project mild implications of climate change for the overall rate of economic growth, particularly over the next 10–20 years, the implications for employment are correspondingly mild.

Employment growth is, both in the economy-wide model employed and in reality, extremely sensitive to labour market policies and institutions. Consequently, the potential impacts of climate change, at least at the national scale are overshadowed by these other potential uncertainties. It is clear, however, that a more flexible labour market is likely to provide resilience under future climate and other uncertainties as it allows for the movement of labour and other resources (land, water and capital) between regions and between sectors that are more or less impacted by climate change.

Box 1 provides greater details for two particular climate scenarios in the Mvoti-Umzimkulu WMA.

Box 1: Differences between extreme climate scenarios

The wide range of hydro-climatic possibilities can cause large variations in crop yields, which may vary between different crops and WMAs. This, in turn, manifests itself in a wide range of economic impacts. It is important to understand this uncertainty in order to appropriately respond to the different impacts that the various climate possibilities portend. To illustrate this wide band, we select two climate scenarios and discuss their impact on sugarcane production.

Climate scenario 159 (derived from IGSM run 233 with regional outcomes estimated based on the Goddard Institute for Space Studies climate model) projects a favourable environment for dryland sugarcane production in Mvoti-Umzimkulu (WMA 11). Better temperature and rainfall outcomes raise the production potential of dryland sugarcane, and this attracts factors to the activity, resulting in increased sugarcane production.

The additional labour and capital required to expand production can be drawn from other sectors without greatly increasing wage rates and capital returns. However, the scarcity of land to expand production means that rental rates increase. The increased supply of sugarcane is supportive of slightly lower sugarcane prices.

Conversely, climate scenario 176 (derived from IGSM scenario 135 with regional outcomes estimated based on a climate model from the Institute of Numerical Mathematics, Russian Academy of Science) predicts large, climate-induced yield losses which negatively impact dryland sugarcane activity. As dryland sugarcane from Mvoti-Umzimkulu makes up nearly half of national sugarcane production, this impact is significant. Sugarcane production becomes increasingly reliant on irrigated crops in the Mvoti-Umzimkulu area, but also from the Inkomati (WMA 5) and Usutu-Mhlatuze (WMA 6). However, these areas cannot fully compensate for the loss in production because of land and water supply constraints.

Therefore, the price of sugarcane increases considerably, by about 28% in real terms.

Unskilled labour employed by dryland activity falls by two-thirds relative to 2002, which affects incomes of the poor in rural areas, although the increase in other agricultural sectors, such as irrigated sugarcane, provides some relief. Food prices are pushed generally higher.

The differences between the impacts of scenario 159 and scenario 176 on macroeconomic aggregates are small. However, the changes are meaningful to the agricultural sectors of Mvoti-Umzimkulu, other sugarcane producing areas, the national market for sugarcane and downstream industries.

5.4. Potential climate change impacts on inequality

The economy-wide model employed for this analysis contains 95 representative households, opening the possibility for analysis of the distributional impacts of climate change. The households in the model were developed using the 2000 income and expenditure survey (the base year for the social accounting employed is 2002) (StatsSA 2000). To obtain the household disaggregation, households from the income and expenditure survey were first divided by income quintiles. These income quintiles were then further divided by WMA (5 quintiles multiplied by 19 WMAs yields 95 representative households). To calculate inequality, the average expenditures of each household around 2050 were employed. These values were divided by the estimated population corresponding to each of the 95 representative households in order to obtain per capita expenditure. For computational ease, the Theil measure of inequality was calculated across households for the World Price scenario and for all climate change scenarios.

The results indicate only very small changes in overall inequality relative to the baseline in all climate change scenarios. This result stems principally from three factors. First, the very large majority of household income is derived from labour and capital. These factors of production are, over time, mobile across industries. This mobility implies that differentials in factor returns tend to be flattened through time as factors move towards industries with high returns and away from industries with low returns. Hence, differences in factor returns across scenarios tend to be small.

A similar dynamic occurs in commodity markets where commodity prices are smoothed by adjustments in production and imports/exports. In addition, consumers devote only a relatively small share of expenditure to basic agricultural commodities where the action in prices is most pronounced. Rather than consume basic agricultural commodities directly, the bulk of food consumption involves purchase of products that have been processed, transported and then sold in a retail establishment. As the implications of climate change for these latter steps are relatively small, the price of this value addition remains relatively constant, which further stabilises food prices.

Finally, while 95 households and nearly 30 commodities represent a highly detailed economy-wide model, the model remains far less detailed than reality. There is no doubt that some households will suffer as a consequence of climate change while others may gain. The implications of these distributional shifts are only roughly captured in the existing modelling framework.

Box 2 provides an example of how climate change could potentially impact on the more vulnerable communities using results for the Thukela and Mzimvubu-Keiskamma WMAs as an example.

Box 2: Climate change outcomes and the impact on the vulnerable

Poverty in South Africa varies across regions. Areas with high levels of poverty are generally characterised by larger shares of the population living in rural areas and a greater reliance on dryland agriculture. The results indicate that the impact of climate change in these areas is uncertain as the changes in temperature and precipitation levels are highly variable across potential future climates.

Examples of such regions are Thukela (WMA 7) and Mzimvubu-Keiskamma (WMA 12), which lie along the east coast of South Africa (see table below). In these regions the mean per capita consumption in rural areas is well below the national average and more than 60% of the population live in the bottom two consumption quintiles. The impoverished communities in rural areas tend to rely on dryland agriculture for employment, and on subsistence farming for food. Climate changes in these areas pose significant food security risks as residents may have difficulty adjusting to climate shifts. Further research on climate change impacts on the vulnerable is important for any adaptation planning.

Table 2: Areas with high levels of poverty and rural population dependent on dryland agriculture

					Possible impacts on agriculture QVA*		
Water Management Area (WMA)	% Dryland agriculture	GDP per capita	Rural mean per capita consumption	Share of population in consumption quintile 1 and 2	Low	Median	High
National	**80**	**23282**	**7834**	**40**	**-9%**	**-4%**	**5%**
12 Mzimvubu-Keiskamma	77	8142	4301	64	-21%	-5%	29%
7 Thukela	68	9042	4427	71	-25%	-12%	15%
1 Limpopo	76	16334	4989	50	-10%	-2%	21%
6 Usutu-Mhlatuze	73	10554	5196	67	-30%	-1%	39%
11 Mvoti-Umzimkulu	81	22797	5808	42	-34%	-2%	26%
4 Olifants	81	22629	5895	46	-16%	-3%	14%
2 Luvhuvhu-Letaba	4	13113	6269	61	-6%	0%	5%
10 Lower Vaal	85	13768	6280	53	-26%	-13%	20%
5 Inkomati	37	16041	6492	53	-15%	-9%	54%

* QVA – quantifiable value added
Source: Author's compilation

5.5. Regional economic impacts of future climate change

On aggregate the impacts of climate change tend to be fairly small at national level, especially when considering average annual economic growth rates. Nevertheless, at finer spatial scales, there are cases where the impacts, particularly on agriculture, become large and highly variable across climate futures.

Figure 50 and **Figure 51** illustrate the potential impact of climate change by 2050 on agricultural value added across the 19 WMAs assessed. There are three key findings from this analysis that have implications for future development scenarios and adaptation options that require further research.

The first key finding is the large variability in results, especially in areas with high poverty rates. The dependence of many of these regions on dryland farming makes these regions particularly susceptible to changes in temperature and precipitation. One such region is KwaZulu-Natal (WMAs 6, 7, and 11), which has the second highest poverty rate among provinces and in which the impact of climate change is highly variable depending on the climate future. The impacts of climate change vary by between -30% and +35% in Usutu-Mhlatuze (WMA 6), between -25% and +32% in Thukela (WMA 7), and between -34% and +26% in Mvoti-Umzimkulu (WMA 11). In each of these areas, more than 10% of unskilled workers are employed in agriculture. The wide variation in agricultural value added means that the outlook for these types of workers is uncertain. Negative shocks or high adjustment costs could exacerbate the degree of poverty in these areas.

The second key finding relates to the impact of climate change on agriculturally important areas, such as the Vaal region (WMAs 8, 9 and 10). The Vaal region is a major domestic producer of summer cereals, winter cereals, and oilseeds. It accounts for about one quarter of national agricultural value added. In the upper and middle Vaal regions (WMA 8 and 9), more than 55% of climate futures indicate that agricultural value added deteriorates by more than 10%, and about 23% of climate futures suggest this deterioration exceeds 20%. This could have sizeable impacts on national agricultural production, and additional implications for food security.

The third key finding from the regional comparison of potential impacts of climate change on the agricultural sectors in the individual WMAs shown in **Figures 50** and **51** relates to regions with almost universally negative impacts on agriculture. These include the Olifants/Doorn (WMA 17) and Berg (WMA 19) areas along the west and south-west coast.

These areas are important domestic producers of winter cereals, deciduous fruits, and vegetables. Deciduous fruit is a high value commodity and, as over 60% of it is exported, it is an important agricultural export commodity. More than 99% of climate futures show deteriorating agricultural value added in the Olifants/Doorn area, and more than 96% of climate futures indicate lower agricultural value added in the Berg area. While the severity of the decline appears limited (no climate future shows a decline of more than 10%), the impact on agricultural activity in these areas has important implications for agricultural exports, and the production of winter cereals. This is also significant at national level as the Western Cape contributes some 25% to the national agricultural GDP with a high level of export crops that could negatively impact the export earnings and foreign trade balance of the country.

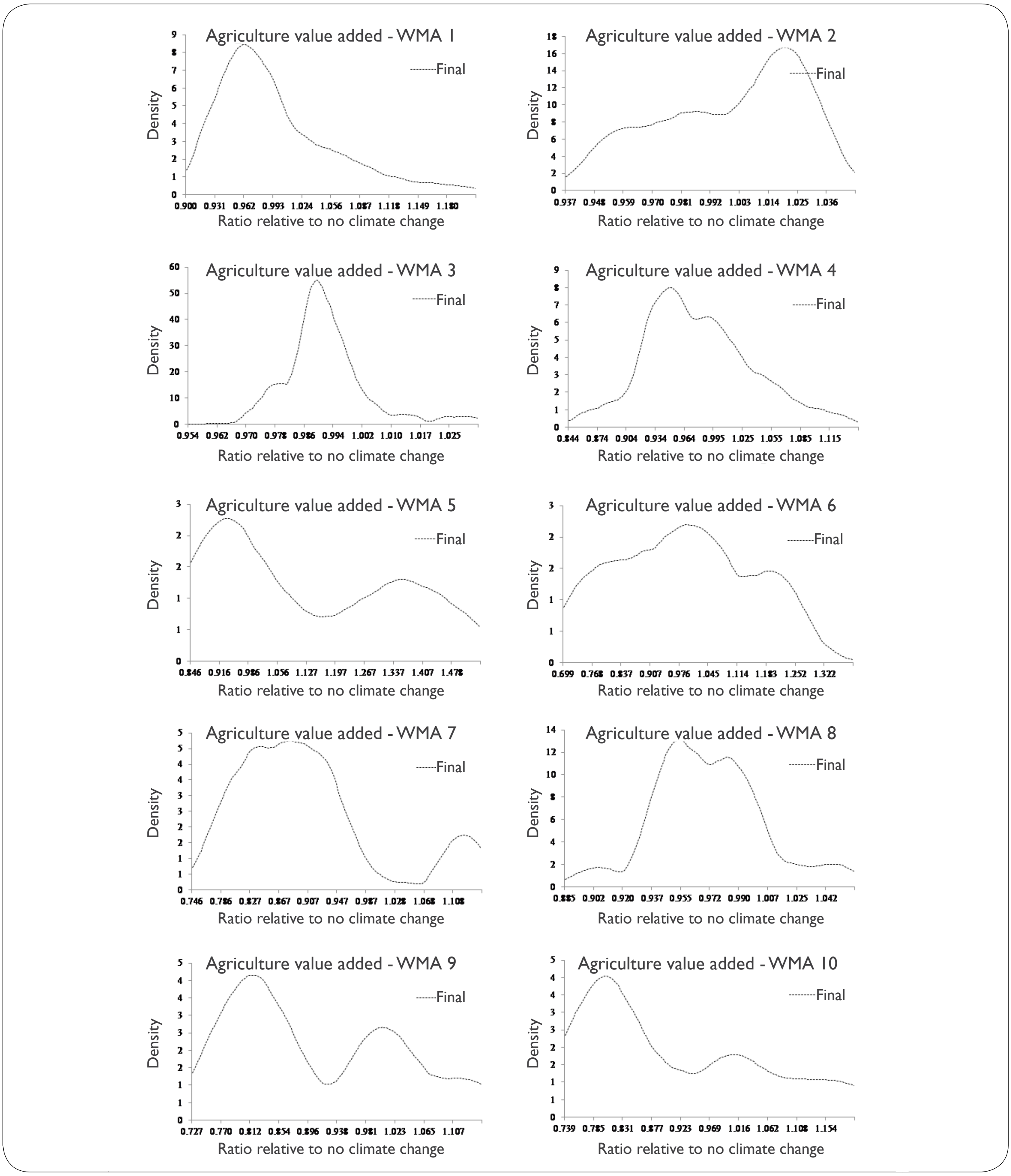


Figure 50: Potential climate change impacts by 2050 on the average annual value added in the agricultural sector for WMA 1 (Limpopo) to WMA 10 (Lower Vaal). The figures show the kernel density of the relative change in the average annual value for each decade for each of the 367 individual UCE climate scenarios relative to the historic base scenario.

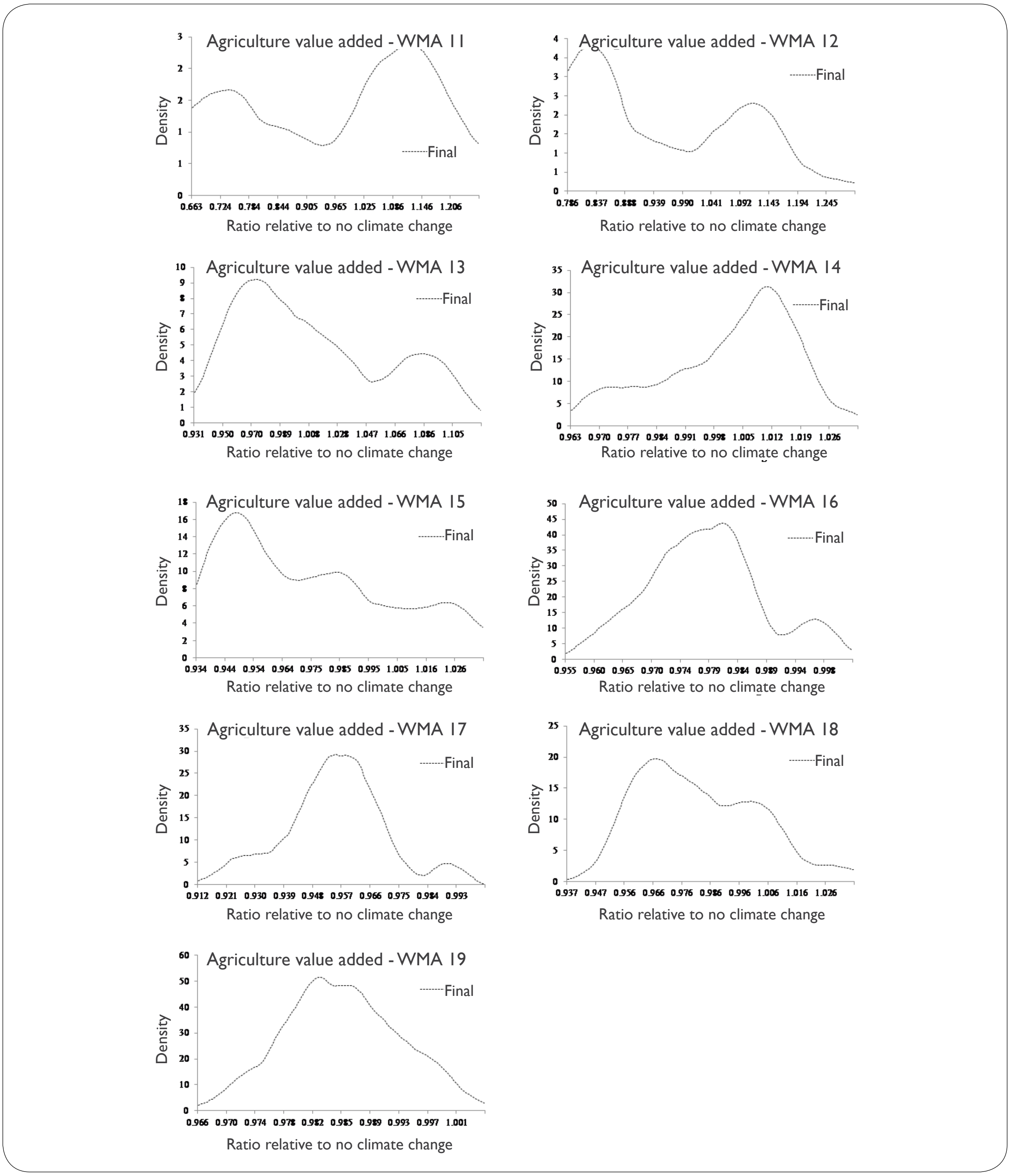


Figure 51: Potential climate change impacts by 2050 on the average annual value added in the agricultural sector for WMA 11 (Mvoti–Mzimkulu) to 19 (Berg). The figures show the kernel density of the relative change in the average annual value for each decade for each of the 367 individual UCE climate scenarios relative to the historic base scenario.

5.6. Summary of economic modelling results

The following principal conclusions emerge from the analysis of the potential future economic impacts of climate change at national, subnational and sectoral level in South Africa.

- The implications of climate change for the overall rate of economic growth are overwhelmingly likely to be negative. The potential growth implications, although significant, are not likely to be a large percentage of national GDP, especially within the next 10–20 years. There are, however, very significant impacts in individual sectors and at sub-national level.

- While the implications for growth are likely to be small, the implications are, under the large majority of future climates, consistently negative and become more pronounced with time. Accumulated economic losses due to climate change over the next 35 years are likely to be large in net present value terms. **The expected loss amounts to more than 10% of 2007 GDP.**

- The principal impact channels arise from **more rapid depreciation of transport networks** and changes in the **productivity of dryland agriculture.** Importantly, the **water resource management system appears to be quite robust** across a wide array of possible climate futures. Broad-scale and extended disruption to municipal and industrial water supplies, particularly in the major urban centres, appears to be unlikely, but could be a concern in the smaller centres and for stand-alone systems with less integrated and limited alternative water supply options.

- With the exception of the southwest where persistent drying is expected, the water resource management system is frequently able to provide a reasonably steady supply of irrigation water. As a result, broad-scale failures of the water resource system are not anticipated to be a major source of economic drag. **On the contrary, expansion of irrigated agriculture is a major endogenous adaptation to reduced dryland agricultural productivity.**

- The aggregate impacts of climate change disguise very substantial variations at the **sectoral level or at finer spatial disaggregation.** This is particularly true **for agriculture where impacts are large and highly variable across climate futures for different parts of the country.** With respect to agriculture, a series of additional observations are pertinent:

    o The dependence of many regions with high poverty rates on agriculture in general, and dryland farming in particular, generates an undesirable positive correlation between zones of high variability in possible long-run economic outcomes and areas with substantial poverty. For example, KwaZulu-Natal (WMA 6, 7, and 11) has the second highest poverty rate of any province and exhibits marked variation in long run growth trends depending on the climate future. **The wide variation in agricultural value added means that the outlook for these types of workers is uncertain, which could exacerbate the degree of poverty in these areas.**[3]

3 Changes in climate are distinct from variations in weather on a year to year basis. Climate could be viewed roughly as expected weather. The variations in agricultural value added presented and discussed here are due to differential trends in climate. Variations in weather come on top of these trends.

- The Vaal region (WMA 8, 9 and 10) is a major domestic producer of summer cereals, winter cereals, and oilseeds. It accounts for about one quarter of national agricultural value added. **In WMAs 8 and 9, more than 55% of climate futures indicate that agricultural value added deteriorates by more than 10%, and about 23% of climate futures suggest this deterioration exceeds 20%.** National level production trends are likely to be driven substantially by outcomes in this region.

- While large variations are typical, the results almost all identify regions with universally (or nearly so) **negative impacts on agriculture**. These include WMAs 17 and 19 along the west coast. These areas are important domestic producers of winter cereals, deciduous fruits, and vegetables. Deciduous fruit is a high value commodity and, as over 60% of it is exported, it is an important agricultural export commodity. **More than 99% of climate futures show deteriorating agricultural value added in WMA 17 (Olifants/Doorn), and more than 96% of climate futures indicate lower agricultural value added in WMA 19 (Berg).** While the severity of the decline appears limited (no climate future shows a decline of more than 10%), the impact on agricultural activity in these areas has important implications for agricultural exports, and the production of winter cereals.

6. ADAPTATION AND DEVELOPMENT RESPONSES UNDER FUTURE CLIMATES

Based on the results of the biophysical and economic model of the potential impacts of climate change under the different climate change scenarios, a number of conclusions can be drawn in terms of potential impacts on development and possible adaptation responses. These are described below.

1) Development is the best form of adaptation, but it must be clever development

A recent World Bank study on the potential cost of adaptation for developing countries derived the following general conclusions that are particularly relevant to climate change adaptation in SA:

1. Adaptation to a 2 °C warmer world will be costly, but not impossible as it is a relatively small percentage of GDP, equivalent to the current levels of international aid.
2. The world cannot afford to neglect mitigation. Adaptation minimises the impacts of climate change, but it does not address the main causes/drivers of climate change.
3. Development is imperative as it will address many of the adaptation concerns, but it must take a new form to be more sustainable and incorporate future uncertainty (World Bank 2010a).

South Africa currently suffers from an adaptation deficit to even current climate variability. Improved social and economic development is required to address the current adaptation deficit and must also be promoted to reduce future adaptation concerns under alternative climate futures. This development must take a new form, incorporating, for example, sensitive green urban design, improved regional planning and enforced zoning such as 1:100 year flood lines and coastal set-back lines.

▷ ***Response action:*** Guidelines for appropriate climate resilient and sustainable development should be developed to assist national departments, local municipalities and developers with adaptation.

2) Adaptation must work on all components of the risk equation

Risk = Hazard x Vulnerability/Adaptive capacity

Mitigation can potentially reduce the hazard, but only to a limited degree and over the long term. Mitigation also requires global collaboration, agreements and action with a significant lag in results. Adaptation can have a more immediate and direct impact and reduce the risk under different climate futures (both wetter and drier). Adaptation must work to reduce vulnerability (for example, moving people out of flood plains) and strengthen adaptive capacity (for example, improved social support and safety nets). Analysis of the potential impacts on roads infrastructure shows that mitigation can have similar impacts to adaptation, but that ideally there should be a combination of both to give best results.

▷ ***Response action:*** South Africa should continue to address mitigation in the long term, but it is critical that current vulnerabilities are addressed including people living in flood prone areas.

3) Flexible and adaptive systems that allow for the movement of resources to more efficient sectors can provide resilience and potentially mitigate the future impacts of climate change.

Provisional analysis of the economic impacts of climate change showed only marginal impacts on the national economy. This is in part due to the movement of resources, including water, labour, land and capital between sectors and regions, both in the water supply and in the economic models, that results in the most efficient allocation of these resources. This is only possible in the real world if supported by a flexible and adaptive system that allows, for example, the transfer of water between users and even between sectors, as well as the movement of labour, land and capital between sectors and regions.

The current South African economy and many government policies and interventions are not necessarily conducive to the efficient allocation of resources in this way and barriers to reaching these optimal solutions must be identified and where possible removed or addressed. This could, for example, include mechanisms for water trading, changed policies on land and water reform, and improved skills development and changes in labour laws to enable labour to move more easily between sectors.

▷ ***Response action:*** Mechanisms that allow for endogenous adaptation within the economy need to be identified and strengthened. Alternatively, blockages to these adaptation responses need to be removed.

4) Investment in adaptation now will pay benefits in the future

Initial investments in upgrading roads, for example, are costly but after about 2040 the adaptation costs will be less than the additional impact costs if current design standards continue to be used, particularly under a hotter and wetter future. The future benefits of adaptation appear to be as significant as the benefits of mitigation, but ideally there should be a combination of both. This is shown in terms of the road impact results (**Section 4.6**) with significant benefits from adaptation realised in the second half of the century, but with changes to design standards and adaption measures required now due to the 30 year lifetime for paved roads in South Africa and the extent of the existing road network potentially impacted.

▷ ***Response action:*** Consideration of adaptation options should not be delayed as it will take time to realise the benefits. Additional safety factors applied to road culvert design for new or rehabilitated roads for example could potentially result in significant future reduction in flooding risks and cost.

5) Adaptation will require us to rethink/redefine our current design standards

Many of our current design standards (roads, buildings, floods, and so on) are based on climate variables (temperature, precipitation, and other factors) that were analysed during the 1970s and 1980s based on records for a relatively short timespan and the assumption of stationarity. **Figure 52** shows regions of the country used for the selection of the type of pavement binder in the design of a road. The regions are defined in terms of the Weinert N-value which is a ratio of evaporation to precipitation. These regions were defined in the 1980s and are likely to have shifted already and will most definitely shift given future predictions of increased temperatures across South Africa. Road designers are already opting to use higher levels of pavement binders given evidence of increasing temperatures around the country. In this regard SANRAL should initiate or support a study to review the current road pavement and drainage design standards under current and future climate uncertainty.

Similar climatic zones have also been defined for the determination of flood frequencies used in road, bridge and dam design standards. These are also likely to have to be updated, particularly in a wetter future with the expected increase in flood frequencies. **Figure 53** shows some provisional results of the potential change in the 1:10 year maximum daily rainfall across South Africa by the end of the century for a selection of different climate models (DEA 2015). The different models show significant increases in flood-producing rainfall, particularly in Limpopo, the southern Cape and the Eastern Cape.

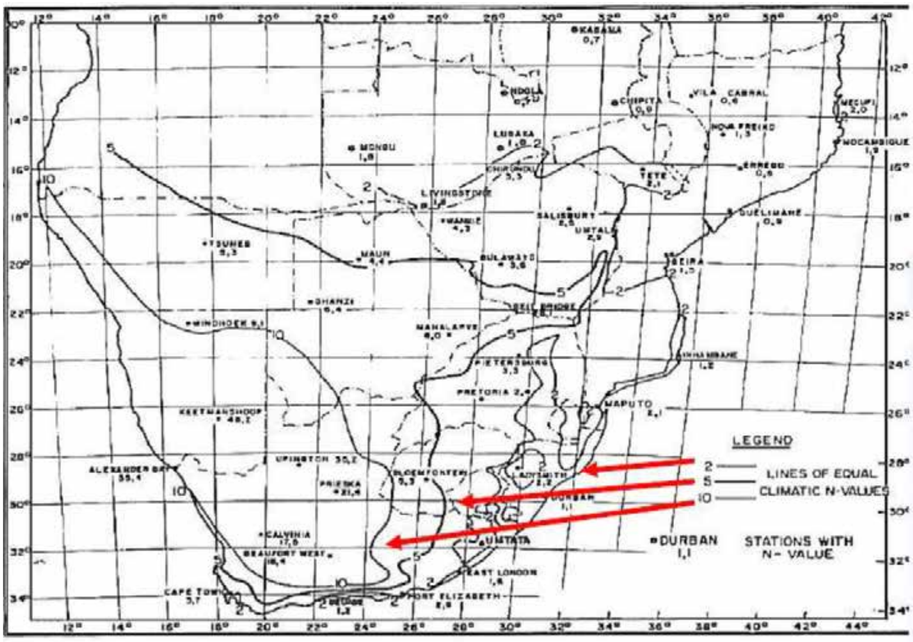


Figure 52: Classification of climatic regions for the selection of pavement binder type (Weinert 1980)

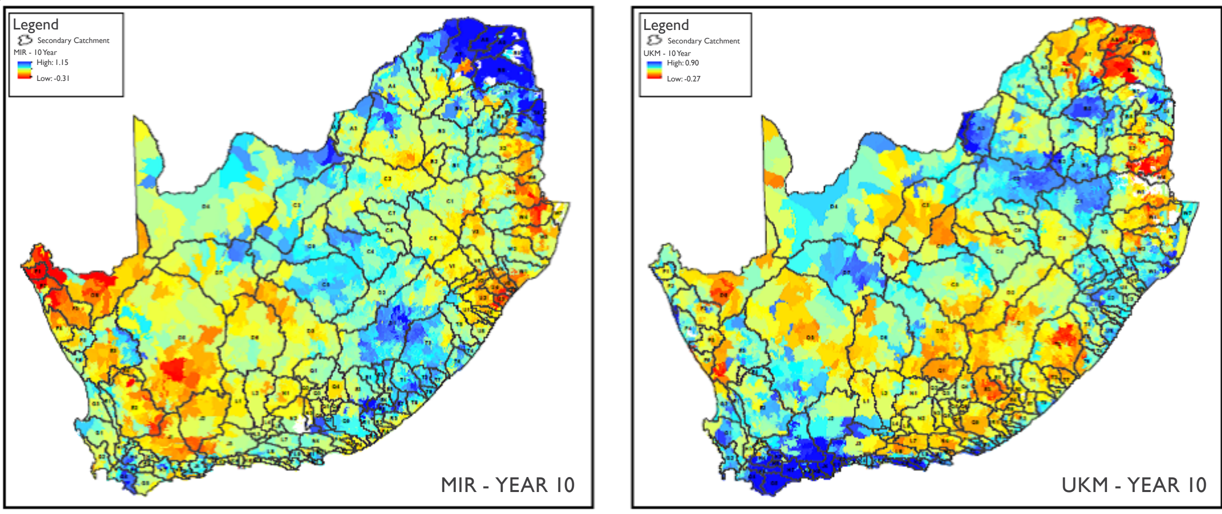


Figure 53: Potential change in the 1 in 10 year recurrence interval maximum daily rainfall across South Africa by the end of the century under four different climate change models (DEA 2015)

- *Response action:* Current design standards for appropriate pavement design and concrete mixes should be revised along with design flood methodologies taking into account more recent climate information and assessing the increased risk under future climate change scenarios.

- ***Response action:*** Opportunities for benefiting from climate change, for example, in areas with potentially warmer climates and increased precipitation should be identified and potential climate change impacts should be taken into consideration in prioritising future development opportunities.

6) There will be potential winners as well as losers due to future climate change

A comparison of the potential economic impacts on the agriculture sector in the Olifants/Doorn WMA (17) and the Inkomati WMA (5) presented in **Figure 54** shows the former to be a consistent loser under climate change, while the latter has the potential to benefit from increases in rainfall, particularly under a warmer and wetter future. This concurs with similar findings in the DWA climate change status quo assessment (DWA 2013) which showed that climate change has the potential to alleviate some current resource constraints such as in the Inkomati catchment. The challenge is to identify these potential winners and to find ways to realise these potential benefits, and at the same time reduce the negative impacts on the potential losers elsewhere in the country.

7) The most vulnerable communities are likely to be the most severely impacted.

Subsistence farmers and dryland agriculture are the most significantly impacted by increasing temperatures and reduced rainfall, although some areas could benefit from increased rainfall during critical months. Urban, industrial and service-based industries are less directly dependent on climate variability and have greater resilience due to access to integrated water supply systems and controlled working environments (such as air conditioners). This is likely to lead to increased inequality with potential for increased social tension and unrest. In the urban areas the poorer communities tend to be located in the most hazardous locations (for example informal settlements in flood plains) and have limited resources for coping with even current climate variability and flooding risks.

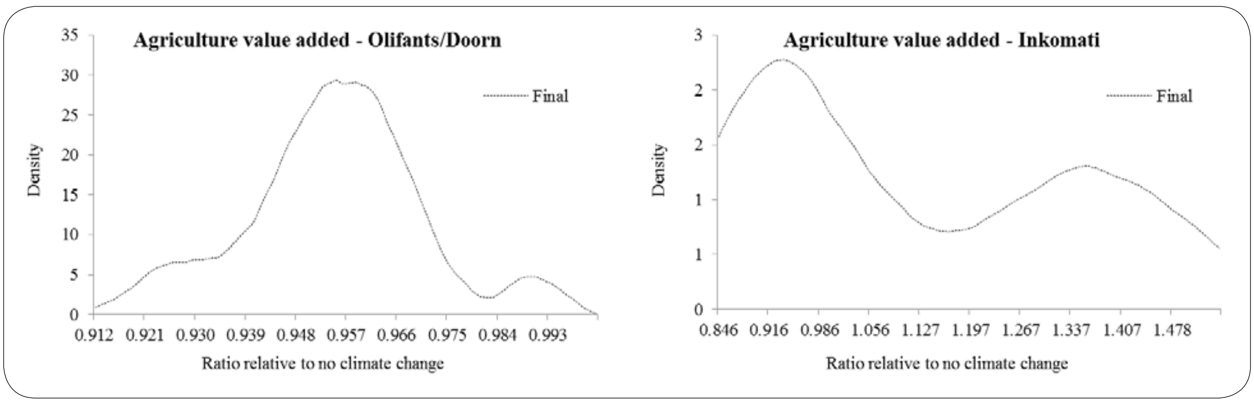


Figure 54: Potential impacts of the UCE climate change scenarios on the value added in agriculture under a range of possible climate futures by 2050 for the Olifants/Doorn WMA (left) and the Inkomati WMA (right) showing the potential for losers and winners respectively due to climate change.

▷ ***Response action:*** Adaptation should focus on the most vulnerable communities as they lack the necessary coping mechanisms and adaptation will assist in improving livelihoods in general.

8) Economic impacts are likely to be most significant at sub-national and sector level rather than at national scale and this could further increase inequality

Economic impacts may be only a few per cent of GDP, but these are still big numbers in rands and will be more significant in particular sectors such as agriculture and in different parts of the country. This could increase unemployment and inequality, with unskilled labour unable to transfer from agriculture to other sectors of the economy, and regional inequalities resulting in increased potential to migrate, particularly from rural to urban areas.

Figure 55 presents provisional results of the potential impact of a range of possible climate futures on the agriculture and services sectors, showing potential negative impacts for agriculture and minimal impacts on the services sector. The non-agricultural sectors may even benefit as resources (land, water, labour and capital) are released from agriculture and taken up in the services and industrial sectors.

▷ ***Response action:*** Further research is required to identify specific impacts at sector and sub-national level, particularly in vulnerable sectors such as agriculture and in more vulnerable regions.

9) Adaptation requires us to rethink the concepts of food security and food sovereignty

Dryland crop yields are likely to be severely impacted, particularly under a dry scenario. This includes staple crops such as maize and wheat. This may force us to look to the region and to increased food imports, or alternatively to change our diets to reduce our dependence on these staple crops and consider alternative more resilient crop types and genetic variations.

Figure 56 presents the potential impacts on the total dryland crop yield for maize and wheat under two possible climate futures – the hotter UCE scenario and the warmer LIS scenario. In both cases the median impact is a reduction of about 3.5% for maize and 4.8% for wheat. There is, however, a significant risk of more than a 10% reduction in wheat yields, particularly under

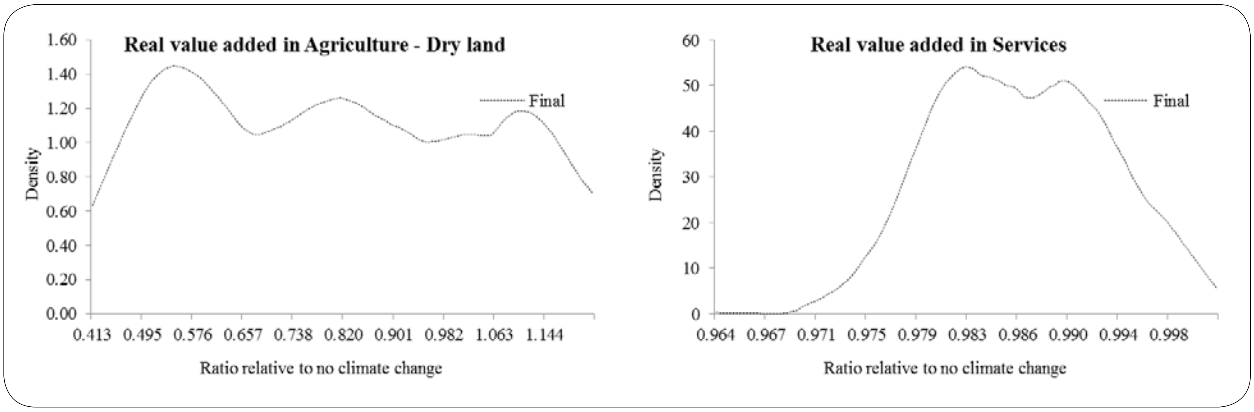


Figure 55: Potential impact of the UCE climate change scenarios on the dry-land agricultural sector (left) and the services sector (right) of the national economy.

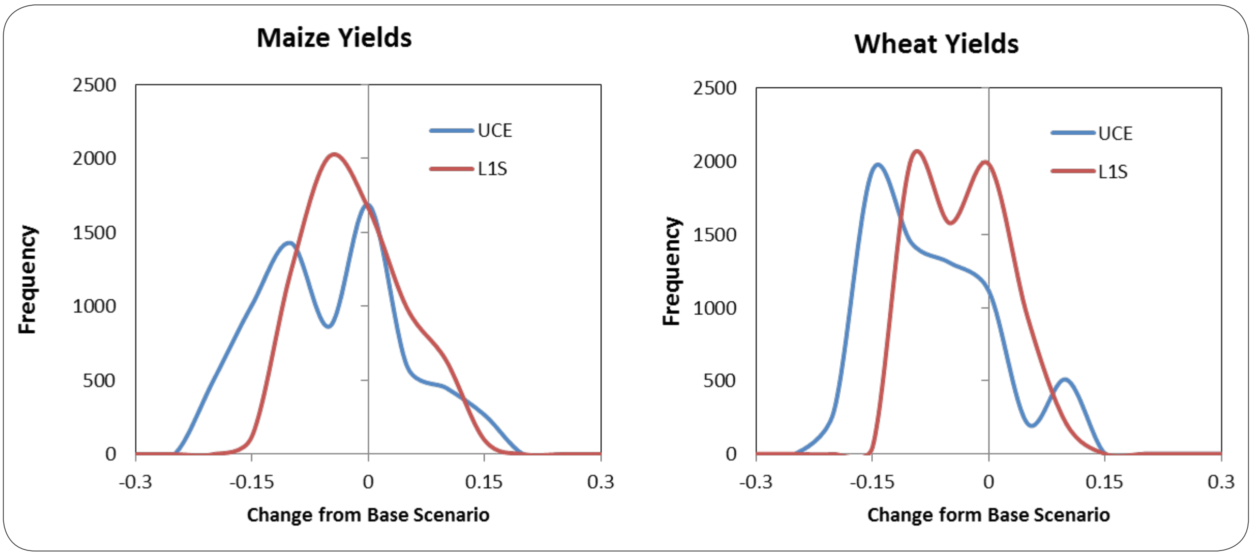


Figure 56: Hybrid frequency distribution (HFD) of the potential impacts on the total average annual dryland yields for wheat and maize under the UCE and L1S climate scenarios by 2050.

the UCE scenario, with the majority of scenarios showing a decrease in the average annual yield relative to the base scenario. On the other hand, there is the potential for increased yields under certain particularly wet future scenarios.

▷ ***Response action:*** Research into improved crop varieties and improved farming practices is required. In addition, a regional assessment of future food security including the potential to become more reliant on food imports from neighbouring countries less impacted by climate change should be undertaken.

10) Well planned and integrated water supply infrastructure can increase resilience under future climate change uncertainty (and other future uncertainties), but building more dams or inter-basin transfers is not necessarily an appropriate adaptation response.

South Africa has a well-planned and integrated water supply system which provides a certain degree of resilience, at least in the major water supply systems to urban areas. The challenge is to continue this development through continued monitoring and regular updates of reconciliation strategies that incorporate the additional uncertainty and risk of climate change and, were possible, diversify and improve the integration of existing and planned water supply systems. A recent DWA workshop on incorporating climate change into modelling to support water resources planning in South Africa highlighted the importance of adopting a risk-based uncertainty approach to water resources planning and the need for future research to "book-end" potential uncertainties including climate change.

Building more dams or more inter-basin transfers, however, is not necessarily an appropriate solution, particularly under a drying future where there is a risk that the dams may not fill up and the result is the storage of large volumes of hot air. Inter-basin transfers will also only potentially improve resilience if the different systems

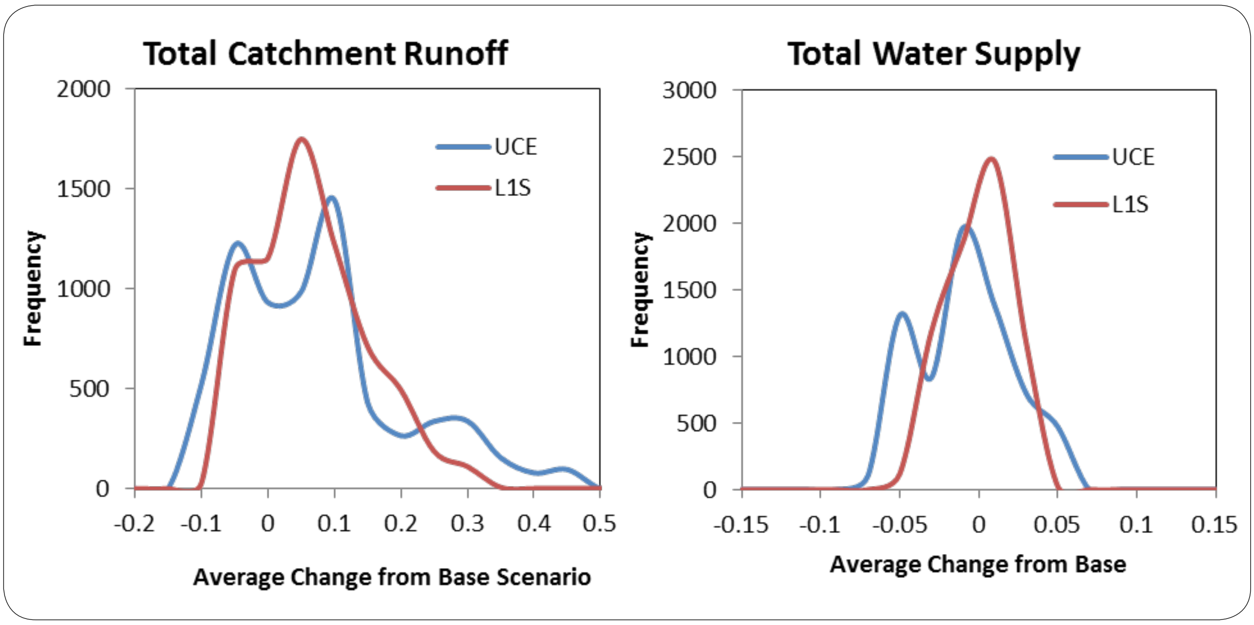


Figure 57: Comparison of the potential impacts of climate change under the UCE and LIS scenarios in terms of total catchment runoff for the country and the change in the ability to meet the total national water supply demands for the period 2040 to 2050.

are not subject to the same variability, that is to say they are out of phase. See, for example, Cullis et al. (2011) which showed that building additional storage capacity in the Olifants catchment did not necessarily result in added resilience to climate change impacts under a future drying climate.

Figure 57 presents a hybrid frequency distribution (HFD) of the potential impact of climate change under two mitigation scenarios (UCE and LIS) on the total catchment runoff and the total water supply for South Africa by 2050. The results show how the current water supply infrastructure, including dams and inter-basin transfer schemes (of which South Africa has many) mitigate the potential impacts of climate change on future water supply. Much of this infrastructure is designed to deal with a high degree of natural climate variability which contributes to potential future resilience.

▷ ***Response action:*** Further research, supported by the DWA and the Water Research Commission (WRC), is required to investigate the sensitivity of individual systems and to provide a consistent approach to incorporating the risks and uncertainties of climate change into large-scale water resources planning in South Africa. This should involve identification of critical thresholds at which the existing and future water resources systems fail and the development of indicators for monitoring if or when these critical thresholds are being approached and appropriate responses to the pending risk of failures. This is particularly important for smaller, more isolated systems that are not suitably addressed or resourced through national level planning and where responsibility falls to local and regional levels of government.

II) Climate resilience in the water sector has additional potential costs including implementation of more costly water supply options and increased pumping through inter-basin transfer schemes

While the results of this study show that South Africa has a potentially resilient water supply system (at least in terms of the major supply systems in the country), this resilience does come with the potential for significant additional costs. Two of these adaptation associated costs are (i) increased movement of water around the country through pumping and inter-basin transfer schemes with associated added pumping and electricity costs, and (ii) the early adoption of more expensive water supply options.

With respect to the first observation **Figure 58** shows the relative change in the average transfer rate for water for two of the larger pumped inter-basin transfer schemes in the country that show potential for increased transfer under the UCE and LIS climate futures as the system looks to adapt to future spatial variations in climate change impacts. These represent significant additional future energy costs.

With respect to the second observation, the DWA has evaluated the additional NPV of the early adoption of more expensive water supply options, including desalination, to the Western Cape System (DWA 2010) as a result of declining yields from existing sources due to climate change shown in **Figure 59**. The result was an additional NPV cost (in 2007) of over R417 million.

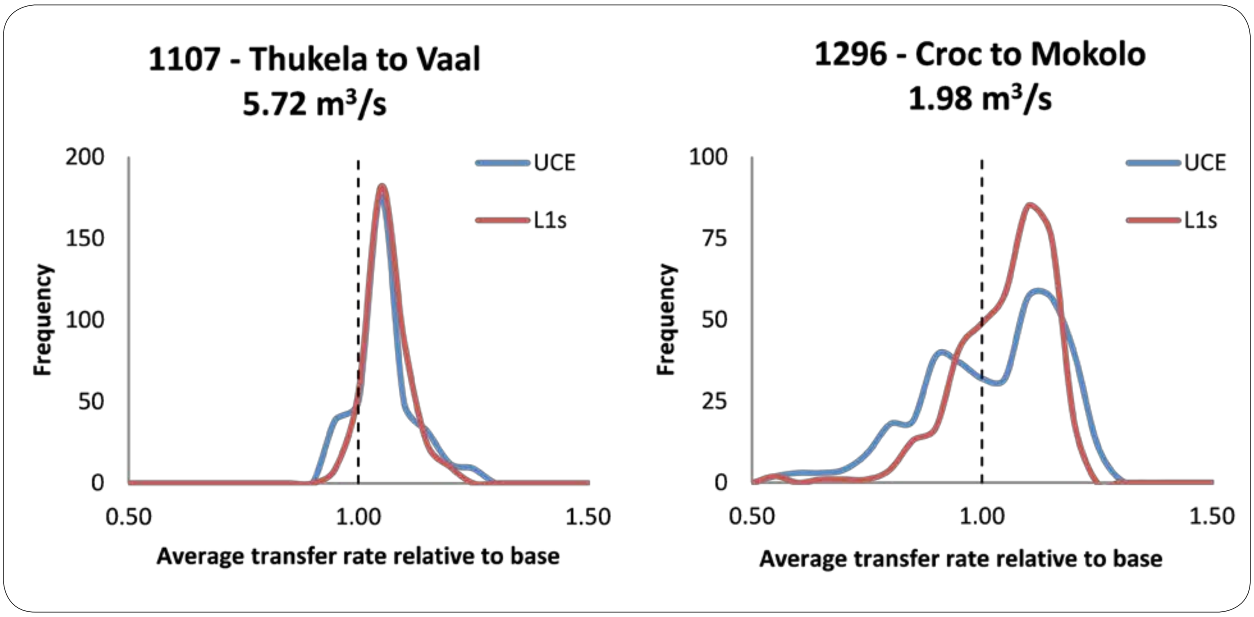


Figure 58: Change in the average transfer capacity for the period 2040 to 2050 of two existing pumped inter-basin transfer schemes under the UCE and LIS climate futures.

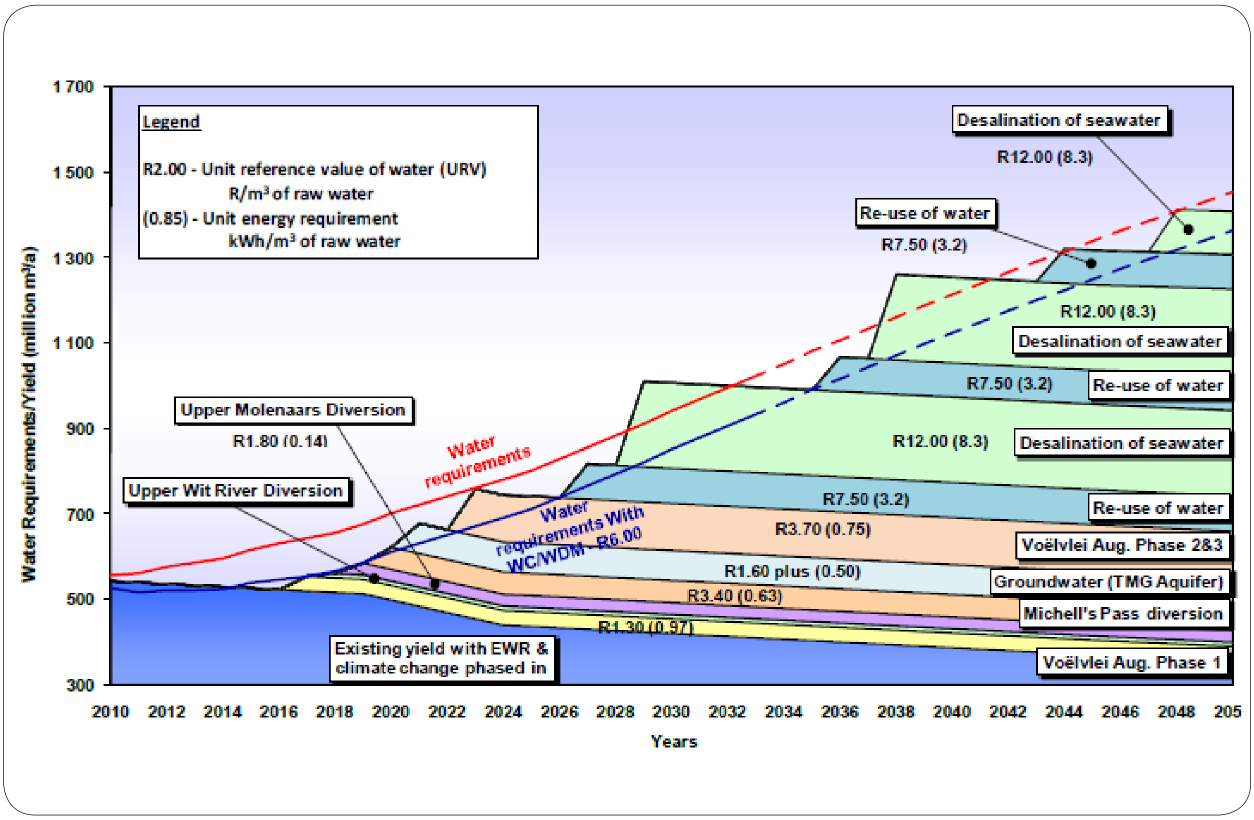


Figure 59: Reconciliation of future water supply options to the Western Cape Water Supply System with the potential for a 15% decline in existing surface water yields due to climate change (DWA 2010).

▷ ***Response action:*** The potential additional cost of climate change in terms of increased inter-basin transfers and the early adoption of new schemes including seawater desalination needs to be evaluated.

12) Sustainable adaptation options require new thinking for cost-benefit analysis

The results from this study have shown that the potential economic impacts, measured in terms of traditional economic metrics such as GDP are relatively small at national scale, although they can be quite significant at local or individual sector level. There remains a wide range of uncertainty in the potential climate change impacts and even more so in the economic impacts. Much of this uncertainty is independent of potential climate change impacts, as it relates to uncertainty in model parameters and adaptation responses. This makes consideration and prioritisation of potential adaptation options challenging. Added to this are very significant capacity and resource limitations for many municipalities across South Africa.

A recent study for the eThekweni Municipality (Cartwright et al. 2013) provides a novel approach to an alternative analysis of adaptation options under uncertainty and resource constraints. An example of the resulting cost curve for climate change adaptation options for eThekweni is given in **Figure 60**.

The model used generates the benefit-cost ratios and total benefits for each of the intervention clusters under a range of future climate scenarios. It emphasises how these are influenced by choices of time frames. It also highlights how the most efficient interventions across all futures and time frames tend to be socio-institutional including the creation of a cross-sector disaster management forum, sea level rise preparedness and an early warning system, and creating climate change adaptation capacity within the water services unit. Ecosystem-based adaptation measures had moderate benefit-cost ratios, probably because in Durban the land that needs to be purchased for this is relatively expensive. Infrastructure-based clusters generally had the lowest benefit-cost ratios. Adoption of this approach to adaptation should be considered at national level. Interested readers should refer to the original report for more details.

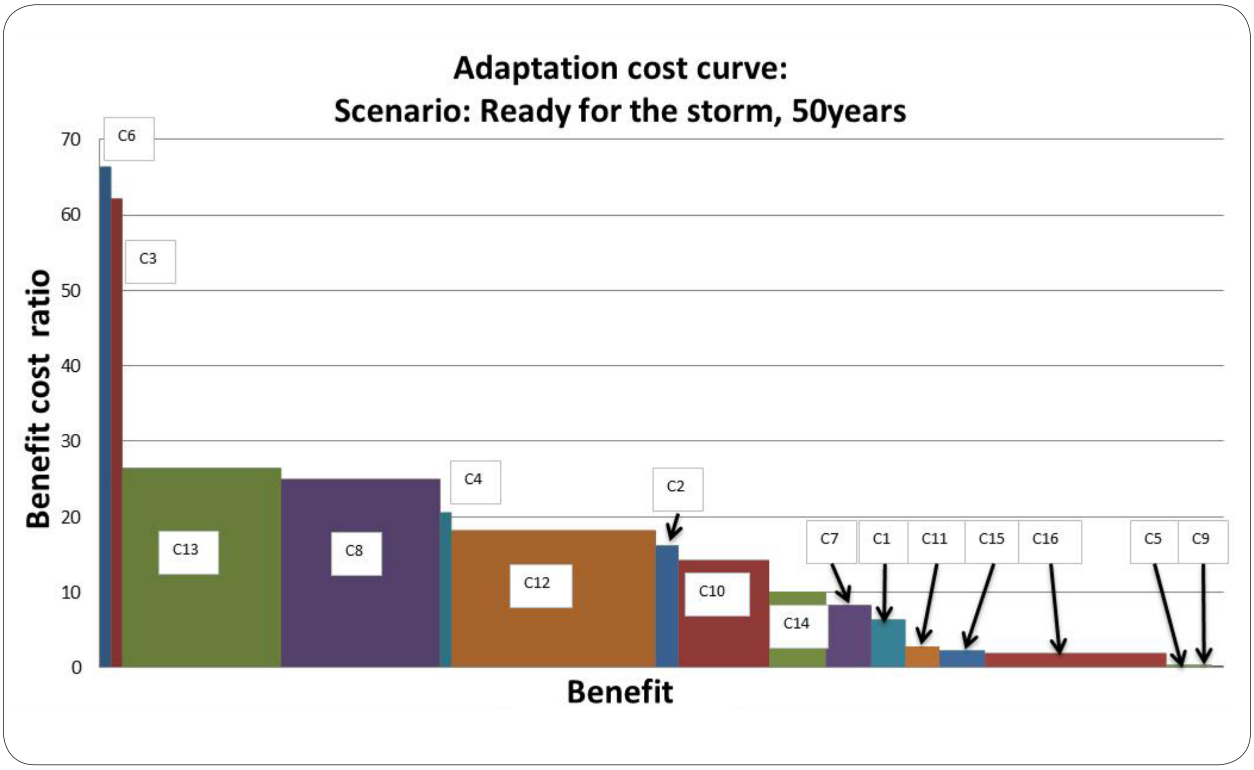


Figure 60: Example of a benefit-cost curve generated by the model in the 'Ready for the storm' scenario and over a 50-year time horizon. The lables C1–C16 represent the respective municipal adaptation clusters (MACs). (Cartwright et al. 2013).

▷ **Response Action:** This approach is considered to be at the forefront of adaptation response and economic planning under climate change uncertainty and resource limitations and should be developed and extended to other areas of concern and applied to multiple climate change impacts in South Africa.

7. FUTURE RESEARCH NEEDS AND APPLICATION FOR ADAPTATION SCENARIOS

While the primary objective of this study was to undertake a first order estimate of the potential biophysical and economic impacts of climate change on the national economy of South Africa, a secondary objective was to establish an integrated framework for further research and assessment of potential adaption scenarios in South Africa. This study has highlighted some of the key areas of concern and these results should be used to define and fine-tune the way forward with future research.

A number of recommendations for further research on, and application to, adaptation scenarios are described briefly. The first recommendation relates to the potential for consideration of alternative development and adaption scenarios, while the second relates to the potential for contrasting, comparing and combining the HFD approach with the more fine scale regional climate models. A number of more general research recommendations are also given arising from the results of this initial assessment.

While there is much endogenous adaptation built into the models used in this study, particularly the water supply system model and the CGE economic model, and comments on the significance of these adaptation responses are described, this study has not investigated in detail particular adaptation responses or alternative development scenarios. Provided that the appropriate "levers" can be identified in the modelling framework that should be adjusted to account for particular adaptation scenarios, then the potential impacts of these can be modelled and compared to the current results. The particular adaptation responses should be derived from the LTAS process and could become the focus for applying the current integrated modelling framework in future adaptation studies.

The HFD approach used in this study has benefits in that it provides a wider range of potential climate futures that are in line with the general LTAS scenarios of hotter and warmer, wetter and drier. They are, however, still at a relatively coarse resolution and the regional downscaled models do provide significant additional information, particularly on the spatial variations of climate change impacts across the country. Further work applying a selection of the regional climate models to the same integrated modelling framework will provide insight into these potential impacts at national and WMA level.

A similar biophysical and economic analysis making use of the different regional climate models should also be undertaken and compared to the HFD results. In addition to this the potential for blending the HFD methodology and regional downscaled models should be explored, with the regional models providing the pattern kernels necessary to apply the outputs from the IGSM in a more detailed way to South Africa.

General recommendations on future research and analysis in support of alternative development and adaptation scenarios that arise from this study include the following:

- Further analysis of the potential for South Africa's integrated national water supply infrastructure to provide resilience to future climate change. This should include an analysis of relative impacts in different systems and whether these impacts are similar or varied due to different primary climate drivers, and the impact that this has on the ability to redistribute water across the country using current or future transfers in response to future climate change scenarios. In this context the potential for "virtual" water transfers (namely relocating water intensive production) should be considered as an alternative to the physical transfer of water.
- More detailed analysis of the potential impacts on the agriculture sector and the impacts that this might have on the local, national and regional (SADC) economies and the implications for livelihood support, food

security and food sovereignty. Additional issues include impacts on CO_2 fertilisation, flooding, water logging, pests, the requirements for new crop varieties and improved irrigation and agricultural practices and other related issues.

- A review of the current and proposed dam locations within South Africa to identify priority dams for consideration of additional hydropower capacity particularly under a wetter future. In addition a regional analysis should be done to determine the potential opportunities for increased hydropower resources in neighbouring countries to either supplement or augment local renewable energy sources especially in a drying scenario that limits hydropower potential.

- More detailed analysis of the potential impacts of extreme events particularly floods and the associated costs in terms of specific infrastructure (dams and bridges) at risk.

- Further research into identifying the critical sections of the transport infrastructure (including roads, railways and bridges) threatened by future climate change and improved modelling of the potential economic impacts including the additional costs of interruptions due to failure.

- A review of current design standards, particularly for roads, in response to future increases in temperature, which are very probable, and increase in flooding impacts, which are also likely in large parts of the country in the medium to long term future. In some places these changes are already happening and engineers are already increasing design standards and safety factors.

- More focused regional analysis of climate change impacts in particular areas of concern including the western and southern Cape for water resources availability as well as the eastern and northern provinces (North West and Limpopo) in terms of potential increases in flooding.

- Review of current dam operating rules to consider added flood control mechanisms, particularly under a wetter future with increased probability of flood events, and options for improved resilience through diversification of water supply options under drier climate futures.
- More detailed analysis of the individual water supply systems to identify critical thresholds of failure and develop monitoring criteria to give early warning about the risks of these thresholds being realised.
- Additional research in the agricultural sector to determine the range of potential impacts on both dryland and irrigated agriculture and the impacts this would have on crop types, farming practices, and food security. Added to this a review of potential adaptation options including more regional integration to find the most efficient use of limited resources (land and water).
- More detailed investigation of the role and key aspects of endogenous adaptation used in the economic model to mitigate the economic impacts of climate change, and consideration of the critical aspects of the South Africa economy that could limit the potential for such adaptation.

The LTAS process has addressed a number of areas of concern and the potential for adaptation responses in South Africa including the results of the biophysical and economic modelling presented here. This approach has provided a variety of insights and recommendations that now need to be integrated and reflected on in order to set the agenda for the way forward. Some of this integration will be realised through the development and adaptation scenarios prepared as part of phase 2.

Going forward to other work focused on adaptation including the preparation of the third national communication on climate change to the IPCC, there should be further reflection, discussions and synthesis of results to identify the key messages and areas of concern. A synthesis of these results should also identify the priority areas for adaptation, not least of which is identifying the no regrets strategies that should be implemented with immediate effect, as well as the slow burning structural changes that may take decades to realise. Only by starting now, and by taking a long-term and comprehensive approach, will it be possible not only to improve resilience to climate change in South Africa, but potentially also to put in place measures to realise the benefits under certain climate futures.

8. CONCLUSION

This study represents the first attempt at an integrated approach to assessing the potential impacts of climate change on multiple impact channels that influence the national economy of South Africa. The results show the wide range of potential impacts of climate change and the importance of spatial and temporal variation in these impacts. The study has highlighted in particular the potential impacts of climate change on the water supply sector, roads infrastructure and dryland agriculture that manifest in terms of overall impacts on GDP growth, inequality impacts and employment potential as well as significant variations between regions and economic sectors.

The results in the water sector suggest that climate change will have a **limited impact on water supply at national level, but could be quite significant at regional level particularly under drier futures. The limited impact in terms of national water supply can be attributed to the current high level of development and integration of the major water supply infrastructure and supply system.** In particular the climate change impacts on the urban and industrial centres in Gauteng appear to be minimal and could even be positive under wetter futures due to the integrated nature of the Vaal system, the development of the Polihali Dam as part of the Lesotho Highlands Water Project (LHWP) and the fact that many of the climate scenarios show potential wetting over the eastern half of the country including Lesotho and the Upper Vaal.

In contrast the results show all models **predicting a reduction in streamflow in the Western Cape including the Berg River catchment with the potential for reduced ability to supply the future water demands for Cape Town.** The greatest negative impact on future water supply is in the **Gouritz WMA** where urban and bulk water supply depend on smaller and less integrated local resources and the climate models predict likely future drying. **In general the areas of greatest concern are the isolated systems that are dependent on a single resource including small farm dams in headwater catchments and water supply schemes for rural towns. Where possible these systems require increased integration and diversification to improve resilience** to future climate change uncertainty.

The results for the agriculture sector show a **general increase in irrigation demands** based on existing crop types and management practices due to increased evaporative demand. These impacts vary across the country, with increases in some areas, notably the east coast and KwaZulu-Natal, potentially being offset by increases in precipitation. Overall the median impact on irrigation demand across the country by 2050 is around 5%. This is, however, not considered to be significant as there is potential to address these increases through improved irrigation practices and the development of new crop varieties.

The potential impact on **land use change of future water supply**, either directly or indirectly related to climate change, has not been investigated and must be investigated further. This includes the potential for increased bush encroachment, expansion of forests, and the spread of invasive alien plants.

The potential impact on **dryland crop yields is mixed** with some crops showing an increase in yields, while others show a reduction in potential yields. The reduction in yields results primarily from an increase in evaporative demand where additional water supply is required to produce the same yield response as for current climatic conditions. These impacts are greatest in areas that also show a reduction in precipitation and runoff such as the major wheat growing areas of the Western Cape, but the results also indicate a potential reduction in yield from other staple crops such as maize. **The median impact on wheat and maize yields across the country is estimated to be around 3.5% and 3% respectively, but with some very dry scenarios**

showing potential reductions of up to 25% in total yields for the country.

It is important to note that the crop yield impacts are based on empirical results relating changes in water supply to changes in annual crop yields, and do not take into account other potential impacts such as direct temperature effects and CO_2 fertilisation or indirect impacts such as increased pests and diseases. These require more detailed analysis, particularly given the apparent significant economic impacts resulting from potential climate change impacts on the agriculture sector.

The study of potential impacts on **roads infrastructure** shows **significant advantages in implementing adaption options** to the repair and rehabilitation of the existing roads network, particularly in the second half of the century with the cost for no adaptation overtaking the costs for adaption around 2050. Given that the average design life of a major road is 30 years, however, **it is important that adaption measures are implemented sooner rather than later** in order to realise these potential benefits. At provincial level the **Eastern Cape Province shows the highest impact of additional costs** from climate change as it has the greatest number of roads, although many of these are gravel roads. **The second most impacted province is Gauteng**, which although having a smaller total road inventory has a very high proportion of more expensive primary and paved roads. The cost estimates do not take into account the potential additional costs of interruption in the transport sector due to damage to roads as a result of no adaptation.

The study of potential economic impacts showed significant impacts particularly resulting from additional roads infrastructure costs and variability in dryland agricultural yields, with only limited economic impacts due to variability in the ability to supply future water demands. The total impact of climate change on the level of real **GDP is found to range between -3.8% and +0.3%**, although results indicate that for nearly all climate futures the impact on total GDP will be negative. **The median results show that by 2050 South Africa's real GDP level will be 1.5% lower than in the baseline scenario.** This, however, translates into only a 0.03% decline in the average annual real GDP growth rate.

It is important to note that a key assumption of the general equilibrium model used is the ability of resources, including water, labour, land and capital, to move between sectors. **This is considered to be a form of endogenous adaptation that is critical in limiting the potential negative impacts of climate change on the national economy.** However, this is not necessarily a true reflection of the state of the South African economy. Further research is required to identify these critical endogenous adaptation mechanisms and to evaluate their role in mitigating potential climate change impacts, particularly in terms of impacts on inequality, and then to identify aspects of the national economy that either help or hinder these response strategies so that they can be addressed.

The decline in dryland agriculture, particularly under hotter, drier climate futures, has the potential to release resources to the rest of the economy. These resources are found to primarily shift to irrigated agriculture which becomes more profitable due to higher domestic selling prices. Irrigated agriculture is largely found to increase, although in about 27% of the climate futures GVA decreases reflect increased dryland agriculture. The positive impact on irrigated agriculture may, however, be overestimated as the ability to move between dryland and irrigated agriculture may be less than anticipated.

The net present value of the potential impact on GDP by 2050 is highly variable ranging from **losses of R930 billion to gains of R310 billion**, although **96% of the climate scenarios show overall losses. The median NPV loss is approximately R259 billion**

(2007 prices) which, at nearly 12.8% of 2007 GDP, is sizeable and should motivate for action in terms of both mitigation and consideration and funding of potential adaptation scenarios. The impacts are also much greater in some sectors and regions than in others.

Finally, considerable effort has been expended in the LTAS process to construct and then integrate models that reflect South African realities. These have resulted in many observations and in identification of critical areas of concern for adaptation. **Nevertheless, as with any modelling effort, the suite of integrated models employed here contain shortfalls and over-simplifications. They are not South Africa. The crucial value that the models offer is to structure thinking in a rigorous way in order to achieve insights that would be difficult to obtain in their absence.** In future, the framework employed can no doubt be improved. As climate change seems unlikely to disappear, this will not be the last opportunity to investigate potential economic impacts. The modelling framework developed for this study should be used as a platform for future analysis, with continual refinements where required, and to target specific issues or regional areas of concern given the uncertainty of future climates and impacts.

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Environment House
473 Steve Biko
cnr Steve Biko and Soutpansberg Road
Arcadia
Pretoria, 0083
South Africa

Postal Address
Department of Environmental Affairs
P O Box 447
Pretoria
0001

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