An uncertainty approach to modelling climate change risk in South Africa

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This study represents the first attempt at an integrated approach to assessing 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 on outcomes by about 2050. The results show the multiple impacts of climate change and the importance of spatial and temporal variation in these impacts. The study focused in particular on the potential impacts of climate change on the water supply sector, dry-land agriculture, hydropower, roads infrastructure costs and sea level rise. These factors have not been previously considered in a fully integrated way for South Africa. The study considers two future global emissions scenarios-- an Unconstrained Emission Scenario (UCE) where global policies to reduce emissions fail to materialize and a Level 1 Stabilization Scenario (L1S) where aggressive emissions policies are pursued.

Based on the full range of impact channels considered, economic impacts are showed to be potentially significant particularly resulting from additional roads infrastructure costs and variability in dryland agricultural yields, with only limited impacts due to variability in the ability to supply future water demands. The total impact of climate change on the level of real GDP by about 2050 is found to range between -3.8% and 0.3% compared with a fictional 'no climate change' baseline. While positive outcomes are possible, 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 average annual real GDP growth rate. The net present value of the potential impact on GDP out to 2050 is highly variable, ranging from losses of R 930 billion to gains of R 310 billion (real 2007 Rand). About 96% of the climates scenarios show overall losses. The median loss in NPV is approximately Rand 259 billion which, at more than 10% of 2007 GDP, is sizeable and should motivate for action in terms of both mitigation and consideration and funding of potential adaptation scenarios.

Keywords: climate change, South Africa, runoff, streamflow, uncertainty, water resources, crop yields, roads, sea- level rise, impacts, adaptation, economic growth, development.
JEL classification: O5, O2, Q54, Q56

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1   Introduction

1.1   Background

The National Treasury and the National Planning Commission are interested in assessing the potential economic impacts of climate change in South Africa. With assistance from the United Nations University World Institute for Economic Development Research (UNU-WIDER) they have developed a general equilibrium model (GEM) model to assess the potential impacts of climate change on future employment and economic development for the country.

The economic impacts of climate change manifest through a number of key impact channels. Modelling of the biophysical impacts through these channels is necessary to support the economic model. Three of the primary impact channels, identified at a study definition workshop were water, transport and the impacts on coastal infrastructure and land inundation due to sea level rise and storm surge.

At the same time the Department of Environmental Affairs (DEA) is also interested in assessing the potential economic impacts and adaptation options as part of the Long Term Adaptation Strategy (LTAS). The LTAS process is a response to the South African National Climate Change Response White Paper and aims to provide a coherent view of South Africa's climate change vulnerabilities over the short (next decade), medium (next two decades), and long term (mid-century to end of century) across multiple sectors.

After understanding the key vulnerabilities and impacts due to climate change, LTAS will scope adaptation requirements including the costs, strategies, and cross linkages between sectors to provide potential responses to climate change. The LTAS process will also provide a knowledge-base to support the development of the 3rd National Communication on Climate Change impacts and adaptation in South Africa to the United Nations Framework Convention on Climate Change (UNFCCC).

This study is seen as the first attempt at an integrated assessment of the economic impacts of climate change on South Africa. This is an ambitious undertaking and given finite time and the broad scope of the study, a number of assumptions and simplifications had to be made. However, the modelling framework developed during this study and the initial outputs from the study will provide a valuable tool to both National Treasury and the LTAS in terms of assessing the likely impacts and potential adaptation options through the key sectors of water, transportation, and coastal infrastructure.

Further work could focus on refining specific aspects of the individual models and modelling the potential impacts of alternative development and adaptation scenarios for South Africa as well as incorporating other aspects or impact channels not included in the current modelling framework.

1.2   Aims and objectives

The primary objective of this study is to provide inputs to an economic model for the assessment of the impacts of climate change on the national economy of South Africa. Specific outputs include:

1. A time series of the impacts on annual catchment runoff of multiple climate scenarios for each secondary catchment and water management area (WMAs) in South Africa

2. A time series of impacts on the annual water supply to urban, industry, and agricultural sectors for each WMA in South Africa for multiple climate scenarios;
3. A time series of the potential impacts of multiple climate scenarios on the yield from dryland crops based on existing crop areas for each WMA in South Africa;
4. A time series of annual repair and rehabilitation costs for existing roads infrastructure for each province according to a 'no adapt' and 'adapt' scenario to climate change impacts;
5. A time series of estimated annual costs of sea level rise impacts on coastal infrastructure.

These outputs are achieved through an integrated set of biophysical models. The structure of these models, as well as a discussion of the specific outputs are presented in this report. While the focus of this study is on current levels of development in order to identify the potential impacts of climate change, further developments will include consideration of potential alternative development options including specific adaptation measures for individual or integrated sectors. The framework of models developed for this study is ideally suited to this further analysis and the investigation of options for a robust and climate resilient economy for sustainable development and future generations.

1.3   The impacts of climate change

Global changes

There is an overwhelming body of evidence for an increase in greenhouse gas emissions, often expressed in terms of an increase in the atmospheric concentration of CO^2, derived from anthropogenic sources over the past few decades (IPCC 2007). This in turn has resulted in an increase in the global mean temperature above pre-industrial levels with future increases in CO_2 concentrations and global temperatures inevitable. By 2050 it is likely that the globe will exceed 400 ppm of CO_2 with a global mean surface temperature in excess of 2°C above pre-industrial levels.

Associated with this increase in global temperature are significant changes in precipitation, sea level rise and the occurrence of storms and severe weather events. There is, however, greater uncertainty in the magnitude, and spatial extent of these associated impacts and even the direction of change, as some models show significant drying in certain parts of the globe, while other models show significant wetting.

There is, however, general agreement on some regional scale trends including:

- Warming greatest over land and at most high northern latitudes and least over Southern Ocean and part of the North Atlantic Ocean, continuing recent observed trends;
- Contraction of snow cover area, increases in thaw depth and decreases in sea ice extent;
- *Very likely* increases in frequency of hot extremes, heat waves, and heavy precipitation;
- *Likely* increases in tropical cyclone intensity, but less confidence in a global decrease of tropical cyclone numbers;
- Poleward shift of extra-tropical storm tracks with consequent changes in wind, precipitation and temperature patterns;
- *Very likely* precipitation increases in high latitudes and *likely* decreases in most subtropical land regions, continuing observed recent trends;
- *Very likely* increase in annual river runoff and water availability at high latitudes and decreases in some dry regions in the mid-latitudes and tropics;
- *Very likely* decrease in water resources in many semi-arid areas (e.g. Mediterranean Basin, western United States, southern Africa and north-eastern Brazil).

Regional changes

While global climate models are useful for showing potential global trends, they are limited in their ability to characterize future climate change impacts at a more local or regional scale.

The Second National Communication on Climate Change (DEA 2011) identifies the following general regional climate trends as identified for South Africa from the suite of global climate models:

- Likely strengthening of upper air subsidence over the continent, with implication for stronger elevated inversions that can inhibit weak convective events;
- Shifts in the spatial west-east positioning of the summer rainfall gradient;
- Stronger long-shore winds on the west coast with implications for coastal upwelling;
- Increased atmospheric moisture content over the continent, which could translate to potentially more intense precipitation and a likely increase in orographic cloud cover and topographically-induced rainfall;
- Weaker frontal systems to the south, which could translate to weaker penetration of fronts onto the continent, drier conditions in the Western Cape (possibly compensated for by an increased orographic rainfall on mountain ranges).

In general the global general circulation models (GCMs) show increased warming over the sub-continent, while there is a general increase in drying in the west and south-west of the country and increased wetting in the east.

In order to develop an improved understanding of the potential regional impacts of climate change in South Africa, two different approaches are used for downscaling of the global GCM outputs to reflect the local and regional influences on climate variables. The benefits and limitations of these two general approaches - statistical (empirical) and dynamical downscaling – are summarized in Table 1.

Outputs from the two downscaling methods show a much more detailed impact of climate change over southern Africa. The dynamic model shows enhanced drying, particularly over the south-west of the country and the extreme north. The statistical downscaling model show significant increases in precipitation in the eastern parts of the country and limited drying in the south-west.

Regional impact channels

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). The LTAS has identified the following key climate change impact channels for South Africa:

1. Agriculture and forestry
2. Fisheries
3. Human health
4. Water
5. Human settlements (urban, rural, coastal)
6. Ecosystems and biodiversity, and
7. Disaster risk reduction and management.

Table 1: Comparison of statistical (empirical) and dynamic (RCM) climate models used in South Africa

	Statistical (empirical) downscaling	RCM (Regional Climate Models)
Definition	Large-scale climate features are statistically related to local climate for a region – historical observations are utilized	A dynamic climate model (either a limited-area) model or variable resolution global model) is nested/nudged within a GCM.
Advantages	• Station-scale output • Less computation resources required • Available for more GCMs allowing an assessment of probabilities and risks. • Can be applied to an observed variable, e.g. streamflow.	• 10 – 50 km resolution • Physical interactions and local fine-scale feedback process (not anticipated with statistical methods) can be simulated. • Improved simulation of regional climate dynamics • Can include additional processes not included by the GCM simulations • Consistent with GCM simulations • Do not rely on assumptions of stationaritry in climate
Limitations	• May not account for some local-scale interactions e.g. between the land and the atmosphere • Assumes present-day statistical relationships between synopotic and local-scale climates will persist into the future • Requires high quality observational data • Choice of predictor variables can change results • Results do not feed back to the GCM • Choice of statistical transfer scheme can affect results.	• Computationally demanding • Only a few scenarios usually developed • Susceptible to the choice of physical parameterizations • Not easily transferred to new regions • Limited regional-to-global feedbacks may be considered but often are not.

Source: After Davis (2011).

An additional impact channel that has been identified as significant, particularly in the context of developing countries is the transport sector (Chinowski et al. 2011). Roads in particular are vulnerable to increases in temperature, changes in precipitation, and flooding. In addition to the direct impacts of increased maintenance and rehabilitation costs, are the indirect impacts of the loss of vital transport links on other sectors, particularly the agricultural sector in terms of getting produce to markets. Additional costs incurred as a result of the impacts of climate change on the maintenance of the existing roads infrastructure are considered to have a direct impact on the potential to develop additional roads infrastructure in support of economic growth and development in a region.

In this study we focus specifically on the following four impact channels:

- Water
- Agriculture
- Transport
- Coastal infrastructure

These impact channels are considered to be the most critical in terms of impacts on the national economy. In addition well developed modelling frameworks exist for each of these sectors. Where possible these existing modelling frameworks are utilized and adapted as required to support the requirements of the integrated assessment of potential impacts from multiple climate futures.

Water sector: The water channel is considered to be one of the most significant channels for the realisation of climate change impacts. This is due to the fact that water supply is directly related to changes in precipitation, temperature, and evaporation. In addition water is a fundamental requirement for life and critical to most, if not all, requirements for livelihood support, economic growth, and development.

A recent review of the impacts of climate change on the water sector (Schulze 2011) concluded that it was not all 'doom and gloom for South Africa. Due to variability in the impacts of climate change some areas of South Africa would most likely be 'winners' while other areas and other sectors would be 'losers'. Particular 'hotspots' of concern primarily due to decreasing rainfall are the south-west of the country, the West Coast and to a lesser extent the extreme north of the country. Even in areas considered to be winners as a result of increasing precipitation there are potentially increases in risks due to increases in the intensity of rainfall events and associated water logging and flooding.

There are also likely to be significant impacts on groundwater recharge, increased evaporation from dams and rivers, increased losses from forestry, invasive alien plants and certain dryland crops, water quality impacts, and sediment transport in rivers. These are all important considerations when assessing the potential impacts of climate change and the opportunities for mitigation and adaptation.

Water availability in South Africa, however, is already limited and highly variable with water use in the majority of catchments already well in excess of the natural availability (DWA 2004). This has resulted in a very well develop water resources planning system and significant investments in water related infrastructure designed to deal specifically with current variability that will ensure reliability of supply at least until 2030 (DWA 2004). Studies that have considered the potential impacts of climate change on water supply infrastructure in South Africa. Cullis et al. (2011) have shown that the application of best practice such as continues monitoring, flexibility of operations, and efforts to improve efficiency through water conservation and demand management are critical to reducing the risk from current climate variability as well as adaptation and increasing the resilience to future climate change.

The focus of this study is on the potential impacts of climate change on water supply and hydropower potential. While these constituted the major contributors to the economic impacts of climate change, there are other potential impacts on the water sector that should be considered.

These include:

1. Increased storm intensities and flooding potential
2. Impacts on water quality (temperature, nutrients, sedimentation)
3. Increased sedimentation of dams and reservoirs
4. Increased streamflow reduction due to forestry and invasive alien plants (IAPs)

Agriculture: The agricultural sector is directly impacted by climate change primarily through changes in precipitation, but also in the availability of water for irrigation, changes in temperatures, increased carbon dioxide concentrations, and impacts on pests and diseases (Schulze 2010). As a major contributor to livelihoods, employment and economic development, associated impacts of climate change on agriculture are also manifested in direct and indirect impacts on the national economy.

The SADC Handbook on Climate Risk and Vulnerability (Davies 2011) identified a number of potential impact channels for the agricultural sector in South Africa including direct and indirect

impacts. It also concluded that the greatest impact on production is expected to be in the most marginal areas of the country where low and irregular rainfall is already experience. Emerging, small-scale farming (including subsistence farming) is also likely to be the most vulnerable to climate change due to a high dependence on rainfed agriculture and fewer capital resources and management technologies.

An analysis of the sensitivity of agriculture production to changes in climate in South Africa (Blignaut 2009) shows a very strong historical relationship between rainfall and crop yields. In general it was found that a 1% decline in rainfall was found to result in a decline in maize production of 1.16% and a decline in wheat production of 0.5%. These results indicate that crop production is highly sensitive to potential climate change and that future increasing temperature and reducing rainfall is likely to have a very significant impact on the regional and national economies of South Africa.

The focus of this study will be on the potential impacts of climate change on commercial agriculture rather than on substance or small-scale agriculture. In addition the study focuses primarily on the impacts of potential changes in precipitation on the yield from dryland crop and increases in water demand for irrigated crops. The study is limited to existing crop areas but could easily be extended to investigate the potential impact on future areas of expansion or alternative crop mixes.

Transport: A function and efficient transport system is essential to the functioning of all economies. These also require large amounts of funding to build and maintain. Any disruptions to the transport infrastructure not only result in a direct cost for replacement or rehabilitation, but also an indirect cost for disruptions to the transport of goods and people from points of production to points of sale or export. In addition, particularly in developing countries, there are opportunity costs associated with having to do more regular maintenance of the existing infrastructure rather than utilising these funds to expand and develop the transport system in support of economic growth and development (Chinowsky et al. 2011).

Like most aspects of society, transport networks are also potentially at risk from climate change. While the potential threat of climate change to transport networks has been identified by the IPCC, efforts to quantify these impacts have generally been qualitative in nature. More recently the World Bank (2010) developed methodologies for quantifying the likely cost of climate change on transport infrastructure. In Africa, it has been estimated that the continent is facing the potential of a US$183.6 billion liability to repair and maintain roads damaged from temperature and precipitation changes related to climate changer through 2100 (Chinowsky et al. 2011). This represents an average annual cost of US$22 million per country if they adopt a pro-active approach to climate change or US$54 million per country for a reactive approach.

While South Africa has a far more developed roads infrastructure network than the rest of Africa, it is still likely that climate change will have a significant impact on the future upgrading and maintenance costs. This study will adopt the same methods used in the Africa-wide study to assess the potential impacts of climate change on the South African roads network and the benefits of a pro-active adaptation response to these potential impacts.

Coastal infrastructure: The potential impact of rising sea levels on coastal infrastructure has been identified as a major concern with future climate change as over 60% of the world's population are estimated to live in the coastal zone. Increases in sea level arise through a combination of thermal expansion, increased runoff from rivers, and melting of the polar ice caps. The IPCC's fourth assessment report (2007) estimates and average change in sea level of between 0.17 m and 0.59 m by 2100.

While South Africa has a long coastline it is generally relatively steep with no significant areas of development at very low elevation. The potential impacts of future sea level rise are therefore not considered to be significant as compared to other countries with major developments in low lying areas of river deltas such as in Bangladesh, Vietnam, or Nigeria. There have been a few studies that have attempted to quantify the potential impacts of sea level rise in South Africa including studies in Cape Town, EThekwini (Durban), and the Eden District (Knysna and Mossel Bay). This study will synthesize the results from these studies as well as make some general first level estimates of the extent of potential inundation along the remainder of the South African coastline.

Vulnerability and adaptive capacity

When considering the potential impacts of climate change, it is important to consider these in the context of existing vulnerability or resilience to climate shocks and the potential for adaptation. South Africa, as a relatively well developed country, has the resources and potential to adapt to future climate change impacts.

An assessment of the potential vulnerability to future impacts of climate change for southern Africa (Midgley et al. 2011) concluded that while South Africa was at risk due to the impacts of climate change, it was better off than some of our neighbours in terms of being able to deal with these impacts due primary to a higher level of economic development, institutional development, and long term planning.

This adaptive capacity, however, is not universal across the country with many vulnerable groups particularly at risk due to the potential impacts of climate change. In addition significant capacity constraints and a lack of operations and management expertise at all levels of government not only increase the vulnerability to current climate variability, put limits to the ability to adapt to the future impacts of climate change. However, the pro-active nature of the South African government to consider the potential impacts of climate change shows a commitment to improving this adaptive capacity and reducing the vulnerability and potential negative impacts of future climate change.

1.4   General modelling framework

Integrated modelling framework

The objective of this study is to make an initial estimate of the potential economic impact of climate change on the national economy of South Africa. The general modelling framework for translating climate change impacts to economic impacts is shown in Figure 11. This general framework has been implemented for a similar assessment of the potential economic impacts of climate change in Mozambique (Arndt 2011), Vietnam (UNU-WIDER 2012) and the Zambezi River Basin (Schlosser and Strzepek 2013) and is generally referred to as the SACRED framework: Systematic Assessment of Climate REsilient Development.
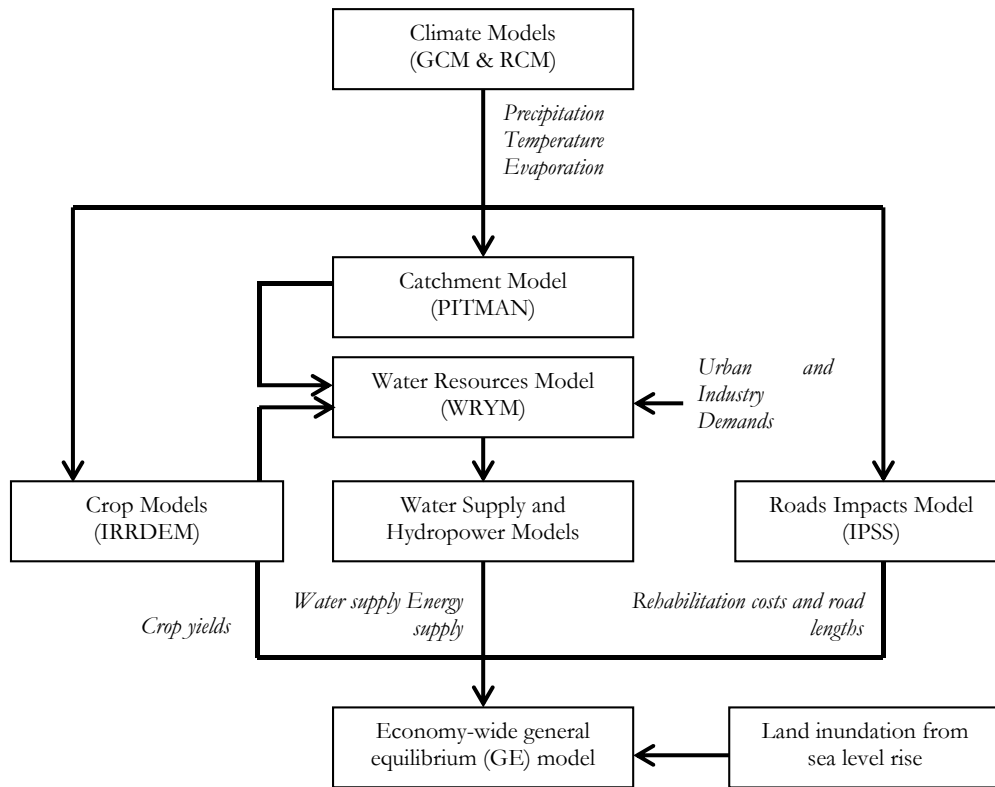
Figure 1: Integrated modelling framework

Source: Authors' compilation, see this study.

The focus of this study is on the biophysical modelling of the four primary impact channels shown in Figure 11: agriculture, water, roads, and coastal infrastructure. Where possible models currently used in South Africa have been used and adapted where necessary for the specific objectives of this study.

Baseline data

Impacts or determined relative to a selected baseline. For the baseline we use monthly precipitation and evaporation data for all quaternary catchments in South Africa for the period 1950 to 2000 obtained from the Water Resources of South Africa 2005 data base (Middleton and Baily 2009). 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.

Future climate scenarios

For the climate change scenarios, outputs form both GCMs and regional models including both statistically (empirically) downscaled and dynamically downscaled models, are considered for the period up to mid-century (2050). For the GCMs we consider all possible model outputs in the form of hybrid frequency distributions (HFD) developed by the MIT Global Change Group (Schlosser et al. 2012). While the use of multiple climate futures presents significant challenges in terms of impact modelling, the significant advantage is that they provide decision makers with an estimate of the likely risk of a range of possible climate change impacts.

The outputs from the climate models (precipitation, temperature, and evaporation) are used as inputs to (1) a rain-fall runoff and water resources model for South Africa, (2) a crop model, and

(3) a roads infrastructure model adapted for South Africa. The outputs from these models combined with an assessment of the additional economic impacts of climate change are incorporated into the general equilibrium model (CGE) of the country giving outputs at sub-national and national scale.

Catchment runoff and water supply

The rain-fall runoff model used is the Pitman model (Pitman 1973) which is still used as the bases for water resources planning studies in South Africa. The model is a monthly model used for water resources planning studies and is based on existing calibrations for South Africa. It does not take into account natural land use changes as a result of future climate change impacts.

South Africa has a highly developed water supply system with thousands of dams and large interbasin transfer systems. Modelling this at a national scale requires substantial simplification of the real operating system, but is necessary to provide the national context required for this study. The water resources model is used to determine the volume of water that can be supplied to agriculture, urban, and bulk industry under future climate change scenarios as inputs to the national economic model. The water resources model used is a national configuration of the Water Resources Yield Model (WRYM). WRYM is also used for detailed water resources modelling of individual systems in South Africa, but in this study we undertake to develop a national version of WRYM.

Irrigation demands and crop yields

A simple crop water deficit model (IRRDEM) is used to determine irrigation demands as inputs to the water resources model. Other demands including urban and bulk industry demands are estimated using available information at a national scale. 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. Other potential impacts such as direct temperature impacts, flooding impacts, or increased CO_2 fertilization are not considered. Neither are the potential benefits from new and more resilient crop types or improved irrigation and agricultural practices or the expansion of existing crop types to new areas that become suitable for cultivation under future climate scenarios.

Hydropower

Hydropower is not a major consideration for water resources management in South Africa. There are only a few hydropower dams in operation, but none of these are operated specifically for the production of power. Hydropower is rather produced as a by-product of releases made for other downstream users. The impact of climate change on the output from these facilities is quantified using a simple model of reservoir levels, simulated outflows, and generating efficiency.

Sea level rise

The impacts of sea level rise are quantified at a desktop level based on existing studies and provisional estimates of the value of land and municipal infrastructure at risk from both permanent inundation and temporary impacts due to elevated storm surges. Due to the complexity of impacts and the variability and highly dynamic nature of the South African coastline, numerous assumptions are made and the results are considered at best a scoping level assessment of potential impacts.

Economic model

The impacts of climate change are integrated through a national GEM for the South African economy (Thurlow 2008). The economic model is developed to investigate the potential impact of specific stresses to the system through for example reduced water supply to agriculture or increased costs for road rehabilitation and repair based on an annual 50-year simulation of impacts from 2000 to 2050. The model will be used to determine the potential economic impacts of climate change to mid-century (2050) relative to the baseline.

2   Future climate scenarios

2.1   Introduction

Growing demands for climate change vulnerability assessments and adaptation strategies have placed a need for risk-based quantification of regional change. Considerable attention has been directed toward developing nations where the capability to make informed decisions and/or capital investments based on climate risk are at a premium. In this section we present analyses for South Africa that quantify the likelihood of changes in precipitation and surface air temperature through the middle of this century. These probabilistic climate outcomes have been prepared for an integrated assessment of the anticipated economic shocks to the basin from climate change and other socio-economic forces as shown in Figure 2.

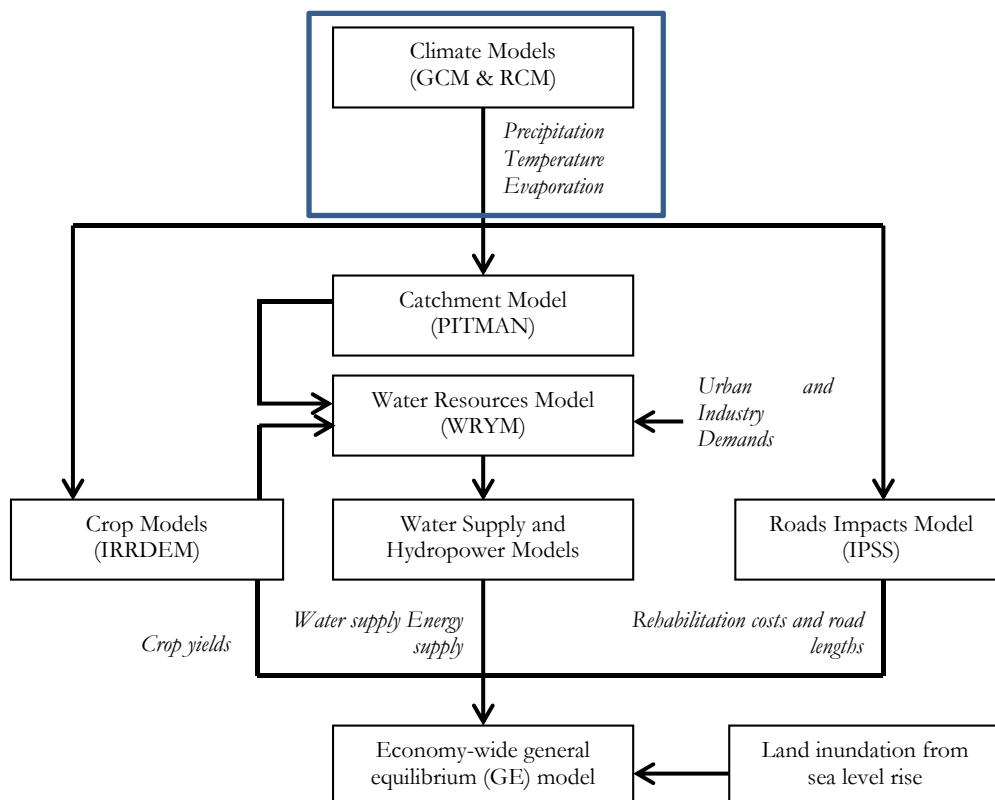Figure 2: Integrated modelling framework highlighting climate scenarios modelling component

Source: Authors' compilation, see this study.

In this chapter the regions of focus and analytic approach is outlined, which includes the construction of an observation-based climatology as well as the downscaled, normalization procedure of the climate model patterns of regional change and their fusion to the zonal output

of the MIT Integrated Global System Model (Sokolov et al. 2005). These steps are based on GCM ensemble results from the IPCC AR4. The resulting HFD are evaluated for a select number of regions to evaluate the shifts in these derived distributions under a moderate climate stabilization policy. Closing remarks and directions for future work and applications are then provided.

2.2   Regional climate change pattern kernels

The construction of the HFDs of climate changes follows that of previous work (Schlosser et al. 2011). The MIT Integrated Global Systems Model (IGSM, Sokolov et al. 2009 and Webster et al. 2012) provides probabilistic projections of T_a and precipitation out to the middle of this century at the zonal level of detail. Given this, we expand in the longitude through a Taylor expansion technique (described by Schlosser et al. 2012). This transformation requires the construction of climate change pattern kernels as the global temperature changes, and the numerical relationship can be expressed as:

$$V_{x,y}^{IGSM}(\Delta T_{Global}) = C_{x,y}\big|_{t_0} \overline{V}_y^{IGSM} + \left[\frac{dC_{x,y}}{dT_{Global}}\Delta T_{Global}^{IGSM}\right]\overline{V}_y^{IGSM}$$

(1)

where $C_{x,y}\big|_{t_0}$ is the downscaling transformation coefficient (from the zonal mean down to a longitudinal point along the zonal band) for any reference time period, and in our case, we can base this on a climatological set of values, $\overline{C}_{x,y}$, based on observational data. Accordingly, ΔTGlobal is the (projected) change in global temperature that has occurred relative to the reference or climatological period. Then, based on supporting data the derivative of these transformation coefficients, $\frac{dC_{x,y}}{dT_{Global}}$, for any point (x,y) must be estimated (for further details on the construction of these, refer to Schlosser et al. 2012). Therefore, the regional specificity of the climate change probabilities is governed, in large part, by the $\frac{dC_{x,y}}{dT_{Global}}$ terms that serve as 'pattern kernels' of regional climate shifts. A set of these pattern kernels is based on the climate model results from the Coupled Model Intercomparison Project Phase 3 (CMIP3, Meehl et al. 2007).

2.3   Hybrid frequency distributions for South Africa

Through the numerical hybridization of the IGSM ensemble of zonal trends with each of the pattern kernels of regional climate change from the IPCC AR4 models, a meta-ensemble of climate change projections is produced, and we refer to as 'hybrid frequency distributions' (HFDs). For this study, we focus on the decadal-averaged climate conditions that are achieved at 2050 and construct frequency distributions of the changes in precipitation and T_a relative to the end of the 20th century. Decadal averaged results are provided in order to highlight the salient features of the climate-scale changes (and remove effects of weather-scale noise).

The IGSM ensembles produce a range of climate outcomes under an unconstrained emissions pathway (Sokolov et al. 2009) as well as a range of global climate policies (Webster et al. 2012). For this study we present results for the unconstrained emissions (UCE) case and a best case greenhouse gas stabilization scenario in which an equivalent CO_2 concentration of ~480 ppm is achieved by the end of the century – and is referred to as the 'Level 1 stabilization' (L1S) policy in Webster et al. (2012). The HFD scenarios are also compared to a number of regional South African

climate models that are based on both statistical and dynamic downscaling of selected GCM outputs.

As the HFDs represent the outcomes from the full range of available GCMs, it is anticipated that the results will provide a much wider range of possible climate futures than the regional climate models which are bounded by on a select few GCM models. The HFDs are therefore considered to provide a better assessment of the range of potential climate change risks in a region, although there might be issues with regards to the scale of the models when considering impacts at a more local scale.

Temperature and 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 average precipitation which accounts for other factors that impact on evaporation such as cloud cover, humidity, and wind (Hargreaves and 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 3. 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 light dashed lines show the inter quartile and full range respectively of the potential impacts under the different model scenarios.
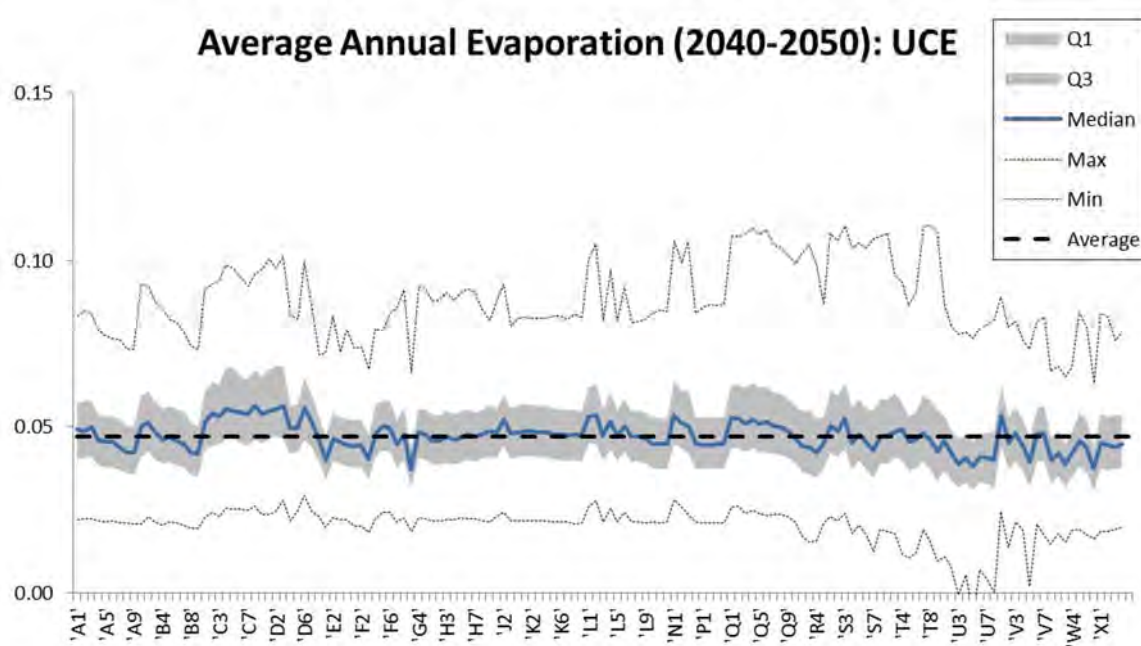
Figure 1: Range of potential impacts on the change in the average annual evaporation by 2050 in each secondary catchment of South Africa under the UCE climate scenario

Source: Authors' compilation, see this study.

The results show a relatively consistent impact across the country, but some variation in particular due to variations in precipitation. 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 scenario for some models.

Precipitation impacts by 2050

The potential impacts on precipitation are much more uncertain and vary more significantly between models and across the country. The HFD for the average annual and average seasonal change in the total precipitation over the country derived from the UCE and L1S climate scenarios are shown in Figure 4. The results show a wide range of potential impacts, both positive and negative, that is slightly greater for the UCE scenario than for the L1S scenarios.
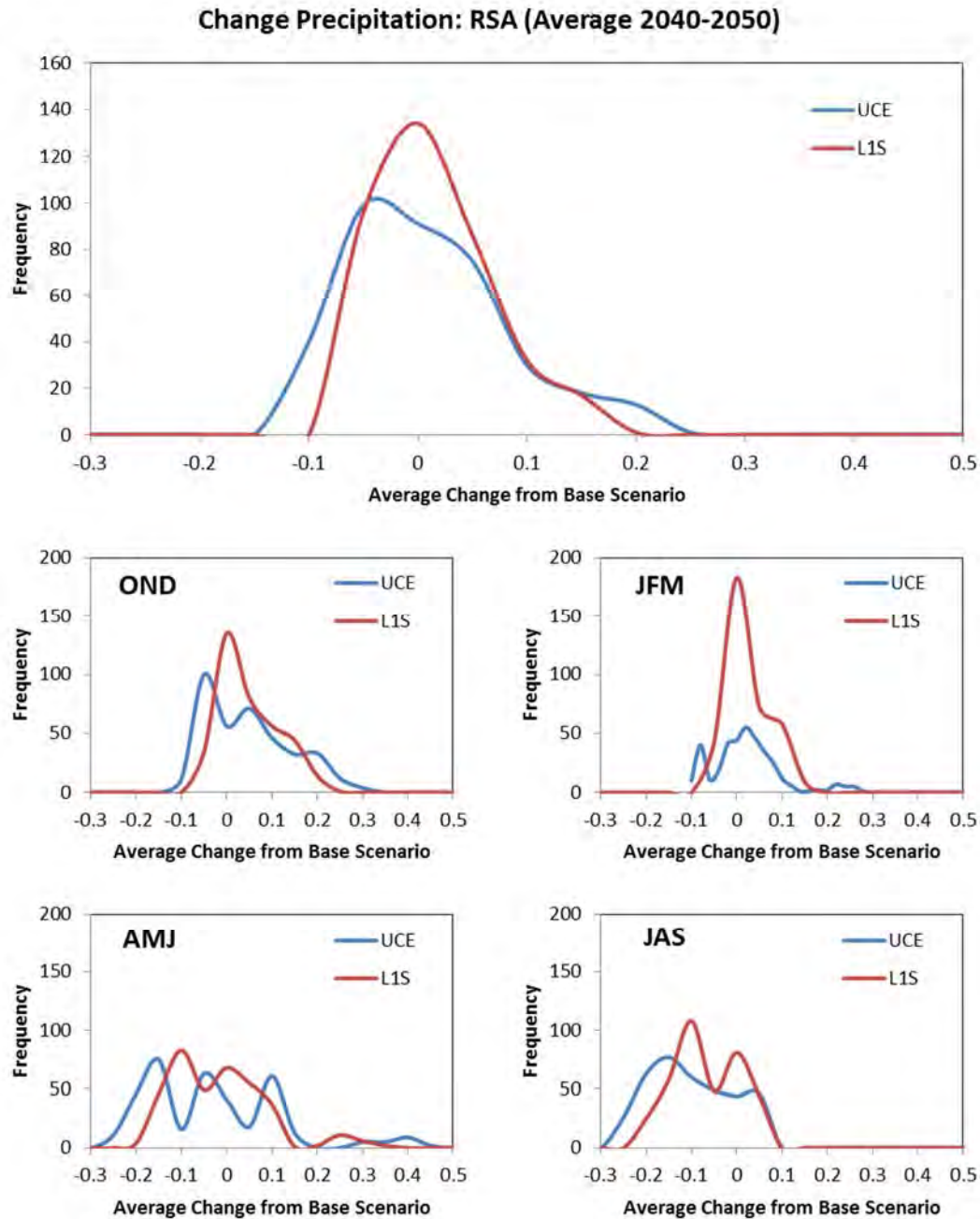

Figure 4: Hybrid frequency distribution of the average annual and average seasonal change in the total precipitation over South Africa for the UCE and L1S climate scenarios relative to the base scenario by 2050

Source: Authors' compilation, see this study.

The Unconstrained Emission (UCE) scenario impacts range from -12.5% change to +20.6% with a median impact of a 1.9% reduction in the total average annual precipitation over the country by 2050. The L1S 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%.

In terms of the seasonal impacts, the most negative impact appears to be during the winter months with up to a 28% reduction under the UCE scenario. The greatest uncertainty appears to be during autumn with the UCE showing potential impacts ranging from -28% to +41%.

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 L1S climate scenario are shown in Figure 5.
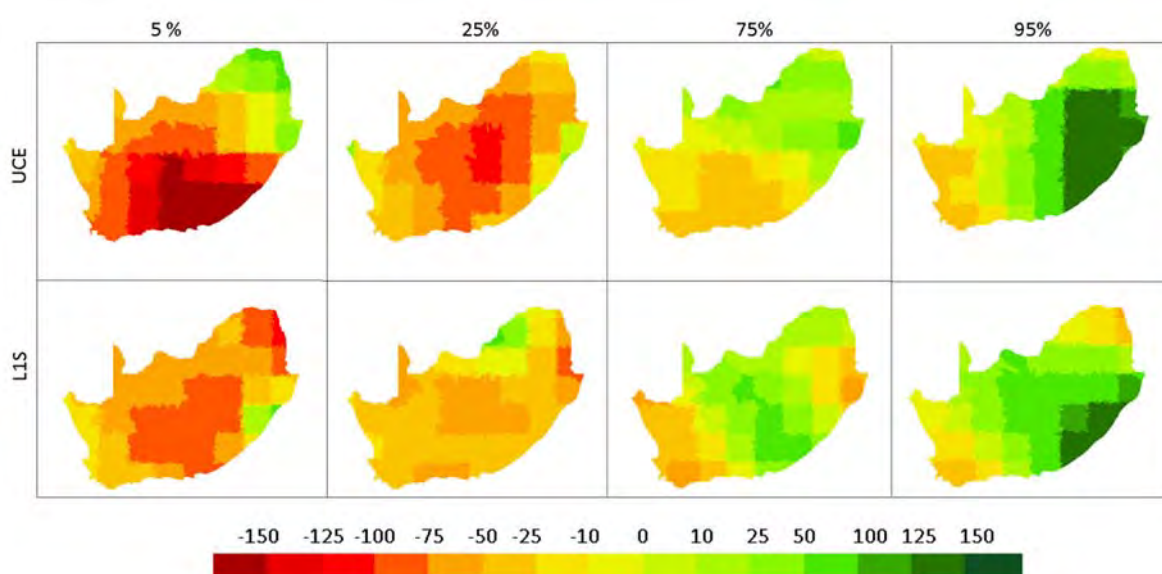
Figure 5: Change in the average annual precipitation (2040 to 2050) across the country for individual models representing the 5th, 25th, 75th and 95th percentile of the total change over the country under the UCE and L1S future scenarios

Source: Authors' compilation, see this study.

The ratio of potential impacts under the UCE relative to the base scenario in each secondary catchment scenario is shown in Figure 6. The solid 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 around 3.6% reduction in the median impact on the average annual precipitation for all secondary catchments across the country

Figure 6: Range of potential impacts on the change in the average annual precipitation by 2050 in each secondary catchment of South Africa under the UCE climate scenario

Source: Authors' compilation, see this study.

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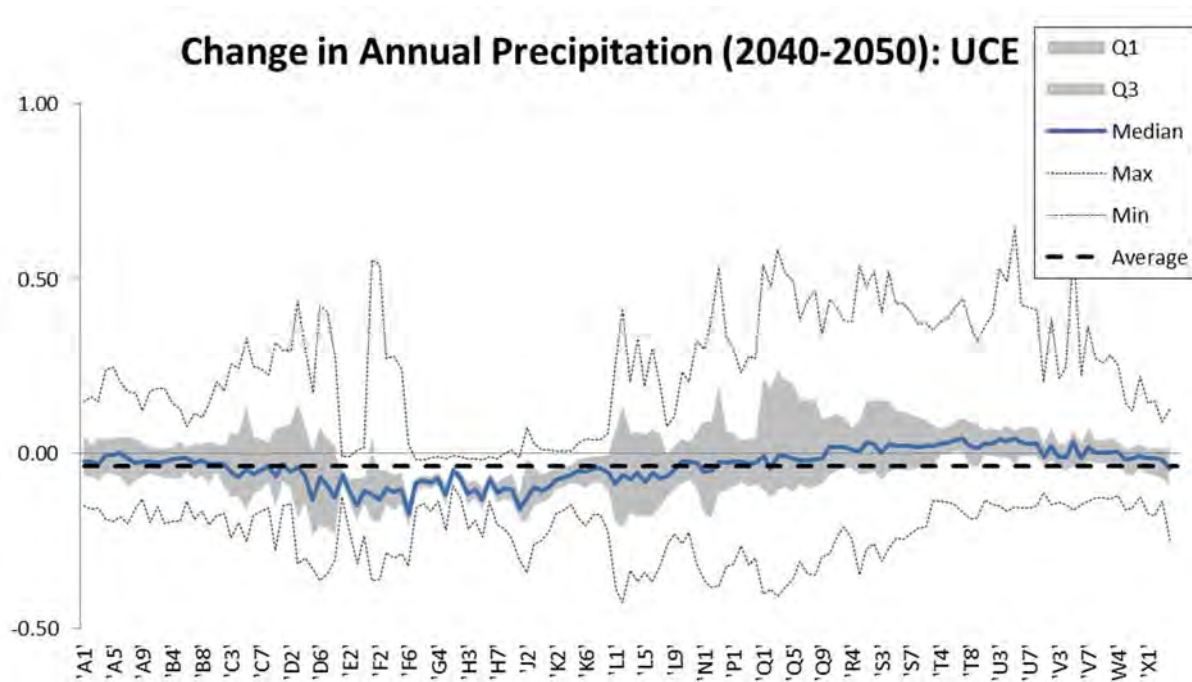howing reduced precipitation in the F, G, and H secondary which are located in the south-west of the country including the west coast, the Berg River and the Breede River catchments. In contrast the catchments in the east of the country (T and U) show a general increase in the average annual precipitation,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

2.4   Comparison of HFDs with regional climate models

For comparison with the HFDs, outputs from both statistical (empirical) downscaled (Hewitson and Crane 2006) and dynamic downscaled (Engelbrecht et al. 2011) regional climate models were obtained for the whole of South Africa from the Climate Systems Analysis Group (CSAG) at the University of Cape Town, and the Centre or Scientific and Industrial Research (CSIR), respectively. The outputs from these regional climate models were based on the A2 and B1 climate scenarios from the CMIP3 suite of global climate models as well as the CMIP5 suite of global climate models for both the 4.5 and 8.5 relative concentration pathways. These regional climate scenarios were prepared during phase 1 of the Long Term Adaptation Strategy (LTAS) and are collectively referred to as the LTAS climate scenarios.

As with the HFDs, a time series of average monthly changes in precipitation and temperature was determined for each of the LTAS scenarios relative to the base period of 1970 to 2000 and applied to the same base scenario as was used for the HFDs to represent the possible future scenarios from 2000 to 2050. The outputs from the HFDs and the LTAS scenarios are compared in terms of the average change over the last ten years of the simulation (i.e. 2040 to 2050) and grouped

according six hydro-climatic zones (Figure 7) as defined by DWA in its climate change strategy (DWA 2013).
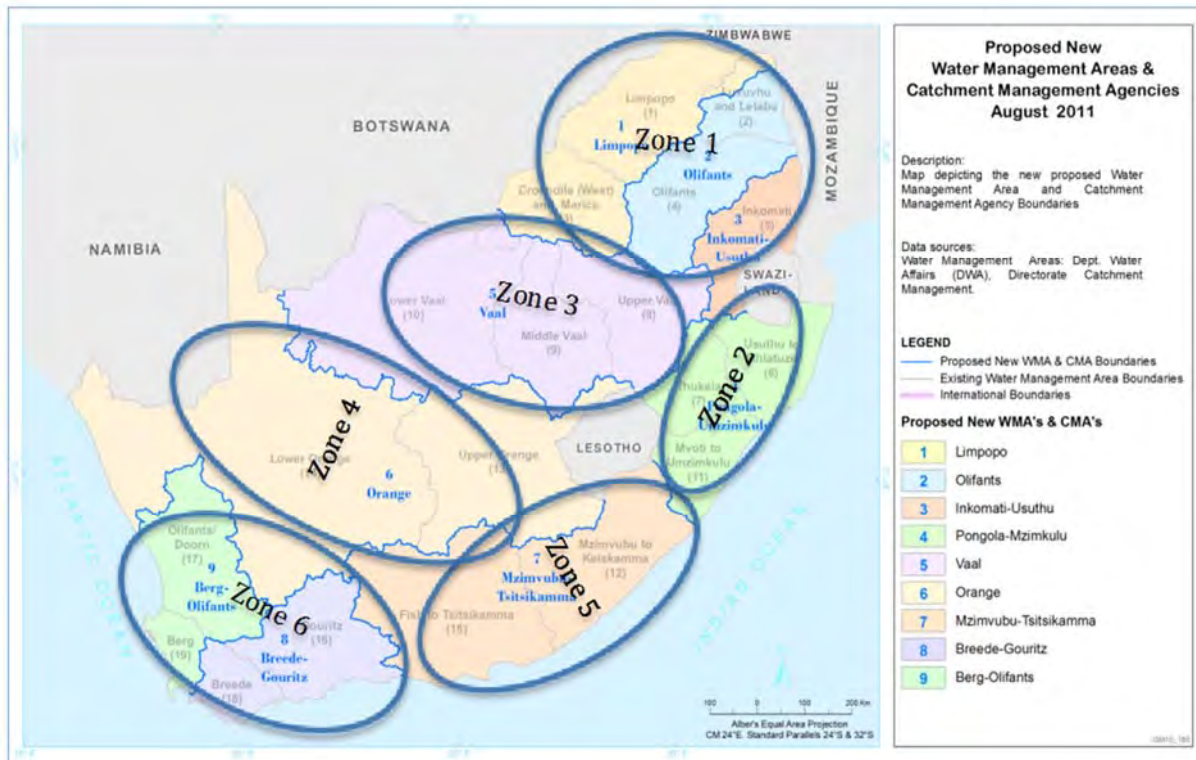
Figure 7: Hydro-climatic zones used for summary of HFDs and comparison with outputs form regional climate models

Source: DWA (2013).

Temperature impacts

The median output from the global GCM models shows an average increase in the annual temperature across South Africa of between 1.5 and 2°C by mid-century (2050) as shown in Figure8. Correspondingly the median of the L1S scenarios is an increase of around 1°C by 2050. In addition the results of the HFD analysis of all possible future climate scenarios shows that the spread of possible temperature increases across all regions of South Africa is much greater under the UCE scenarios than the L1S scenarios reaching an average increase in annual temperature of up to 3°C.

Figure 8: Increase in average annual temperature in ˚C for the period 2040-50 as compared to the period 1990 to 2000 for the six hydro-regions of South Africa. Comparison of HFD outputs from all global climate models with outputs from 14 statistically downscaled regional climate models (CSAG B1 and A2 scenarios) and 8 dynamically downscaled regional climate models (CCAM A2). The UCE scenario of the HFDs is broadly comparable with the A2 scenario, while the L1S for the HFDs is broadly comparable with the CSAG B1 climate scenario

Source: Authors' compilation, see this study.

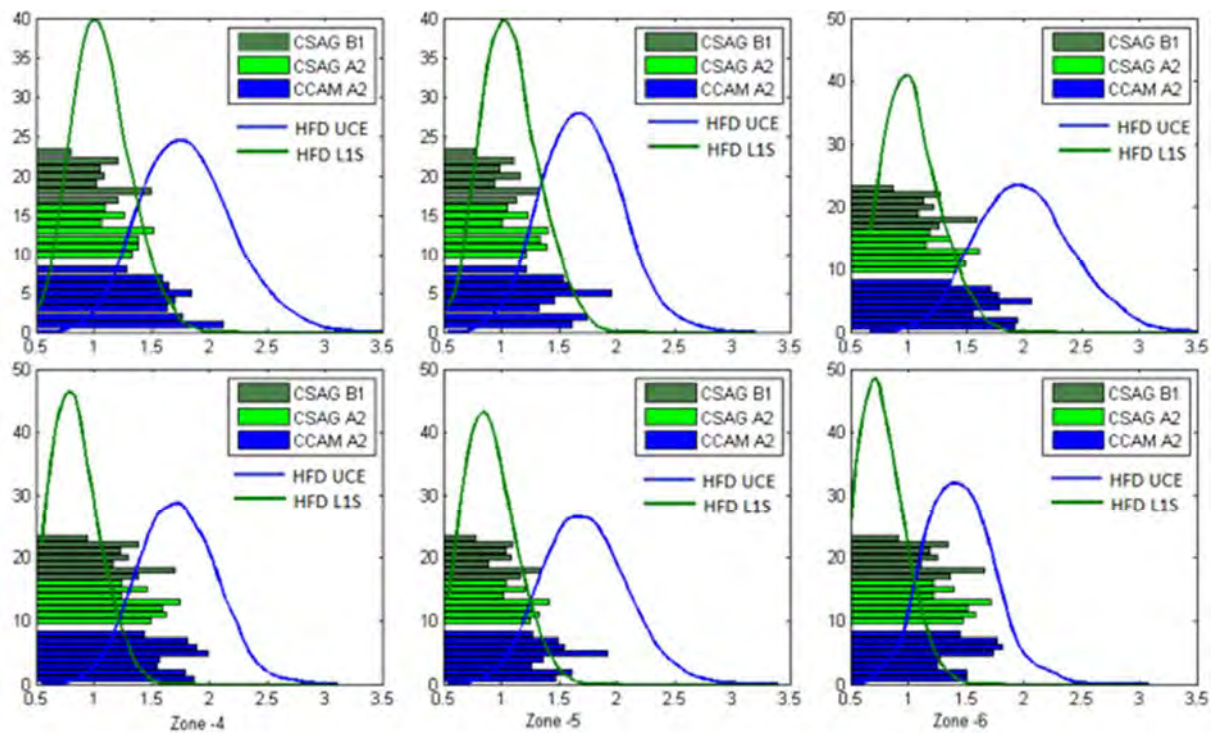The outputs from the South African regional models show slightly higher average temperature increases for the conformal-cubic atmospheric model (CCAM) scenarios than for the CSAG scenarios. The outputs from the CCAM scenarios are generally consistent with the median values for the HFDs of the L1S scenarios. In contrast the CSAG A2 scenarios plot in the range of the 25th percentile for the L1S HFDs. The exception is Region 6 where the HFDs show reduced increases in the average temperature with the result that some of the CCAM and CSAG scenarios plot above the median value for the L1S HFD scenarios.

Precipitation impacts

The HFDs for the UCE estimate of the change in the average annual precipitation for the six hydro-zones are given in Figure9, along with the corresponding outputs from the regional dynamically downscaled CCAM A2 scenarios and the statistically downscaled CSAG models (Ltas CMIP5). These results show the range of potential impacts considered using the HFD approach and how this encompasses the range of the more complex regional downscaled models.
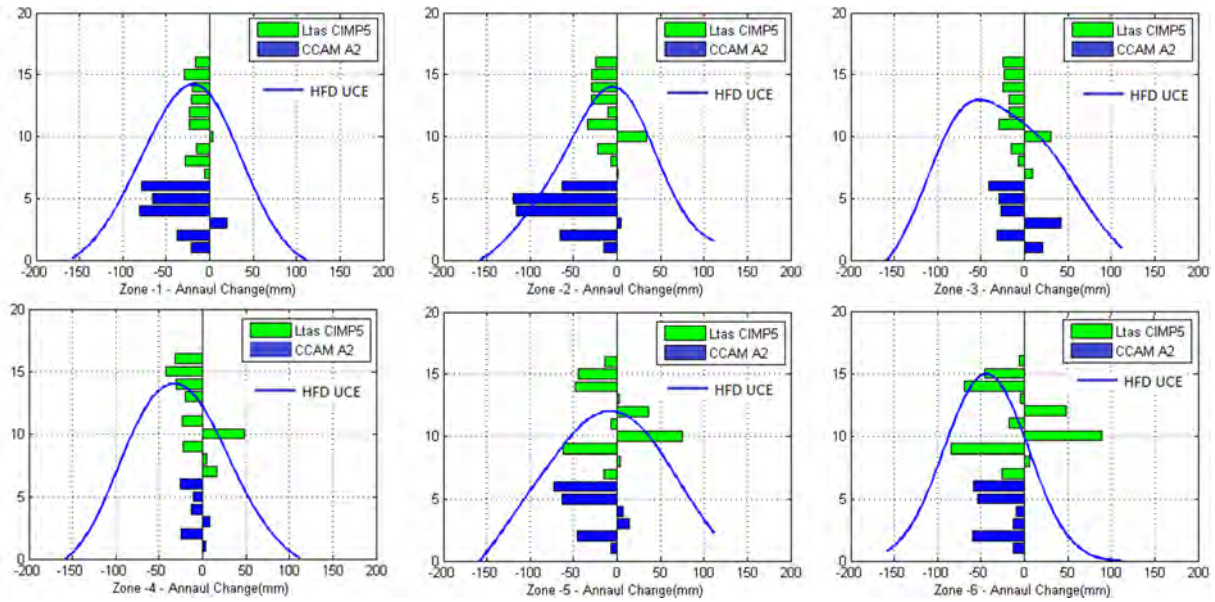
Figure 9: Median increase in average annual precipitation in mm/year for the period 2040-50 as compared to the period 1990 to 2000 for the six hydro-regions. Comparison of the HFD of UCE mitigation scenario from the IGSM model with outputs from a number of statistically and dynamically downscaled regional climate models for South Africa

Source: Authors' compilation, see this study.

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 5, the mode of the HFD is around a 50 mm reduction in the average annual precipitation, while for zone 4 it is around 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 around a 150 mm reduction in the mean annual precipitation (MAP).

The bulk of the regional downscaled models show a reduction in the average annual precipitation across all six zones. The greatest impact is for the CCAM A2 scenarios in Zone 2 with over 100 mm reduction in the average annual precipitation. This zone represents the east coast of South Africa, which is generally the wettest part of the country.

The CSAG scenarios (Ltas CMIP5) show much reduced impacts and even a few models showing increased precipitation. In general, however, the HFDs encompass the full range of the regional downscaled models as well as including some additional scenarios, both positive and negative impacts that are not considered by the regional models.

Analysis of the results from the HFD scenarios can therefore be considered to encompass the potential impacts of the regional downscaled models, although further analysis is required to determine if the additional regional texture resulting from the downscaling has an impact on the overall water resources and economic impacts.

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 however, should also be considered in future studies as this would combine the best of the HFD and regional downscaling approaches.

3 Catchment runoff

3.1 Introduction

The purpose of this section of the report is to present the results for the modelling of the impacts of the HFD climate change scenarios for the UCE and L1S scenario on catchment runoff for South Africa. The outputs from the modelling of climate change impacts on catchment runoff are required as inputs to the water resources model used to investigated the potential impacts of climate change on water supply and in terms of the impacts on the national economic as part of the integrated modelling framework shown below.
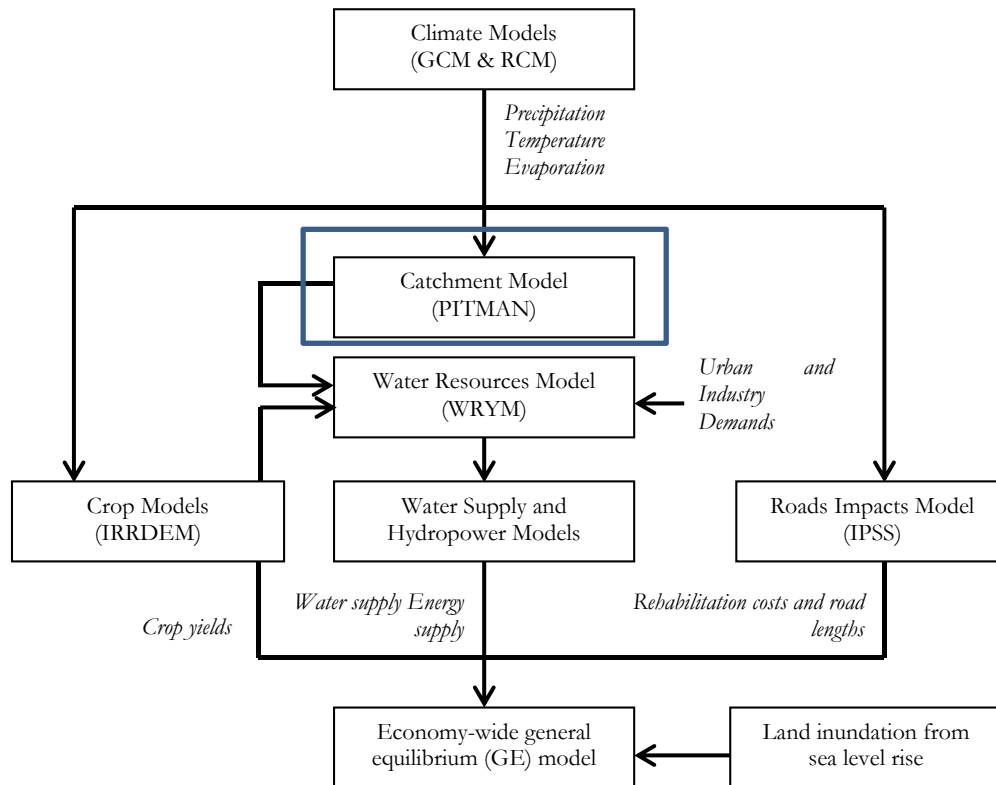
Figure 10: Integrated modelling framework highlighting the catchment rainfall-runoff modelling component

Source: Authors' compilation, see this study.

3.2 Background

South Africa is a semi-arid country with a high spatial and temporal variability in precipitation, high rates of evaporation and a very low conversion of precipitation into rainfall. The average MAP for South Africa is only 480 mm. This is well below the world average of around 860 mm/a (DWAF 2004). In addition there is significant variation across the country with 20% of the country receiving less than 200 mm per year (Lynch 2004), while some areas along the east coast and the escarpment receive over 1000 mm per year.

Rainfall in South Africa is also highly seasonal and highly variable from year to year. The annual variability in rainfall, expressed as a the coefficient of variation CV (%) ranges from less than 20% in the high rainfall regions of the east coast to over 50% in the Northern Cape (Schulze 2011).

The mean annual evaporation (MAE) across the country is also very high at around 1790 mm/a. The combination high temporal variability in rainfall and high evaporation results in a very low

conversion of rainfall to runoff. The total estimated natural catchment runoff for South Africa is some 49,000 Mm^3/a (DWA 2004). This is less than half of the annual flow in the Zambezi and results in an average conversion factor for rainfall to runoff across the country of less than 10%. This also varies significantly across the country from less than 5% in the drier parts of the country to over 20% in a handful of high rainfall catchments along the east coast, the escarpment and the Cape Mountains.

Catchment runoff is generally very sensitive to changes in precipitation and the current relationship between mean annual precipitation (MAP) and mean annual runoff (MAR) for all catchments in South Africa can be well described by an exponential function (Figure 1). This means that runoff is more sensitive to increases in precipitation than reduction in precipitation. Specifically increases in precipitation generally result in a much higher proportional increase in runoff while reductions in precipitation result in lower proportional reduction in runoff.
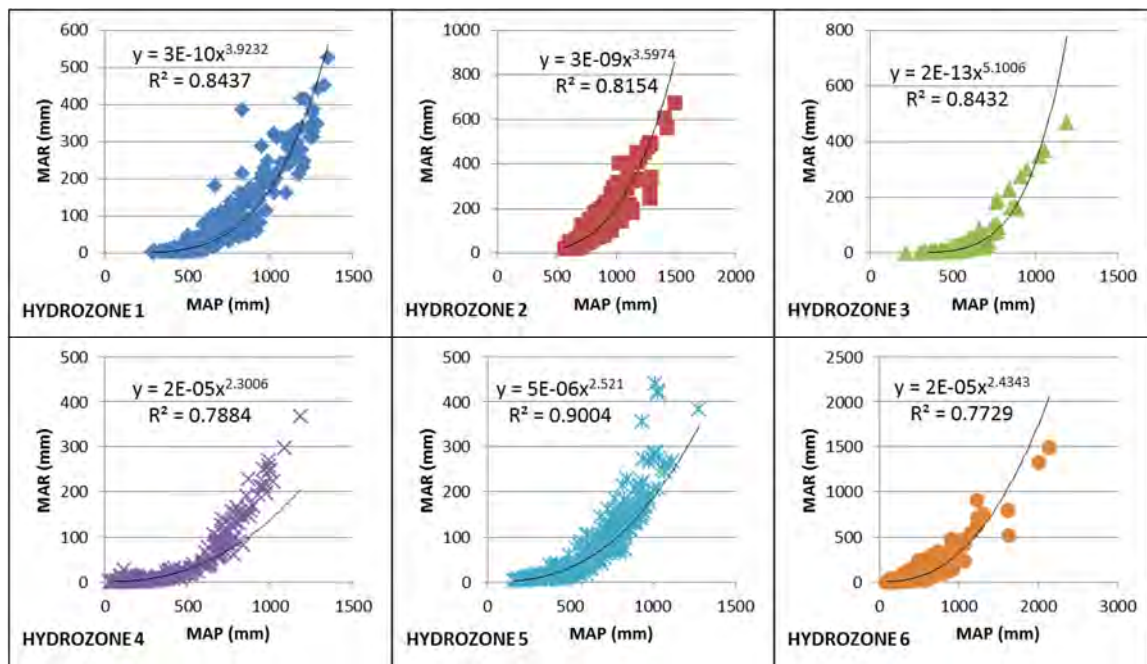
Figure 11: Relationship between MAP and MAR for quaternary catchments in six hydroclimatic zones of South Africa showing the sensitivity of runoff to changes in rainfall

Source: Authors' compilation, see this study.

Climate change is likely to impact on catchment runoff through changes in both precipitation and evaporation as well as potential changes in vegetation type over time (Schulze 2011). For this study we consider only the impacts of changes in total precipitation and not changes in the intensity of precipitation. We also do not consider potential changes in land cover type as a result of climate change. This is considered to be a slow and incremental change in catchment characteristics and not resulting in significant impacts during the period of simulation up to mid-century.

3.3   Methodology

Selection of a baseline scenario

Impacts or determined relative to a selected baseline. For the baseline we use monthly precipitation and evaporation data for all quaternary catchments in South Africa for the period 1950 to 2000 (DWA 2005) and project this out to 2050. 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. It is, however, important to consider any potential impacts of climate change in relation to current natural variability in precipitation and runoff across the country.

Figure 22: Total annual precipitation over South African catchments ($10^9 m^3/a$) 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.

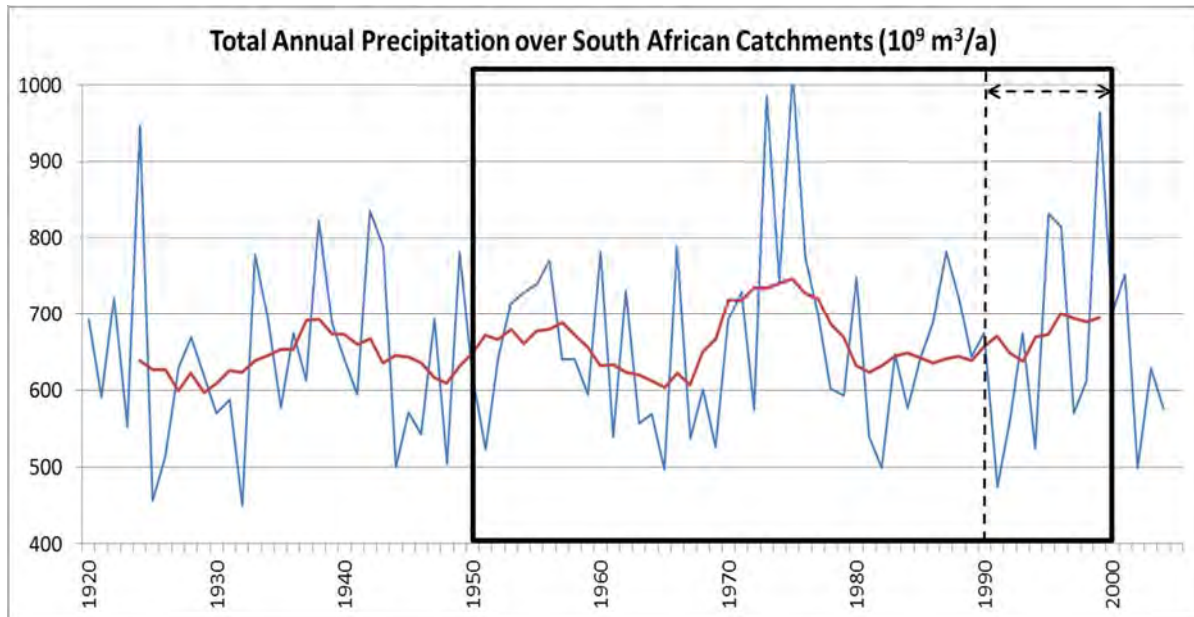Source: Authors' compilation, see this study.

Precipitation and evaporation changes

The precipitation and evaporation changes used in this analysis are described in the previous section. In all cases the climate models were used to determine the absolute monthly change in both precipitation and evaporation in mm. These absolute changes, or deltas, where then applied to the baseline scenario for precipitation and evaporation obtained from the WR2005 database. In total 367 possible climate scenarios were generated from the GCMs using the HFD approach for both the UCE and L1S scenario. These represent the range of possible climate future for South Africa.

Monthly changes in evaporation under the different climate futures and mitigation scenarios (UCE and L1S) are calculated using the modified Hargreaves equation which calculates changes in PET as a function of temperature and average precipitation which accounts for other factors that impact on evaporation such as cloud cover, humidity, and wind (Hargreaves and Allan 2003). These changes are then converted to S-pan evaporation estimates which are used as inputs to the Pitman rainfall runoff model and A-pan evaporation estimates used for determining the changes in the average annual irrigation demand.

Rainfall-runoff model

The Pitman model (Pitman 1973) was used to determine a time series of monthly catchment runoff for all quaternary catchments in South Africa for all possible climate futures. 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 model consists of storages linked by functions design to represent the main hydrological processes prevailing in the basin.

The parameters of the model include surface runoff (ZMIN, ZMAX), soil moisture storage and runoff function (ST, POW, FT) and groundwater recharge. The main inputs include catchment area, monthly precipitation and monthly evaporation data. These data have been developed for all quaternary catchments of South Africa as part of the Water Resources 90 (WR90) dataset (Midgley et al. 1994).Updated parameters were provided for South Africa as part of the Water Resources 2005 study, but these parameters included an additional groundwater component to the original Pitman model that was not considered in this study. The WR90 parameters were therefore used.

The Pitman model was coded into MATLAB to facilitate the running of multiple climate scenarios. The MATLAB version of the Pitman model was checked using the 70 years of precipitation and evaporation data contained in the WR90 database and was found to reproduce the corresponding previously calculated naturalized flows very well in the majority of catchments, with an R^2 of 0.99.
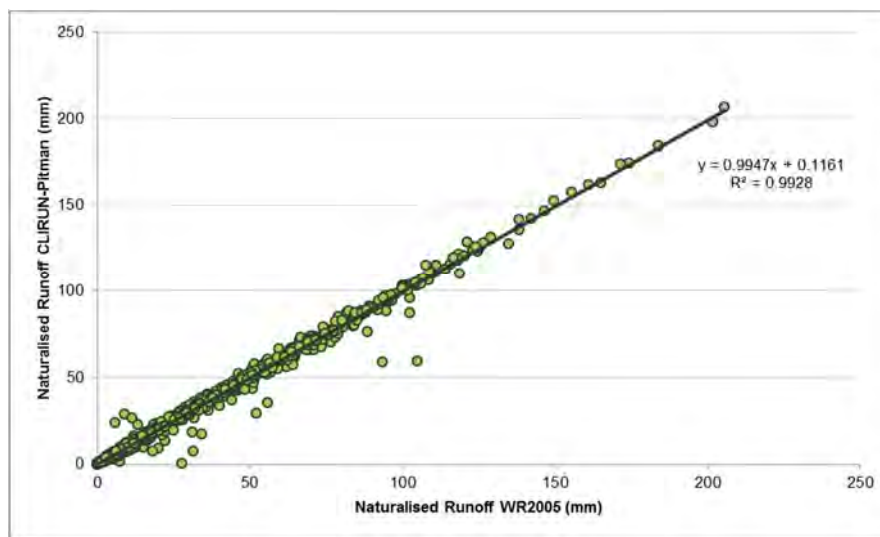
Figure 13: Comparison of the average annual naturalised runoff values generated using the CLIRUN-PITMAN model for all quaternary catchments in South Africa

Source: Authors' compilation, see this study.

The model was the used to generate a time series of monthly naturalized runoff values for all quaternary catchments for all possible climate scenarios using the average monthly precipitation and evaporation values contained in the WR2005 database using the period 1950 to 2050 as the baseline scenario. The monthly runoff from individual quaternary catchments were aggregated to secondary catchment level as inputs to the water resources model described in a later section.

The monthly runoff volumes were determined by considering the net catchment area provided in the WR2005 database to account for endoreic areas of the country that do not contribute to downstream runoff. In addition current annual estimates of channel losses for each quaternary catchment were used form the WSAM database and adjusted proportionally to account for variations in evaporation due to climate change as a major driver of changes in the channel losses.

3.4   Results

A comparison of the HFD of the average change in the annual catchment runoff and the average change in the annual seasonal runoff for the whole of South Africa for the period 2040 to 2050

resulting from the outputs of the HFD models for the UCE and L1S climate scenarios relative to the base scenario is given in Figure 14. 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 L1S 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 however is reduced under the L1S climate scenario. For the UCE scenarios the potential impacts on total catchment runoff range from 13% reduction to a 48% increase, while under the L1S scenario the range is from only a 10% reduction to a 30% increase.

The variation in the impact on the annual runoff for different secondary catchments across the country is shown in Figure 15. 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 stream flow. In contrast there are some very large potential increases in runoff for the east coast (Q to W) which could result in increased flooding risks.

The impact of the L1S 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 (Figure16). While some models were showing the potential doubling in annual runoff in selected secondary catchments in the eastern half of the country, under the L1S scenario the additional risk is only half, but still shows possible increases up to 100% of 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 show in Figure. These results show that even under a very wet scenario there is still drying in the Western Cape.

A time series of impacts on the annual runoff from selected secondary catchments are shown in the figures below along with the impacts on the average monthly runoff for the period 2040 to 2050. The six catchments selected are representative of each of the six hydro-climatic regions of South Africa as shown in Figure 18.

These results are an example of the input to the water resources yield model that is used to quantify the potential impacts on the availability of water supply across the country.
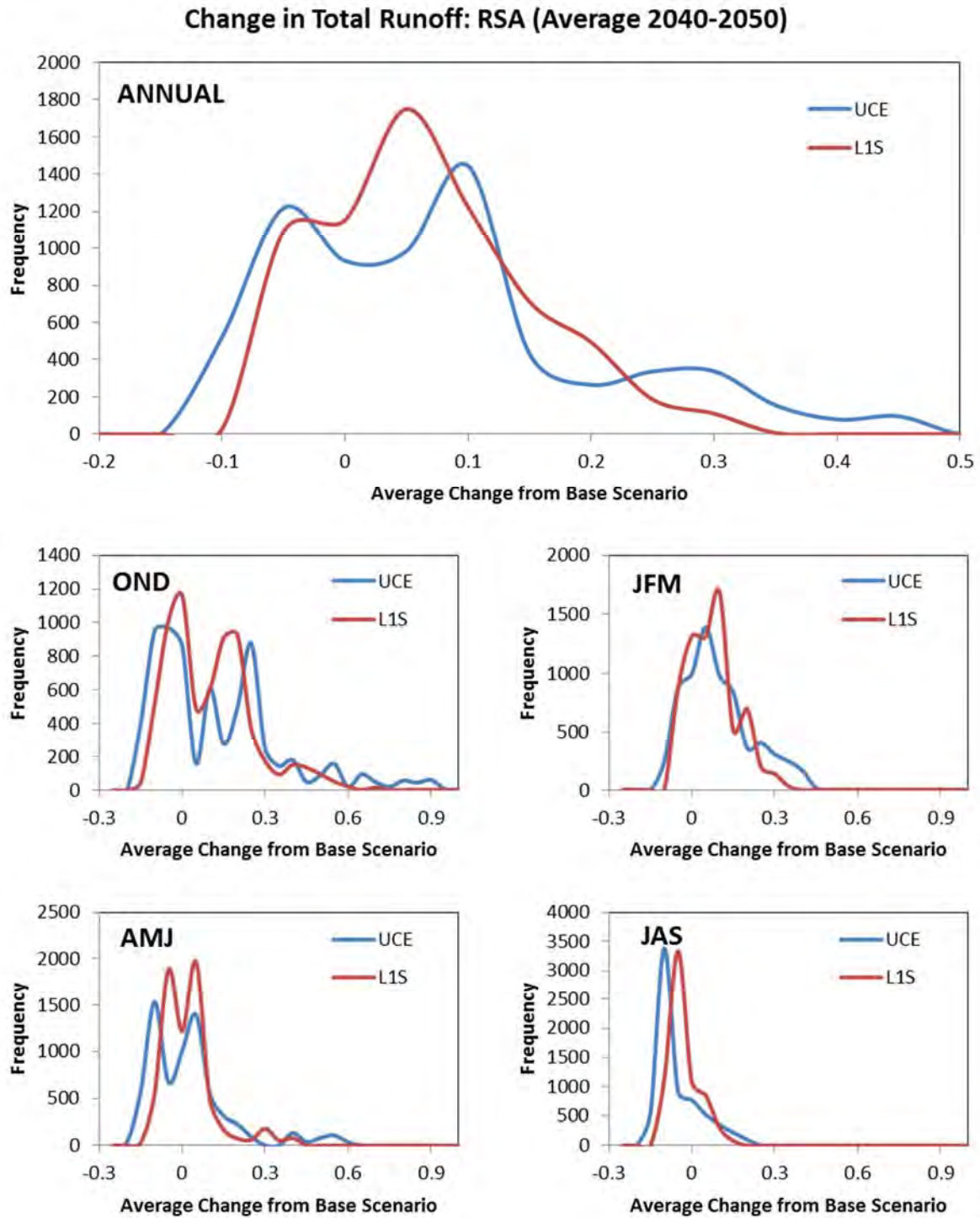
Figure14: Hybrid frequency distributions of the impacts of the UCE and L1S global climate scenarios on the average annual and seasonal catchment runoff for all catchments for the period 2040-50 relative to the base scenario.

Source: Authors' compilation, see this study.
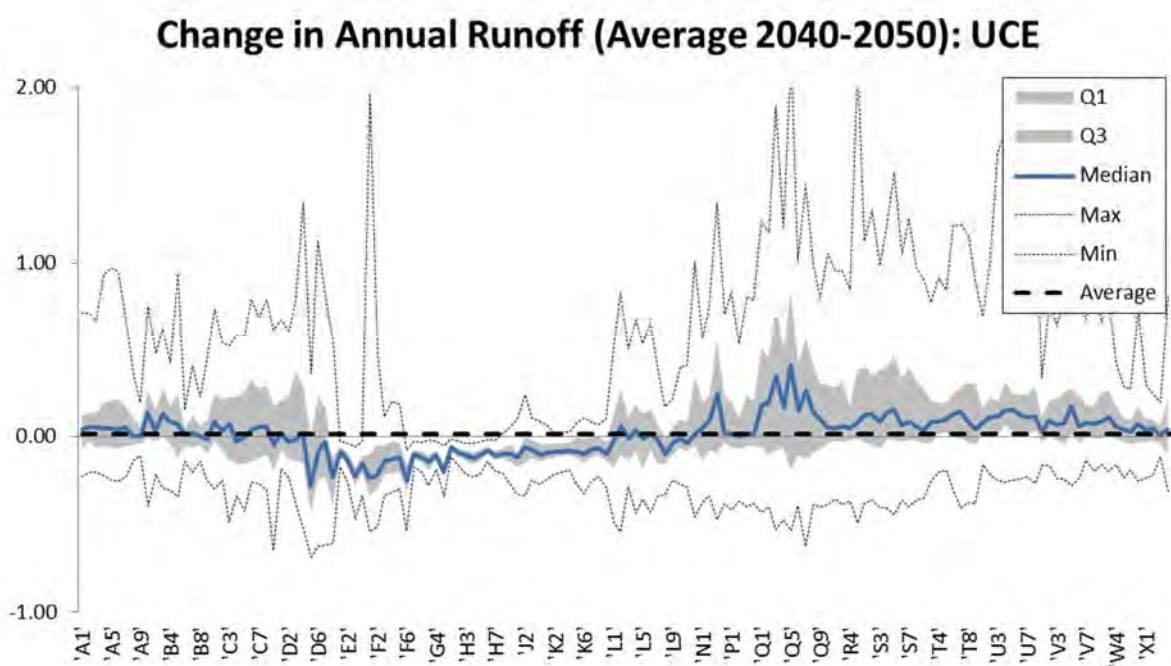
Figure 15: Range of potential impacts of climate change on the average annual catchment runoff for all secondary catchments for the period 2040 to 2050 due to the UCE scenario relative to the base scenario

Source: Authors' compilation, see this study.
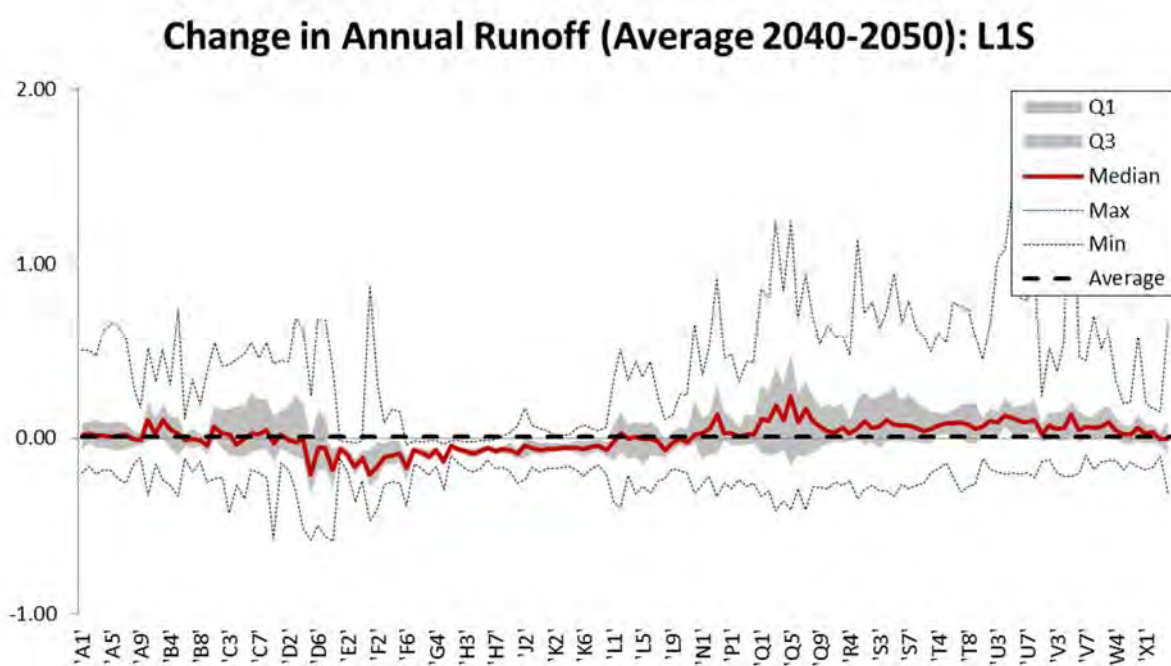
Figure 16: Range of potential impacts of climate change on the average annual catchment runoff for all secondary catchments for the period 2040 to 2050 due to the L1S scenario relative to the base scenario

Source: Authors' compilation, see this study.
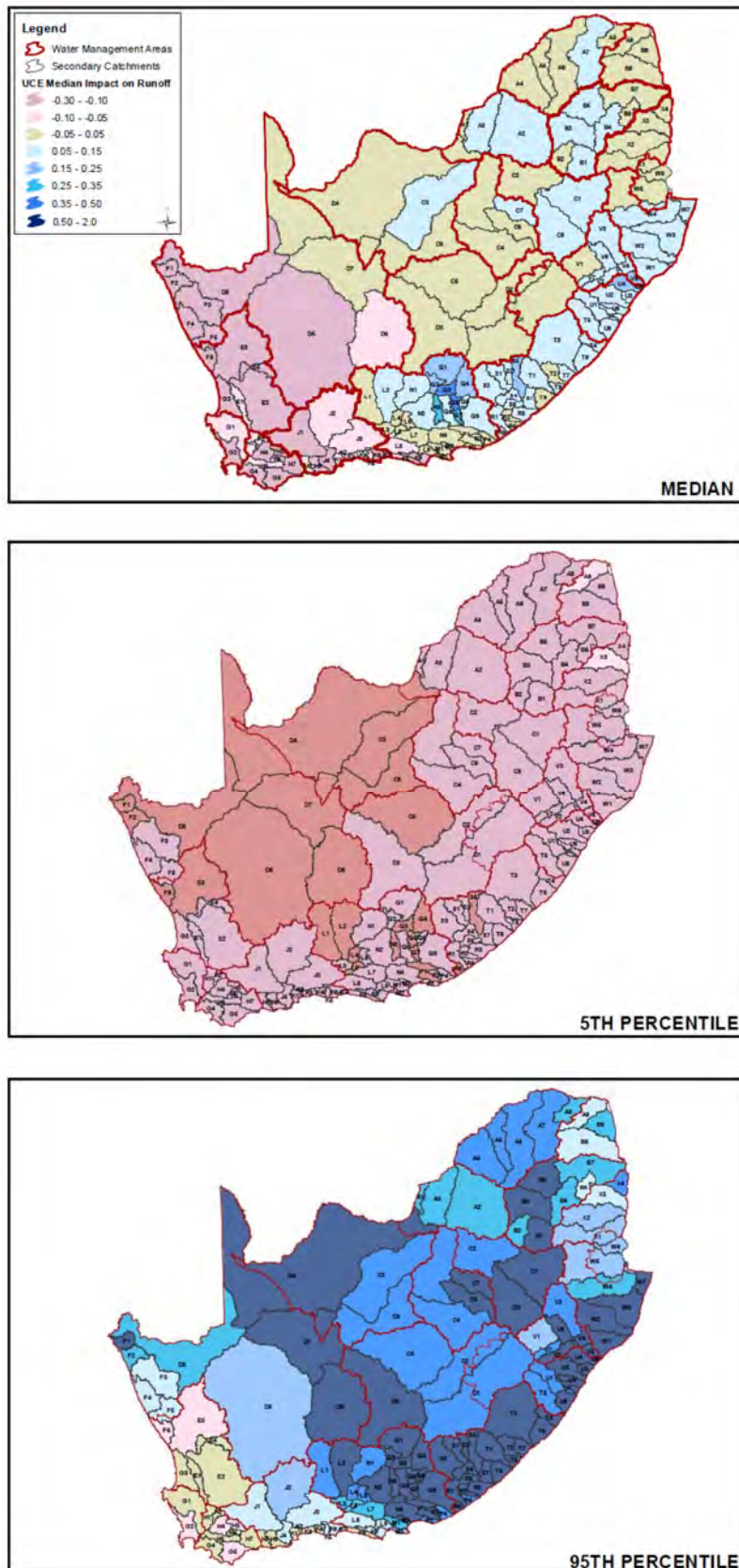
Figure 17: Median, 5th percentile and 95th percentile impact on the average annual catchment runoff at secondary catchment scale under for the UCE scenario by 2050 across South Africa

Source: Authors' compilation, see this study.
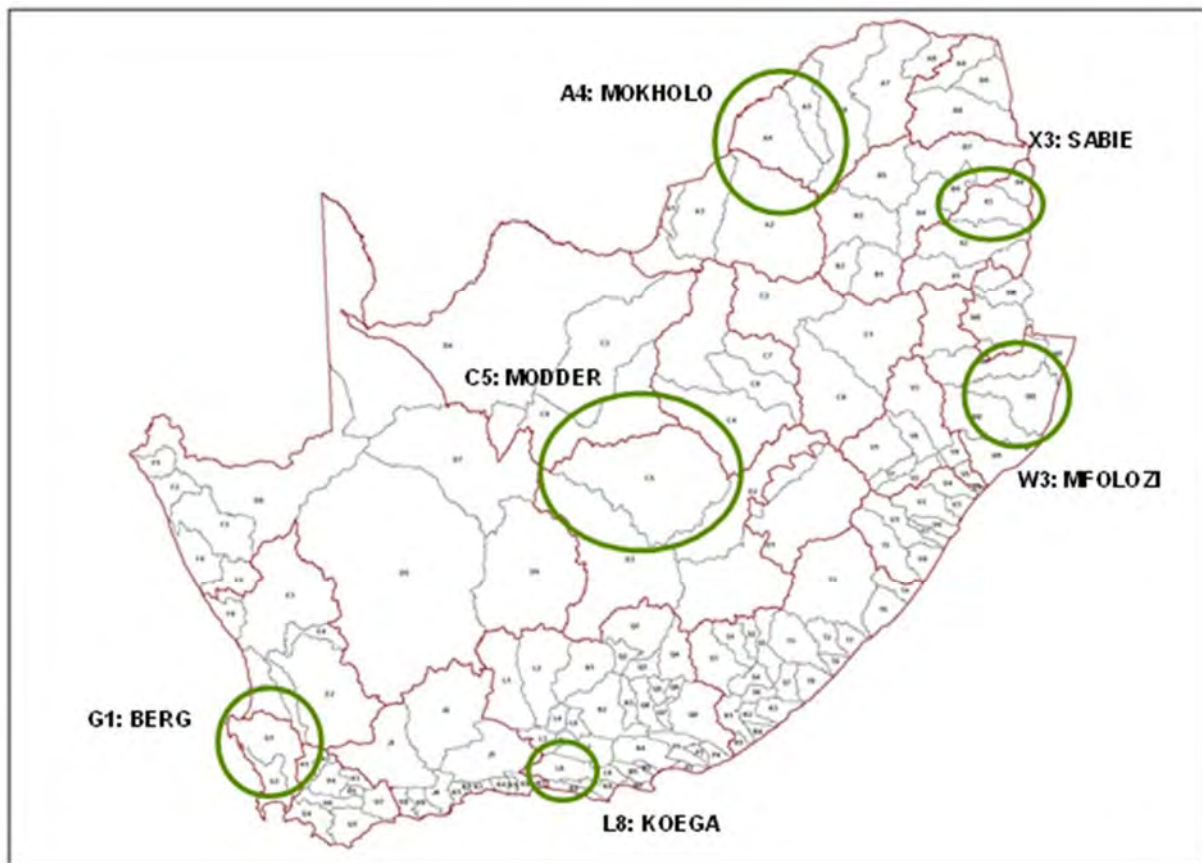
Figure18: Representative catchments for six hydroclimatic zones in South Africa

Source: Authors' compilation, see this study.

The following general observations can be made based on these results

A4: Mokholo River: Even distribution of potential 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: 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: 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: 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: 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: Possibility for increased runoff outside of current variability with the greatest impact being during the wetter months (December and January).
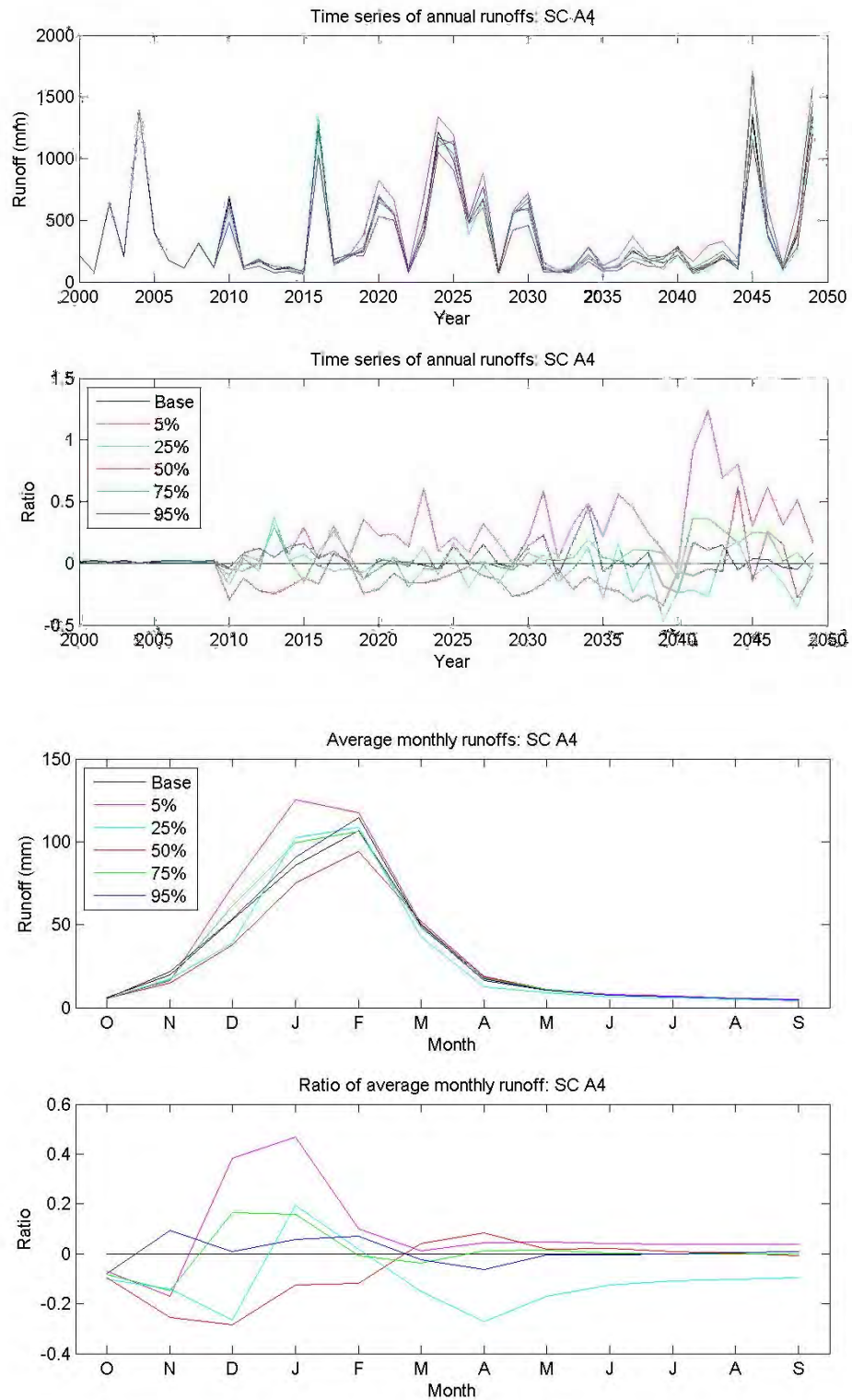
Figure19: Catchment A4: The Mokholo River. Impact of the UCE scenarios on the time series of average annual flow up to 2050 (Top) and the average monthly flows for the period 2040 to 2050

Source: Authors' compilation, see this study.

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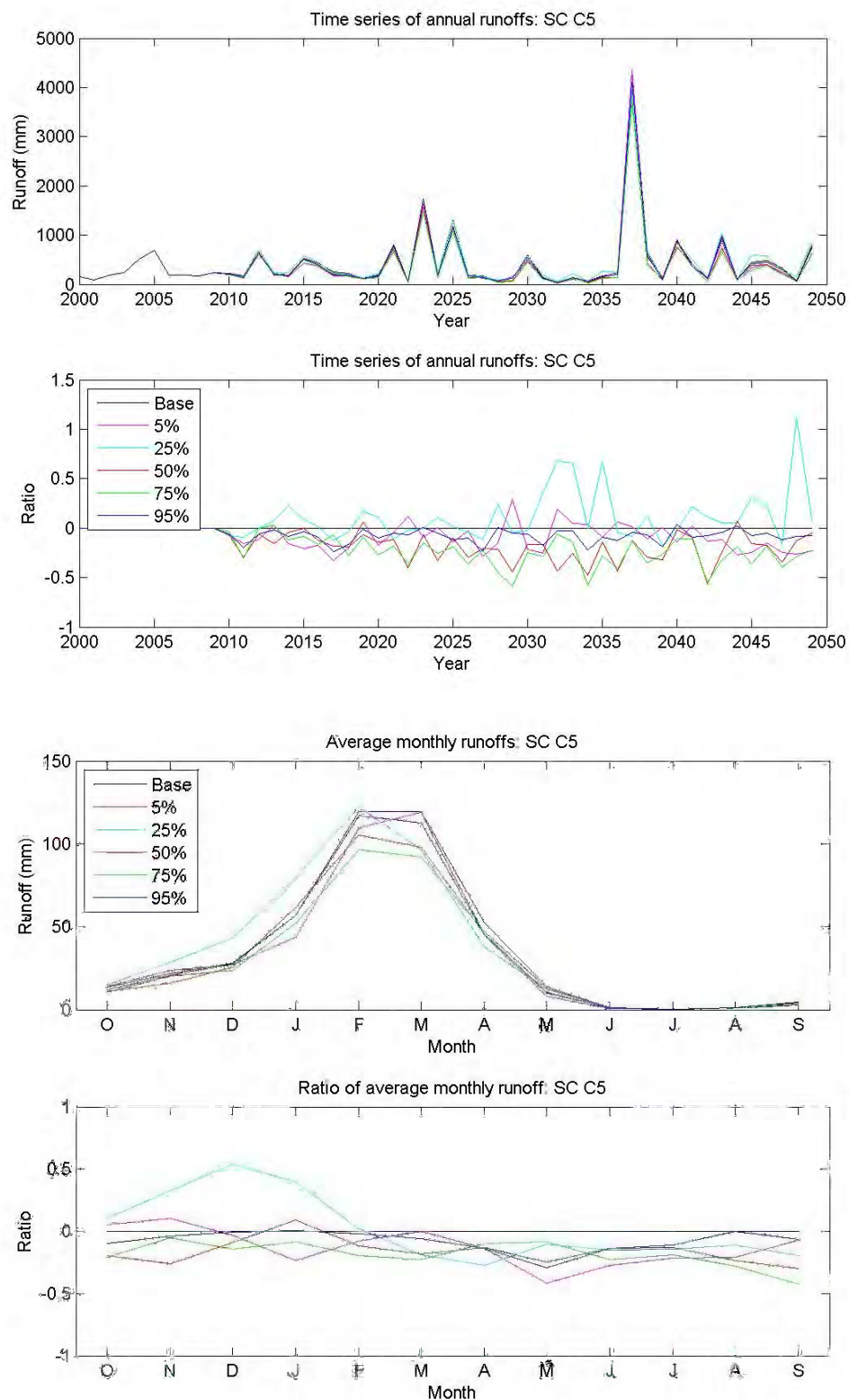
Figure 20: Catchment C5: The Modder River. Impact of the UCE scenarios on the time series of average annual flow up to 2050 (Top) and the average monthly flows for the period 2040 to 2050

Source: Authors' compilation, see this study.
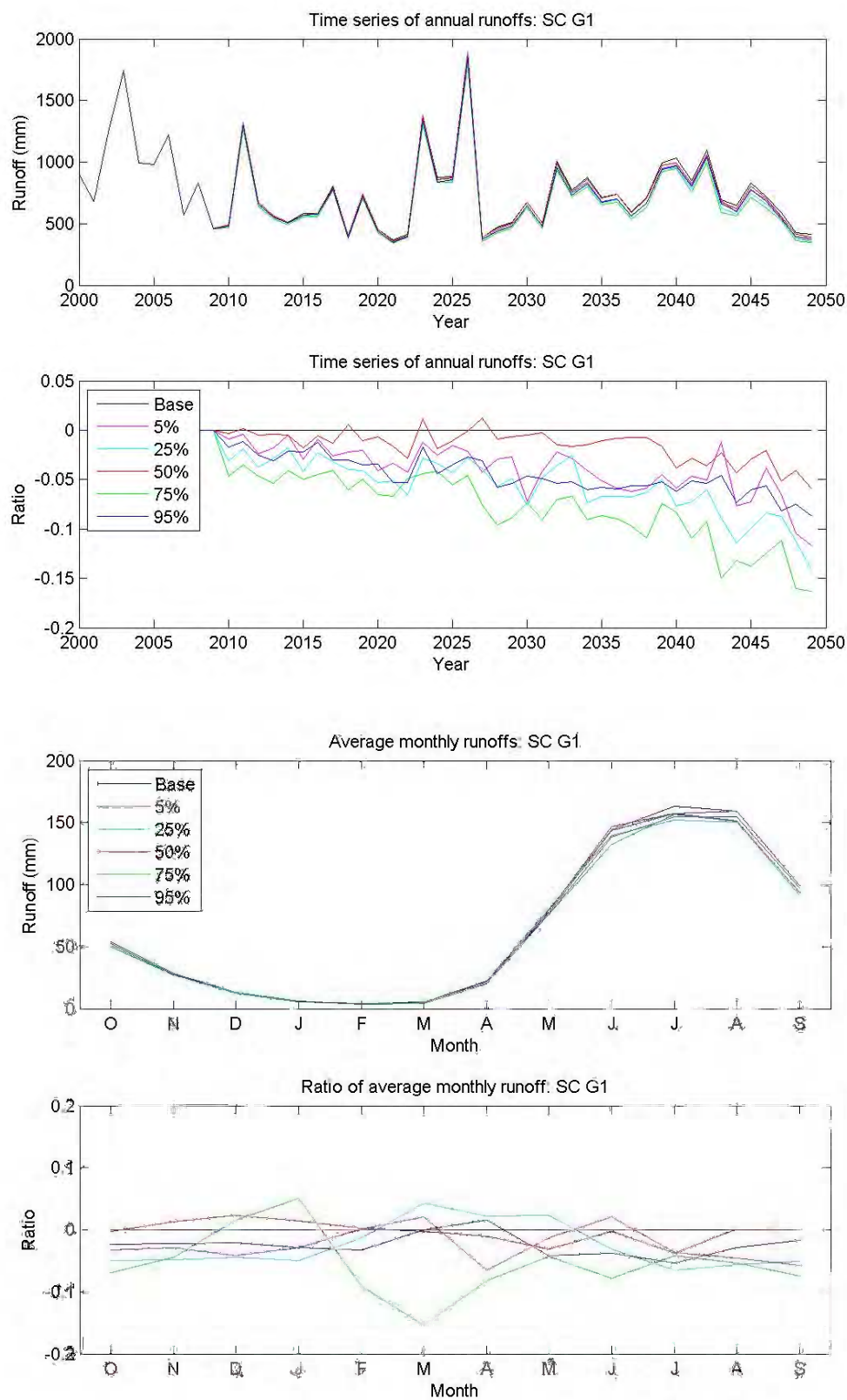
Figure 21: Catchment G1: The Berg River. Impact of the UCE scenarios on the time series of average annual flow up to 2050 (Top) and the average monthly flows for the period 2040 to 2050

Source: Authors' compilation, see this study.
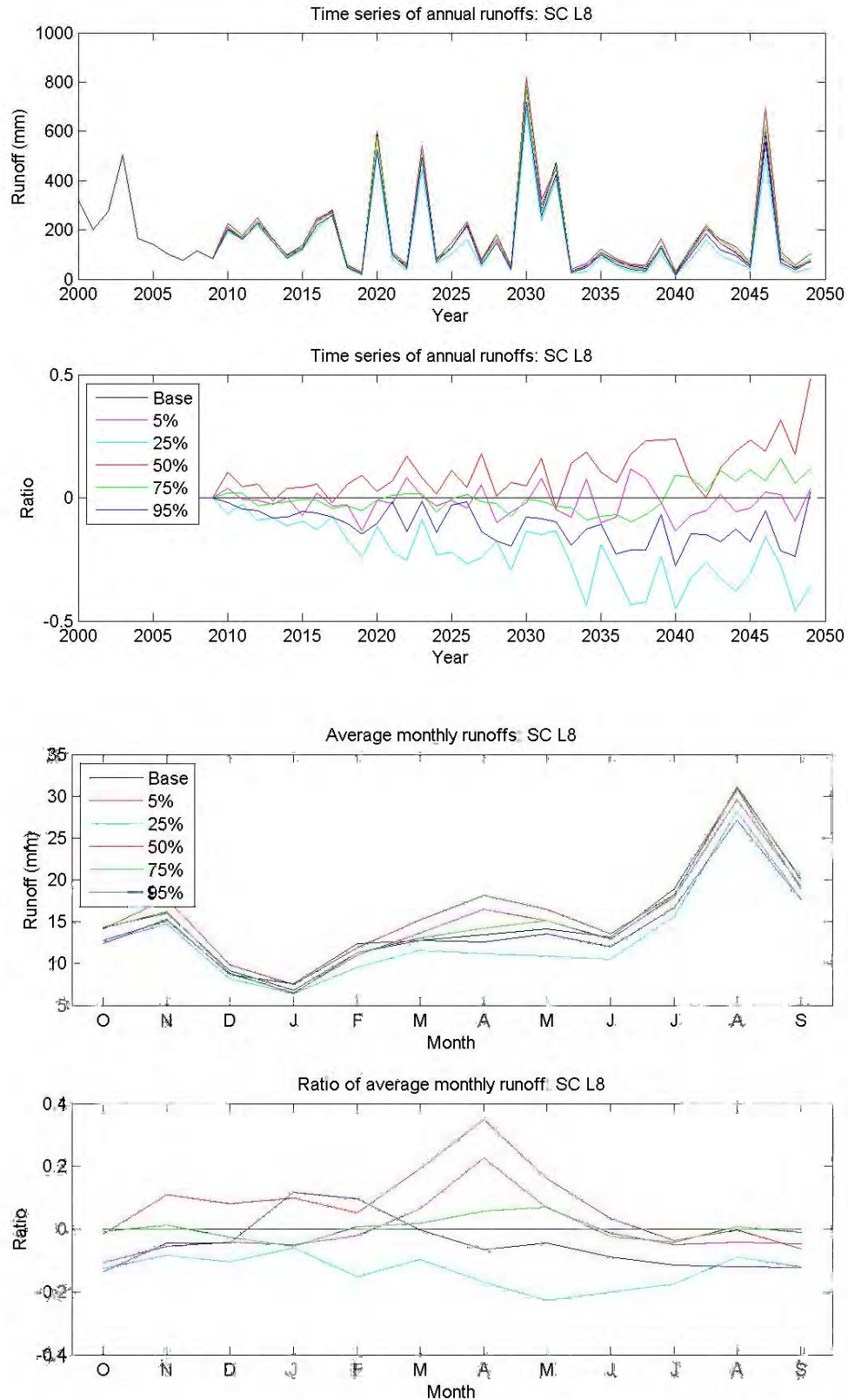
Figure 22: Catchment L8: The Koega River. Impact of the UCE scenarios on the time series of average annual flow up to 2050 (Top) and the average monthly flows for the period 2040 to 2050

Source: Authors' compilation, see this study.
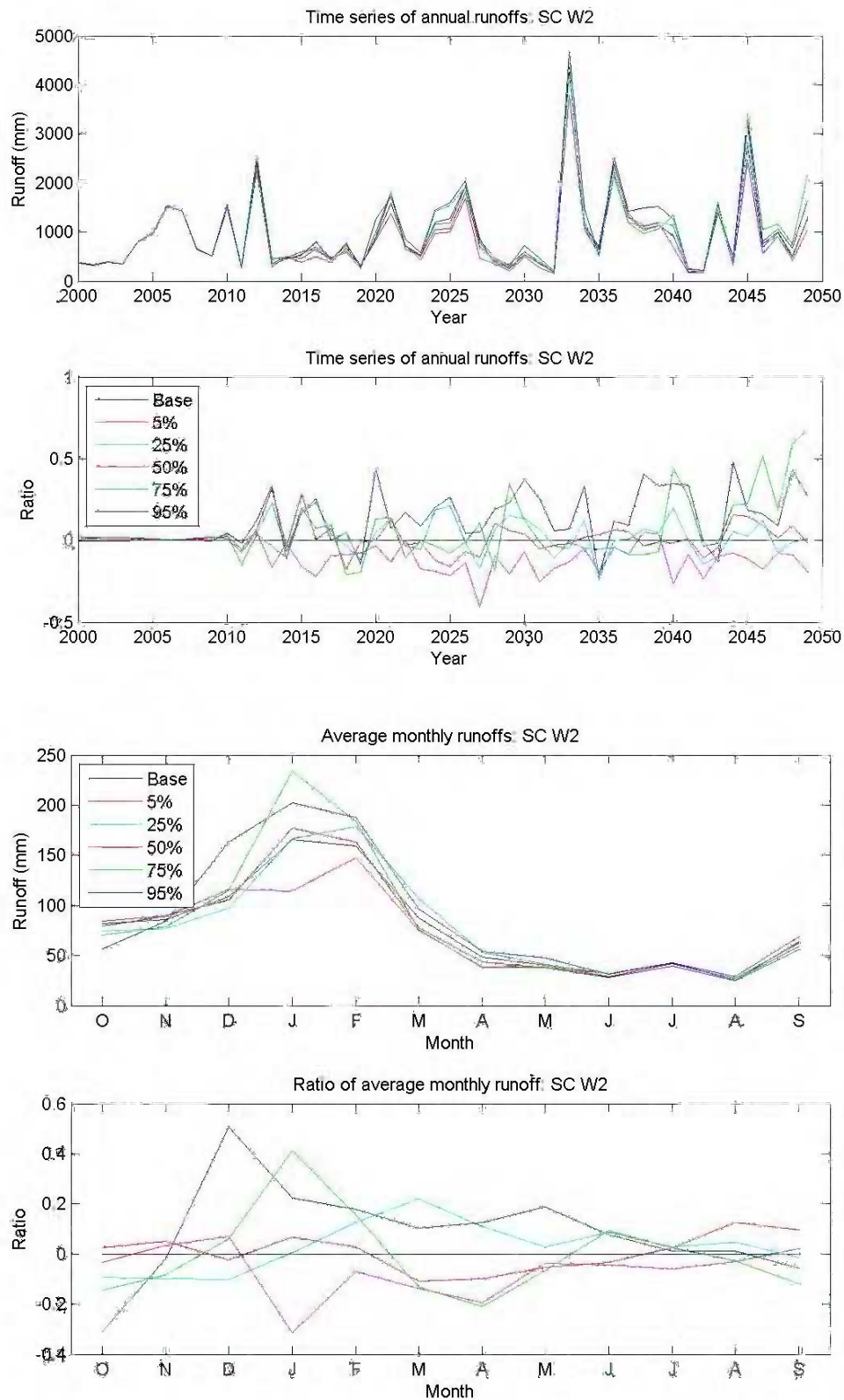
Figure 23: Catchment W2: The Mfolozi River. Impact of the UCE scenarios on the time series of average annual flow up to 2050 (Top) and the average monthly flows for the period 2040 to 2050

Source: Authors' compilation, see this study.
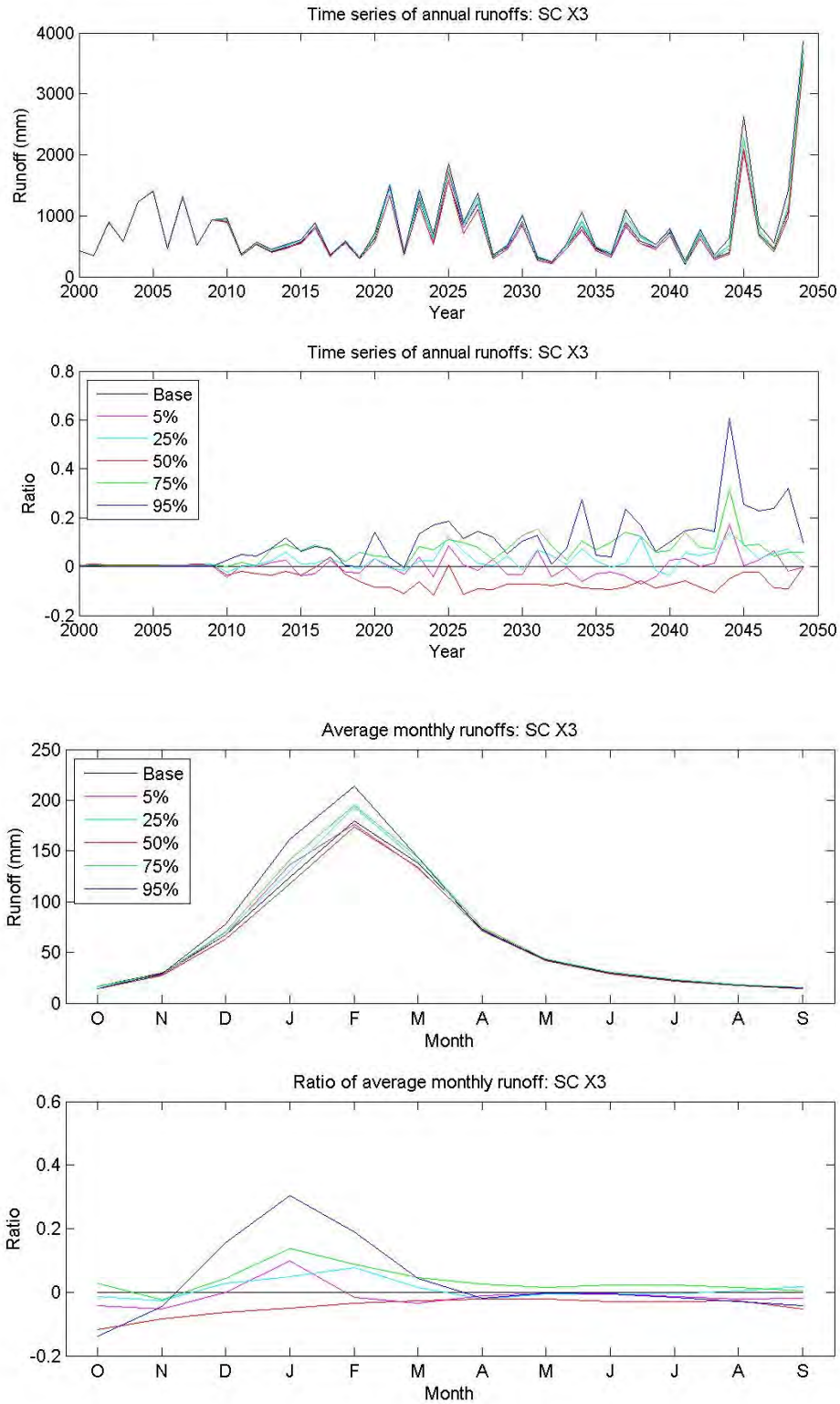
Figure 24: Catchment X3: The Sabie River. Impact of the UCE scenarios on the time series of average annual flow up to 2050 (Top) and the average monthly flows for the period 2040 to 2050

Source: Authors' compilation, see this study.

## 3.5   Conclusions

The results of the analysis of the potential impact of the HFD climate change scenarios suggests that in general there could will be a slight increase in total catchment runoff for South Africa, but that there is significant spatial and temporal variation. There is also still a wide range of possible impacts with some models showing overall reductions of up to 13% and other showing an increase of 48% in the average annual total catchment runoff for the country by 2050 under the UCE scenario. The risks of both increased runoff (floods) and reduced runoff (droughts) is reduced under the L1S scenario.

In general there is likely to be an increase in catchment runoff in the eastern part of the country, particularly during the early part of the wet season (January), and a reduction in the west and south-west. While the potential benefits of increased runoff could include increased availability of supply, it is likely to also be accompanied by an increase in the potential flooding risk.

All the models show drying over the south-western Cape including the Berg River catchment which is a critical water supply source for the City of Cape Town and some high value export agriculture.

4   Irrigation demand and crop yields

4.1   Introduction

The purpose of this section is to present the results for the modelling of irrigation demands and dryland crop yields as a component of the integrated modelling framework shown in Figure25 for assessing the potential impacts of climate change on the national economy of South Africa. The current analysis is based on the outputs for the HFD set of global climate models for the UCE and L1S scenarios (Schlosser 2012). Future analysis will consider the potential impacts of a range of downscaled South African regional climate models.

In this section we look at the potential direct impacts of climate change, principally changes in precipitation and evaporation, on irrigation demand, and the yields from rain fed agriculture. We do not consider other impacts of climate change on crop yields such as increased CO_2 fertilization, or changes in heat and chill units. We also do not consider the indirect impacts of climate change through for example potential increases in pest and diseases. We also do not consider impacts on other agricultural sectors including livestock farming, meat production, or forestry.
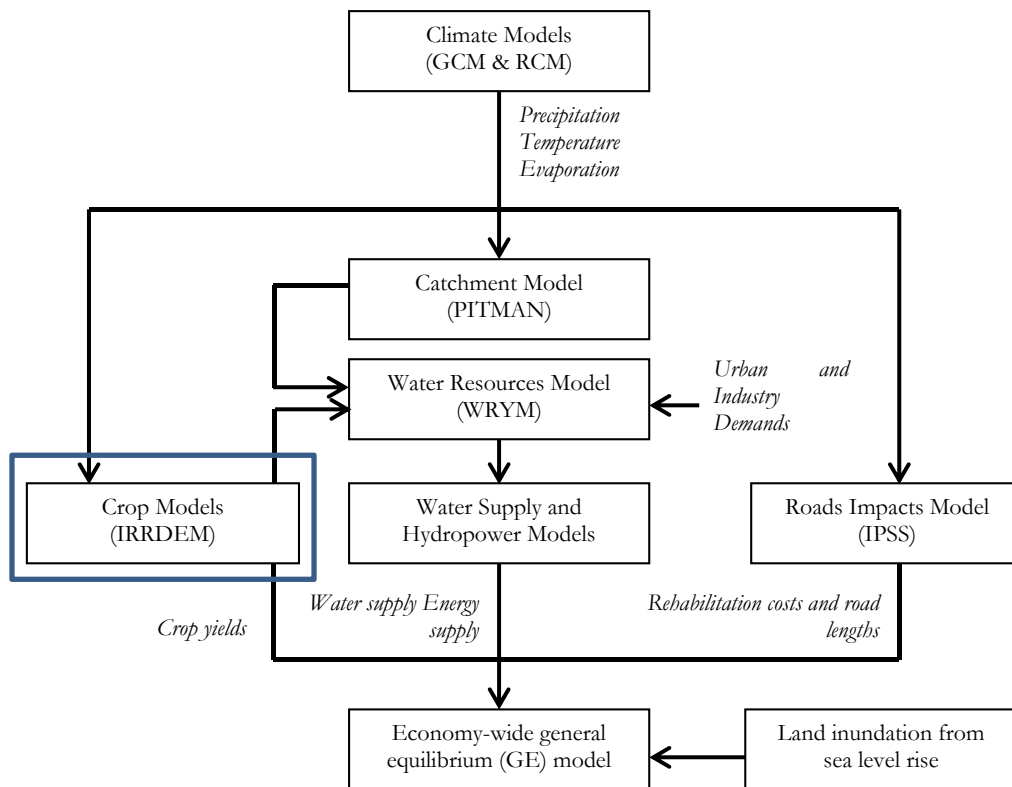
Figure 25: Integrated modelling framework highlighting crop modelling component

Source: Authors' compilation, see this study.

4.2   Background

Although only contributing about 3% to the national Gross Domestic Project (GDP) and 7% of total employment, the agricultural sector has many knock on effects in the economy and is considered a critical sector in terms of future economic growth, job creation and national food security. Agriculture also currently utilizes about 60% of the available water resources of South Africa.

South Africa is a semi-arid country with only 14% of the land considered to be arable with one-fifth of this land having high agricultural potential. At least half of the country receives less than 500 mm of rainfall a year which is considered to be a threshold for viable agricultural activities. The potential for future expansion in agriculture is limited as the majority of the arable land in the country is already cultivated either through large-scale commercial farming or small-scale subsistence farming (Figure 26). In addition there are only a few areas where there is surplus water to support increases in irrigation. In other areas of the country increases in the demand for water from other sectors such as mining and urban consumption could see a reduction in the allocation of water to agriculture.
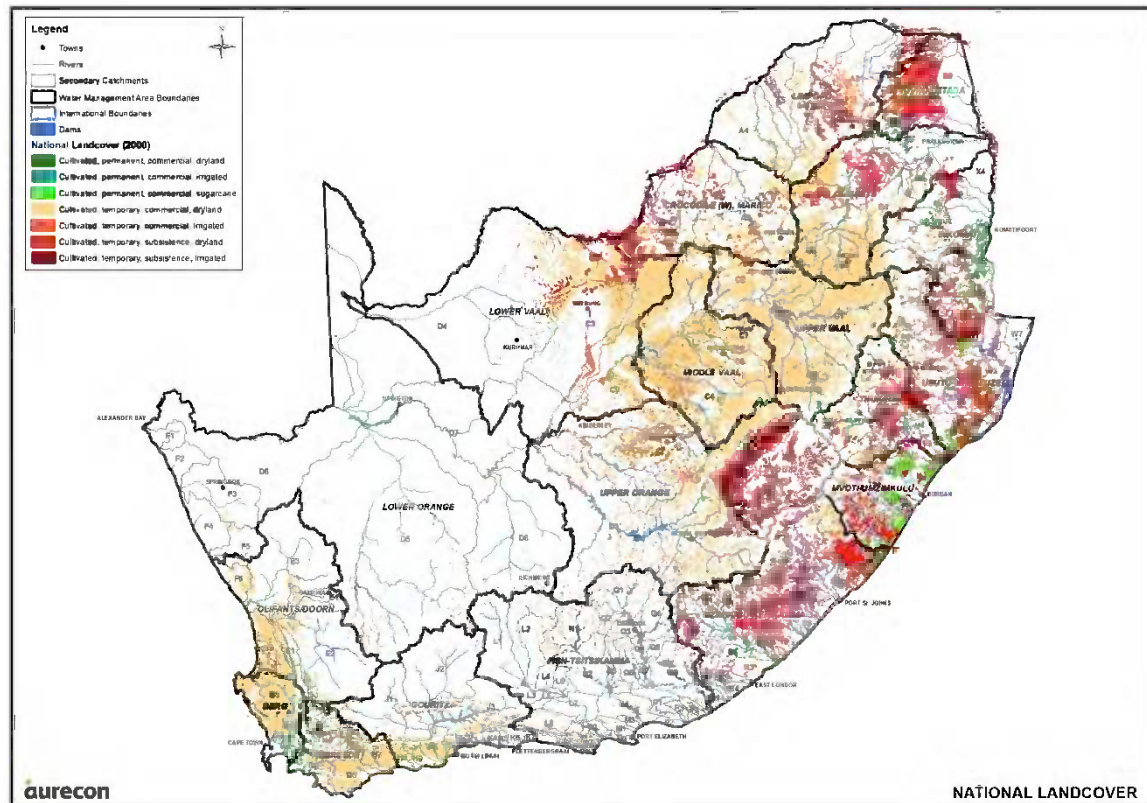
Figure 26: Map of currently cultivated areas in South Africa

Source: Authors' compilation, see this study.

The agricultural sector is considered to be one of the most critical sectors in terms of potential impacts of climate change (DEA 2011; Schulze 2010). Agriculture is impacted directly be changes in precipitation, temperature, and evaporation. The impact of climate change, however, could be different for different crop types. This is due either to differences in the response of different crop types to changes in climatic variables, but also differences in the spatial impacts of climate change relative to where the different crops are currently grown or will be grown in the future.

Rainfed agriculture is particularly sensitive to climate variability. For example an analysis of the sensitivity of agriculture production to historical changes in climate in South Africa (Blignaut 2009) found that a 1% decline in rainfall resulted in a decline in maize production of 1.16% and a decline in wheat production of 0.5%. While some crops may suffer from a reduction in precipitation, other crops such as sugarcane may benefit from both an increase in precipitation and an increase in temperature (Schulze 2010). In all cases it is anticipated that future increases in temperature and evaporation will results in an increase in the irrigation demands across the country. Climate change is thought to also have an indirect impact on crop production through impacts on pest and diseases (Schulze 2012).

4.3   Methodology

Irrigation demand model

A time series of monthly volumetric irrigation demand was calculated for each crop type in each quaternary catchment for the base scenario and each of the various climate change scenarios. These crop demands were summated to obtain the total irrigation demand for the quaternary catchments, and then aggregated to secondary catchment scale for input into the water resources yield model.

The monthly irrigation demand (V) for each crop was determined using a simple crop water deficit model currently used for water resources planning studies in South Africa (Pitman et al 2006):

$$V = 0.001 \times A \times \max(Apan \times Cropf - P \times Reff, 0) \times \frac{1}{Ieff}$$

where V   =   monthly volumetric irrigation demand (Mm^3)

A   =   Area under irrigation (km^2)

Apan   =   Mean monthly A-pan evaporation for each calendar month (mm)

Cropf   =   Crop factor for each calendar month and crop type

P   =   Actual rainfall for the month (mm)

Reff   =   Effective rainfall factors for each calendar month (assumed 0.6)

Ieff   =   Irrigation efficiency factor (assumed 0.8)

Crop mix and total irrigated area

The irrigated area for each quaternary catchment in South Africa was obtained from the database for the Water Situation Assessment Model (WSAM). An analysis of the estimated irrigation demand using these areas was found to provide the closest match to the irrigation demand estimates in the NWRS (DWA 2004).The proportional crop mix was obtained from the Commercial Census of Agriculture (CCA) for 2002 as this is the bases of the economic model to be used (Thurlow 2008). This provides estimates of the crop areas and crop yields for a full range of both dryland and irrigated crops. The proportion of each crop types was then spatially disaggregated from municipal areas to quaternary catchments to given an estimate of the proportion of irrigated area under each crop type.

There is a high level of uncertainty about the exact area of irrigated crops across South Africa. Alternative areas of irrigated agriculture that were considered included the actual areas given in the CCA, rather than the proportional crop mix, the total irrigated areas contained in the database for the WR2005 model and the actual irrigation demands given in Thurlow (2008). As mentioned above, the results for the areas used in this study (labelled as WSAM in Figure27) resulted in the closest match to the estimated irrigation demand for each WMA in the NWRS (DWA 2004).
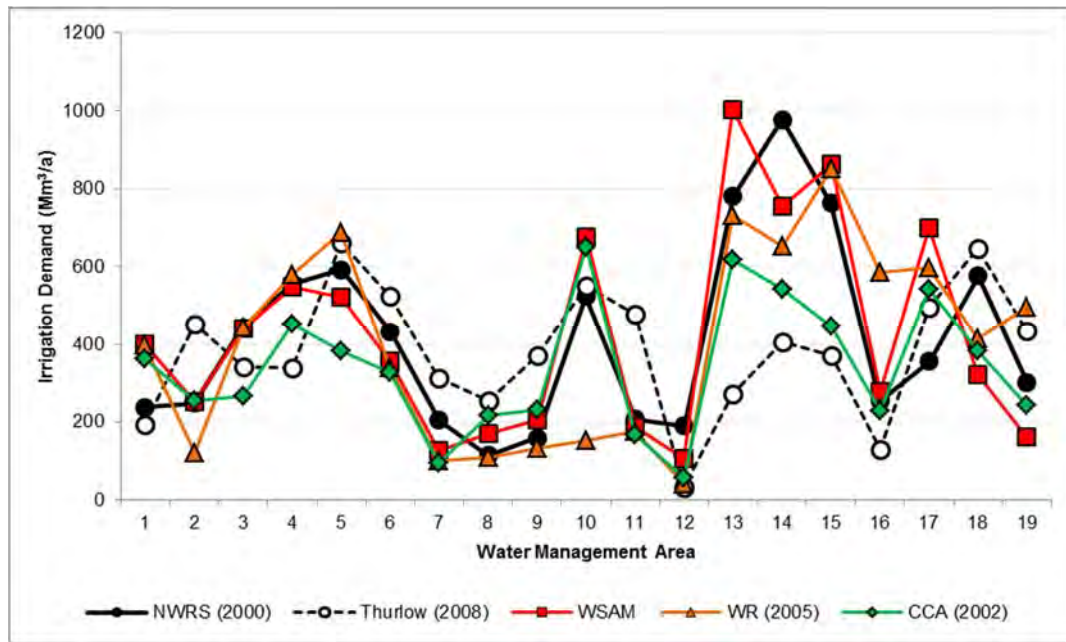
Figure 27: Comparison of the average annual irrigation demand for each WMA from the NWRS and Thurlow (2008) with the outputs from the irrigation demand model used in this study based on the total irrigated areas provided in the WSAM model, the WR2005 model and the Commercial Census of Agriculture (CCA)

Source: Authors' compilation, see this study.

Monthly evaporation and precipitation

Each quaternary catchment in South Africa is located within a specified evaporation zone as defined in WR90 and WR2005. Monthly S-pan evaporation values were determined from the monthly evaporation values as a percentage of MAE for each evaporation zone. The S-pan values for evaporation can then be converted to monthly A-pan values required for the irrigation demand model using the following equation (Bosman 1990):

$$Apan = 26.3622 + 1.0786 \times Span$$

where Span = Mean monthly S-pan evaporation for each calendar month (mm)

Similarly, each quaternary catchment is located within a rainfall zone. Monthly rainfall for each quaternary catchment was determined from the mean annual precipitation (MAP) and time series of monthly rainfall as a percentage of MAP obtained from the WR2005 study. The effective rainfall factor varies between catchments depending on the nature and timing of the rainfall, but for this study it was assumed constant at 0.6 for all catchments.

Monthly crop factors for irrigation demand

The monthly crop factors (Cropf) used in this study are based on those given inWR90 (Midgley et al. 1994). These are fairly general and based on an assumed initial planting date and monthly crop water demand during a typical annual growth cycle. The final crop factors used are given in Table 2.

Several assumptions were made with regards to specific crops where there was either no crop factor defined or a composite crop factor was required as only composite crop areas were reported:

- Maize, sorghum, and other summer cereals were grouped into a summer cereals crop category with crop factors composed of combined early and late maize crop factors;
- Wheat, barley, and other winter cereals were grouped into a winter cereals crop category with assigned monthly crop factors for winter wheat.
- Where no crop factors were available for a certain crop, it was assigned the same or similar crop factors as a crop within the same class, e.g. it was assumed that pineapples have the same crop factors as other subtropical fruit such as avocadoes and mangoes.

Table 2: Crop factors used to determine the monthly irrigation demands in each quaternary catchment.

Crop type	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Summer cereals	0.5	0.9	0.65	0.88	0.71	0.95	0.25	0	0	0	0	0
Winter cereals	1	0.65	0	0	0	0	0	0	0	0.3	0.5	0.95
Sunflower	0.4	0.5	0.6	0.65	0.73	0.8	0.8	0	0	0	0	0
Groundnut	0.15	0.5	0.65	0.55	0.5	0.25	0	0	0	0	0	0
Soya bean	0	0	0.33	0.73	0.93	0.95	0.43	0	0	0	0	0
Oil other	0.18	0.33	0.53	0.64	0.72	0.67	0.41	0	0	0	0	0
Legume	0.65	0.47	0	0.15	0.5	0.7	0	0	0	0	0	0.35
Fodder	0.7	0.8	0.8	0.8	0.8	0.75	0.6	0.5	0.4	0.4	0.45	0.55
Sugarcane	0.81	0.81	0.81	0.79	0.8	0.88	0.95	0.98	0.94	0.89	0.85	0.82
Cotton	0	0.18	0.29	0.69	0.82	0.62	0.31	0	0	0	0	0
Tobacco	0	0.3	0.74	0.9	0.4	0	0	0	0	0	0	0
Field other	0	0.24	0.52	0.8	0.61	0.31	0.16	0	0	0	0	0
Potato	0	0	0	0.29	0.69	0.99	1	0	0	0	0	0
Tomato	0	0.3	0.4	0.7	0.7	0.7	0	0	0	0	0	0
Cauliflower	0.68	0.7	0	0	0	0.2	0.58	0.7	0.7	0.12	0	0.48
Cabbage	0.68	0.7	0	0	0	0.2	0.58	0.7	0.7	0.12	0	0.48
Onion	0	0	0	0	0.3	0.37	0.47	0.6	0.7	0.7	0.47	0
Beetroot	0	0	0	0.29	0.69	0.99	1	0	0	0	0	0
Carrot	0	0	0	0.29	0.69	0.99	1	0	0	0	0	0
Sweet potato	0	0	0	0.29	0.69	0.99	1	0	0	0	0	0
Green bean	0.65	0.47	0	0.15	0.5	0.7	0	0	0	0	0	0.35
Pumpkin	0.51	0.68	0.47	0	0	0	0	0	0	0	0	0.33
Green pea	0.65	0.47	0	0.15	0.5	0.7	0	0	0	0	0	0.35

Horticulture other	0.29	0.3	0.08	0.2	0.43	0.62	0.51	0.18	0.19	0.09	0.04	0.18
Citrus	0.45	0.45	0.5	0.55	0.6	0.65	0.7	0.65	0.6	0.45	0.45	0.45
Pineapple	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Avocado	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Banana	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Mango	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Paw paw	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Subtropical other	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Deciduous	0.27	0.31	0.41	0.5	0.59	0.42	0.2	0.2	0.2	0.2	0.2	0.23
Table grape	0.15	0.2	0.3	0.4	0.35	0.25	0.2	0.1	0.1	0.1	0.1	0.1
Wine grape	0.23	0.38	0.38	0.38	0.38	0.3	0.2	0.2	0.2	0.2	0.2	0.2
Macadamia	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Pecan	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.35	0.35	0.35	0.65	0.65
Nuts other	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.5	0.5	0.5	0.65	0.65
Tea	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85

Source: Authors' compilation, see this study.

Effective rainfall and irrigation efficiency factors

Effective rainfall refers to rainfall which is useful for meeting crop water requirements, and excludes water percolating below the root zone of the crop, and surface runoff. A conservative effective rainfall factor of 0.6 was used for all crop types in the quaternary catchments.

Irrigation efficiency factors account for the additional irrigation water needed to cater for inefficiencies caused by delivery and field losses. An irrigation efficiency factor of 0.8 was assumed for all catchments in this study. The irrigation efficiency will vary significantly between different irrigation practices available for different crop types. This is also an area in which substantial improvements in the efficiency of water use in agriculture can be made to offset any potential impacts of climate change on increased irrigation demands in a given area and the impact of improved irrigation efficiency can be investigated using this model in future studies.

Irrigation demands supplied from groundwater

The objective of this study was to determine the irrigation demands as an input to the water resources yield model. As the yield model considers surface water supply only, the irrigation demand in each catchment was reduced by an estimate of the amount of demand that is currently met through groundwater. No consideration was given to the potential impacts of climate change on groundwater yields and this is an area where further research is required given that a possible adaptation option is to consider increased groundwater use. Current estimates of the groundwater supply to agriculture in each quaternary catchment were obtained from the GRAII database (DWA 2004).

Yields from dryland crops

Thurlow (2008) developed a water and agriculture-focused social accounting matrix (SAM) which disaggregates agriculture into different crops, livestock, and other sectors, identifies monetary flows for irrigation, industrial and domestic uses, and disaggregates sectors, factor markets, and households across South Africa's nineteen WMAs. Using data obtained from the Agricultural Research Council (ARC) Thurlow identified empirical relationships between water supply and crop yields for both irrigated and dryland agriculture according to 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)

      $\beta_{0i}, \beta_{1i}, \beta_{2i}$: Empirically derived coefficients for crop type *i*.
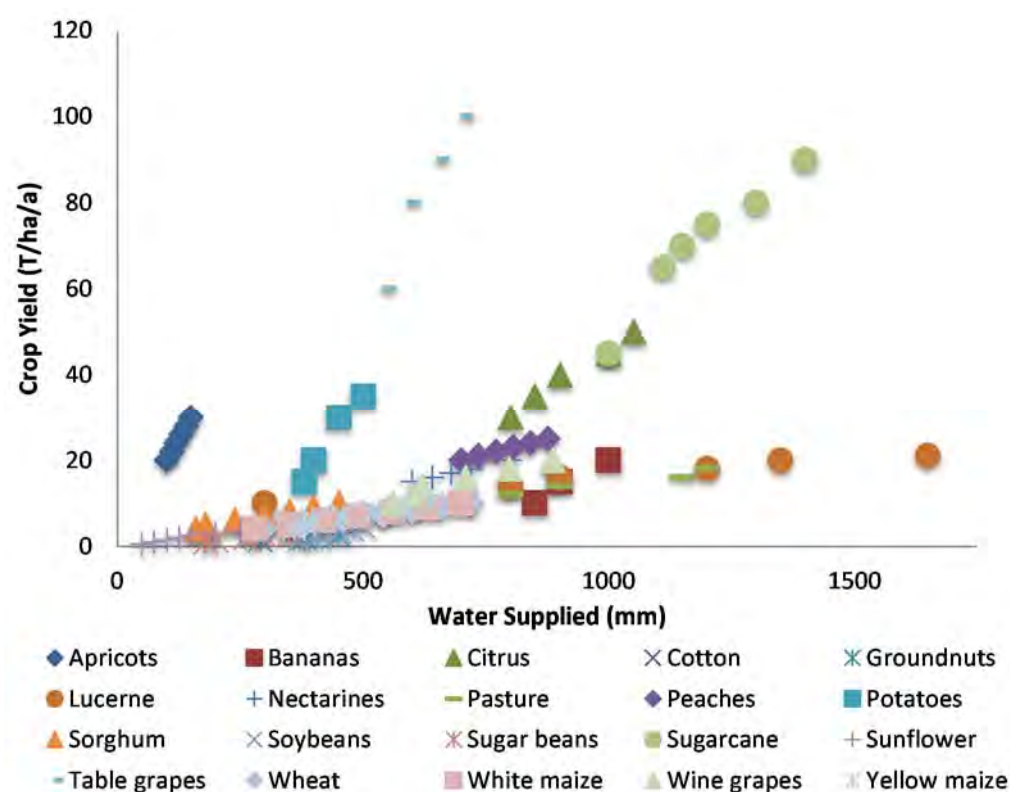
Figure 28: Empirical relationships between water supply and crop yields

Soure: Adaption of Thurlow (2008).

These empirical relationships were used to estimate the potential impacts of climate change, primarily the impact of changes in rainfall, on a selection of dryland crops for which data was available on both crop areas disaggregated to quaternary catchment scale for the whole country and water supply yield coefficients given in
Table 3.

Table 3: Crop water production function coefficients for selected dryland crops (Thurlow 2008)

Crop type	β_0	β_1	β_2
Maize	-10 783	54.8	-0.0352
Sorghum	912	21.6	-0.0034
Wheat	1 564	5.7	0.0083
Sunflower	-824	28.0	-0.0429
Groundnuts*	9 821	-1.1	0.01
Soybeans	-12 625	48.7	-0.0288
Lucerne	6 130	12.6	-0.0022
Sugarcane	-350 688	608.3	-0.2113
Cotton	-10 783	54.8	-0.0352

Note: * Not indicated in Thurlow (2008) but derived in the same manner from the data provided.

Souce: Based on Thurlow (2008).

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 rainfed, or 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 L1S scenario. Results

4.4   Impacts on 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 below. Under all scenarios irrigation demand is likely to increase in the future due to increases in temperature and evaporation. The UCE scenario results in a very wide spread of possible impacts with some models showing more than 12% increase in the total annual average irrigation demand. The median increase for the UCE scenario is approximately 6.3%.

Irrigation demands are reduced under the L1S scenario with the median impact being only an increase of around 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 around 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 the overall water demand.
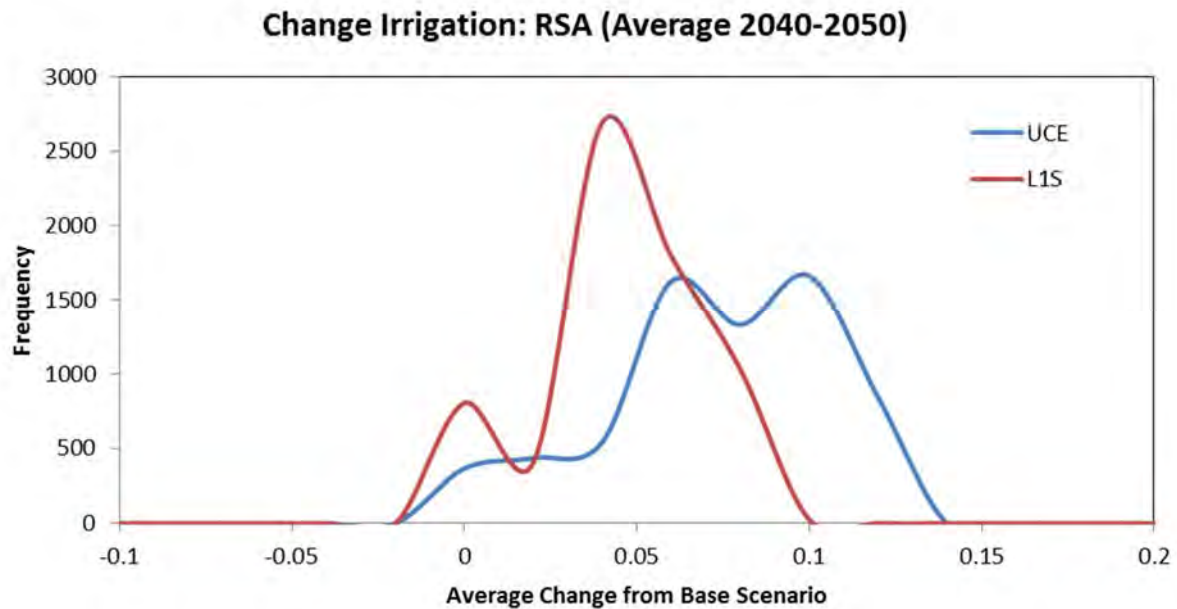
Figure 29: Hybrid frequency distributions of the impacts of the UCE and L1S global climate scenarios on the average annual irrigation demands for all catchments for the period 2040-50 relative to the base scenario based on the current crop mix and estimate of total irrigated area in each quaternary catchment

Source: Authors' compilation, see this study.

The impacts of climate change on irrigation demand do vary across the country as shown in Figure 30, 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) 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.
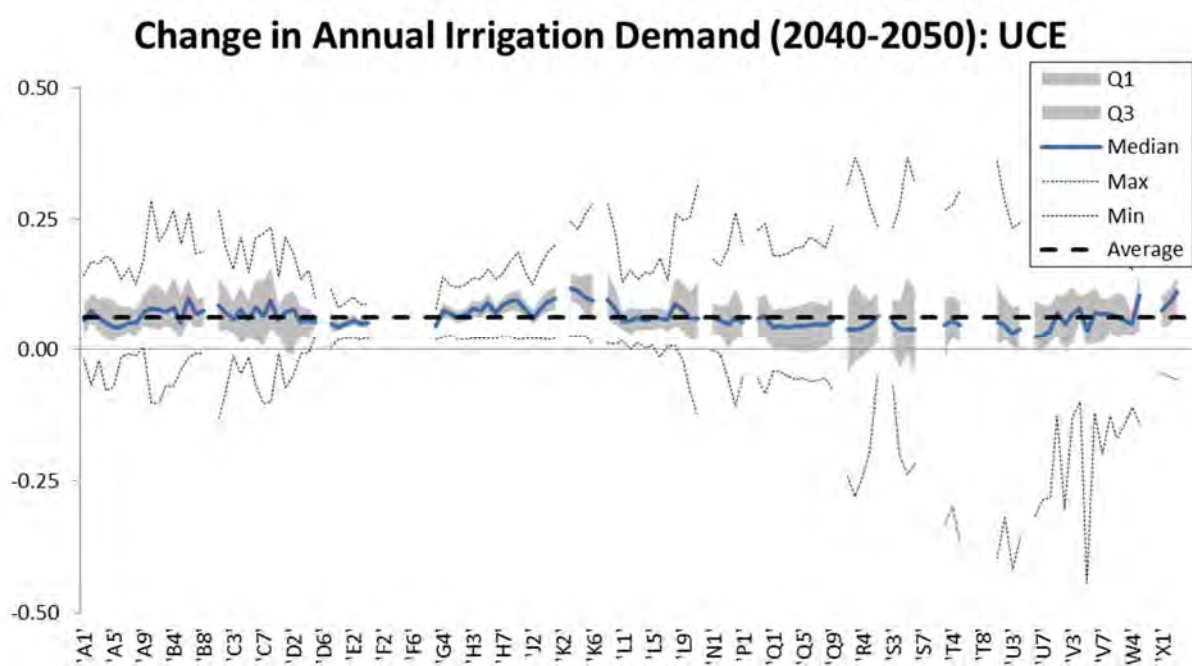
Figure 30: Range of potential impacts of climate change on the average annual irrigation demand for all secondary catchments for the period 2040 to 2050 due to the UCE scenario relative to the base scenario. Missing data points indicate secondary catchments in which there is currently no significant irrigated agriculture

Source: Authors' compilation, see this study.

4.5 Impacts on dryland crop yields

The impact of the potential climate futures developed from the HFD model for the UCE and L1S scenario are determined for the current distribution of nine major rain fed crop types. These include maize, sorghum, wheat, sunflowers, groundnuts, soybean, lucern, sugarcane, and cotton. The frequency distributions of the potential impacts on the yield from these crops are given in Figure 1. The results show a very wide range of possible impacts on the average annual yield of dryland crops by 2050 under the UCE scenario. Most concerning, however, 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 UCE scenario is, however, a reduction of around 3.5% and only a slightly less reduced impact of 3% on total maize yields under the L1S scenario by 2050.

Although maize is grown across most of South Africa, the greatest impact of future climate change appears to be in the catchments in the northern and central parts of the country. These are catchments A, B, and C in Figure 2. These are also the main maize growing areas of the country.

The potential impacts on the yield of wheat is similar with the median impact for the UCE scenario being a decrease of 4.3% and the median impact for the L1S scenario being a decrease of 1.8% with a much narrower range of potential impacts. Under the UCE scenario the greatest impact is on the Western Cape catchments. These are catchments G and H in Figure 2. These are also the main wheat growing areas of the country. Under the L1S scenario these catchments show an increase in the total wheat yield as a result of the simulated increases in precipitation under this scenario.
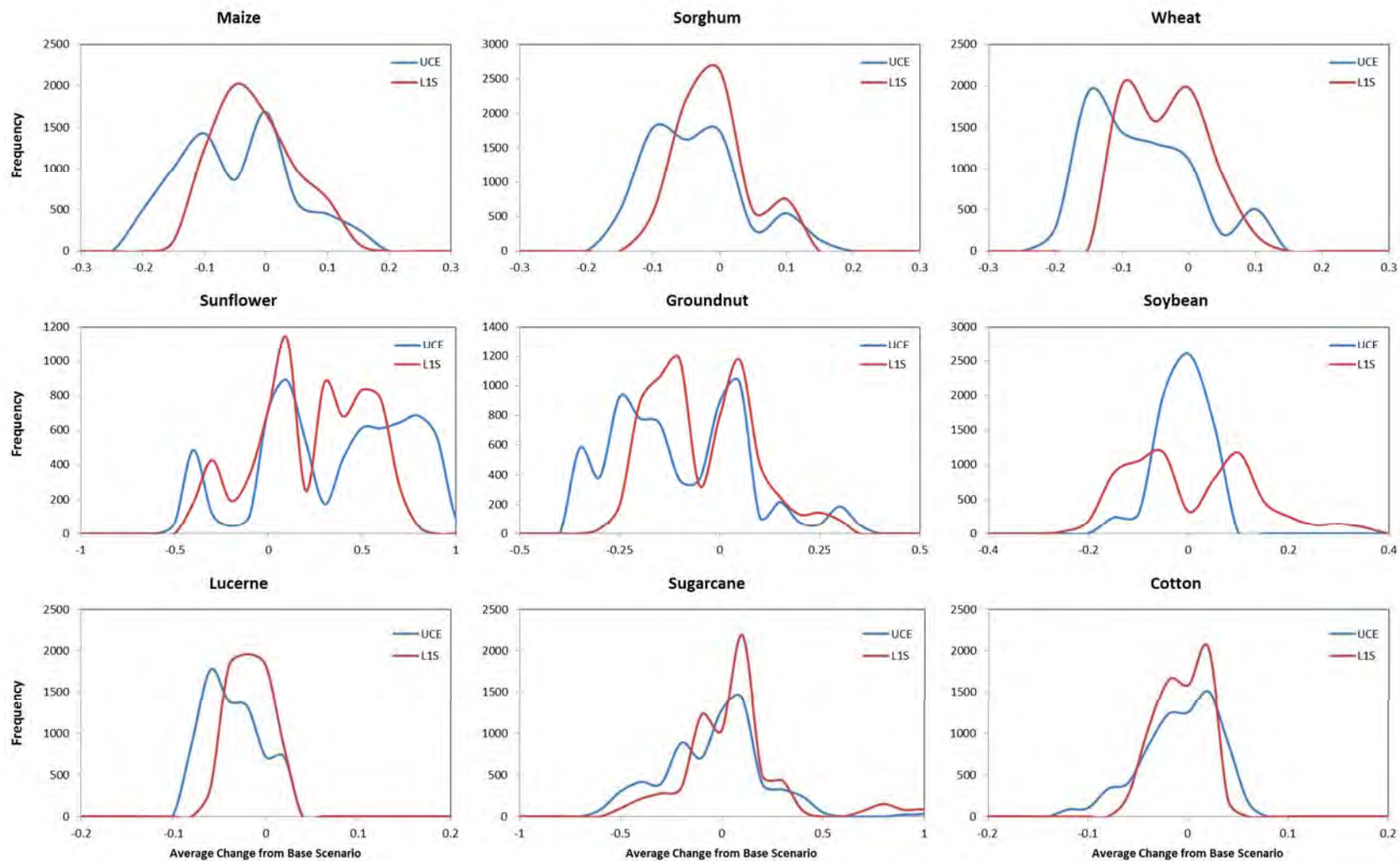
Figure 31: Combined impact of changes in precipitation and evaporation on dryland crop yields for South Africa for the period 2040-50 relative to the baseline scenario

Source: Authors' compilation, see this study.
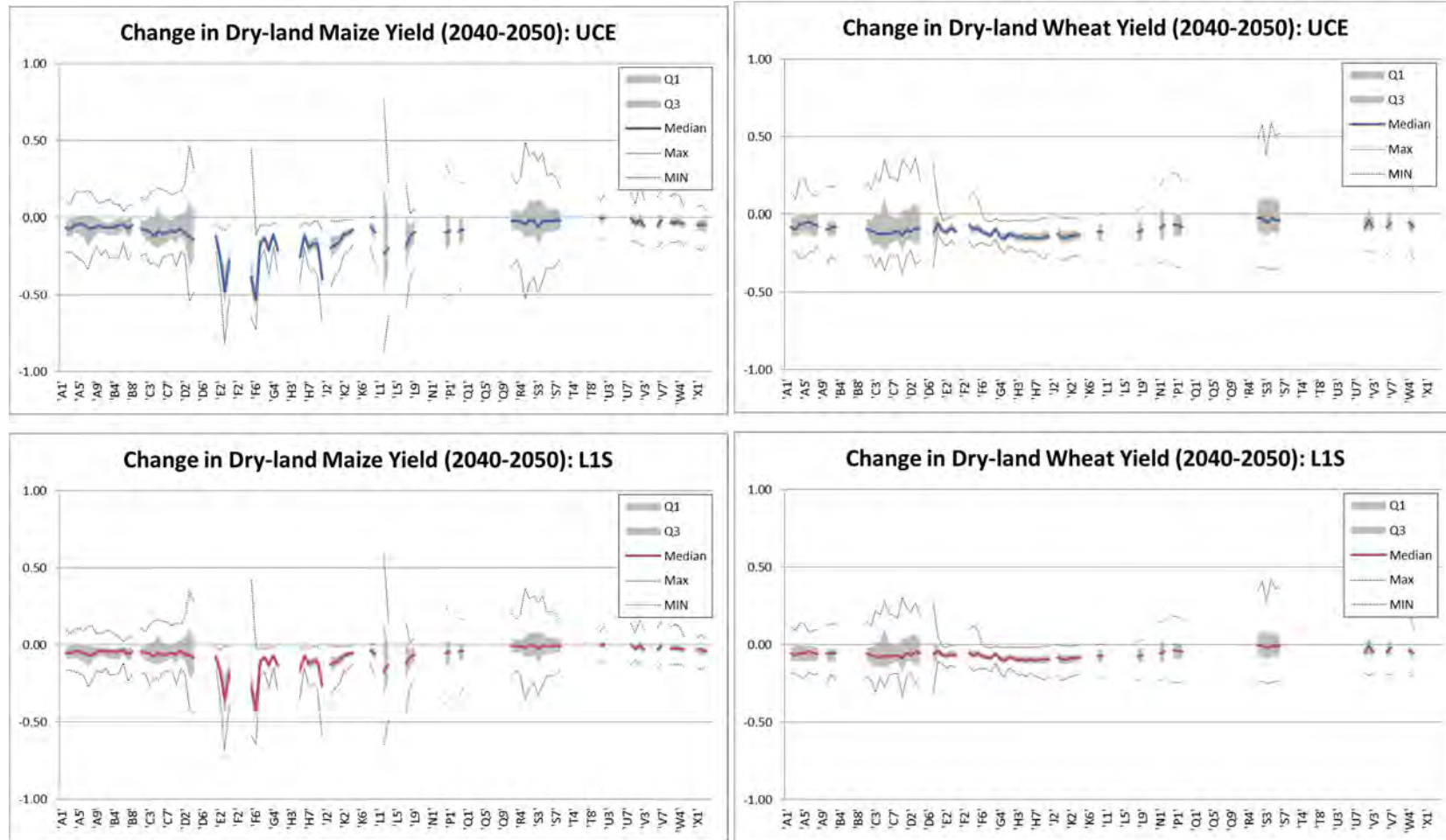
Figure 32: Median impact and the range of potential impacts of climate change on the average annual dryland crop yield for maize (left) and wheat (right) for all secondary catchments across South Africa for the period 2040 to 2050 due to the UCE and L1S climate scenarios relative to the base scenario

Source: Authors' compilation, see this study.

4.6   Conclusions and recommendations

Increased temperature and associated increases in PET are likely to result in increases in irrigation demand across the country. These impacts are consistently around a 6% increase in the average annual irrigation demand under the UCE scenario and a 3% increase under the L1S scenario. Given that agriculture already accounts for more than 60% of the water requirements in South Africa, this increase is likely to result in added pressure on existing water resources or results in reduced assurance of supply and yields from irrigated agriculture if this additional demand cannot be met.

The results of modelling the potential impacts of the HFD climate scenarios on the yield from major dryland crops shows quite a wide range of potential impacts, as well as significant differences between the UCE and L1S scenarios. Often the differences between the UCE and L1S scenario are not significant in terms of the median impact, but rather are more significant in terms of the range of potential outcomes as well as regional variations in the impacts that may or may not coincide with where the crops are grown. Most concerning is the potential for significant declines in the dryland yield for staple crops such as wheat and maize, particularly under the UCE climate scenario.

The results show a slight reduction in the yields for maize and wheat. The median impact for both crops, however, is less than about 5%. While this will have an impact on the agricultural sector it is most likely that this impact can be reduced through improved agricultural practices and the development of more resistant and high yielding crop varieties. Some climate scenarios, however, suggest the potential for up to 25% reduction in the dryland yield for maize and up to 20% reduction for wheat. Mitigation (i.e. the impacts of the L1S scenario) could significantly reduce the risk of these potential large impacts on dryland yield, but still results in a genera reduction in yields.

It is important to note that the crop yield model used on this study is based primarily on empirically observed relationships between annual water supply (precipitation) and average annual crop yields. This type of model was used given the limited timeframe and broad scope of the study. More sophisticated models do exist for determining the potential impacts of climate change on crop yields and these could be incorporated into the modelling framework for future analysis. In addition more fine-scale modelling of regional variations in crop yields could be considered based on soil type etc.

There have also been significant advances in improving the yields from most crop types around the world due to advances in farming practices including improved tillage and irrigation efficiency as well as new crop varieties. These improvements could off-set the potential negative impacts of climate change. There is, however, an opportunity cost as without climate change impacts these improvements in crop yield would translate directly into increased food security, but under a dryer climate future they are necessary just to keep yields consistent with current levels of demand.

5   Water supply and hydropower

5.1   Introduction

The purpose of this section is to provide a detailed description of the methodology and results of the water resources modelling component of the integrated modelling framework shown in Figure 3. The objective of this component was to assess the potential regional impacts of global climate

change on water availability, water supply, and hydropower generation potential in South Africa and consisted of two main aspects, namely:

- The development of a *national water resources model* to provide a modelling platform for assessing climate change impacts based on a selected combination of climate change scenarios, water requirement projections, water resources infrastructure developments and system operating rules.
- Application of the above to model projected water supply to the urban, industrial, and agricultural sectors for each of the 19 WMAs in South Africa under multiple climate scenarios. These results will be incorporated into the economic model, to assess the potential impacts of climate change on the national economy of South Africa.
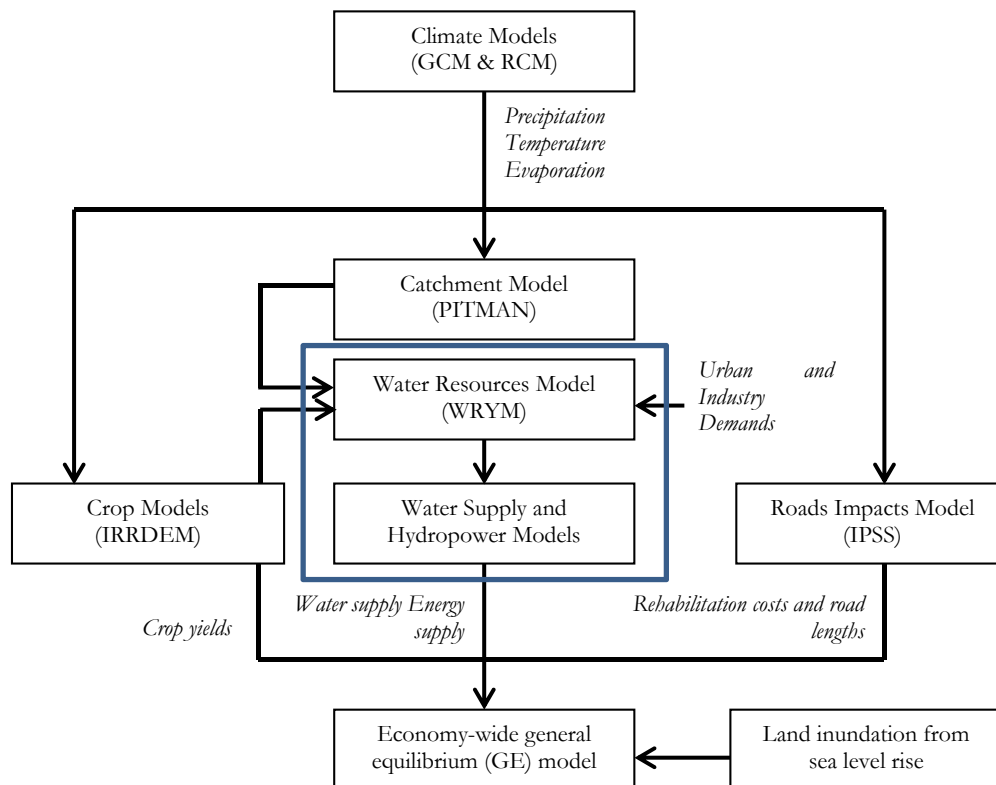
Figure 33: Water resources modelling within the integrated modelling framework

Source: Authors' compilation, see this study.

5.2   Background

South Africa is a dry country with an average annual precipitation less than the global average. Water resources are already under pressure and due to increasing demands and natural variability in supply (Figure). A reliable water supply, however, is critical to future livelihoods and economic growth and development. Most options for future supply also require a number of years of development and review before they can be implemented. In this respect long term planning is essential.
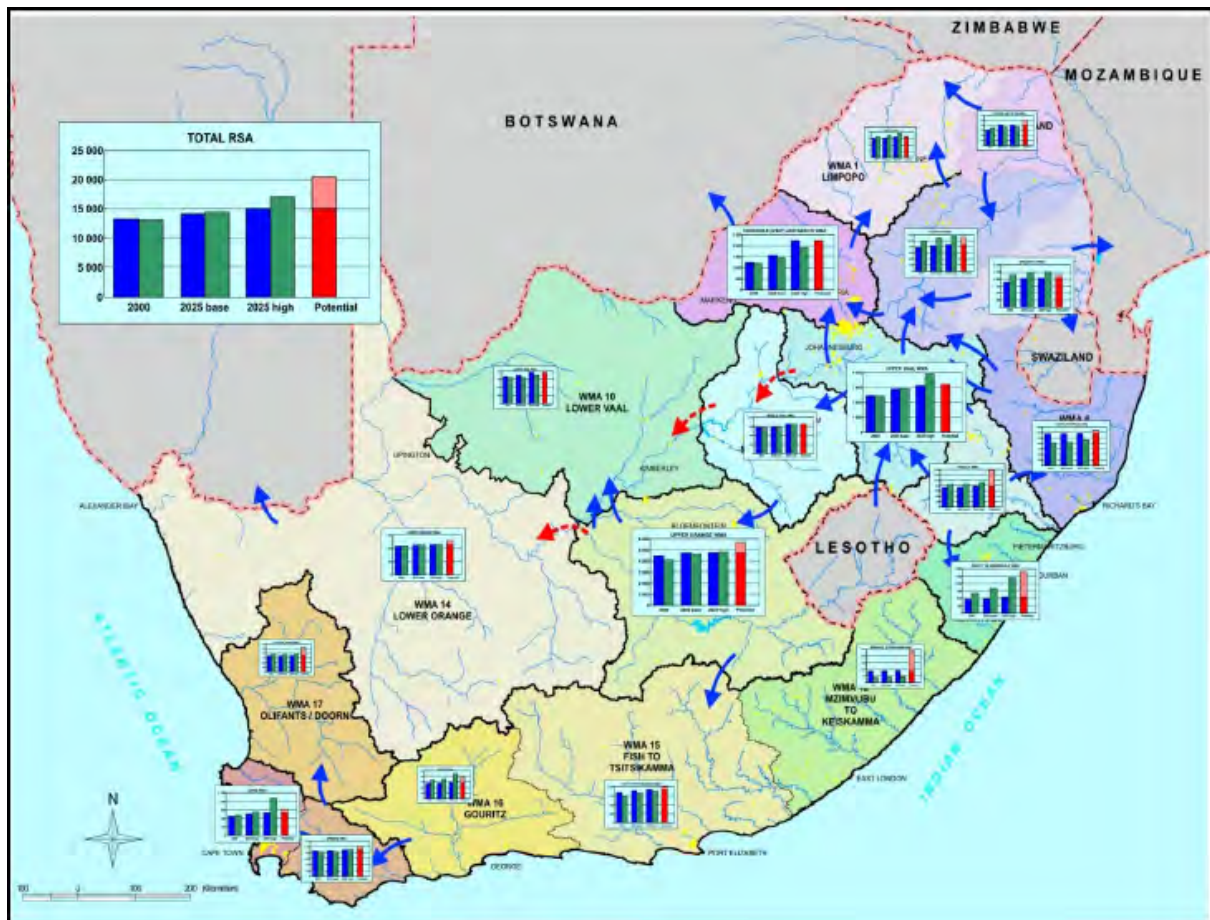
Figure 34: Estimated current and future water use relative to available supply for South Africa

Source: DWA (2004).

South Africa already has a highly developed water supply infrastructure that has been designed in response to the current highly variable climate. The DWA is also very active in future planning of water supply options with all the major systems undergoing a continuous process of reconciliation studies to balance future demands with future supplies. Currently these Reconciliation Studies provide options for meeting future demand until around 2030.

Only a few of these studies, however, take into account the potential impacts of climate change. In addition, since the publication of the first National Water Resources Strategy (DWA 2004) there has been no systematic national assessment of current or future water supply options that considers either future climate change or regional comparisons for national level strategic planning. Such a study is required to identify potential areas of concern, to develop a standard approach to incorporating climate change into individual system planning, and to consider potential adaptation options.

The results of the study presented here goes some way to putting in place the tools for such as national level strategic assessment of the potential impacts of climate change. The models developed here will be useful not only for assessing the potential economic impacts of climate change, but could also form the basis for future national strategic planning by DWA.

5.3   Methodology

Model selection

During the initial stages of the study, various available modelling platforms were considered for the purpose of developing a national water resources model for this study. The possible alternatives included (i) a national configuration of the DWA *Water Resources Yield Model* (WRYM); (ii) a revised/updated version of the DWA *Water Situation Assessment Model* (WSAM); or (iii) developing new configurations using internationally-developed models such as WEAP or MIKE BASIN. The advantages and disadvantages of each model were considered and, ultimately, WRYM was selected as being the most appropriate for application in this study.

This decision was based on a number of considerations, most importantly that WRYM provides the following:

- Flexibility in modelled water resources system configuration, operating rule definition, and modelled level of complexity.
- The ability to model very large systems.
- Time-series based system simulation.
- Visual network model configuration.
- Database-supported scenario management.
- Various results presentation and interpretation functions.
- Hydropower and stochastic analysis modelling capabilities.

Furthermore, WRYM is well-known, tested, and accepted in South Africa and has been used as an important tool for managing the country's water resources for over three decades. As a result, a large number of data sets and detailed system configurations are available from earlier studies and could be used as a basis for developing the national model configuration without the need for extensive redesign or reformatting of data sets.

Generic modelling units

WRYM was configured for the entire country on a secondary catchment scale (including catchments within Lesotho and Swaziland) based on a generic modelling unit shown in Figure35.

Each modelling unit includes the following basic elements:

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

- The impact on runoff of stream flow reductions (SFRs) including commercial forestry and invasive alien plans (IAPs).
- Ecological water requirements (EWRs) located at the outlet of each secondary catchment.
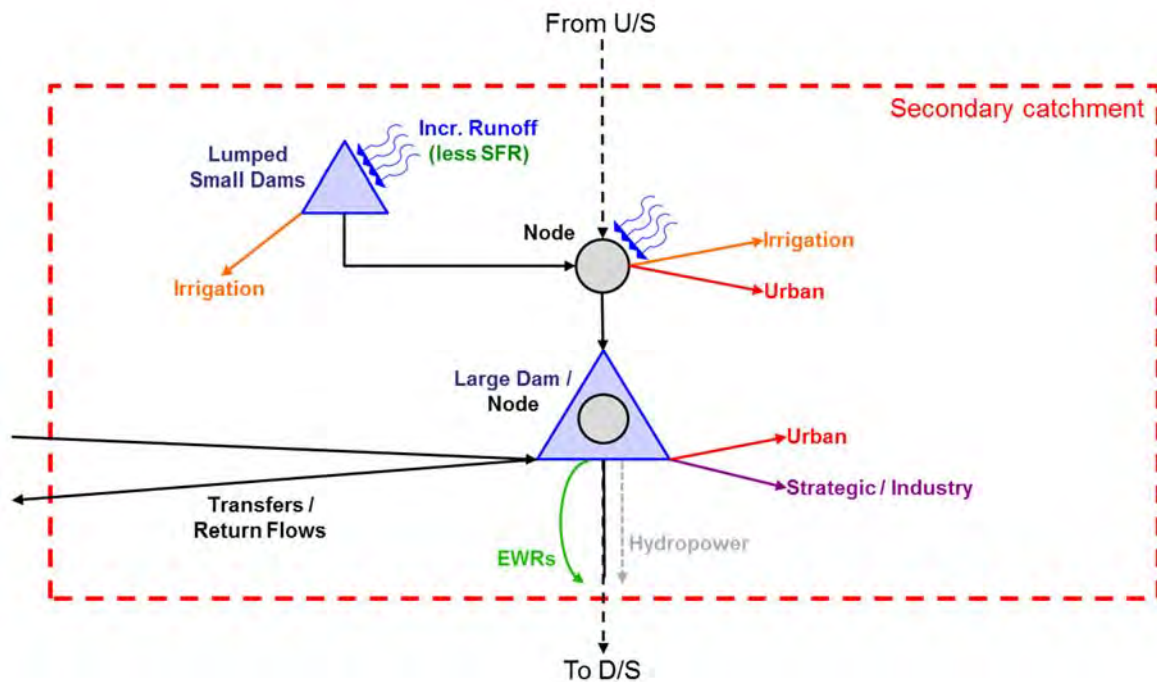
Figure 35: Generic modelling unit used for configuration of WRYM

Source: Authors' compilation, see this study.

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 Figure36.

In its current format the model 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 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 36.

Finally, it should be noted that in its current form the model does not account for the possible future utilisation of alternative water sources such as desalination or water re-use. Groundwater use is also not explicitly modelled although projected water requirements were adjusted downward to account for current groundwater supply. This is because WRYM is essentially a surface water

based model, future refinements or consideration of alternative models could incorporate these options.
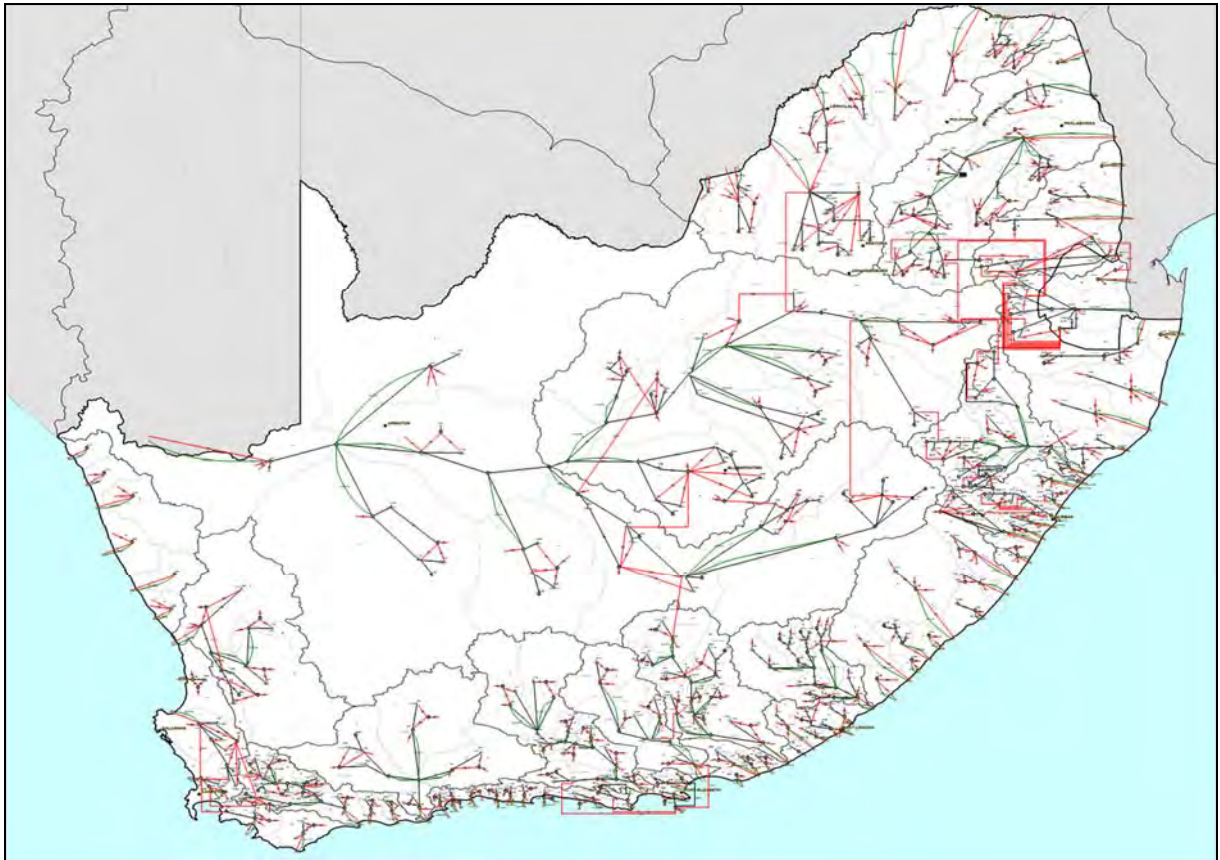
Figure 36: Schematic diagram of the national WRYM system model

Source: Authors' compilation, see this study.
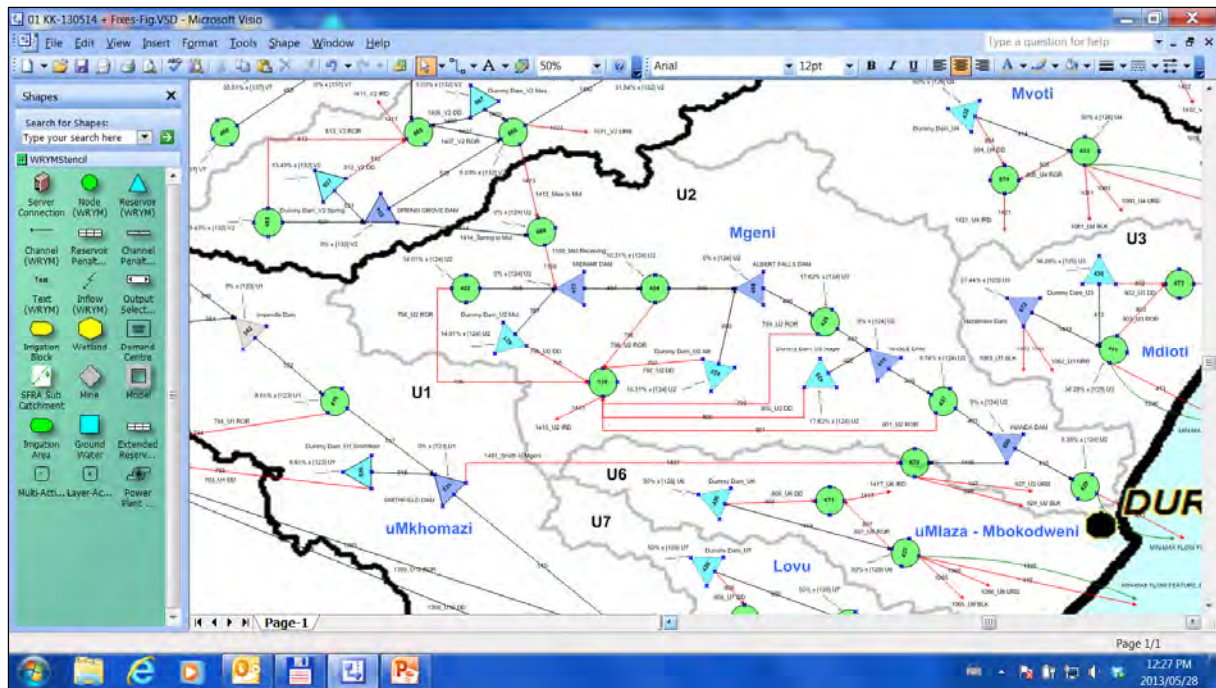
Figure 37: Detail of the national WRYM system model (Mooi-Mgeni River System)

Source: Authors' compilation, see this study.

Operating rules

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

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

- Ecological water requirements
- Bulk water users
- Urban water users
- Irrigation

The utilisation of water sources within a secondary catchment was prioritised such that downstream sources are used before upstream sources (e.g. a major dam at the bottom of the catchment is used before an upstream one) as this approach generally results in the minimisation of spills and therefore higher overall system yields. Furthermore, dams were modelled in such a way that they were allowed to draw down entirely before utilisation of the next source of water.

This approach was adopted in preference to more practical ones (such as the dual drawdown of dams or where water users would be subjected 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 to not make releases for the supply of EWRs.

In certain cases operating rules were customised to improve the modelled behaviour of the model for the system in question. This was of particular importance 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 Vaal Dam releases made to the downstream Vaal Barrage for water quality purposes.

Model validation and testing

Extensive model validation and testing was undertaken in order to ensure that the model was configured correctly, and accurately represents the physical system. However, due to the large scale of the model, the testing in question was focused largely on the modelled behaviour of the system (i.e. aspects such as the storage trajectories of major dams, the utilisation of inter-basin transfers and water supply) and a high-level assessment of whether these appeared to be realistic.

Description of scenarios

The national WRYM system model was used to analyse the following three distinct scenarios:

- A **baseline** scenario which represents the historical situation over the 50-year period 1950 to 2000 (hydrological years). The purpose of the baseline scenario is not to predict future weather patterns but to provide a basis of comparison for climate change scenarios
- The **Unconstrained Emissions** (UCE) future climate scenario
- The **Level-1 Stabilisation** (L1S) future climate change scenario.

Both the UCE and L1S scenarios are representative of the 50-year period from 2000 to 2050 (hydrological years) and are derived from a HFD approach using outputs from the MIT IGSM global simulation model and represent different mitigation scenarios.

Precipitation and evaporation

Precipitation and lake evaporation data (both in units of mm) are used in WRYM, amongst other things, to model the net impact (losses) from the exposed surface area of dams.

For the baseline scenario monthly precipitation time series (covering the period 1950 to 2000) were obtained from the *Water Resources of South Africa 2005* (WR2005) database (WRC 2009). However, the WR2005 data sets are quaternary catchment-based while the national WRYM model was configured for this study at a secondary catchment scale. The WR2005 data sets were therefore aggregated up to secondary catchments, on a monthly basis, by area-weighting.

Monthly historical lake evaporation data for major dams were obtained from existing WRYM model configurations, particularly those developed for the recent DWA *Water Availability Assessment* and *Reconciliation Strategy* studies. For small dams ('dummy dams') quaternary catchment monthly S-pan evaporation data from WR2005 was used and converted to lake evaporation using pan factors for open water evaporation (Bosman 1990). These were also aggregated up to secondary catchments by area-weighting.

For both the UCE and L1S scenarios a total of 367 individual 50-year monthly precipitation time series data sequences were used which were derived in this study based on the HFD methodology (Schlosser et al. 2011). 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 (as discussed above) 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'. The calculation is shown below:

$$\text{Net } P_i = P_i - (E_i - E_0)$$

where Net Pi   =   Net precipitation for scenario i (mm)

       Pi   =   Precipitation for scenario i (mm)

       Ei   =   Evaporation for scenario i (mm)

       E0   =   Evaporation for base scenario (mm)

Finally, as for the base scenario, the quaternary catchment-based net precipitation time series were aggregated up to the secondary catchment-level by area-weighting.

Catchment runoff

The Pitman rainfall-runoff model (Pitman 1973) was used to develop monthly runoff time series (in million m^3) for all quaternary catchments in South Africa as described in a previous section. The analysis was undertaken using both the baseline and climate change scenarios-based precipitation and evaporation data sets (as discussed above) resulting in runoff time series for the following scenarios:

- The baseline scenario (1950 to 2000)
- The UCE future climate scenario, which is represented by 367 individual 50-year future climate runoff sequences (2000 to 2050)
- The L1S climate change scenario, also represented by 367 sequences as for UCE above.

For application in the national WRYM model, the quaternary catchment runoff time series were aggregated up to secondary catchment level by adding, on a monthly basis, runoff volumes for the quaternaries in question.

Irrigation demands

Time series of monthly irrigation requirements (in units of million m^3) were modelled for each quaternary catchment using IRRDEM and aggregated to secondary catchment scale. As was done for catchment runoff the analysis was undertaken using both the baseline and climate change scenarios-based precipitation and evaporation data sets, resulting in irrigation time series for the following scenarios:

- The baseline scenario (1950 to 2000)
- The UCE future climate scenario, which is represented by 367 individual 50-year future climate irrigations sequences (2000 to 2050)
- The L1S climate change scenario, also represented by 367 sequences as for UCE above.

Direct and indirect urban water use

Future increases in the direct and indirect urban demand were assumed to be directly proportional increases in population. The total population of South Africa was assumed to increase as per the predictions of the World Bank (Figure38). These estimates assume that the population growth rate

will start at around 2% in 2000 and decreases in the future reaching close to a zero percentage increase by mid-century. The estimated population by 2050 is approximately 5.6 billion people.
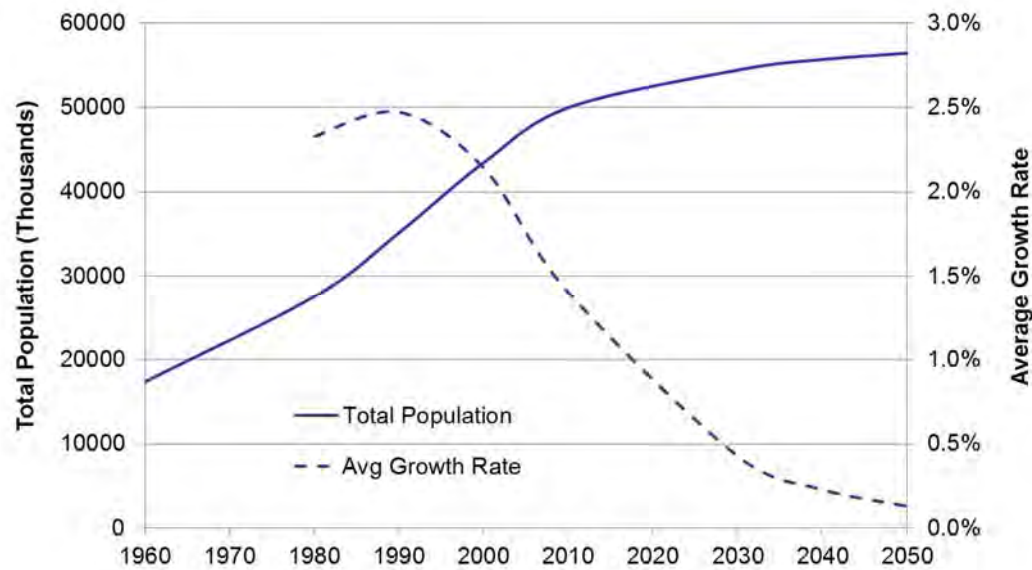
Figure 38: Future population estimates and average annual growth rates for South Africa

Source: Authors' compilation, see this study.

It is recognised that future population growth will not be uniform across the country. The growth in the total country population was therefore weighted regionally according to an analysis of the differences in the historical growth rate observed between the 2001 and 2011 national census for each of the 19 WMA as shown in Figure39.
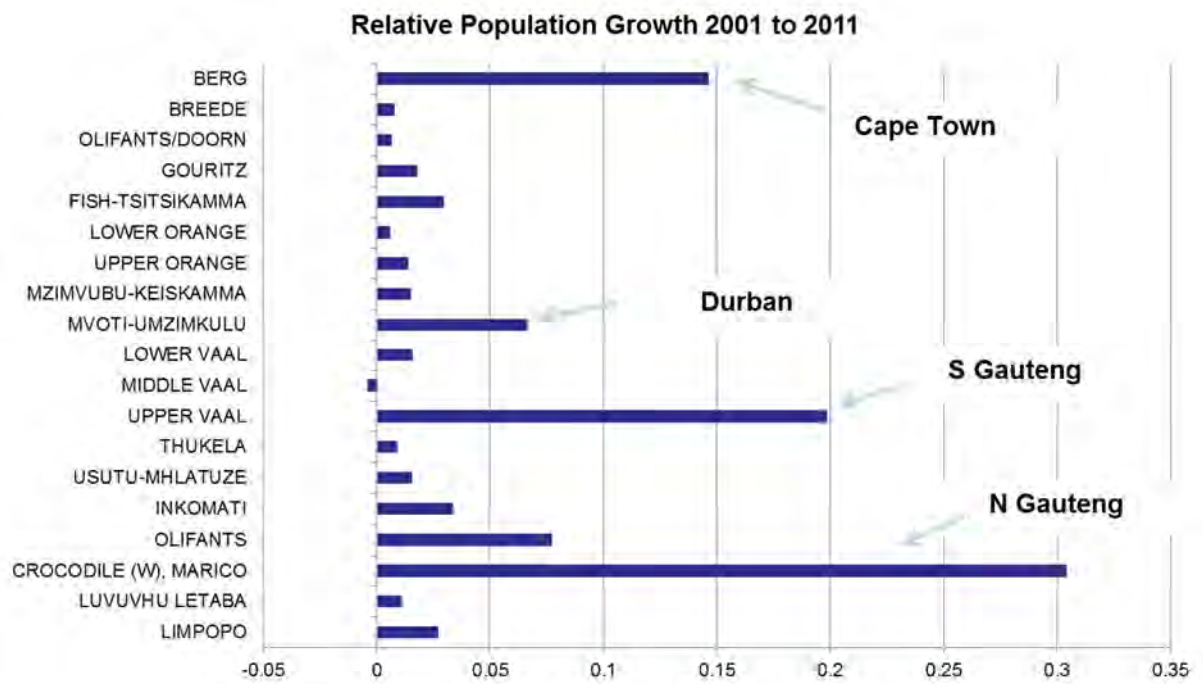
Figure 39: Relative population growth for individual WMAs in South Africa based on comparison of the 2001 and 2011 National Census regional population estimates

Source: Authors' compilation, see this study.

The total direct and indirect urban demand was calculated using current estimates of the per capita urban demand in the WSAM model. These per capita amounts were calculated for all quaternary catchments in South Africa and vary quite significantly between regions. The histogram of the per capita demands for all quaternary catchments is given in Figure 0. The average and standard deviation of daily per capita urban demand for the country is 174 ± 117 l/c/d.
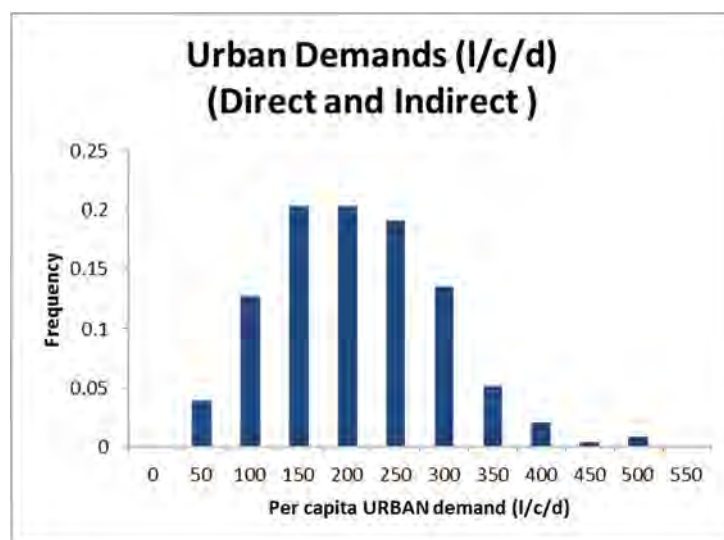
Figure 40: Distribution of average daily per capita demand (l/c/d) for direct and indirect urban water requirements for each quaternary catchment in South Africa

Source: Authors' compilation, see this study.

In addition to the direct and indirect demands allowance was made for system losses. These are generally very high in South Africa due to a combination of aging water supply infrastructure, poor maintenance, bad management, and inefficient water use practices. Again the estimates of losses for each quaternary catchment were obtained from the WSAM model. The average and standard deviation of the percentage of system losses for the country is 28 ± 12 %

Urban demand is also driven by increasing development on the one hand and improved management on the other. As an initial estimate it was assumed that these two measure balance each other out for future demands, i.e. any increases in future demand that are above the rate of increase in the urban population are balanced by equal reductions in the per capita demand through improved management practice and successful water conservation and demand management. The distribution of urban demands was assumed to equal for each month during the year.

Bulk water users

The requirements for bulk water supply in each secondary catchment were also considered. These included current and future allocations for strategic purposes, including for power supply, for mining, and for other bulk industries. 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. This was 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 (which is 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.

Furthermore, projected return flow volumes in the Crocodile (West) River catchment and the planned utilisation of these return flows to augment supply to Lephalale via the *Mokolo and Crocodile Water Augmentation Project* (MCWAP) project were also implemented in the model. The information in question was obtained from the *Continuation of the Crocodile (West) Water Supply System Reconciliation Strategy* study currently being undertaken for DWA.

Apart from the above, it was assumed that future plans to increase power supply would have to be met without significant increases in water usage. This is possible because future power stations are likely to be dry-cooled. The reconciliation study for the Olifants catchment actually predicts that water demand for power generation will decrease as newer, more efficient, plants replace the existing plants. An important consideration for this, however, is the requirements for clean coal technologies as the requirements for scrubbers or carbon capture could add significantly to the water requirements of future plants. Other future energy sources such as nuclear power, wind, or solar use are either located by the coast and use sea water for cooling or having minimal water requirements. There are no plans for significant increases in hydropower potential within South Africa although regional sources are being considered such as the Zambezi River and the Congo River

Forestry and invasive alien plants

Stream flow reductions due to commercial forestry and invasive alien plants (IAPs) are also incorporated in the water resources yield model. The original Scott curves (Scott and Smith 1997)

were used for predicting the percentage reduction in low flow stream flows due to forestry (Figure 1).

Commercial forestry was assumed to be represented by pines under optimal growing conditions with an average rotation of ten years, and thus a 55% reduction in stream flow. Similarly, IAPs were assumed to be represented by pines under sub-optimal growing conditions with an average rotation of 15 years, with a stream flow reduction of 17% as for previous estimates of the potential impact of IAPs on water supply (Cullis et al. 2007). These are both conservative estimates. In additions to these assumptions, average densities of 100% and 25% were assumed for forestry and IAPs, respectively.
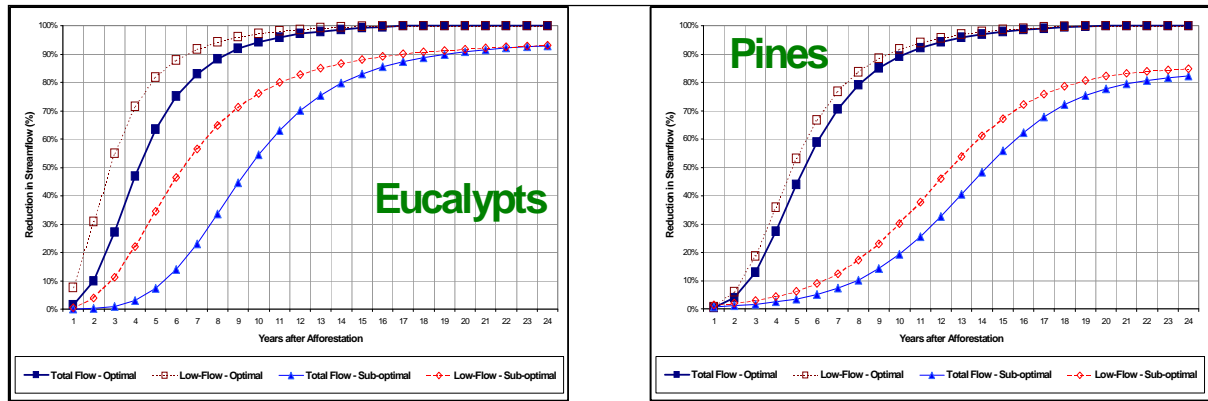
Figure 41: Average annual and low flow streamflow reduction due to eucaltypts and pines

Source: After Scott (1997).

The first step in calculating the stream flow reductions was to determine the average runoff from each catchment. This was determined using the outputs from the Pitman runoff model and the monthly demands from forestry and IAPS were estimated from the following equation:

$$SFR = RO \times A \times SFR_{red}$$

where SFR = Stream flow reduction (mm)

RO = Naturalised runoff (mm/km2)

A = Area (km2)

SFRred= Percentage reduction in area (%)

For IAPs it was assumed that the average invasion level was only 25% and the equivalent fully invaded area was used to estimate the SFR due to IAPS from the above equation.

The time series of monthly SFR due to forestry and IPAS was generated for each quaternary catchment, determined using the baseline runoff volumes and aggregated to secondary catchment scale as an input to the yield model upstream of all dams in the catchment.

As the SFR is derived based on empirical observations under current climate conditions it is not sensitive to the potential impacts of future climate change. It is likely that increasing evaporative demand will increase the potential SFR by forestry and IAPs. This relationship, however, has not been investigated in South Africa and requires further research and potential refinements to the model.

Ecological water requirements

EWRs for the main dams were determined at the outlet of all secondary catchments using the Desktop Model within the SPATSIM framework. 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.

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* 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 (i.e. smaller than 50 million m^3) 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, which was 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 in 50% of catchment runoff is generated upstream of dummy dams.

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* and *Reconciliation Strategy* studies.
- The 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. Consideration of these smaller dams and transfer schemes would be important in more detailed analysis of the potential climate change impacts at a regional or local scale.

Hydropower

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

For the purposes of quantifying the potential impacts of climate change on hydropower generation and potential at a national scale, the most significant existing and planned hydropower schemes in the country were chosen as indicative of the impacts and used for assessment. This included the two schemes on the Orange River, namely at Vanderkloof and Gariep Dams, as well as an earmarked scheme at Hartbeespoort Dam on the Crocodile (West) River. There are many other smaller schemes in the country, but although important on a localised scale, are not significant with regards to South Africa's power generation capacity as hydropower only constitutes a small portion of South Africa's total energy production.

Pumped-storage schemes were not considered as they are for all practical purposes closed systems that only require water to replace evaporative losses.

To assess the impact of climate change on hydropower generation, the annual power generation potential at the three chosen indicative sites was calculated based on releases from the dams, and the head available based on the water levels behind the dams.

Model limitations

As a direct result of the large scale of the national WRYM system model configured for this study and, therefore, the generic nature of the modelling approach and information sources used, the resulting model does present a number of limitations. These are discussed below and should be taken into account in the interpretation of the modelled results obtained.

- Modelling at a secondary catchment scale (based on the generic modelling unit described before) is a significant simplification that ignores the spatial distribution of water sources and users within the catchment and could, in some cases, result in an overestimation of water supply.
- The use of generic operating rules is not necessarily applicable in all systems and, although significant effort was made to ensure that the modelled behaviour of major systems is realistic, some scope remains for further case-specific refinements.
- The WRYM does not model the time-based implementation of schemes and therefore analyses are generally undertaken on a scenario basis. For this study the national model was configured to include both existing and likely future infrastructure developments and, as a result, water supply over the short-term (i.e. for the period prior to the actual implementation of new schemes) may be overestimated. Similarly, over the latter period of the analysis (i.e. when new schemes may be implemented that have not yet been identified), water supply may be underestimated.
- The WRYM is a monthly time-step model and will therefore tend to overestimate water supply in cases where the available dam storage is small (or zero in the case of run-of-river diversion schemes). Although the model provides a feature to account for the impact of diversion scheme efficiencies this feature was not used in the national system model configuration.
- The WRYM does not model water quality and the national model therefore does not account for water quality-related considerations in modelled system operation (although, as mentioned earlier, basic assumptions have been included relating to releases made from Vaal Dam to Vaal Barrage for this purpose).

5.4 Impacts on future water supply

The potential impacts of climate change on future water supply were quantified in terms of the change in the percent of the average annual demand for each of the three sectors (urban, bulk, and

agriculture) that could be supplied over the last ten years of the simulation (2040 to 2050) under each of the climate scenarios relative to the base scenario. The resulting HFD for the change in the proportion of the average annual demand that can be supplied relative to the base scenario for each sector under the UCE and L1S scenarios is given in Figure 2.
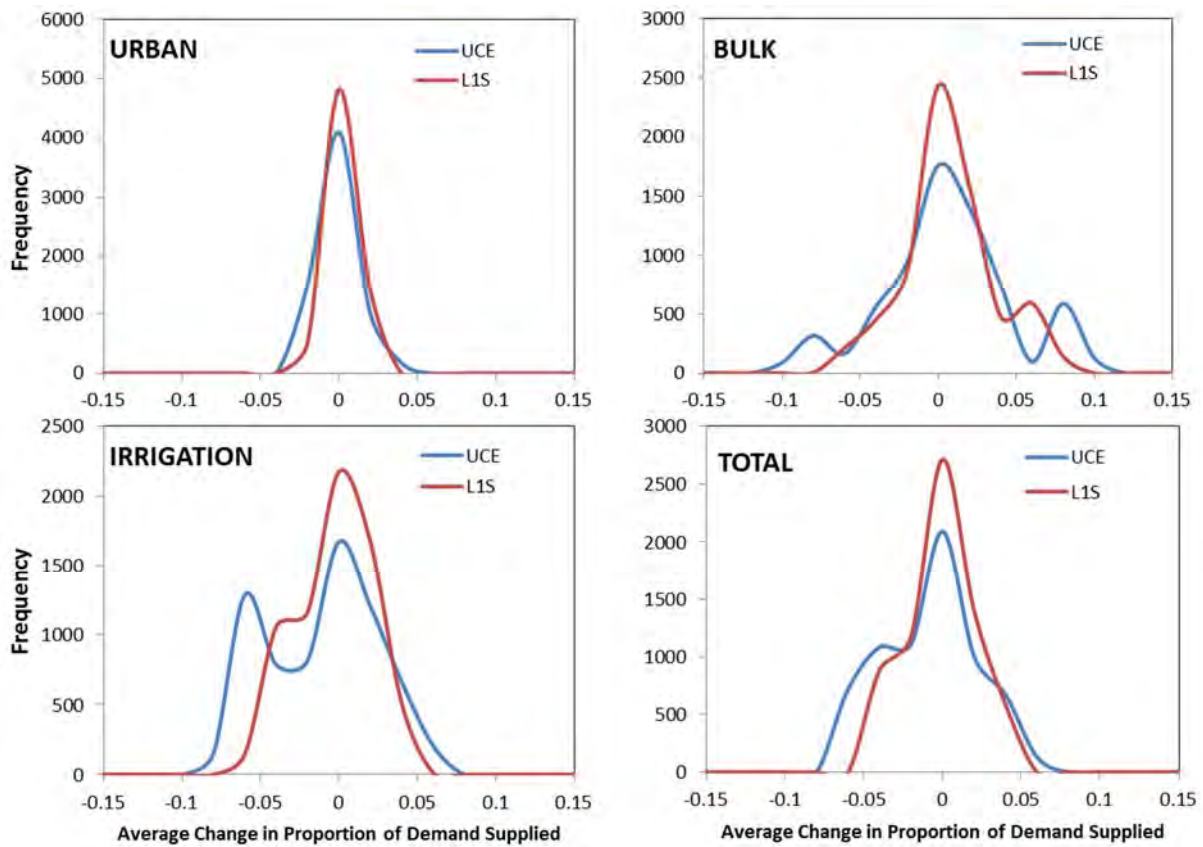
Figure 42: Hybrid frequency distribution of the change in the proportion of the average annual demand for the whole country and from different sectors that can be met under different climate scenarios over the period 2040 to 2050

Source: Authors' compilation, see this study.

These results show a narrow range of impacts in terms of urban supply with very little difference between the UCE and L1S scenarios. In both cases the mode is at zero although the median impact of the model scenarios is around a 1% reduction. Under both scenarios there is less than a 5% change in the ability to supply the average annual demand by 2050 indicating a resilient water supply system.

There is a greater range of potential impacts in the ability to supply both the bulk industry and the irrigation demands. Under the UCE scenario the median impact in terms of the ability to supply the average annual demand is only a 1.5% reduction but with the possibility of up to a 9% reduction under the hotter, dryer future climate scenarios. Under the L1S scenario this risk is reduced with the maximum impact being reduced to a reduction of 6.7% of the average annual demand. The impact on supply to bulk industry is similar 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 (i.e. in Gauteng and the north eastern part of the country).

Despite that apparent limited impact of climate change in terms of the ability to supply future demands at the national level there are potential for very significant impacts at the regional level.

Figure3 shows the estimated total average annual demand for each sector in each of the nineteen 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 the average annual demand that can be supplied under the base scenario in each WMA while the box plots show the median and the inter quartile range and the bars show the maximum and minimum model results.

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

The potential impacts on the water supply to bulk industry and irrigation tend to show an equal likelihood of both increases and reductions in the ability to supply future demands under different climate futures with the median impact being very similar to the current base scenario. The most vulnerable area, i.e. showing the greatest potential for a significant reduction in the ability to meet future demands, appears to be the Gouritz WMA (WMA 16) in the southern Cape, although if some of the drier scenarios are realised either on average or during future dry periods then there are likely to be significant impacts across all sectors and across all regions.
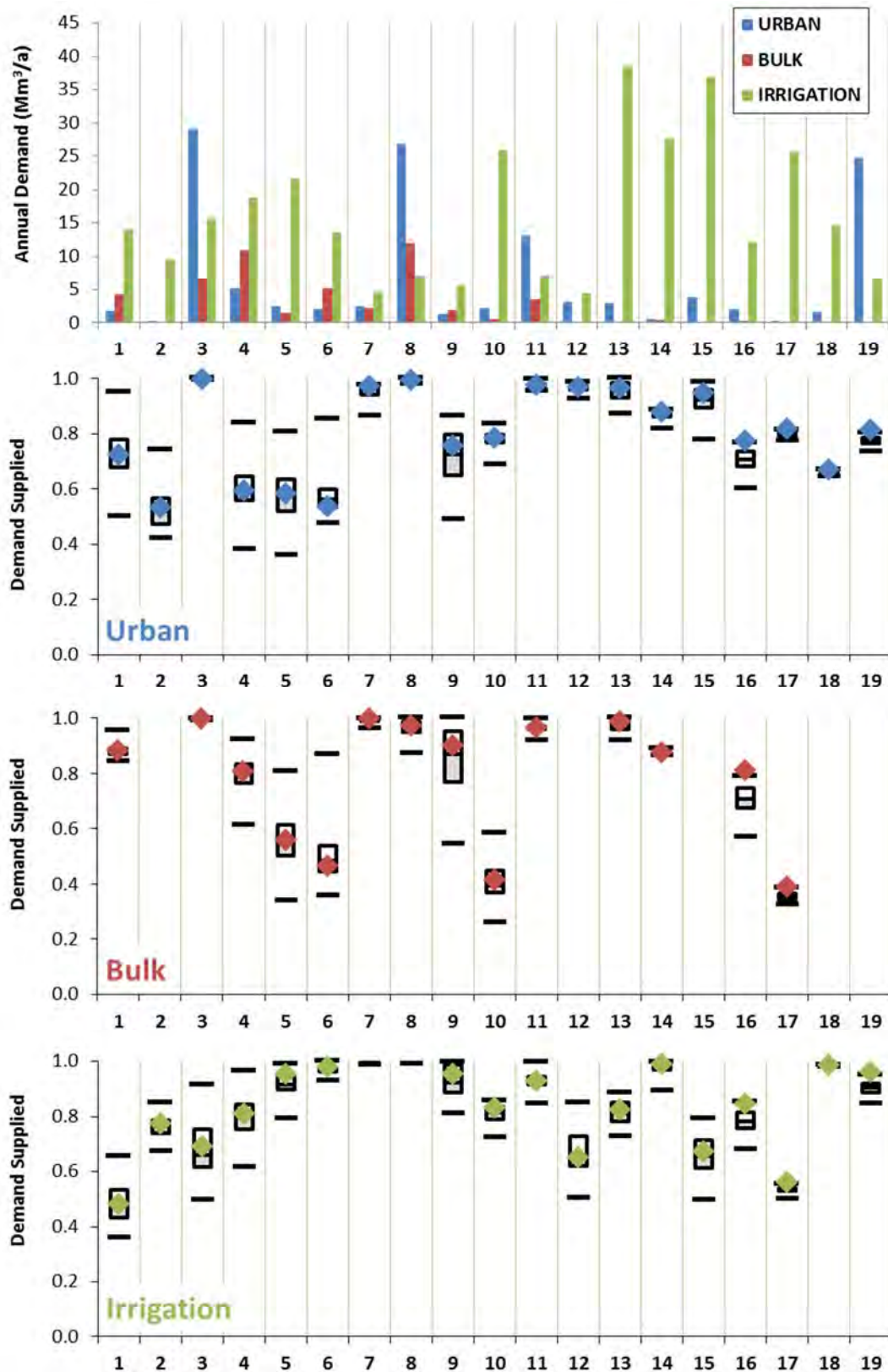
Figure 43: The average annual demand (top) for the 19 WMAs for the period 2040 to 2050 and the estimated proportion of the demand that can be supplied under the base scenario (symbols) and specific models representing the minimum, 25th percentile, median, 75th percentile and maximum impact under the UCE scenario for different water use sectors

Source: Authors' compilation, see this study.

5.5   Impacts on future hydropower potential

Hydropower is not a significant contributor to power production in South Africa. Hydropwer is produced by Eskom at the Gariep and Vanderkloof Dam on the Orange River and s number of pump-storage schemes. There are also few other smaller hydropower dams for example on the Haartbeesport Dam in the North West. None of these dams, however, are operated specifically as hydropower dams and it is rather a by-product generated when releases are made for other downstream users. There is, however, pressure on DWA to consider installing turbines at more of its existing dams, weirs and even canals to provide additional renewable energy potential.

The results from an initial assessment of the likely impacts using the HFD UCE and L1S climate scenarios on the potential hydropower production at the Vanderkloof Dam and the Hartbeesport Dam are given in Figure 44 and show significant differences for different locations in the country. There appears, however, to be little difference between the UCE and L1S mitigation scenarios.
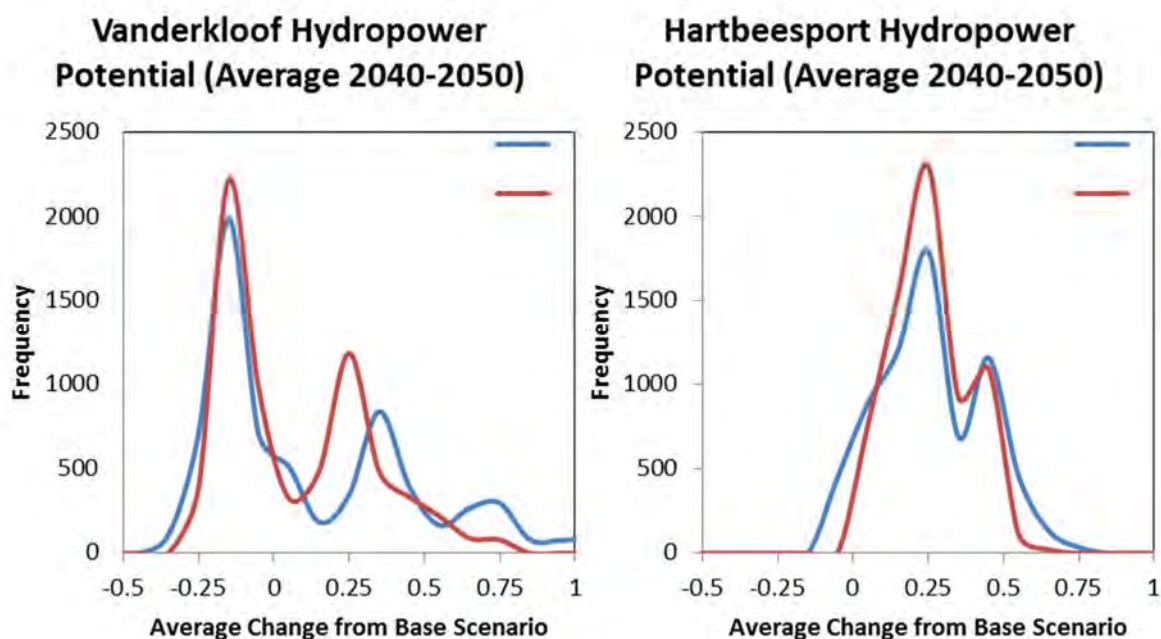
Figure 44: Hybrid frequency distribution of the change in the potential average annual hydropower production for the Vanderkloof and Hartbeesport dams for the UCE and L1S climate scenarios

Source: Authors' compilation, see this study.

The results show a general reduction in the hydropower potential from the Vanderkloof dam, which is the largest hydropower dam in South Africa, with a median impact of - 4.9% for the UCE scenario. There are, however, some models showing a potential positive impact on hydropower even up to a 75% increase. 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 this may be limited by daily flow variations, the turbine capacity and the potential risk of increased flooding. The results do, however, suggest that certain dams could have increased hydropower potential in the future and DWA should consider this in terms of incorporating hydropower turbines into existing and future dams in order to provide alternative energy sources.

5.6   General observations and conclusions

Based on the results presented above the following general observations can be made:

- For South Africa as a whole the impact of climate change on urban and industrial water supply is fairly limited. This is specifically notable in the larger systems like the Upper Vaal, Crocodile (West), and Mooi-Mgeni (in the Mvoti and Umzimkulu WMA) that, combined, supply water to more than 50% of the country's urban and industrial water users. This phenomenon may be attributed largely to the inherent resilience of our approach to water resources planning which accounts for the possible occurrence of severely extreme periods through probabilistic analysis.
- The agricultural sector may, however, be more vulnerable with a significant number of future climate sequences analysed resulting in lower water supply characteristics compared to the baseline. Most notable in this regard is the Luvuvhu and Letaba, the Crocodile West and Marico, the Olifants, the Inkomati, and the Mzimvubu to Keiskamma WMAs.
- Notwithstanding the above, in the case of almost all water user sectors and for both future climate scenarios, the results show that for the majority of sequences analysed water supply is higher than for the baseline – suggesting that climate change may result in increased wetting for most of the country. However, possible concerns have also been raised over the course of the study that HFD-based climate change scenarios used for these analyses may be too wet compared to scenarios developed locally that show more drying and greater climate change impacts.
- Water supply under the L1S scenario is generally significantly higher than under UCE, with the latter showing a far broader range of results (the 'tails' on the histograms) for the 367 sequences analysed.
- Hydropower potential appears to increase under both climate change scenarios analysed. This can be attributed to the fact that hydropower is a secondary benefit reliant on the releases of water for downstream users, and that there is a general increase in water supply shown for the climate change futures.

With consideration of the methodology, sources of information, and general assumptions applied in the water resources system analysis described in this section, the results presented should be considered as preliminary. Significant scope exists for future refinement and improvement including:

- Further analyses should be undertaken to assess the impact of possible revised HFD-based climate change scenarios, as well as climate change scenarios developed locally.
- As the impacts of climate change scenarios appear to be affected by the level of stress in a water resource system, different scenarios of water resource infrastructure development levels can be considered. The aim of this would be to better match growing water demands with appropriate increases in water availability, as is currently the reconciliation strategy in South Africa. In this way, the possibility of climate change exaggerating the impacts of improper planning can be evaluated.
- The national WRYM system model could be significantly refined based on information from existing WRYM model configurations, particularly those developed for recent DWA *Water Availability Assessment* and *Reconciliation Strategy* studies, including:
    - System-specific configuration and operating rules, focusing on the major supply systems
    - Modelled urban and bulk water requirements
    - Significant sources of return flows, other than those already included for the Crocodile (West) River catchment

- The characteristics of inter-basin transfer schemes
- EMCs and/or EWRs which were derived at a higher level of confidence
- The variability of results obtained under climate change scenarios should be evaluated against the natural hydrological variability of water resource systems, as currently included in South Africa's probabilistic water resources planning and management approach.

6 Roads impacts

6.1 Introduction

Climate change has both short- and-long term impacts on road pavements and adaptation is a lengthy process due to the fact that the existing road infrastructure cannot be altered or adapted overnight (Austroads 2004). There have, however, been few studies that have attempted to quantify these potential impacts let alone suggest suitable adaptation and mitigation measures (Chinowsky 2011).

Unlike many other African countries, South Africa has an extensive well developed and relatively well maintained roads network. The climate of South Africa is, however, highly variable and current projections are that it will generally become hotter in the future with potential increases in precipitation or at least in the intensity of precipitation (DEA 2011). It is therefore important that the potential impacts of climate change on the roads infrastructure of South Africa be investigated.

In this section we describe the implementation of the Integrated Planning Support System (IPSS) model for assessing the potential impacts of climate change on the current road inventory of South Africa. This model forms part of the integrated modelling framework shown in Figure 45 for investigating the potential impacts of climate change on the regional and national economy.
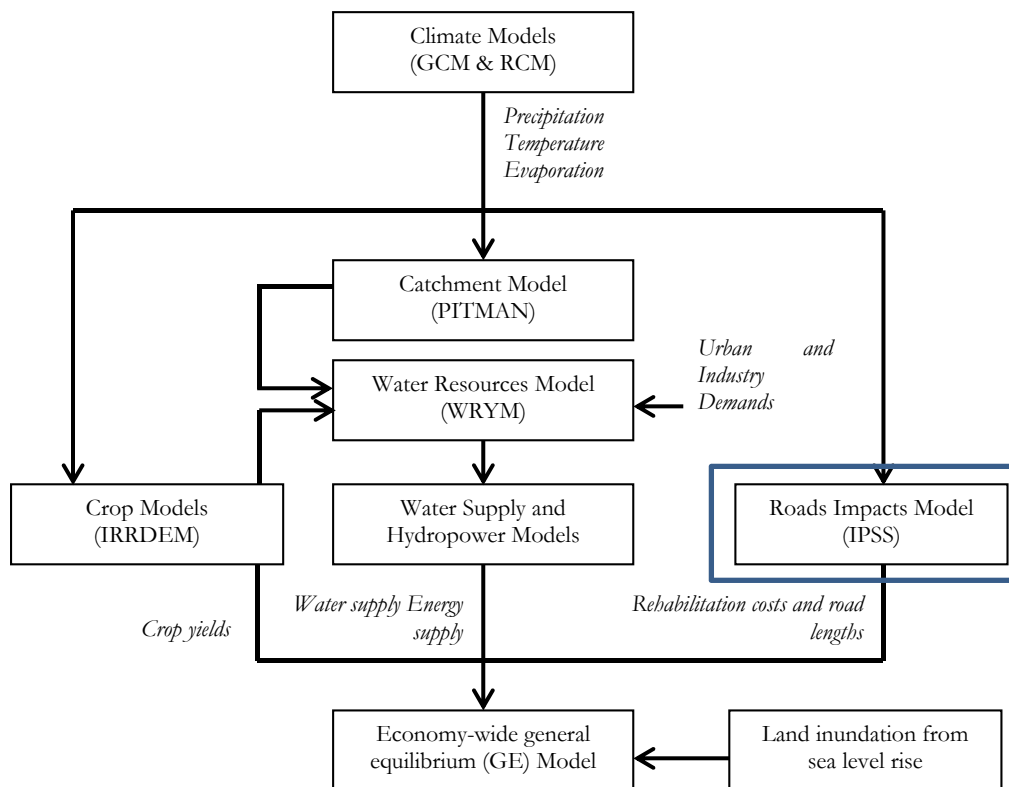
Figure 45: Integrated modelling framework highlighting the roads impacts modelling component

Source: Authors' compilation, see this study.

6.2 Climate impacts on roads

The road network is a critical part of the national economy and social wellbeing. Climate change will impact the road infrastructure of South Africa through changes in temperature, changes in precipitation and changes in runoff. These impacts are discussed briefly below.

Temperature impacts

For road pavements, increased air temperatures have an effect on the road surface temperature. Maximum road surface temperatures in South Africa can reach temperatures close to 70°C in the northern regions but is generally between 45-55 °C in summer.

An increase in frequency of very hot days as well as heat waves on bituminous pavement layers are the primary impacts that are manifested by an increased risk of rutting, bleeding, flushing and cracking of asphalt surfacing. Specifically the bituminous binder phase loses stiffness when the asphalt mixture (or thin surface seal) temperature increases. When the stress level and load duration stays the same, the irrecoverable creep deformations that are caused by dynamic as well as static traffic loading will therefore accumulate at a much faster rate.

The results of higher temperatures that are accompanied by increased intensity as well as duration of ultraviolet radiation, cause an increase in severity and in the rate of hardening of the binder phase. This usually occurs in the exposed upper parts of the bituminous surfacing. This eventually has the result that the binding ability of the bitumen decreases and it may then be less able to

withstand any forces imposed by traffic as well as climate. This results in an increased rate of cracking development and aggregate loss from the surfacing.

These effects will manifest as an increased rate of rutting and deformation of asphalt pavements. Asphalt pavements are costly to construct and are therefore reserved for use on only the highest trafficked primary road network and within urban areas. For the majority of the South African road network, thin bituminous surface seals are constructed. Because the temperature sensitive bituminous materials are limited to 10 to 20 mm thick, the increases in road surface temperature will manifest as bleeding or flushing. This effect results in a general loss of surface texture and unsafe slippery road conditions.

Engineers already understand to a large extent how to accommodate ambient road surface temperatures in pavement design, particularly in asphalt mixture design and surface seal design. The following approaches exist, however, not all are practiced in the industry due to cost constraints:

- The adjustment of bituminous mixture design (performance-related binder selection including polymer modification of bitumen)
- Adjustment of maintenance plan (e.g. more frequent surfacing)
- Adoption of base bitumen binders with higher softening points for surface seals and asphalt: adjustment of construction processes and timing
- Forced cooling of thick asphalt pavements.

There are some long-term solutions that could be adopted (and that are used occasionally) to deal with the increase in frequency of very hot days and heat waves and these are the use of material technologies such as using concrete pavements instead of bituminous (asphalt of thin surface seals) (PIARC 2012) as concrete is less sensitive to temperature fluctuations than bitumen.

Precipitation impacts

Increases in average precipitation lead to generally higher ground moisture conditions. South African road pavements are predominantly constructed with moisture sensitive granular materials (gravels and crushed rock) which lose their load bearing capacity when wet. This, together with the fact that our road surface seals are generally very thin (10–20 mm) and prone to surface water ingress if not adequately maintained, makes a strong case for taking increased precipitation effects very seriously.

The different types of materials used in the construction of roads are influenced by the climate in which they are functioning. Essentially, road construction materials are susceptible to two primary forms of weathering – disintegration and decomposition. Disintegration is a physical process and decomposition is a chemical weathering process. Decomposition is more harmful to the quality and durability of road building materials because this process tends to generate more moisture sensitive clay minerals. A road constructed in an arid region will not have to endure the chemical weathering processes brought about by large amounts of precipitation. Subsequently, the life span of roads may be significantly shortened if the climate for which they were built were to gradually change.

For pavement design purposes, South Africa is divided into certain climatic zones where there is a clear boundary in terms of where disintegration and decomposition takes place. The coastal areas of South Africa, except the West Coast, are predominantly areas where moderate to higher precipitation occurs and therefore tend towards decomposition of road building materials.

Evaporation also plays a large part in the process of decomposition and disintegration. The following formula was developed by Weinert (N-value) which takes into account the evaporation in the warmest month divided by the total annual precipitation:

$$N = 12 \, Ej \, / \, Pa$$

where   Ej = Evaporation in warmest month (January in South Africa)

Pa = Total annual precipitation in mm

In areas where N < 5, rocks typically decompose and these are within the moderate to wet areas. Special attention is thus required for drainage (both surface and subsurface) in these areas. Also, road pavements constructed in these areas are provided with additional supporting layers to compensate for the expected poorer materials. Where N > 5, disintegration is the main form of weathering and these are typically the dry areas where less than 500 mm precipitation per year is recorded. In these areas, lighter and cheaper pavement structures can be constructed.

The following mitigation techniques for increasing precipitation impacts are possible but are implemented taking into consideration current, or even historic, climatic conditions with no regard or understanding of how these may change over time:

- Increasing the load bearing capacity of pavements through increased/additional supporting layers
- The adaptation of the drainage capacity of roads, including cross fall adaptation as well as transportation of the water via drainage systems or other means away from the road – this is done to prevent water from penetrating into the lower layers
- Green verge maintenance to ensure that water can be transported from the road to the verge
- Informed material selection linked to structural design that is linked to appropriate drainage provisions
- Improvement or upgrading of storm water systems.

Runoff impacts (flooding)

An increase in frequency of intense precipitation events is likely to cause flooding, if this is not adequately addressed through adaptation. Some of the existing drainage infrastructure (bridges, causeways, and culverts) may be inadequate to convey the higher flow rates anticipated during the more extreme storm events. Increases in precipitation intensity would require the use of larger drainage structures in the future. Where the drainage is inadequate and leads to standing water or wash aways then the worst case scenario road closure may be necessary for safety reasons. The economic costs of such road closures can be significant.

6.3   Methodology

The infrastructure planning support system

The IPSS software was developed by the Institute of Climate and Civil Systems (iCliCS) based in Boulder Colorado, USA. It was developed to fill an information gap in previous climate change impact studies which lacked specific costs attached to damages, adaptation, and non-adaptation. These studies focused on producing qualitative results and forecasts; speaking to how, why, and possibly when the construction industry would have to change some of its practices in light of a

changing climate. The ability to quantify a monetary cost is useful to policy and decision makers (Chinowsky et al. 2011).

The IPSS primary goal is to be used as a guidance tool for policy and decision makers, not specialists in the technical field. The model has been used in both developed and developing countries from Europe and North America to Africa and the Far East. It was used in the World Bank's Study on Economics of Adaptation and a study on China, South Korea, Japan, and Mongolia for the Asian Development Bank.

The software was designed and programmed by iCLiCS and therefore has a lot of hard coding in the program that could not be specifically customised for this study. The user interface itself has very few user-defined inputs. There is, however, a number of variables and modelling parameters contained in external spread sheet files, from which the program reads. Manipulating and customising this data for local South African conditions was challenging as the program requires a very specific input structure to read from. For use in the South African contest, no additional coding was done by the project team. The project team also found it particularly challenging to get a full understanding of all the input variables and modelling parameters since no formal documentation on this was provided.

The primary change that needed to be made to the software was how the global climate changes predicted by the GCMs would be applied to South Africa. The IPSS software had to be modified to fit the specifics of South Africa. It models climate change on a global scale, and then scales it down to a 'regional' effect. At this level it will encompass South Africa. South Africa has a very diverse climate across the provinces, and was therefore divided into Climate Reporting Units (CRUs) (grids of 48 km x 48 km) as illustrated in Figure 46.
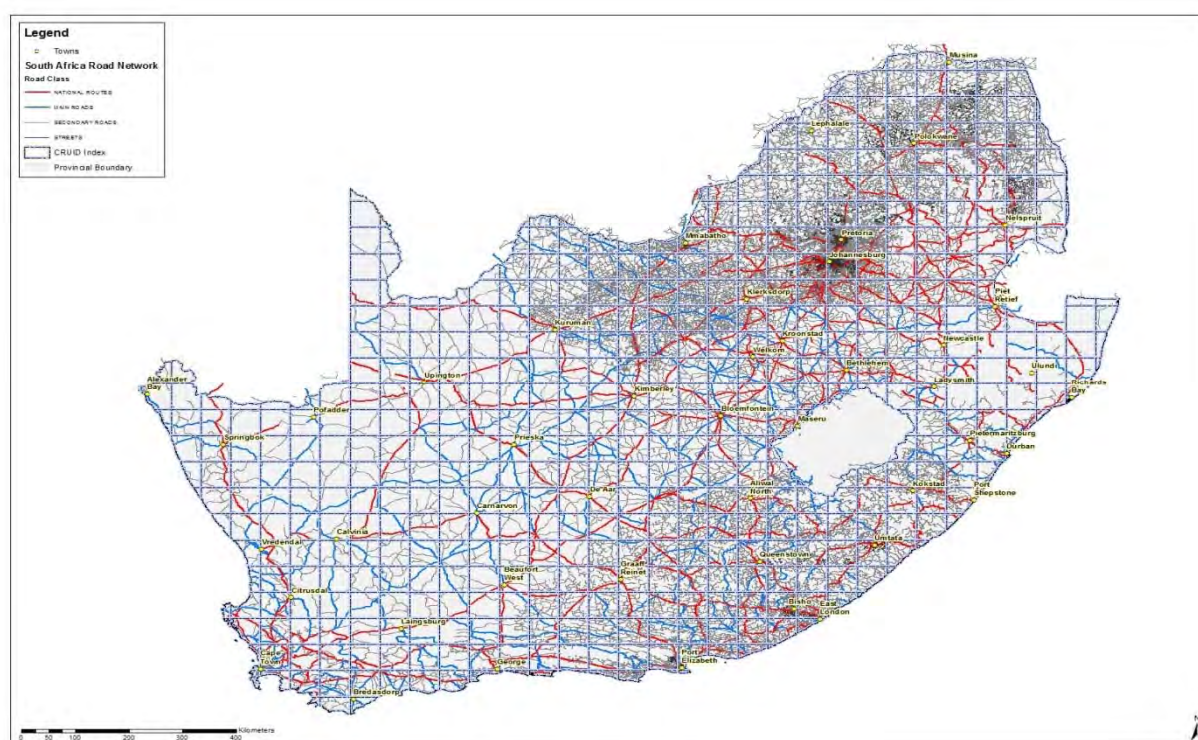
Figure 46: South African road network and the grid of Climate Reporting Units

Source: Authors' compilation, see this study.

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The regional effect is applied to each of these CRUs. So, in a sense, there is one climate impact for each of these CRUs. A weighting, proportionate to the length of roads, was applied to each CRU. This was so that the correct proportion of road would be modelled under the correct climate change (i.e. within the applicable CRU).

Model structure

Although it is essentially a cost model, at its core it takes into account actual engineering design standards in relation to the climate in a stressor-response methodology. This methodology purports that for each external stressing factor, there is one specific, quantifiable response. That is to say, the changing climate is the stressor and a certain adaptation in engineering is the response. In this model, two primary climate stressors were considered: temperature and precipitation; as well as their associated stressors like, evaporation, storm frequency, and severity.

Table 4 shows the climate stressor responses for precipitation and temperature for different road types.

Table 4: Description of climate stressor responses for different road types

Stressor-response descriptions for construction and maintenance costs		
Road type	Precipitation (stressor)	Temperature (stressor)
Paved roads (Construction and re-paving)	Change in costs of constructing a km of paved road per 100 mm change in annual precipitation projected during lifespan relative to baseline climate	Change in cost of constructing a km of paved road per stepwise increase in the maximum of monthly maximum temperature values projected during lifespan relative to baseline climate
Paved roads (Existing) Maintenance	Change in annual maintenance costs per km of paved road per 100 mm change in annual precipitation projected during lifespan relative to baseline climate	Change in annual maintenance cost per km per 3ºC change in maximum of monthly maximum temperature projected during lifespan
Paved roads (New road) Maintenance	For roads constructed during forecast period (2010 – 2100), no maintenance impact if designed for changes in climate expected during lifetime	
Gravel roads (Construction)	Change in construction costs per km per 100 mm change in the maximum of the monthly maximum precipitation values projected during the lifespan	Not estimated. Impact assumed to be minimal
Gravel roads (Maintenance)	Change in maintenance costs per km of paved road per 100 mm change in annual precipitation projected during lifespan relative to baseline climate	Not estimated. Impact assumed to be minimal

Source: After Chinowski (2011).

A certain Rand value cost is fixed to every response 'threshold'. One is then able to determine the cost(s) of an engineering adaptation every time a climate threshold is broken. By 'one' response, we mean that for a specific adaptation measure there is no chance for possible alternatives or choices to be made. There may, however, be multiple responses. The other aspect to this modelling methodology is the concept of 'adapt vs. no-adapt' policy. The real analysis comes from the two scenarios that are forecasted for comparison. The 'no-adapt' scenario predicts the costs that would be incurred if engineering practices are not adapted for the future changing climate. The 'adapt' scenario predicts the costs of using an adapted engineering approach.

Future climate scenarios

The climate data within IPSS is currently based on the outputs from 56 Global Circulation Models (GCMs). The annual cost for the 'adapt' and 'no-adapt' scenario are calculated for each climate model used to determine the average annual cost for each decade out to the end of the century. The median impact cost is then reported as a time series of relative cost impacts along with the spread of outputs from the different models which can be used to determine a relative risk profile for the cumulative impact costs up to the end of the century. Impact costs are reported for the whole country, but can also be determined for individual provinces or sub-regions.

Future development of the model will take into consideration the specific impacts of regional climate models for South Africa, recognising that regional models are better at predicting the regional impacts, particularly in terms of precipitation impacts and finer scale spatial resolution.

The engineering response

The road construction engineering and design standards considered in this model are limited to:

- Precipitation – increase or decrease in rainfall
- Temperature – increase or decrease in temperature
- Extreme events – frequency and severity (measured in damage costs)

Each of these climatic aspects has a different engineering solution. An increase in temperature would require the use of an upgraded asphalt binder. Similarly increased rainfall would require larger culverts for increased drainage capacity. The following assumptions are made in terms of temperature and precipitation parameters in the IPSS model:

- The precipitation threshold is 100 mm, i.e. the stressor response that is attached to the increase/decrease in rainfall is used for each 100 mm incremental change in annual rainfall
- The impact on maintenance costs associated with precipitation is determined as a percentage of the current maintenance cost
- There is also a percentage 'impact' on the road per threshold – this negative impact is as a result of the increased precipitation and accounts for things like increased chemical weathering, and the need for larger culverts
- The temperature thresholds are given in specific temperature units that have adaptation(s) attached to each one; there is no interpolation between threshold values
- As is evident here, there are specific increases in binder cost for each increasing temperature unit. Specific binders that would be required at each threshold cannot have an input.

The input parameters to the model for temperature and precipitation impacts are given below:

Table 5: Additional assumptions about temperature and precipitation impact parameters used in the IPSS model

Additional assumptions about temperature and precipitation								
param.pThresh	100	precipitation threshold is 10cm (10cm = 100 mm)						
param.pMaint	0.04	percent impact on road maintenance costs						
param.pPerThresh	0.008	impact on roads per threshold						
param.tMaint			0.36	percent impact per temp threshold				
param.adaptBinderCost (% costs per threshold; e.g. 1000*[197 210 225 241 258 276 295])	197	210	225	241	258	276	295	
param.adaptPavedThreshTemp = [46 52 58 64 70 76 82]; pave temp thresh levels	46	52	58	64	70	76	82	

Source: Authors' compilation, see this study.

Although the design life of paved roads is typically 20 years, the current reality in South Africa is that roads are not reconstructed every 20 years and remain functional for up to 30 years. The lifespan of gravel is much lower than that of paved roads at ten years. The table below shows the expected lifespan of the different road types, based on current design and construction standards.

Table 6: Road design life information

Road life information	Paved	Gravel
Years of life for paved and gravel roads	30	10

Source: Authors' compilation, see this study.

Unit costs

Six variables for costs are considered in the model. These require determining the unit cost per km for the construction, maintenance, and upgrading of the different road types. These cost considerations are shown graphically in Figure 47 and are described below:

A- Base cost for building a new road – the cost per km of the construction of a new road (this also applies to rehabilitation)

B- Adaptation cost for upgrading road – 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 km of repairing a road damaged by a flood

E- Maintenance costs – the cost per km of maintenance of a gravel road only; calculated as a percentage of construction cost

F- Maintenance savings.

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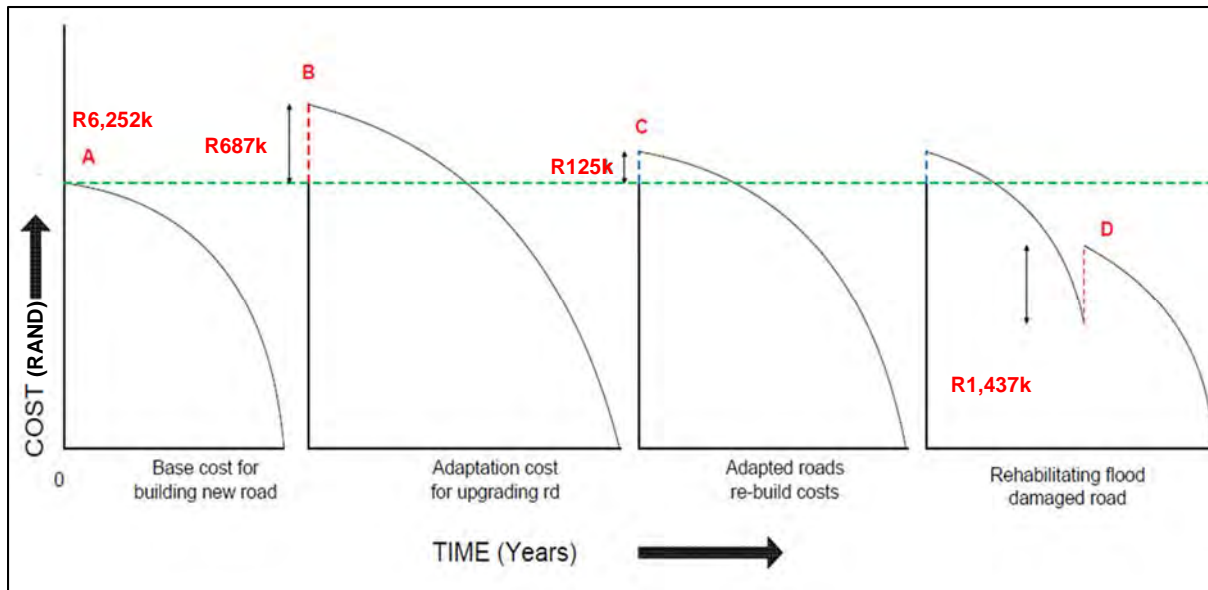
Figure 47: Illustration of costing variables for different scenarios

Source: Authors' compilation, see this study.

Base construction costs were developed per km 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 are given in Figure 48.
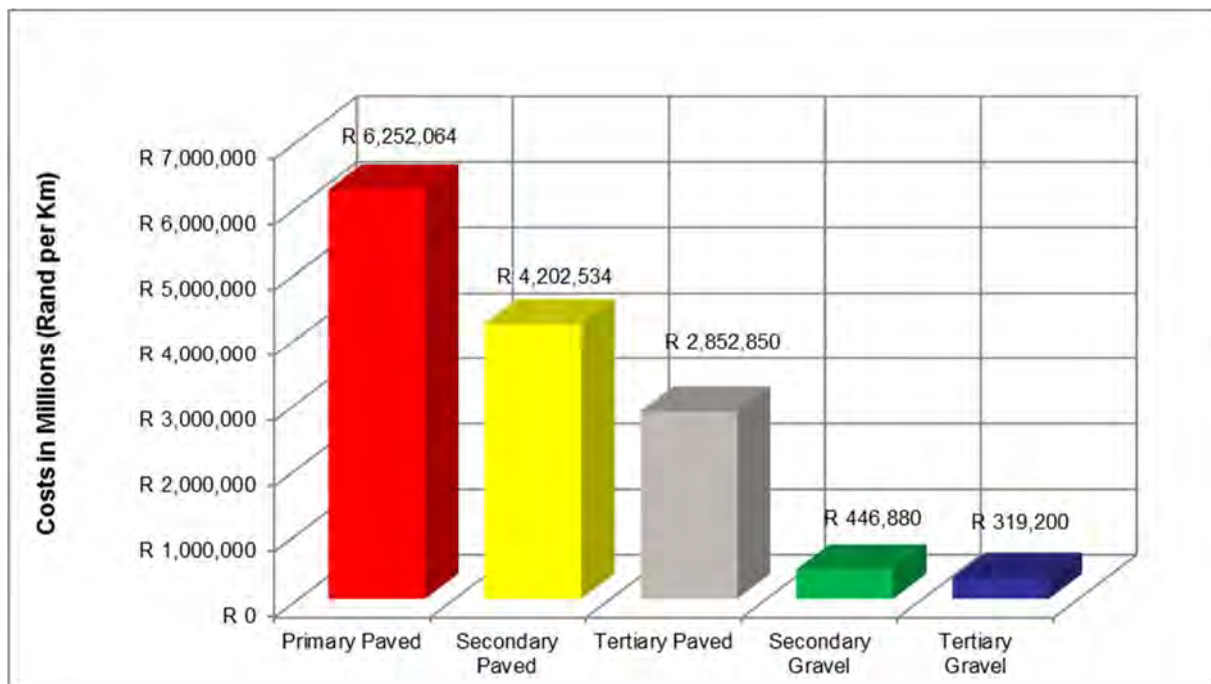
Figure 48: Typical road construction cost in South Africa

Source: Authors' compilation, see this study.

The road stock inventory

Information on the current road stock for each province in South Africa was obtained from MapIT, who provide the information for the use in GPS units. These were validated using information on the national roads inventory supplied by the South African National Roads Agency. 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 to 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).

The total length of roads in South Africa's was estimated to be just over 600,000 km. More than half of this is for gravel roads as shown in Figure 49. The most roads are located in the Eastern Cape as shown in Figure 50 and consisting mostly of gravel roads. In contrast almost 90% of the roads in Gauteng are paved roads and almost 50% in the Western Cape.

	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
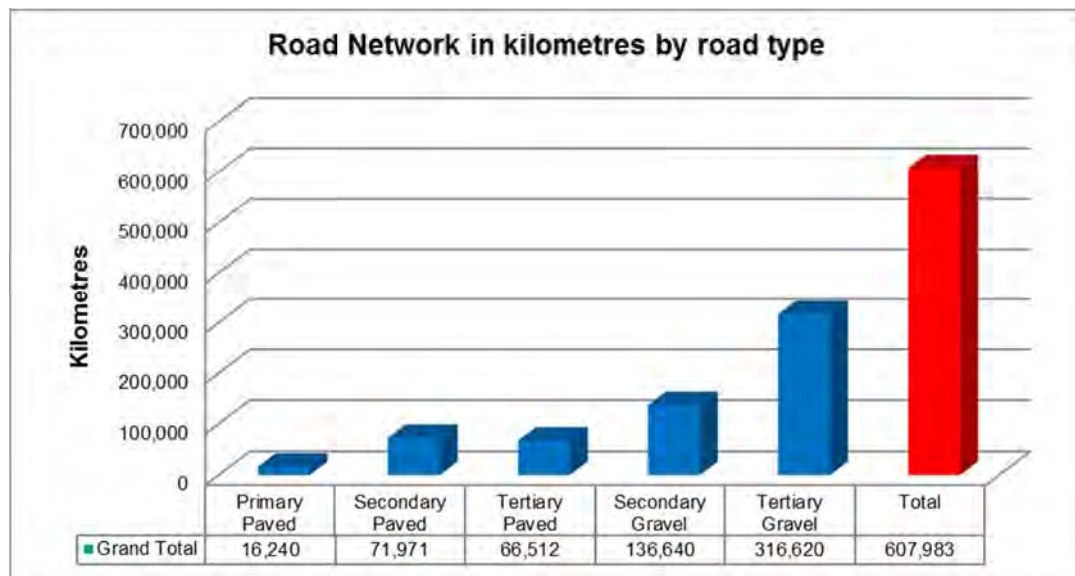
Figure 49: Total length of road type in South Africa

Source: Authors' compilation, see this study.

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	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 50: Total length of road type per province

Source: Authors' compilation, see this study.

6.4 Results

A time series of potential additional costs for the 'adapt' and 'no adapt' scenario is given in Figure 1. 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. These results show that by the end of the century the annual additional costs for road rehabilitation and repair will be approximately ZAR19 billion more for the UCE 'no adapt' scenario, but only ZAR6 billion for the L1S 'no-adapt' scenario and ZAR4 billion for the UCE 'adapt' scenario. These 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. These costs also do not include the indirect costs due to road closures or the opportunity costs of reduced funds available for the construction of new roads or upgrading of existing roads and other public facilities.
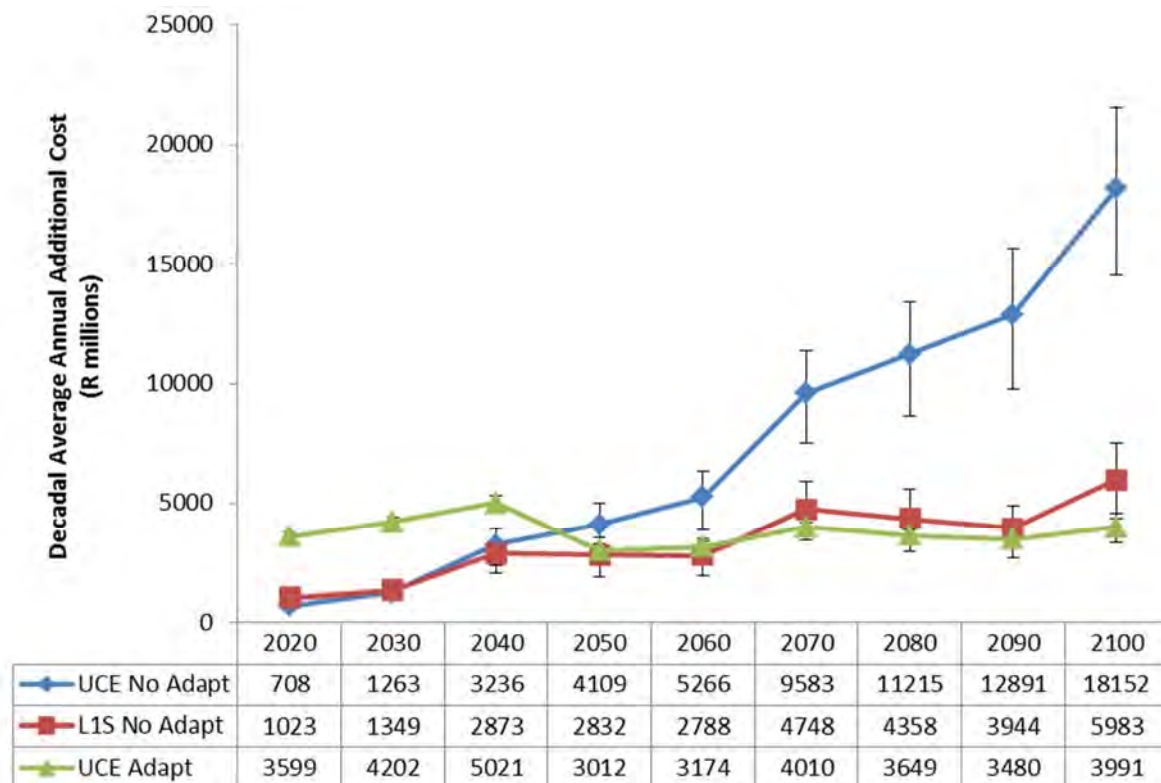
Figure 51: Median decadal average annual additional costs (ZAR millions) on the roads infrastructure of South Africa for the 'adapt' and 'no-adapt' management scenarios under the UCE and L1S climate scenarios. Whiskers represent one standard deviation in the results for individual climate models

Source: Authors' compilation, see this study.

The range of outputs from the different impacts and adaptation scenarios on the average annual additional cost for rehabilitation and repair are given in Figure 51. 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 ZAR94 billion by 2100.

There is, however, a wide range of possible outcomes with some models predicting a cumulative impact cost of up to ZAR 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 ZAR 46 billion. These results highlight the importance of considering the potential climate change impacts on the roads infrastructure for South Africa.
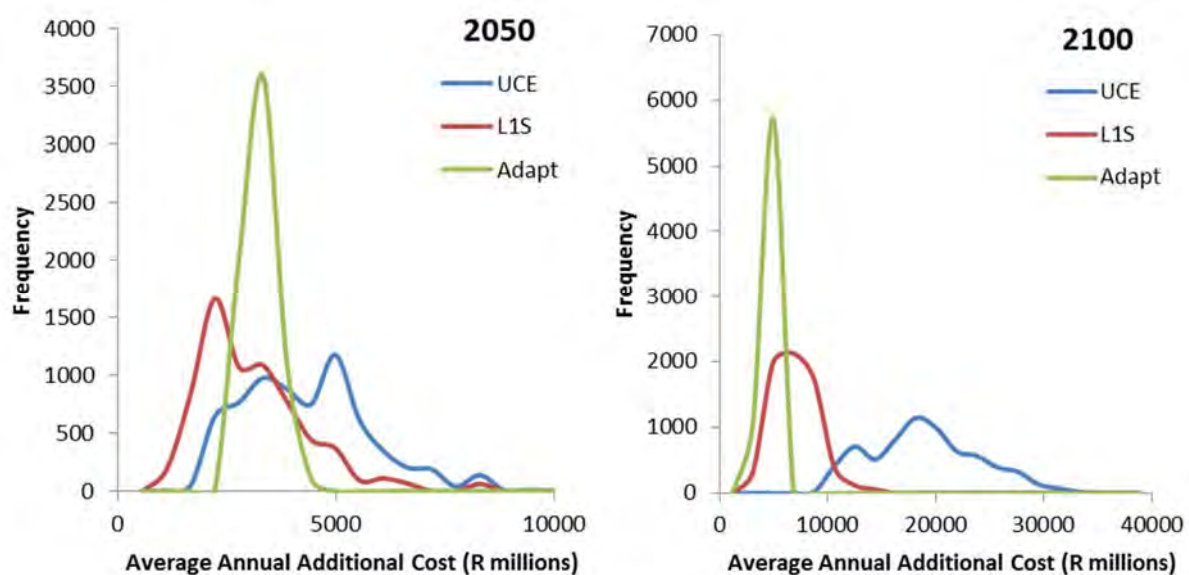
Figure 52: Range of potential impacts of future climate change scenarios on the decadal average annual additional costs for roads infrastructure in South Africa by 2050 and 2100 under the 'adapt' and 'no adapt' management scenarios

Source: Authors' compilation, see this study.

The variation in the potential impact of climate change on road maintenance costs for the difference provinces by 2100 is shown in Figure 52. The greatest impact under the UCE scenario is in the Eastern Cape which has the largest number of roads in total. The second most significant impact is in Gauteng, which although having the least amount of total road network has 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 53: Average annual additional costs for the final decade of the century (2095 to 2105 by province for the UCE and L1S 'no adapt' scenarios and the UCE 'adapt' scenarios. Values shown are the median of the HFD climate scenarios and the whiskers represent the range of potential impacts from the 5th to the 95th percentile of the modelled scenarios

Source: Authors' compilation, see this study.

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These results show the significant benefit of either mitigation (i.e. under the L1S mitigation scenario) or adaptation to climate change with both options resulting in similar reductions in the additional maintenance costs. In some provinces it would appear that mitigation is marginally more beneficial than adaptation (GP and NW), but ideally there should be a combination of both mitigation and adaptation to achieve the greatest benefits.

6.5   Concluding remarks

Climate change will have an effect on the road pavements in South Africa as a result of increased temperatures and precipitation. Some areas will be affected more than others and more specifically the areas where higher temperatures and precipitation are expected as well as areas with a more extensive road network and a higher proportion of more vulnerable gravel roads.

Road binder (bitumen) adaptation will be required within the areas where the higher temperatures are predicted as well as more robust structural pavement designs in areas with predicted precipitation increases. By adapting for increased temperatures, the correct road binder options will ensure that more flexibility is achieved with the ability to cater for more extreme temperatures.

Flooding has serious and more visible impacts as existing road drainage infrastructure in many instances is not able to withstand higher flows. Extreme event adaptation is therefore crucial for flood risk reduction to ensure that potential high intensity precipitation impacts are minimised on the road network. This study considered only the local impacts of increased precipitation and runoff. A more extensive analysis of the potential flooding impacts on catchment hydrology is required for assessment of the potential impacts on large bridge structures particularly on major routes.

Short- and long-term effects of climate change may necessitate shorter maintenance intervals as well as rehabilitation and reconstruction tha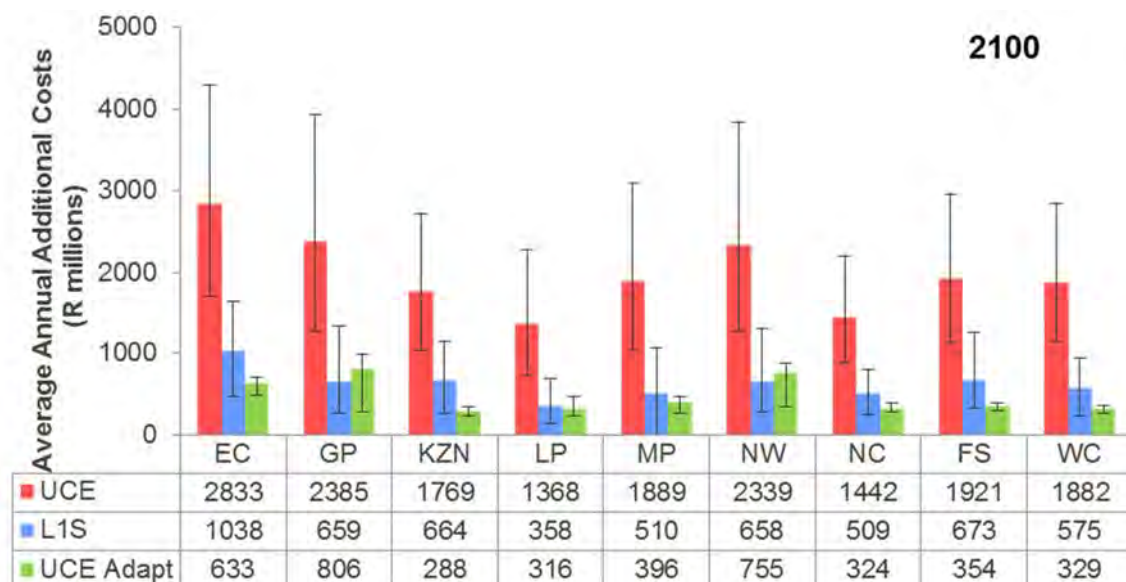t will impact on the budgets of road agencies. Climate change is expected to increase the cost of maintenance and rehabilitation over time, particularly beyond 2040 if an adaptation policy is not adopted in South Africa.

It is imperative that existing infrastructure, which cannot be changed overnight, is differentiated from new infrastructure that is planned. Adaptation strategies could be phased in over time during periodic maintenance or rehabilitation for existing infrastructure, however this is with the assumption that climate change will only change over time.

The 'adapt versus no-adapt' scenario analysis indicates that the annual average cost is expected to:

- Have a high initial input at commencement for the 'adapt' scenario
- Flatten over the decades if adaptation is implemented
- Reach a 'break-even' point in 2040, thereafter costs will increase dramatically for the 'no-adapt' scenario
- Increase dramatically up to 2100 if 'no-adaptation' is taking place.

The initial cost for the 'adapt' scenario relative to the 'no adapt' scenario is approximately ZAR3 billion per year. This represents approximately 7% of the approved total roads budget of ZAR42 billion for the financial year 2013/2-14. 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 life time 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 the climate change impacts start to become really significant.

Further analysis based on regional climate models is also required to further develop the impact scenarios and to identify the key areas of concern, such as the Eastern Cape Province. A regional assessment of the potential impact of flooding events on major bridges is also required particularly on the major transport routes in South Africa. These impacts are already being felt with the resent wash out of the N2 near Grahamstown in the Eastern Cape.

7 Sea level rise

7.1 Introduction

Recognising that climate change has economic consequences is important and economic assessments of climate change costs have become increasingly popular since the celebrated Stern Revue in 2006. A 2010 World Bank Study put the cost of adapting to a 2°C warmer world in 2050 at US$70-US$100bn per annum between 2010 and 2050, and suggested that as much as 80% of that cost would be carried by cities in developing countries (World Bank 2010). Such studies are, however, also fraught with difficulty particularly at the local scale where predicting exact climate change impacts and their economic consequences is complicated (Tol 2012; Cartwright et al. 2013). This is a problem; it is at the national and sub-national scale that climate change adaptation is most effective and where decision makers confront difficult tradeoffs around the allocation of scarce resources in an attempt to both enhance and secure human livelihoods.

This report sets out to establish the cost of sea level rise to the South African economy between 2010 and 2050 in the absence of adaptation, with the intention of ensuring proportionality when it comes to responding to this risk. The report begins with an outline of the global and national sea level rise context, followed by summaries of five pieces of recent sea level research at specific locations along the 2798 km of South African coastline. It is clear from this summary that there is no single approach or set of assumptions applicable to estimates of either the extent of sea level rise or its economic impact in South Africa. However, drawing on the extent of existing research, a set of assumptions for a 'high' and a 'low' sea level rise scenario was developed. The assumptions were used to calculate the cost of sea level rise in terms of public infrastructure, private real estate and tourism over the forty year period, for the two scenarios. The results are discussed below and summarised in Table 7.

Table 7: Summary of cost of sea level rise to South Africa by 2050

	Low		High	
	Inundation 0.25 m	Swash 2.50 m	Inundation 0.50 m	Swash 4.50 m
Area affected (km^2)	400.0	1,307.0	575.2	1,976.0
Public infrastructure (ZAR bn)	2.0	2.4	8.0	6.4
Private real estate and assets (ZAR bn)	0.0	25.5	56.0	57.8
Lost tourism revenue (ZAR bn)	20.4		4.8	
Total cost (ZAR bn)	50.5		169.0	

Source: Authors' compilation, see this study.

7.2   Global and South African sea level rise

Atmospheric concentrations of carbon dioxide are approaching 400 parts per million, a level that the World Bank (2013) and Jim Hansen, a scientist with NASA's Goddard Institute, believe pushes the planet beyond the 'tipping point' and guarantees atmospheric warming of an intensity and pace that is unprecedented in the past 120,000 years. One of the multiple changes that is anticipated as a result of an anthropogenically warmed global climate is a rise in sea level. Mean global sea level has already begun rising; over the 20th century mean sea level rose 0.17 m (with a range of 0.12m-0.22m). Significantly the rate of this rise was seen to accelerate towards the end of the century.

Records show that sea levels and atmospheric temperature have fluctuated in correlation during the Earth's history. During the Pliocene, three million years ago, sea level was about 25-35 m higher than today, while temperatures were just 2-3°C warmer (Dowsett et al. 1994). 40 million years ago, the Earth was almost ice-free, due to elevated CO_2 levels and sea levels were around 70 m higher than today. In spite of these records sea level rise has, until recently, been assumed to be one of the less critical climate change risks for all but a few small-island states. The IPCC's Fourth Assessment Report (2007) anticipated a rise in mean sea level of between 18 to 59 cm by 2100. This projection was based predominantly on thermal expansion of the oceans. Subsequent work has focused on the role of melting terrestrial ice-sheets, particularly the West Antarctic and Greenland ice-sheets and the thick arctic ice sheets,[1] and the interaction between sea level rise and other meteorological events such as terrestrial flooding and storm-surge. In late 2012 Stefan Rahmstorf used data from satellites, which are perceived to be more accurate than localised sea-gauges, to establish that ocean surfaces are rising on average at 3.2 mms per annum, as opposed to the IPCC's previous estimate of 2 mm per annum. This more recent work suggests that the IPCC's 2007 projections may have been too conservative and that at particular locations during specific (sometimes short-lived) periods of storm surge and high tides, the sea levels that locals experience could be an order of magnitude greater than the IPCC projections.

South African assessments of the rate of sea level rise along the 2798 km of coastline rely on tide gauges. In 2009, Mather et al. drew on a wide set of gauge readings to report that sea levels along South Africa's west coast were rising at 0.42 mm per annum, while those along the east coast of the country were rising at 3.55 mm per annum, and that levels along the south-western and southern Cape coast were rising at 1.57 mm per annum. Earlier work by Searson and Brundrit (1995) relied on a decade of readings in Simon's Bay (West Coast) to suggest that sea levels in that region (south-west coast) were rising at 2 cm per decade – similar to the estimated rates of global sea level rise at the time.

7.3   Existing South African sea level rise research

Sea level rise projections are necessarily assumption-dependent. In order to ensure that the assumptions applied in calculating the economic impact of sea level rise on South Africa are appropriate, it is important to take stock of preceding work on this issue.

Developing country study by World Bank

In a 2007 study Dasgupta et al. (2007) reviewed the extent of sea level rise risk for 84 coastal developing countries on behalf of the World Bank. The approach used GIS overlays of 1-5 m sea level rise events and data for population, agriculture, urban extent, wetlands, and GDP, to compile

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[1] Greenland's ice sheets are melting more quickly than anticipated, largely due to the previously under-estimated influence of friction between ice sheets as they melt. In addition thick arctic sea-ice was not projected to melt until the end of the 21st century, but more recent projections suggest it may have disappeared by 2035 (Le Page 2012).

an index of risk across the countries. The research did not take urbanisation trends into account. In the study South Africa ranks 24th out of 29 sub-Saharan countries in terms of the proportion of the country exposed, which suggested that less than 1% of the total population may risk exposure to a 5-metre increase. The Dasgupta et al. (2007) study represents an important global comparison and early reference point, but appears to under-estimate the extent of population and economic activity that is either located in the coastal zone or is directly dependent on the coastal zone for transport routes, ports, and economic linkages in South Africa.

City of Cape Town – Environmental resource management department

In 2008, the City of Cape Town drew upon work by University of Cape Town's Professor Geoff Brundrit, to model sea level rise along its 307 km coastline (including park areas not under the City's jurisdiction). The 2008 research drew on data for Highest Astronomical Tide (HAT) and past storm-surge events to model the impact of a 2.5 m, 4.5 m, and 6.5 m storm surge event.

It was not anticipated that the flooding scenarios would impact the entire Cape Town coastline at the same time. Applying a set of assumptions that were (by the authors' own admission) based on the inadequate data available at the time, the study put estimates to the cost of sea level rise risk in Cape Town that ranged between ZAR4.9 and ZAR20.2 billion over the ensuing 25 years (see Table 8).

Based on this study the City of Cape Town proceeded to identify 19 critically exposed 'hotspots' and paid particular attention to the reasons why these locations were vulnerable – including 'imprudent development' and 'exposure to wave set up and run up' (Brundrit and Cartwright 2010). Cape Town also conducted significant work on the engineering, biological, and institutional measures that could be applied to reduce the risk of sea level rise. This research has led to the tabling of a coastal set-back by-law (as required by South Africa's Integrated Coastal Management Act, ICMA) and the demarcation of a coastal over-lay zone.

Table 8: Value of sea level rise risk for three different scenarios from the Cape Town study

	Assumed prob. of occurring in the next 25 years	Value of real estate at risk	Value of tourism revenue at risk	Value of public infrastructure at risk			Total potential cost to the city	Value of the risk to the city
				Stormwater	Roads	Electricity		
Scenario 1 - 2.5 m	0.95	ZAR3,255 billion	ZAR750 million	ZAR167.3 million	ZAR900 million	ZAR94.8 million	ZAR5,167 billion	ZAR 4,908 billion
Scenario 2 – 4.5 m	0.85	ZAR 19,459 billion	ZAR1.44 billion	ZAR408.25 million	ZAR2,197 billion	ZAR230,2 million	ZAR23,734 billion	ZAR20,174 billion
Scenario 3 – 6.5 m	0.20	ZAR 44,460 billion	ZAR3.60 billion	ZAR635.80 million	ZAR5,702 billion	ZAR358,6 million	ZAR54,756 billion	ZAR10,951 billion

Source: After Cartwright (2008).

Eden District Municipality – DEA&DP, Western Cape government

In 2010 Umvoto (Pty) Ltd undertook a qualitative sea level rise risk assessment of the 370 km of Southern Cape coastline in the Eden District Municipality on behalf of the Provincial

Government's Department of Environmental Affairs and Development Planning. The study assessed the probability and impact of coastal erosion, groundwater contamination, and extreme storm surge events in order to rank the relative risk at 43 different zones within the district municipality. Unsurprisingly, the study found risk to be highest in areas where investment in coastal property was high, and identified the Sedgefield-Swartland region, Wilderness West, Wilderness East, and the Knysna region as being most at risk. The study did not project sea level rise in the region and did not put an economic value to the risks.

The focus in the Eden study was on the 'Present worst case…sea level rise scenario'. This was described as a sea level raised 140-150 cm caused by the 18.6 year HAT and a simultaneous 50-60 cm caused by meteorological forcing. The study describes this as a 1:500 year event, but suggests that this could become, 'A 1:30 year event by the end of the next decade, or a one in every two-week event by the end of the century as a result of a higher base sea level…'. Importantly the study set-about trying to establish the areas in which wave action was focused by the coastal topography resulting in temporary 'swash run-ups' of 4.5-6.5 m. Witsands, Skurwebaai, and Stilbaai, for example, were identified as being exposed to these types of high seas, and as having coastal property and roads 50-70 m from the current shore-line that were exposed to storm surge.

KwaZulu Natal - eThekwini municipality

The City of Durban's efforts to understand its sea level rise risk were focussed by the severe storm surge event that caused 'hundreds of millions of rands' worth of damage (Mather 2007). The event which took place on 19 and 20 March 2007 was generated by an off-shore low pressure system coinciding with the 18.6 year HAT. The passing of cyclones Dora and Gamede did not coincide exactly with the high tide, but did generate wave heights of 8.5 m at the CSIR buoy 30 m off-shore and contribute to elevated sea conditions (Mather 2007).

Subsequent work in Durban has focussed on establishing a model that accurately predicts the extent of wave run-up along the KZN coastline (Mather 2011) in an attempt to comply with ICMA and introduce a coastal set-back line. The approach relies on the relatively constant relationship between the distance off-shore at which the sea is 15 m deep and the distance inland that storm surges encroach. This research is important in identifying vulnerable areas, but does not on its own give an indication of sea level rise risk or the value of assets that are at risk from sea level rise.

Overberg municipality – DEA&DP

Research commissioned by the Western Cape Department of Environmental Affairs and Development Planning in the Overberg District Municipality, in which Andrew Mather was a lead researcher, focused on establishing an appropriate coastal set-back line. The study was based on observations of significant wave heights at Slangkop off the Overberg coast of 9.1 m (with an annual return period) 11.1 m (with a 50-year return period) and 11.7 m (with a 100-year return period). In the Overberg study, sea level rise was estimated to be 1 m over the course of the 21st century. This rise was anticipated to cause erosion, and the landward retreat of sandy sections of the coast. The research suggested a landward movement of the 'safe zone' of 2 m per annum over the 21st century, and accordingly recommended that the set-back line move landward by 200 m over the century (orange line in images below). Although the Overberg study produced maps of 'damage zones' it did not convert these into into a GIS application that would have enabled an estimate of the amount of land affected or the value of this land.

7.4   Making sense of South Africa's sea level rise

South Africa's coastal zone is valuable for ecological, social and economic reasons. The economic value relates directly to real estate, tourism, and infrastructure located in the coastal zone and indirectly to risk reduction offered by coastal buffers, fish breeding grounds, and heritage value. The actual value given to these coastal goods and services is subjective – it varies between people – but it is apparent that changes in sea levels caused by rising atmospheric temperatures over the past century, threaten a significant extent of this value.

It is reasonable, then, to try and anticipate the extent of sea level rise damage and to establish the economic cost of this damage, so as to mobilise a proportionate response to this risk. In theory, such an effort requires a probabilistic projection of sea level rise events, an identification of the economic value that is destroyed by this rise and the use of discount rates to convert future costs into a net present value. In practise it is clear that there are many different approaches (even within South Africa) to gaining a reasonable sense of damage and the scale of response required.

A review of existing practise reveals that the actual process of quantifying sea level rise risk is remarkably difficult for a number of reasons:

- **Multiple parameters generate uncertainty**: Measuring sea level is difficult and making sea level rise projections is fraught with uncertainty. Rahmstorf (2012) concludes that, 'Physical modelling of sea level rise does not yet provide reliable results' and encourages instead 'semi-empirical methods'. A part of the difficulty is that mean sea level changes for a variety of reasons: (i) Increasing volume of the water mass though thermal expansion and contraction – a process that lags changes in atmospheric temperature by a few hundred years. (ii) Adding or removing water mass; the principle change here comes from terrestrial ice-melt. Melting sea-ice does not make a significant impact on sea levels. Mass addition (or removal) can also come from storage of water in human-built reservoirs, which corresponds to about 3 cm worth of sea level over the past century (Chao et al. 2008), or from pumping up water from deep aquifers for irrigation purposes which ends up in the ocean (Wada et al. 2010). (iii) Changing the depths of ocean basins though continental shift or through the lifting of continents as terrestrial ice melts and continents rise. Current estimates of this influence are for a drop in oceans of 3 cm per century.

- **The sea is not, and is never, level**: Even where sea levels are known, the impact of sea level rise tends to be associated with storm surge events that coincide with high tides. While tidal flux is perfectly predictable, the meteorological phenomena that generate storm surges are not predictable with any level of accuracy over the medium and long term. Figure 54 taken from Simon's Bay on South Africa's south-west coast, shows that relatively small changes in mean sea level caused by global warming can have disproportionately large impacts on the return time of storm surge events generated by meteorological phenomena. This makes predicting exactly when sea level rise damage will occur impossible.

**Port Diagram
Simon's Bay**
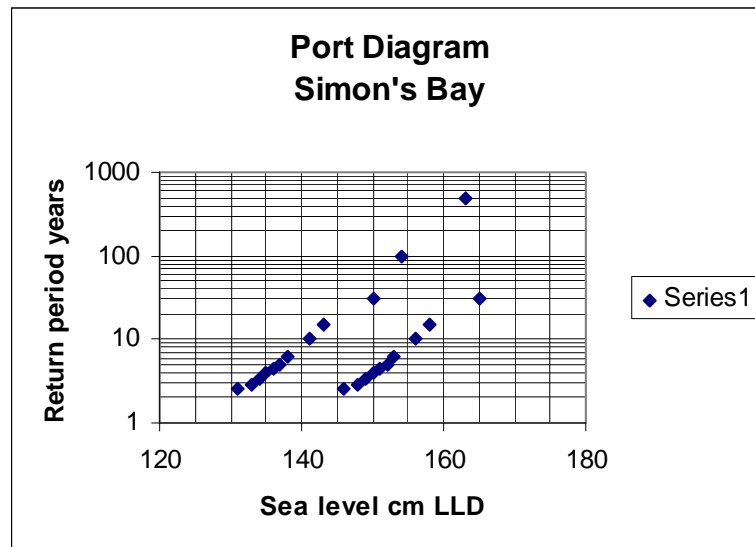
Figure 54: Return period of extreme sea levels expected in sheltered areas at the present time, and after sea level rise of 20 cm. The figure shows that return times of extreme sea level events are a log function of land levelling datum; small changes in land level

Source: After Mather et al. (2007).

- **Economic impact can be difficult to predict**: Where economic data are poor or where GDP data are a poor proxy for economic well-being (due to high levels of informality, dependence on subsistence activities that are heavily dependent on ecosystem goods and services or where inequality is a definitive feature of society) discerning the economic consequences of a bio-physical event can be complicated. Furthermore it is difficult to predict how institutions and people will react to sea level rise, and whether their reactions will amplify and spread the risk and cost, or curtail it. New and Hulme (2000) describe the 'cascade of uncertainty' (Figure 55) that ensues as assumptions about atmospheric green-house gases interact with assumptions about equally complex ecological, institutional, and social systems to produce a local impact. As a result it is very difficult to construct a damage function that translates rising temperature (or mean sea levels) into foregone GDP (Cartwright et al. 2013). This is not due to poor science, but rather the inherent 'unknow-ability' that characterises the interaction of complex systems and the generation of systemic risk.
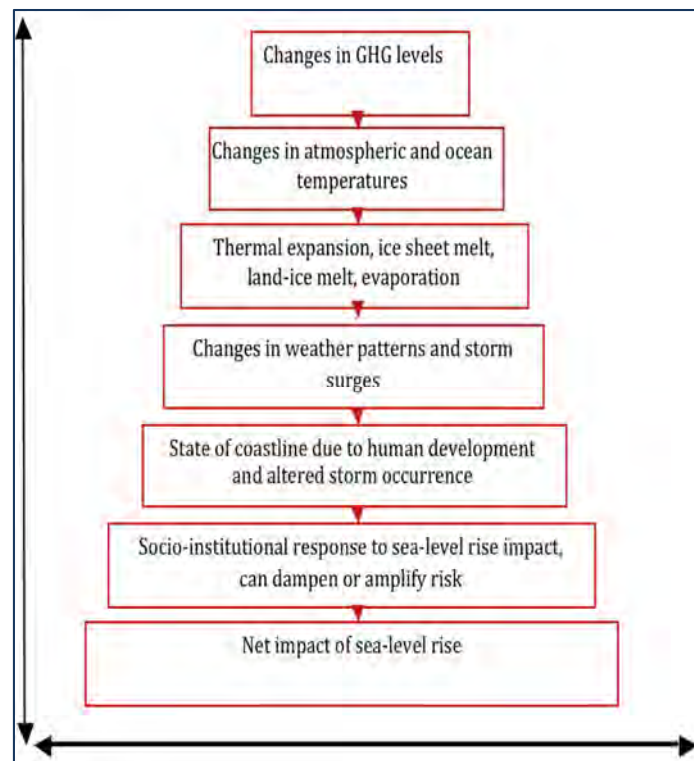
Figure 55: The 'cascade of uncertainty' that characterises downscaled efforts to predict climate change impacts. Uncertainty, depicted along the horizontal access, increases as assumptions are localised

Source: Adapted from New and Hulme (2000).

This does not necessarily mean that sea level rise risks assessments are futile. On the contrary, putting economic estimates to sea level rise can be useful in order to generate a sense of scale and perspective, to reiterate the reality that climate change has real economic consequences and to mobilise action. What is required, then, is a set of plausible assumptions applied in a transparent manner.

In South Africa there is a case for building on Cape Town's approach of selecting a range of sea levels for inundation and swash run-up by 2050, identifying the key public infrastructure and public and private real estate that is at risk and generating estimates for tourism losses, as proxies for economic impact. The assumptions that underpin estimates of sea level rise impact to South Africa's 2798 km of coastline need to be agreed upon. The section below describes the assumptions applied in doing this.

7.5 Model assumptions

Ongoing research has revealed an increasingly wide range of projections for mean sea level rise by 2050, but there is some consensus that the current rate of increase in South Africa is between 1.5-3.5 mm per annum and that the rate of increase is accelerating. The state of existing knowledge does not permit precision, and attempting to be over-precise can conceal important uncertainty, lead to a false sense of confidence and undermine the case for ongoing measurement.

It seems clear, however, that the zone of land that is exposed to inundation and storm surge activity is moving landward in South Africa, and that the area that might be considered at risk of some form of sea level rise damage is, in most instances, expanding.

In order to capture the economic impact of this change the following assumptions have been developed drawing on existing research.

Assumption 1 – Eustatic rise: It is reasonable, for the purpose of an economic assessment, to assume that mean sea level will be one metre higher at the end of the 21st century than at the beginning. This increase will change the dynamic interaction between the sea and the coastline, and lead to new erosion equilibria and shoreline retreat. At the most basic level, however, it will lead to inundation of all land and infrastructure that is located within 1 m contour of the long-term mean sea leve.l[2]. For the purpose of this study, which adopts a 2050 time horizon, it is assumed that mean sea level will have increased by between 0.25 m (min) and 0.50 m (max) relative to 2010.

Assumption 2 – Swash run-up: The non-linear relationship between eustatic rise and the height attained by swash run-up. The implication is that the increase in mean sea level will generate high levels of swash even if local meteorological forcing of the sea level is assumed to be unchanged by climate change. Given that the platform of mean sea level is anticipated to be raised by 0.25 m and 0.50 m by 2050 ('low' and 'high' scenarios) the corresponding increases in swash run-up by 2050 are assumed to be 2.50 m and 4.50 m, respectively, relative to 2010. Swash causes periodic damage that typically coincides with the duration of a storm or a high tide. As a result the extent of damage caused by swash is significantly less than that caused by inundation (see Assumption 6).

Assumption 3 – Public infrastructure loss: The value of public infrastructure is reported by all municipalities in terms of the Municipal Finance Management Act. eThekwini Municipality, for example, reported its assets to be worth ZAR 100 billion in 2008 (see Table 9). Given the rate of new investment (especially around the 2010 World Cup), depreciation and inflation, it is assumed that this asset value would have increased to roughly ZAR 120 billion by 2013. Figures for Cape Town's public infrastructure in 2009 report similar depreciated asset values: stormwater infrastructure at ZAR 4.2 billion, road infrastructure at ZAR 30 billion, for example.

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2 Establishing the long-term mean sea level is not easy, and a part of the difficulty of calculating sea level rise.

Table 9: Depreciated value of eThekwini's public assets in 2008

Asset group	Replacement value (ZAR billions)
Roads	32,5
Water	13,5
Buildings	13,0
Electricity	11,5
Sanitation	10,0
Costal and stormwater	9,5
'uShaka etc'	7,0
Land	0,8
Durban solid waste	0,7

Source: eThekwini Municipality, South Africa.

For the purpose of estimating sea level rise damage, depreciated value is less appropriate than replacement value. As a rule of thumb for city assets in South Africa, replacement value is 2-2.5 times the depreciated value.

For the purpose of this study, the total replacement value of public infrastructure in South Africa's four coastal metropolitan municipalities is considered to be worth ZAR500 billion. Although coastal zones contain a disproportionate amount of infrastructure, most of this infrastructure (with the exception of the ports, a few transport routes located on wave-cut platforms such as the Cape Town-Simons Town railway line) is not located within 0.50 m of the mean-sea level in 2010. The model assumes that 0.25% of total public infrastructure value in coastal municipalities will be affected by a 0.25 m rise and 1% of total public infrastructure value will be affected by a 0.50 m rise. Similarly 4% and 8% of public infrastructure value will be affected by a 2.50 m and a 4.50 m swash event, respectively, although the extent of damage caused by swash and by inundation will differ markedly (see Assumption 6).

Assumption 4 – Private real estate values (including privately owned infrastructure): Estimating the extent of real estate affected by sea level rise requires a GIS shape-file of the area of land above the 2010 high-water mark affected by 0.25 m, 0.50 m, 2.50 m, and 4.50 m of sea level rise, respectively. Generating these shape files is not easy given that there is no existing high level survey of the whole of the South African coastline. Previous studies have relied on high resolution LiDAR surveys for accurate modelling of the coastal zone.

For this study numerous data sources were used resulting in reasonable representation of the national ground elevations below 10 m above sea level for the whole coastline. While this gives a first order estimate of the amount of land below a specified height above sea level and was used to provide estimates of impacted areas given in Table 10, it is important to note that many local features, particularly resulting from hard engineering and coastal infrastructure means that the inundated areas are likely to be an over-estimate of the area truly at risk. On the other hand, the model also does not account for coastal processes such as slope value that could result in areas

currently not below a given elevation being at risk, becoming at risk due to increase in sea level and storm surges.

Table 70: Area of land and private property respectively affected by varying increases of mean sea level along the South African coastline

Adjusted MSL	0.25m	0.5m	1.0m	1.5m	2.0m	2.5m	3.0m	3.5m	4.0m	4.5m
Affected area (km^2)	400	575	804	983	1149	1307	1465	1625	1792	1976
Pvt. real estate affected (km^2)	150	300	428	538	630	761	835	950	1061	1293
Percent of LM affected	0,25%	0,36%	0,50%	0,61%	0,72%	0,82%	0,91%	1,01%	1,12%	1,21%

Source: Authors' compilation, see this study.

Cadastral maps have been used to identify the extent of affected land that is privately owned (see Table 71). In order to attach values to the real-estate and private assets that would be affected by respective levels of sea level rise, a distinction was made between the land adjacent to:

- The 600 km of metropolitan municipality coastline (Cape Town, Nelson Mandela Bay, East London, and Durban)
- The 800 km of coastline developed as towns (such as Hermanus, Knysna, and Richards Bay)
- The 1400 km of relatively undeveloped land on the west, south and east coast in which there is little infrastructure within the coastal zone and where real estate is cheap
- The 4 km of coastline developed as ports.

Mean values per kilometre squared of coastal property were obtained for these four coast types. However, it is apparent that the area affected by inundation (in particular) and swash is atypical of coastal real estate in metros, town etc. The shape-files reveal that much of the affected area consists of estuaries, islands in estuaries, and land that is known to be at risk. As a result real estate in this zone is not as expensive as average real estate in the region, and the extent of private sector assets is typically less than average. Accordingly, the applied value of real estate and assets has been adjusted downwards to reflect the mean value of land in the affected zone. Land below 0.25 m above mean sea level in 2010, for example, is assumed to have a real estate value of ZAR0.00/m^2 while metropolitan real estate that within 0.50 m of 2010 mean-seal level is assumed to have a value of ZAR225/m^2 once privately owned assets on that land are included (see Table 11).

Table 11: Mean price of real estate and assets in four coastal areas and mean price of real estate affected by sea level rise in four coastal areas[3].

	Mean price of real estate and assets (ZAR bn/km^2)	Mean price of affected real estate and assets below certain levels (ZAR bn/ km^2)	
Metros	0.9	Below 0.25	0
		Below 0.5 m	0,225
		Below 2.5 m	0,450
		Below 4.5 m	0,675
Towns	0.6	Below 0.25	0
		Below 0.5 m	0,150
		Below 2.5 m	0,300
		Below 4.5 m	0,450
p	0.01	Below 0.25	0
		Below 0.5 m	0,013
		Below 2.5 m	0,025
		Below 4.5 m	0,038
Ports	0.7	Below 0.25	0
		Below 0.5 m	0,175
		Below 2.5 m	0,350
		Below 4.5 m	0,525

Source: Authors' compilation, see this study.

By multiplying the area of affected privately owned land by the adjusted value of that land, the cost to private real estate has been calculated for various sea levels that are of interest.

Table 12: Cost to private real estate of increased sea levels

Adjusted MSL	0.25 m	0.5 m	2.5 m	4.5 m
Cost to private real estate and assets (ZAR bn)	0	56.0	254.7	577.6

Source: Authors' compilation, see this study.

The figures reported in Table 12 above are for inundation. That is they assume mean sea level will increase by the reported amount. In reality the figures of 2.5 m and 4.5 m reflect the height of

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[3] Mean affected price is lower than mean price as much affected land is within existing damage zone.

swash by 2050. Damage caused by swash is assumed to be considerably less than damage caused by inundation due to the temporary nature of swash (see Assumption 6).

Assumption 5 – Tourism losses: South Africa's tourism industry is significantly supported by the coastal zone and access to beaches in particular. Experiences from the Kwa-Zulu Natal 2007 storm surge suggest that beaches and the tourism industry have a propensity to recover following a storm, but that short-term losses are incurred. In 2012 tourism's direct contribution to South African GDP was roughly ZAR85 billion.[4] If one assumes that 40% of this tourism revenue is the result of our coastline and that sea level rise has the ability to cost on average 2% of coastal tourisms revenue between 2010 and 2050 then, in the absence of adaptation, the annual impact of unchecked sea level rise on tourism is likely to be ZAR0.51 billion and ZAR1.02 billion for the low and high scenarios, respectively (expressed in real 2013 prices). The cumulative impact on tourism (in 2013 prices) between 2010 and 2050 would be ZAR2040 billion and ZAR4080 billion assuming no increases or discounting of future tourism earnings.

Assumption 6 – Inundation and swash damage: Damage to public infrastructure and private real estate caused by inundation (0.25 m under the 'low' scenario and 0.50 m under the 'high' scenario) is assumed to be permanent and absolute. That is, inundation destroys all value. In contrast, damage caused by swash is minimal; things get wet and wave action causes destruction, but much of the value is restored when the storm surge and high-tide subside. In the model, swash only destroys 10% of the value of public infrastructure and private real estate that it encounters.

7.6   Results

Sea level rise projections are assumption-dependent. It is for this reason that this report goes to lengths to establish and describe assumptions in the model. The results represent a proxy for the economic cost caused by sea level rise under a 'high' and 'low' scenario between 2040 and 2050. This cost is to be inserted into the macro-economic model that is being applied in the broader assessment of climate change impacts on flooding and drought in South Africa.

In the model, economic cost is comprised of damage to public infrastructure, private real estate and assets, and tourism impacts. Two scenarios are applied: 'high' is comprised of a 0.50 m rise in mean sea level and results in swash run-up of an additional 4.5 m above the 2010 sea level, 'low' involves a 0.25 m increase in mean sea level and an additional 2.5 m of swash run-up. The results are summarized in Table 3 as the combined cost between 2010 and 2050 of sea level rise for a 'high' and 'low' scenario.

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4 http://www.thedti.gov.za/trade_investment/tourism.jsp

Table 13: Summary of results for sea level rise impact

	Low		High	
	Inundation 0.25 m	Swash 2.50 m	Inundation 0.50 m	Swash 4.50 m
Area affected (km^2)	400.0	1,307.0	575.2	1,976.0
Public infrastructure (ZAR bn)	2.0	2.4	8.0	6.4
Private real estate and assets (ZAR bn)	0.0	25.5	56.0	57.8
Lost tourism revenue (ZAR bn)	20.4		4.8	
Total cost (ZAR bn)	50.5		169.0	

Source: Authors' compilation, see this study.

7.7 Concluding remarks

The costs amount to ZAR1,26 billion and ZAR4,22 billion annually if the damage is assumed to be distributed equally over the 40 year period. This should not be interpreted as 'impact on GDP' – an estimate that will emerge once this cost has been inserted in the macro-economic model, but to place these estimates in context, this is the equivalent of 1.68% and 5.63% of 2012 GDP over the 40-year period, or 0.04% and 0.14% of GDP annually. The bulk of this cost comes from damage to private sector real-estate and assets, which in South Africa makes up the bulk-share of capital. Tourism losses are also high as an indirect impact of damage to capital and due to disruptions in services and negative perceptions.

The sea level rise cost estimates have not been adjusted for anticipated increases in infrastructure as a result of accelerated investment or growth. Nor has the value of capital been depreciated or the costs discounted according to the convention for economic projections. These adjustments for the time-value of capital and costs are expected to be made by the macro-economic model, but would be easy to apply in this study if necessary.

8 Economic impacts

8.1 Introduction

In this chapter, we present the economic impacts of climate change on the South African economy. We focus on three important impact channels: road infrastructure, water availability, and dryland agriculture. To accomplish this, we draw from assessments of the biophysical impacts of the same climate change futures considered here (i.e. Cullis et al. 2014 and de Jager et al. 2014).

Understanding the economic impacts of climate change is important as it informs long-term planning and policy-making. Given the possible damaging impacts of changing weather and climate patterns, the South African government is in the process of formulating adaptation strategies for the country, known as the Long Term Adaptation Scenarios (LTAS). This macroeconomic assessment seeks to inform this process by identifying the principal channels through which climate change may affect the economy as well as highlight the most vulnerable groups and regions. Results from the study will also set forth areas of future work.

8.2 Literature review

Developing countries are expected to experience significantly larger climate change costs, relative to the size of their economies, than developed economies (Parry et al. 2007 and Ahmed et al. 2009). Some studies point to very strong effects in particular sectors, especially in the latter half of the century. For example, Knox et al. (2012) find that, for Africa, climate change would result in a 40% decline in all crop types by 2050. For Southern Africa, the median decline was estimated to be -11% with the most significant decline occurring for maize crops. Using an integrated modelling framework, research by UNU-WIDER has assessed the impacts of climate change on a number of sub-Saharan African countries including Malawi, Mozambique, Tanzania, and Zambia (see, for example, Arndt et al. 2011; and Arndt and Thurlow 2013). The findings from these studies have shown that climate change impacts on economic growth and development are expected to be negative, especially if global mitigation fails to emerge. While broad ranges of outcomes, including positive outcomes, are typically possible under unconstrained emissions (i.e., absence of global mitigation policy), the bulk of outcomes are for lower levels of activity and income.

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 agricultural sector, using econometric approaches to determine the impact of climate and other variables on net farm revenues (see, for example, Gbetibouo and Hassan 2005; Turpie and 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) provide 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.[5]

These studies fall short of capturing the macroeconomic impacts of climate change, and may omit the impact on other activities, income, and spending. To our knowledge, there are no South African studies that have taken an integrated modelling approach that incorporates biophysical and economic impacts of climate change.

This paper aims to add to the existing literature for South Africa as well as help inform the policy debate around climate change and identify possible mitigation and adaptation options. The paper adds value in that it is the first to consider the overall impacts of climate change on macroeconomic variables such as GDP and employment; and it uses an integrated framework to do so.

8.3 Model description

The integrated modelling framework employed for this analysis is reproduced below. As discussed, the framework begins with changes in climate outcomes as derived from general circulation models of the earth, oceans, and atmosphere. These changes in climate are then passed to a series of biophysical models in order to assess the implications of changes in climate, particularly changes in precipitation and temperature, on outcomes relevant for economic activity. Three impact channels are in particular focus for this study. These are: implications for roads and other transport infrastructure; implications for water availability for municipal, industrial, and agricultural uses (whilst respecting environmental flow constraints), and implications for non-irrigated crop yields.

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[5] Enhanced risk of widespread malaria due to climate change is not included as an impact channel in this analysis due to considerable uncertainties concerning the actual likelihood of spread in future.

These implications are then passed to a detailed economy-wide model of South Africa in order to analyse the implications of climate change for a range of economic outcomes.
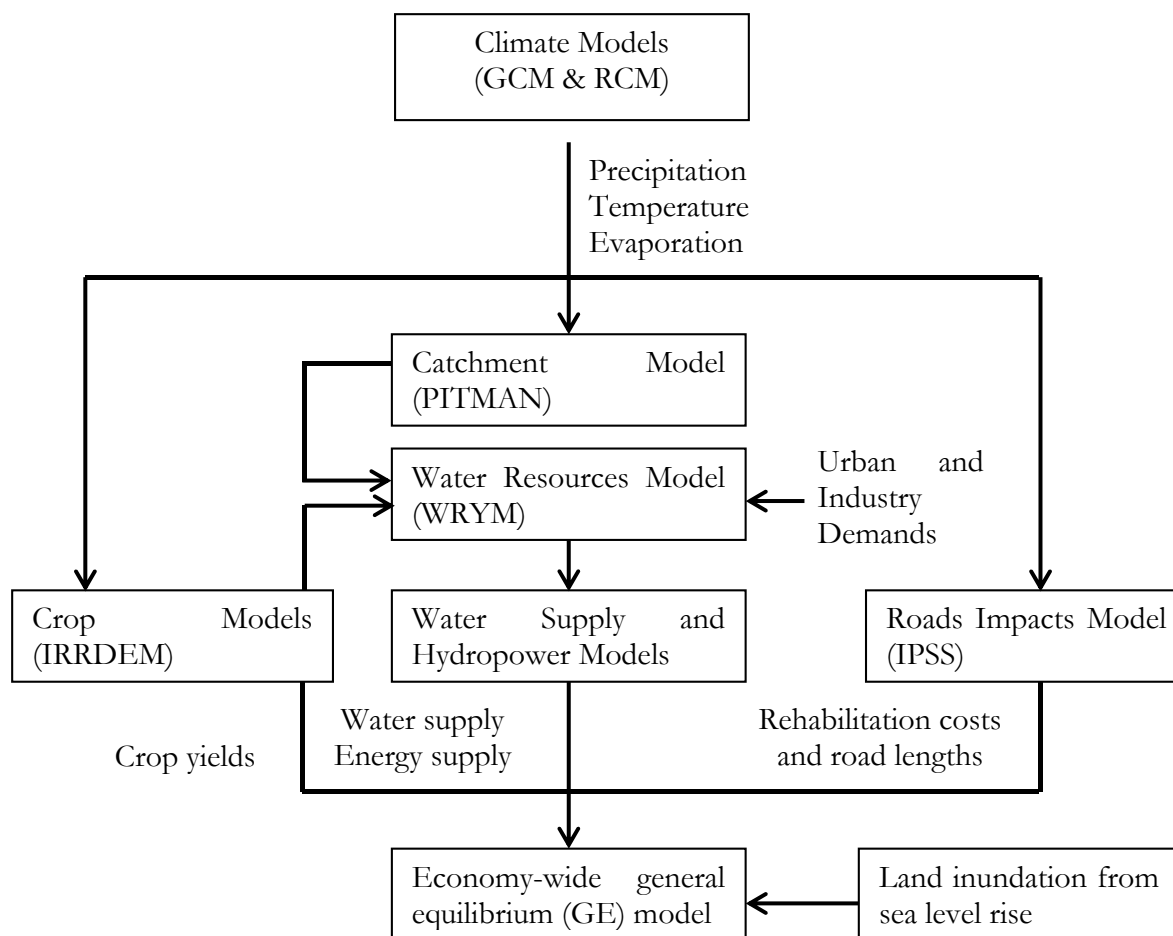
Figure 56: Integrated modelling framework

Source: Authors' compilation, see this study.

Economy-wide models, also known as computable general equilibrium (CGE) models, 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.

A dynamic CGE model is used to simulate the economy-wide impact of the 367 possible climate futures. As noted above, specialised models estimate climate impacts on world commodity prices, road infrastructure, water supply and demand per level of user, and dryland crop yields. These biophysical impacts are linked to the dynamic CGE model, which then determines how resources are reallocated because of these changes. This demonstrates how different activities and institutions respond to changing climate (endogenous adaptation) without deliberate adaptation measures undertaken by government.

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 in period t is driven by savings from period t-1. 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 between dryland and irrigated cultivation. The activities are distributed across each of South Africa's 19 WMAs. Seven factors of production are identified, and are also disaggregated by WMAs. The factors include three labour categories (unskilled, skilled, and highly-skilled), capital, land, agricultural water, and municipal and industrial 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. Labour is assumed to be fully employed and mobile across sectors. 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 the size of the sector) while the existing stock of capital is immobile or fixed within the sector. Agricultural and domestic water and land are also assumed to be fully employed and fully mobile within a WMA but immobile across WMAs.[6]

8.4   Economic structure

The structure of the South African economy, as described in the 2002 SAM, is summarised in Table 14. Real gross domestic product in 2002 amounted to about ZAR1.4 trillion. The majority of expenditure accrues to households, while investment comprises 15% of GDP.

Services account for the bulk of value added and employment. Exports are largely composed of mineral products and machinery. The agricultural sector is a relatively small contributor to GDP and exports. However, it makes up a relatively larger share of employment, at 8.3%.

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[6] Reallocation of water across WMAs is handled in the water resource modeling (WRYM). The economy-wide model takes the supply of available water, after accounting for increased demand due to, for example, the effects of higher temperatures on crop irrigation demand as fixed.

Table 14: Expenditure shares of GDP and sectoral decomposition of production, employment and trade (%).

	Share of Total GDP
Domestic absorption	96.3
Household consumption	62.8
Gov't consumption	18.4
Investment	15.1
Exports	32.8
Imports	29.1

	GDP	Employment	Exports	Imports
Agriculture	4.31	8.25	3.81	2.23
Field crops	1.78	3.20	0.58	1.49
Horticultural crops	0.99	1.81	2.17	0.25
Livestock	1.28	2.94	0.83	0.27
Other agriculture	0.26	0.31	0.24	0.21
Industry	33.38	30.28	76.25	81.56
Mining	8.72	5.81	31.92	11.20
Manufacturing	19.91	18.56	44.33	70.25
Electricity	2.04	1.14	0.00	0.04
Water distribution	0.42	0.20	0.00	0.00
Construction	2.27	4.6	0.00	0.06
Services	62.33	61.47	19.94	16.21

Source: Authors' compilation, see this study.

Regional characteristics of agriculture

As cropping and water use characteristics differ between various WMAs, the agricultural sectors in each region are likely to be affected by climate change in varying degrees. These dimensions, alongside the relative sizes of the different agricultural activities, are important to understand the agricultural impact of climate change on these regions, and the agricultural sector on a national level.

Most cultivated land in South Africa is used for dryland farming, particularly of summer cereal crops. The Vaal region accounts for 52.3% of cultivated land in South Africa, and is comprised mainly of dryland cereal and oilseed crops. The region is responsible for about 61% of the

country's production of summer cereals, 37% of its winter cereals, and 64% of its oilseed crops. Sugarcane is largely produced in dryland fields in the Mvoti-Umzimkulu area, with sizeable irrigated fields in Inkomati, Usutu-Mhlatuze, and Thukela.

Poverty in South Africa is particularly acute in provinces with larger rural populations, such as Limpopo, KwaZulu-Natal, the Eastern Cape, and Mpumalanga. Bhorat and van der Westhuizen (2009) find that these provinces show the highest poverty headcount and poverty gap ratios in 2005. Poverty indicators by Statistics South Africa (2009) for 2008/09 suggest the same.

Table 15: Land use and agricultural production in 2002

	Water Management Area	Planted area ('000 ha)	Dryland (%)	Irrigated (%)	Contribution to national production by crop (%)								
					Summer cereals	Winter cereals	Oilseeds and legumes	Sugarcane	Other field crops	Vegetables	Citrus fruits	Deciduous fruits	Other horticulture
Limpopo	1	227.1	76	24	2	1	7	0	21	6	3	0	1
Luvhuvhu-Letaba	2	91.3	4	96	0	0	0		1	20	29	0	26
Crocodile-Marico	3	245.9	61	39	3	3	6		8	7	1	0	2
Olifants	4	420.2	81	19	9	2	4	0	22	7	10	1	0
Inkomati	5	123.0	37	63	1	0	1	12	6	2	9	0	33
Usutu-Mhlatuze	6	226.8	73	27	3	0	3	20	2	1	2	0	8
Thukela	7	173.4	68	32	2	1	3	11	2	1	4		0
Upper Vaal	8	999.1	92	8	16	10	12		0	7	0	0	1
Middle Vaal	9	2 017.4	96	4	31	18	33		9	8	0	0	0
Lower Vaal	10	975.7	85	15	15	9	19		6	4	0	0	1
Mvoti-Umzimkulu	11	404.0	81	19	3		1	57		5	1	0	6
Mzimvubu-Keiskamma	12	52.2	77	23	1	0	7			2	0		3
Upper Orange	13	302.2	75	25	4	7	2		3	1		0	0
Lower Orange	14	121.3	28	72	3	4	0		8	1	0	9	4
Fish-Tsitsikamma	15	133.9	36	64	3	0	0		6	2	26	4	4
Gouritz	16	133.4	60	40	2	2	0		1	1	0	2	1
Olifants/Doorn	17	261.7	63	37	1	10	0		0	18	10	21	4
Breede	18	360.7	61	39	2	12	1		0	3	4	43	0
Berg	19	361.2	68	32	0	19	1		3	5	2	19	4
Total		7 630.3	80	20	100	100	100	100	100	100	100	100	100

Source: Own calculations based on 2002 SAM.

Irrigation water is used predominantly by WMAs with large horticultural and irrigated sugarcane crops. About 96% of Luvhuvhu-Letaba crop land is irrigated, and thus uses 6.3% of South Africa's irrigation water. The Inkomati, Usutu-Mhlatuze, Thukela, and Mvoti-Umzimkulu regions are responsible for 29% of South Africa's irrigation water, due largely to large irrigated sugarcane fields. The Olifants/Doorn, Breede, and Berg areas, which account for 83% of South Africa's production of deciduous fruit, use 22% of South Africa's irrigation water.

Table 16: Agricultural water use, by crop

| | Irrigation water use (million m³) | Share of irrigation water use (%) | | | | | | | | |
		Summer cereals	Winter cereals	Oilseeds and legumes	Sugarcane	Cotton and other field crops	Vegetables	Citrus fruits	Deciduous fruits	Other horticulture
Limpopo	193	33.0	7.5	3.6	2.3	10.9	28.1	8.7	1.3	4.6
Luvhuvhu-Letaba	451	2.9	0.1	0.0	0.0	0.0	31.7	26.7	0.1	38.4
Crocodile-Marico	342	35.4	18.5	17.2	0.0	2.5	18.6	1.5	1.1	5.3
Olifants	339	43.6	13.9	2.6	0.2	8.3	15.6	13.0	2.1	0.6
Inkomati	662	3.4	0.6	0.5	62.9	1.3	1.8	6.1	0.0	23.3
Usutu-Mhlatuze	528	9.3	0.6	0.5	81.0	0.3	2.0	1.3	0.1	5.0
Thukela	312	25.1	6.4	4.7	55.4	0.4	2.5	4.9	0.0	0.6
Upper Vaal	254	54.7	12.6	4.6	0.0	0.2	23.8	0.1	1.6	2.4
Middle Vaal	371	64.3	12.1	4.0	0.0	0.1	17.7	0.1	0.8	0.9
Lower Vaal	552	54.3	28.7	9.1	0.9	5.0	0.3	0.7	1.0	0.0
Mvoti-Umzimkulu	479	6.8	0.4	76.1	8.4	0.7	0.2	7.4	0.0	0.0
Mzimvubu-Keiskamma	34	30.7	1.2	0.0	0.0	0.0	37.8	0.4	0.0	29.9
Upper Orange	271	63.4	28.3	2.0	0.0	1.1	5.0	0.0	0.1	0.0
Lower Orange	407	47.6	18.0	1.6	0.0	2.1	2.2	0.2	22.1	6.2
Fish-Tsitsikamma	371	45.0	1.0	0.1	0.0	0.6	4.3	32.9	11.8	4.2
Gouritz	129	56.0	3.3	0.2	0.0	1.3	13.3	0.4	17.7	7.8
Olifants/Doorn	497	7.5	1.9	0.2	0.0	0.1	26.1	8.8	49.0	6.5
Breede	648	5.6	1.8	0.3	0.0	0.0	3.5	3.2	82.0	3.7
Berg	435	0.8	5.8	0.0	0.0	0.0	8.6	2.1	77.1	5.6
Total	7 275									

Source: Own calculations based on 2002 SAM.

8.5   Description of scenarios

Table 17 presents the scenarios considered. In the modelling, the scenarios build on one another in the order presented. We focus on three of the eight key channels identified by LTAS, namely agriculture, transport, and water. At the outset of the modelling process, these were considered to be the most important in terms of social and macroeconomic impacts hence meriting detailed analysis. The Baseline scenario does not include the impact of climate change while the remainder do. Results from scenario 5 therefore present the aggregate impact of climate change on the South African economy under the LTAS unconstrained emissions climate change scenario. Each scenario is discussed in more detail in the sections below.

As noted, we consider 367 climate futures for South Africa. These are represented by frequency distributions of precipitation, temperature and evaporation and come from the Global General Circulation Models (Schlosser et al. 2011) which is underpinned by the MIT Integrated Global System and the MIT emissions prediction and policy analysis models (Sokolov et al. 2009 and Webster et al. 2012).

Table 87: Summary of scenarios

Scenario name	Description
1 Baseline	This presents the business as usual path for South Africa without annual weather or climate shocks or changes in world prices. No climate change is assumed.
2 World prices	World prices changes to 2050 as projected by Paltsev (2012) are imposed as derived from the unconstrained global emissions scenario.
3 Roads	World prices plus additional costs for rehabilitating and maintaining existing road infrastructure networks. Increased road infrastructure spending negatively impacts productivity. This result is captured by reducing the growth in TFP in accordance with existing literature on the links between transport and economywide productivity growth.
4 Irrigation	Roads plus the impact of climate change on the availability of water by water management area.
5 Dry agriculture (Total)	Irrigation plus climate change temperature and precipitation impacts on the productivity of dryland agriculture.

Source: Authors' compilation, see this study.

Baseline path

The baseline scenario sets out a plausible growth path for the economy in the absence of climate change, based on assumptions on factor and productivity growth rates. Under the baseline scenario, historical weather patterns over the last 50 years are assumed to repeat themselves. In the baseline and in all other scenarios, all categories of labour in all regions are assumed to grow by 2% per annum initially, decelerating in a linear fashion to 1.5% by 2050. Cultivated land is assumed to expand in all areas, initially by 2% per annum, moderating to 1.5% by 2050. Total factor productivity (TFP) is assumed to initially grow at 1% per annum across all activities, declining linearly to 0.5% by 2050.

Water supply is assumed fixed over the time period. It is, however, assumed to be more productive, to reflect the adoption of more efficient technology in light of restricted water supply and an increase in cultivated land. The productivity of both agricultural and domestic water is expected to

grow by 2% each year, moderating to 1.53% by 2053, across all WMAs. Water enters as a factor of production for irrigated agriculture and for a water processing sector that furnishes water to households and for industrial use.

Under these assumptions, South Africa's GDP grows by 4.5% per annum, with the agricultural share of GDP falling to 3.5% in 2050, from 4.3% in 2002.

World prices

In this scenario, we impose the world price changes derived by Paltsev (2012) for fuels and agricultural products. These price changes are taken from the same model that generated the global emissions profile, which drives the temperature and precipitation changes estimated for South Africa in this analysis. Figure 57 illustrates the changes in these prices as imposed on South Africa. While trends in future world prices are difficult to predict, they are potentially important to the analysis. For example, a hotter and drier climate may negatively affect agricultural product supply. A potential endogenous reaction to reduced domestic supply of a commodity would be to increase imports. However, as illustrated in the figure, the price of agricultural commodities on world markets is projected to rise (reversing the 20th century trend of a general decline in the relative price of agricultural products). As a result, the costs of greater reliance on imports are higher and the implications of lower productivity due to climate change are magnified.

This world price scenario serves *as the basis of comparison* from which the economic implications of climate change are inferred.
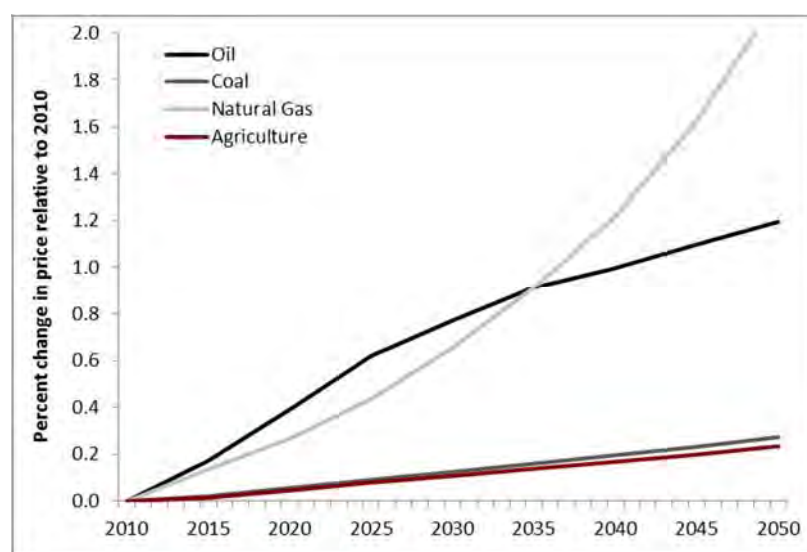

Figure 57: World commodity prices

Source: Own calculations and Paltsev (2012).

Roads

Changes to temperature, precipitation, and runoff can have extensive implications for infrastructure (Chinowsky et al. 2010). In South Africa, road transportation is particularly important as it is used extensively in the production process, sharing extensive forward and backward linkages with other industries. Transport accounts for about 7.9% of commodity input costs across activities in the economy. In agriculture and mining this share increases to 11.5% and 34.5%. Higher temperatures and in some areas increased rainfall could cause significant damage

to road surfaces. In order to maintain the same level of productivity from existing infrastructure, more frequent rehabilitation and maintenance would need to occur.

In this study (Section 6) we estimates that in order to maintain the existing road infrastructure using current material, additional expenditure on roads would have to increase by ZAR3 billion in 2020 rising to ZAR19 billion by 2100 or a cumulative cost of ZAR94 billion (see Figure 58).

Increasing the budget share spent on maintaining existing road networks would mean that funds would have to be directed away from other productive investment such as expanding road networks. To incorporate this impact in the analysis a slower rate of total productivity is assumed relative to the baseline. TFP growth is assumed to vary with the costs of maintaining the road network. On average, the TFP level in about 2050 is than 1 percentage point lower than in the baseline and world price scenarios by 2050. This is considered to be a conservative estimate. Fernald (1999) finds that, for the period 1953 to 1989, road investments in the USA increased total factor productivity by 1 percentage point per annum.
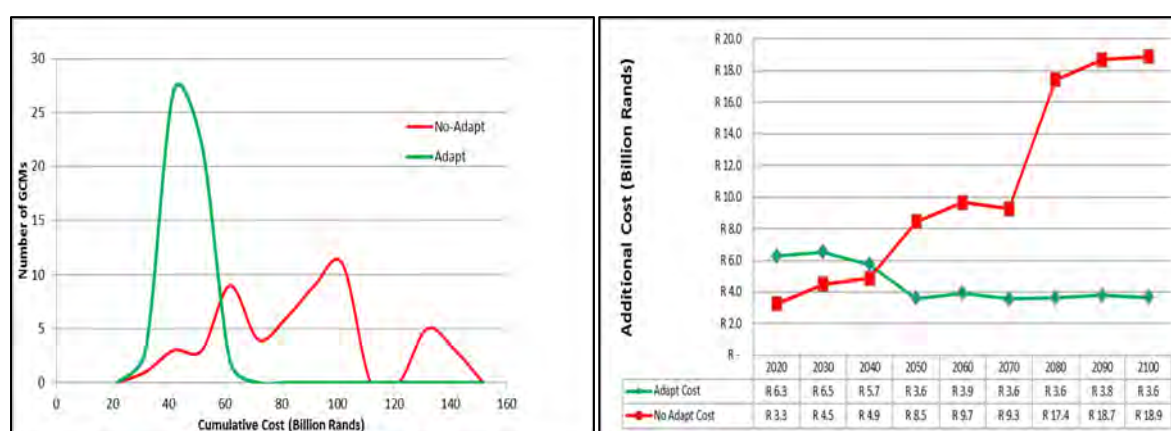

Figure 58: Potential and average costs for road maintenance (median value)

Source: Cullis et al. (2014).

Water for industrial and agricultural use

Decreased supply of water represents a potentially very strong macroeconomic impact channel. This is particularly true if high value municipal and industrial water supplies are compromised. In agriculture, irrigation supports a number of high value added crops. In turn, these crops (such as grapes) are frequently further processed into even higher value commodities (such as wine). An inability to deliver the irrigation water required reduces both the value added generated in agricultural production and the downstream value added generated via processing.

In this study (Section 5) we use a national configuration of the Water Resources Yield Model (WRYM) to estimate the volume of water available for agriculture, urban and bulk industry for each of the 19 WMAs for the alternative climate futures considered. The WRYM includes all major demands on water, including system losses, and also takes into account existing water transfer systems.

While, in principle, the potential for economic disruption due to water shortages is large, the water system appears to be relatively robust to the climate shocks imposed. The results from the analysis show that the impact on aggregate urban and bulk industry is distinctly limited as a result of South Africa's extensive water transfer system. While agriculture is more diffuse and more vulnerable due to the rise in irrigation demand (median annual irrigation demand is estimated to increase by

5% relative to the baseline), this system also appears to be relatively robust in delivering water to meet requirements (aided by increases in precipitation and runoff in many zones with the exception of the Southwest). This is especially true in WMAs where irrigation is important. Nevertheless, increased demand cannot be met by increased water supply in all WMAs for all potential climate futures.

Dry agriculture

Climate change results in increased temperatures in most of South Africa as well as sometimes stark precipitation changes across WMAs. The climate scenarios considered identify the south-west, west Coast and extreme north as areas of particular concern. This result is important for a country such as South Africa where almost 80% of agriculture production is currently rainfed. As illustrated in Table 16, this pattern spans across almost all 19 WMAs and includes most small-scale and subsistence farming.

IN this study (Section 4) we use an augmented version of the regression approach undertaken by Thurlow (2008), estimate the output yields of nine major rainfed crops in South Africa up to 2050. Median outputs from the Global GCMs are used to inform temperature/evaporation and precipitation rates. For most dryland crops, excluding sunflower and sugarcane, output decreases. This is particularly the case for maize and wheat which are largely produced in the identified hotspots. Knox et al. (2012) confirms this result. The average decrease in both maize and wheat output is estimated to be less than 5%. This result is captured in CGE model by total factor productivitychanges in line with the results from the study discussed here.

8.6   Simulation results

In this section we present the results from the scenarios discussed above. We focus primarily on the macro economic impacts and highlight some of the interesting regional effects identified. Unless otherwise noted, all results are for 2046-50 average and are presented as ratios to the World Prices scenario. A ratio of greater than 1 indicates a positive impact while a ratio of less than one indicates a negative impact.

Growth and economic structure

Figure 59 below illustrates the impact of the Roads, Irrigation and Dry Agriculture scenarios (referred to as Total) on total real GDP at factor cost. 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. 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. This translates into a 0.03 percentage point decline in average annual real GDP growth over the period 2011 to 2050.[7]

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 dryland agricultural productivity. Insufficient water availability in some scenarios has a marginal negative impact on real GDP as South Africa's extensive water transfer system ensures that in most climate scenarios, particularly for urban and bulk use, the share of water demand met remains relatively unchanged when compared to the baseline.

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[7] In other words, if the no climate change growth rate were 4.5% from 2011 to 2050, the with climate change growth rate would be about 4.47% with climate change on average.
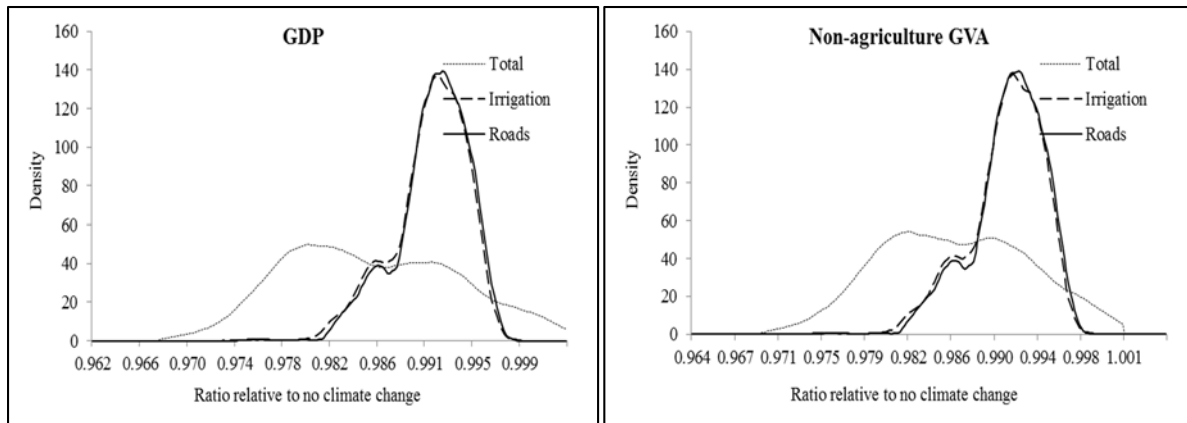
Figure 59: GDP and non-agriculture GVA

Source: Authors' compilation, see this study.

In the Roads scenario, the need for increased road maintenance raises the cost of deriving the same benefit from the road network system while pulling funds away from other productivity enhancing investments by government. This has a negative impact on the productivity of all sectors. In this study we show 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 rainfed agriculture production to changes in precipitation and temperature. Furthermore, it is important to highlight that impacts to productivity in dryland agriculture are not restricted to the agricultural sector. In the case of non-agriculture 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 (e.g., fruits to fruit juice and wheat to flour). In addition, the model will endogenously allocate factors of production to alternative uses in accordance with productivity and prices. For example, 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 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 endogenous adaptation (ceterus 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, whose prices, as a consequence, are not strongly linked to world markets. Opposite flows also occur. In almost 30% of the climate futures, the non-agriculture sector expands relative to the results from the Irrigation scenario implying a movement of resources away from agriculture and towards non-agriculture.

Figure 60 illustrates the impact of the scenarios on agriculture gross value added (GVA). The rise in road maintenance costs and loss in 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 agriculture GVA estimated at -0.9%. Including the impact dryland agriculture broadens the possible impacts of climate change. 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 Mzimvubu-Tsitsikamma regions which experience a wide range of possible temperature and precipitation changes (see Cullis et al. 2014: 18). These areas largely

produce cereals and sugar and account for 39.3% and 41.6% of dryland agriculture GVA and 23.2% and 27.5% of total agriculture GVA.
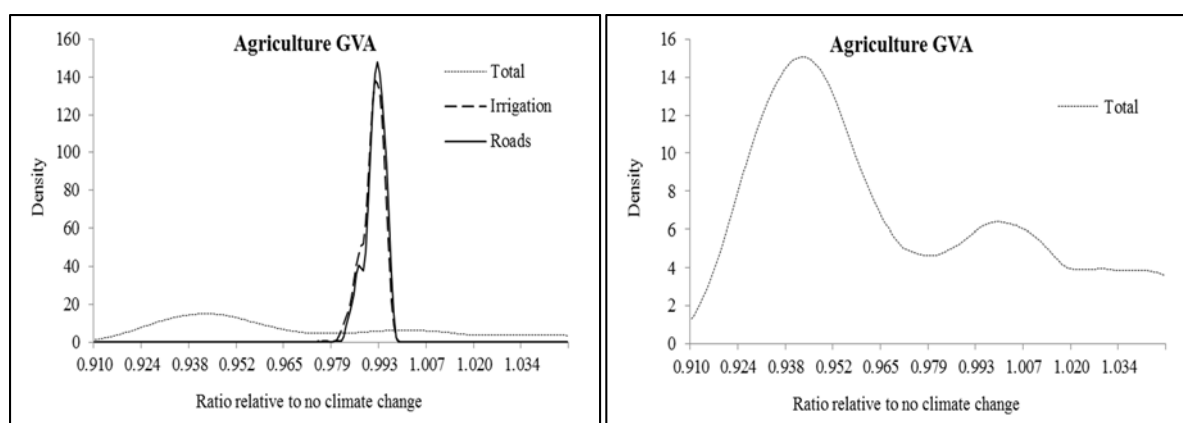

Figure 60: Total agriculture gross value added across scenarios

Source: Authors' compilation, see this study.

While the impacts on GVA in agriculture as a whole are broad, the implications within the agricultural sector tend to be much more pronounced. For example, a very important endogenous adaptation channel involves relative expansion and decline of dryland and irrigated agriculture. Figure 61 illustrates that the change in dryland agriculture GVA is very broad ranging between - 58.7% and 22.1%. Consistent with average negative impacts on dryland crop productivity, the median impact is estimated at -20.3%. However, movement in irrigated agriculture is in the opposite direction. Real value added in irrigated agriculture is expected to increase, sometimes substantially. Hence, as productivity in dryland agriculture declines, the relative attractiveness of irrigated agriculture increases. Overall, the model points to an ability to expand (or contract) irrigated agricultural area as an important endogenous adaptation channel.[8]
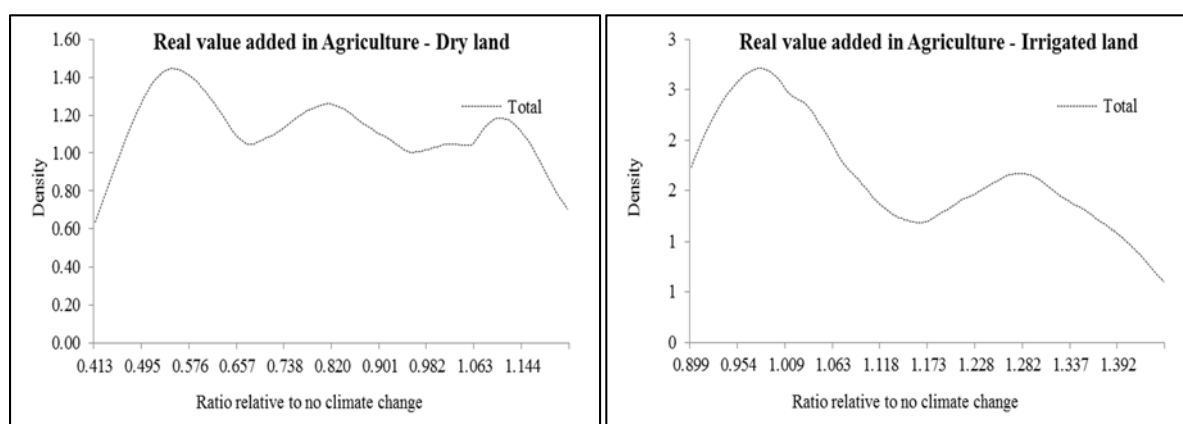

Figure 61: Dry and irrigated land agriculture value added

Source: Authors' compilation, see this study.

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[8] The economy-wide model as currently constructed may overstate the ease with which resources can flow between irrigated and dryland agricultural production. More constrained possibilities for reallocation would reduce the magnitudes of the shifts depicted in Figure 61. 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.

Finally, with respect to agriculture, Figure 62 illustrates the implications of climate change for gross value added in agriculture by WMA. The story that emerges is one of highly varied impacts both within and across WMAs. Typically, agricultural value added may either increase or decrease. The range of potential impacts also varies dramatically. In some instances, the range of potential impacts is relatively circumscribed. In other instances, it is extraordinarily large.

In interpreting these results, it is important to recall that the results reported are relative to a counterfactual scenario where economic growth is proceeding at about 4.5% per annum. At this rate over a span of 38 years, the overall economy would be expected to be more than five times larger than it is today. If, in a particular WMA, growth in value added in the World Price scenario were 4.5% per annum and in a particular climate scenario it declined to 3.5% per annum (as would appear to be plausible under unfavourable climate), the size of agricultural sector in that WMA would be only 70% of the no climate change level after a period of 38 years. Hence, it is important to interpret these results as reductions in the rate of growth rather than as actual contractions in activity.
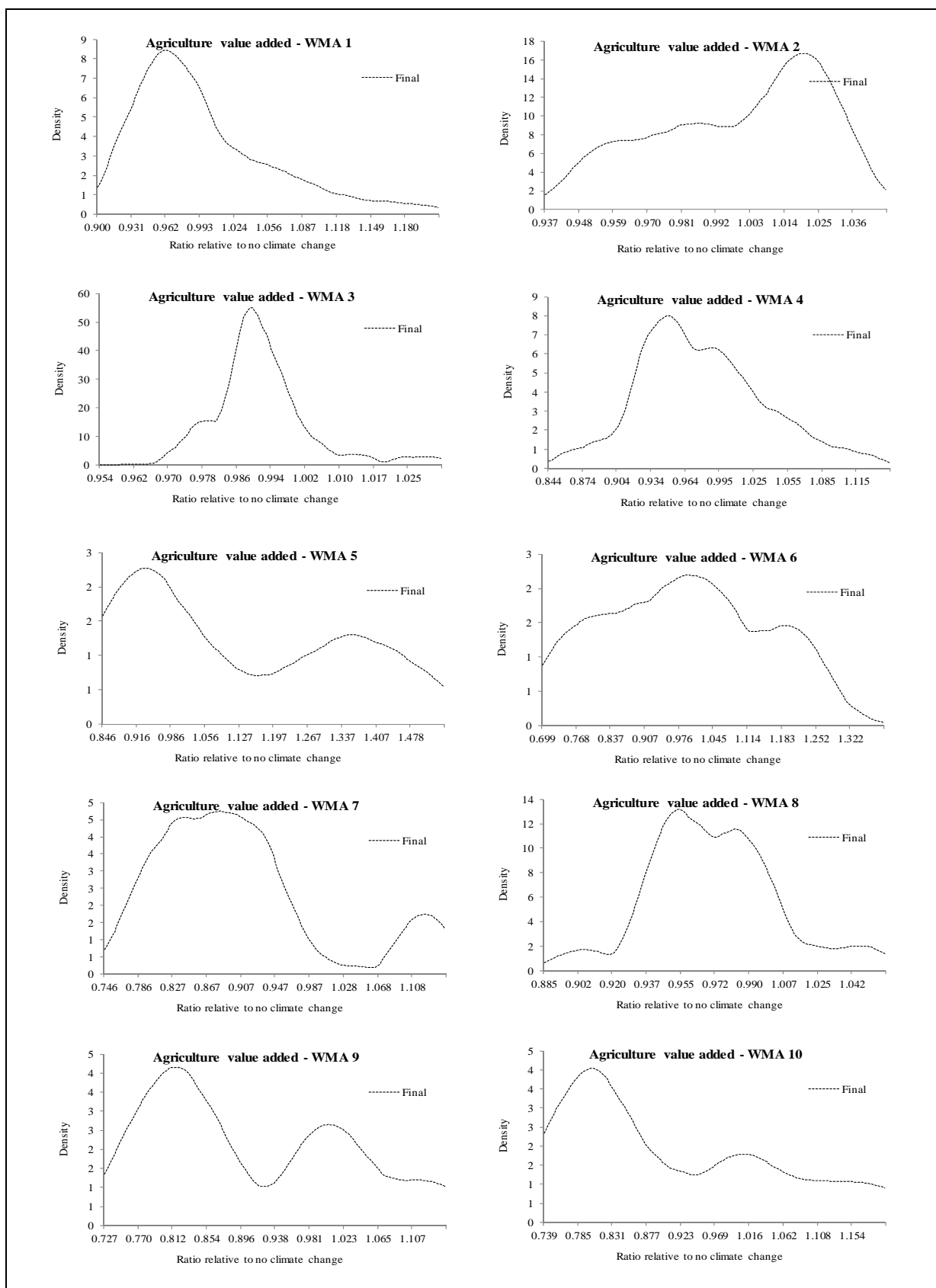
Figure 62: Agriculture GVA by water management area

Source: Authors' compilation, see this study.

Net present value of losses

While the implications for the average annual growth rate of GDP are small, these reductions are consistent and they accumulate through time. Consequently, in terms of net present value of losses, the total value of GDP losses induced by climate change is noteworthy. The net present value 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 63. The losses are presented in US$ in 2007 prices using a discount rate of 5%. Total discounted GDP losses in the Roads scenario range between US$1.5 billion and US$55.1 billion for all climate futures, with a median loss of about US$16 billion. Including the Irrigation impact, this range extends to between US$2.7 billion and US$58.2 billion, with a marginally higher median loss of about US$17 billion. In the Total scenario, the impact on GDP is much more variable, ranging from losses of US$93 billion to gains of US$31 billion, although 96% of climates show losses, which tend to be more severe than the Irrigation scenario. The median loss is approximately US$37 billion which, at nearly 10% of 2012 GDP, is sizeable.

The right hand panel of Figure 63 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. In sum, a window of opportunity exists to prepare to confront the challenges posed by climate change. In two or three decade's time, the challenges posed by climate change are likely to be much more profound, especially in the absence of global mitigation policy.
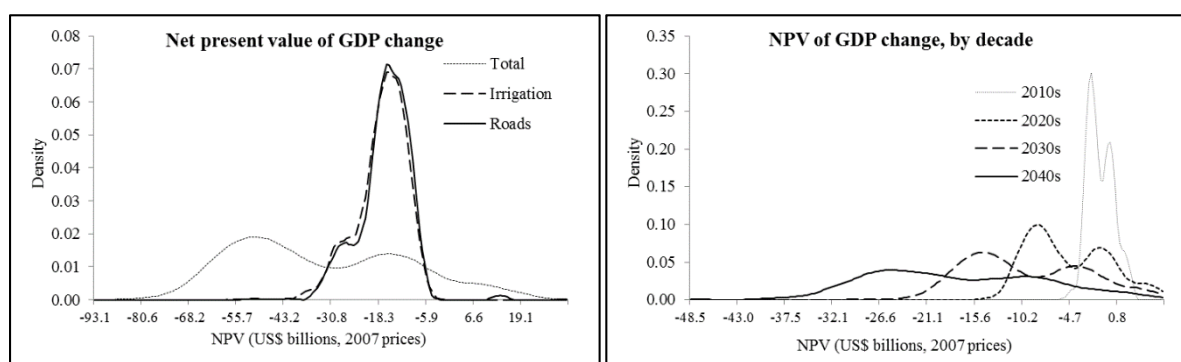
Figure 63: Net present value of GDP losses

Source: Authors' compilation, see this study.

Employment structure

Overall employment levels and trends are of clear interest in the South African context. This is particularly true for unskilled labour while 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, vastly more sensitive to labour market policies and institutions. Consequently, we elect to focus on the structure of employment across the three major sectors: agriculture, services, and industry.

Figure 64 depicts the movement of labour between agriculture and services across WMAs.[9] The left hand panel of the figure shows the ratio of agricultural employment in each future climate to agricultural employment in the World Price scenario. These ratios are calculated for each WMA and each climate future. Hence, the figure summarizes nearly 7000 ratios (19 WMAs times 367 climates). The distribution illustrates that unskilled labour is slightly more likely to move into rather than out of agriculture though movements in both directions are possible depending on the nature of climate outcome. These movements are confirmed by the right hand panel, which illustrates a mild tendency for unskilled labour to move out of services (trends in industry are very similar to services). In most scenarios, the economy is expending greater effort to make up for productivity shortfalls in the agricultural sector (as opposed to shifting out of agriculture and importing a greater volume of foodstuffs).
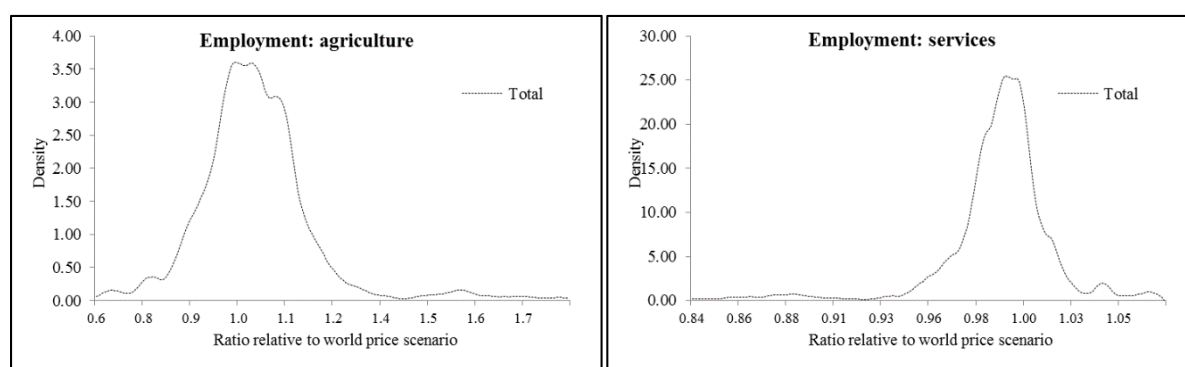

Figure 64: Ratios of employment by sector (agriculture and services) to World Price scenario across all WMAs

Note: The graphs for services and industry are qualitatively very similar.

Source: Authors' compilation, see this study.

As noted in Figure 61, a substantial component of this endogenous response involves an increase in irrigated agriculture. It is important to highlight that this reaction is not responding to any increase in the quantity of irrigation water available. Rather, the response involves greater allocations of labour and capital to irrigated agriculture in order to produce more with the existing supply of irrigation water. Box 1 provides greater details for two particular climate scenarios in one important 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. 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.

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[9] The graphs for services and industry are qualitatively very similar. Hence, we omit the graph for industry.

However, the scarcity of land to expand production means that rental rates increase. The increased supply of sugarcane is supportive of slightly lower 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 the 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 and Usutu-Mhlatuze areas. 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 per cent in real terms. Unskilled labour employed by the 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 159 m and 176 m on macroeconomic aggregates are small. However, the changes are meaningful to the agricultural sectors of Mvoti-Umzimkulu, and other sugarcane producing areas, the national market for sugarcane and downsteam industries, as well as the factors that rely on them.

Inequality

The economywide 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). 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 over the period 2046-49 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 income is derived from labour and capital. These factors of production are 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 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 stabilizes 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. Nevertheless, climate change

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appears unlikely to be a major driver of the distribution of income, especially over the next 10-20 years.p

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) where the mean per capita consumption in rural areas is well below the national average and more than 60 per cent of the population live in the bottom two consumption quintiles. The poor population in rural areas tend to be reliant on dryland agriculture for employment and, in the case of subsistence farming, and 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.

Water management area (WMA)	% Dryland agriculture	GDP per capita	Rural mean per capita consumption	Share of populaiton in consumption quintile 1 and 2	Possible impacts		
					Low	Median	High
12 Mzimvubu-Keiskamma	77	8142	4301	64	-21%	4%	29%
7 Thukela	68	9042	4427	71	-25%	-5%	15%
1 Limpopo	76	16334	4989	50	-10%	5%	21%
6 Usutu-Mhlatuze	73	10554	5196	67	-15%	19%	54%
11 Mvoti-Umzimkulu	81	22797	5808	42	-34%	-4%	26%
4 Olifants	81	22629	5895	46	-16%	-1%	14%
2 Luvhuvhu-Letaba	4	13113	6269	61	-6%	-1%	5%
10 Lower Vaal	85	13768	6280	53	-26%	-3%	20%
5 Inkomati	37	16041	6492	53	-15%	19%	54%

Source: Authors' compilation, see this study.

Discussion

Although on aggregate the impacts of climate change are quite small, when looking closer at the spatial impacts there are cases when the impacts, particularly on agriculture, become large and highly variable across climate futures. Figure 62 illustrates the final impact of climate change on agriculture value added across the 19 WMAs assessed. There are three key findings from the spatial results that have implications for adaptation policy and would require further research.

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 farming makes these regions particularly susceptible to changes in temperature and precipitation. One such region is Kwa-Zulu Natal (WMAs 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 impacts of climate change vary by between -30% and 35% in WMA 6, between -25% and 32% in WMA 7, and between -34% and 26% in 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, which could exacerbate the degree of poverty in these areas.

The second interesting result is the impact of climate change on agriculture 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, and accounts for about one quarter of national agriculture 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%. This could have sizeable impacts on national agricultural production, and additional implications for food security.

Third, the results identify regions with almost universally 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, is an important agricultural export commodity. More than 99% of climate futures show deteriorating agricultural value added in WMA 17, and more than 96% of climate futures indicate lower agricultural value added in WMA 19. 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.

There is no doubt that, in reality, 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. Nevertheless, climate change, on its own, appears unlikely to be a major driver of the distribution of income, especially over the next 10-20 years.

8.7   Summary and conclusions

The following principal conclusions emerge from the analysis.

- The implications of climate change for the overall rate of economic growth are overwhelmingly likely to be negative. The growth implications are, however, not likely to be large, especially within the next 10-20 years.

- 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 not quite 10% of GDP in 2012.

- 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.

- With the exception of the south-west 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. 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, Kwa-Zulu Natal (WMAs 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 impacts of climate change vary by between -30% and 35% in WMA 6, between -25% and 32% in WMA 7, and between -34% and 26% in 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, which could exacerbate the degree of poverty in these areas.[10]

- o The Vaal region (WMAs 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.

- o While large variations are typical, the results almost 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, and more than 96% of climate futures indicate lower agricultural value added in WMA 19. 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.

In terms of adaptation options, the analysis highlights at least four key areas of action.

- Roads and other transport infrastructure: Unless adaptation measures are taken, changes in climate are shown to robustly lead to more rapid deterioration of road infrastructure with negative implications for GDP growth and other important economic variables. Cullis et al. (2014) show that, if appropriate adaptation measures are taken in terms of materials used for road surfacing, for example, the total incremental road maintenance costs due to climate change are reduced. The roads analysis also show that the upfront investment costs can be substantial. However, the analysis undertaken to date was broad scale in order to achieve national coverage. More refined analysis at localized levels would almost surely reveal a hierarchy of priorities for adaptation investment allowing one to focus investments on more vulnerable infrastructure.

- Water resource management: The results highlight the importance of, at a minimum, maintaining the existing water resource management system. Improvements to the system, through investment or institutional/policy reform, would be desirable. This is particularly

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[10] 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 comes on top of these trends.

so in light of the key role irrigation investment plays in adaption response, which is the next key area.

- Irrigation. Compared to dryland agriculture, irrigated agriculture offers much more dependable output (particularly if the water resource management system is maintained or improved). As such, irrigation represents, as noted, an important endogenous response to climate change. Given the uncertainties, lower cost irrigation systems would tend to be favoured. Efficient use of water is also highly desirable.

- Movement of labour and other factors of production. In all scenarios, climate change both imposes costs and presents opportunities (in a relative sense at a minimum). Adaptation involves minimizing costs and grasping opportunities. Unfortunately, with the exception of a few highly robust results, it is largely unclear exactly where the costs and opportunities will present themselves. In this context, adaptations that help to facilitate movements of factors of production from low value to high value uses are valuable. Importantly, the factor movements required to confront climate change should happen over time and in a context of growth, which should facilitate the adjustment process. Nevertheless, there is a strong likelihood of a need for adjustments in factor allocations, perhaps significant adjustments, across sectors and across space. The policy framework should, on balance, at least permit and perhaps facilitate the adjustment process.

The agenda for future research is broad and comprehends: (i) more detailed analysis of road adaptation options; (ii) improved crop modelling particularly for dryland areas; (iii) better understanding of the actual mechanics and requirements of shifts from rainfed to irrigated agricultural production; and (iv) analysis of opportunities and vulnerabilities in the water resource management system.

To finish, we note that considerable effort has been expended in this LTAS process to construct and then integrate models that reflect South Africa. It is, nevertheless, important to highlight that these models are not South Africa. As with any modelling effort, the suite of integrated models employed here contain shortfalls and over-simplifications. The best the models can do is to structure thinking in a rigorous way in hopes of providing insights that would be difficult to obtain in their absence. We hope that this exercise has provided some insights. In future, the framework employed remains and can no doubt be improved. As climate change seems unlikely to disappear, we hope this work also provides a platform for future analysis.

9   Overall conclusions and recommendations

This study represents the first attempted 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 multiple 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 roads infrastructure and sea level rise that has not been previously considered.

The results in the water sector suggest that climate change will have a limited impact on water supply, particularly given the uncertainty in other demand impacts and the high level of development and integration of the South Africa water supply infrastructure and supply system. In particular the impacts on the main urban and industrial centres in Gauteng appear to be minimum and could even be positive due to the integrated nature of the Vaal system, the planned development of the Polohale Dam as part of the Lesotho Highland Water Supply System 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. 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 catchment where urban and bulk water supply are dependent on smaller and less integrated local resources and the climate models predict likely future drying.

In terms of alternative mitigation scenarios the results show little impact on the median change in the average annual streamflow or ability to supply future water demands between the UCE and L1S scenarios, however some of the risk of extreme impacts both in terms of potential flooding and potential reduction in water supply and droughts are reduced under the L1S climate scenario. The largest impact of mitigation is in terms of future irrigation demands which are likely to increase in the future under all scenarios, but more so under the UCE scenario due to higher temperatures.

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. These impacts vary across the country, with increases in some areas, notably the east coast and KZN, potentially being offset by increases in precipitation. Over all the median impact in irrigation demand, however is around 5%. This is not considered to be significant as there is potential that these increases can be addressed through improved irrigation practices and the development of new crop varieties.

The potential impact on dryland crop yields are 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 reducing 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 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 over taking 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 a 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. These costs also do not take into account the potential additional costs of interruption in the transport sector due to damage to roads.

Consideration of potential sea level rise impacts concludes that significant local impacts will be realised, but that these are relatively small in terms of impacts on the national GDP. Consideration for best practice including the demarcation and enforcement of set-back lines will be an important adaptation option to address the potential impacts of future sea level rise in South Africa.

This study has not considered potential adaptation options or the impacts of alternative development futures. The study has, however, established a modelling framework and a set of modelling tools that can now be used to investigate these options. In addition improvements can be made to the individual component of the models based on the lessons learned and development

in other sectors particularly resulting from the work of the Long Term Adaptation Strategy (LTAS).

This study presents a first order assessment of the potential impacts of climate change. The results will now be incorporated into an economic model of the country to translate these impacts into economic impacts. In addition further research will consider improvements to the modelling framework and consideration of alternative climate and development futures.

While this study has been based largely on the outputs from global climate models, future research should also focus of assessing the potential impacts of downscaled regional models. The assessment of these models relative to the global climate models presented in this study, show potentially quite different responses based on the regional models. These will also be important when considering regional impacts at the provincial or WMA scale for South Africa.

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