CLIMATE CHANGE IMPACTS ON WATER RESOURCES:
Implications and Practical Responses in Selected South African Systems

WATER RESEARCH COMMISSION

SP 155/22

Climate Change Impacts on Water Resources: Implications and Practical Responses in Selected South African Systems

WATER
RESEARCH
COMMISSION

WRC Report no. SP 155/22

ISBN 978-0-6392-0174-0

August 2022

Obtainable from:
Water Research Commission
Private Bag X03
Gezina
0031

orders@wrc.org.za or download from www.wrc.org.za

Editor: Brilliant M Petja
Production Editor: Lani van Vuuren
Cover Design: Anja van der Merwe

Published in the Republic of South Africa

Preface

The Water Research Commission's (WRC's) climate change research programme regularly assesses the role and impact of climate on water resources while also characterising its contribution to climate induced disasters. This programme is implemented through a flagship programme (the so-called *Climate Change Lighthouse*) which has operationalised collaborative research on priority water-related climate issues with partnerships forged along the innovation value-chain to enhance water research and development to address the water sector challenges in light of the changing climate.

The ultimate goal is to ensure empowerment of people and communities to increase resilience, and to develop the knowledge base for climate adaptation and decision support tools, together with guidance and building a framework for sectoral response. Water is critical for development, economic growth and a better life. It is a key factor for inter-sectoral linkages and forms a basis for development. Therefore, climate change impacts on water resources and development cannot be underestimated. The role of this lighthouse in climate-change response is embedded within adaptive capacity, resilience, improvement of early warning systems, reduced vulnerability and an improved ability to respond, coupled with proactive planning.

The lighthouse therefore serves as a primary vehicle to drive research and knowledge generation on climate change adaptation, response, characterisation of change and risks/ vulnerabilities and to contribute to human capital development to improve sectoral adaptive capacity and future response. It is premised upon improving the adaptive capacity of the people, communities and the sector at large in order to increase resilience and development of a knowledge base for climate change adaptation and decision support, while providing strategic guidance and a framework for sectoral response.

The lighthouse has made a significant impact in addressing a variety of issues on water and climate. These include, among others, sectoral impacts of climate change, planning for future scenarios, characterisation of future disasters (drought, heat waves, floods), impacts on large mega dams and estuaries, adaptation, greenhouse gas dynamics and environmental footprints, as well as societal impacts (displacements, vulnerability, gender etc.). This publication provides feedback on such studies while reflecting on their impact on development and policy. It also provides a glimpse of a set of toolboxes that will contribute to increasing the resilience of the water sector to climate change. The publication is a culmination of a series of research conducted collaboratively with the WRC's partners, and aims to provide the necessary direction and advice in dealing with the consequences for climate change. The focus in this case is on rivers, wetlands, the coastal zone and practical case studies at a catchment scale within inland ecosystems.

Brilliant M Petja
Editor

Foreword

The overall vulnerability of South Africa to climate change impacts has been fully characterised. The emphasis is, therefore, on the necessity to carry out adaptation measures and developmental response within the country. This cuts across the key strategic areas of the WRC in addressing the challenges of the water sector and also leverage on partnerships to deal with the consequences of climate change. We acknowledge that climate change is a complex cross-cutting issue and may not be the sole prerogative of one government department. Nor can a single sector respond to the consequences of the changing climate. For the effective integration of adaptation and mitigation measures, almost every department in government and the entire administrative system (including decentralised levels of government and parastatal entities) should mainstream climate change and integrate it into policies and interventions.

The WRC first recognised the potential impacts of climate change on the water resources of South Africa as a priority area for research in the mid-1980s. At the time it was impossible even to begin to address the topic in a meaningful way because of the lack of scientific capacity and (especially computational) resources. Hydro-climatology was prioritised as a research field deserving dedicated support, and funding commenced in this area in 1988. Research initially focused on mechanisms and teleconnections (especially links with sea surface temperatures that affect South Africa's climate). In work commissioned by the WRC in the mid-2000s (**WRC Report No: KV 207/08**), a strategic direction was crafted by the WRC for conducting climate change research. Consequently, the climate change research portfolio was integrated into the larger sphere of national climate change research, thereby embracing a multi-sectoral and multi-level approach towards securing the water sector's contribution to enabling South Africa to deal effectively with a multiplicity of existing stresses that climate change impacts will undoubtedly be adding to over coming decades. Significant progress has been made to date, and this publication reports on those specific activities that can contribute to the water sector regaining its resilience. It is important that the products of research are mainstreamed into practice to encourage uptake and science-based interventions.

Evidence throughout the country shows a record increase in natural disasters and extreme weather events. Changes in climate and increased variability brings significant implications to production and viability of different sectors. These changes in climate advocates for balanced planning while adapting to the new normal within the context of development. It is important to adequately plan in advance to respond to both droughts and floods while increasing resilience to these extremes. Future infrastructural development needs to increase storage capacity such that more floodwater is captured and stored to prevent disasters and minimise vulnerability. This can include underground storage where more water may be stored for future use. While climate change may bring many negative impacts, planning and addressing those impacts in advance will contribute to making the future water supply sustainable.

Findings reported in this publication are aimed at positioning the water sector so as to better respond to atrocities that will be brought by climate change. This will, in essence, contribute to improving the adaptive capacity of the sector and positioning for a resilient response which will sustain economic growth. Within the context of South Africa as a developing country, it is important to take advantage of the proactive climate policies spearheaded by the Government to guide investment in infrastructure and other spheres of development in order to ensure a climate resilient economy.

Dr Jennifer Molwantwa
WRC Chief Executive Officer

Acknowledgements

The authors acknowledge with appreciation the support received throughout the years from the Water Research Commission. We also appreciate our stakeholders, which include among others the national government (RSA), Government Departments (Department of Forestry, Fisheries and Environment, Department of Rural Development and Land Reform, Department of Science and Innovation, and Department of Water and Sanitation, etc.), provincial governments, industry, water users, NGOs and communities at large.

Special appreciation goes to our reviewers:

Dr Jody Reizenberg, UCT

Mr Steven Weerts, CSIR

Dr Mark Matthews, Cyanolakes Pty Ltd

Dr Lorren Haywood, CSIR

Dr Luxon Nhamo, WRC

Prof Nikki James, SAIAB & NMU

Contents

Acronyms

4IR	Fourth industrial revolution
AET	Actual evapotranspiration
AGB	Above-ground biomass
AOI	Area of interest
CCAM	Conformal Cubic Atmospheric Model
CDD	Consecutive dry days
CFE	Cape Fold Ecoregion
CMIP	Coupled Model Inter-Comparison Project
CORDEX	Coordinated Regional Downscaling Experiment
CSIR	Council for Scientific and Industrial Research
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTE	Critical thermal endpoint
CTM	Critical thermal method
CWD	Consecutive wet days
DD	Drought duration
DF	Distant future
DEM	Digital elevation model
DI	Drought impact
DIN	Dissolved inorganic oxygen
DS	Drought severity
DWS	Department of Water and Sanitation
EBV	Essential biodiversity variables
EFGs	Ecosystem functional groups
EFZ	Estuarine functional zone
EHI	Estuary Health Index
ENSO	El Niño Southern Oscillation
EO	Earth observation
ETM	Enhanced Thematic Mapper

GEE	Google Earth Engine
GSMs	Global climate models
GIS	Geographical Information System
GMFD	Global Meteorological Forcing Dataset
GSW	Global surface water
GWL	Global warming level
HABs	Harmful algal blooms
HGM	Hydrogeomorphic
HRU	Hydrological Response Unit
HWD	Heat wave duration
HWMID	Heat Wave Magnitude Index Daily
ILT	Incipient lethal temperature (method)
ILUT	Incipient lethal upper temperature
IPCC	International Panel for Climate Change
IRB	Inkomati River Basin
IUCN	International Union for Conservation of Nature
LRB	Limpopo River Basin
LULC	Land use/land cover
MAWMV	Mzansi-Amanzi Web Map Viewer
MCP	Multiple country publications
MERIS	Medium Resolution Imaging Spectrometer
MLD	Mpumalanga Lakes District
MWAT	Maximum weekly allowable temperature
NBA	National Biodiversity Assessment
NDVI	Normalised Difference Vegetation Index
NEMP	National Eutrophication Monitoring Programme
NF	Near future
NLC	National Land Cover
NWM5	National Wetland Map version 5

NWMP	National Wetland Monitoring Programme
OLCI	Ocean and Land Colour Instrument
OLI	Operational land imager
OT	Optimal temperature
PET	Potential evapotranspiration
RCP	Representative Concentration Pathways
ROI	Region of interest
SCP	Single country publications
SDG	Sustainable Development Goal (of the United Nations)
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardized Precipitation Index
SPOT	*Satellite Pour l'Observation de la Terre*
SWAT	Soil and Water Assessment Tool
SWIR	Shortwave infrared
USGS	United States Geological Survey
TSI	Thermal sensitivity index
UAV	Unmanned aerial vehicle
VRB	Vaal River Basin
WCRP	World Climate Research Programme
WRB	Western (Cape) River Basin
WRC	Water Research Commission

Chapter 1

Climate change and the water futures: An overview

Brilliant Petja [1]*, John Ngoni Zvimba[1], Sylvester Mpandeli[1] and Luxon Nhamo[1]

[1] Water Research Commission
* Corresponding author: brilliantp@wrc.org.za

Abstract: Water is one sector witnessing depletion and degradation due to the increasing frequency and intensity of extreme climate-related events such as droughts, heatwaves, and flooding. These events have been consistently increasing with the corresponding change in climate. These developments have compromised the water and sanitation initiatives to achieve sustainability in the sector by 2030. This chapter provides an introductory context and highlights the brevity and enormity of climate change in South Africa, highlighting common areas of interest and the need for resilient response to sustain the water sector. The recurrence of droughts caused by the El Niño Southern Oscillation (ENSO) continues to devastate the country, affecting poor households and the environment. Although South Africa is classified as food secure at national level, over 40% of households remain food insecure, a situation that requires immediate policy interventions to enhance resilience and meet the 2030 global agenda on sustainable development. This paper, therefore, advocates for site-specific diagnoses of climate change impacts starting at a local scale, which will ultimately lead to practical solutions that will increase resilience and adaptive capacity.

Keywords: Adaptive capacity; resilience; extreme events; climate change; sustainable development

1. Introduction

Climate change is a complex cross-cutting issue and may not be the sole prerogative of one government department. A single sector cannot respond to the consequences of the changing climate alone. For the effective integration of adaptation and mitigation measures, almost every department in government and the entire administrative system (including decentralised levels of government and parastatal entities) should mainstream climate change and integrate it into policies and interventions. Furthermore, a multiplicity of actors is intervening and influencing discussions and actions. Policymakers need to take these features into account and address the governance of climate change as a complex, cross-cutting, multilevel, multi-actor process that is deeply embedded in local realities [1]. The southern Africa region is extremely vulnerable to the impacts of climate change both in terms of the region's water resources and development. The projections into the future show declining trends in rainfall because of the changing climate. This, coupled with projected increasing temperatures translates into a forecast for drier areas. Evidence shows a record increase in natural disasters and extreme weather events [2,3]. Changes in climate and increased variability brings significant implications for production and viability of different sectors. These changes in climate advocate for balanced planning while adapting to the new normal within the context of development. It is important to adequately plan to respond to both droughts and floods while increasing resilience to these extremes. Future infrastructural development needs to include the increase of storage capacity such that more floodwater is captured and stored. This can include underground storage where more water may be stored for future use. This will reduce societal vulnerability to the impacts of floods while reserving these extremely high volumes of water for use in drier periods and also for groundwater recharge. On the other hand, recovery from droughts is a timely process. This bears negative implications for economic activities, such as agriculture, as they may take longer than usual to recover after each drought season. While climate change may bring lots of negative impacts, planning and addressing those impacts in advance will contribute to making the future bearable [4,5]. This publication serves as a toolbox to reflect on the challenges brought on by climate change to water resources and ecosystems. It is aimed as an eye opener and will by no means cover all the climate change issues facing the water sector.

2. Context

It is important to regularly reflect on the future likely to be brought on by climate change. There is a need to assess each development relying on water, with a particular emphasis on increasing the resilience, adaptive capacity and proactive response of each sector. This may include, among others, strengthening infrastructural capacity. The projected climate future will be covered in detail in chapters two and three. Examining climate change impacts on society and the environment should not only focus on temperature and precipitation, but also on the resultant impacts on socio-economic implications on population shifts, migration, resource needs and development requirements above the ordinary threshold. Water-intensive industry and developments may need to relocate, change water use patterns or explore further alternatives which may affect the locality of current economic hubs. It is critical to establish new protocols for assessing vulnerability of existing infrastructure emphasizing the need to incorporate global climate science into them to improve their resilience. Design of new infrastructure requires in depth consideration of the future climate to encourage sustainability and resilience. It is important to adequately plan to respond continually to both droughts and floods while increasing adaptive capacity. This will contribute to reducing societal vulnerability while encouraging sustainable development.

3. Rationale for climate change research

Actions and interventions responding to the changing climate require the research sector to identify the likely impacts of climate change and to develop strategies and position the sectors to respond to identified risks and opportunities. Improved observation, process understanding and modelling of the climate system will deliver more robust information on the timing, extent and nature of likely changes to temperature, rainfall, water availability, sea level and extreme climate events. Determining how important climatic variables will change, quantifying their natural variability on multi-decadal or longer timescales, and improving confidence in climate projections will allow for better risk management, reduce the cost of managing the impacts of climate change, and enable exploitation of potential opportunities. Detecting and attributing current changes in the climate will enable informed government decision-making for climate change response. Understanding the sources of uncertainty in projections of future climate change will help quantify likely impacts on communities (including coastal communities), biodiversity, water resources, primary production sectors and major infrastructure. Extreme climate events including tropical cyclones, flooding, veld fires and drought have posed severe impacts on the economy, community and ecosystems over recent years. These events are closely linked to known drivers of climate variability, such as the El Niño Southern Oscillation, with possible contributions from climate change. Understanding how these global drivers have previously behaved, are behaving today, and how they will change in the future, as well as how they are influenced by climate change, will help us forecast and plan for future extreme climate events with greater confidence. Ensuring that climate models capture these processes will underpin the capacity to predict changes with greater confidence and better understand uncertainties about future climate [6] and advice accordingly on the appropriate responses [5,6].

4. Framework for mitigation and adaptation

It is acknowledged that climate change is a complex and cross-cutting problem that is impacting on all sectors [7]. As a challenge that is affecting all sectors, climate change adaptation needs to be addressed holistically through transformative and circular models that consider the interlinkages of sectors and reduce uncertainties that are associated with linear approaches [8]. Transformational change is critical when responding to societal changes and when shifting from the norm. There are four climate change thematic areas that need to be addressed to achieve resiliency in the water sector [8,9,10]. These include (a) integrated policy and institutional frameworks, (b) adoption of water use efficiency technologies, (c) development of a water adaptation strategy, and (d) adoption of transformational and circular approaches to manage water resources (Figure 1).

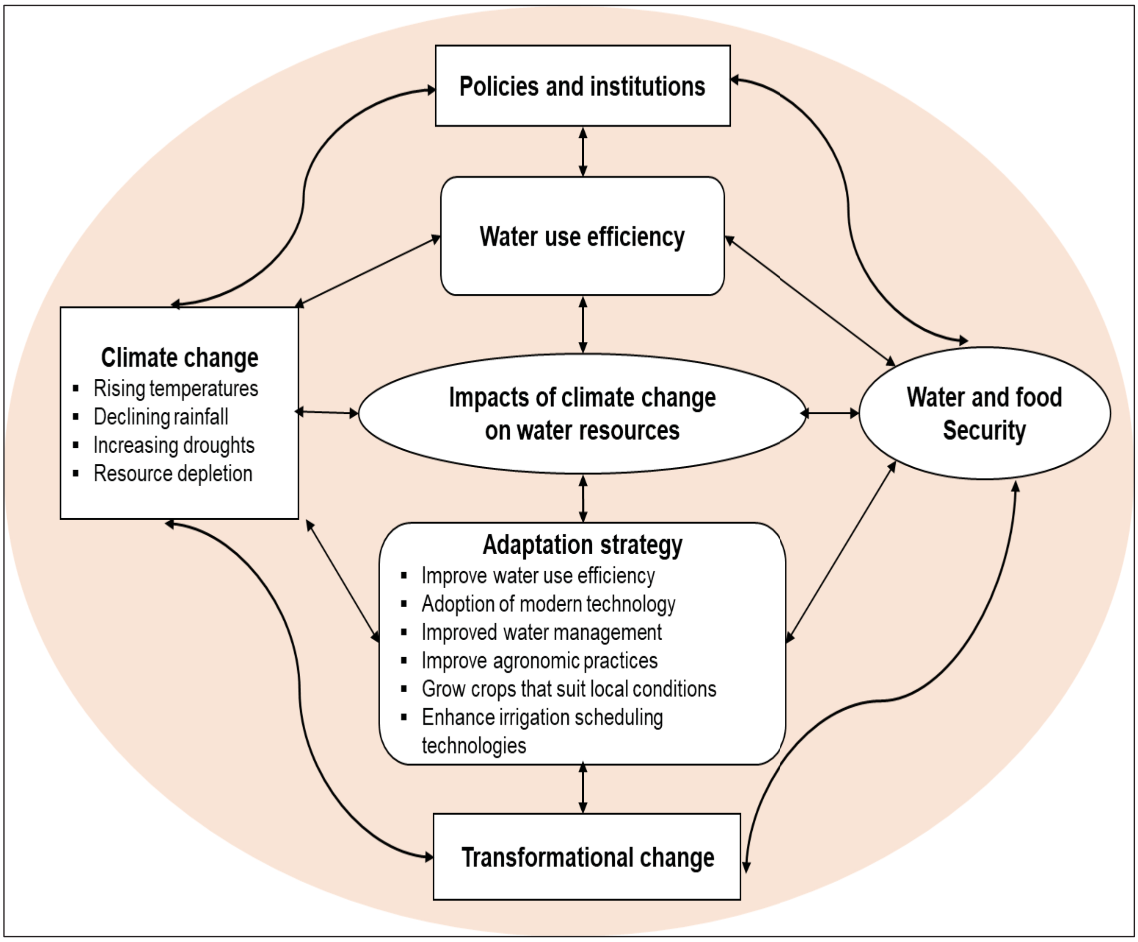


Figure 1. Conceptualised pathways towards climate change adaptation and resilience in the water sector.

The water sector climate change adaptation thematic areas address the drivers of climate change that impact water resources. The implementation of these fundamental themes is envisaged to enhance water and food in the country. Climate change adaptation through transformational, multicentric and circular approaches inform policy- and decision-making on managing resources effectively without transferring challenges to other sectors [11,12]. Responses to climate change in the water sector range from autonomous coping strategies to reactive interventions towards climate variability and extreme weather events, and proactive interventions to long-term changes in climate [10]. Reactive/autonomous adaptations refers to deviations from current production and management practices (such as changes in crop mixes, and crop varieties) in response to changes in local climatic and growing conditions [9]. Proactive interventions, on the other hand, include planned policy and investment decisions to enhance adaptive capacity of target water and agricultural systems, such as investments in efficient irrigation systems and new crop varieties [11]. While reactive/autonomous responses are useful in the short-term, it is proactive interventions that contribute to long-term adaptation and sustainability. One such initiative is to promote and cultivation of indigenous underutilised crops that are suitable for local harsh environmental conditions and do not require a lot of water.

Policies on climate change adaptation need to be aligned to governance capabilities such as (a) reflexivity, (b) resilience, (c) responsiveness and (d) revitalisation [11]. Reflexivity is the ability to deal with a variety of problem systematically and continuously as they emerge; resilience is the ability to bounce back to the original basic state of function after a perturbation; responsiveness is the ability to deal with dynamic demands and expectations, and revitalisation is the ability to reignite policies and ensure their continuous application [13,14]. Ideally, these approaches must be flexible to allow upscaling and downscaling, depending on and in response to the prevailing challenges at local and transboundary scales. In addition, adaptive management, which allows for iterative decision, is needed to manage climate change risk and uncertainty. Table 1 provides some of the climate change risks on water and the adaptation strategies.

5. Implications for local scale response

The South African water sector is expected to be significantly impacted by projected climate change. Such experiences have already been witnessed during the recent El Niño event (2015 – 2016). The entire water services value chain is vulnerable to the effects of climate change, from the raw water source, through to the purification and distribution processes and subsequent wastewater treatment. Increased temperatures will affect existing water treatment infrastructure and conveyance systems. In this regard, storage tanks, flocculation chambers, and the pipeline network used for water distribution may be exposed to increased corrosion as a result of higher temperatures. In turn, an increase in extreme events, such as floods, may damage infrastructure. An increase in temperature will also lead to a concomitant increase in water demand and use despite a decrease in available water at the source due to higher rates of water loss, especially from dams. This will result in an increased level of pollutants in water resources, which will translate to an increase in the cost of treatment, an important area for municipalities to be able to put in place the necessary plans to adapt to these changes. All of these changes will be an added burden to municipalities, who are already having to cope with eradicating service backlogs in support of improved service delivery, ensuring proper operation and maintenance of water and wastewater systems and ensuring water security amid rising demand and dwindling water supplies. To assist with addressing above challenges guidelines dealing with the selection of relevant water sector adaptation technologies and approaches for specific climate change impacts over the short-, medium- and long term have been developed (see, for example, **WRC Report No. TT 663/16**, [15]). The concept for adaptation articulated in these guidelines is to provide solutions that can be applied across various geographical settings and municipal capabilities, thus setting the basis for adaptation to be planned and applied where and when required, especially in the most vulnerable regions and within suitable timeframes.

When municipalities compose their climate change adaptation response, as they are now being encouraged to do, they should consider their specific local circumstances. The options selected should optimise prevailing and anticipated environmental, social, economic and cultural aspects. Options should also be associated with a favourable economic assessment after accounting for the social components for which monetary returns are not expected. In this regard, rural municipalities are considered to have the poorest adaptive capacity, making them more vulnerable to the additional stresses, while large urban municipalities are associated with a higher level of service delivery, thus reducing vulnerability. The Blue- and Green Drop scores also point to the nature of vulnerability in water and wastewater services. A poor score also means that the institution and the service delivery process are highly vulnerable to the impacts of external factors such as climate change. As such, these vulnerabilities have to be dealt with before accounting for climate change. Water sector bylaws and management of restrictions are currently evolving at a slower pace which do not necessarily cater for the threat of climate change to water service provision but rather attempts to respond to disasters already in dire situations. In this regard, plans for implementing climate change adaptation are still failing to make it onto the list of prioritised projects for the municipalities, even though several climate change strategies may have been developed. This often results in failure of cities to respond to disruption in water supply for example in case of extended and unusual drought which are the modern features of the changing climate [15].

6. Conclusions

The overall vulnerability of South Africa to climate change impacts to the water sector has been fully characterised, and the emphasis now falls on translating findings into adaptation measures and developmental interventions, with the aim of providing site-specific responses. From the overview, it can be noted that climate change can be classified as a permanent problem which needs to be dealt with sustainability. The basis for climate change response is dependent, among others, on adaptive capacity, increasing resilience, improvement of early warning systems, reducing vulnerability, identifying specific impediments and the ability to respond while prioritising proactive planning. It is upon this premise that consequences of climate change can be addressed in an attempt to contribute to a climate resilient society. Considering water as both a constraint and opportunity to sustainable growth and development under a changing climate, the research outcomes therefore need to be robustly mainstreamed into water-related policy practice as well as developmental and adaptation needs while integrating a cross sectoral capacity development and at the same time informing the future sectoral response. This publication therefore talks to the site-specific climate change impacts and attempts to bring forth the strategies that advocates for resilience and sustenance of the water sector in light of the changing climate.

Funding: No funding was solicited for this article.

Acknowledgments: Production of this chapter was enabled with support from the Water Research Commission.

References

1. DEA, Department of Environmental Affairs (2011) Governance of Climate Change in South Africa. Department of Environmental Affairs, Pretoria.
2. DEA, Department of Environmental Affairs (2013). Long-term adaptation scenarios flagship research programme (LTAS) for South Africa: climate trends and scenarios for South Africa. DEA, Pretoria.
3. Kephe, P.N., Petja, B.M., Kabanda, T.A. (2016) Spatial and inter-seasonal behavior of rainfall in the Soutpansberg region of South Africa as attributed to the changing climate. *Theoretical and Applied Climatology,* **121**(1-2), DOI 10.1007/s00704-015-1569-9.
4. Petja, B.M. (2017) Perspectives of development under climate change and the need to invest in a climate resilient future. *Development Finance Agenda*, **3**(4), 14-16.
5. WRC. (2018) Water Research Commission Corporate Plan 2018-2023. Water Research Commission (WRC): Pretoria, South Africa.
6. DCCEE, Department of Climate Change and Energy Efficiency (2012) A Plan for Implementing Climate Change Science in Australia. Department of Climate Change and Energy Efficiency, Commonwealth of Australia.
7. Nhamo, L., Mabhaudhi, T., Modi, A. (2019a) Preparedness or repeated short-term relief aid? Building drought resilience through early warning in southern Africa. *Water SA* **45**(1), 75-85.
8. Mpandeli, S., Naidoo, D., Mabhaudhi, T., Nhemachena, C., Nhamo, L., Liphadzi, S., Hlahla, S., Modi, A. (2018) Climate change adaptation through the water-energy-food nexus in southern Africa. International Journal of Environmental Research and *Public Health* **15**, 2306.
9. Iglesias, A., Garrote, L. (2015) Adaptation strategies for agricultural water management under climate change in Europe. *Agricultural Water Management* **155**, 113-124.
10. Mpandeli, S., Nhamo, L., Moeletsi, M., Masupha, T., Magidi, J., Tshikolomo, K., Liphadzi, S., Naidoo, D., Mabhaudhi, T. (2019) Assessing climate change and adaptive capacity at local scale using observed and remotely sensed data. *Weather and Climate Extremes* **26**, 100240.
11. Nhamo, L., Matchaya, G., Mabhaudhi, T., Nhlengethwa, S., Nhemachena, C., Mpandeli, S. (2019b) Cereal production trends under climate change: Impacts and adaptation strategies in southern Africa. *Agriculture* **9**, 30.
12. Nhemachena, C., Nhamo, L., Matchaya, G., Nhemachena, C.R., Muchara, B., Karuaihe, S.T., Mpandeli, S. (2020) Climate change impacts on water and agriculture sectors in Southern Africa: Threats and opportunities for sustainable development. *Water* **12**, 2673.
13. Magidi, J., Nhamo, L., Mpandeli, S., Mabhaudhi, T. (2021) Application of the Random Forest Classifier to map irrigated areas using Google Earth Engine. *Remote Sensing* **13**, 876.
14. Nhamo, L., Mabhaudhi, T., Magombeyi, M. (2016) Improving water sustainability and food security through increased crop water productivity in Malawi. *Water* **8**, 411.
15. Dube, R.A.; Maphosa, B.; Fayemiwo, O.M. (2016) Adaptive Climate Change Technologies and Approaches for Local Governments: Water Sector Response, WRC Report No. TT 663/16. Water Research Commission: Pretoria.

Chapter 2

Projected climate change impacts on water-linked sectors

Joel O. Botai [1,2,3]*, Christina M. Botai [1]*, Katlego P. Ncongwane[1], Abiodun M. Adeola[1] and Jaco P. de Wit[1], and Brilliant Petja[4]

[1] South African Weather Service
[2] Department of Geography, Geoinformatics and Meteorology, University of Pretoria
[3] Department of Information Technology, Central University of Technology, Free State
[4] Water Research Commission
* Corresponding authors: Joel.Botai@weathersa.co.za; Christina.Botai@weathersa.co.za

Abstract: Climate change, manifested in the form of drought and heat extremes, will lead to great impacts on key economic sectors such as water resources, human health, and agriculture, among others, in South Africa. Such impacts are likely to hinder national efforts to achieve Sustainable Development Goals. In this chapter, impacts of drought and heat stress on climate-sensitive sectors have been assessed for the 2036 – 2065 and 2066 – 2095 projected periods, across 52 district municipalities of South Africa, under two different Representation Concentration Pathways scenarios (e.g., RCP4.5 and RCP8.5). The impacts were assessed based on availability and accessibility of a set of exposure and sensitivity determinant indicators, e.g., describing the degree to which people, and systems are exposed to climate variations, as well as the degree to which the systems are affected by climate change and its extreme events, respectively. Based on the results, both drought and heat stress are likely to increase during the two projected periods, although the level of the impacts will be mostly localised. Considering drought projections, South African district municipalities are likely to experience low to moderate drought potential impacts over both the near and distant periods, with possibility of the impacts reaching higher level of the moderate category in municipalities situated in the upper north, central and south-eastern regions. Moreover, most of the district municipalities in the southern region are anticipated to experience moderate to high heat stress impacts. This study contributes towards effective planning and management of water resources and support the development and implementation of adaptation strategies and decision-making to build climate resilience in the most vulnerable communities and district municipalities.

Keywords: Climate change; drought; heat extremes; water-linked sectors; health

1. Introduction

The threats and challenges of climate change have unquestionably become the central and key fixation of governments, in both developed and developing countries. The preoccupation around climate change is attributed to greater societal concerns over increasing socio-economic demands and ecological constraints, which to a large extent impedes the equitable implementation of sustainable development goals. Socio-economic threats of poverty and inequality, together with other factors that underpin the society such as population growth, loss of biodiversity, land use and degradation, unmanaged migration, reduced soils health and economic development, add to the mounting challenges, thus leading to greater vulnerability and volatility of ecological and socio-economic systems [1].

The Earth's climate has demonstrably changed at an alarming rate both at regional and global scales since the pre-industrial era [2], and the associated impacts observed in the more severe and frequent weather events, shifts in climatic patterns and natural disasters have become highly variable and uneven. For instance, while some regions are already experiencing prolonged periods of drought events [3], others are progressively facing severe and recurring floods and storms [4], and in some regions, both sets of the hydrological extremes are being experienced [5,6]. Certain regions in Africa are experiencing an increase in high temperature extremes attributed to the changing climate that continues to alter weather and climate systems [7]. The immediate impacts of climate change are manifested in key economic (or climate-sensitive) sectors such as water resources, human health, agriculture, transport, and tourism, among others. While the impacts of climate change in Africa (particularly as the most vulnerable continent) are irrefutable, global climate model projections and other climate-related studies have determined that the distribution of the future impacts will vary, depending on the availability of resources as well as the ability of individual nations to respond [8-11].

South Africa, like many developing countries in Africa, is more vulnerable to climate change. In the National Climate Change Strategy, climate change is cited as one of the greatest challenges facing the country, and consequently, affecting the sustainability of key socio-economic resources [12]. Undoubtedly, changes in climatic variables, such as the increasing temperatures and extreme rainfall events, pose a significant threat to South Africa's climate-sensitive sectors such as water resources, food security, health, transport, infrastructure, ecosystem services and biodiversity, among others. In addition, climate change is expected to increase the frequency and magnitude of natural hazards such as drought, floods, extreme heat, wildfire smoke and ozone episodes [13]. All these impacts are of great concern to the national development, considering the country's exorbitant levels of unemployment, poverty, and inequality [14]. For poor and vulnerable communities to cope, adapt and build resilience to the ongoing climate change, the root cause of unemployment, poverty, inequality, and vulnerability risk, in general, need to be properly addressed across all government spheres.

Impact studies investigating climate changes of natural hazards such as drought, floods, and heat stress contribute towards understanding climate vulnerability, spreading risk and to build adaptive capacity among susceptible communities. Furthermore, assessment studies of climate change impacts are essential for effective policy and decision-making to mitigate the inherent impacts, including providing supportive measures for local-level service planning, proper management and sustainability of key economic resources as well as promote resilience within communities to manage climate-related hazardous conditions [15]. Notwithstanding contributions of climate change impacts studies, such assessments are hindered by limited local-level data and models that integrate water-linked sectors, as well as climate and climate projections down to local community levels [16]. For instance, climate change impacts studies are dependent on the combined elements of hazard exposures (e.g., drought, floods or extreme heat events expected to increase with climate change) as well as community's pre-existing sensitivities (determinants that make the community more likely to be impacted by the exposures). The availability of these determinants varies within local communities, or municipalities, yet their combinations provide great opportunities and are likely to reduce inherent impact risk and support local-level service planning and prioritization of resources under changing climate.

The scientific knowledge on climate change impacts in South Africa remains fragmentary. While an effort has been made to understand and characterise historical extreme events that have impacted climate-sensitive sectors at various spatial-temporal scales, studies focusing on the potential impacts of climate change on key economic sectors are limited or non-existent. A sound quantification of the expected climate change impacts under different emission scenarios and at municipality or community levels is needed for local-level service planning, prioritisation, and management of economic resources as well as the development and implementation of climate-related adaptation and mitigation policies.

In this chapter we investigate the impacts of climate change on water-linked sectors over South Africa. The determinants of climate-related hazards (i.e., projected drought duration and severity as well as heat stress indicators) were identified and assessed across the 52 district municipalities in South Africa. The remainder of the chapter is structured as follows. Section 2 provides an overview of climate change research undertaken in South Africa. Section 3 provides an overall perspective of climate change on water-linked sectors. Section 4 is devoted to observed and CORDEX-Africa simulated data, the methodology followed to assess projected potential drought and heat stress impacts under changing climate and report on the results. The results as well as the potential implications to water-linked sectors and climate-related policy and decision-making are discussed in Section 5. Section 6 concludes the chapter and provides recommendations.

1.2. Overview of climate change research in South Africa and methods

Climate change is certainly one of the critical concerns in South Africa. With the mean annual temperatures, extreme rainfall events, and heatwaves, among others, expected to increase in future, the country, through various initiative programmes, is making every effort to develop and implement adaptation strategies to support development of climate resilient, and alleviate potential damages, including the loss of lives as well as the destruction of infrastructure and property. South Africa has highly maintained hydro-meteorological observing networks through the South African Weather Service (SAWS), the Department of Water and Sanitation (DWS), and other agencies. The country is also well equipped with in-country weather forecasting and climate modelling expertise led by institutions like the Council for Scientific and Industrial Research and universities, as well as advanced and modern technologies. The datasets and overwhelming expertise have been used to support climate change research and development studies [17-19] in the country, including climate model forecast development and evaluation and climate projections [20-22]. Consequently, there is vast advanced research that has been conducted in South Africa and has been widely reported in the literature. For instance, approximately 3 383 scientific documents focusing on climate change studies in South Africa, have been published in various accredited journals worldwide, between 2000 and 2022. Annual distribution of scientific publications (Figure 1) indicate that research in climate change subject matter has linearly increased over years. As noted in Figure 1, the number of published scientific documents peaked in 2021 (n=403). In general, climate change research in South Africa has increased by approximately 6.1% average annual growth over the last two decades. The overall percentage growth rate of annual publications reaffirms that the body of research literature has surged much interest among the science community, practitioners and other relevant stakeholders owing to a growing national concern on issues of climate change.

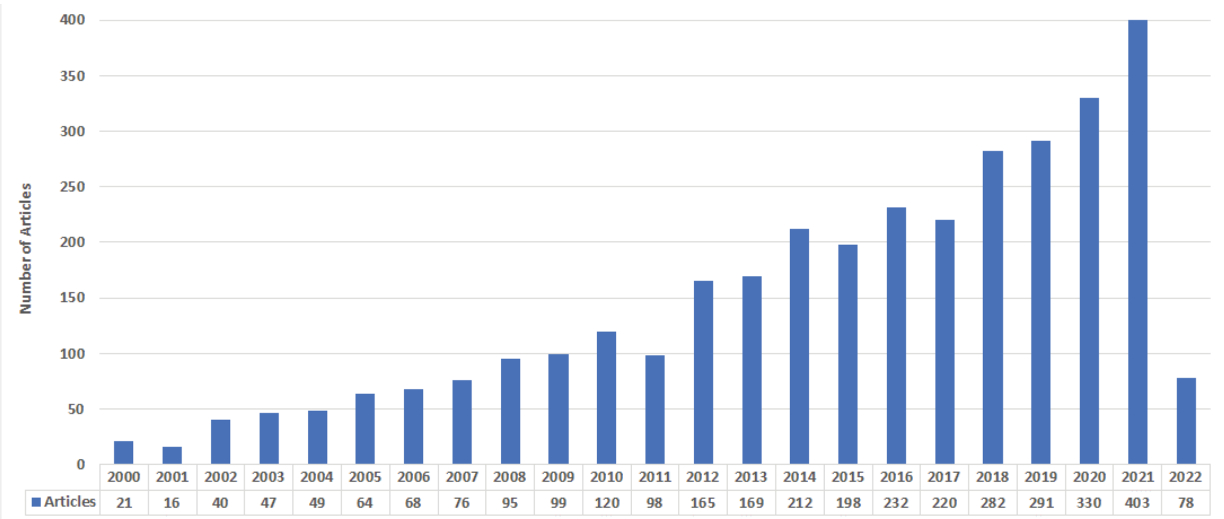


Figure 1. Annual scientific publications in South Africa between 2000 and 2022.

A number of institutions in South Africa are involved in climate change research and development. These institutions cut across government entities, universities, and science councils. In addition, undertaken research activities within climate change subject matter mostly cover aspects of earth system science such as hydrology, atmosphere, land surface, and oceans, among others. Key academic institutions that are actively involved in climate change research in South Africa are shown in green in Figure 2. The institutions are the University of KwaZulu-Natal, University of the Witwatersrand, University of Pretoria, and the University of Cape Town. These universities collaborate with each other as well as with other academic institutions. The universities of Pretoria and Cape Town are leading in terms of collaborations, both having collaborated with at least nine institutions locally and abroad. The University of Cape Town is one of the country's foremost centres for climate modelling, focusing on ocean-atmosphere process studies, seasonal forecasting, and climate change projections [13].

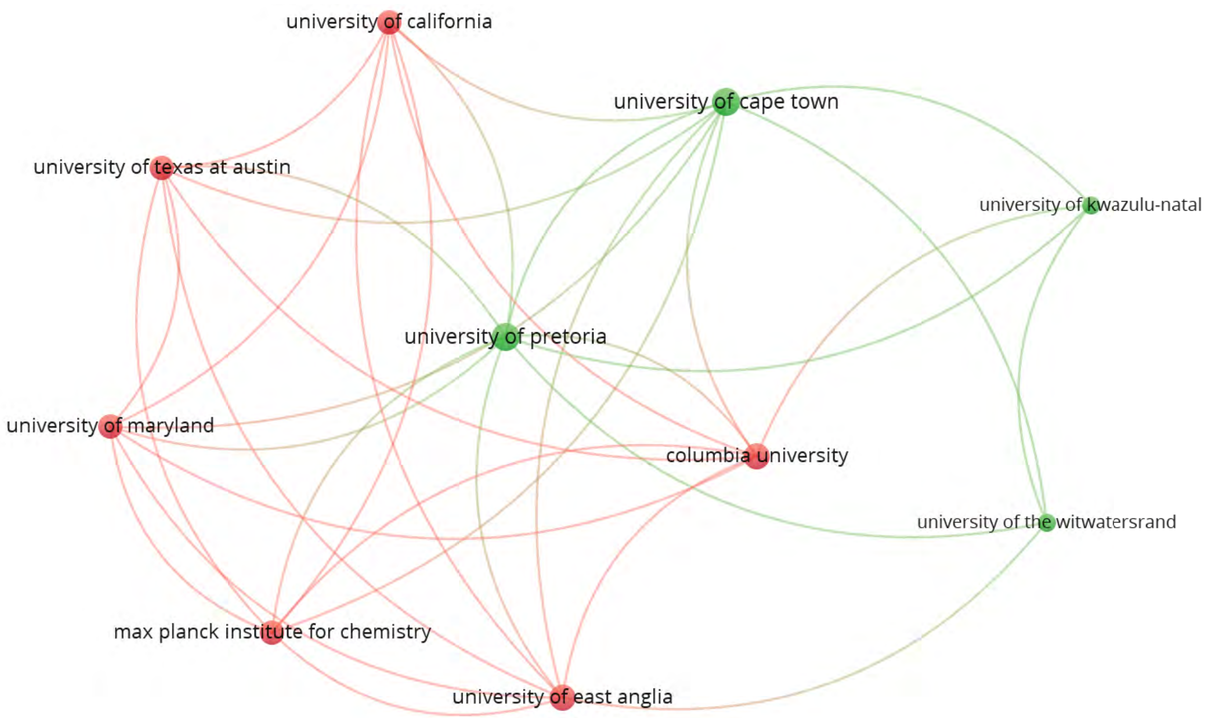


Figure 2. Collaborations between national and international institutions in the area of climate change.

There is consensus that climate change is a complex and multifaceted problem, both nationally and globally. As researchers continue to undertake climate change research and development studies in South Africa, the focus varies according to the theme of the research. As shown in Figure 3, climate change studies reported in South Africa have focused on trends and variability of climatic variables such as precipitation, temperature and runoff; climate change models and modelling; mechanisms that control seasonal to decadal climate variability; understanding how such mechanisms and climate change, in general, affect sustainable development of food security (agricultural production) and water resources availability and supply thereof, as well as environmental and biodiversity impacts. The Western Cape Province appears in the top list of keyword co-occurrences. This is expected given that the province has experienced severe drought that has significantly impacted water resources over the years, with the worst reported events in 2015. Consequently, researchers have paid most attention to the province, making great efforts to understand drought conditions in the region.

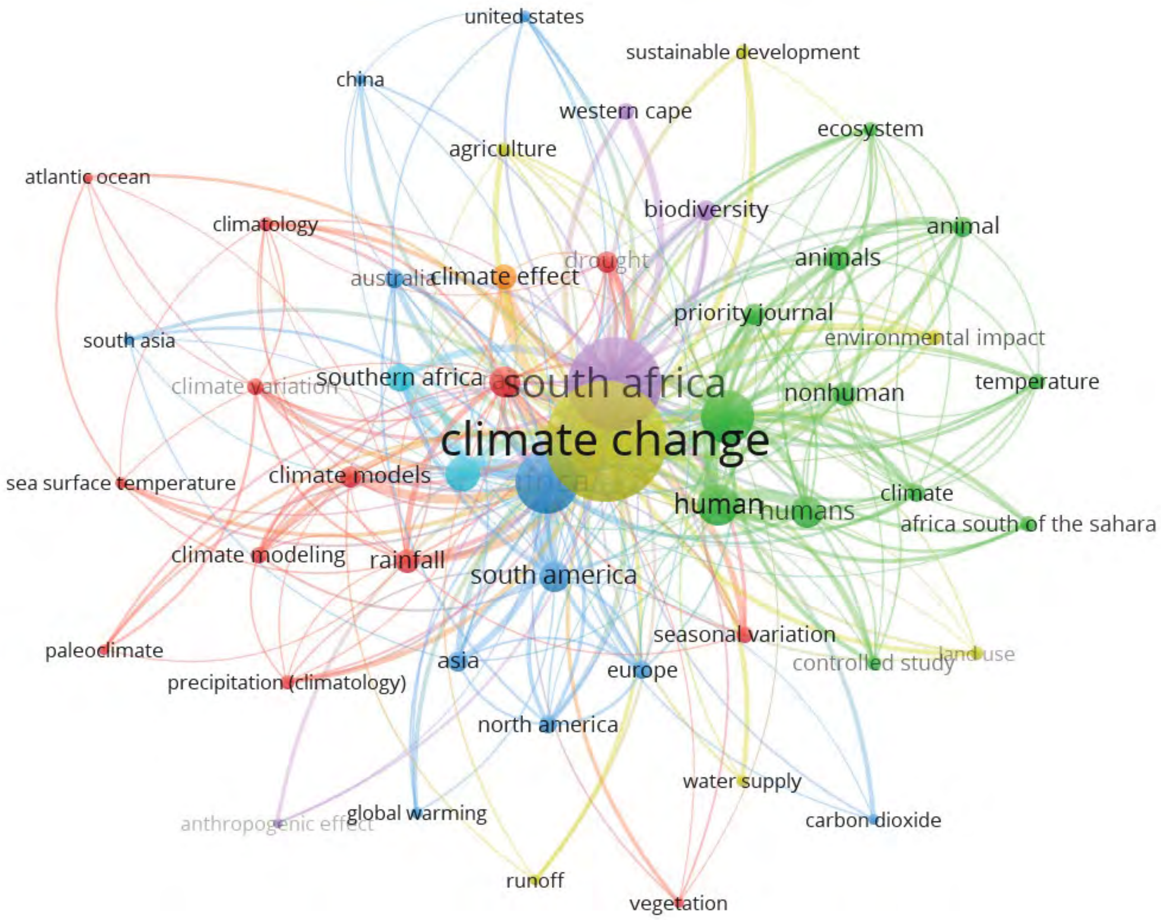


Figure 3. Keyword co-occurrences in climate change scientific published documents in South Africa.

Over the last two decades (2000 – 2022), the 3,383-climate change scientific documents published in South Africa were accomplished by a total of 10,813 authors, of which approximately 4.2% (95.8%) were classified as single (multi) authored documents. Since authors are classified in terms of their affiliation country, climate change research output is identified as Single Country Publications (SCP), where authors worked alone or collaborated with other authors at national level, and Multiple Country Publications (MCP), where authors from South Africa have collaborated with authors from other countries. It is clear from the top-panel of Figure 4 that most climate change research was conducted in South Africa through MCP collaborations. The extent of such country collaborations is illustrated in the bottom panel of Figure 4. There are noticeable collaborations between South Africa and international countries such as the United States of America, the United Kingdom, Germany, China, France and Australia, among others. This collaboration is essential given that most of these developed countries have put systems in place, use advanced technologies and high-resolution remote sensing data and models for weather forecasting and climate change monitoring projections. Consequently, South Africa, through country collaborations platforms, stands to benefit a lot on issues of climate change through information sharing, knowledge, and skills transfer.

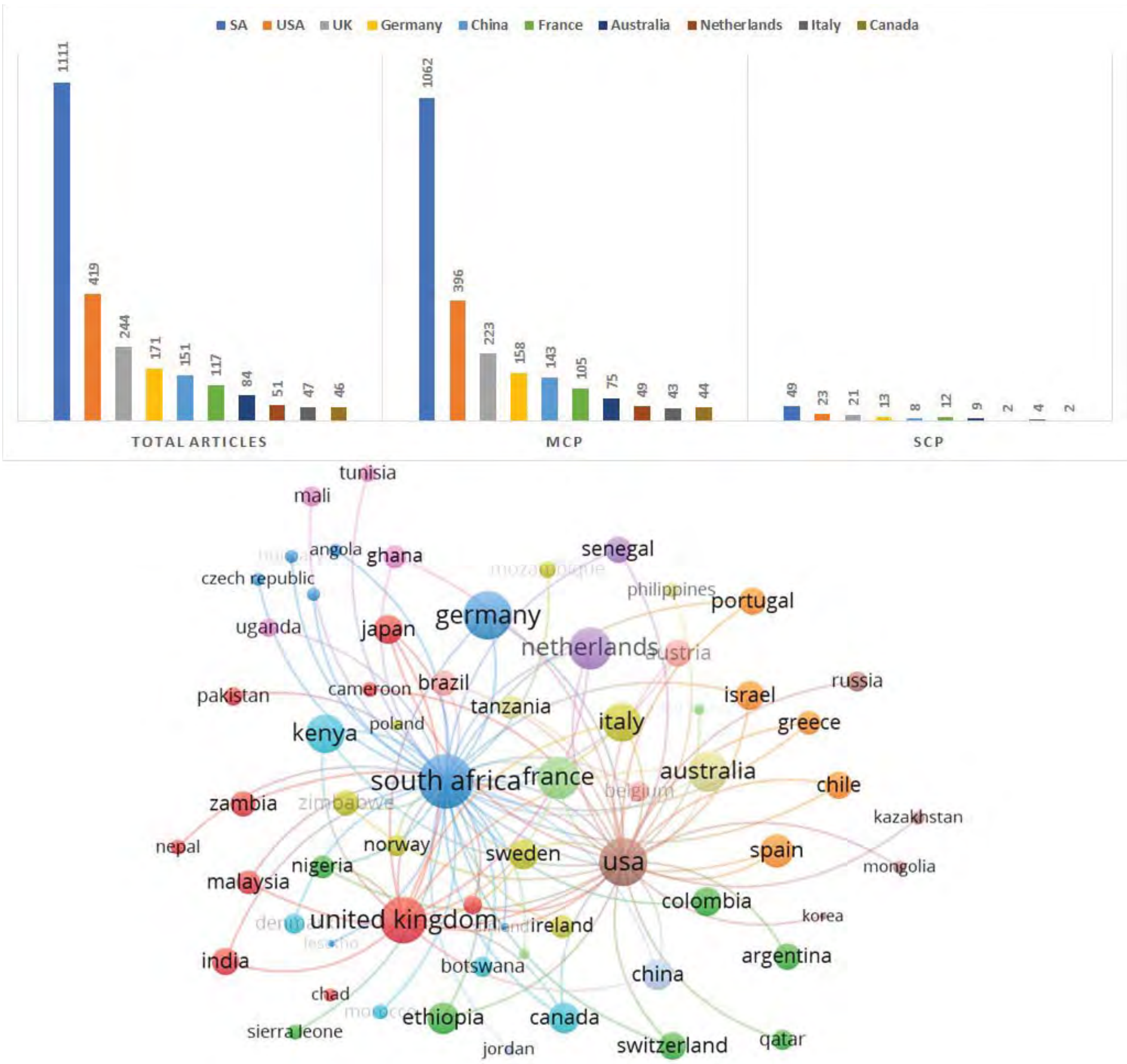


Figure 4. The top panel depicts the top ten countries that have contributed towards research and scientific publications of climate change in South Africa. The bottom panel illustrates collaborations between South Africa and other international countries.

1.3. Perspectives of climate change impacts on water-linked sectors

Climate change impacts are episodic, long term, and sometimes irreversible. Frequent flooding, heavy rainfall events and intense storms, heatwaves, wildfires, droughts, and the rise in the frequency of days with extreme temperatures are some of the examples of episodic consequences while shrinking glaciers, for example, can be regarded as permanent long-term effects [23]. As commonly agreed, the amplified natural greenhouse effects will intensify and increase the frequency of recorded catastrophic weather occurrences and disasters, causing enormous humanitarian calamities both at local and global scales [24]. As captured in literature, South Africa is not exempt from the rapidly escalating effects of climate change [13,25]. Because of the gravity of these threats, which affect a wide range of inextricably linked climate-sensitive sectors which we value and depend on, there is widespread consensus on the need for improved scientific understanding that will address uncertainties regarding the direction, pace, and severity of the impacts of climate change [26]. Certainly, the evaluation of changes at the local level in terms of seasonality, interannual variability, statistical high and low flows are essential in comprehending the effect of climate change as observed in every part of our lives and across sectors. Socio-economic drivers are constantly evolving, such as increased population growth, urbanisation, economic development or lack of, significantly influence how climate change propagates and affects current and future generations. Noted disparities at different regional scales and within the same communities exacerbate vulnerability among disadvantaged populations, often exposed to the highest exposure hazards and have limited resources to respond.

Water supply and sanitation, energy, transportation, wildlife, agriculture, food security, land use and forestry, ecosystems and biodiversity, settlements and infrastructure, and human health are some of the recognized climate-sensitive industries [27,28]. The effects of climate change on selected climate-sensitive industries are briefly examined.

1.3.1 Water

According to the Intergovernmental Panel on Climate Change’s (IPCC's) Fourth Assessment Report on Climate Change and Water, climate change's effects on water resources can be grouped under three outlined categories:

- Changes in precipitation – increasing flooding and drought
- Increased water temperature – exacerbating water pollution and impacting water quality; and
- Reduced water supplies in glaciers, resulting in decreased water supplies to major mountainous regions

The first two water resource impacts are notable hydrometric extremes in South Africa. As reported in the literature, as climate changes, some regions will become drier – and thus more prone to drought – while others will become wetter and thus more susceptible to flooding. Flooding events have been reported in the Western Cape, Limpopo, KwaZulu Natal and Free State provinces. Drought conditions are prevalent mainly in the Northern regions of the country, which are aggravated by high temperatures and changes in precipitation patterns [29]. Because South Africa is already a water-stressed country, with an average annual rainfall of 450 mm, well below the global average of 860 m [30], projected climate change impacts will exacerbate the country's already-existing water crisis.

1.3.2 Health

The scientific literature largely accepts that climate change has both direct and indirect effects on human health and well-being. Direct effects include a rise in ambient temperature and the corresponding increase in morbidity and mortality occurrences, and the health burden of dust and air pollution exposure has been reported to aggravate respiratory diseases. The change in the frequency and incidence of vectors and water-borne infectious illnesses, among other things, has an indirect influence. According to the National Climate Change Response White Paper, nine health and environmental factors have been identified as potential key risks for South Africa, including: (i) heat stress; (ii) natural disasters; (iii) housing and settlements; (iv) communicable diseases; (v) exposure to air pollution and respiratory diseases; (vi) non-communicable diseases; (vii) vector- and rodent-borne diseases; (viii) food insecurity, hunger and malnutrition; and (ix) mental ill-health [14]. These factors must be assessed to reduce the compounding impacts of climate change, which continue to expose the most vulnerable groups in communities to greater climatic hazards. This includes children and the elderly, as well as persons who work in outdoor areas and those who have pre-existing health conditions.

1.3.3 Agriculture

The agricultural sector (i.e., cropland, livestock, forests and fisheries) depends on weather and climate conditions. Significant changes in precipitation patterns and increase in minimum and maximum temperatures that are already being felt pose momentous challenges to the sector with far-reaching effects on crop yields and nutritional quality of agricultural production, thus food security [31]. Compounding water-related challenges, invasive crops and pests and competition for land further affect the agricultural sector, in particular socio-economic factors. The impact of climate change in the agricultural sector is unevenly distributed. While South Africa might be classified as food secure, food access and productivity will in the foreseeable future be challenged due to less favourable weather and climate patterns brought about by changing climate. To reduce climate change vulnerabilities, socio-economic resilience must be built up through measured and effective responses.

1.3.4 Energy

Climate change is one of the driving forces behind the low carbon transitional energy policies that respond to climate change mitigation and related policies. Like many countries, the low carbon energy transition in South Africa started gaining momentum in support of the global quest to limit global warming below 2°C. The transitioning and energy supply system diversification (i.e., renewable energy systems) is crucial for South Africa, which is currently heavily reliant on fossil fuel-generated energy. Such a transition will ensure that energy supplies remain secure and reliable in support of low carbon economic development on which many sectors are dependent [32].

2. Materials and methods

2.1. Study site

South Africa is situated in the southernmost tip of Africa, stretching latitudinally from 22^{o}S to 35^{o}S and longitudinally from 22^{o}E to 33^{o}E, with surface area of approximately 1,219,602 km^2. The country shares common boundaries with neighbouring countries such as Namibia, Botswana, Zimbabwe, Mozambique and Eswatini (formerly Swaziland), with the Mountain Kingdom of Lesotho locked within the South African land in the south-east. South Africa is a fairly arid to semi-arid country, with an average annual rainfall of approximately 464 mm. Rainfall seasons demarcate the country into all-year-round, winter- and summer-rainfall regions, with most of the country falling under summer-rainfall. South Africa is divided into nine provinces and further demarcated into 52 districts (metropolitan or district municipalities). These district municipalities are the second level of administrative division, below the provinces and above the local municipalities. The current study was carried out in the 52 districts municipalities, see their location across the nine provinces in Figure 5.

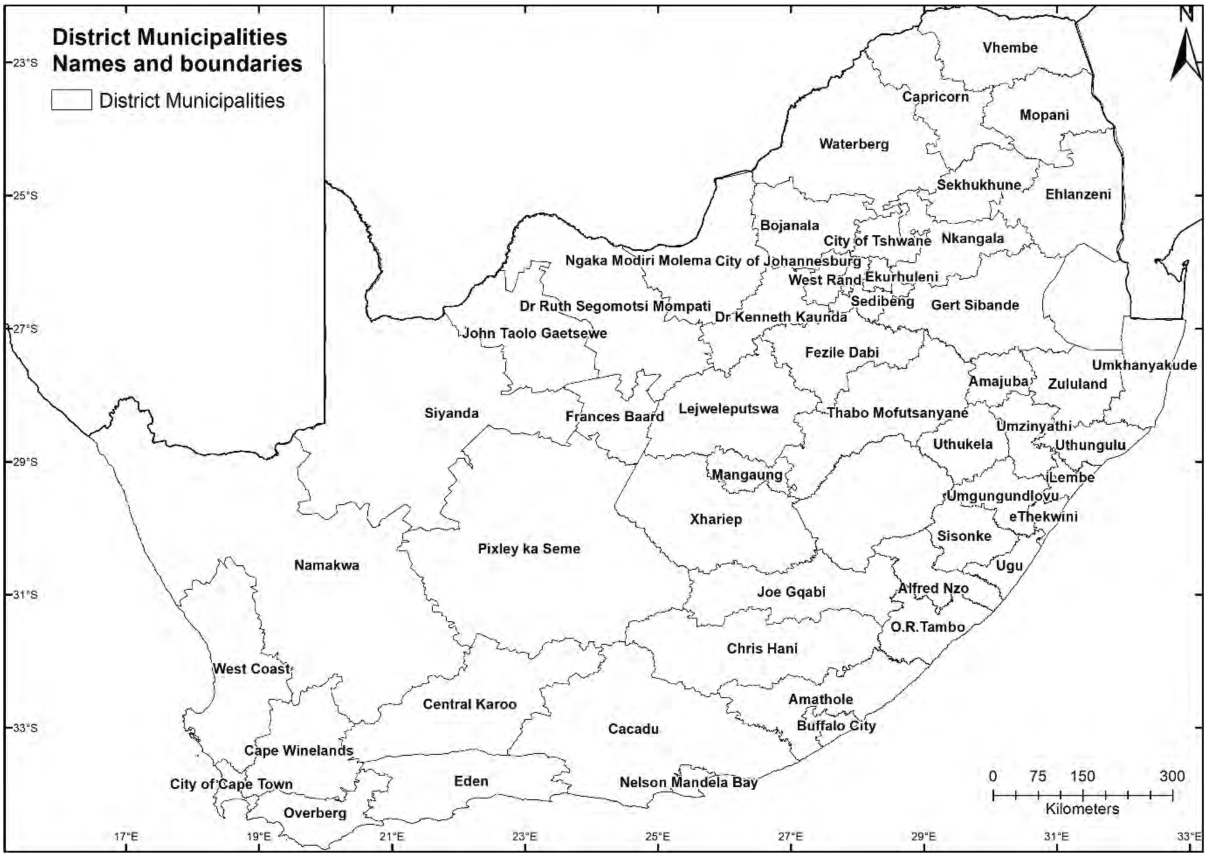


Figure 5. South African district municipalities.

2.2. Data

2.2.1. Climate data

In this study, daily Coordinated Regional Downscaling Experiment (CORDEX) climate simulations (e.g., precipitation, minimum and maximum temperatures) from the CORDEX Rossby Centre regional model (RCA4) were used. These CORDEX climate simulations were driven by eight Global Climate Models (see Table 1) of the 5th Phase of the Coupled Model Inter-Comparison Project (CMIP5) [33], dynamically downscaled across the African domain with a spatial resolution of 0.5° × 0.5° [34]. An ensemble model was then computed from the eight CMIP5 GCMs projections under two Representative Concentration Pathways (RCP4.5 and RCP8.5) scenarios. These RCPs are developed under dissimilar hypotheses of, for instance, future political and economic human behaviour [35]. The climate projections cover the near- and distant-future, spanning from 2036 – 2065 and 2066 – 2095, respectively. Moreover, the historical CORDEX RCA4 RCMs, spanning from 1976 – 2005, were forced by eight CMIP5 GCMs historical GCMs. Climate projections' simulations were run in relation to the historical reference period from 1976 – 2005.

Table 1. Global Climate Models used for the model ensemble

Model name	Country	Resolution	Reference
CCAma-CanESM2	Canada	2.8° x 2.8°	[36]
CNRM-CERFAC_CNRM-CM5	France	1.4° x 1.4°	[37]
CSIRO-Mk3-QCCCE-CSIRO-MK3-6-0	Australia	1.9° x 1.9°	[38]
IPSL-IPSL-CM5A-MR	France	1.9° x 3.8°	[39]
MIROC-MIROC5	Japan	1.4° x 1.4°	[40]
MPI-M-MPI-ESM-LR	Germany	1.9° x 1.9°	[41]
NCC-NorESMI-M	Norway	1.9° x 2.5°	[42]
NOAA-GFDL-ESM2M	USA	2.0° x 2.5°	[43]

2.2.2. Non-climate data

The projected impacts of climate change on water-linked sectors assessed by selecting exposure and sensitivity indicators. According to the IPCC [2,44] the exposure describes the nature and degree to which people, property and systems, among others, are exposed to climatic variations, whereas sensitivity is the degree to which the systems are affected by the changing climate as well as the inherent extreme events. The metric indicators used to assess impacts of drought and heat stress are summarized in Table 2.

The Drought Duration (DD) and Drought Severity (DS) were the only climate-related extremes used to measure the exposure indicator. Both DD and DS indicators were computed from the Standardized Precipitation Evapotranspiration Index (SPEI) [45]. The SPEI, which takes into account both precipitation and potential evapotranspiration (PET), was computed for 6-month accumulation period across the two projected timescales. The calculation of the SPEI is built upon the change between precipitation and PET, and its computational process follows the concept of the Standardized Precipitation Index (SPI) [46]. Detailed information on the calculation of the SPEI can be found in [45], and references therein. In this study DD represents the number of months of a drought event, whereas DS is the absolute sum of the SPEI within DD.

Similarly, the Heat Wave Duration (HWD) and Heat Wave Magnitude Index Daily (HWMID) represented environment exposure in the assessment of heat stress hazards across the 52 district municipalities. The HWD is defined as the duration of the year's longest heatwave (days), while the HWMID is defined as the sum of the magnitude of the consecutive heatwave days based on daily maximum temperature, where a heatwave is defined as the period of at least three consecutive days with a maximum temperature above the calendar 90th percentile centred on a 31-day window for the reference period [47].

Table 2. Metric indicators of drought and heat stress impacts analysis

Determinants of Impact	Indicator/Metric	Description/Implication
		Drought impacts indices
Sensitivity	Population density Surface water Water access totals	Higher population density, greater sensitivity More surface water, less sensitivity Greater water access, less sensitivity
Exposure	Drought duration Drought severity	The longer the drought the greater exposure The higher the severity the more the exposure
		Health impacts indicators
Sensitivity	Total population per district Percent of the elderly Percent of children	All population groups. A large population means more people exposed to risk Percentage of the population over 65 years old Percentage of the population under 5 years old, (0 – 4 years)
Environmental exposure	Heat Wave Duration (HWD) Heat Wave Magnitude Index Daily (HWMID)	Duration of the year's longest heatwave (days) The maximum magnitude of the heatwaves occurring in a year

2.3. Methods

2.3.1. Projected extreme precipitation events

Dynamics of precipitation extremes were assessed based on the Consecutive Dry Days (CDD) and Consecutive Wet Days (CWD) climate change indices. The CDD is a drought index that represents the maximum number of consecutive dry days per time period, with daily precipitation amount of less than 1 mm. This climate index measures below-normal precipitation. In this case, extreme values represent prolonged periods of below-normal precipitation, a condition that manifests as drought. An increase of CDD with time suggests that there is a likelihood of drought conditions to increase. Similarly, the CWD represents the maximum number of consecutive wet days per time period with daily precipitation amount greater than 1 mm. High values of this precipitation index corresponds to potential flooding. Both climate extreme indices were calculated based on RClimDex package. Detailed information on the calculation of CDD and CWD climate extreme indices can be found in [48,49] http://cccma.seos.uvic.ca/ETCCDI and http://etccdi.pacificclimate.org/list_27_indices.shtml.

2.3.2. Drought and heat stress potential impacts

The impacts of drought and heat stress were quantified based on two selected determinants, which are the sensitivity and exposure, as given in Table 2. The original form of both exposure and sensitivity indicators are often not standardised, e.g., they have different International System of Units. For ease of reference, each of the indicators was normalised using either Equation 1 or 2, depending on the indicator's maximum and minimum values, thus leading to positive or negative correlation,

$$Z_i = \frac{x_i - x_{imin}}{x_{imax} - x_{imin}} \quad (1)$$

$$Z_i = \frac{X_{imax} - X_i}{X_{imax} - X_{imin}} \quad (2)$$

where x is the value of a specific indicator for the i^{th} district municipality, and x_{min} and x_{max} represent the maximum and minimum values of the indicator, respectively. Equation 1 is used when the indicator has a positive correlation, whereas Equation 2 applies for the negative correlation. The normalised values (Z) range from 0 to 1, where zero represents the least sensitive (exposure), whereas 1 represents higher sensitivity (exposure). After the normalisation, the sensitivity and exposure indicators were calculated by using Equation (3),

$$Z_{ji} = \frac{\sum_{i=1}^{n} V_i}{n} \tag{3}$$

where n is the number of metrics in sensitivity or exposure indicators, and Z_{ji} is the value of the indicator j (i.e., sensitivity or exposure) for the district municipality i. Equation (4) was used to calculate the potential drought and heat stress impacts.

$$Pl = Sensitivity \times Exposure \tag{4}$$

The higher the Potential Impacts (*PI*) score, the more significant the adverse impact caused by heatwave or drought events. The z-score (i.e., statistical deviation from a mean value) approach was used to normalize the data for each variable, and each factor score was combined into quantiles to create composite PO scores [50]. A four-point quantile scale was used to interpret the level of impacts at the 52 district municipalities as shown in Table 3.

Table 3. Categories of exposure, sensitivity, and potential impact scores

Category	Sensitivity	Exposure	Potential Impact
0 < *Indicator* < 0.25	low risk	low	low
0.25 < *Indicator* < 0.50	moderate risk	medium	moderate
0.50 < *Indicator* < 0.75	high risk	high	high
0.75 < *Indicator* < 1.0	extreme risk	extreme	Extreme

3. Results

3.1. Changes in the projected extreme precipitation and temperature events

3.1.1. Consecutive wet days

The results of the CWD at national scale for each province is depicted in Figure 6. Under the RCP4.5 scenario, the CWD is projected to increase to an average of about 5 days/year majorly in the west-central parts of Free State province, north-eastern part of North West, KwaZulu-Natal, Mpumalanga and Limpopo provinces. The spatial extent of the CWD is projected to decline into the far future. Under the RCP8.5 scenario, CWD is projected to decline having an average of 4 days/year with a considerable reduction in the spatial distribution.

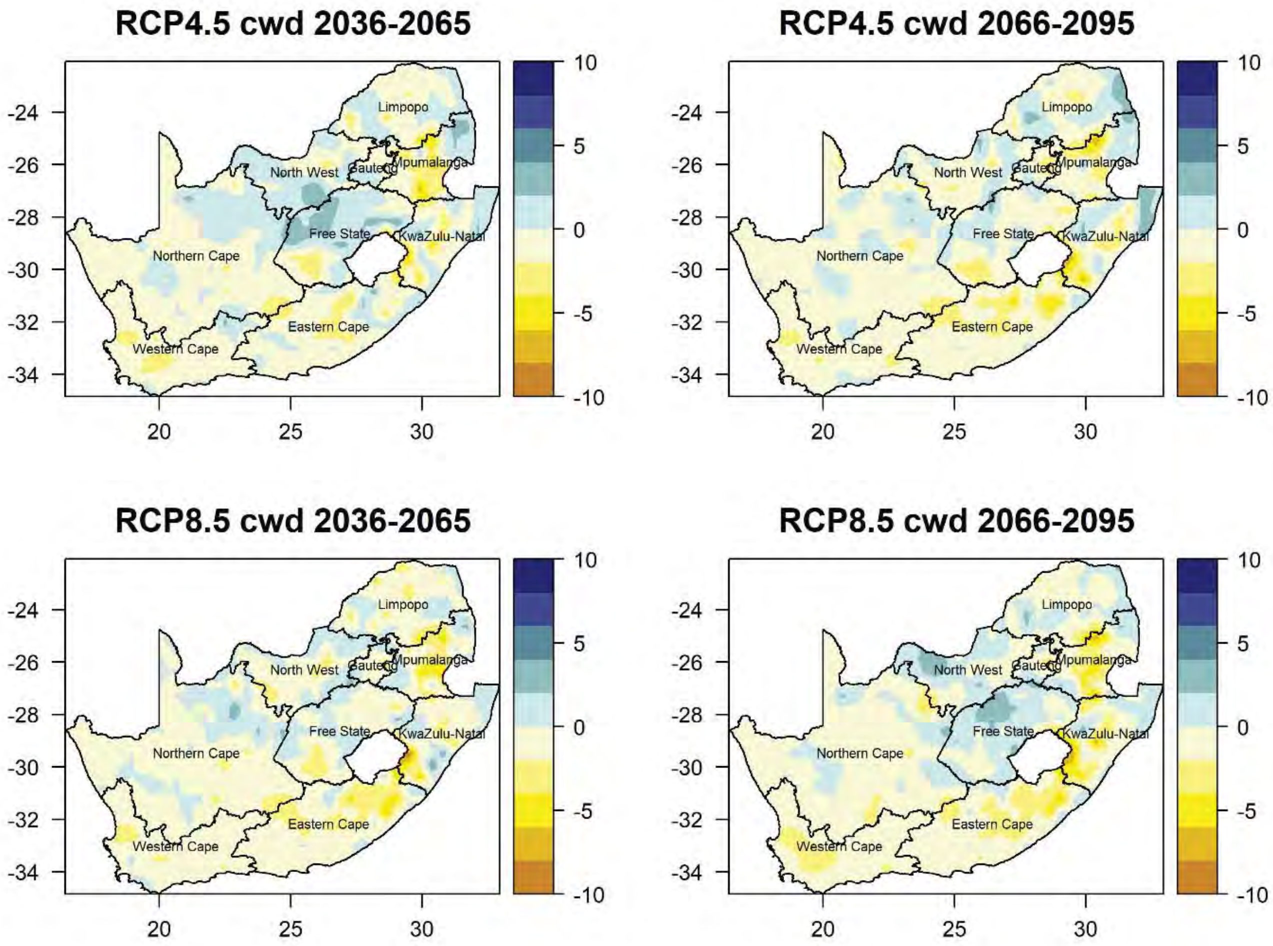


Figure 6. Projected Consecutive Wet Days in South Africa under (top) RCP4.5 and (bottom) RCP8.5 for 2036 – 2065 and 2066 – 2095 referenced to 1975 – 2005.

3.1.2. Consecutive dry days

As shown in Figure 7, CDD is projected to increase from about 5 to 65 days/year under the RCP4.5. The Western Cape Province is likely to experience the highest number of CDD of about 45 days/year in near future climate (2036 – 2065) and to more than 50 days/year in the far future climate (end of the century). The CDD are projected to further increase under the RCP8.5 for all time periods reaching more than 90 days/year in the far future.

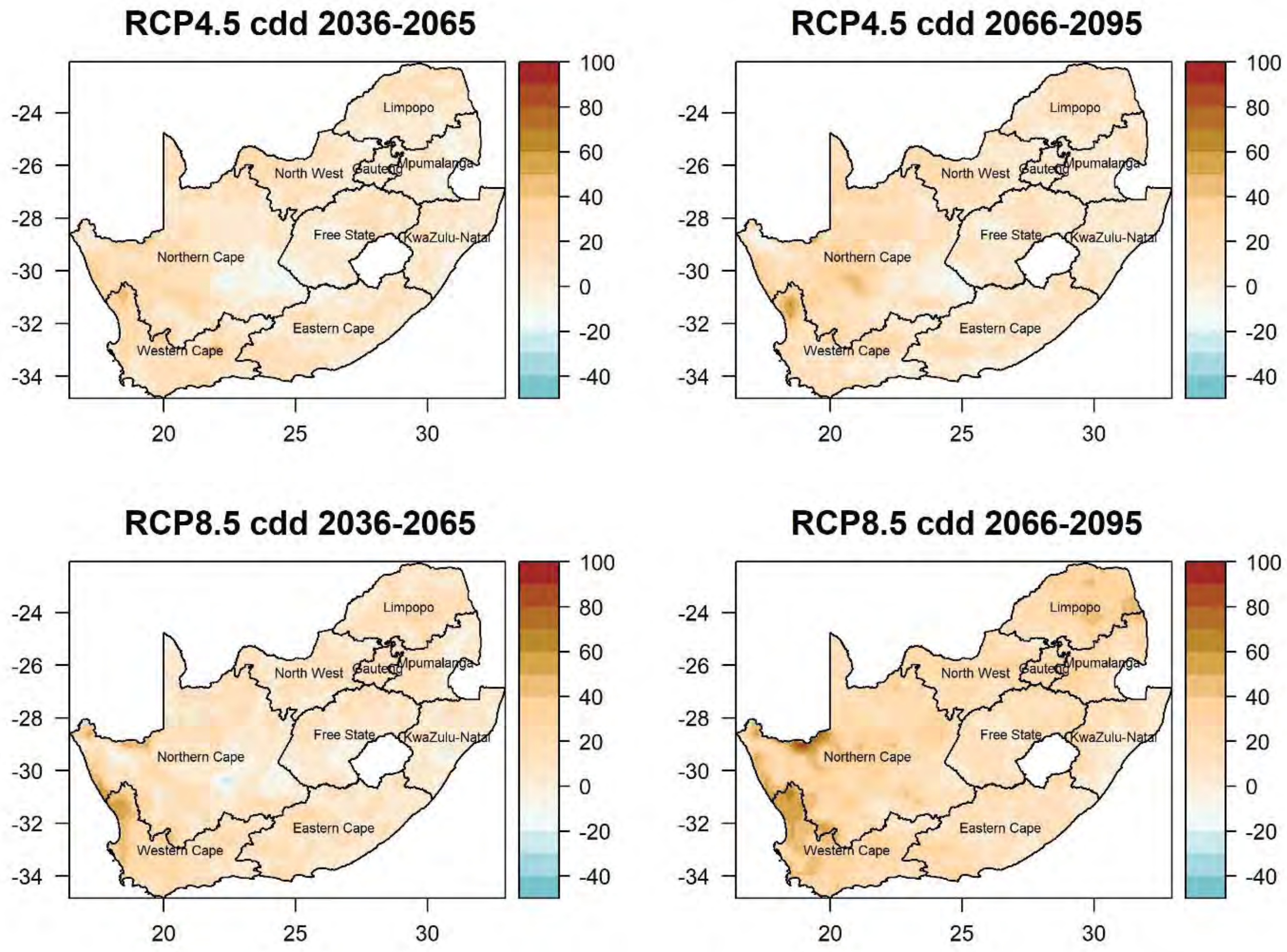


Figure 7. Projected Consecutive Wet Days in South Africa under (top) RCP4.5 and (bottom) RCP8.5 for 2036 – 2065 and 2066 – 2095 referenced to 1975 – 2005.

3.2. Projected drought impacts on decadal timescales

3.2.1. Sensitivity indices and their impacts

As alluded in the methodology section, a number of sensitivity determinants (these are indicators that are likely to be affected by projected increase of climate change) were selected to quantify the drought exposure at national scale. These indicators were first assessed to evaluate the risk levels across the country at district municipality spatial scale. The levels of risk were categorised based on a quantiles categories summarized in Table 3. Results for sensitivity risks across the country and district municipalities are shown in Figure 8 and Figure 9. The green indicates the lowest risk, whereas the red represents the highest risk within a category. Notably, most of the indicators are affected by drought although the levels of risks as measured by different indicators vary across the district municipalities. In general, most of the South African district municipalities are under moderate sensitivity risk (0.25 < Indicator < 0.50) category, when measured using total population indicator. District municipalities in KwaZulu-Natal, the Free State and few in the North West and Northern Cape, particularly, are at the lower level of moderate sensitivity risk category. The Eastern Cape is the solely province notable at high sensitivity risk category (0.50 < Indicator < 0.75). In terms of access to in-house piped water, the central, north-western and southern parts of the country are highly sensitive to drought conditions. When considering borehole as a water access indicator, a number of district municipalities are least sensitive to drought as they are under 0 < Indicator < 0.25 category. However, the uppermost of the northern parts, the eastern and some pockets in central are highly sensitive to drought. In terms of accessibility of dams, rivers and streams, there is least drought sensitivity in the Eastern Cape, and in some pocket's areas in the northern regions. High drought sensitivity is detected in the south and central regions of the country.

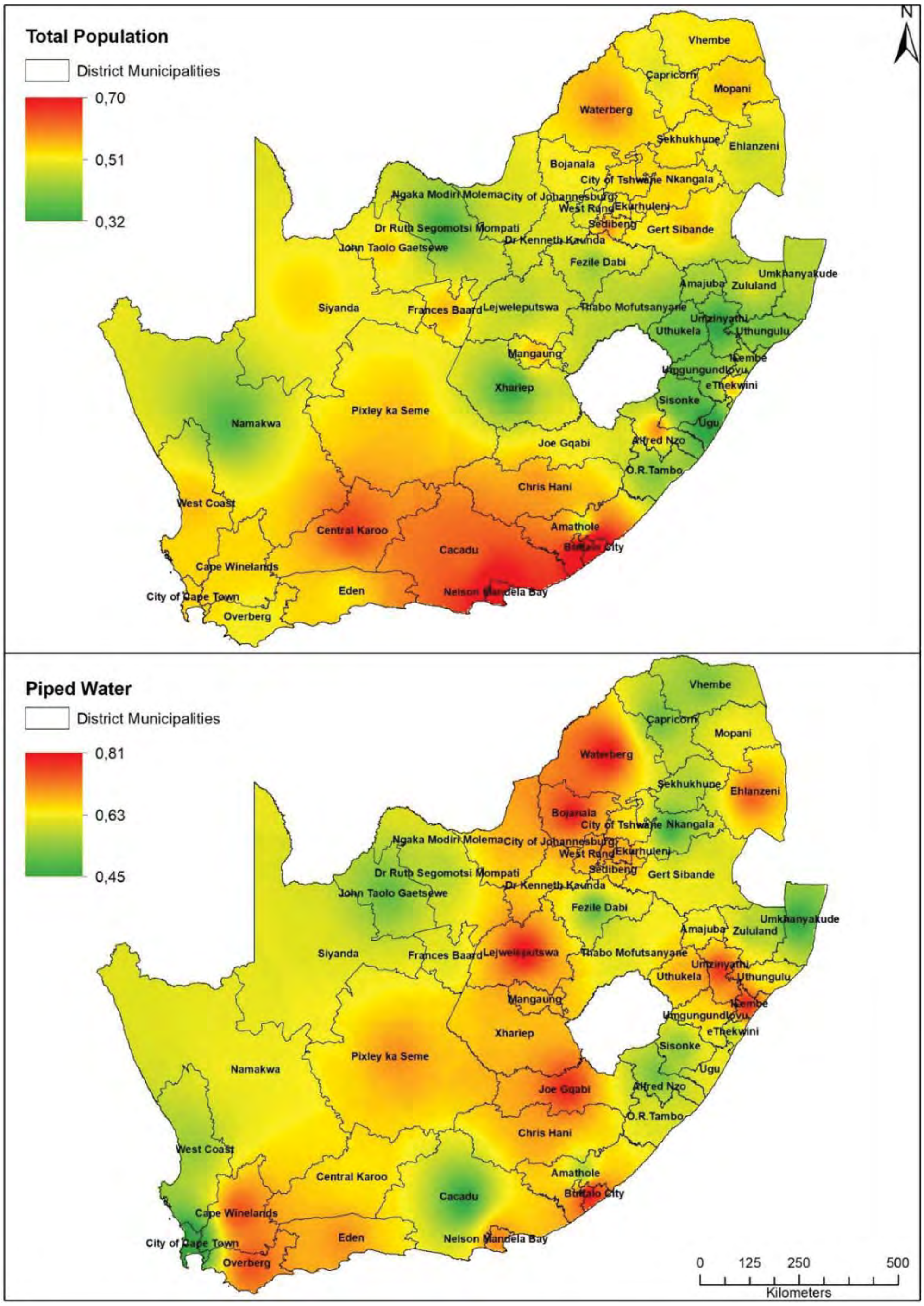


Figure 8. Sensitivity indicators and their impacts across the country.

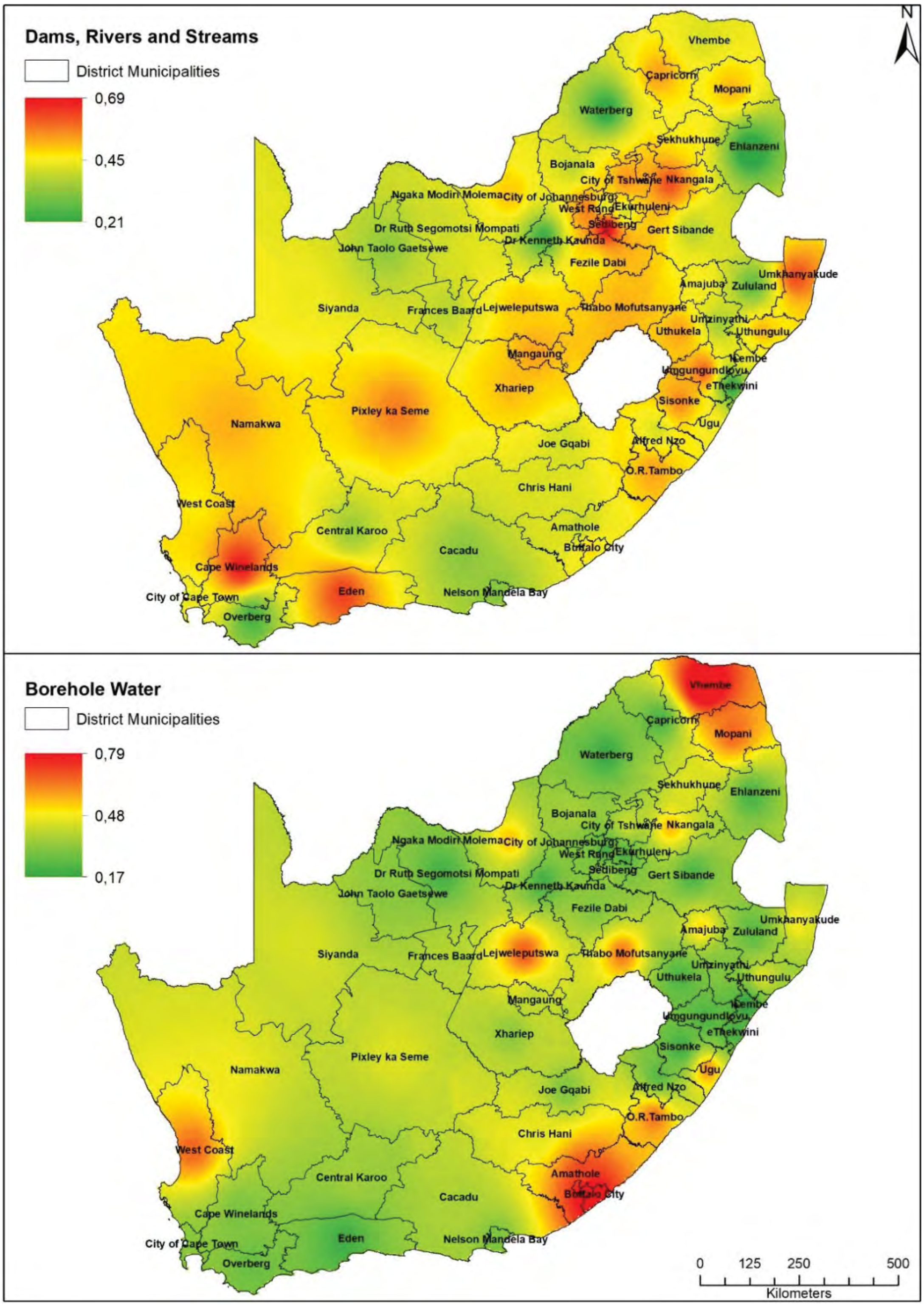


Figure 9. Same as Figure 8 but showing different sensitivity indicators.

Figure 10 depicts spatial distribution of the averaged sensitivity across the district municipalities. The averaged sensitivity risk ranges from a moderate sensitivity risk, illustrated in green, to a high level of sensitivity risk, shown in red. In particular, scores ranging between 0,39 and 0,49 are notably observed in most parts of KwaZulu-Natal, the North West and Mpumalanga provinces, indicating moderate sensitivity risk. High sensitivity risk is observed in the Eastern Cape, parts of Limpopo, the central and southern regions of the country.

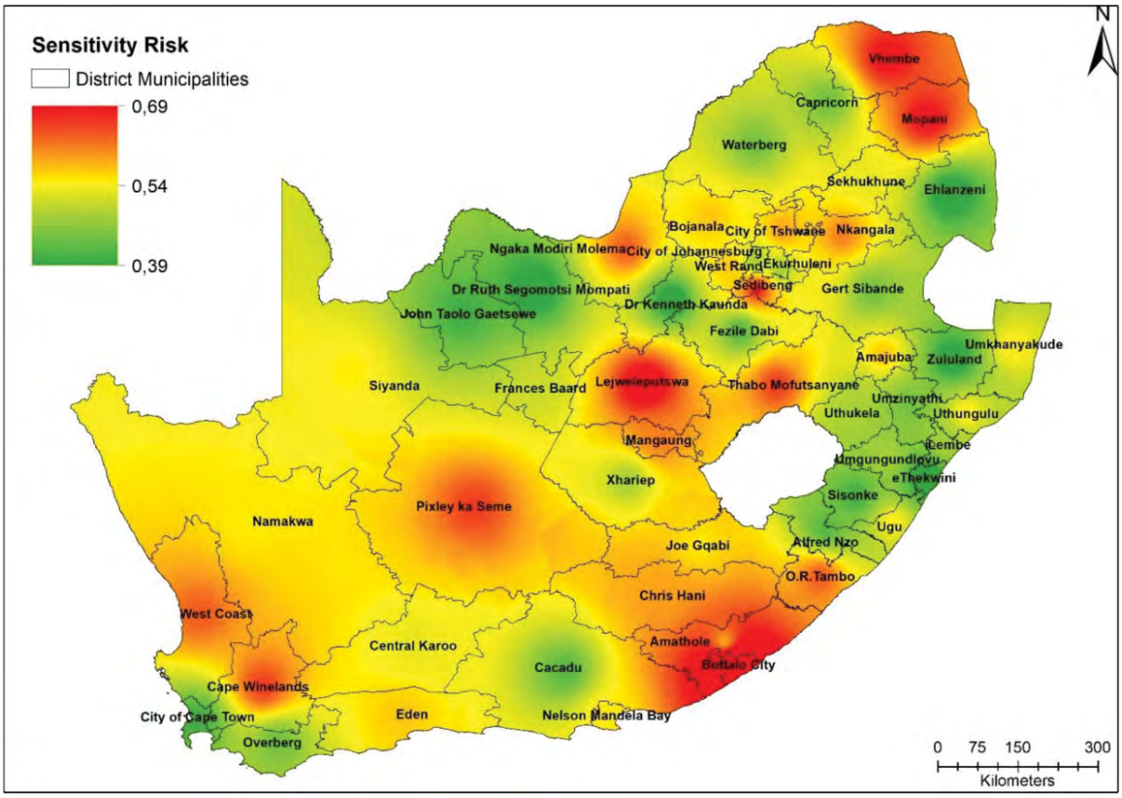


Figure 10. Averaged sensitivity risk across the district municipalities.

3.2.2. Exposure indices and derives characteristics

The exposure determinant indicators were based on the projected DD and DS over the near future (NF) (2036 – 2065) and distant future (DF) (2066 – 2095) periods, computed from SPEI at 6-month accumulation time-step. The results are presented in Figure 11 and Figure 12 for the projected DD and Figure 13 and Figure 14 for DS under the RCP4.5 and RCP8.5 emission scenarios and across the timescales, respectively. As noted in the maps, the projected DD and DS exhibit localised and spatial variability across the timescales and emission scenarios. The risk of persistent and prolonged DD in the NF is high (shown in red) in most parts of the country under the RCP4.5 emission scenario and in the eastern, parts of the southern and towards the northern regions under the RCP8.5 emission scenario. Similarly, the central and southwestern regions indicate a high possibility of persistent and prolonged drought in the DF under the RCP4.5, and mostly the south-eastern and some pockets in the northern parts under RCP8.5 emission scenario.

As shown in Figure 13 and Figure 14, the projected DS sensitivity score ranges from 0,24 (0,23) in green, indicating low risk of drought becoming severe and 0,68 (0,69) in red, indicating a high risk of district municipalities experiencing severe drought over the NF (DF) period across both the RCP4.5 and RCP8.5 simulations. Undoubtedly, the results indicate that most of the South African district municipalities are likely to experience severe drought conditions in the NF period under the RCP4.5

simulations, whereas drought is expected to be less severe in the central parts of the country under the RCP8.5 simulations. Similar results are observed for the DF period, though there is a spatial shift in the projected severity of drought in specific district municipalities under both the RCP4.5 and RCP8.5 simulations.

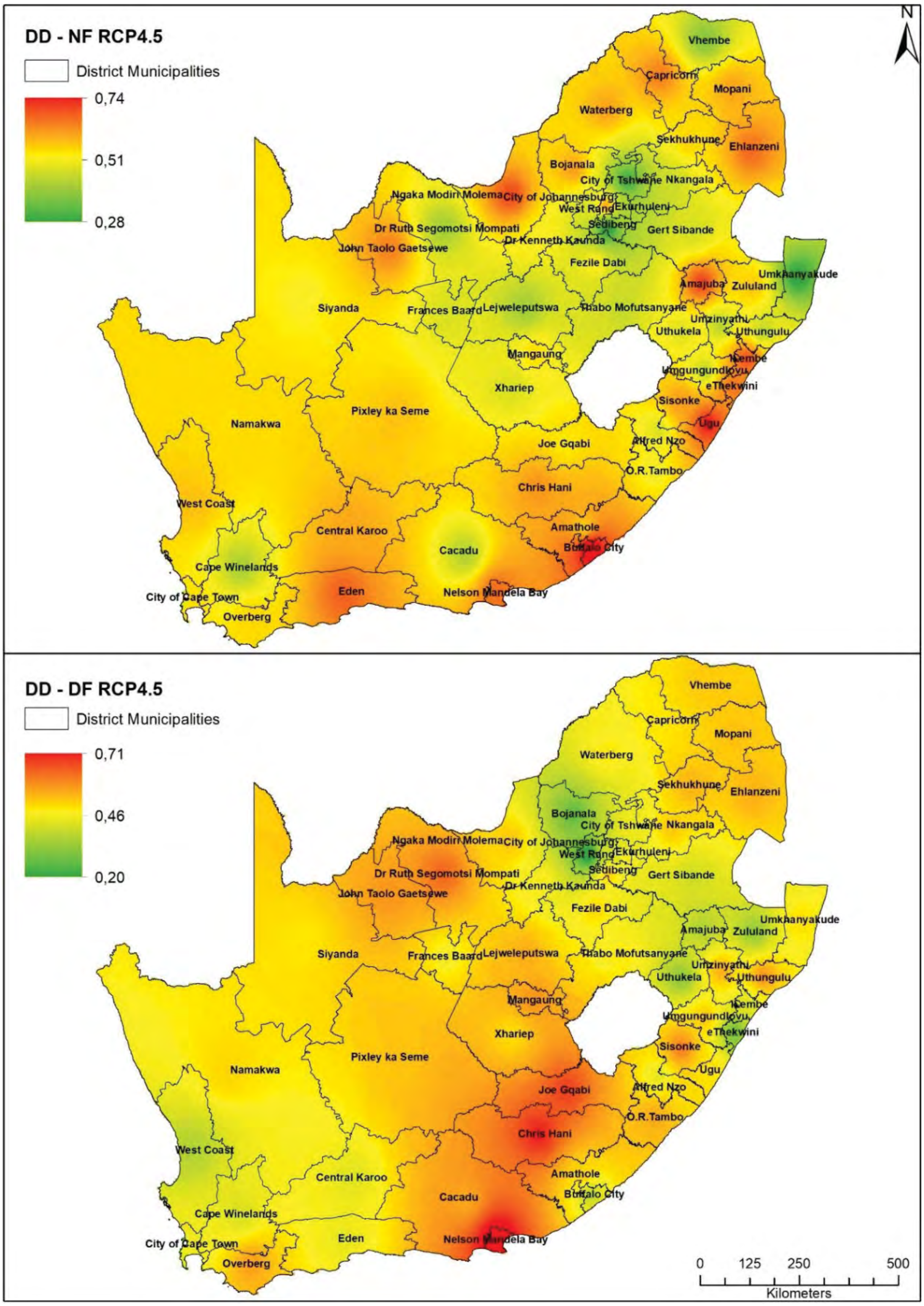


Figure 11. Projected drought duration during the near future (2036 – 2065) and distant future (2066 – 20950 under RCP4.5 emission scenario.

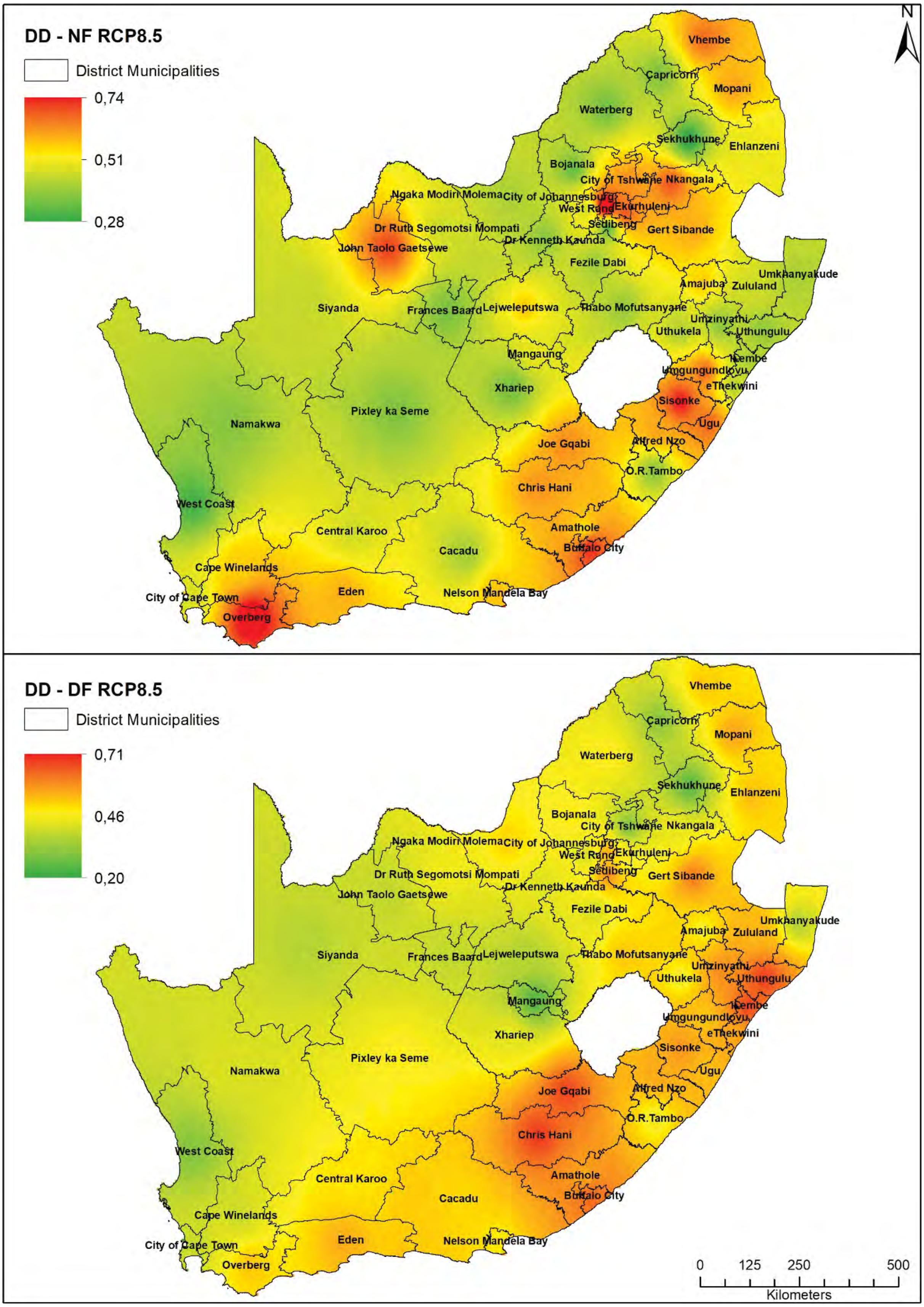


Figure 12. Same as Figure 11 but for RCP8.5 simulations.

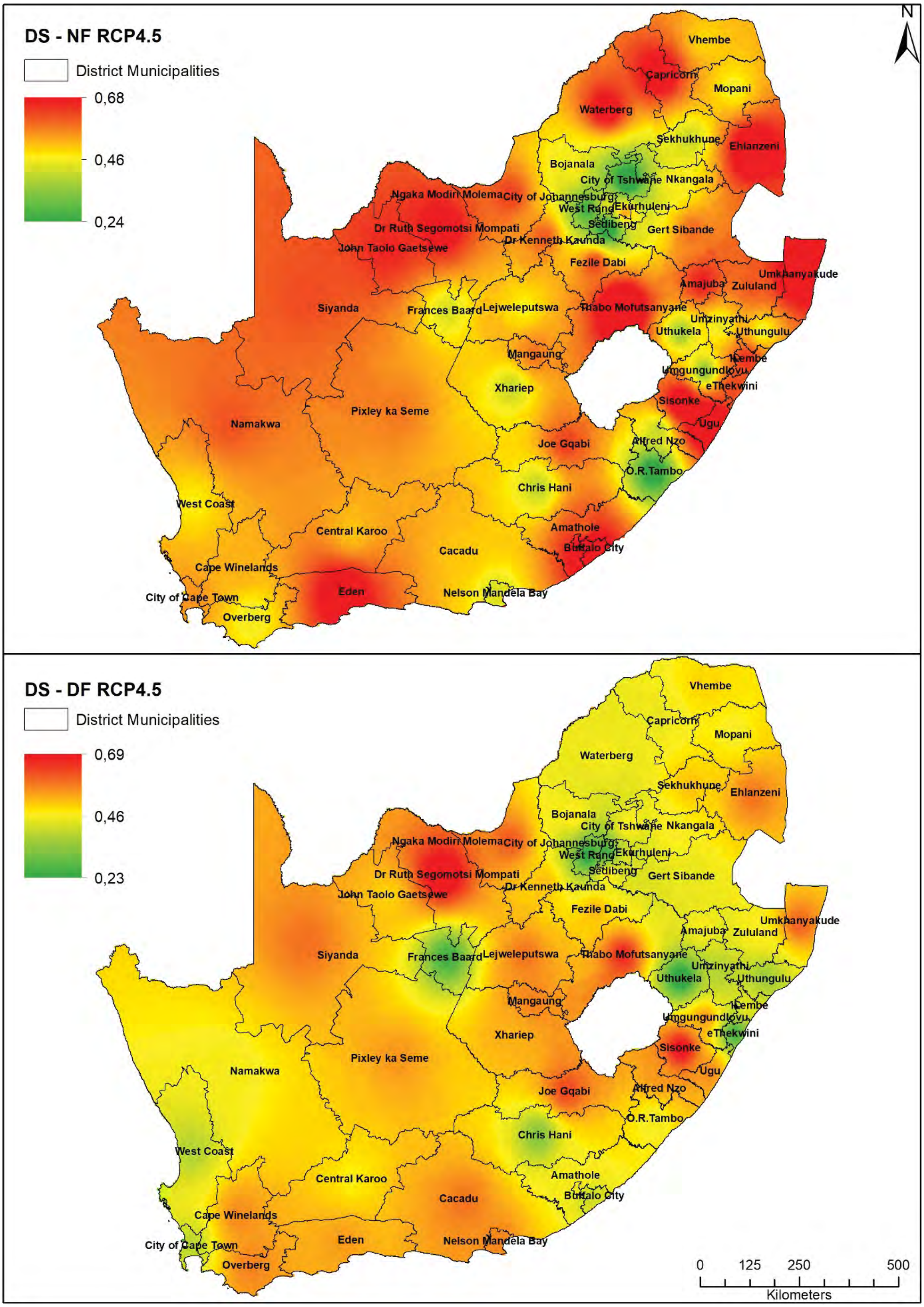


Figure 13. Projected drought severity during the near future (2036 – 2065) and distant future (2066 – 2095 under RCP4.5 simulations.

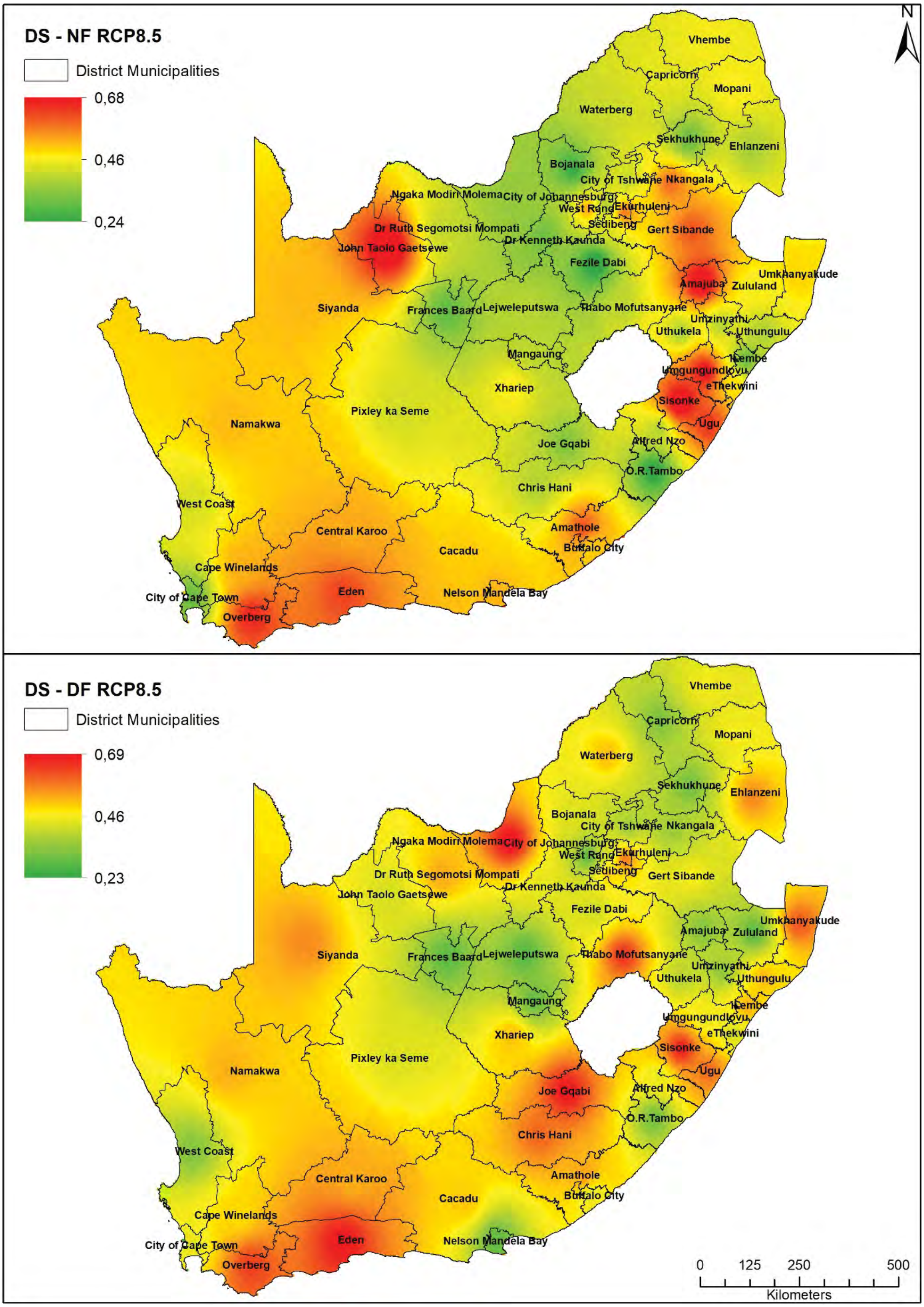


Figure 14. Same as Figure 13 but for RCP8.5 simulations.

3.2.3. Projected potential drought impacts

Results for the spatial distribution of the potential drought impact (DI) during the NF and DF periods across the RCPs are shown in Figure 15. The projected DI ranges between 0.14 – 0.45 and 0.11 – 0.35 during the NF and DF periods, under the RCP4.5 and RCP8.5 simulations, respectively, complementing the low (green) to moderate (red) impact category. Most district municipalities under RCP8.5 simulations during the NF period show low impacts to drought and climate changes. Only few district municipalities in the northern, eastern, and southern show moderate drought impacts under the same RCP simulations. While there is a slight decline in the potential DI over the DF period, the impact category remains within low to moderate level. Nonetheless, the spatial shift indicates areas that are expected to be densely impacted by drought in the DF period.

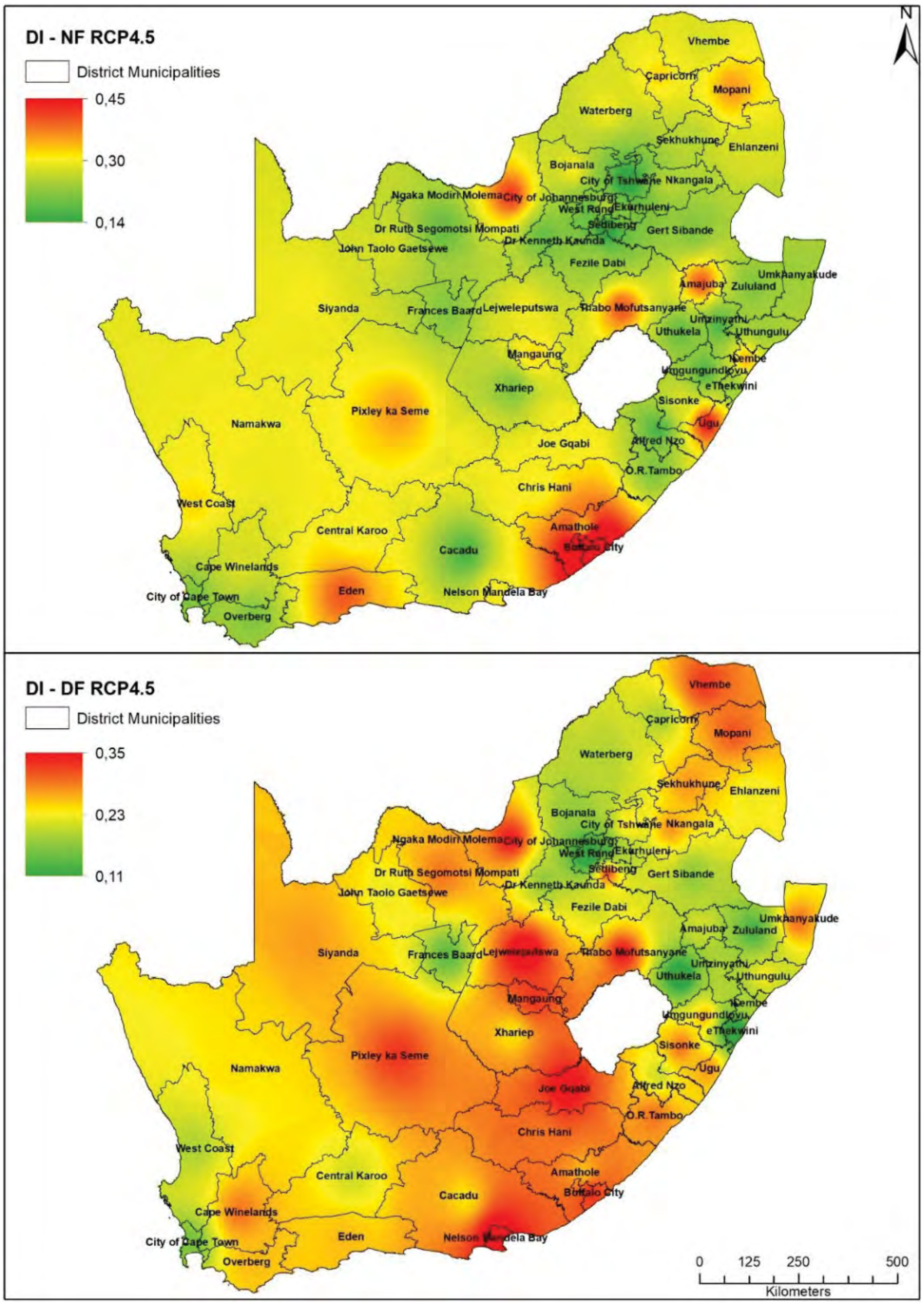


Figure 15. Potential drought impact in the NF (2036 – 2065) and DF (2066 – 2095) under RCP4.5.

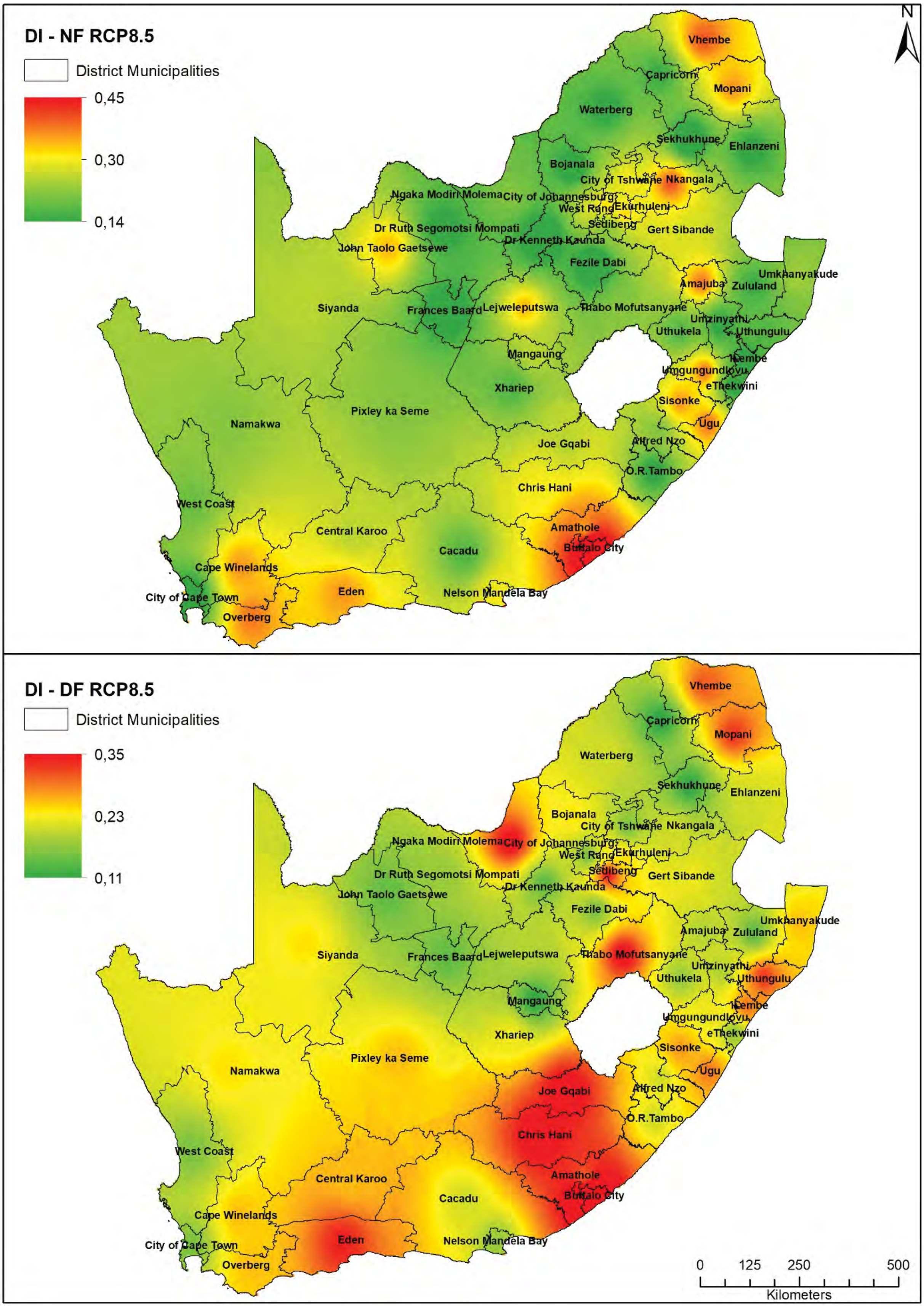


Figure 16. Same as Figure 15 but for RCP8.5 simulation.

3.3. Projected impacts of heat stress over South Africa

As defined by the IPCC, sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli [51]. In this heat stress assessment, demographic data, including (i) the percentage of the total population as well as (ii) the percentage of the elderly population over 65 years old, and (iii) the percentage of children between the age group of (0-4) were taken into account. The heat stress assessment uses the same categories as the drought assessment, with green representing the lowest sensitivity risks and red indicating the highest. The sensitivity risks for the individual indicators for heat stress are depicted in Figure 17. In terms of the total population indicator, the Eastern Cape, the second largest province, experiences high sensitivity risk (0.5<indicator<0.75), in particular regions in the eastern coastal zone, where population density is reported to be four times higher than the average within the Sarah Baartman District Municipality [52]. Regions in the western and northern parts of the country are under moderate to low sensitivity risk. A large proportion of the elderly population and thus the sensitivity risk is high in district municipalities in the north-eastern part of KwaZulu Natal and Sekhukhune district municipality in Limpopo.

Collectively, the three sensitivity indicators provide an integrated sensitivity risk index for South Africa. Overall, as depicted in the bottom panel of Figure 18, there is a wide variation in the sensitivity risks observed across the country, with most of the district municipalities experiencing moderate sensitivity risks (0.25<indicator<0.5). The Free State and Limpopo and the three Cape provinces (Eastern Cape, Northern Cape and Western Cape) exhibit relatively higher sensitivity risks as compared to Gauteng, North West, Mpumalanga and KwaZulu Natal provinces.

Figure 19 shows the spatial pattern of integrated heat stress exposure risks based on HWD and HWMID. The heat stress exposure risks are high (0.5<indicator<0.75) and spatially extended. During the near future (2036 – 2065), under the 4.5 and 8.5 emission scenarios, the western and eastern parts are experiencing risks ranging between 0.15 and 0.57, with most district municipalities covering districts near the shore in the Western Cape province and parts of the north-eastern region of KwaZulu-Natal Province. Compared to the RCP8.5, heat stress risks are mainly low to moderate, with greater pronouncement in the future (2066 – 2095), particularly in the interior regions and selected district municipalities in the Western Cape, KwaZulu-Natal, Mpumalanga and parts of Limpopo Province.

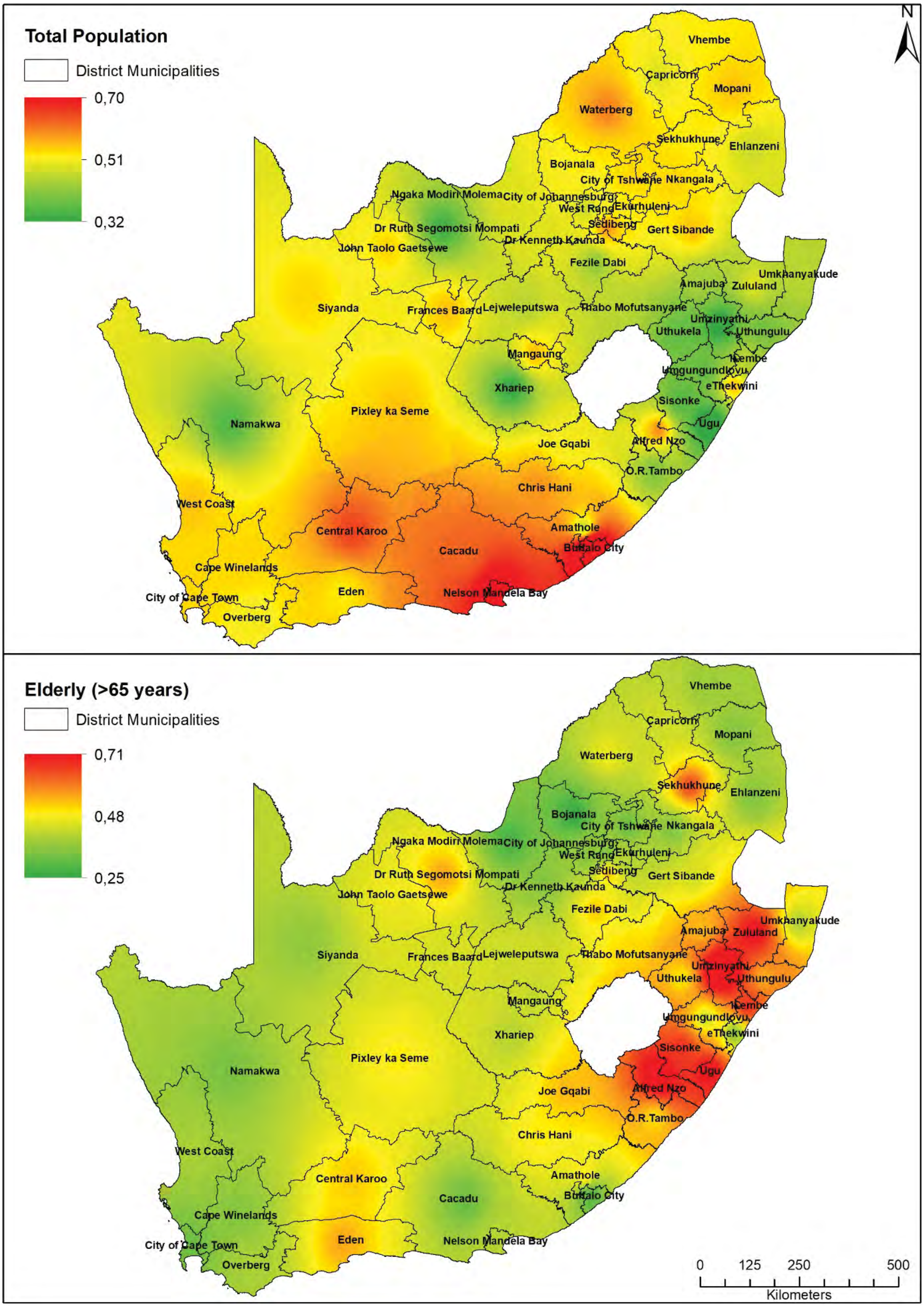


Figure 17: Heat stress sensitivity indicators and their impacts across the country.

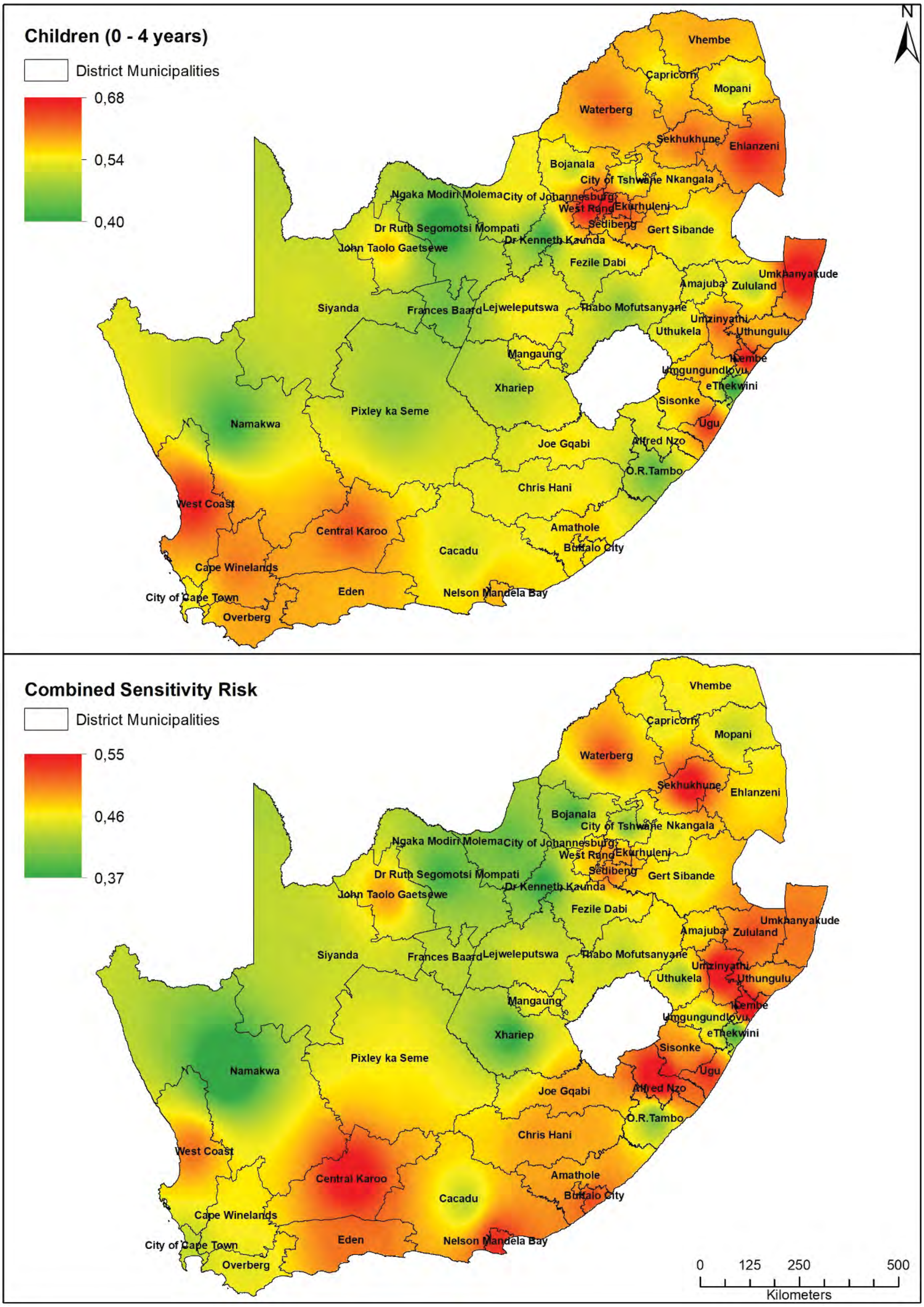


Figure 18. Same as Figure 17 but for children between 0 – 4 years and combined sensitivity risk across the indicators.

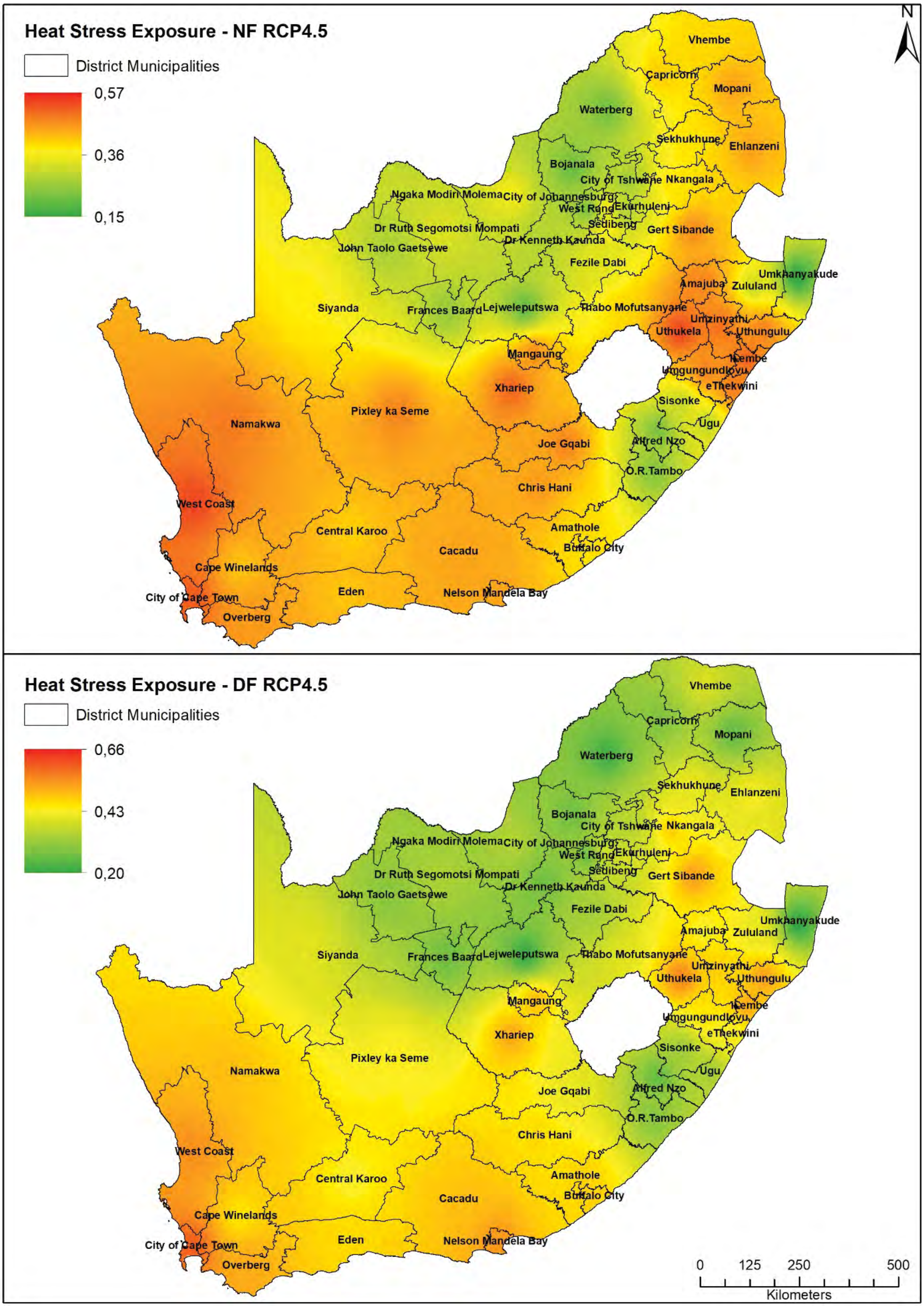


Figure 19. Heat stress exposure risk across district municipalities under the RCP4.5 simulations.

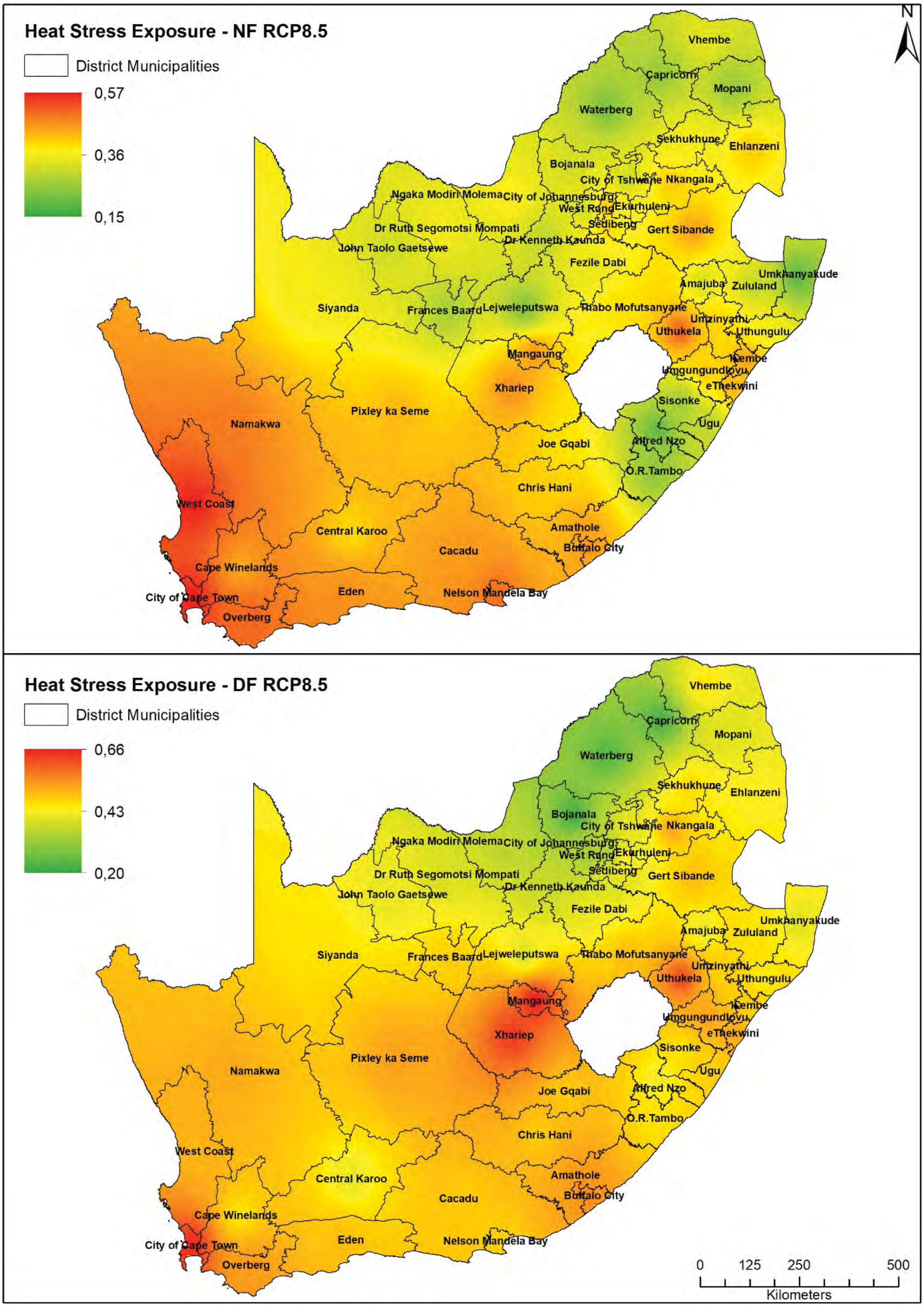


Figure 20. Same as Figure 19 but for RCP8.5 simulations.

The regional distribution of heat stress potential impacts for the NF (2036 – 2065) and DF (2066 – 2095) under the intermediate (RCP4.5) and very high (RCP8.5) emission scenarios are illustrated in Figure 21. Heat stress exposure impacts are high and widespread across the country for the DF under RCP8.5 with the exception of selected district municipalities in the North West and Limpopo provinces which demonstrate low exposure impacts. Moderate exposure risks are observed in selected regions across the country, particularly coastal regions. The spatial distribution of heat stress exposure impacts follows more or less the same pattern and intensity, with few districts in the Limpopo Province experiencing relatively higher exposure risk for RCP4.5 under NF period. By comparison with the rest of the country, the north-western region, and parts of Limpopo exhibit low exposure risk (0 < Indicator < 0.25), with the Northern Cape Province mainly to experience moderate exposure risk (0.25<indicator<0.5) in the future under the intermediate emission scenario.

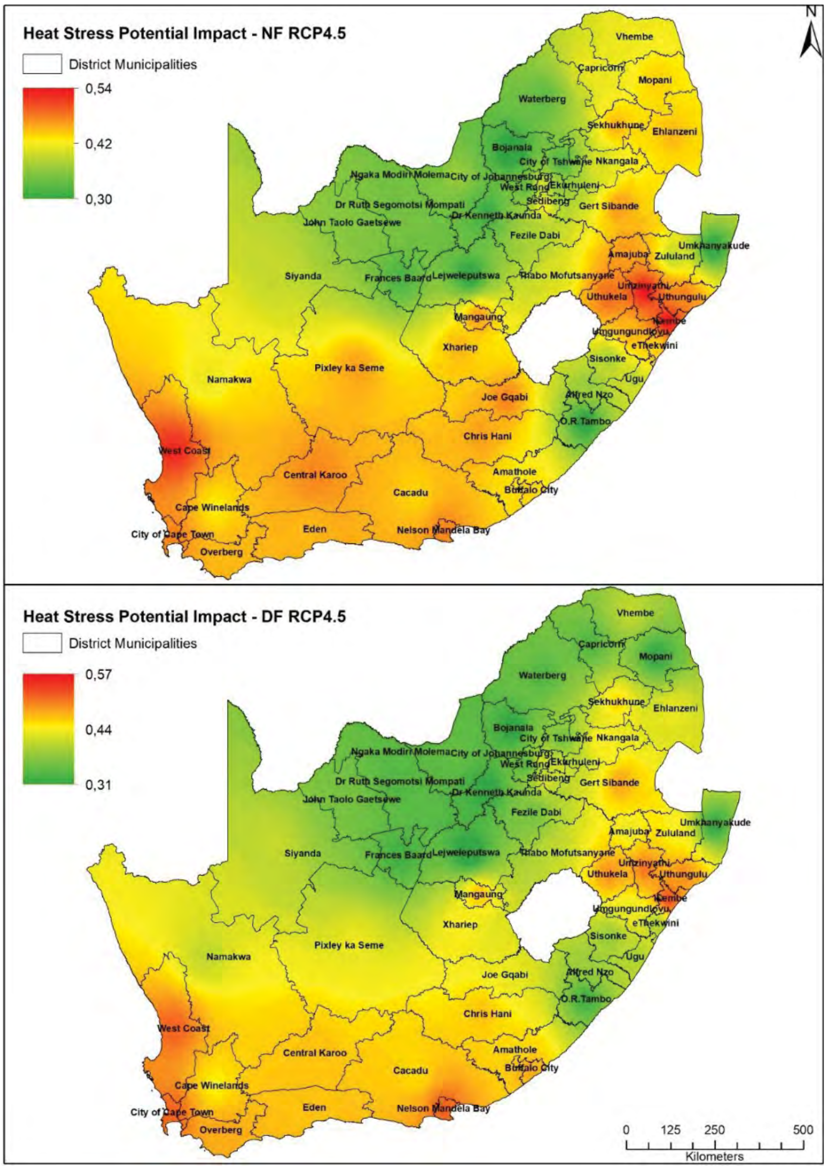


Figure 21. Projected heat stress potential impact during the near-future (top) and distant-future (bottom) under RCP4.5.

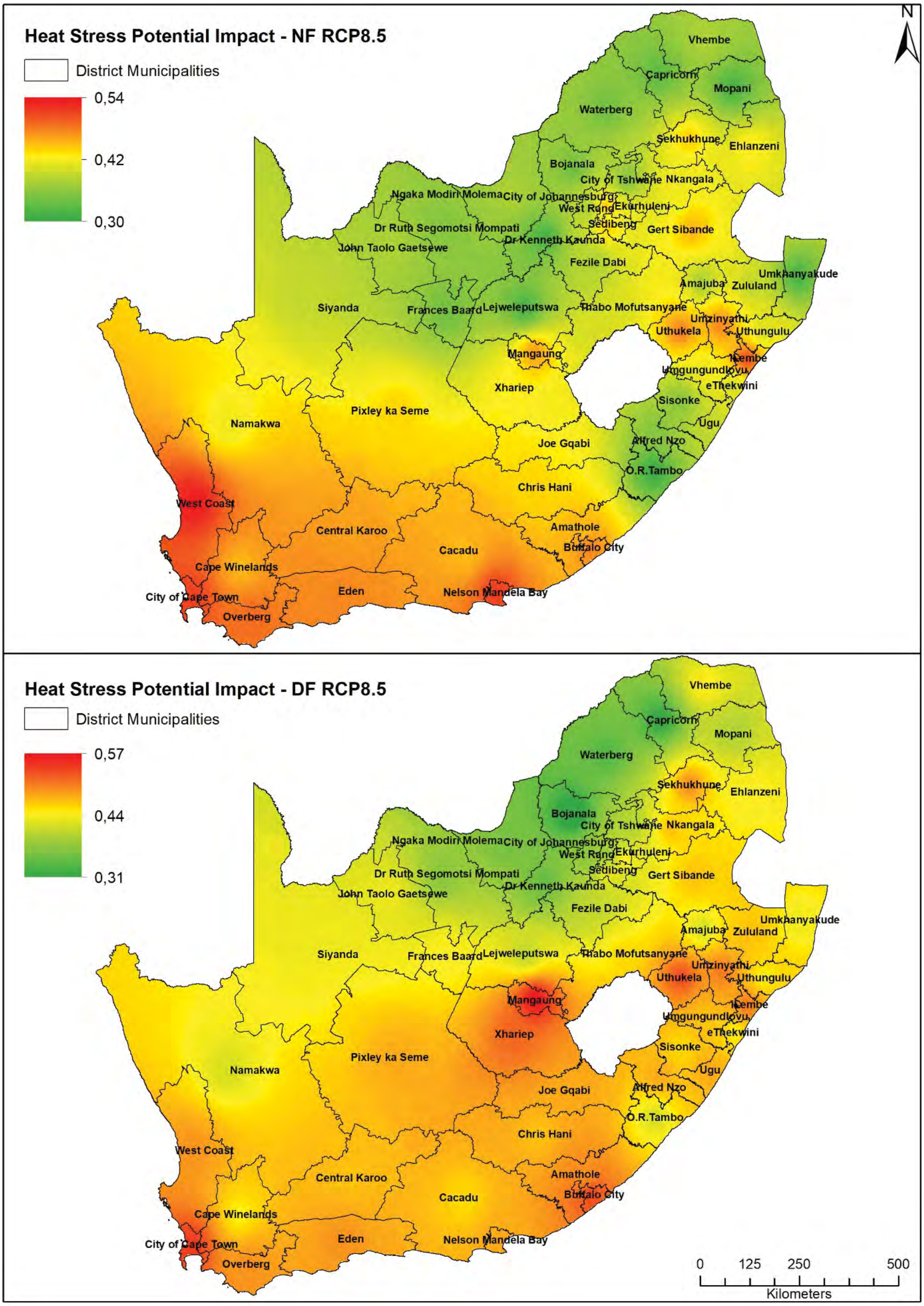


Figure 22. Same as Figure 21 but for RCP8.5 simulations.

4. Discussion

In this chapter, we have assessed projected climate change impacts on climate-sensitive, particularly the water-linked sectors, in 52 South African district municipalities by analysing the potential spatial-temporal characteristics of drought and heat stress over two projected periods defined as the NF (2036 – 2065) and DF (2066 – 2095). Both drought and heat stress potential impacts were assessed through selected exposure and sensitivity determinant metrics. While the sensitivity indicators mostly included water sources and demographic related information, the exposure considered metrics relating to climate change extremes such as drought duration and severity as well as heat wave duration and magnitude. It is worth to mention that while both the selected sensitivity and exposure metric measures are not exhaustive due to the unavailability of data, the results provide a general view of projected drought and heat stress potential impacts in South Africa over the two future timescales. Consequently, the results presented in this chapter can be considered as the cornerstone for building a body of empirical evidence and knowledge on issues pertaining to climate change impacts on water-linked sectors. Moreover, the results form the basis for policy and decision-making in support of preparedness for and adaptation to climate change across the most vulnerable district municipalities of South Africa.

The general overview of the present results is that climate change will continue to have significant impacts during both the NF and DF projected periods. As indicated in Figure 8, all sources of water depict, to some extent, moderate to high sensitivity risk to drought conditions across most district municipalities. The spatial distribution of both DD and DS indicators depicts localised variability across the RCPs, districts, and projected timescales (Figure 11 and Figure 13, respectively). Most of the district municipalities are expected to be highly exposed to prolonged DD during both the NF and DF projected periods. In terms of projected drought potential impacts, most district municipalities are anticipated to experience moderate drought impacts during the projected timescales. While the results across the exposure and potential impacts depict contrasts in spatial distribution under the two RCP emission scenarios, they seem to follow a similar pattern. The observed spatial contrasts and variability could be attributed to uncertainty and general changes in precipitation projections [9]. There is evidence that rainfall in South Africa exhibits year-to-year and inter-annual variability [53]. In terms of climate projections, models have projected a decreased rainfall by 2050, particularly during the growing season, because of reductions in soil moisture and runoff [9].

The results presented in this chapter generally support the spatial distribution of drought propagation periods (Figure 23), which delineates South Africa into four main transition timescales, which are, the shorter periods covering 1 – 3 months; intermediate covering 4 – 6 months; longer, between 7 – 12 months; and extended timescales which go beyond 12 months [54]. In this case, the central, eastern, and partly southern regions are characterized by short-to-intermediate drought transition periods. Aridity, higher temperatures, catchment properties, aquifer depth, the presence of lakes and wetlands, soil types, land cover/use, and climate change signals are some of the attributes contributing to the variation of drought transition periods across regions [55,56]. Consequently, water in the affected district municipalities is likely to be lost much quicker, either into the soil or through evapotranspiration processes. Most of the regions exhibiting short to intermediate drought propagation periods are projected to experience prolonged drought duration and upper level of moderate drought potential impacts category. Furthermore, areas depicting delayed or extended drought propagation periods, which could be attributed to seasonal rainfall or existence of dams, and aquifers are projected to experience shorter drought duration and low drought potential impacts.

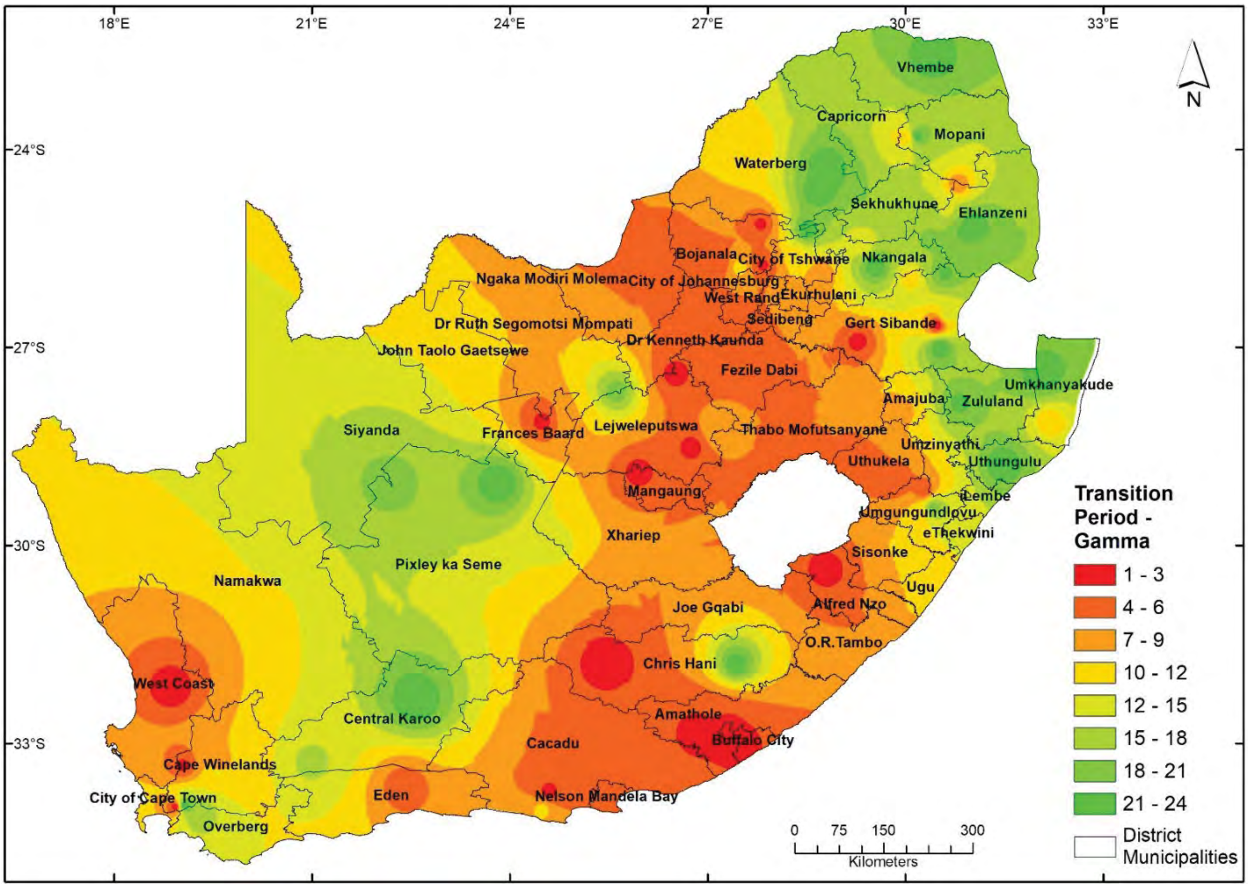


Figure 23. Drought transition periods, from meteorological to hydrological [54].

The results presented in this chapter demonstrate that climate change is apparent and has manifested across South African district municipalities, mostly in the form of drought. Drought has been persistent in most parts of South Africa, predominantly in the south-eastern, the central and partly in the northern regions of the country. In this study, the results of the drought impacts analysis have identified drought-prone areas across different district municipalities. These results agree with previously reported studies on drought in various regions of the country (e.g., [29,58-62], and references therein). Persistent and prolonged drought has caused significant impacts on key water-linked sectors, such as agriculture, energy, and tourism, as well as manufacturing and production industries, which sustain socioeconomic development in these affected regions. The Western and Eastern Cape provinces are some of the provinces that have been previously declared drought disasters areas, having been significantly affected by drought events that resulted in a decline of water levels (reaching the lowest of approximately 30% full storage capacity) in key water supplying dams.

Such events left the most vulnerable communities with great uncertainty of facing the famously so-called "day zero" state. The present results suggest that these drought-prone areas will continue to experience persistent drought conditions in both the near and distant projected periods.

A plethora of studies have shown that the impacts of extreme heat exposure on vulnerable populations are already being felt and will worsen as the earth's climate continues to warm. As captured in the newly released Sixth Assessment Report of Working Group I of the IPCC (AR6), global temperatures are anticipated to rise by 1.5°C or more over the next two decades and will be accompanied by extreme heat, heatwave events and record-breaking temperatures that will be more frequent, severe, and prolonged [63]. As widely documented, the warming in South Africa is said to be 1.5 higher than the global annual mean [64,65], and as predicted by climate models, this trend will continue. The results from this book chapter which are consistent with the expanding body of research in South Africa on temperature and heat exposure [66-68], revealed a marked increase in heat exposure in the coming decades in most district municipalities across South Africa. These findings are supported by local studies that have revealed greater warming in the Northern Cape Province, as well as selected regions over Gauteng, Limpopo, and KwaZulu-East Natal's Coast [69], including the western half, as well as the parts of the north-east and east of South Africa [19]. Adding to these previous findings are regions in the central interior of the country that will also experience increased heat exposure. Undoubtedly, heat is an immediate climate hazard to many vulnerable communities in South Africa, and climate change will further the trends of excessive exposure in the future as well as related medical conditions. As well captured in literature, the elderly, children, the chronically ill, socially isolated, and at-risk occupational groups are particularly vulnerable.

The general consensus in the scientific research community alludes to the undeniable fact that the climate is changing at an alarming rate. The likelihood of future climate change impacting on water-linked sectors has been noted in the current climate impact studies. There is no doubt that drought and other hazards, such as heatwaves, will continue to be the most dominant climate risks in South Africa, although the degree of the impact will be localised. As alluded by various research scholars, these climate risks have far-reaching effects on agriculture, human health, energy, urban development, and many other water-linked sectors. In addition, frequent occurrence of drought and heatwaves, coupled with changes in other climate factors, are likely to exacerbate existing non-climate stressors such as deforestation, migration, and population growth, and put development goals such as the economic growth, poverty, and access to education, among others, at risk.

In order to alleviate future impacts of drought and extreme heat and protect the most vulnerable communities, there is a need to develop and implement robust and innovative solutions to respond to climate change challenges, including adaptation strategies and mitigation measures at district municipality level [70,71]. Frameworks and adaptation measures relating to climate change response should include a holistic suite of measures guided by climate projections, development goals, and inclusion of non-climatic stressors as well as supported by local policy initiatives, including education and awareness that will involve various stakeholders across the government and private sectors. The existing climate-related frameworks address various climate change themes such as climate change impacts, climate risks and vulnerabilities, climate resilience, climate change adaptation and mitigation, climate change response, as well as climate and non-climate drivers ought to be conceptualised and implemented at various district municipalities to support water resource management and planning as well as climate-related decision-making and policies.

Examples of developed and tested climate-related frameworks include the IPCC [2] framework, which focuses on the anthropogenic causes and impacts of climate change. The framework considers four components, namely (i) climate change characterised by temperature, precipitation, and the occurrence of extreme events, (ii) climate change impacts and vulnerability, (iii) socio-economic developments and (iv) climate process drivers (including greenhouse gas emissions). The framework also recognises climate change as the key component in mitigating and adapting to it. Other frameworks include the climate change risk assessment conceptualised on the premise of the need to understand various mechanisms through which climate change creates risks for society [72]; climate-resilient developmental framework to support climate-related policies [73]; water security and climate-resilient developmental framework [74] and framework for cross-border climate change impacts formulated by [75]. Due to localised variation of the observed degree of projected drought and heat stress impacts (attributed to various factors including both climatic and non-climatic drivers), different frameworks can be implemented to different district municipalities.

The results presented in this study also call for both medium- and long-term sustainable developments that integrate adaptation strategies to minimize inherent impacts of changing climate on water-linked sectors, as well as to adapt and build resilience within the poor and most susceptible communities. Adaptation to climate change and its inherent impacts on the water sector can be facilitated through several water-management adaptation options by integrating various factors such as changes in hydrological variables and regimes, water demand and supply, water conservation, operation and maintenance of water infrastructure, water pricing, use of wastewater and water transfer, as well as water management policies [76-78]. Subsequently, it is imperative to identify the best water resources management and heat-related strategies to attain sustainability in water management and cope with future drought and heat extremes within the district municipalities.

5. Conclusions

In this study, drought and heat stress potential impacts in 52 district municipalities of South Africa during the periods 2036 – 2065 and 2066 – 2095 were assessed using a set of selected exposure and sensitivity determinant indicators collected from the study sites and derived from CORDEX ensemble model data, respectively. Based on drought analysis, moderate but at higher level, drought potential impacts are expected in most district municipalities situated in the upper north, interior and south-eastern parts of the country. On the basis of the heat stress analysis, majority of district municipalities in the southern parts of the country are likely to experience moderate to high heat stress potential impacts. During this study there has been challenges in accessing some of social and environmental data, which hindered comprehensive analysis of climate change impacts on water-linked sectors, including agriculture and energy, at national level. Nonetheless, the findings of this study can be considered as the cornerstone, particularly in building a body of empirical evidence and knowledge on issues pertaining to climate change impacts on water-linked sectors. Moreover, the results from the basis for policy and decision-making in support of preparedness for and adaptation to climate change, including planning and management of water resources across most vulnerable district municipalities of South Africa.

Funding: This research was funded by the Water Research Commission of South Africa, grant number C2019/2020-00017.

Acknowledgments: Support from the South African Weather Service and our stakeholders is gratefully appreciated.

References

1. The United Nations World Water Development Report. Nature-based Solutions for Water (United Nations Educational, Scientific and Cultural Organization, Paris, 2018)
2. International Panel on Climate Change (IPCC). Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland. p. 104.
3. Pan, Z.; Liu, P.; Xu, Ch-Y.; Cheng, L.; Tian, J.; Cheng, S.; Xie, K. The influence of a prolonged meteorological drought on catchment water storage capacity: A hydrological-model perspective. *Hydrol Earth Syst Sci*, **2020** (24), 4369-4387
4. Thieken, A.H.; Mohor, G.S.; Kreibich, H.; Muller, M. Compund inland flood events: Different pathways, different impacts and different coping options. *Nat Hazards Earth Syst Sci*, **2022** (22), 165-185.
5. Krysanova, V.; Buiteveld, H.; Haase, D., Hattermann, F.F.; Van Niekerk, K., Roest, K., Martınez-Santos, P.; Schluter, M. Practices and lessons learned in coping with climatic hazards at the river-basin scale: Floods and droughts. *Ecol Soc*, **13**(2), pp 32.
6. Pinho, P.F.; Marengo, J.A.; Stafford-Smith, M. Complex Socio-economical dynamics driven by extreme events in the Amazon. *Reg Environ Change* **2014** (15), 643-655.
7. Iyakaremye, V.; Zeng, G.; Siebert, A.; & Yang, X. Contribution of external forcings to the observed trend in surface temperature over Africa during 1901–2014 and its future projection from CMIP6 simulations. *Atmos Res*, **254**(9), 105512.
8. Kurukulasuriya, P.; Rosenthal, S. Climate Change and Agriculture: A Review of Impacts and Adaptations. Climate Change Series 91. Environment Department Papers, World Bank, Washington, D.C. 2003.
9. Christensen, J.H.; Hewitson, B.; Busuioc, A.; Chen, A.; Gao, X.; Held, I.; Jones, R.; Kolli, R.K.; Kwon, W.-T.; Laprise, R.; Magaña Rueda, V.; Mearns, L.; Menéndez, C.G.; Räisänen, J.; Rinke, A.; Sarr, A.; Whetton, P. Regional Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. 2007.
10. Thornton, P. K.; Jones, P. G.; Owiyo, T.; Kruska, R. L.; Herrero, M.; Orindi, V.; Bhadwal, S.; Kristjanson, P.; Notenbaert, A.; Bekele, N.; Omolo, A. Climate Change and Poverty in Africa: Mapping Hotspots of Vulnerability. *Afr J Agr Resou Econ* **2008** (2), 24-44.
11. Niang, I.; Ruppel, O.C.; Abdrabo, M.A.; Essel, A.; Lennard, C.; Padgham, J.; Urquhart, P. Africa. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014, 1199-1265.
12. Department of Environmental Affairs and Tourism (DEA). South African National Climate Change Response Strategy, September 2004.
13. Ziervogel, G.; New, M.; Archer van Garderen, E.; Midgley, G.; Taylor, A.; Hamann, R.; Stuart-Hill, S.; Myers, J.; Warburton, M. Climate change impacts and adaptation in South Africa. Wiley Interdisciplinary Reviews: *Climate Change*, **5**(5), 605-620.
14. Department of Environmental Affairs and Tourism (DEA). South Africa's Second National Communication under the United Nations Framework Convention on Climate Change. Pretoria, South Africa: Department of Environmental Affairs, Republic of South Africa (RSA), 2011.
15. Hallegatte, S.; Henriet, F.; Corfee-Morlot, J. The Economics of Climate Change Impacts and Policy Benefits at City Scale: A Conceptual Framework. OECD Environment Working Papers, No. 4, OECD Publishing, 2008.
16. Yu, J.; Castellani, K.; Forysinski, K.; Gustafson, P.; Lu, J.; Peterson, E.; Tran, M.; Yao, A.; Zhao, J.; Brauer, Met al. Geospatial indicators of exposure, sensitivity, and adaptive capacity to assess neighbourhood variation in vulnerability to climate change-related health hazards. *Environ Health* **2021** (20), 31.

17. Ndiritu, J.; Franks, S.; Wagener, T.; Bogh, E.; Gupta, H.; Bastidas, L.; Nobre, C.; Gbalvão, Cd. Long-term trends of heavy rainfall in South Africa. Regional Hydrological Impacts of Climatic Change - Hydroclimatic Variability (Proceedings of symposium S6 held during the Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil, April 2005). *IAHS Publication* **2005**, 296, 178-183.
18. New, M.; Hewitson, B.; Stephenson, D. B.; Tsiga, A.; Kruger, A.; Manhique, A.; Gomez, B.; Coelho, C. A. S.; Masisi, D. N.; Kululanga, E.; Mbambalala, E.; Adesina, F.; Saleh, H.; Kanyanga, J.; Adosi, J.; Bulane, L.; Fortunata, L.; Mdoka, M. L.; Lajoie, R. Evidence of Trends in Daily Climate Extremes over Southern and West Africa. *J Geophys Res* **2006** (111) (D14).
19. Kruger, A.C.; Sekele, S.S. Trends in extreme temperature indices in South Africa: 1962-2009. *Int J Climatol*, 33(3), 661–676.
20. Engelbrecht, F.; Landman, W.; Engelbrecht, C.; Landman, S.; Bopape, M.; Roux, B.; McGregor, J.; Thatcher, M. Multi-scale climate modelling over Southern Africa using a variable-resolution global model. *Water SA*, 37(5). 647-658
21. Landman, W.A.; DeWitt, D.; Lee, D.-E.; Beraki, A.; Lötter, D. Seasonal Rainfall Prediction Skill over South Africa: One- versus Two-Tiered Forecasting Systems. Weather and Forecasting, **27**(2), 489–501.
22. Landman, W.A.; Kgatuke, M.-J.; Mbedzi, M.; Beraki, A.; Bartman, A.; Piesanie, A.du. Performance comparison of some dynamical and empirical downscaling methods for South Africa from a seasonal climate modelling perspective. *Int J Climatol*, **29**(11), 1535–1549.
23. Rafiq, M.; Mishra, A. Investigating Changes in Himalayan Glacier in Warming Environment: A Case Study of Kolahoi Glacier. *Environ Earth Sci* **2016**, 75(23), https://doi.org/10.1007/s12665-016-6282-1
24. IPCC. 2019. Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/srccl
25. Chersich, M.F.; Wright, C.Y. Climate change adaptation in South Africa: A case study on the role of the health sector. *Global Health,* **15**(22), https://doi.org/10.1186/s12992-019-0466-x
26. Stone, D. A.; Christidis, N.; Folland, C.; Perkins-Kirkpatrick, S.; Perlwitz, J.; Shiogama, H.; Wehner, M. F.; Wolski, P.; Cholia, S.; Krishnan, H.; Murray, D.; Angélil, O.; Beyerle, U.; Ciavarella, A.; Dittus, A.; Quan, X.-W.; Tadross, M. Experiment Design of the International CLIVAR C20C+ Detection and Attribution Project. Weather and Climate Extremes 2019, 24, 100206.
27. USAID. Climate Change and Water: An Annex to the USAID Climate Resilient Development Framework, draft, January 2013.
28. Bates, B.C.; Kundzewicz, Z.W.; Wu, S.; Palutikof, J.P. Eds. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 2008, 210 pp.
29. Botai, C. M.; Botai, J. O.; de Wit, J. P.; Ncongwane, K. P.; Murambadoro, M.; Barasa, P. M.; Adeola, A. M. Hydrological Drought Assessment Based on the Standardized Streamflow Index: A Case Study of the Three Cape Provinces of South Africa. *Water*, **13** (24), 3498.
30. Popoola, O.O.; Yusuf, S.F.G. South African government palliative funds for agriculture amid Covid-19: Challenges of implementation and suggestions for improvements. *S Afr J Agric Ext*, 49(3), 16-30.
31. Mabhaudhi, T.; Nhamo, L.; Mpandeli, S.; Nhemachana, C.; Senzanje, A.; Sobratee, N.; Chivenge, P.P.; Slotow, R.; Naidoo, D.; Liphadzi, S.; Modi, A.T. The water-energy-food nexus as a tool to transform rural livelihoods and well-being in southern Africa. *Int J Environ Res Public Health*, 16(2970), https://doi.org/10.3390/ijerph16162970
32. Strambo, C.; Burton, J.; Atteridge, A. The end of coal? Planning a "just transition" in South Africa. 2019. Stockholm Environment Institute. Available online: https://www.sei.org/wp-content/uploads/2019/02/planning-a-just-transition-in-south-africa.pdf (Accessed 13 February 2022)
33. Taylor, K.E.; Stouffer, R.J.; Meehl, G.A. An Overview of CMIP5 and the Experiment Design. *B Am Meteorol Soc* **2011**, 93, 485-498.
34. Jone, C.D.; Hughes, J.K.; Bellouin, N.; Hardiman, S.C.; Jone, G.S.; Knight, J.; Liddicoat, S.; O'Connor, F.M.; Andres, R.J.; Bell, C.; Boo, K.-O.; Bozzo, A.; Butchart, N.; Cadule, P.; Corbi, K.D., et al. The HadGEM2-ES implementation of CMIP5 centennial simulations. *Geosci Model Dev* **2011**, 4, 543–570
35. Meinshausen, M.; Smith, S.J.; Calvin, K.; Daniel, J.S.; Kainuma, M.L.T.; Lamarque, J-F.; Matsumoto, K.; Montzka, S.A.; Raper, S.C.B.; Riahi, K.; Thomson, A.; Velders, G.J.M.; van Vuuren, D.P.P. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change* 109(213), https://doi.org/10.1007/s10584-011-0156-z
36. Arora, V. K.; Scinocca, J.F.; Boer, G.J.; Christian, J.R.; Denman, K.L.; Flato, G.M.; Kharin, V.V.; Lee, W.G.; Merryfield, W.J. Carbon emission limits required to satisfy future representative concentration pathways of greenhouse gases. *Geophys Res Lett* **2011**, 38(5), https://doi.org/10.1029/2010GL046270
37. Voldoire, A.; Sanchez-Gomez, E.; Salas y Mélia, D.; Decharme, B.; Cassou, C.; Senesi, S.; Valcke, S.; Beau, I.; Alias, A.; Chevallier, M.; Deque, M.; Deshayes, J.; Douville, H. et al. The CNRM-CM5.1 global climate model: description and basic evaluation. *Clim Dyn* **2013**, 40, 2091-2121.
38. Jeffrey, M.; Rotstayn, L.; Collier, M.; Dravitzki, S.; Hamalainen, C.; Moeseneder, C.; Wong, K.; Syktus, J. Australia's CMIP5 submission using the CSIRO-Mk3.6 model. *Aust Meteor Oceanogr J*, **63**, 1-13.
39. Hourdin, F.; Foujols, M.A.; Codron, F.; Guemas, V.; Dufresne, J.L.; Bony, S.; Denvil, S.; Guez, L.; Lott, F.; Gatthas, J.; Braconnot, P.; Marti, O.; Meurdesoif, Y.; Bopp, L.; et al. Impact of the LMDZ atmospheric grid configuration on the climate and sensitivity of the IPSL-CM5A coupled model. *Clim Dyn* **2012**. https://doi.org/10.1007/ s00382–012–1411–3
40. Watanabe, S.; Hajima, T.; Sudo, K.; Nagashima, T.; Takemura, T.; Okajima, H.; Nozawa, T.; Kawase, H.; Abe, M.; Yokohata, T.; Ise, T.; Sato, H.; Kato, E.; Takata, K.; Emori, S.; Kawamiya, M. MIROC-ESM 2010: model description and basic results of CMIP5-20c3m experiments. *Geosci Model Dev* **2011**, 4, 845-872.

41. Ilyina, T.; Six, K.; Segschneider, J.; Maier-Reimer, E.; Li, H.; Núñez-Riboni, I. Global Ocean biogeochemistry model HAMOCC: Model architecture and performance as component of the MPI-Earth System Model in different CMIP5 experimental realizations. *J Adv Model Earth Syst* **2013**. doi:10.1029/2012MS000178
42. Tjiputra, J.; Roelandt, F.C.; Bentsen, M.; Lawrence, D.M.; Lorentzen, T.; Schwinger, J.; Seland, Q.; Heinze, C. Evaluation of the carbon cycle components in the Norwegian Earth System Model (NorESM). *Geosci Model Dev* **2013**, **6**, 301-325.
43. Dunne, J.P.; John, J.G.; Adcroft, A.J.; Griffies, S.M.; Hallberg, R.W.; Shevliakova, E.; Stouffer, R.J.; Cooke, W.; Dunne, K.A.; Harrison, M.J.; Krasting, J.P.; Malyshev, S.L.; Milly, P.C.D.; Phillips, P.J.; Sentman, L.T.; Samuels, B.L.; Spelman, M.J.; Winton, M.; Wittenberg, A.T.; Zadeh, N. GFDL's ESM 2 global coupled climate-carbon Earth System Models, Part I: Physical formulation and baseline simulation characteristics. *J Clim* **2012**, 25, 6646-6665.
44. IPCC 2011: Summary for Policymakers. In: Intergovernmental Panel on Climate Change Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C. B., Barros, V., Stocker, T.F., Qin, D., Dokken, D., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S. K., Tignor, M. and Midgley, P.M. (eds)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. Available at: http://ipcc-wg2.gov/SREX/
45. Vicente-Serrano, S.M.; Beguería, S.; Lopez-Moreno, I. A Multiscalar Drought Index Sensitive to GlobalWarming: The Standardized Precipitation Evapotranspiration Index. *J Clim* **2010**, 23, 1696-1718.
46. McKee, T.B.; Doesken, N.J.; Kleist, J. The relationship of drought frequency and duration to time scales. In Proceedings of the 8th Conference on Applied Climatology, Anaheim, CA, USA, 17–22 January 1993; American Meteorological Society: Boston, MA, USA, **1993**, 179-183.
47. Russo, S.; Dosio, A.; Graversen, R.G.; Sillmann, J.; Carrao, H.; Dunbar, M.B.; Singleton, A.; Montagna, P.; Barbola, P.; Vogt, J.V. Magnitude of extreme heat waves in present climate and their projection in a warming world. *J Geophys Res Atmos*, 119(22), 12, 500–512
48. http://cccma.seos.uvic.ca/ETCCDI (Accessed 20 February 2022)
49. http://etccdi.pacificclimate.org/list_27_indices.shtml (Accessed 20 February 2022)
50. Mallen, E.; Stone, B.; Lanza, K. A methodological assessment of extreme heat mortality modeling and heat vulnerability mapping in Dallas, Texas. Urban Climate, 30(3), 100528.
51. Birch, E. L. A Review of "Climate Change 2014: Impacts, Adaptation, and Vulnerability" and "Climate Change 2014: Mitigation of Climate Change." *J Am Plann Assoc*, 80(2), 184-185.
52. Sarah Baartman District Municipality Integrated Development Plans (IDP) 2017 to 2022. Available online: https://www.sarahbaartman.co.za/index.php?option=com_zoo&task=callelement&format=raw&item_id=219&element=f85c494b-2b32-4109-b8c1-083cca2b7db6&method=download&args[0]=0.0&args[1]=10a8d156387bddf57a5b3c1794e68b65&Itemid=1988&lang=en (Accessed on the 13 February 2022)
53. Kane, R.P. Periodicities, ENSO Effects and Trends of Some South African Rainfall Series: An Update. *S Afr J Sci*, **105**(5/6). https://doi.org/10.4102/sajs.v105i5/6.90
54. Botai, J.O.; Botai, C.M.; de Wit, J.P.; Muthoni, M.; Adeola, A.M. Analysis of drought progression physiognomies in South Africa. *Water* **2019**, 11, 299.
55. Ali, M.G.; Younes, K.; Esmaeil, A.; Fatemeh, T. Assessment of Geostatistical Methods for Spatial Analysis of SPI and EDI Drought Indices. *World Appl Sci J* **2011**, 15, 474-482.
56. Van Loon, A.F.; Laaha, G. Hydrological Drought Severity Explained by Climate and Catchment Characteristics. *J Hydrol* **2015**, 526, 3–14.
57. Hornby, D.; Vanderhaeghen, Y.; Versfed, D. A Harvest of Dysfunctional: Rethinking the Approach to Drought, Its Causes and Impacts in South Africa; Ngubane, M., Ed.; In report for Oxfam South Africa, 2016.
58. Botai, C.; Botai, J.; Dlamini, L.; Zwane, N.; Phaduli, E. Characteristics of Droughts in South Africa: A Case Study of Free State and North West Provinces. *Water*, **8**(10), 439.
59. Botai, C.M.; Botai, J.O.; De Wit, J.P.; Ncongwane, K.P.; Adeola, A.M. Drought Characteristics over the Western Cape Province, South Africa. *Water*, **9**(11), 876.
60. Mahlalela, P.T.; Blamey, R.C.; Reason, C.J.C. Mechanisms behind Early Winter Rainfall Variability in the Southwestern Cape, South Africa. *Clim Dyn*, **53**(1-2), 21–39.
61. Burls, N.J.; Blamey, R.C.; Cash, B.A.; Swenson, E.T.; Fahad, A.al; Bopape, M.-J.M.; Straus, D.M.; Reason, C.J.C. The Cape Town "Day Zero" Drought and Hadley Cell Expansion. *Npj Clim Atmos Sci*, 2(1), https://doi.org/10.1038/s41612-019-0084-6
62. Adeola, O.M.; Masinde, M.; Botai, J.O.; Adeola, A.M.; Botai, C.M. An Analysis of Precipitation Extreme Events Based on the SPI and EDI Values in the Free State Province, South Africa. *Water*, **13**(21), 3058.
63. IPCC. in Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Masson-Delmotte, V. et al.). Cambridge University Press.
64. Engelbrecht, F.; Adegoke, J.; Bopape, M.-J.; Naidoo, M.; Garland, R.; Thatcher, M.; McGregor, J.; Katzfey, J.; Werner, M.; Ichoku, C.; Gatebe, C. Projections of rapidly rising surface temperatures over Africa under low mitigation. *Environ Res Lett*, **10**(8), 085004.
65. Engelbrecht, F.A.; Monteiro, P.M.S. The IPCC Assessment Report Six Working Group 1 report and southern Africa: Reasons to take action. *S Afr J Sci*, 117(11/12), https://doi.org/10.17159/sajs.2021/12679

66. Garland, R.M.; Matooane, M.; Engelbrecht, F.A.; Bopape, M.-J.M.; Landman, W.A.; Naidoo, M.; van der Merwe, J.; right, C.Y. Regional Projections of Extreme Apparent Temperature Days in Africa and the Related Potential Risk to Human Health. *Int J Environ Res Public Health*, **12**(10), 12577-12604.
67. Mbokodo, I.; Bopape, M.-J.; Chikoore, H.; Engelbrecht, F.; Nethengwe, N. Heatwaves in the Future Warmer Climate of South Africa. *Atmosphere*, **11**(7), 712.
68. Ncongwane**,** K.P.; Botai, J.O.; Sivakumar, V.; Botai, C.M.; Adeola, A.M. Characteristics and Long-Term Trends of Heat Stress for South Africa. *Sustainability* **2021**, 13, 13249.
69. Wright, C.Y.; Kapwata, T.; du Preez, D.J.; Wernecke, B.; Garland, R.M.; Nkosi, V.; Landman, W.A.; Dyson, L.; Norval, M. Major climate change-induced risks to human health in South Africa. *Environ Res* **2021**, 196, 110973.
70. Abeysinghe, A.; Dambacher, B.M.; Byrnes, R. National adaptation plans: Understanding mandates and sharing experiences. London: IIED 2017.
71. McEvoy, S.; Haasnoot, M.; Biesbroek. R. How are European countries planning for sea-level rise? Journal of Ocean and Coastal Management **2021**, 203, 105512.
72. Simpson, N.P.; Mach, K.J.; Constable, A.; Hess, J.; Hogarth, R.; Howden, M.; Lawrence, J.; Lempert, R.J.; Muccione, V.; Mackey, B.; New, M.G.; et al. A framework for complex climate change risk assessment. One Earth **2021**, 489-501.
73. USAID. (2013) Climate Change and Water: An Annex to the USAID Climate Resilient Development Framework, draft.
74. AMCOW. Water Security and Climate Resilient Development: Strategic framework. 2012.
75. Carter, T.R.; Benzie, M.; Campiglio, E.; Carlsen, H.; Fronzek, S.; Hilden, M.; Reyer, C.P.O.; West, C. A conceptual framework for cross-border impacts of climate change. *Glob Environ Change* **2021**, 69, 102307.
76. Loomis, J.; Koteen, J.; Hurd, B. Economic and institutional strategies for adapting to water-resource effects of climate change. In: Lewis Jr., William M. (Ed.), Water and Climate in the Western United States. University Press of Colorado, Boulder, CO, **2003**, 235-249
77. Brekke, L.D.; Maurer, E.P.; Anderson, J.D.; Dettinger, M.D.; Townsley, E.S.; Harrison, A.; Pruitt, T. Assessing reservoir operations risk under climate change. *Water Resour Res* **2009**, 45, W04411.
78. Olmstead, S.M. Climate change adaptation and water resource management: A review of the literature. *Energy Econ* **2013**. http://dx.doi.org/10.1016/j.eneco.2013.09.005

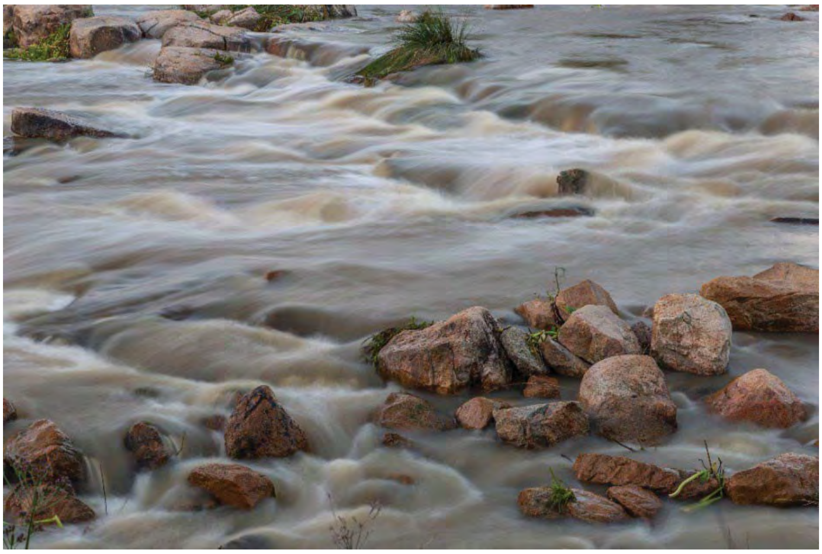
Chapter 3

Potential impacts of global warming on water availability and hydroclimatic droughts in South African river basins

Babatunde J Abiodun[1]*, Myra Naik[1], Tlakale Mogebisa[1] and Nokwethaba Makhanya[1]

[1] Climate Systems Analysis Group, Department of Environmental and Geographical Science, University of Cape Town

*Corresponding author: babiodun@csag.uct.ac.za



Abstract

Understanding the potential impacts of global warming on water resources at basin scale is crucial for planning effective climate change adaptation strategies, especially in a water-limited country like South Africa. In this chapter, we assess the potential impacts of global warming over four river basins and show how such impacts could influence water availability and drought frequency. The river basins studied are the Vaal River Basin (VRB), the Limpopo River Basin (LRB), the Inkomati River Basin (IRB), and the Western Cape River Basin (WRB). Using climate projection datasets as forcing, we simulate the hydrology of these four basins under the RCP8.5 future climate scenario, then study the climate change impacts at four global warming levels (GWLs 1.5, 2.0, 2.5 and 3.0°C). Seven indices were used to characterise the hydroclimatic droughts. Our results show that global warming would induce an increase in temperature and a decrease in rainfall over the basins in the future. Among these four basins, LRB is projected to experience the most pronounced warming, while WRB is indicated to receive the most severe drying. The warming would increase the atmospheric evaporative demand over the basins, with a commeasurable increase in evaporation over streams, but not over land, because the decreased rainfall thwarts an increase in evapotranspiration. A decrease in soil moisture (20% - 30%), runoff (20% - 30%), and streamflow (37% - 69%), with an increase in the frequency of all the hydroclimatic droughts, are projected over all four basins. The results emphasise the need for more concerted and strategic efforts towards mitigating the impacts of global warming on water resources and droughts in South Africa.

Keywords: River basin; climate change; droughts; hydrology; CORDEX; SWAT+

1. Introduction

Global warming (or climate change) is one of the major challenges of the 21st century. The impacts of global warming have been identified to include long-term trends in climate variables and extreme events at global, regional, and local scales [1-3]. Among the identified impacts, those related to regional water availability and climate extreme events are usually more devastating because of their implications for socio-economic activities. Since the vulnerability of these impacts varies across the regions of the world, there is a need for a better understanding of how the impacts can affect water resources in developing countries such as South Africa.

The impacts of global warming on water resources are expected to be particularly severe in South Africa for three main reasons. Firstly, most socio-economic activities in South Africa depend on river basins, which provide freshwater to support activities such as agriculture, fisheries, livestock, forest products, mining, industry, power generation, and tourism. Through the storage of water in dams, the basins also support urban services and accommodate a range of water-based leisure activities, such as swimming, boating, water skiing, and yachting. They also provide fertile soil for cultivating a variety of crops [4]. However, the ongoing rapid urbanisation and population growth could escalate water demand from these river basins in the future. Secondly, South Africa is a water-stressed country due to its semi-arid to arid climate, which is characterised by low rainfall and high evaporation rates [5]. The country's average annual rainfall (<500 mm) is lower than the global average annual rainfall (860 mm) [5]. Less than 9% of the annual rainfall ends up in rivers, and only about 5% recharges the groundwater in aquifers [6]. Rainfall and river flow are unevenly distributed across the country, with only 12% of the land area generating 50% of the streamflow. Thirdly, South Africa's rainfall is highly variable in both time and space. Such rainfall variability usually results in extended severe droughts across the country. Meanwhile, there are indications that global warming is likely to amplify the atmospheric evaporative demand. This could trigger more droughts, as well as make droughts more intense and longer lasting. Hence, the water resource decision-makers in South Africa are confronted with complex problems of understanding the future impacts of global warming on freshwater availability in the country's river basins. While some studies have investigated the impacts of global warming over major river basins in South Africa (e.g., [7, 8]), their focus has been on climate variables and meteorological droughts.

The aim of this chapter is to examine the future impacts of global warming on water availability and on the frequency of hydroclimatic drought over four river basins in South Africa. The chapter is thus organised as follows: Section 2 describes the characteristics of the selected basins, the climate dataset used for the future projections, the hydrological model adopted for this study, the hydrological simulation set-up and the characterisation of hydroclimatic droughts. Section 3 presents the results and the discussion, while Section 4 provides concluding remarks.

2. Materials and methods

2.1. Study domain

Four major river basins in South Africa were used as our study domain. They are the Vaal River Basin (VRB), the Limpopo River Basin (LRB), the Inkomati River Basin (IRB), and the Western Cape River Basin (WRB) (Figure 1). These river basins were selected because of their economic importance for the country and because of their vulnerability to severe droughts.

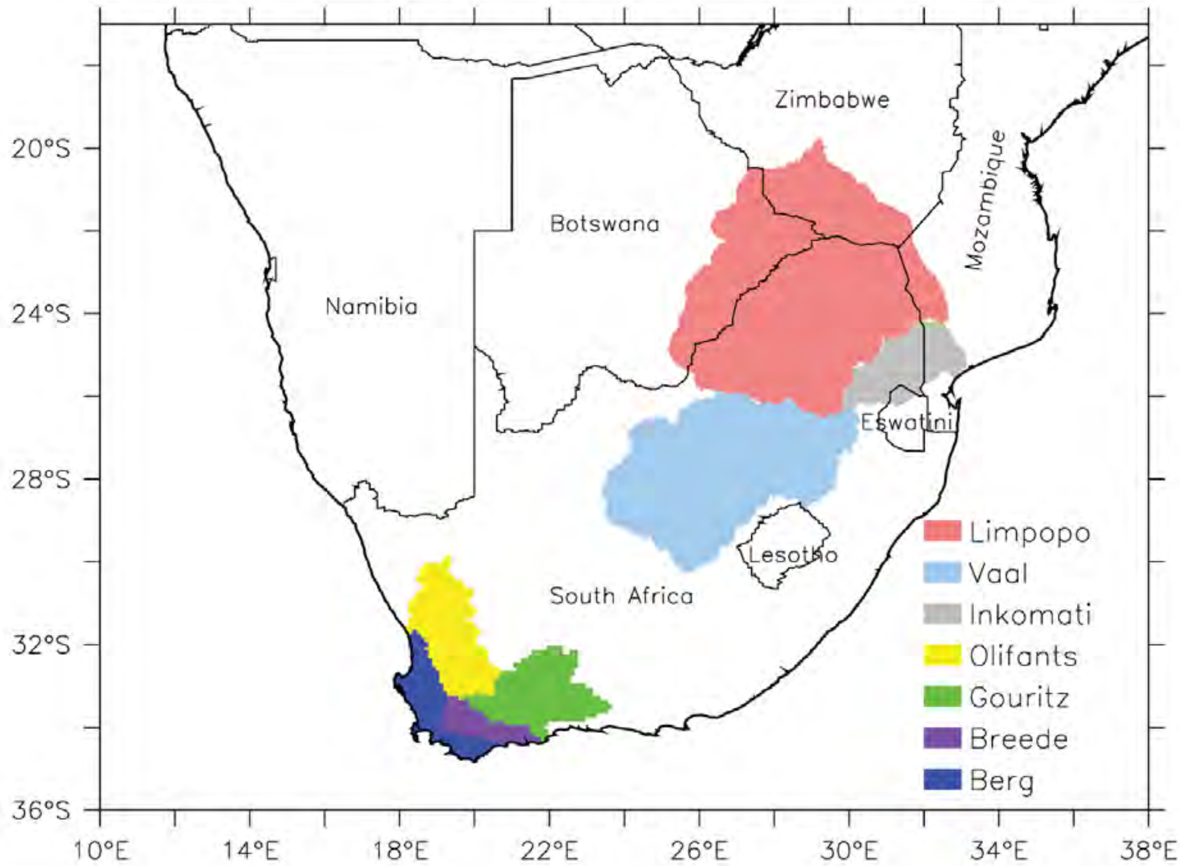


Figure 1. Map of Southern Africa, showing the location of the selected river basins for the study, namely: Vaal (Vaal River Basin; VRB), Limpopo (Limpopo River Basin; LRB), Inkomati (Inkomati River Basin; IRB), and Olifants, Gouritz, Breede and Berg (Western Cape River Basin; WRB).

The VRB (26° – 30°S, 23.5° – 30°E) is perceived to be the most 'hardworking' river basin in South Africa [9, 10] because it is the heartbeat of many socio-economic activities in the country. It accounts for more than 24% of the country's gross domestic product (GDP) and serves more than 45% of the nation's population [11,12]. The Vaal River flows westward from its source in Mpumalanga Province (26.5° S, 30.0° E) to join the Orange River near Douglas (29.1° S, 23.8° E). The Vaal River is about 1,300 km long and the VRB covers an area of about 196,000 km^2. The major dams along the Vaal River include the Vaal Dam (2,200 million m^3 at 26.9° S, 28.1° E) and the Bloemhof Dam (1,200 million m^3 at 27.7° S, 25.7° E). The climate of the basin is a subtropical dry savanna with the mean annual evaporation (about 1,300 mm) exceeding the annual precipitation (about 600 mm) [13]. The precipitation varies from about 1,000 mm in the east to about 300 mm in the west [14]. Its annual mean temperature is about 15°C, ranging from 10°C in July to 23°C in January (Figure 2). The dominant land cover in the basin is grassland (54%), cropland/grassland mosaic (29.3%), and cropland (18%) with a trace of savanna (3.4%) (Figure 3). The predominant land use is agriculture, of which dry-land commercial cultivation is the most important. Although the Vaal River is the most developed and most regulated river in South Africa, hydrological drought poses a big challenge to water resource management in the VRB.

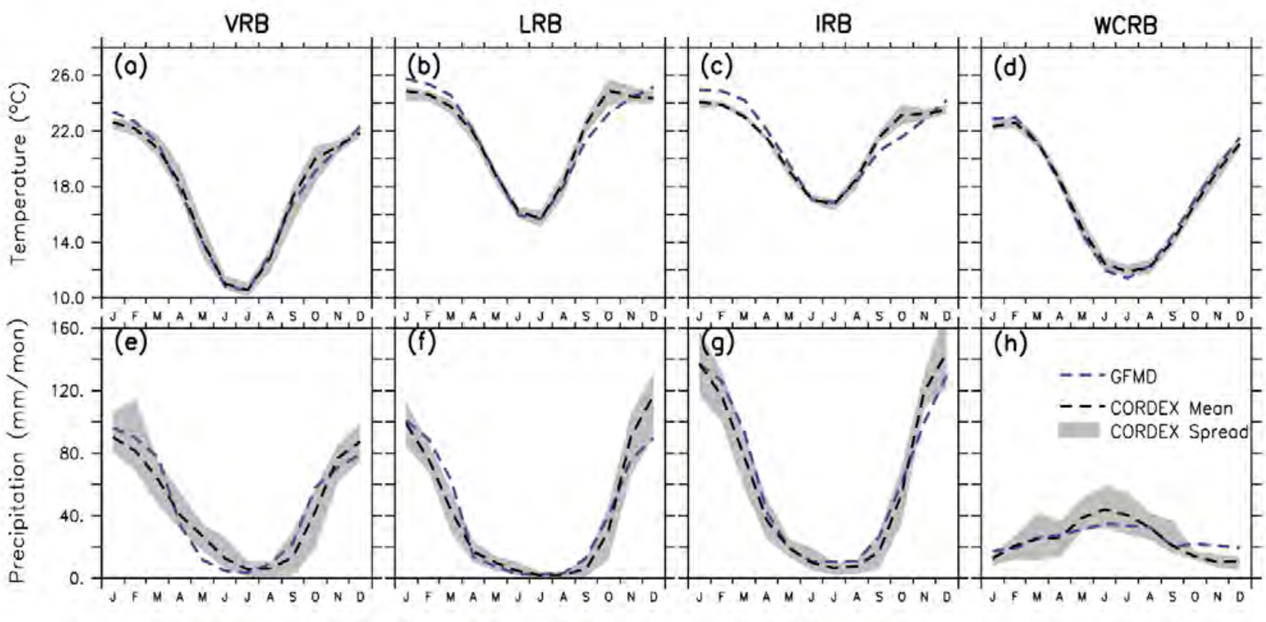


Figure 2. The annual cycle of mean temperature and precipitation over the selected river basins (VRB, LRB, IRB and WRB) as depicted by GMFD and CORDEX datasets.

The LRB (25° – 35°E, 19° – 27°S) is one of the most economically important river basins in Southern Africa, where it sustains about 18.8 million people and supports the economy of four adjoining riparian countries (South Africa, Botswana, Mozambique, and Zimbabwe) [15, 16]. It also contributes to the economy of the entire Southern African Development Community (SADC) region by supporting a wide range of socio-economic activities, such as mining, industry, agriculture, and tourism. The basin drains an area of approximately 415,000 km^2, and the river itself extends more than 1,750 km in length (Figure. 1). The climate of the LRB varies considerably, ranging from predominantly arid in the west to semi-arid and temperate in the central zones, to tropical rainy conditions along the coastal plain of Mozambique, and tropical dry savannah towards the Indian Ocean [17]. Rainfall over the basin is largely influenced by the movement of the InterTropical Convergence Zone (ITCZ), which gives rise to two distinct rainfall seasons. These include a warm wet season during the summer (December – February) and a cold dry season during winter (June – August). The mean temperature over the basin ranges from 16°C in July to 26°C in summer (Figure 2), and evaporation is about 1,970 mm/year on average, ranging from 800 to 2,400 mm/year [18]. However, drought poses a big threat to water availability in the LRB.

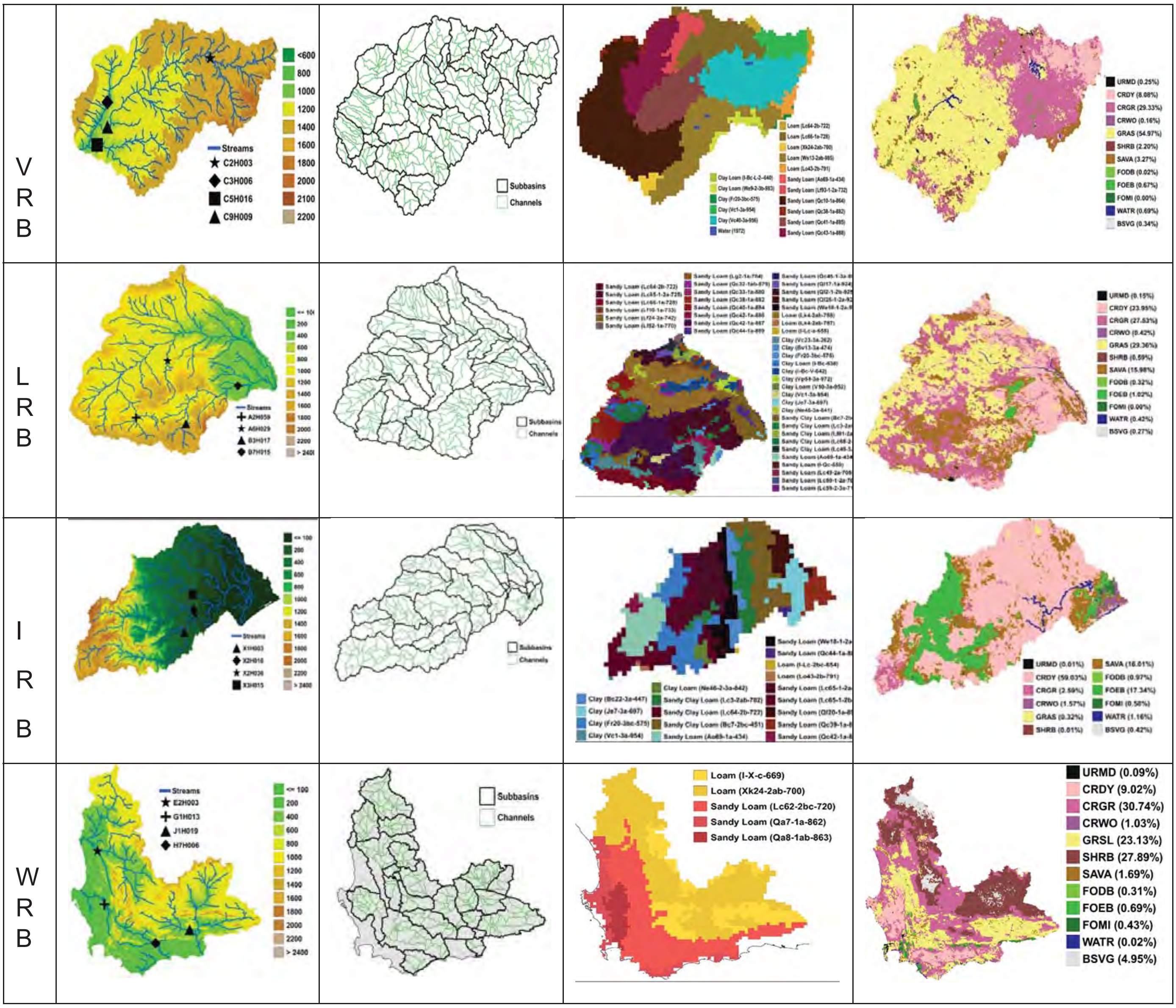


Figure 3. Characteristics of the selected river basins (VRB, LRB, IRB and WRB) as seen by SWAT+. From left, first column: the topography of the region (i.e., DEM), streams, and location of streamflow observation stations; second column: the SWAT+ delineation of the basin to sub-basins and channels; third column: soil types; and last column: LULC types. The land-use types are urban residential medium density (URMD), cropland/dryland and pasture (CRDY), cropland/grassland mosaic (CRGR), cropland/woodland mosaic (CRWO), grassland (GRAS or GRSL), shrubland (SHRB), savanna (SAVA), forest – deciduous broadleaf (FODB), forest – evergreen broadleaf (FOEB), forest – mixed (FOMI), water (WATR), bare ground, sparsely vegetated (BSVG). The percentage of each LULC type is indicated in brackets.

The IRB (24°S - 26°S; 29° - 33°E) plays a fundamental role in the economies of the adjoining riparian countries (i.e., South Africa, Mozambique and Swaziland). It contributes more than 1.3% of South Africa's GDP [12]. Its largest economic contributions are to the agriculture and forestry departments. The river flows from the south-western part of the basin, across the western mountains and the plateau of Mpumalanga province, continuing its flow across Swaziland and the Great Escarpment, before it rapidly descends north through the midlevel and the lowveld, and into Mozambique [19, 20]. The mean annual temperature of the IRB is about 17°C, with its hottest mean temperature of 24°C occurring in January and the coldest temperature averaging 18°C during the month of June (Figure 2). It experiences summer rainfall between October and March. Rainfall reaches annual averages of approximately 740 mm with approximately 1,900 mm potential evaporation annually [21, 22]. Nevertheless, the IRB experiences large precipitation variation, which often leads to hydrological extremes, such as flooding and drought.

The WRB (30° S – 35° S; 17° E – 25° E) supports various economic activities in the province, including manufacturing, construction, mining, and agriculture. The WRB consists of four river systems (Figure 1): the Breede (12,348 km^2), Berg (7,715 km^2), Gouritz (45,715 km^2) and Olifants (46,220 km^2). All of these are rich in biodiversity and have high ecological importance. Six major dams within this basin form part of the Western Cape Water Supply System (WCWSS). The climate conditions across the region are temperate Mediterranean, with warm dry summers and mild moist winters. The average temperature is about 13°C in winter and 22°C in summer (Figure 2). The Western Cape is one of South Africa's driest regions, receiving only ~350 mm of rain annually, well below the national annual average of ~500 mm [5]. Much of the rainfall occurs during the austral winter months (extending from about May to September), and is typically received from cold fronts and associated extratropical cyclones, or occasional westerly disturbances, such as cut-off lows. Rainfall is, however, highly heterogeneous and varies considerably, from semi-arid areas to relatively wet areas on the windward slopes of mountains [23].

2.2. Data

We use the Geographical Information System (GIS), climate, and hydrological datasets in this study. The GIS datasets, which include the digital elevation model (DEM), land use/land cover (LULC), and soil type datasets over the four river basins, were used to set up the hydrological model over the basins (Figure 3). The DEM (90 m spatial resolution) dataset was obtained from the Consultative Group of International Agricultural Research [24, 25], and the land cover/land information maps (400 m resolution) were acquired from the United States Geological Survey Global Land Cover Characterization [26], while the soil information maps (at a scale of 1:5 000 000) were obtained from the FAO-UNESCO Digital Soil Map of the World [27]. The climate datasets include the Global Meteorological Forcing Dataset (GMFD; version 3.0; Sheffield et al., 2006) and the Coordinated Regional Downscaling Experiment (CORDEX, [28]).

The GMFD is a climate reanalysis dataset developed by the Terrestrial Hydrology Research Group of Princeton University for global land surface modelling at 1.0° high spatial resolution and a 3-hourly time step between 1948 and 2000 [29]. This dataset is often used as an observational climate dataset in place of poor-quality observation datasets in large watershed areas. The GMFD datasets comprise six climate variables (maximum temperature, minimum temperature, precipitation, solar radiation, relative humidity, and wind speed). The datasets were used for forcing hydrological simulations during calibration and validation periods, and for the bias correction and evaluation of the climate CORDEX dataset. The CORDEX dataset is a database established by the World Climate Research Program (WCRP) to produce regional climate simulations worldwide [28]. Seven RCA ensemble simulations (i.e., RCA_CCCma, RCA_CNRM, RCA_MIROC, RCA_MPI, RCA_NCC, RCA_IPSL and RCA_CSIRO; [30] at 50 km resolution were extracted from the CORDEX dataset. The simulation dataset has been bias-corrected over the basins to remove systematic errors [30, 31]. The bias-corrected CORDEX dataset was used to force all the hydroclimatic simulations under the Representative Concentration Pathway (RCP) 8.5, which represents the current high greenhouse gas emission trajectories that have led to the highest concentration levels (~1370 ppm CO_2) by the end of the 21st century [32]. The hydrological datasets were generated with a hydrological model.

2.3. Hydrological model and simulations

The hydrological model used in this study is SWAT+, a revised version of the SWAT (Soil and Water Assessment Tool) model [33]. The SWAT model is a spatially distributed, continuous-time and process-based hydrological model, well-known for its successful scientific application in hydrological simulations over complex watersheds [34]. The model was developed by the United States Department of Agriculture – Agricultural Research Service (USDA-ARS) in the early 1990s [35,36]. The model comprises several components, including weather, hydrology, soil temperature and properties, plant growth, nutrients, pesticides, bacteria and pathogens, and land management [36]. The hydrological processes in the SWAT simulations are done at watershed level, which is first divided into sub-basins and then into Hydrological Response Units (HRUs). The HRUs comprise a combination of unique soil, land use and slope properties that can be grouped into files for each sub-basin, and that are scaled to cover the whole respective sub-basin. The development of SWAT+ from SWAT addressed some limitations that existed in the SWAT model. Hence, SWAT+ is more efficient, advanced, and flexible than SWAT due to its independent module construction for easier development and maintenance as well as manual calibration. A more detailed description of SWAT and SWAT+ models can be found in [33]. The SWAT+ hydrological model has been calibrated and evaluated over the four South African basins studied herein [30, 31].

Over each basin, we applied the calibrated SWAT+ model to perform hydrological simulations for past and future climates (1970 – 2099, after a 5-year spin-up period), using the bias-corrected CORDEX data (seven-member ensemble) as the climate forcing. The characteristics of the basins, as seen by SWAT+ model in the simulation, are shown (Figure 2). To investigate the impact of climate change under a global warming level (GWLs: 1.5, 2.0, 2.5 or 3.0°C), the simulations for the present-day climate period (1971 – 2000) were subtracted from those for the GWL climate period. In accordance with [37], the GWL climate periods were defined as a 30-year period in which the climatology of the global mean temperature is higher than that of the preindustrial baseline period (1861 – 1890) by the targeted global warming value (e.g., 1.5, 2.0, 2.5 or 3.0°C).

2.4. Characterisation of hydroclimatic droughts

Seven standardised drought indices were used to characterise droughts in this study (Table 1). Two of the indices (SPI and SPEI) characterise meteorological droughts, while the remaining indices (SWI, PERCI, RFI, WYLDI, and SFI) characterise various hydrological droughts. The use of standardised indices has become increasingly popular in drought assessment since the introduction of the SPI by [38]. A major advantage of standardised indices is their comparability across time, space, and variables. The SPI is formulated by fitting long-term precipitation (P) records to a gamma probability density function, which is transformed to a normal distribution. The transformed probability gives the SPI values, which mainly vary from -2 to 2 [38]. Details of the equation formulation and the calculation for the drought index are specified in previous studies [38,39]. Like SPI, SPEI is a probability-based function calculated using climatic water balance data (precipitation minus potential evaporation) instead of precipitation data [40]. The advantage of using SPEI is the inclusion of the potential evaporation (PET), which has been shown to play a crucial role in drought severity [41, 42]. In this study, PET was obtained using the Hargreaves method (HG) [43]. All the hydrological drought indices (SWI, PERCI, RFI, WYLDI, and SFI) were calculated following the same procedure as for SPI, but using different hydrological variables (soil water, percolation, runoff, water yield and streamflow), instead of precipitation, as the input data. We employed the SPI and SPEI algorithm in R software (https://cran.r-project.org/web/packages/SPEI/SPEI.pdf) to calculate the two indices at a 12-month timescale over the study domain and averaged over each basin (Figure 1). The focus of this study is on the number of months with droughts that attain at least a moderate drought category (i.e., the drought index < -1.0).

Table 1. Description of drought indices used in the study

Drought Indices	Descriptions
SPI	Standardised Precipitation Index, calculated using precipitation data
SPEI	Standardised Precipitation Evapotranspiration Index, calculated using climate water balance (precipitation minus potential evapotranspiration) data
SWI	Standardised Soil Water Index, calculated using soil water data
PERCI,	Standardised Percolation Index, calculated using percolation water data
RFI	Standardised Runoff Index, calculated using runoff data water data
WYLDI	Standardised Water Yield Index, calculated using water yield data
SFI	Standardised Streamflow Index, calculated using Streamflow data

3. Results and discussion

In this section, we present and discuss the results of our analysis on the potential impacts of global warming over four South African river basins. We start by showing how global warming could alter the local climate over each basin, then indicate how such alteration would influence the atmospheric evaporative demand and the actual evaporation (or evapotranspiration), and then consider the consequences on surface water availability. Finally, we show the response of hydroclimatic droughts over the basins to global warming.

3.1. Projected changes in local climate over the basins

Figures 4 to 6 show that global warming alters the local climate over the four basins. In response to the warming, the local temperature of the basins increases linearly. The temperature increase is most evident over the LRB and the VRB (about 3°C at GWL3.0) and the least pronounced over the WRB (2.5°C at GWL3.0), probably because the influence of the cold Atlantic Ocean lowers the warming rate over the WRB. Despite the strong influence of each basin's topography on the spatial distribution of climatological temperature, the spatial distribution of the projected temperature increase is constant over each basin at all the GWLs (Figures 3 and 5). This suggests a weak topographical feedback on the temperature projections over each basin. The response of precipitation to global warming is more complex than that of temperature in several ways. Firstly, the direction of changes in the precipitation projection differs across the basins. While a linear precipitation decrease is projected over the WRB, no discernible trend is indicated over the VRB. However, all the basins feature a decrease in precipitation at GWL3.0, with the largest decrease occurring over the WRB (about 13%) and the lowest over the VRB (about 2%). Secondly, in most cases, not all the models agree on the precipitation projection. For example, at GWL3.0, while all simulations agree on the decreased precipitation over the WRB, less than 75% of them agree on it over the VRB (Figure 4). Thirdly, over each basin, the spatial distribution of precipitation change is strongly influenced by the basin's topography, and the direction of the influence varies across the basins. For instance, at GWL3.0, over the VRB, a decrease in precipitation (> 4mm month^{-1}) is projected over the mountain ranges, but an increase (< 2mm month^{-1}) is indicated over the lowlands.

Over other basins (LRB, IRB, and WRB), a decrease in precipitation is projected across the whole basin, but while the maximum decrease occurs over the mountain ranges in the IRB and the WRB, it occurs over the lowlands in the LRB. Fourthly, the spatial pattern of precipitation projections also varies across the GWLs. For example, over the VRB, the north-east mountain range is projected to experience increased precipitation (> 2mm month^{-1}) at GWL1.5 but decreased precipitation (-2 mm month^{-1}) at GWL3.0. However, despite the complexity in the precipitation projections, all the basins indicate that, as the GWLs grow, the area of increased precipitation shrinks, while the area of decreased precipitation expands. Hence, it can be deduced that global warming would impose a warmer and drier climate over all four basins.

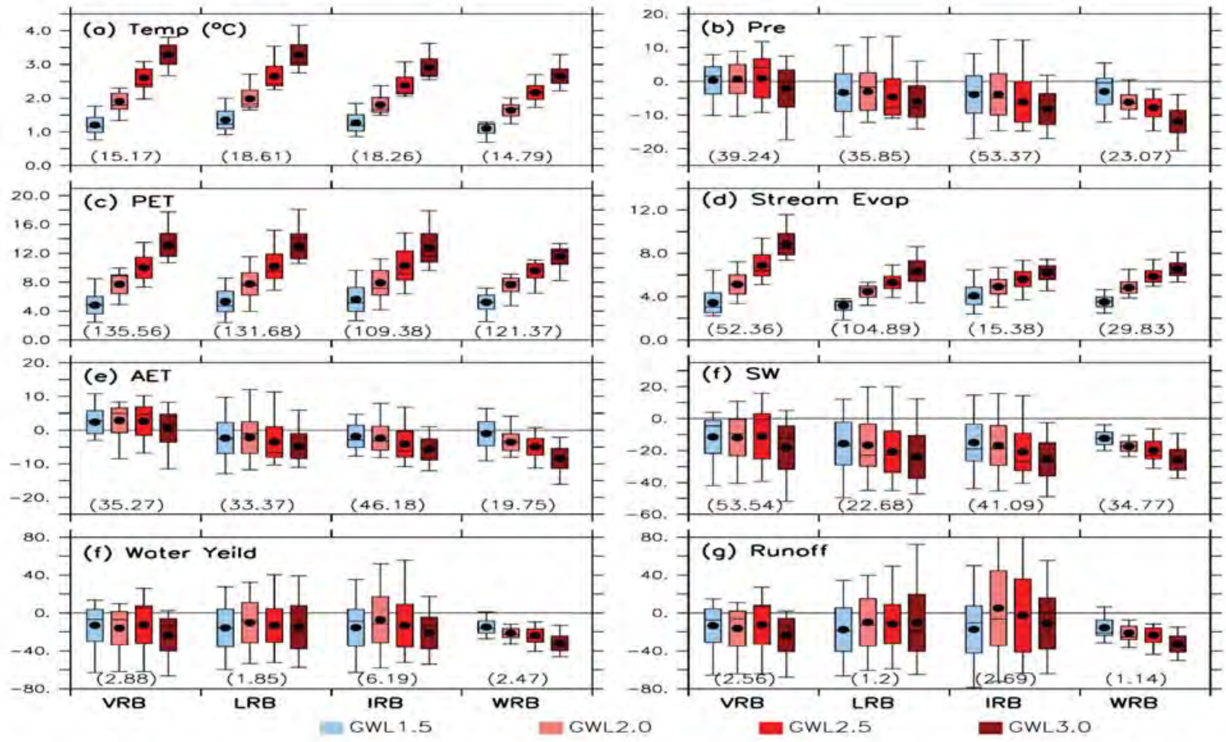


Figure 4. Projected changes in hydroclimatic variables over the selected river basins (VRB, LRB, IRB and WRB) at various global warming levels (GWL1.5, GWL2.0, GWL2.5, and GWL3.0). The temperature changes are in °C while the changes in other variables are in %. The boxplots indicate the minimum, 1st quadrant, median, 3rd quadrant, and maximum of the simulation ensemble, while the dots show the mean.

These results are consistent with those reported in previous studies over the basins [14,44,45]. In particular, [13] and [14] projected a 5°C decrease in temperature and 30% decrease in precipitation over the VRB during the period 2071 – 2100 under the RCP8.5 scenario. On the other hand, [44] found a temperature increase of about 2.5°C at GWL2.0 over parts of Southern Africa, but with a maximum increase over Namibia and Botswana. They also found a robust decrease in precipitation of 10% – 20% over the LRB at GWL1.5 and GWL2.0 over the LRB and the WRB. [45] projected an increase of about 4°C in temperature and 30% reduction in precipitation over the Olifants catchment of the LRB. [46] found no noticeable change in precipitation over the Western Cape during the period 2081 – 2100 under the RCP2.6 and the RCP4.5 scenarios but found a decrease in precipitation over the region during the period under the RCP 8.5 scenario that has been considered in the present study. Nevertheless, the projections in the present study show that, among the four basins (VLB, LRB, IRB and WRB), the LRB may experience the highest temperature increase, while the WRB may experience the highest rainfall decrease in the future.

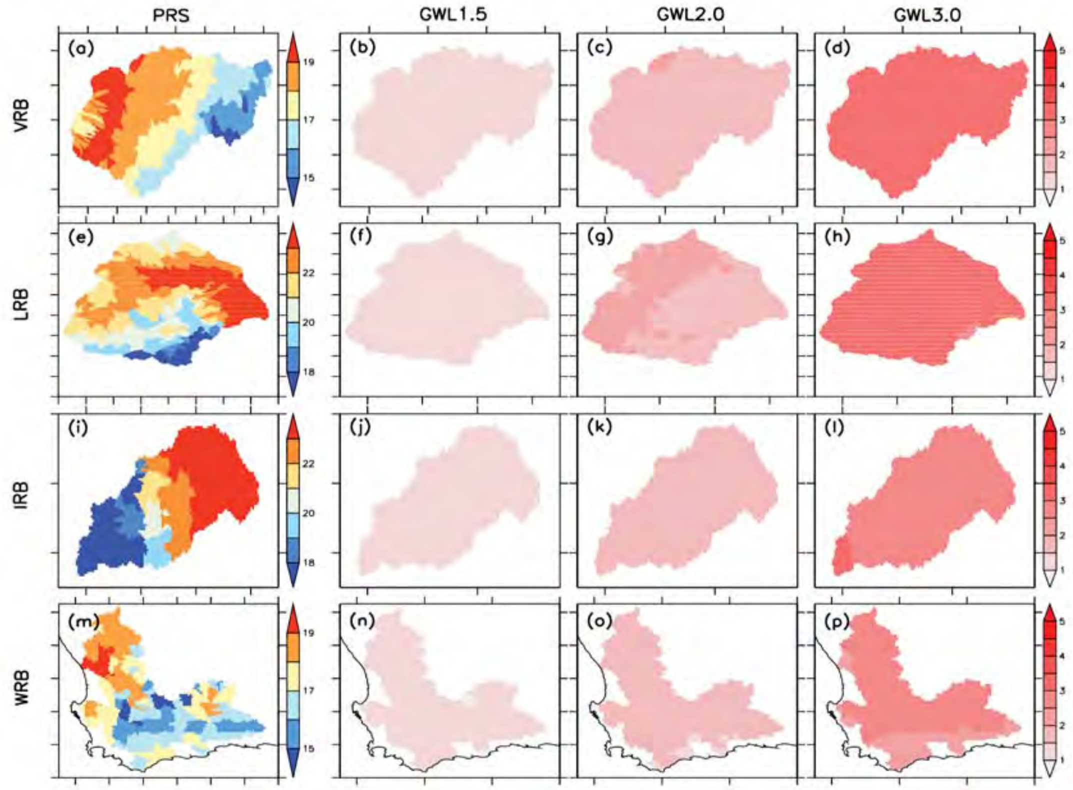


Figure 5. Spatial distribution of the annual temperature (1971 – 2000) and the projected changes over the selected river basins at various global warming levels.

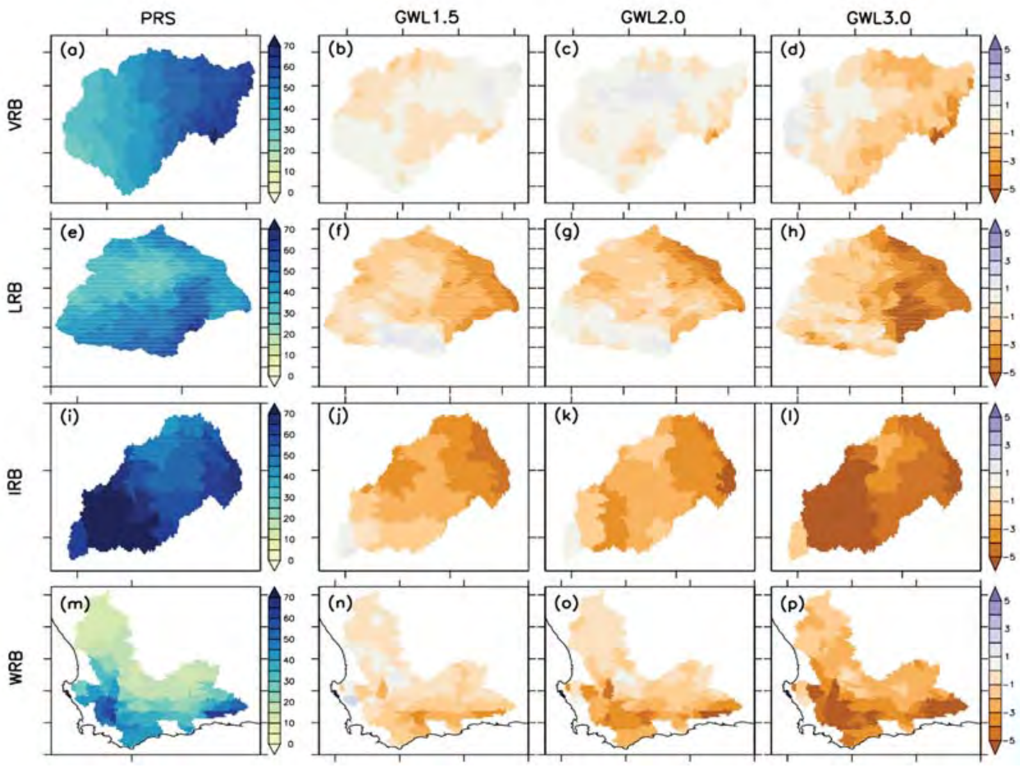


Figure 6: Same as Figure 5, but for precipitation.

3.2. Impacts on atmospheric evaporative demand and evaporation

The projected warmer and drier local climate influences the atmospheric evaporative demand and evaporation over the basins (Figures 4, 7, 8 and 9). The warming fosters a linear increase in atmospheric evaporative demand (PET) over all the basins, and the spatial distribution of the increase is consistent with that of the temperature increase. The strong link between PET and temperature changes is because, as atmospheric temperature increases, the capacity of the atmosphere to contain water vapour also increases, causing PET to increase. Nevertheless, Figure 4 shows that the response of actual evaporation to the increased PET differs over water surfaces (i.e., stream evaporation) and land surfaces (i.e., actual evapotranspiration, AET). Consistently with the enhanced PET, the stream evaporation increases linearly over the four basins, featuring the maximum increase over the VRB and the minimum increase over the WRB. In contrast to the strong linear increase in PET, a weak increase in AET (< 10%) is projected over the VRB (at all the GWLs) and a strong linear decrease is indicated over the other basins (LRB, IRB and WRB). The inconsistency between the responses of stream evaporation and AET to the enhanced PET is because, while the continuous availability of stream water sustains the linear increase in stream evaporation, the insufficient soil water hinders the increase in AET. Although AET depends on PET, it also depends on soil water availability, which is strongly influenced by the precipitation changes. So, a decrease in precipitation will reduce soil water availability and limit the response of AET to the enhanced PET. The weak increase in AET over the VRB is consistent with the weak increase in precipitation over the basin (especially at GWL1.5 to GWL2.5), while the strong linear decrease of the AET over the WRB can be attributed to the strong precipitation decrease over the basin. Hence, the response of AET to the enhanced PET is more complex than the response to stream evaporation.

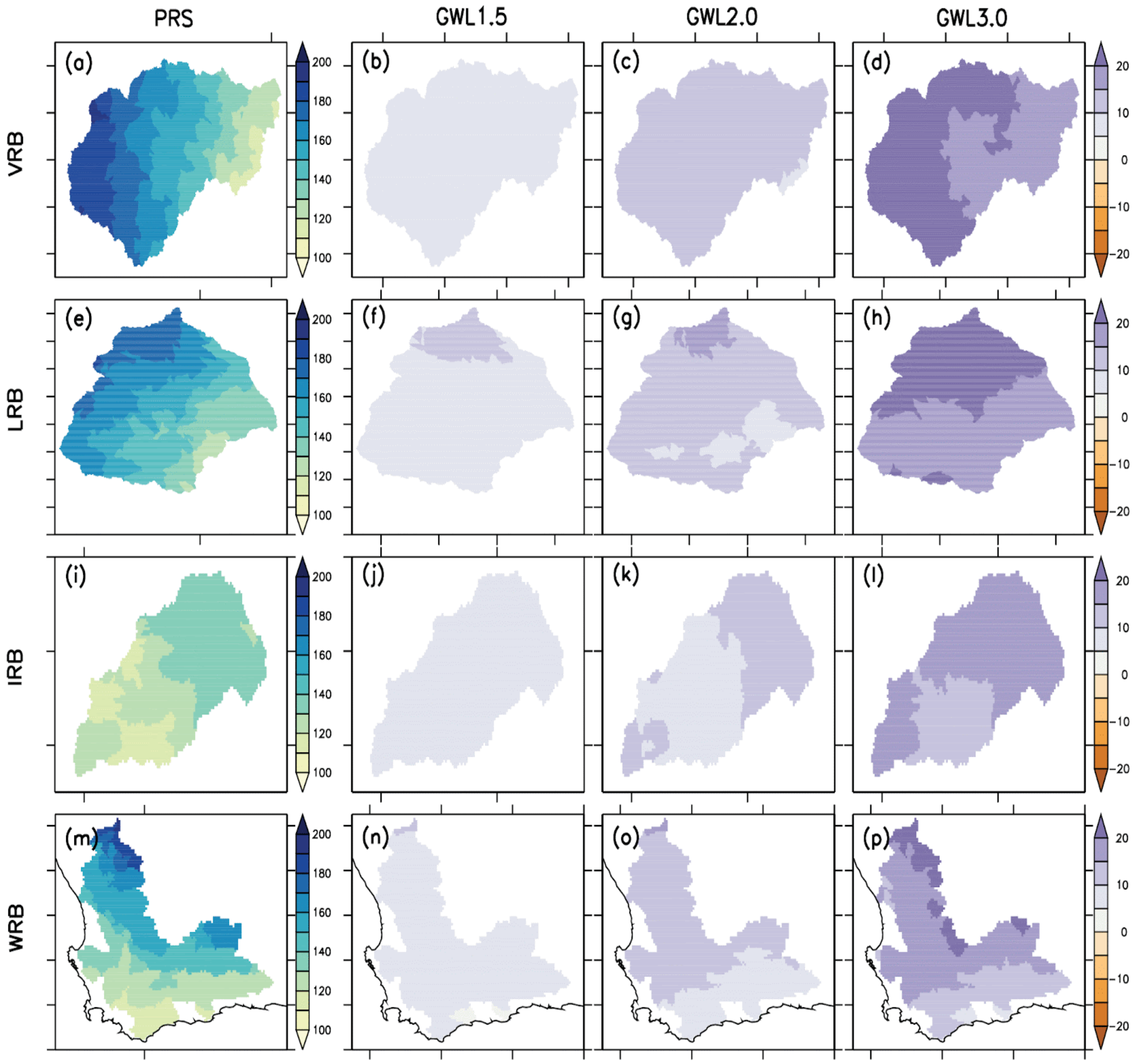


Figure 7. Same as Figure 5, but for potential evapotranspiration.

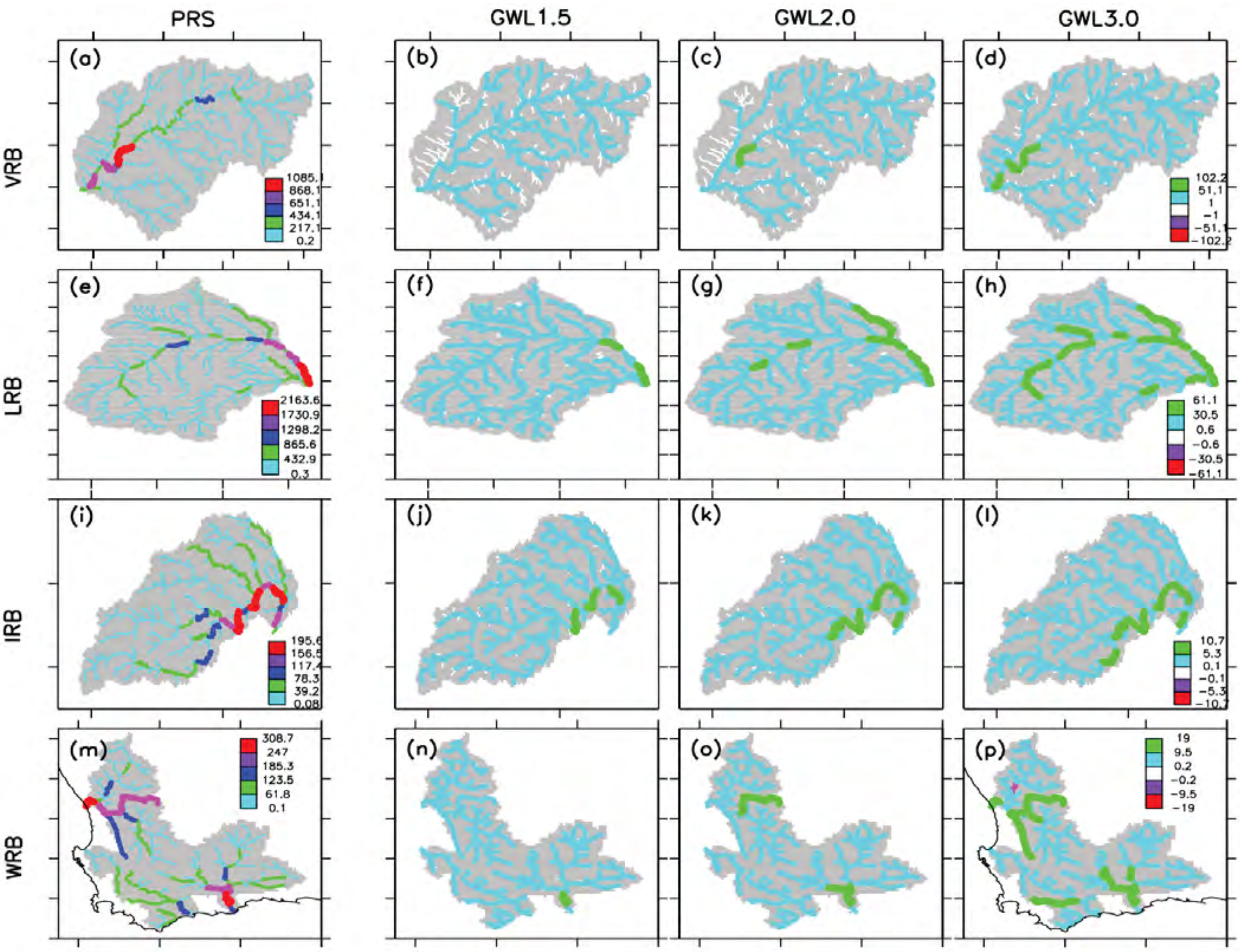


Figure 8. Same as Figure 5, but for stream evaporation.

The spatial distribution of AET changes over each basin is also more complex than the spatial distribution of the stream evaporation changes. For example, over the VRB, an increase in stream evaporation occurs over all the streams in the basin (Figure 8); but while an increase in AET is projected over one part of the basin, a decrease is indicated over the other parts (Figure 9). In general, the spatial distribution of the AET changes can also be explained by the spatial distribution of the precipitation changes, but there are areas where the direction of the changes in AET deviates from that of the precipitation changes. For instance, in the VRB basin, despite the projected decrease in precipitation over the north-eastern mountain range, an increase in AET is projected over the area; this increase occurs at the expense of the residual soil moisture (Figure 10). Nevertheless, a consistent finding across all four basins is that, as GWLs increase, the fraction of the basin that experiences increased AET reduces, while the fraction that experiences decreased AET expands. Hence, the projected warmer and drier local climate would enhance PET and stream evaporation, but decrease AET in the future. These results concur with those of previous studies on the impacts of global warming on PET and AET over southern Africa [47,48]. [48] also projected an increase in PET over the IRB. The future projections of [47] over Southern Africa feature an increase in AET over the areas of increased precipitation and a decrease in AET over the areas of decreased precipitation. However, the results of the present study show that the enhanced PET fosters a linear increase in stream evaporation, despite the decrease in precipitation.

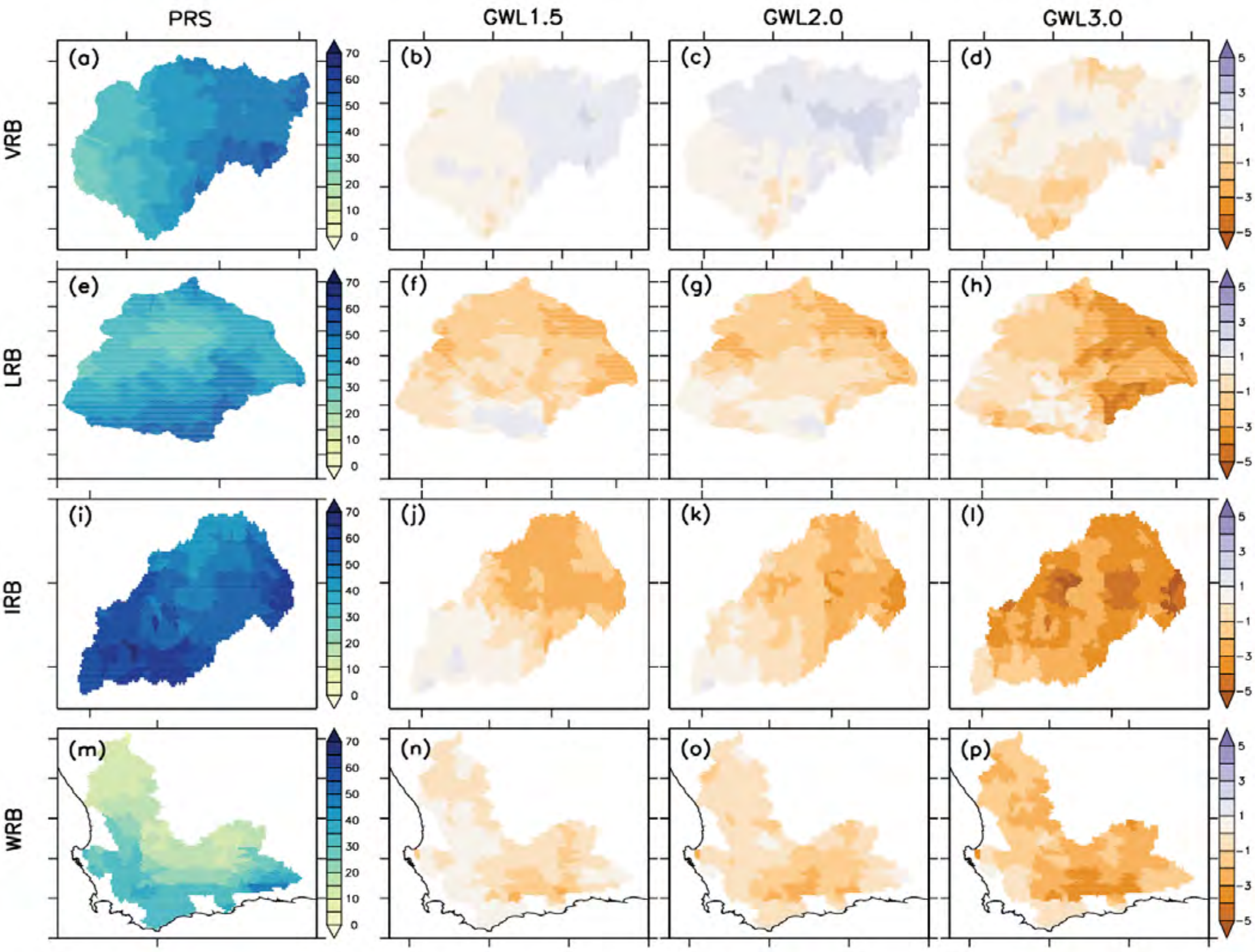


Figure 9. Same as Figure 5, but for evapotranspiration.

3.3. Impacts on water availability in the basin

The projected decrease in precipitation together with the increase in atmospheric evaporative demand induce a decrease in all the hydrological variables (i.e., soil water, water yield, runoff and streamflow) over all the basins (Figures 4, 10, 11, and 12). However, the magnitude of the decrease, which grows with higher GWLs, varies across the basins. The robustness of the projection (i.e., the agreement among the simulations on the projections) also varies across the basins. The largest decrease and the most robust projection occur over the WRB, where all the simulations agree on the decrease, and the simulation ensemble mean indicates a 30% decrease in soil water, runoff and water yield at GWL3.0. The spatial distribution of the changes shows that, although there are cases of local increase in some hydrological variables (e.g., increased streamflow up to 20 m^3 s^{-1} over the eastern part of the LRB), a decrease in hydrological variables dominates all the basins. At GWL3.0, the maximum decrease in soil water and runoff occurs over the mountain ranges in the VRB, IRB and WRB, but over the lowlands in the LRB. This pattern is consistent with the spatial distribution of precipitation over the basins. The maximum decrease in soil water is up to 15 mm (17%) in the VRB, 12 mm (30%) in the LRB, 15 mm (21%) in the IRB, and 15 mm (17%) in the WRB (Figure 4). The maximum decrease in streamflow occurs toward the mouth of the rivers due to the combined effects of the decrease in runoff and decrease in streamflow (further upstream). The maximum decrease is up to 65 $m^3 s^{-1}$ (69%) in the VRB, 56 $m^3 s^{-1}$ (44%) in the LRB, 29 $m^3 s^{-1}$ (37%) and 16 $m^3 s^{-1}$ (57%) in the WRB (Figure 12). Projected changes in the spatial distribution of 90th and 10th percentiles of the streamflow are shown in Appendix A.

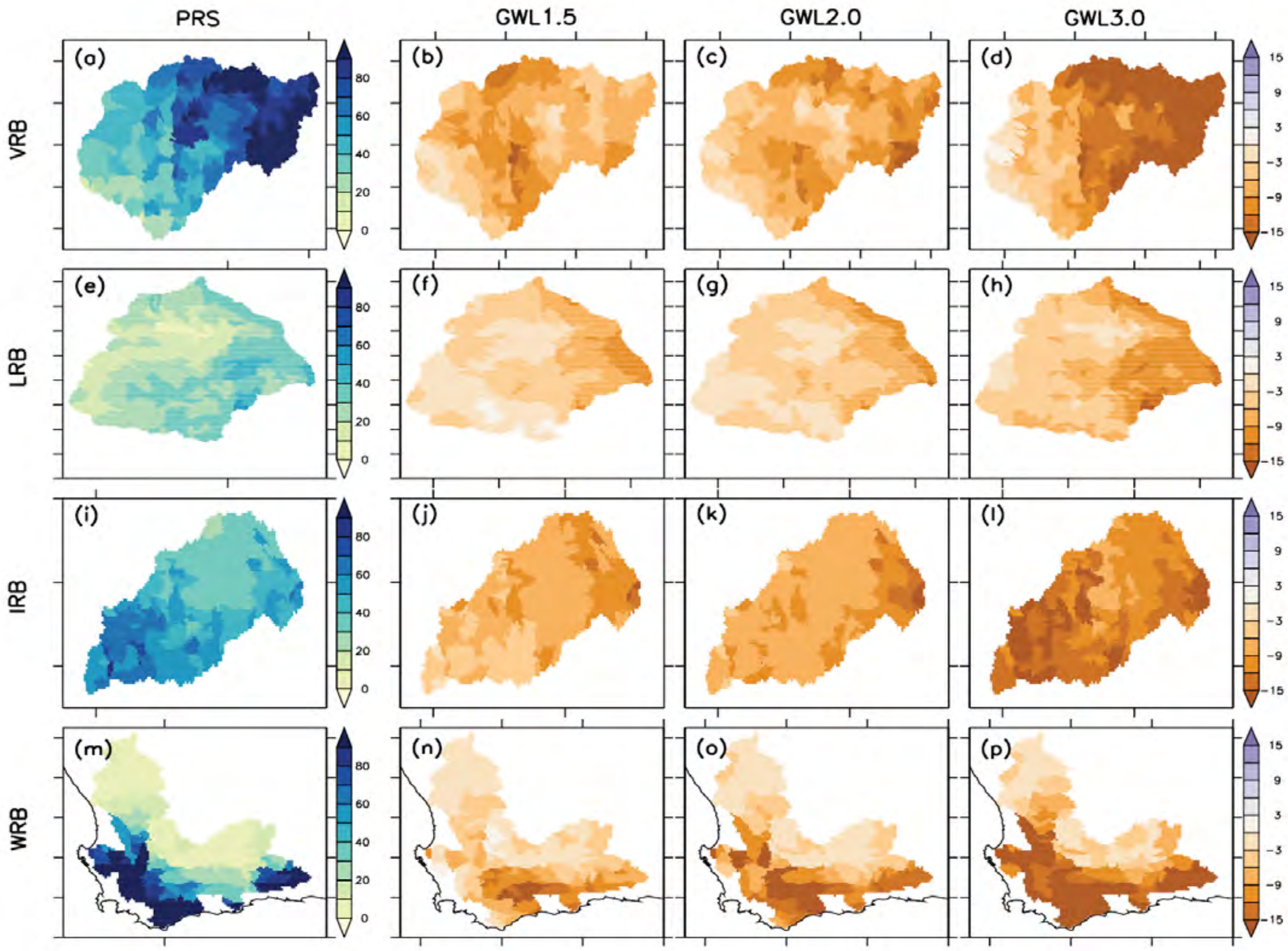


Figure 10. Same as Figure 5, but for soil water.

These results agree with those of previous studies that projected a reduction in water availability over southern Africa (i.e., [46,48,49]. For example, [47] projected a decrease in soil moisture over the whole of South Africa. [14] projected an 8% and 10% reduction in streamflow over the VRB during the period 2071 – 2100 under the RCP 4.5 and RCP 8.5, respectively. Similarly, [50] projected a decline in streamflow over the LRB in both the near and the distant future under RCP8.5. [49] projected a 14-26% reduction in river flow over the Zambezi River basin due the increased stream evaporation. However, the projections in the present study show that, among the four basins (VLB, LRB, IRB, and WRB), the reduction in water availability may be the most severe over the WRB, where the decrease in precipitation is the most pronounced.

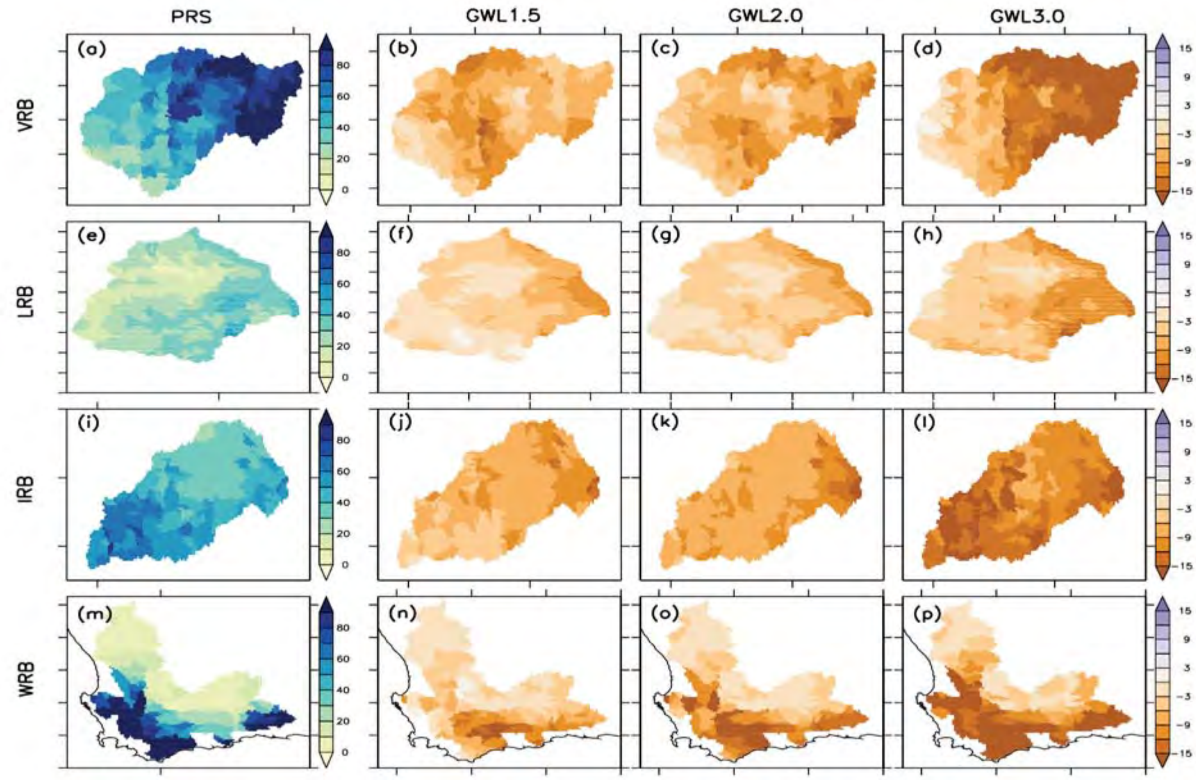


Figure 11. Same as Figure 5, but for runoff.

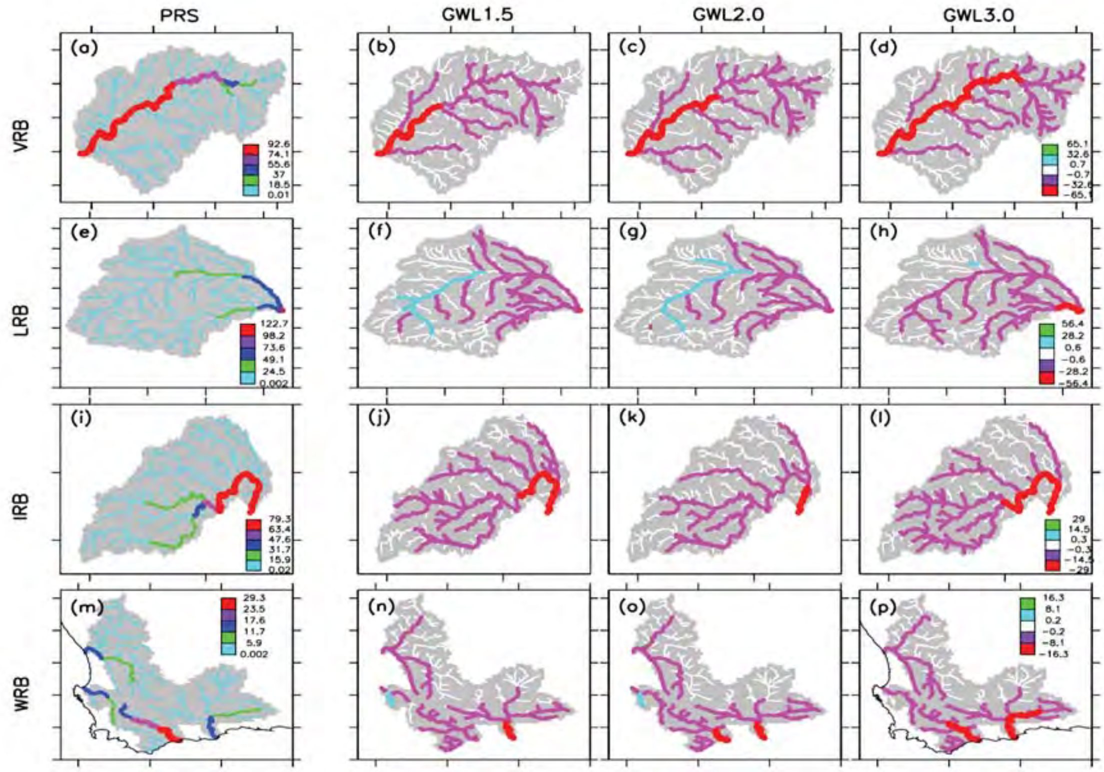


Figure 12. Same as Figure 5, but for streamflow.

3.4 Impacts on frequency of hydroclimatic droughts

The response of hydrological droughts to the projected changes in hydroclimatic variables over the basins is summarised in Figure 13. The figure shows a linear increase in drought frequency for both meteorological droughts (SPI and SPEI). However, the increase is higher for SPEI droughts than for SPI droughts. At GWL3.0, both indices feature their highest increase in drought frequency over the WRB (20 and 80 months per decade^{-1} for SPI and SPEI, respectively), but while SPI features its lowest increase over the LRB, SPEI features it over the IRB. The discrepancy between the two indices can be attributed to the influence of enhanced PET from global warming. While SPEI drought projections (based on climate water balance) incorporate the influence, the SPI drought projections (based on only precipitation) do not include the influence. Hence, using SPI for drought projection may underestimate the severity of the future droughts [7,51]. Nevertheless, SPEI drought projections too may overestimate the impact of the warming on future droughts over the basins, because, as discussed earlier, the linear increase in PET produced by the warming does not translate to a linear increase in AET over the basins.

The projected decrease in precipitation limits the response of AET to the enhanced PET. However, the SPEI indicates the maximum drought stress over a basin, not the actual drought stress. The actual drought stress over a basin can only be obtained by means of hydrological drought indices. Following global warming, an increase in drought frequency is projected for all hydrological drought indices. Their projected increase lies within those of the two meteorological droughts. For some hydrological droughts (e.g., RFI), the increase is close to (but still higher than) that of SPI droughts, while for others (e.g., SWI), the increase is more than twice that of the SPI, but less than half that of the SPEI droughts. This confirms that the SPI drought projections may underestimate the impacts of global warming on water availability and hydrological droughts over the basins. However, among all the hydrological droughts, the projected impacts are most pronounced on the SWI and PERCI droughts.

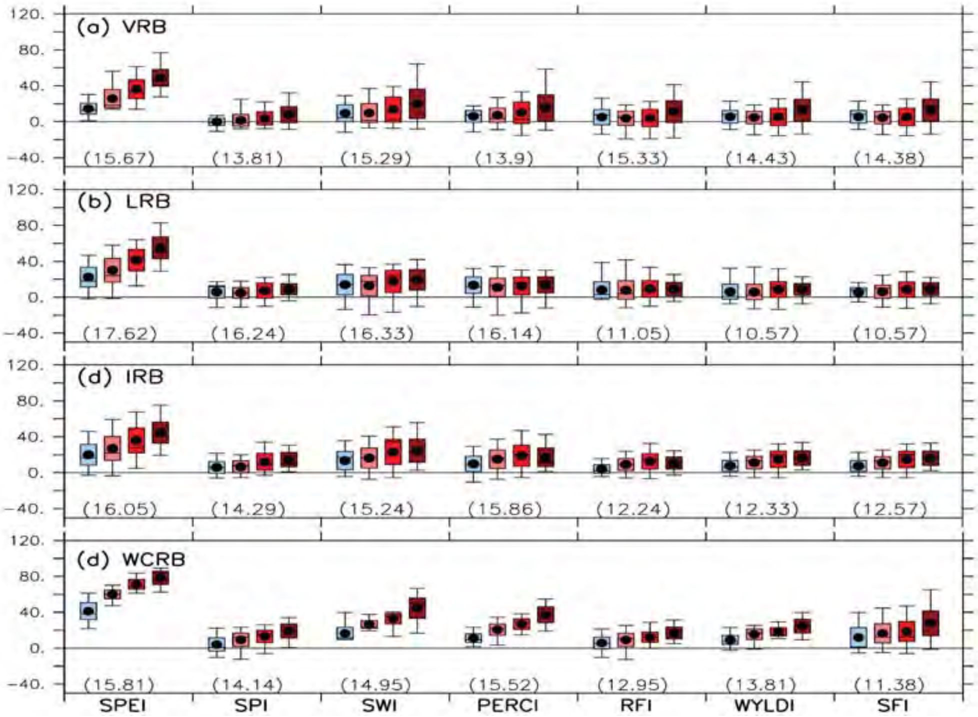


Figure 13. Projected changes in the frequency of hydrodynamical droughts over the river basins at 12-month scales.

4. Conclusion

As part of ongoing efforts to understand the socio-economic impacts of global warming in South Africa, the present study has investigated the impacts of climate change on water availability and hydroclimatic droughts over four river basins in South Africa. The four river basins were chosen based on their importance for socioeconomic activities in the country and based on the prevalence of droughts over the basins. A bias-corrected climate simulation dataset (CORDEX) was used to force a hydrological model (SWAT+) in simulating the hydrological response of the past and future climates (under the RCP8.5 scenario) over the basins. The meteorological droughts were characterised with two indices (SPEI and SPI), while the hydrological droughts were characterised with five indices (SWI, PERCI, RFI, WYLDI, and SFI). The impacts of global warming on hydroclimatic variables and droughts were quantified at four global warming levels (GWLs 1.5, 2.0, 2.5 and 3.0). The results of the study can be summarised as follows:

- In response to global warming, a warmer and drier climate is projected over each of the four basins, but with the highest warming rate occurring over the LRB, and highest drying rate over the WRB.
- The warmer climate is projected to increase PET and stream evaporation, while the decreased precipitation may constrain the corresponding increase in AET over some basins, but a decrease in actual evapotranspiration over other basins.
- A decrease in water availability is projected over all the basins, but the spatial distribution and magnitude of the decrease differs. The largest decrease in soil water and runoff is projected over the mountain ranges (highlands) in the VRB, IRB and WRB, but over the lowlands in the LRB.

- The maximum decrease in streamflow along the main river channels ranges from 37% in the LRB to 69% in the VRB.
- Both SPI and SPEI indicate a future increase in meteorological drought frequency over all the river basins, but the magnitude of the increase is higher for SPEI than SPI droughts.
- An increase in the frequency of all hydrological droughts is projected over all the basins, however the increase is higher than that of SPI droughts and lower than that of SPEI droughts.

The results have provided a basis for developing strategic research and policies toward mitigating the impacts of global warming on human health and socioeconomic activities over the basins. For example, the results show that global warming would increase local temperature over all the basins, but also indicate that the highest increase would be over the LRB. The Limpopo province is the hottest province in South Africa and is characterised by heat waves [52,53,54]. The projected increase in temperature might be accompanied by more frequent, more intense, and longer-lasting heat waves. This could have devastating impacts on the human health and socio-economic sectors, since heat waves are well known for destroying plant and animal species, damaging agricultural production (crops and livestock), increasing energy and water consumption, causing heat stroke, and even killing people [53]. To mitigate these impacts, future research may quantify future changes in characteristics of heat waves over the LRB and assess the implications for human health and socio-economic sectors. As a results, the research efforts may contribute towards reinforcing local climate change adaptation strategies. In addition, decision-makers can formulate policies that motivate and incentivise activities that mitigate temperature increases locally over the LRB. Such activities may include, for instance, planting of indigenous vegetation in the basin (to improve water use) or installing reflective roofing on buildings (to help keep buildings cooler and make them more energy efficient).

The results also show that global warming would reduce water availability and increase hydrological drought frequency over all the basins, with the largest impacts in the WRB. The Western Cape province is well known for experiencing severe droughts. This province experienced one of its most devastating droughts in the period 2015 – 2017. The multi-year severe drought, which reduced annual rainfall consecutively for the three years, cascaded from the meteorological drought to an agricultural drought and a hydrological drought with devastating socio-economic impacts. It reduced the water storage levels of the Western Cape's major dams to about 23% (meanwhile the last 12% of the dam water was unusable) and the water supply to the City of Cape Town was reduced by about 60% [55]. This led to severe water restrictions on agricultural, urban, and industrial consumers as well as on citizens (50 litres per person per day), while the dwellers of the mega city prepared for the so-called 'Day Zero' (a day when regional dam levels would decline to critically low levels and the city's domestic taps would have to be switched off; [56]. The drought led to a decline in agricultural output with economic losses of R5.9 billion and 30,000 job losses [57]. However, results from the present study concur with those of [8,58], that global warming might make a severe drought like this more frequent in the future. The reduction of water availability in the WRB is projected to occur via a decrease in precipitation and an increase in PET. To mitigate the potential impacts of reduced precipitation, decision makers may have to invest more resources into infrastructure for alternative water sources (e.g., extraction from underground water aquifers and water desalination instead of the current reliance on surface water sources). They could also incentivise activities that will promote the more efficient use of available rainfall water (e.g., rain harvesting), reduce the evaporation of stream water (i.e., by creating underground water storage and V-shape lakes, or implementing water evaporation prevention technology measures for dams of the WCWSS), and minimise the evapotranspiration of soil water (through mulching, planting of grasses, or planting of indigenous rather than exotic tree species, particularly in riparian areas).

Additional information that emerges from the results relates to the usage of meteorological drought indices (e.g., SPEI and SPI) as indicators for water availability in river basins. Because climate projection datasets are more available and accessible than hydrological projection datasets, SPEI and SPI drought projections are often used (in place of hydrological drought projections) as indicators of water availability over river basins in the future (e.g., [7,51,59]). The results of this study revealed that the SPI drought projection may underestimate the impacts of droughts on future water availability, because it does not account for the influence of the enhanced PET on evaporation or evapotranspiration over the basins. The SPEI, too, may overestimate the impacts of droughts on future water availability because it exaggerates the influence of the enhanced PET evapotranspiration over the basins. Hence, in the absence of hydrological projection datasets, the policy makers may have to combine and compare SPI and SPEI drought projections when assessing the impact of climate change on water availability in the basins. While SPI would provide a lower limit for the projection, SPEI would provide an upper limit. In addition, the gap between SPEI and SPI would also provide a good indication of the extent to which impacts of enhanced PET (from global warming) can be mitigated over the basins.

Funding: The study was supported by research grants from the Water Research Commission.

Data Availability Statement: The simulation data used for the study can be made available on request.

Acknowledgements: We appreciate the technical support of Mr Phillip Mukwenha. The Centre for High Performance Computing (CHPC, South Africa) provided the computing facility used for the study.

References

1. James, R. and Washington, R. Changes in African temperature and precipitation associated with degrees of global warming. *Climate Change*, **117**, 859 - 872.
2. Lennard, C., Nikulin, G., Dosio, A. and Moufouma-Okia, W. (2018). On the need for regional climate information over Africa under varying levels of global warming. *Environmental Research Letters*, **13**(6), pp. 1–26.
3. Vautard, R., Gobiet, A., Sobolowski, S., Kjellström, E., Stegehuis, A., Watkiss, P., Mendlik, T., Landgren, O., Nikulin, G., Teichmann, C. and Jacob, D. (2014) The European climate under a 2° C global warming. *Environmental Research Letters*, **9**(3), p. 034006.

4. Limpopo Business. (2017). *The guide to business and investment in The Limpopo Province*. Global Africa Network. Available online at: https://webkiosk.globalafricanetwork.com/limpopo-business-2019-20-edition/62780110. Accessed on 26 October 2020.
5. Dennis, I. and Dennis, R. (2012). Climate change vulnerability index for South African aquifers. *Water SA*, **38**(3), 417–426.
6. Department of Environmental Affairs (DEA). (2013). Long-Term Adaptation Scenarios Flagship Research Programme (LTAS) for South Africa*. Climate Change Implications for the Water Sector in South Africa*. Pretoria, South Africa.
7. Abiodun, B.J., Makhanya, N., Petja, B., Abatan, A.A. and Oguntunde, P.G. (2019). Future projection of droughts over major river basins in Southern Africa at specific global warming levels. *Theoretical and Applied Climatology*, **137**, 1785–1799. https://doi.org/10.1007/s00704-018-2693-0.
8. Naik, M. and Abiodun, B.J. (2020). Projected changes in drought characteristics over the Western Cape, South Africa. *Meteorological Applications*, **27**(1), p. e1802.
9. Otieno, F., Oching, G., Haji, H. and Dzwairo, B. (2009). Integrated water management of the Vaal River catchment. *Civil Engineering*, **17**(5), 37–40.
10. Van Vuuren, L. (2008). Start saving or start paying, river studies warn. *The Water Wheel*, **7**(3), 14–18.
11. Braune, E. and Rogers, K.H. (1987). The Vaal River catchment: Problems and research needs. *South African national scientific programme*. Report No. 143. ISBN 0 7988 4122 2.
12. Department of Water Affairs and Forestry (DWAF). (2003). *Upper Vaal Water management area: Overview of water resources availability and utilization*. Report No. P WMA 08/000/00/0203.
13. Jury, M.R. (2016). Climate influences on Vaal River flow. *Water SA*, **42**(2), 232–242.
14. Remilekun, A.T., Thando, N., Nerhene, D. and Archer, E. (2021). Integrated assessment of the influence of climate change on current and future intra-annual water availability in the Vaal River catchment. *Journal of Water and Climate Change*, **12**(2), 533–551.
15. Merz, L., Yang, D. and Hull, V. (2020). A Metacoupling Framework for Exploring Transboundary Watershed Management. *Sustainability*, **12**(5), 1879.
16. Trambauer, P., Werner, M., Winsemius, H.C., Maskey, S., Dutra, E. and Uhlenbrook, S. (2015). Hydrological drought forecasting and skill assessment for the Limpopo River basin, Southern Africa. *Hydrology and Earth System Sciences*, **19**(4), 1695–1711.
17. Seibert, M., Merz, B. and Apel, H. (2017). Seasonal forecasting of hydrological drought in the Limpopo Basin: A comparison of statistical methods. *Hydrology and Earth System Sciences*, **21**(3), 1611–1629.
18. Food and Agriculture Organization (FAO). (2004). *Drought Impact Mitigation and Prevention in the Limpopo River Basin: A Situation Analysis*. Land and Water Discussion Paper. Food and Agriculture Organization (FAO): Rome, Italy.
19. Riddell, E., Jewitt, G., Chetty, K., Saraiva Okello, A., Jackson, B., Lamba, A., Gokoo, S., Naidoo, P., Vather, T. and Thornton-Dibb, S. (2014). *A management tool for the Inkomati Basin with focus on improved hydrological understanding for risk-based operational water management*. WRC Report no. 1935/1/20, Water Research Commission (WRC): Pretoria.
20. UNEP/Nairobi Convention Secretariat (2010). Environmental Profile of the Inkomati River Basin, UNEP, Nairobi Kenya, 82p.
21. Joint Incomati Basin Study (JIBS). (2001). Joint Incomati Basin Study Report. Phase 2. Consultec Report No: C14- 99MRF/BKS ACRES
22. Leestemaker, J. (2000). The domino effect, a downstream perspective in water management in Southern Africa. *Green Cross International, Water for Peace in the Middle East and Southern Africa, Geneva*.
23. Blamey, R., Mahlalela, P. and Reason, C. (2019). The Cape Town 'Day Zero' Drought: Mechanisms behind early winter rainfall variability in the southwestern Cape, South Africa. *Geophysical Research Abstracts*, 21 (January), p. EGU2019-15602.
24. CGIAR Consortium for Spatial Information, http://srtm.csi.cgiar.org/

25. Jarvis, A., Reuter, H.I., Nelson, A. and Guevara, E. (2008). Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database. http://srtm.csi.cgiar.org.
26. USGS Global Land Cover Characterisation: https://www.usgs.gov/media/images/africa-land-cover-characteristics-data-base-version-20
27. FAO-UNESCO: https://swat.tamu.edu/data/
28. Giorgi, F., Jones, C. and Asrar, G.R. (2009) Addressing climate information needs at the regional level: The CORDEX framework. *World Meteorological Organization (WMO) Bulletin*, **58**(3), 175–183.
29. Sheffield, J., Goteti, G. and Wood, E.F. (2006). Development of a 50-year high-resolution global dataset of meteorological forcing for land surface modelling. *Journal of Climate*, **19**(13), 3088–3111.
30. Abiodun, B.J., Naik, M., Mogebisa, T., Makhanya, N., Nguvava, M., Adaramola, R., and Yocgo, R. (2021). Using land-use change to mitigate impacts of future droughts on water yield in South Africa. *Water Research Commission Report* (in press).
31. Mogebisa, T. (2021). *Potential Impacts of Climate Change on Hydrological Extremes in the Incomati River Basin*. MSc Thesis, University of Cape Town (under review).
32. Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., Van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T. and Meehl, G.A. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, **463**(7282), 747–756.
33. Bieger, K., Arnold, J.G., Rathjens, H., White, M.J., Bosch, D.D., Allen, P.M., Volk, M. and Srinivasan, R. (2017). Introduction to SWAT+, a completely restructured version of the soil and water assessment tool. *JAWRA Journal of the American Water Resources Association*, **53**(1), 115–130.
34. Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R. and King, K.W. (2005). *SWAT theoretical documentation version 2005*. Soil and Water Research Laboratory, ARS, Temple Texas, USA.
35. Arnold, J.G., Engel, B.A. and Srinivasan, R., 1993. Continuous time, grid cell watershed model, application of advanced information technologies. *Effective management of natural resources. ASAE Publication*, pp.04-93.
36. Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., Van Griensven, A., Van Liew, M.W., Kannan, N. and Jha, M.K. (2012). SWAT: Model use, calibration, and validation. *Transactions of the American Society of Agricultural and Biological Engineers (ASABE)*, **55**(4), 1491–1508.
37. Nikulin, G., Lennard, C., Dosio, A., Kjellström, E., Chen, Y., Hänsler, A., Kupiainen, M., Laprise, R., Mariotti, L., Maule, C.F. and Van Meijgaard, E. The effects of 1.5 and 2 degrees of global warming on Africa in the CORDEX ensemble. *Environmental Research Letters*, **13**(6), p.065003.
38. McKee, T.B., Doesken, N.J. and Kleist, J. The relationship of drought frequency and duration to time scales. In *Proceedings of the 8th Conference on Applied Climatology*, **17**(22), 179–183.
39. Edwards, D.C. and McKee, T.B. (1997). Characteristics of 20th century drought in the United States at multiple time scales. *Climatology Report*, 97–2, Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado.
40. Vicente-Serrano, S.M., Beguería, S. and López-Moreno, J.I. A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, ***23***(7), 1696–1718.
41. Meque, A. and Abiodun, B.J. Simulating the link between ENSO and summer drought in Southern Africa using regional climate models. *Climate Dynamics*, **44**(7), 1881–1900.
42. Ujeneza, E.L. and Abiodun, B.J. Drought regimes in Southern Africa and how well GCMs simulate them. *Climate Dynamics*, **44**(5), 1595–1609.
43. Hargreaves, G.H. and Samani, Z.A. Reference crop evapotranspiration from temperature. *Applied Engineering in Agriculture*, **1**(2), 96–99.

44. Maúre, G., Pinto, I., Ndebele-Murisa, M., Muthige, M., Lennard, C., Nikulin, G., Dosio, A. and Meque, A. The Southern African climate under 1.5°C and 2°C of global warming as simulated by CORDEX regional climate models. *Environmental Research Letters*, **13**(6), 065002.
45. Olabanji, M.F., Ndarana, T., Davis, N. and Archer, E. Climate change impact on water availability in the Olifants catchment (South Africa) with potential adaptation strategies. *Physics and Chemistry of the Earth, Parts A/B/C*, **120,** 102939.
46. He, B. and Ding, K.J. Localize the Impact of Global Greenhouse Gases Emissions under an Uncertain Future: A Case Study in Western Cape, South Africa. *Earth*, **2**(1), 111–123.
47. Cheng, W., MacMartin, D.G., Dagon, K., Kravitz, B., Tilmes, S., Richter, J.H., Mills, M.J. and Simpson, I.R. Soil moisture and other hydrological changes in a stratospheric aerosol geoengineering large ensemble. *Journal of Geophysical Research: Atmospheres*, **124**(23), 12773–12793.
48. Li, L., Diallo, I., Xu, C.Y. and Stordal, F., 2015. Hydrological projections under climate change in the near future by RegCM4 in Southern Africa using a large-scale hydrological model. *Journal of Hydrology*, ***528***, 1-16.
49. Hamududu, B.H. and Killingtveit, Å. Hydropower production in future climate scenarios: The case for the Zambezi River. *Energies*, ***9***(7), 502.
50. Botai, C.M., Botai, J.O., Zwane, N.N., Hayombe, P., Wamiti, E.K., Makgoale, T., Murambadoro, M.D., Adeola, A.M., Ncongwane, K.P., de Wit, J.P. and Mengistu, M.G. Hydroclimatic Extremes in the Limpopo River Basin, South Africa, under Changing Climate. *Water*, **12**(12), 3299.
51. Oguntunde, P.G., Abiodun, B.J., Lischeid, G. and Abatan, A.A. Drought projection over the Niger and Volta River basins of West Africa at specific global warming levels. *International Journal of Climatology*, **40**(13), 5688–5699.
52. Kruger, A.C. and Shongwe, S. Temperature trends in South Africa: 1960–2003. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, **24**(15), 1929–1945.
53. Maposa, D., Seimela, A.M., Sigauke, C. and Cochran, J.J. Modelling temperature extremes in the Limpopo province: bivariate time-varying threshold excess approach. *Natural Hazards*, **107**, 1-20.
54. Phophi, M.M., Mafongoya, P. and Lottering, S. Perceptions of climate change and drivers of insect pest outbreaks in vegetable crops in Limpopo province of South Africa. *Climate*, **8**(2), 27.
55. Botai, C.M., Botai, J.O., de Wit, J.P., Ncongwane, K.P. and Adeola, A.M. Drought characteristics over the Western Cape Province, South Africa. *Water*, **9**(11), 876.
56. Gibson, D. (2018). Water crisis in cape town: Lessons to be learnt. Voices of South Africa (Febrero). Konrad-Adenauer-Stiftung eV, pp.1–4.
57. Green Cape (2019). *Sustainable Agriculture 2019 Market Intelligence Report*. Cape Town, South Africa. Available online: www.greencape.co.za. Accessed on: 17 August 2021.
58. Odoulami, R.C., New, M., Wolski, P., Guillemet, G., Pinto, I., Lennard, C., Muri, H. and Tilmes, S. Stratospheric Aerosol Geoengineering could lower future risk of 'Day Zero' level droughts in Cape Town. *Environmental Research Letters*, ***15***(12), p.124007.
59. Nguvava, M., Abiodun, B. and Otieno, F. Projecting drought characteristics over East African basins at specific global warming levels. *Atmospheric Research*, **228**, 1–14.

Appendix A

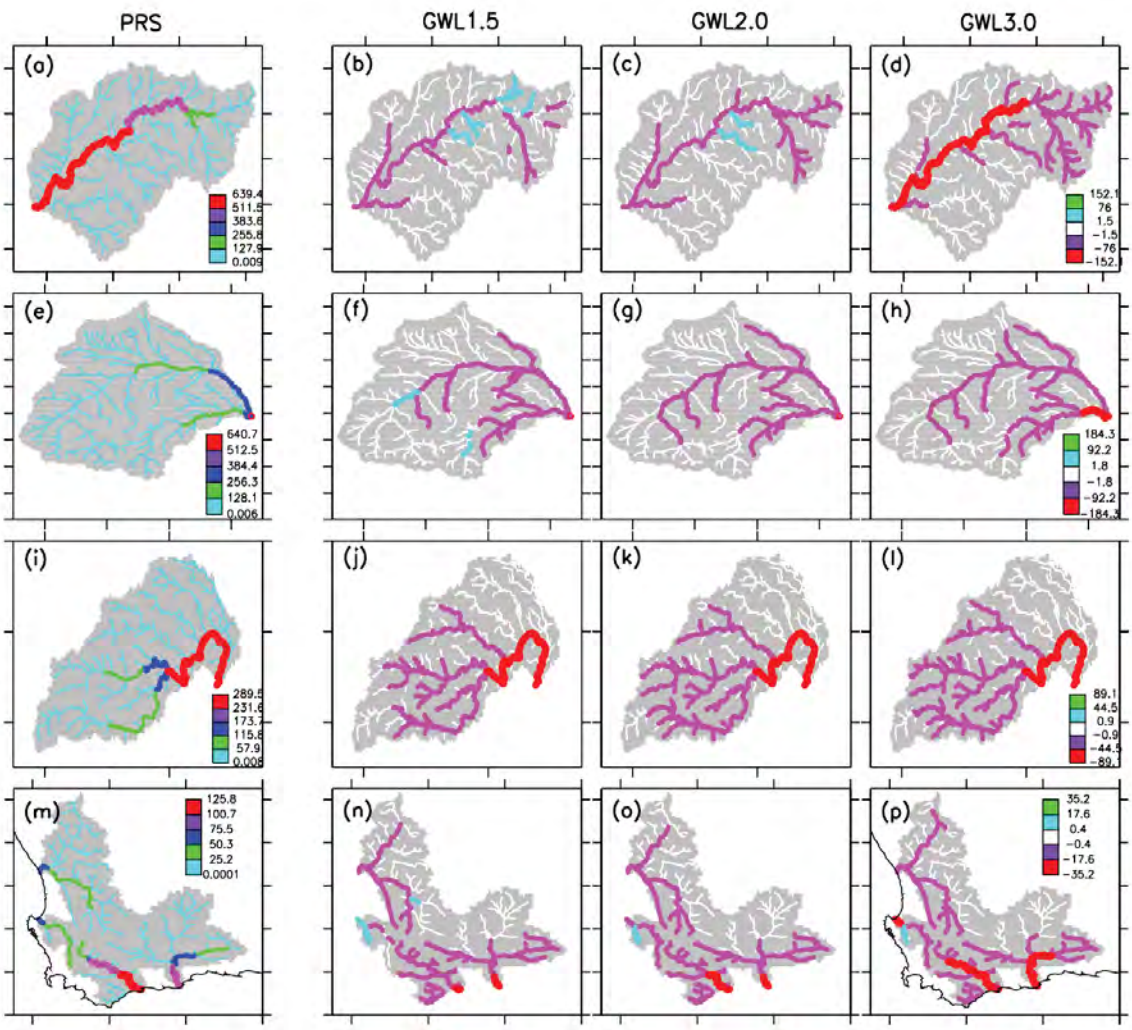


Figure A1: Same as Figure 4, but for extreme monthly streamflow (90th percentile).

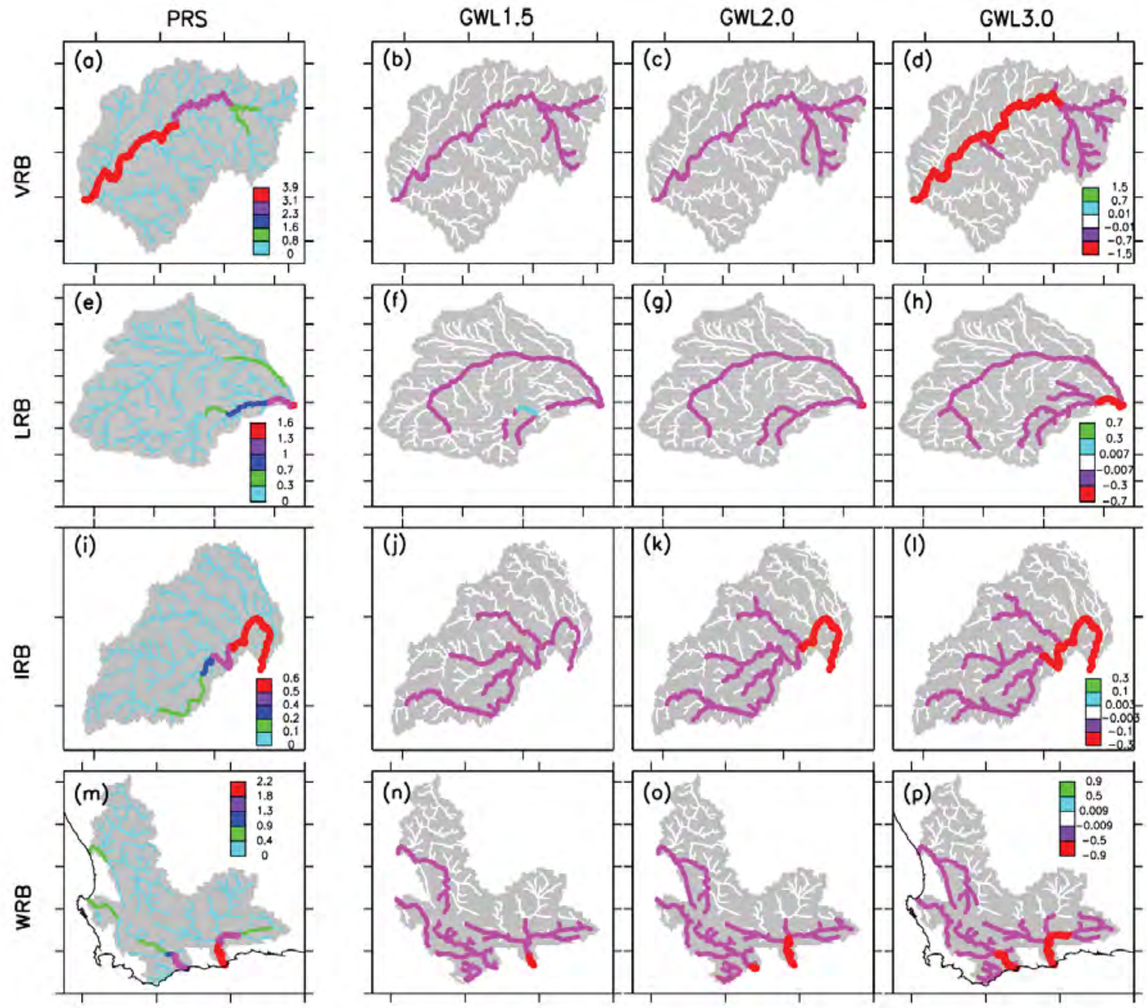


Figure A2: Same as Figure 4, but for extreme monthly streamflow (10th percentile).

Chapter 4

Fifty years of remote sensing of mapping and monitoring the impacts of global change on wetlands in South Africa

Heidi van Deventer [1,2*]

[1] Council for Scientific & Industrial Research
[2] Department Geography, GeoInformatics & Meteorology, University of Pretoria (UP)
* Corresponding author: HvDeventer@csir.co.za

Abstract: Nearly fifty years ago, in 1972, the first space-borne satellite image (Landsat–1) was launched, which marked a significant change in the ability to understand and report our wetlands. South Africa has a track record of forty years of using space-borne satellite images for the mapping and monitoring of lacustrine (open water) and palustrine (vegetated) wetlands. This chapter provides a review of published literature and some reports for mapping the areal extent of these wetlands, and which attributes can be detected to inform on the types and rates of changes, related to the ecological condition of wetlands, that occurred to date. Despite the fact that wetlands were found to be the most threatened ecosystem type of South Africa in all the National Biodiversity Assessments where it had been included, and that the majority of wetland extent are in fact palustrine, no operational remote sensing system is in place to report on this wetland biome. In addition, the ephemeral category of both lacustrine and palustrine wetlands requires particular attention to improve on the representation and monitoring of these wetlands. A substantial amount of funding for representative nodes within the South African National Wetland Monitoring Programme would likely address this massive gap.

Keywords: Earth observation; freshwater ecosystems; lacustrine; optical sensors; palustrine; radar

1. Introduction

In 2022, earth observation (EO) from a space-borne platform will celebrate its 50 years of existence. South Africa has a record of forty years of research and outputs in the use of space-borne satellite sensors in the detection, characterisation and monitoring of wetlands. According to the South African National Water Act (NWA), Act 35 of 1998, wetlands are defined as '… land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil' [1]. Wetlands include aquatic ecosystems that straddle the freshwater (rivers or inland wetlands) and estuarine realms in South Africa [2]. The International Union for Conservation of Nature (IUCN) recognises two types of natural wetland biomes, namely lacustrine (open water) or palustrine (vegetated), as well as the artificial wetland biome [3]. The areal extent of these two natural wetland biomes is used in reporting to the Sustainable Development Goal (SDG) Indicator 6.6.1.a [4,5] and targets for reporting to the Convention on Biological Diversity in 2030 and 2050.

Wetlands were found to be the most threatened ecosystem type in South Africa in both the 2011 and 2018 National Biodiversity Assessments (NBAs) [6,7]. Multiple anthropogenic pressures, such as changes to the hydrological regime, water quality, habitat transformation and habitat invasion, negatively impact wetlands, with climate change expected to exacerbate these existing impacts, which ultimately could contribute to the collapse of wetlands in South Africa [8]. Increasing temperatures associated with climate change are likely to increase evapotranspiration of wetlands, and combined with severe drought periods, are expected to reduce the resilience of wetlands to withstand anthropogenic and climate change pressures. Consequently, ecosystem services associated with wetlands will likely reduce [9]. While the benefits derived from wetlands may initially increase with their use, the ecological condition of the wetland will degrade with long-term use leading to the ultimate decline in the benefits and services derived from the wetland. The intensification of climatic pressures will multiply these existing anthropogenic pressures and result in irreparable or costly rehabilitation and/or restoration costs, to the extreme of wetlands collapsing.

South Africa has no official operational monitoring system in place to measure or track the ecological conditions of our natural wetlands over time. Currently, there are 157 728 polygons used to represent inland wetlands in the latest National Wetland Map version 5 (NWM5), compared to the 290 estuarine wetland polygons. Some of the number of inland wetland polygons, however, may require further division of units, or removal of slivers [10]. The operational cost of physically monitoring such a number of inland wetlands monthly, seasonal or annual basis is very expensive. But the change in the ecosystem threat status (ETS) and ecosystem protection levels (EPL) of inland wetlands is critical towards informing the NBAs and result of intervention efforts. For the NBA 2011 and NBA 2018, the ecological condition of inland wetlands therefore had to be modelled from ancillary data sets [11]. In contrast, river ecosystem types are monitored *in situ* for water quality parameters as part of the Department of Water and Sanitation's (DWS's) River Eco-status Monitoring Programme (REMP). A framework for the *in situ* biophysical monitoring of wetlands was funded by South Africa's Water Research Commission (WRC) [12] to inform the DWS's planned National Wetland Monitoring Programme (NWMP). This study, however, excluded the use of remote sensing technologies. Subsequently, the WRC funded a study on the contribution of space technologies, *i.e.* remote sensing or EO, to the NWMP [13][1]. The report indicates that EO plays an important role in the mapping and monitoring of wetlands globally and in South Africa. Although EO cannot distinguish the origin of pressures (anthropogenic or climatic) on wetlands, studies have shown that impacts observed in wetlands result predominantly from anthropogenic pressures, with climate change exacerbating these impacts [11]. EO technologies supplement *in situ* measurements through the quantification of natural phenomena at a leaf- to landscape scale at temporal intervals that could inform the rate of change over time.

Nearly 50 years ago the first space-borne satellite with the Landsat–1 sensor was launched. It was launched on 23 July 1972 from California in the United States of America (USA) and was called the Earth Resources Technology Satellite (ERTS-1). Later the satellite was renamed Landsat–1, the first of a series of Landsat sensors which, to date, have been remotely monitoring features on Earth. Since the launch of the first EO satellite, three distinct periods of space-borne remote sensing could be distinguished: (i) the first period during which space-borne images were costly to acquire; (ii) the second period during which the images became increasingly accessible to the public; and (iii) the third period, characterised by the fourth industrial revolution (4IR) of technologies. In the first period satellite images were sold as proprietary items and very costly for South Africans to acquire. Images from the Landsat and *Satellite Pour l'Observation de la Terre* (SPOT) sensors were acquired for South Africa through a consortium of public and private institutions, sharing the cost of the images. The second period was characterised by the development and release of space-borne satellite images to the public via Google Earth (https://en.wikipedia.org/wiki/Google_Earth) from about 2001 onwards. Although the access was initially costed, the company Keyhole Inc, increasingly made satellite images available to the public and even people without any remote sensing training were able to access and use the images for viewing and mapping wetlands across the world. This period concluded with the United States Geological Survey (USGS) releasing 30 years of Landsat Archive images which has enabled a significantly amount of work in wetland detection and monitoring globally in 2008 publicly [14]. The third period commenced soon hereafter, with 4IR technologies becoming readily available for use [15]. Firstly, two proprietary sensors marked a change from the traditional four-band sensors to a red-edge band at a fine spatial resolution of ≤5 m. These included the RapidEye sensor launched on 29 August 2008, and the WorldView–2 sensor launched on 8 October 2009. Several studies at leaf-level scale provide the value of improved estimation of vegetation health, above-ground biomass (AGB) and mapping plant species using the red-edge band. In addition, cloud-computing capabilities such as the Google Earth Engine (GEE) platform, which has the ability to replicate the process of larger geographic extents and time-series data through online servers, became available in 2010 [16]. In

[1] Co-funded by the Council for Scientific & Industrial Research (CSIR)

addition, the temporal frequency of reporting has increased from the 16-day revisit cycle of Landsat to almost weekly cycle of the Sentinel–2 sensor.

This chapter aims to provide an overview of the use of space-borne satellite images for the detection and monitoring of South African wetland types and their characteristics over the past fifty years. The period overlaps with the WRC's 50 years celebration of work it has funded in the remote sensing of wetlands. Examples are provided on the monitoring of the two natural wetland biomes, namely lacustrine and palustrine wetland biomes across two respective sections in the chapter. Where relevant, examples of the remote sensing of wetlands in the artificial wetland biome or estuarine realm are also provided since these have relevance to the capabilities of the remote sensing of inland wetlands too. The following questions were addressed in this review:

(i) How has space-borne remote sensing contributed to the delineation and mapping of the areal extent of each wetland biome in South Africa?
(ii) Which attributes of the wetland biome can currently be detected for South African wetlands?
(iii) Are there any operational remote sensing systems in place or in development to inform the NWMP South Africa?

It is the intention with this review is that South Africans obtain a broad overview of the capabilities of remote sensing for monitoring wetlands. Literature cited in this review include only peer-reviewed journal articles papers in reputable journals, as well as reports funded by the WRC.

2. The lacustrine wetland biome of South Africa

The lacustrine wetland biome is defined by the IUCN global ecosystem typology as follows: "The Lakes biome includes lentic ecosystems defined by their still waters. They vary in area, depth, water regime, and connectivity to other aquatic systems across a global distribution. Gradients in water regimes, temperature, lake size and salinity exert critical influences on the function, productivity, diversity, and trophic structure of lake ecosystems. Water regimes vary from permanent open waters to seasonal or episodic filling and drying on inter-annual time scales." [3, p68]. The biome is further divided into Ecosystem Functional Groups (EFGs) based on their size and hydroperiod class, while also including artesian springs and oases, geothermal pools and subglacial lakes [3].

The size of wetlands in South Africa are relatively small and the depth shallow compared to those in the tropics and Americas [13,17]. The South African *Classification System for Wetlands and other Aquatic Ecosystems* [18,19] uses a hydrogeomorphic (HGM) approach to classification and distinguish between the lacustrine and palustrine type only at the lower levels of the tiered *Classification System for Wetlands and other Aquatic Ecosystems* as descriptors and not as biomes. In addition to the deeper lacustrine wetlands defined by Cowardin et al. (1979), South Africa also includes shallower lacustrine systems. Therefore, depending on the depth of a lacustrine wetland, it can be typed as either a lake or limnetic lacustrine wetland (≥2 m inundated to a maximum depth at the average annual low-water level of an open waterbody) or a littoral lacustrine wetland (<2 m) [18,19]. The most recent NWM5 shows that only 11% of the areal extent of wetlands are lacustrine (Figure 1), and only eight limnetic depressions or freshwater lakes occur in South Africa, while the rest are predominantly shallow [10]. The hydroperiod of lacustrine wetlands are determined based on their areal extent and duration of inundation [18]. Three categories of the hydroperiod are used in South Africa, namely permanently inundated if more than nine months in a year, seasonally (3 – 9 months) and intermittently (<3 months) inundated [18,19].

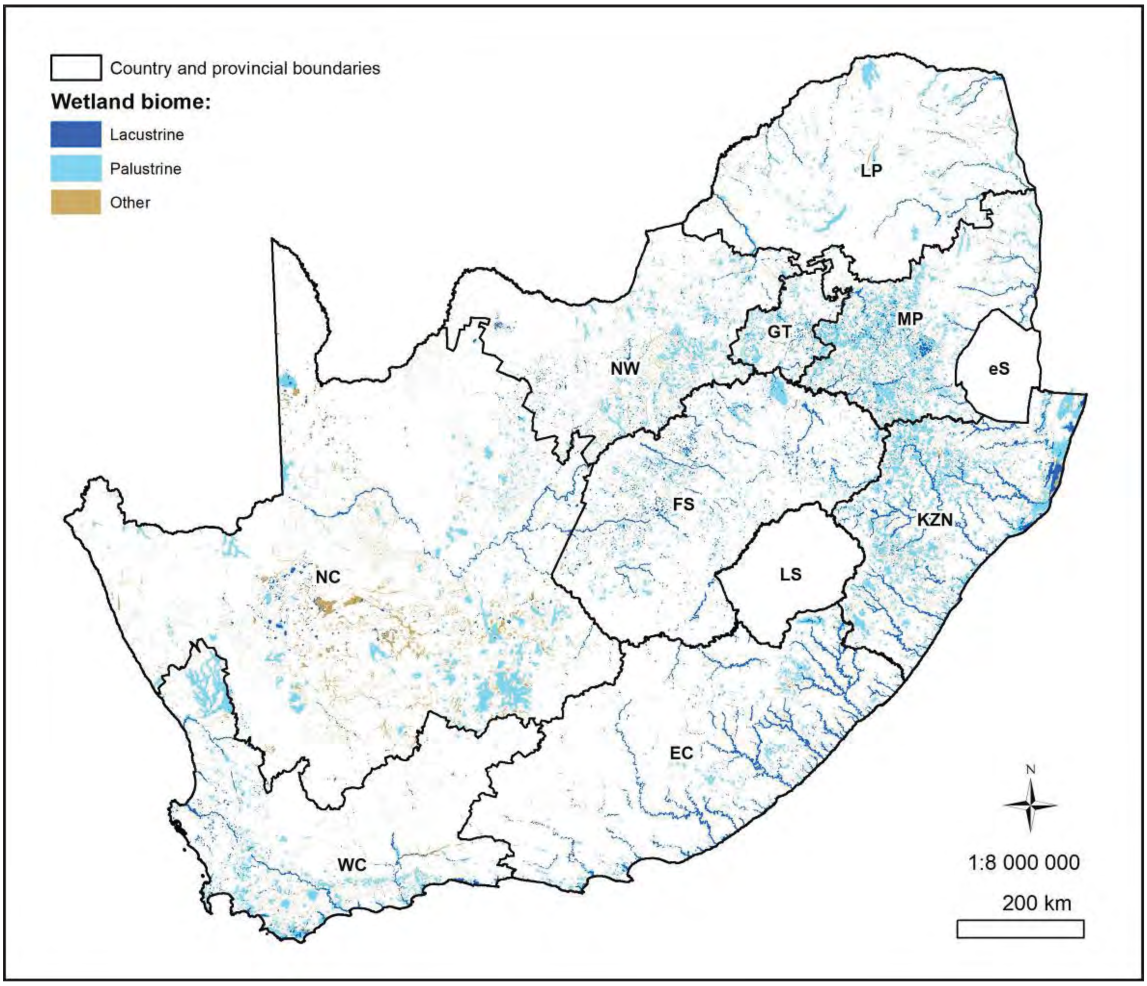


Figure 1. National Wetland Map version 5 displaying inland wetlands as lacustrine, palustrine or other wetland types.

The following two subsections will demonstrate the value of space-borne remote sensing and images in the mapping and monitoring of lacustrine wetlands, providing more information on attributes related to water quantity (the areal extent, depth, hydroperiod) and attributes related to water quality.

2.1. Delineation and mapping water quantity information of South African lacustrine wetlands

South Africa's highly variable rainfall pattern implies that the maximum extent of lacustrine wetlands, the parameter to spatially represent in the NWMs, as well as the hydroperiod should be determined from multi-season images. Historically, aerial photography flown for topographical map production in South Africa was done in the dry season to ensure the least amount of cloud cover and the best view of physical features [17]. This resulted in the minimum extent of wetlands detected and mapped. In addition, if these photographs were taken in times of drought, it would further result in the omission of wetlands represented on the topographical maps. Initially, the land cover products of South Africa of 1996 and 2000 suffered similar omissions because SPOT and Landsat images from dry season imagery were use. Regardless of the limitations, the water and wetlands categories mapped in the South African National Land Cover (NLC) products to date have made a significant contribution to the mapping of the aerial extent of lacustrine wetlands and quantifying changes in these wetlands over the years [20-23]. Aside from the omissions resulting from using a limited number of images over the hydrological cycle and particularly the wet season, the coarse spatial resolution of the Landsat images (30 m) resulted in the omission of small wetlands [24,25]. In fact, De Roeck et al. (2008) indicated that only 12% of the number of small wetlands in the arid region of South Africa (north of Cape Town to Saldanha Bay and from the west coast inland to Tulbagh) could be detected with Landsat, while 73% of the number of wetlands were smaller than the minimum mapping unit of Landsat (< 0.081 ha), and another 15% was subjected to the edge-effect of spectral reflectance of adjacent land cover types. The study then compared the capabilities of the optical Landsat images to map lacustrine wetlands to those of the Envisat Advanced Synthetic Aperture Radar (ASAR) radar (C-band HH[2]-polarised) images, at a pixel size of 12.5 m spatial resolution, and found that Envisat ASAR detected fewer wetlands than Landsat.

After 2010, in the third period of space-borne technologies, the spectral, spatial and temporal resolutions of images used for land cover classification improved. Provincial and national land cover data are now derived from multi-seasonal Sentinel–2 images at a 20 m spatial resolution, such as the NLC 2018 [26]. The Sentinel–2 sensors (A&B) also increased the temporal frequency of freely available satellite images from the bimonthly images of Landsat to four to six images per month in South Africa, which increases the opportunity of minimising cloud cover. In addition to the improvements of spatial resolution, the accuracies of indices used for detecting South African lacustrine wetlands, and even the inundation extent of some river systems are still being tested in South Africa [27].

2.2. Monitoring changes in areal extent and deriving hydroperiod information for South African lacustrine wetlands

The free accessibility of the Landsat Archive from 1984 until 2015 has revolutionised the ability to monitor changes in the areal extent of lacustrine wetlands globally [28,29]. The Global Surface Water (GSW) product used the Landsat archive to produce initially annual, but later also monthly, inundation extent of wetlands and information at a global scale [28]. Subsequently, the use of Sentinel–2 images (sensor A launched 23 June 2015 and B on 7 March 2017) were used to continue with the monitoring, though these images were resampled to Landsat's 30 m spatial resolution to ensure consistency across the last forty-year reporting

[2] HH = Horizontal transmission and received beam.

period. The areal extent of South African lacustrine wetlands mapped by the GSW totals 209 km² while 2,787 km² of the comparable open water bodies classes were mapped in NLC 2013 [5]. With the use of the open water mapping indices, changes in South Africa's lacustrine wetland extent have now been calculated globally, country-wide, and by catchment scales [28,30,31]. Irrespective of the satellite images and indices used, a consistent negative trend in the areal extent of South African wetlands over different periods of time was observed [28,30,31]. Further work is required to determine the consistency of these measurements against indices of drought and whether the changes observed were not related to natural variation in wetland vegetation cover [5].

The maps of lacustrine wetlands derived from remote sensing provides insight into the natural variation of the hydrology of South African wetlands. The first study, looking at estimating hydrological regime changes in lacustrine wetlands in South Africa, was for Soetendalsvlei within the Heuningnes Estuarine Functional Zone (EFZ) in the Western Cape Province [32]. A total of 100 Landsat–5, –7 and –8 images were used for a seasonal time series analysis of the inundation regime of the wetland. Despite the regular 16-day temporal frequency of the Landsat series, cloud cover inhibited a continuous series of observations. Significant annual and seasonal variations in the areal extent of wetland inundation were observed between 1989 and 2017. The spring season showed the highest average and maximum lake inundation, while the autumn season the lowest median values. Interestingly, Mazvimavi [32] derived the areal extent of the wetland highlighting it was permanently inundated, covering 5.8 km² or 34% of the total wetland area, while the remaining 52% of the wetland is seasonal and the remaining 14% intermittently inundated, not accounting for parts that are palustrine in nature.

Time series analysis of inundation has also informed the temporal variation of open water pools for four rivers in the arid Karoo region of South Africa, including the Tankwa, Touws, Breede and Nuwejaars rivers [27]. The classification of these lacustrine pools within the riverbed with Landsat (resampled to 15 m) and Sentinel–2 (10 m spatial resolution) images were compared to monthly rainfall data between 2016 and 2017.

The Mzansi-Amanzi Web Map Viewer (MAWMV) (https://www.water-southafrica.co.za/) is an operational interactive viewer showing the areal extent of wetlands mapped at a country-wide scale for South Africa. The areal extent and statistics lacustrine wetlands are derived from Sentinel–2 images at a 20 m spatial resolution using the GEE platform, that is considered to be a 4IR cloud computing tool [33]. Monthly sample data of the MAWMV illustrates the value in understanding the hydroperiod of the Chrissiesmeer catchment relative to the rainfall and are valuable for SDG and biodiversity reporting [13,34]. Such detailed monthly extent of lacustrine wetlands is available from the MAWMV to subscribed users.

The hydroperiod categories of depressions in the Mpumalanga Lakes District (quaternary catchment W55A), around Chrissiesmeer in Mpumalanga was assessed using sample data derived from the MAWMV [13,34]. The monthly inundation of 416 depressions in this catchment between January 2016 and May 2018 was obtained from GTI as a free sample data set. The results of the analysis showed that only 11% of the total number of depressions (416) were lacustrine, while the others were palustrine (74%), or a mixture of the two (15%). In contrast, the lacustrine depressions covered a larger areal extent than the palustrine depressions, covering 66% of the total areal extent of all depressions, while the palustrine depressions made up only 15% and the mixed category 19%. A comparison between the hydroperiod category derived from the MAWMV data according to the *Classification System for Wetlands and other Aquatic Ecosystems* (permanently, seasonal and intermittently) to those of the topographical map categories, showed a 61% correspondence in hydroperiod classes. The remote sensing data, therefore, has potential for monitoring a large portion of the MLD depressions and contribute to improve hydroperiod classification of these depressions, though cloud cover still hampers the accurate variation in inundation for the wetlands.

GeoTerraImage (GTI) now also collaborates with EkoSource Insight to operationalise and report monthly changes in South Africa's lacustrine wetlands to the MAWMV and http://sbdvc.ekodata.co.za/ websites. This service is now termed the *South African National Water Quantity Information System.* The full dataset can be obtained from the South African National Space Agency (SANSA), Directorate: Earth Observation (Information provided by Cornelia Höll <CHoll@ekosource.co.za> via e-mail on 17 Mar 2021). At the end of July 2021, Mzanzi Amanzi version 2, derived from the combination of Sentinel–1 radar and Sentinel–2 optical data, was made freely accessible to the public. The inclusion of the radar data is likely to minimise the limitations of the optically-derived data of version 1.

Over the three periods of development of remote sensing for mapping lacustrine systems in South Africa, the advances have clearly enabled faster mapping and reporting of the maximum areal extent and changes over time in the areal extent of lacustrine wetlands. Initially the topographical maps were produced as a hardcopy series every 20 years: in the 1960s, 1980 and 2000, with individual maps updated now online as they are produced. The countrywide NLCs were produced in 1996, 2000, and then 2013, 2018, with provincial updates produced more frequently in the past five years. Now in the 4IR period we see the increased use of GEE in the mapping and monitoring of lacustrine wetlands, using automated machine learning algorithms across multi-seasonal images, which speeds up the improvement of map production and reporting.

2.3. Water quality information derived from space-borne satellite images for South African lacustrine wetlands

Water quality information is derived from space-borne satellite images reporting on the nutrient and sediment status of relatively larger and deeper lacustrine wetlands of South Africa [35]. The images record the reflection values of cyanobacteria and algae for each pixel and, depending on the amount of chlorophyll-*a* mass per cubic metre and species, reflection values would increase around 681, 709 and 753 nm [36] or change position across narrow spectral bands of the visible part of the electromagnetic spectrum. These pixel values in the image are used to predict the eutrophication status of these wetlands as oligotrophic (0–10 mg m^{-3}), mesotrophic (10–20 mg m^{-3}), eutrophic (20–30 mg m^{-3}) or hypertrophic (>30 mg m^{-3}) [37].

Historical data from the Medium Resolution Imaging Spectrometer (MERIS) satellite (260 x 290 m spatial resolution) between 2002 and 2012 has been used to inform the eutrophication status and phenology of the blooms for 50 large lacustrine wetlands in the country. MERIS offered repeat visits to South African sites every 3-5 days, with 15 narrow bands between the visible and shortwave infrared (SWIR). Owing to the coarse spatial resolution, only 50 of the 497 large water bodies (with > 1 million m^3 capacity) could be detected by MERIS [37]. Trends were limited to 2005 and 2011 because of missing data between 2002 and 2004 and incomplete recordings in 2012. The fifty lacustrine wetlands reported on included 45 were artificial wetlands, three of the eight freshwater lakes (Barberspan, Chrissiesmeer and Lake Sibaya) and two open water bodies in the EFZs [36]. The latter includes Lake Kuhlange (now Lake Nhlange), the largest of the Kosi estuarine lakes in the Kosi EFZ, and Lake Msingazi, historically part of the Richards Bay estuarine lake system which has been modified by a weir at its outlet to be a freshwater coastal lake falling within the uMhlathuze EFZ. The results of the MERIS study showed that two of the three estuarine lakes, Barberspan and Chrissiesmeer were severely impacted, but also interestingly that the phenology of blooms at Chrissiesmeer differed from other lacustrine systems reported on [36].

Subsequently, an online, operational and near real-time reporting system was developed to enhance the DWS National Eutrophication Monitoring Programme (NEMP), with research and development funded by the WRC since. The Cyanolakes operational remote sensing system (https://online.cyanolakes.com/, launched in July 2018), and a newly developed CyanoLakes Mobile Application (November 2020), now informs a number of stakeholders ranging from DWS to the tourism industry on the monthly variation in water quality of 103 lacustrine wetlands of which 102 are situated within South Africa and one in Swaziland (Figure 2). The Sentinel-3 Ocean and Land Colour Instrument (OLCI) has been used since 2016 [38] to report on the status of these wetlands in South Africa (Figure 2). The updated areas include a total of 92 artificial wetlands, five estuaries, and six freshwater ecosystems. For the freshwater ecosystems, four of the eight freshwater lakes (also including Groenvlei), as well as Eilandsmeer and Leeupan are monitored. A total of five wetlands within the EFZs are monitored monthly, with the additions of Lake Cubhu (historically linked to the uMhlathuze Estuary, but now a freshwater lake within the EFZ), Lake Nhlabane (similarly historically connected with the iNhlabane Estuary and in the iNhlabane EFZ) and Upper Langvlei in the Touw/Wilderness EFZ. Trends in water quality have shown that four of South Africa's largest reservoirs (Bronkhorstspruit, Hartbeespoort Dam, Roodeplaat Dam and the Vaal Dam), providing water for potable and irrigation uses, are regularly hypertrophic [39].

Remote sensing enabled the quantification of the spatial variation of water quality across the lacustrine wetlands. DWS through the NEMP collects water samples for 160 dams, lakes and rivers across the country, which are then analysed in laboratories [36]. These water samples are collected at particular points along the wetlands and rivers, and although it provides more detailed information on water quality [40], it lacks information on the spatial variation across a wetland. Therefore, remote sensing supplements the *in situ* NEMP monitoring system to fill in information gaps. Multiple platforms facilitate now the distribution of the information via Twitter (https://twitter.com/CyanoLakes), and the free mobile apps for iOS (https://apps.apple.com/za/app/cyanolakes/id1537355837) and Android (https://play.google.com/store/apps/details?id=com.CyanoLakes).

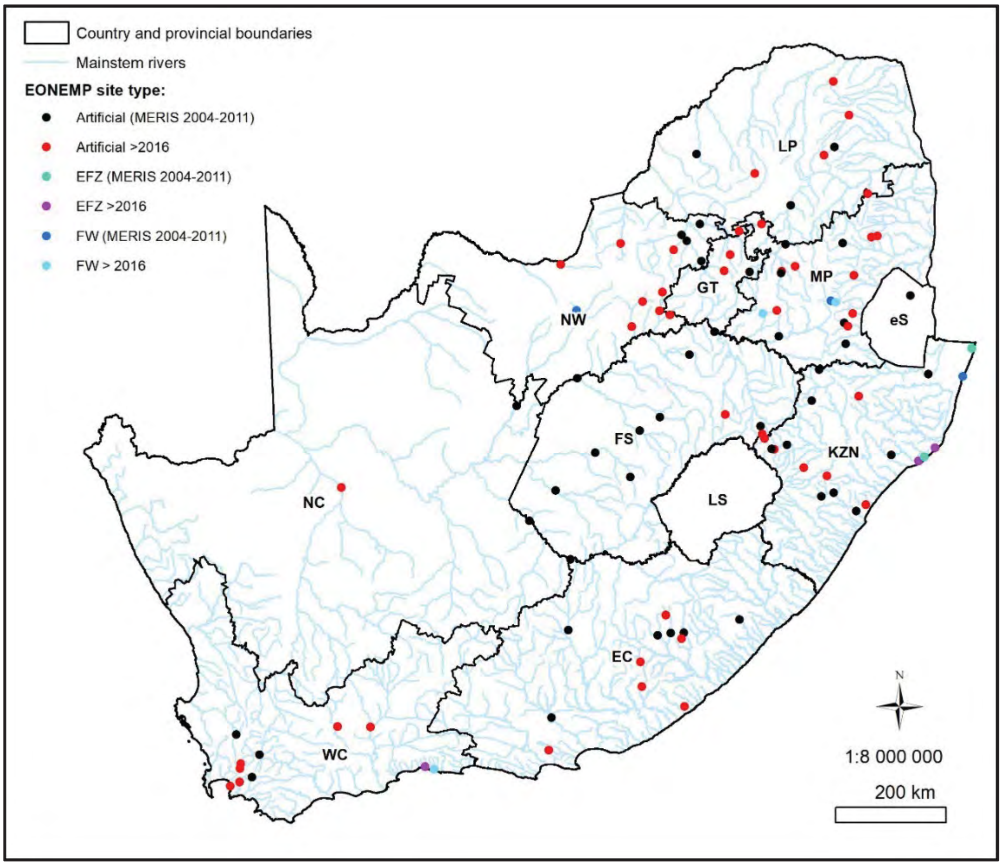


Figure 2. A total of 103 lacustrine wetlands are being monitored on an ongoing basis by Cyanolakes for their eutrophication status (Matthews 2014; Matthews & Bernard 2015). Of these, 50 wetlands were already monitored between 2004 and 2011 with the MERIS. Currently, a total of 92 artificial wetlands, five estuaries, and six lacustrine wetlands are being monitored with the Sentinel–3 sensor. Abbreviations for countries and provinces: EC: Eastern Cape; eS: Kingdom of eSwatini; FS: Free State; GT: Gauteng; KZN: KwaZulu-Natal; LP: Limpopo; LS: Lesotho; MP: Mpumalanga; NC: Northern Cape; NW: North West; WC: Western Cape. The list of the 2013 waterbodies were provided by Dr Matthews to the author on 30 May 2016 and corresponds to those of [38].

The refinement of the spatial resolution of reporting remains of interest, with the optical Landsat Operational Land Imager (OLI) or Landsat–8 pan sharpened to 15 m spatial resolution showing promising results for the Vaal Dam, despite having only seven bands between the visible and SWIR and a 16-day repeat cycle [41]. In another study, the Landsat–8's (30 m spatial resolution) blue-green band ratio and red/NIR of Sentinel 2 (at 10 m spatial resolution) also showed promise for monitoring of the Vaal Dam [42]. The OLCI on the Sentinel–3 sensors, with improved signal-to-noise ratios, records reflectance for 21 bands between the visible and near infrared (NIR), at a 300 m spatial resolution [39]. Two of the four sensors, named A-D have already been launched: Sentinel–3A in February 2016 and Sentinel-3B in April 2018. Sentinel-3C is scheduled for launch sometime in 2021. These satellite images are currently being validated, while improvements in estimating the variation in plant species and their phenologies are also under way [38,39,43].

2.4. Mapping invasive species from space-borne satellite images for South African lacustrine wetlands

The first mapping of invasive species in South African lacustrine wetlands with space-borne satellite imagery that could be found was done in the Greater Lethaba River [44,45]. The overall accuracy resulting from the image classification of water hyacinth (*Eichhornia crassipes*) showed that the Sentinel–2 sensor outperformed the Landsat–8 (30 m) image classification by 10%, with the former achieving 78% and the latter 68% [45]. Using Sentinel–2 at a 10 m spatial resolution, the authors found a minor difference of 1% in the classification accuracies across the wet and dry seasons [44]. The spectral confusion between hyacinth and other floating vegetation remains a challenge [45].

3. The palustrine wetland biome of South Africa

Palustrine wetlands “include vegetated floodplains, groundwater seeps, and mires with permanent or intermittent surface water” [3, p. 53]. According to the typology described by the USA in 1979, palustrine wetlands include “ … all nontidal wetlands dominated by trees, shrubs, persistent emergents, emergent mosses or lichens … .” [46]. In the IUCN typology, EFGs under the palustrine biome are further divided according to climatic regions (tropical, subtropical-temperate and arboreal), vegetation structures (trees or graminoids) and hydroperiods (permanent, seasonal or ephemeral) [3]. A total of seven EFGs are described for the palustrine wetland biome, with codes typifying the categories where “TF” indicates the terrestrial-freshwater transitional realm: TF1.1 Tropical flooded forests and peat forests; TF1.2 Subtropical/temperate forested wetlands; TF1.3 Permanent marshes; TF1.4 Seasonal floodplain marshes; TF1.5 Episodic arid floodplains arid floodplains; TF1.6 Boreal, temperate and montane peat bogs; and TF1.7. Boreal and temperate fens. Within South Africa, only four of these seven EFGs exist, namely, TF1.2, TG1.3, TF1.4 and TF1.5). The tiered South African *Classification System for Wetlands and other Aquatic Ecosystems* distinguish at the sixth level of the typological framework, vegetation types such as aquatic, herbaceous, shrub/thicket and forest, and even allow for further subdivisions [18]. Initial estimations in the NWM5 show that about 55% of South Africa’s wetlands are palustrine (Figure 1).

The occurrence of plant species is one of the essential biodiversity variables (EBVs; Table 1) that remote sensing can contribute to mapping and monitoring of the palustrine wetland biome over time [47]. Historically, the areal extent of palustrine wetlands was poorly separable from terrestrial vegetation, with traditional four-band (having bands only in the red, green, blue and near infrared regions of the electromagnetic spectrum), and coarse spatial resolution satellite images that resulted in poor classification accuracies of plant species or groups. This was primarily attributed to the limited number and broad regions of the four traditional bands and coarse spatial resolutions (≥30 m) that resulted in the omission of small and narrow wetlands, typical of the size and shape of the majority of South Africa’s wetlands. Regardless, South Africa has a research track record on the remote sensing of palustrine wetlands spanning forty years, starting from the first study where Landsat–1 was used, to the most recent using the Sentinel and WorldView sensors. Several studies have informed the capabilities of optical and radar sensors in mapping the aerial extent, structure and function of palustrine wetlands, which informs other EBVs, while mapping changes in land cover assisted in quantifying the geographic extent, types and rate of change. The following sub-sections will elaborate on some of the successes observed to date and challenges still to be addressed.

Table 1. Essential biodiversity variables associated with satellite remote sensing [47].

Ecosystem structure	Ecosystem function
• Ecosystem distribution • Forest cover • Fractional cover • Land cover • Vegetation height	• Above-ground biomass • Fire disturbance • Fraction of absorbed photosynthetically active radiation • Inundation[1] • Leaf area index • Soil moisture • Vegetation phenology

[1] *Associated with both the inundation hydrological regime of lacustrine wetlands and soil moisture hydrological regimes of palustrine wetlands.*

3.1. Delineation and mapping of the areal extent and types of South African palustrine wetlands

Most South African studies mapping the areal extent and types of palustrine wetland with satellite images have used a variety of vegetation species, groups or EFGs, because they appear as visibly separable objects on an image. In some instances, the areal extent of a single species dominates the canopy and forms a homogenous dense stand that can be easily delineated from an image, while adjacent to this object on the image, a mixture of species could be recognised as another distinguishable, habitat unit. As such, palustrine wetlands require representative 'Regions of Interest' (ROIs) or 'Area of Interest' (AOI) points or polygons in the classification for a particular region, as opposed a single index as in the case of the lacustrine wetlands. This imply that studies to date are limited in geographic extent and the results cannot easily be upscaled to a region or province.

The earliest mapping of wetland vegetation groups or communities in South Africa with space-borne imagery, was done in the Langebaan Estuary [48] using Landsat–1 (Table 2; Figure 3). About seven wetland vegetation communities and two lacustrine classes were combined with other land cover and terrestrial vegetation classes to predict 16 vegetation and land cover classes. Although an accuracy assessment had not been done, Jarman commented that it took only forty hours to predict the map on Landsat, compared to months of mapping these classes in the field. Yet fieldwork formed an essential component of the remote sensing modelling.

Table 2. Details of studies in South Africa where space-borne remote sensing was used for wetland mapping. Studies are listed first chronologically then alphabetically in the Citation column. The study number refers to the number reflected on Figure 3, whereas numbers under the sensors refers to the version of the satellite used. Abbreviations for provinces: FS = Free State; GT = Gauteng; KZN = KwaZulu-Natal; LP = Limpopo; MP = Mpumalanga; NC = Northern Cape; NW = North West; WC = Western Cape.

Study #	Site name and reference	Sensor(s)					Number of wetland vegetation classes	Details of palustrine classes uses and overall accuracy
		Landsat	Spot	RapidEye	World-View	Sentinel		
1.	Langebaan (WC) [48]	1					16	23 sub-classes, of which two are lacustrine, seven palustrine. These were consolidated into 16 classes using Landsat–1.
2.	Highmoor (KZN) [24]	1					N.A.	Wetland extents were predicted from a combination of land cover classification and deriving potential valley-bottom and floodplain extent from a Digital Elevation Model.
3.	Glengarry and Kamberg/Stille-rust (KZN) [24]	5						
4.	Walker Bay (Estuary, WC) [24]	5						
5.	Glenhart (WC) [24]	5						
6.	Betty's Bay and Hangklip (WC) [24]	5						
7.	Theewaterskloof dam (WC) [24]	5						
8.	Davel (MP) [24]	7						
9.	St Lucia (KZN) [49]		6	x	2		8	Eight habitat units (macroalgae; submerged macrophytes; reeds and sedges; mangroves; grass and shrubs; salt marsh; swamp forest; floating macrophytes). An overall accuracy of 64.3% was attained for SPOT–6 (2 m spatial resolution), 66.8% for RapidEye (5 m spatial resolution) and 77.9% for WorldView–2 (2 m spatial resolution).
10.	Western Cape palmiet wetlands [50]	1-3, &5					22	Changes in the aerial extent of Palmiet (*Prionium serratum*) was mapped using Landsat images attained across the ten scenes covering the study area. The overall classification accuracy is indicated in brackets after the respective Landsat series: Landsat–1 and –3 of the 1970s (65%); Landsat–5 images of 19802 (64%); Landsat–8 images for 2014 (58%).
11.	St Lucia (KZN) [51]			x			6+	Six wetland tree species (*Avicennia marina*, *Bruguiera gymnorrhiza*; *Ficus trichopoda*; *Ficus sycomorus*; *Hibiscus tilliaceus*; *Syzygium cordatum*) and additional classes (*Acrostichum aureum L;* Coastal lowland

								forest, East coast dune forest; *Phragmites australis/mauritanus;* seasonal wetlands & *Vachellia kosiensis*) were used in the classification attaining an overall accuracy of 86%.
12.	iSimangaliso Wetland Park (KZN) [52]					1 & 2		The classes mapped a terrestrial class, lacustrine wetland class, a wetland class without vegetation and nine palustrine wetland classes which are distinguished based on their vegetation height (high, medium, low) and hydroperiod (permanently flooded, temporarily flooded and permanently moist).
13.	Senary catchment areas around Hogsback (EC) and Tevredenpan (MP) [13]				3	2		For the Hogsback study area, the lacustrine wetlands were separately mapped from palustrine wetland groups (*Eragrostis* spp. & *Themeda* spp., *Andropogon* spp.; *Carex* spp.; *Ficinia* spp.; *Merxmuellera macowanii*; *Phragmites australis*; Sedge-dominant) and other land cover classes (bare soil, cropland, invasive tree species, felled plantations, planted plantations and mountain slopes). An overall accuracy of 82% was obtained for the Sentinel–2 classification compared to the WorldView–3 classification of 85%. For the Tevredenpan study area the lacustrine wetlands were distinguished from other palustrine wetland (*Eragrostis plana* & *Themeda triandra*; *Arundinella nepalensis*); *Aristida* spp.; *Carex* spp.; Grass-sedge communities; *Juncus effusus*; *Phragmites australis*; Sedge dominant (>20%); Wet-grass communities) and other land cover classes (bare soil, cropland, invasive tree species). An overall accuracy of 81% was obtained for the Sentinel–2 classification compared to the WorldView–3 classification of 77%.

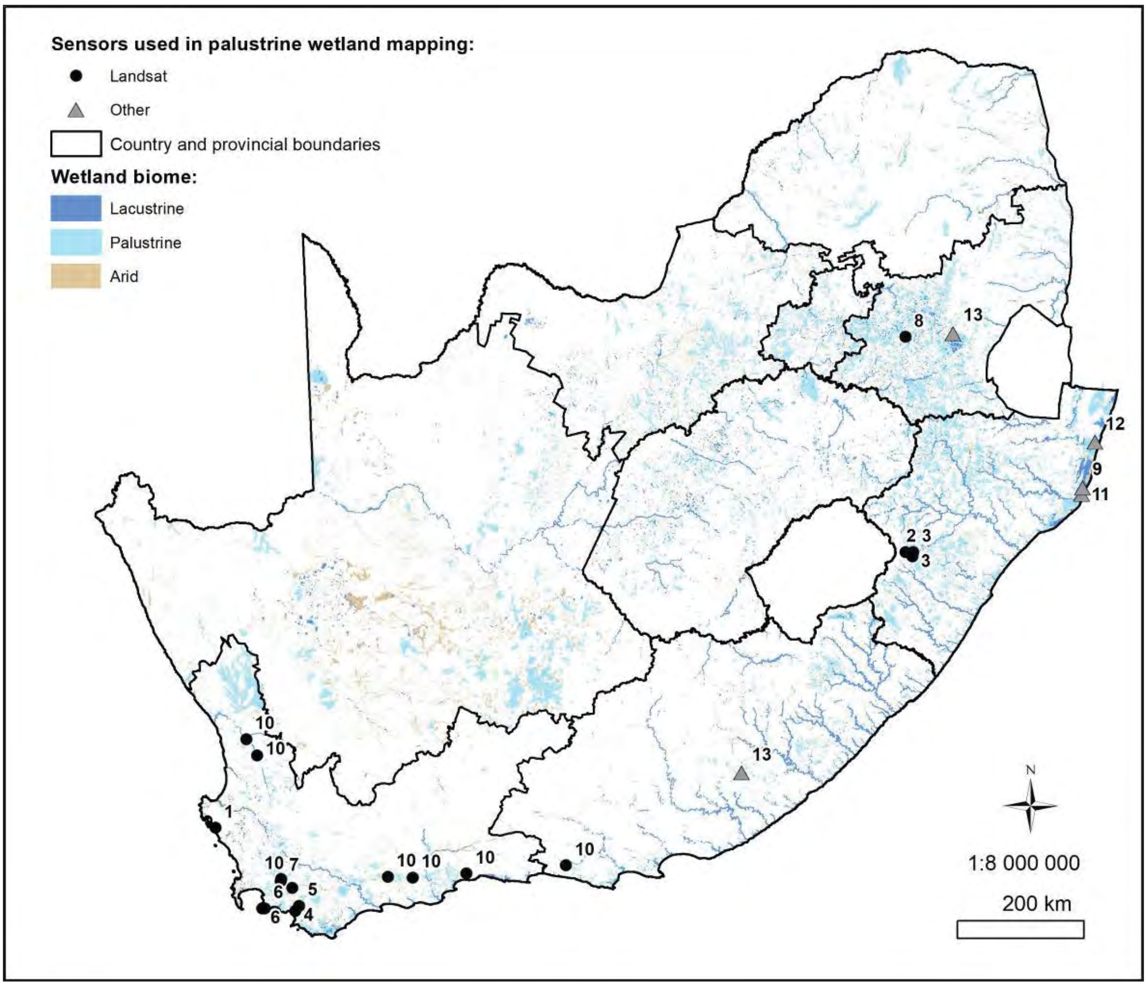


Figure 3. Studies investigating remote sensing of different palustrine wetland types in South Africa. Table 2 lists more details about each of the studies.

A second study published in 2002, used Landsat–5 Thematic Mapper (TM) and Landsat–7 Enhanced Thematic Mapper (ETM+) images for mapping wetlands in several study areas [24]. Three of the four broad areas were situated in the Grassland Biome, including Highmoor (KwaZulu-Natal Province), Glengarry/Kamberg (KwaZulu-Natal Province) and Davel (Mpumalanga Province), while the fourth area was an estuary (Walker Bay, Western Cape Province) (Table 2; Figure 3). The overall accuracy attained was > 72% for the inland sites and 87% for Walker Bay Estuary. For the Davel site, an overall accuracy of 84% was attained when the classification was enhanced with a probability index of wetlands that were derived from a Digital Elevation Model (DEM). The study found that several small and narrow wetlands were present at the sites which could neither be detected by the 30 m spatial resolution of Landsat, nor by the panchromatic enhanced 15 m spatial resolution images. In general, open water was easier to map than palustrine wetlands. A cost-comparison between manual mapping methods and the remote sensing classification of images, showed them to be closely comparable. Images were at stage still costly, and both SPOT and Landsat images had to be purchased at that stage. The suitability of remote sensing for inventorying also had to consider data storage capabilities and computer processing power at that time. Image processing software at that stage was primarily proprietary software requiring skilled and trained professionals [13].

In the St Lucia Estuary, WorldView–2, RapidEye, and SPOT–6 images between 2010 and 2014 were used to map eight habitat units (Table 2) in the estuary, attaining overall accuracies of 64.3% for SPOT–6 (2 m spatial resolution), 66.8% for RapidEye (5 m spatial resolution) and 77.9% for WorldView–2 (2 m spatial resolution) using parametric classifiers [49]. The possibility of mapping six wetland tree species (Table 2) and other dryland and estuarine-associated vegetation was also tested for the Maphelane and St Lucia nodes within the iSimangaliso Wetland Park, with the RapidEye satellite image and non-parametric classifiers, attaining an 86% overall accuracy [51,53].

The most recent areal extent of wetlands dominated by Palmiet (*Prionium serratum*), associated with small wetlands of < 5 km², was mapped using Landsat–8 (30 m spatial resolution and 11 spectral bands) from 2014 at a 30 m spatial resolution for valley-bottom wetlands in the Western Cape [50]. A mean classification accuracy across the ten scenes used to cover the study area attained 65%. For the first time citizen scientist observations were used from the iSPOT records (now iNaturalist https://www.inaturalist.org/) in the classification process. In comparison the earlier Landsat–1 to –3 and Landsat–5 (60 m spatial resolution and four spectral bands) used to classify the historical areal extent of Palmiet were considered less effective, achieving overall classification accuracies of 64% and 58%, respectively, across the ten scenes (Table 2; Figure 3).

More recently, the capabilities of freely available Sentinel–2 data (at 10 m spatial resolution) was compared to proprietary WorldView–3 (1.1 m spatial resolution) images in the mapping of wetland vegetation groups at senary (6th-level) catchments levels for Tevredenpan (Mpumalanga Province) and Hogsback (Eastern Cape Province) using non-parametric classifiers [13]. At Tevredenpan, eight palustrine wetland vegetation groups were separated from terrestrial vegetation and four land use classes (Table 2; Figure 3). For Hogsback, five palustrine wetland vegetation groups were separated from terrestrial vegetation, lacustrine wetlands and six other land use classes. A total of 165 in-field sample points for Hogsback and 164 for the Tevredenpan study areas were supplemented with AOIs from the image totalling 384 and 585 for each study area respectively. Firstly, the ability of the sensors to separate terrestrial and wetland vegetation was reported where a minimum overall accuracy of 91% and a maximum overall accuracy of 96% – 97% was attained by WorldView–3 and Sentinel–2 for both study areas. In addition, the lowest user's accuracy for an individual class was between 88% and 99%, implying that all classes were well separated from each other. WorldView–3 outperformed the Sentinel–2 image classifications in some instances with user's or producer's accuracies increasing up to 7% and was able to map more of the groups with smaller areal extents. However, WorldView–3 has a smaller areal coverage of 7 336 km² for a single tile and is costly, compared to Sentinel–1 and –2 sensors with a tile covering 10 00 km². The work therefore demonstrates that the freely available Sentinel–2 optical images have potential for monitoring palustrine wetlands in South Africa.

Interestingly, a study on the central and southern part of the iSimangaliso Wetland Park proved that the combination of multi-season radar Sentinel–1 and optical Sentinel–2 images maximised the classification accuracies of wetlands [52]. This is the first study of its nature in South Africa with a much larger geographic extent compared to previous studies (Table 2; Figure 3). The classification was based only on ancillary data collected and published by other authors in South Africa with no in-field validation done. The classification accuracies were reported at three levels:

(i) for separating permanent water from wetlands and terrestrial classes, an overall accuracy of 84% was obtained; (ii) for separating high-, medium-, low- and non-vegetated groups, an accuracy of 91% was attained, while separating permanently flooded areas from temporarily flooded and permanently moist areas, an overall accuracy of 82% was attained. The final product combines these classes, which is the closest to IUCN EFGs of the palustrine wetland biome that have been mapped in South Africa.

3.2. Monitoring changes in the areal extent of South African palustrine wetlands

To date, land cover change detection was used in South Africa to determine changes in the extent of wetlands over time. Two categories are used to assess changes in wetlands: the 'wetland' category (see [20]) for the definition as used in the land cover datasets) are used to distinguish palustrine wetlands from lacustrine wetlands (the 'water body' category) in remotely-sensed derived land cover classifications. The palustrine wetlands broadly include vegetated wetlands with graminoid and shrub cover, however, further distinction of different wetland vegetation groups is not possible, owing to the limitations of the coarse-scale sensors in distinguishing these. Several studies, as described in the paragraphs below, used these broad categories to detect changes in the habitat extent of palustrine wetlands. Habitat extent is one of the essential biodiversity variables of wetland ecosystems that could be detected with remote sensing (Table 1).

One of the first change detections done for lacustrine and palustrine wetlands were published for the north-eastern part of the Maputaland Coastal Plain in the KwaZulu-Natal Province surrounding eManguze [54,55]. Landsat–4 and –5 Thematic Mapper (TM) and Landsat–7 Enhanced Thematic Mapper (ETM) images at a 30 m spatial resolution between 1992 and 2008 were used to identify and map lacustrine, as well as permanently and temporary palustrine wetland, swamp forests and three other land use classes (urban, grassland and plantations). The areal extent of wetlands mapped for both the wet and dry season was classified as permanent wetlands while the others were typed as temporary. Three years were used for the change detection analysis. These years were 1992, a dry year, 2000 a wet year, and 2008 another dry year, based on the rainfall records. The 2008 classification results attained an 80% overall accuracy. A 100 x 100 m cell size was used for the comparison, based on the minimum mapping unit associated with Landsat images. The change detection between the resultant classifications of 1992 and 2008 showed an 11% decrease in palustrine wetlands and 7% increase in grassland. The study also highlighted that swamp forests were difficult to map with the Landsat images.

Further south on the Maputaland Coastal Plain, the changes that took place in a part of the uMfolozi Floodplain between 1997 and 2017 were determined using Landsat TM, ETM and OLI [56]. Eight land cover classes were used, including the water and wetland land cover classes that are related to the lacustrine and palustrine wetland biomes, respectively. The overall accuracies ranged from 79% to 88%, with an average of 83% for the seven images used across the 20-year period. The results showed a decrease in wetland extent by 14%, with a substantial increase in subsistence (notably after 2012) and commercial sugarcane farms being established in the area.

Changes in the areal extent of the wetlands dominated by Palmiet in the Western Cape Province was done for a period of 60 – 70 years, using the Landsat–8 classification of 2014 in comparison to aerial photography of the 1940s and 1950s [50]. The results showed that 55% of the areal extent of the Palmiet wetlands was lost, while the wetland perimeter of remaining patches, increased significantly by 29% over this period.

For the Maungani Wetland in the Limpopo Province, land use and land cover changes between 1983 and 2019 were also done using Landsat images [57]. The overall accuracy of the classification ranged from 78% to 93%. About a third of the wetland (31%) was lost by 2019.

Changes in the coastal swamp and floodplain forest (IUCN EFG TF1.2) of the Maputaland Coastal Plain between 2005 and 2017, using the provincial land cover datasets, also report losses for these palustrine wetlands [58]. The provincial land cover data of the KwaZulu-Natal Province from 2005, 2008, 2011 and 2017 with consistent comparable classes at a 20 m spatial resolution were used. Several limitations were found in using the land cover data for recording changes in these palustrine wetlands. On the one hand, the land cover data do not adequately represent the types of transformation that occurred within these wetlands. On the other hand, the rates of degradation, in comparison to a smaller well-mapped focus area, showed an underreporting of the degradation of these wetlands over time. The geographic distribution of different types of wetland degradation types and their rate of change remains a challenge in terms of been able to quantify them more accurately.

At a country-wide scale, the amount of change in the inland wetlands was represented in NWM5 in which the land cover date of 1990 and 2014 were compared [11]. The rate of loss of natural land cover within the wetlands were estimated at 0.3% per annum, with higher rates of loss found in floodplains (3.7% loss), seeps (3.8% loss) and valley-bottom (3.7% loss) wetlands, as opposed to the depression wetlands (1.2% change). The results again supported the findings of research reported earlier in this chapter, that the coarse-scale 30 m resolution data underreports wetland extent and subsequently, also the losses and degradation in these systems.

3.3. Mapping other essential biodiversity variables from space-borne satellite images for South African palustrine wetlands

Progress on the remote sensing of EBVs other than habitat extent (Table 1) is also discussed here and includes metrics that are descriptive to the functioning of palustrine wetland, namely AGB, phenology, soil moisture, fire disturbance and the hydrological regime.

AGB. The first estimation of wetland vegetation AGB was done for papyrus (*Cyperus papyrus*) vegetation sampled in the iSimangaliso Wetland Park (KwaZulu-Natal Province) using WorldView–2 images [59]. WorldView–2 images are provided at 2 m spatial resolution with eight bands, one being in the red-edge region of the EMS. The average fresh AGB was 3.4 kg/m² measured across 82 samples. A comparison was done between the traditional Normalised Difference Vegetation Index (NDVI) and an NDVI where two WorldView–2 bands, one in the red-edge and the other on the shoulder of the near infrared, were used to substitute the usual green and near infrared bands traditionally used in the NDVI. The results showed that the used of these WorldView–2 bands improved the estimation of AGB (where the coefficient of determination, R^2, = 0.7–0.8) and lowered the prediction error, compared to the traditional NDVI index (R^2 = 0.3), that is known to saturate at high AGB levels.

More recently, a study investigated the differences between wetland and terrestrial AGB in the Grassland Biome of South Africa, around Tevredenpan (Mpumalanga Province) and Hogsback (Eastern Cape Province) [13,60]. The results showed that the wetlands had significantly higher AGB in the palustrine wetlands (predicted average of 823 g/m² in the Tevredenpan and 605.9 g/m² in Hogsback study areas, respectively) compared to the terrestrial vegetation of both areas in the summer (predicted average of 421 g/m² in the Tevredenpan and 657 g/m² in Hogsback study areas, respectively). The lower AGB in the terrestrial vegetation could be attributed to the impact of burning terrestrial vegetation to promote grazing, and continuous grazing in these areas. In contrast, macrophytes (*Phragmites australis* and *Typha capensis*) and swamp sedge (*Carex acutiformis*) dominated in some of the palustrine wetlands and were not grazed, resulting in higher AGB during the summer. Using the bands (reflectance or polarisations) only, the Sentinel–1 radar combined with the Sentinel–2 optical data at an image spatial resolution of 20 m, attained a coefficient of determination (R^2) of 0.63, similar to that attained by the 1.1 m spatial resolution WorldView–3 optical images, with comparable error estimations.

Phenology: This has only been studied at leaf-level scale with hyperspectral data for parts of South Africa but not yet at canopy scale using space-borne satellite images [13].

Soil moisture: A study in the Colbyn Wetland Nature Reserve of the Gauteng Province showed that both Sentinel–1 and Sentinel–2 images can be used to estimate the spatial variation of soil moisture for this palustrine wetland [61]. The sensors attained a coefficient of determination R^2>0.9 with relatively low error estimations. Wetlands showed a mean observed Volumetric Water Count of 90.7% for wetlands and 20% for terrestrial areas measures in-field on 28 March 2018, with 75% and 6% recorded on 2 May 2018, respectively. The use of these Sentinel images for monitoring soil moisture content should be further explored for other parts in the Grassland Biome where the vegetation AGB are ≤1 kg/m².

Fire disturbance in peatlands: The capabilities of space-borne sensors for mapping various levels of degradation in peatlands that had previously became desiccated or had been burnt, were assessed at Lichtenburg, Molopo and Molemane in the North West Province [62]. The assessment was done for three scales of remote sensing, namely space-borne, unmanned aerial vehicles (UAVs, or drones) and ground level. The Landsat–7 and –8 images were used to determine changes in the peatlands between 1999 and 2018. Four indices, relating to vegetation, water and heat, were used to quantify the changes in the peatlands. The fire in the Lichtenburg and Molopo peatlands burnt in 2013 – 2014 and 2015 – 2016, respectively, following an observed decrease in the water index and increase in the land surface temperature indices in years prior to the active burn. NDVI, however, was not found to be a reliable indicator of the peat fires. The UAV complemented the space-borne image classification, particularly with a thermal sensor from where variation in temperatures could be determined at individual sites. The reflectance values between 350 and 2 500 nm were assessed in the laboratory to determine how the temperature of the soil changed when ignited. The report concluded with a framework on how the monitoring of burning peatlands can be facilitated at three levels: space-borne, airborne and ground levels.

Hydrological regime of palustrine wetlands: The hydrological regime of palustrine wetlands in South Africa has been limited, for several reasons. Firstly, the spatial resolution of available space-borne sensors for soil moisture indices monitoring was too coarse for the detection of palustrine wetlands, as reviewed by [13,61]. Secondly, it is likely that the current available space-borne optical and radar sensors can only detect soil moisture in the top 5 cm of the surface soil, or through association with the vegetation cover where AGB ≤1 kg/m². Thirdly, validation of this metric would require extensive monitoring across various gradients of soil moisture, for example in the Grassland Biome, to determine the accuracies and error estimations of relevant indices, and their reliability across months, seasons and years. Such an exercise requires a significant amount of funding and most likely collaboration across several organisations for execution. Fourthly, in areas where the wetland vegetation AGB exceeds 1 kg/m², particularly in forested wetlands, the use of currently available radar sensors are insufficient for determining either inundation of water under the canopy or soil moisture content. Other modelling of soil moisture values at regional scale were derived from coarse-scale remote sensing products.

Health indices for wetlands: Although this is not an EBV, some studies have used the variation in NDVI to determine overall health of a wetlands. For the Soetendalsvlei wetland in the Western Cape Province, NDVI was derived from the Landsat ETM and OLI sensors between 2014 and 2018 [63]. The severe decline in NDVI values were observed between 2015 and 2017, corresponding to the most recent decadal drought of the Western Cape Province. The use of the NDVI for wetland health assessments should be carefully considered, however. For example, some trace metals in mine water could promote vegetation vigour and result in high NDVI values [64], or not accurately reflect the variation of desiccation or burning of peat substrates across a wetland when a single value is reported for the whole wetland [62], while in other wetlands the NDVI value may saturate in the case of high AGB [65].

3.4. Mapping invasive species for South African palustrine wetlands

Remote sensing studies of invasive plant species in South Africa have been done at individual sites or catchment scales. Invasive species in catchments have significant impact run-off and therefore negatively impacts wetlands. Many studies have taken a terrestrial focus of the geographic extent of impact, with few quantifying impacts on wetlands explicitly. Furthermore, it was observed that many of the remote sensing mapping of invasive plant species done in South Africa focus on the mapping of a single invasive species [66]. In an attempt to address several current shortcomings in mapping the impacts of invasive plant species on wetlands and their water towers, a study in the headwater catchments of the Southwestern Cape (Western Cape Province), considered to be critical water towers, was done to assess the extent of invasive plant species *Acacia* spp., *Eucalyptus* spp. and *Pinus* spp amongst evergreen fynbos. Sentinel–1 and–2 dated images from January 2019 were used in the GEE platform, with sample points collected from infield validation with Global Positioning Systems, expert knowledge, and drone images. The latter was particularly flown for validating the extent in riparian areas. The outcome of four classification scenarios, predicting the areal extent of invasion in terrestrial and wetland areas, resulted in overall classification accuracies >74% for the invasive alien tree classes, yet challenges remained in improving the user’s classification accuracies of these invasive species.

4. Discussion and conclusion

Although remote sensing or EO technologies are not directly detecting the different impacts resulting from climate or anthropogenic changes in South African wetlands, they are critical for quantifying the areal extent of wetland ecosystems as well as the aerial extent, type and rate of degradation that takes place as a result of global change. Both lacustrine and palustrine wetland biomes, as used in the IUCN ecosystem typology and SDG 6.6.1.a reporting, have been mapped by space-borne satellite images in South Africa to date. The earliest published evidence of the use of Landsat–1 was for the Langebaan Estuary, where wetland vegetation types were mapped [48]. Subsequently, the number of studies, their geographic spread, and the types of space-borne sensors for mapping wetlands in South Africa have diversified. The advances in 4IR technologies have particularly accelerated the operationalising of viewers and online cloud computing, enhancing the ability to report changes globally and at a higher temporal frequency.

One of the biggest challenges faced in using space-borne remote sensing for monitoring South Africa's wetlands, are that they are predominantly palustrine in cover, or a mixture of palustrine and lacustrine. The remote sensing data sets indicate that about 11% of our wetland extent is lacustrine, and 55% palustrine, with 34% considered arid [5,10]. The arid biome reported for NWM5 should, however, be correctly retyped as either ephemeral lacustrine or ephemeral palustrine systems, according to the most recent IUCN typology [3]. Unfortunately, to date, an insufficient amount of information is available to improve the typology of these ephemeral wetlands. The GSW product does not detect any variation in inundation for these areas [5] most likely as a result of using coarse-scale optical sensors that are limited in detecting shallow levels of inundation.

Geographically, the regions where palustrine wetlands have been studied (Figure 3), shows a huge underrepresentation of the diversity of wetland vegetation in South Africa, compared to that reported in the National Wetland Vegetation Database [67]. More extensive funding would be required to cover the larger diversity of wetland vegetation in the country in which leaf-level, airborne-level and space-borne remote sensing research is applied. It is acknowledged that grey literature may be available at universities or reports from the private sector in which additional data and findings related to palustrine wetlands were reported, however, these studies require publication in peer-reviewed journals to ensure high quality outputs. Despite wetlands being the most threatened ecosystem type in the country, and wetlands being predominantly palustrine in nature, very little funding is channelled into improving remote sensing research on this wetland biome. Therefore, outputs produced remain mostly papers resulting from post-graduate studies at universities, or funding from the WRC, CSIR and ARC at this stage, with the geographic extent limited to site or small catchment scales. It is furthermore challenging to represent the diversity of wetland vegetation, their impacts and rates of changes using a single sensor, consistent classes or methods and equal temporal frequency across the country. Perhaps key focus areas need to be selected for the NWMP as soon as possible, where remote sensing products of palustrine wetlands can be developed and monitored over the long term. The options are to investigate hotspot areas from the NBA 2018 threatened wetland ecosystem types, and to consider the six Expanded Freshwater and Terrestrial Environmental Observation Network (EFTEON) landscapes, coordinated by the South African Earth Observation Network (https://efteon.saeon.ac.za/). More than six sites should be selected and a consortium of institutions formed that will be able to fund and sustain the monitoring required over time. These sites should also be supplemented with physical-based sampling of the palustrine wetlands, for example detailed floristic sampling of habitat units, to detect fine-scale changes.

The type and rate of degradation in the palustrine wetland biome and ephemeral lacustrine/palustrine wetlands are of high importance to further research with remote sensing technologies. Land cover products may not be adequate in representing the types and rate of changes for palustrine wetlands. NDVI is also too easily and coarsely used for reporting changes in palustrine wetlands, without understanding the limitations of the index, or measuring the response of vegetation to particular impacts. It is important that we try to improve the quantification of changes observed in a wetland or habitat unit relative to the natural, inter– and intra–annual cycles to be able to accurately identify extreme or deviations from these cycles.

Funding: This research was funded by the CSIR, as part of the Parliamentary Grant MarOPS in the 2021/22 financial year.

Acknowledgments: My gratitude is extended to Mr Steven Weerts from the CSIR for information about the estuaries, and Dr Mark Matthews (Cyanolakes Pty Ltd) for reviewing the water quality section. I am also thankful to Dr Lorren Haywood (CSIR) for reviewing the whole manuscript.

References

1. RSA. National Water Act, Act no. 36 of 1998. 1998*, 2010*.
2. Van Deventer, H.; Smith-Adao, L.; Mbona, N.; Petersen, C.; Skowno, A.; Collins, N.B.; Grenfell, M.; Job, N.; Lötter, M.; Ollis, D. *et al.* South African National Biodiversity Assessment 2018: Technical Report. Volume 2a: South African Inventory of Inland Aquatic Ecosystems (SAIIAE). Version 3, Final Released on 3 October 2019. *CSIR & SANBI* 2018, 195.
3. Keith, D.A.; Ferrer, J.R.; Nicholson, E.; Bishop, M.J.; Polidoro, B.A.; Ramirez-Llodra, E.; Tozer, M.G.; Nel, J.L.; Nally, R.M.; Gregr, E.J. *et al.* The IUCN Global Ecosystem Typology V1.01: Descriptive Profiles for Biomes and Ecosystem Functional Groups. *IUCN* 2020.
4. Department of Water and Sanitation, (DWS). Sustainable Development Goal 6 2020 Data Drive: South African Response to United Nations Environment Programme (UNEP). SDG Target 6.6 Indicator 6.6.1. Change in the Extent of Water-Related Ecosystems Over Time. *DWS*.
5. Van Deventer, H. Monitoring Changes in South Africa's Surface Water Extent for Reporting Sustainable Development Goal Sub-Indicator 6.6.1.A. *South African Journal of Science* 2021*, 117*, Art. #8806.
6. Driver, A.; Sink, K.J.; Nel, J.L.; Holness, S.; Van Niekerk, L.; Daniels, F.; Jonas, Z.; Majiedt, P.; Harris, L.; Maze, K. *National Biodiversity Assessment 2011: An Assessment of South Africa's Biodiversity and Ecosystems. Synthesis Report.*; South African National Biodiversity Institute and Department of Environmental Affairs: Pretoria, South Africa, 2012.
7. Skowno, A.L.; Poole, C.J.; Raimondo, D.C.; Sink, K.J.; Van Deventer, H.; Van Niekerk, L.; Harris, L.R.; Smith-Adao, L.B.; Tolley, K.A.; Zengeya, T.A. *et al. National Biodiversity Assessment 2018: The Status of South Africa's Ecosystems and Biodiversity. Synthesis Report*; SANBI: Pretoria, South Africa, 2019; pp. 228.
8. Snaddon, K.; Robinson, J.; Foden, W.; Van Deventer, H.; Van Rooyen, L.; Genthe, B.; Sieben, E. Chapter 3: Climate change – our changing environment from a freshwater ecosystems perspective. In *South African National Biodiversity Assessment 2018: Technical Report. Volume 2b: Inland Aquatic (Freshwater) Realm. CSIR Report Number CSIR/NRE/ECOS/IR/2019/0004/A. South African National Biodiversity Institute, Pretoria. Http://Hdl.Handle.Net/20.500.12143/6230.*; Van Deventer et al., Ed.; South African National Biodiversity Institute (SANBI): Pretoria, South Africa, 2019; pp. 104-127.

9. Kotze, D.C. Chapter 2: The ecosystem services provided by the Inland Aquatic Realm. In *South African National Biodiversity Assessment 2018: Technical Report. Volume 2b: Inland Aquatic (Freshwater) Realm. CSIR Report Number CSIR/NRE/ECOS/IR/2019/0004/A. South African National Biodiversity Institute, Pretoria. Http://Hdl.Handle.Net/20.500.12143/6230.*; Van Deventer et al., Ed.; South African National Biodiversity Institute (SANBI): Pretoria, South Africa, 2019; pp. 79-104.
10. Van Deventer, H.; Van Niekerk, L.; Adams, J.; Dinala, M.K.; Gangat, R.; Lamberth, S.J.; Lötter, M.; Mbona, N.; MacKay, F.; Nel, J.L. *et al.* National Wetland Map 5: An Improved Spatial Extent and Representation of Inland Aquatic and Estuarine Ecosystems in South Africa. *Water SA* 2020*, 46*, 66-79.
11. Van Deventer, H.; Smith-Adao, L.; Collins, N.B.; Grenfell, M.; Grundling, A.; Grundling, P.; Impson, D.; Job, N.; Lötter, M.; Ollis, D. *et al. South African National Biodiversity Assessment 2018: Technical Report. Volume 2b: Inland Aquatic (Freshwater) Realm.* CSIR report number CSIR/NRE/ECOS/IR/2019/0004/A. ed.; CSIR & SANBI: Pretoria, South Africa, 2019; pp. 456.
12. Wilkinson, M.; Danga, L.; Mulders, J.; Mitchell, S.; Malia, D. The Design of a National Wetland Monitoring Programme. Consolidated Technical Report. Volume 1. *WRC* 2016*, Water Research Commission (WRC)Report No. 2269/1/16*.
13. Van Deventer, H.; Naidoo, L.; Cho, M.A.; Job, N.M.; Linström, A.; Sieben, E.; Snaddon, K.; Gangat, R. Establishing Remote Sensing Toolkits for Monitoring Freshwater Ecosystems Under Global Change. Water Research Commission (WRC) Report no. 2545/1/19. *WRC* 2020, 241.
14. Welder, M.A.; White, J.C.; Loveland, T.R.; Woodcock, C.E.; Belward, A.S.; Cohen, W.B.; Fosnight, E.A.; Shaw, J.; Masek, J.G.; Roy, D.P. The Global Landsat Archive: Status, Consolidation, and Direction. *Remote sensing of environment* 2016*, 185*, 271-283.
15. World Economic Forum, (. Fourth Industrial Revolution for the Earth Series Harnessing the Fourth Industrial Revolution for Water. *World Economic Forum (WEF)* 2018, 26.
16. Gardner, T. Google Unveils Satellite Platform to Aid Forest Efforts. *Reuters* 2010.
17. Van Deventer, H.; Smith-Adao, L.; Petersen, C.; Mbona, N.; Skowno, A.; Nel, J.L. Review of Available Data for a South African Inventory of Inland Aquatic Ecosystems (SAIIAE). *Water SA* 2018*, 44*, 184-199.
18. Ollis, D.J.; Ewart-Smith, J.L.; Day, J.A.; Job, N.M.; Macfarlane, D.M.; Snaddon, C.D.; Sieben, E.; Dini, J.A.; Mbona, N. The Development of a Classification System for Inland Aquatic Ecosystems in South Africa. *Water SA* 2015*, 41*, 727-745.
19. Ollis, D.J.; Snaddon, C.D.; Job, N.M.; Mbona, N. Classification System for Wetlands and Other Aquatic Ecosystems in South Africa. User Manual: Inland Systems. *SANBI Biodiversity Series 22, South African National Biodiversity Institute, Pretoria, RSA* 2013.
20. Thompson, M. A Standard Land-Cover Classification Scheme for Remote-Sensing Applications in South Africa. *S. Afr. J. Sci.* 1996*, 92*, 34-42.
21. Van den Berg, E C; Plarre, C.; Van den Berg, H M; Thompson, M.W. The South African National Land Cover 2000. *Agricultural Research Council - Institute for Soil, Climate and Water* 2008*, GW/A/2008/86*.
22. Fairbanks, D.H.K.; Thompson, M.W.; Vink, D.E.; Newby, T.S.; Van den Berg, H M; Everard, D.A. The South African Land-Cover Characteristics Database: A Synopsis of the Landscape. *S. Afr. J. Sci.* 2000*, 96*, 69-82.
23. GeoTerraImage (GTI) South Africa. *2013-2014 South African National Land-Cover Dataset.*; GTI: Pretoria, South Africa, 2015.
24. Thompson, M.; Marneweck, G.; Bell, S.; Kotze, D.; Muller, J.; Cox, D.; Clark, R. *A Methodology Proposed for a South African National Wetland Inventory. Report to John Dini, Wetlands Conservation Programme, Department of Environmental Affairs and Tourism.*, CSIR Report No. ENV-P_C 2002-018 ed.; Council for Scientific and Industrial Research (CSIR): Pretoria, South Africa, 2002.
25. De Roeck, E.R.; Verhoest, N.E.C.; Miya, M.H.; Lievens, H.; Batelaan, O.; Thomas, A.; Brendonck, L. Remote Sensing and Wetland Ecology: A South African Case Study. *Sensors* 2008*, 8*, 3542-3556.
26. GTI. DEA E1434 Land-Cover South African National Land-Cover 2018 Report and Accuracy Assessment. Public Release Report. *GTI* 2019, 39.
27. Seaton, D.; Dube, T.; Mazvimavi, D. Use of Multi-Temporal Satellite Data for Monitoring Pool Surface Areas Occurring in Non-Perennial Rivers in Semi-Arid Environments of the Western Cape, South Africa. *ISPRS journal of photogrammetry and remote sensing* 2020*, 167*, 375-384.
28. Pekel, J.; Cottam, A.; Gorelick, N.; Belward, A.S. High-Resolution Mapping of Global Surface Water and its Long-Term Changes. *Nature* 2016*, 540*, 418-422.
29. Donchyts, G.; Baart, F.; Winsemius, H.; Gorelick, N.; Kwadijk, J.; Van de Giesen, N. Earth's Surface Water Change Over the Past 30 Years. *Nature Climate Change* 2016*, 6*, 810-813.
30. Nhamo, L.; Magidi, J.; Dickens, C. Determining Wetland Spatial Extent and Seasonal Variations of the Inundated Area using Multispectral Remote Sensing. *Water SA* 2017*, 43*, 543-552.
31. GTI. *South Africa Land Cover Water Feature Splits (1990 - 2013/14). Data Users Report and Meta Data (Version 2).*; Pretoria: GTI.: Pretoria, South Africa, 2016.

32. Mazvimavi, D. Finding "New" Water to Address Conflicting and Competing Water Demands in the Nuwejaars Catchment, Cape Agulhas. Water Research Commission (WRC) Report no. 2324/1/18. 2018, 135.
33. Thompson, M.; Hiestermann, J.; Moyo, L.; Mpe, T. Cloud-Based Monitoring of SA's Water Resources. *Position IT Magazine* 2018*, March*, 38-41.
34. Van Deventer, H.; Linström, A.; Durand, J.F.; Naidoo, L.; Cho, M.A. Deriving the Hydroperiod and Proportion of Open Water from Sentinel–2 imagery for global SDG 6 wetland ecosystem reporting. *Water SA* Accepted.
35. Matthews, M.W.; Bernard, S.; Robertson, L. An Algorithm for Detecting Trophic Status (Chlorophyll-a), Cyanobacterial-Dominance, Surface Scums and Floating Vegetation in Inland and Coastal Waters. *Remote Sens. Environ.* 2012*, 124*, 637-652.
36. Matthews, M.W.; Bernard, S. Eutrophication and Cyanobacteria in South Africa' Standing Water Bodies: A View from Space. *S. Afr. J. Sci.* 2015*, 11*, 1-8.
37. Matthews, M.W. Eutrophication and Cyanobacterial Blooms in South African Inland Waters: 10years of MERIS Observations. *Remote Sens. Environ.* 2014*, 155*, 161-177.
38. Matthews, M.W. The Integration of Earth Observation into the National Eutrophication Monitoring Programme. Water Research Commission Report no. TT770/18. *WRC* 2019, 274.
39. Kravitz, J.; Matthews, M.; Bernard, S.; Griffith, D. Application of Sentinel 3 OLCI for Chl-a Retrieval Over Small Inland Water Targets: Successes and Challenges. *Remote sensing of environment* 2020*, 237*, 111562.
40. Department of Water & Sanitation (DWS). National Eutrophication Monitoring Programme Report. 2020*, 2021*.
41. Tsoeleng, L.T.; Malahlela, O.E.; Mhangara, P.; Oliphant, T. Mapping Chlorophyll-a Concentrations in a Cyanobacteria- and Algae-Impacted Vaal Dam using Landsat 8 OLI Data. *South African Journal of Science* 2018*, 114*, 64-72.
42. Obaid, A.A.; Ali, K.A.; Abiye, T.A.; Adam, E.M. Assessing the Utility of using Current Generation High-Resolution Satellites (Sentinel 2 and Landsat 8) to Monitor Large Water Supply Dam in South Africa. *Remote Sensing Applications: Society and Environment* 2021*, 22*, 100521.
43. Matthews, M.W.; Kravitz, J.A. Sentinel-3 Validation for Water Resources Protection Report to the WATER RESEARCH COMMISSION. 2019.
44. Thamaga, K.H.; Dube, T. Understanding Seasonal Dynamics of Invasive Water Hyacinth (Eichhornia Crassipes) in the Greater Letaba River System using Sentinel-2 Satellite Data. *GIScience & Remote Sensing* 2019*, 56*, 1355-1377.
45. Thamaga, K.H.; Dube, T. Testing Two Methods for Mapping Water Hyacinth (Eichhornia Crassipes) in the Greater Letaba River System, South Africa: Discrimination and Mapping Potential of the Polar-Orbiting Sentinel-2 MSI and Landsat 8 OLI Sensors. *Int. J. Remote Sens.* 2018*, 39*, 8041-8059.
46. Cowardin, L.M.; Carter, V.; Golet, F.C.; LaRoe, E.T. *Classification of Wetlands and Deepwater Habitats of the United States.*, Version 4 December 1998 ed.; United States Department of the Interior: Fish and Wildlife Service: Washington District Capital, USA, 1979; pp. 142.
47. Pettorelli, N.; Wegmann, M.; Skidmore, A.; Mücher, S.; Dawson, T.P.; Fernandez, M.; Lucas, R.; Schaepman, M.E.; Wang, T.; O'Connor, B. Framing the Concept of Satellite Remote Sensing Essential Biodiversity Variables: Challenges and Future Directions. *Remote Sensing in Ecology and Conservation* 2016*, 2*, 122-131.
48. Jarman, M.L. Remote Sensing Applications in Vegetation Mapping with Special Reference to the Langebaan Area, South Africa. 1981, 176.
49. Lück-Vogel, M.; Mbolambi, C.; Rautenbach, K.; Adams, J.; Van Niekerk, L. Vegetation Mapping in the St Lucia Estuary using very High-Resolution Multispectral Imagery and LiDAR. *S Afr J Bot* 2016*, 107*, 188-199.
50. Rebelo, A.J.; Scheunders, P.; Esler, K.J.; Meire, P. Detecting, Mapping and Classifying Wetland Fragments at a Landscape Scale. *Remote Sensing Applications: Society and Environment* 2017*, 8*, 212-223.
51. Van Deventer, H.; Cho, M.A.; Mutanga, O. Multi-Seasons RapidEye Imagery Improves the Classification of Wetland and Dryland Communities in a Subtropical Coastal Region. *ISPRS J. Photogramm. Remote Sens.* 2019*, 157*, 171-187.
52. Slagter, B.; Tsendbazar, N.; Vollrath, A.; Reiche, J. Mapping Wetland Characteristics using Temporally Dense Sentinel-1 and Sentinel-2 Data: A Case Study in the St. Lucia Wetlands, South Africa. *International Journal of Applied Earth Observation and Geoinformation* 2020*, 86*, 102009.
53. Cho, M.A.; Van Deventer, H.; Lück-Vogel, M.; Van Nierkerk, L.; Adams, J.; Mutanga, O. Understanding Estuarine Processes in uMfolozi/uMsunduzi/St Lucia Estuary from Earth Observation Data of Vegetation Composition, Distribution and Health. Water Research Commission (WRC) Report no. 2268/1/15. *WRC* 2016, 104.
54. Grundling, A.T.; Van den Berg, Elzie Catharina; Price, J.S. Assessing the Distribution of Wetlands Over Wet and Dry Periods and Land-use Change on the Maputaland Coastal Plain, North-Eastern KwaZulu-Natal, South Africa. *South African Journal of Geomatics* 2013*, 2*, 120-138.

55. Grundling, A.T.; Van den Berg, E C; Pretorius, M.L. *Influence of Regional Environmental Factors on the Distribution, Characteristics and Functioning of Hydrogeomorphic Wetland Types on the Maputaland Coastal Plain, KwaZulu-Natal, South Africa.*, WRC Report No. 1923/1/13 ed.; Water Research Commission (WRC): Pretoria, South Africa, 2013.
56. Dlamini, M.; Adam, E.; Chirima, G.; Hamandawana, H. A Remote Sensing-Based Approach to Investigate Changes in Land use and Land Cover in the Lower uMfolozi Floodplain System, South Africa. *Trans. R. Soc. S. Afr.* 2021*, 76*, 13-25.
57. Thamaga, K.H.; Dube, T.; Shoko, C. Evaluating the Impacts of Land use Land Cover Change on Unprotected Wetland Ecosystems in the Arid Tropical Areas of South Africa using Landsat Dataset and Support Vector Machine. In review.
58. Van Deventer, H.; Adams, J.; Durand, J.F.; Grobler, R.; Grundling, P.; Janse van Rensburg, S.; Jewitt, D.; Kelbe, B.; MacKay, C.F.; Naidoo, L. *et al.* Conservation Conundrum – Red Listing of Subtropical-Temperate Coastal Forested Wetlands of South Africa. In review.
59. Adam, E.M.I.; Mutanga, O. Estimation of High Density Wetland Biomass: Combining Regression Model with Vegetation Index Developed from Worldview-2 Imagery. *Proceedings Volume 8531, Remote Sensing for Agriculture, Ecosystems, and Hydrology XIV;* 2012, pp. 85310V-9.
60. Naidoo, L.; Van Deventer, H.; Ramoelo, A.; Mathieu, R.; Nondlazi, B.; Gangat, R. Estimating Above Ground Biomass as an Indicator of Carbon Storage in Vegetated Wetlands of the Grassland Biome of South Africa. *International Journal of Applied Earth Observation and Geoinformation* 2019*, 78*, 118-129.
61. Gangat, R.; van Deventer, H.; Naidoo, L.; Adam, E. Estimating Soil Moisture using Sentinel-1 and Sentinel-2 Sensors for Dryland and Palustrine Wetland Areasa. *South African Journal of Science* 2020*, 116*, Art. #6535.
62. Abd Elbasit, M. A. M.; Abutaleb, K.; Grundling, A.T.; Chauke, M. Multi-Platform Remote-Sensing Tools for Peat Fire Detection and Monitoring. *WRC* 2020, 64.
63. Ndlala, N.C.; Dube, T. Use of Remotely Sensed Derived Metrics to Assess Wetland Vegetation Responses to Climate Variability Induced Drought at the Soetendalsvlei Wetland System in the Western Cape Province of South Africa. In review.
64. Van Deventer, H.; Cho, M.A. Assessing Leaf Spectral Properties of *Phragmites Australis* Impacted by Acid Mine Drainage. *S Afr J Sci* 2014*, 110*.
65. Mutanga, O.; Adam, E.; Cho, M.A. High Density Biomass Estimation for Wetland Vegetation using WorldView-2 Imagery and Random Forest Regression Algorithm. *International Journal of Applied Earth Observation and Geoinformation* 2012*, 18*, 399-406.
66. Holden, P.B.; Rebelo, A.J.; New, M.G. Mapping Invasive Alien Trees in Water Towers: A Combined Approach using Satellite Data Fusion, Drone Technology and Expert Engagement. *Remote Sensing Applications: Society and Environment* 2021*, 21*, 100448.
67. Sieben, E.J.J.; Mtshali, H.; Janks, M. National Wetland Vegetation Database: Classification and Analysis of Wetland Vegetation Types for Conservation Planning and Monitoring. WRC Report no. 1980/1/14. *WRC Report, Pretoria, South Africa* 2014*, 1980/1/14*.

Chapter 5

Quantifying climate change impacts on river system ecology in South Africa

Nicholas A. Rivers-Moore [1*] and Helen F. Dallas [2]

[1] Freshwater Research Centre and Centre for Water Resources Research, University of KwaZulu-Natal
[2] Freshwater Research Centre and Faculty of Science, Nelson Mandela University
* Corresponding author: blackfly1@vodamail.co.za

Abstract: Rivers integrate what is happening in catchments. They are longitudinal "ribbon" networks within the landscape yet contain a disproportionately high number of species and are recognised as the most threatened ecosystems globally. Landscape degradation and catchment development lead to increased levels of river disconnectivity, and climate change amplifies the effects of such stressors. These leave signatures both on the time series of flows and temperatures – the two master abiotic variables; and biological communities. In the latter case, impacts may include changes in lifecycle length, and/ or changes in species distributions in response to reductions in available suitable thermal habitat. In recognising the importance of, and knowledge gaps in, thermal research in river systems, the WRC has funded a number of eco-hydrological studies over the past 15 years. Beginning with a three-year project in 2008, knowledge on the regional and temporal variations in thermographs was deepened, and techniques were developed to statistically describe such time series. Biological knowledge, particularly for aquatic macroinvertebrates, was gained both through laboratory studies and in biological response models. The identification of thermal thresholds for invertebrates was ground-breaking, with this research being both highly cited across the globe and also replicated. These methods were subsequently extended to understand seasonal plasticity within taxa, and applied to native and non-native fish in the Cape Floristic Region. Tools and frameworks have been developed more recently, to assist with screening of the relative importance of different thermal impacts, and how to assess risk. Implications are that pest species are likely to become worse, while less-common but high conservation value species could begin to drop out of ecological communities. Aside from the economic implications of such outbreaks, a shift towards more variable, event-driven river systems dominated by generalist species implies a loss of the uniqueness and resilience of our rivers. It becomes critical that river connectivity be maintained as far as possible so that river biota will be able to adapt.

Keywords: Aquatic macroinvertebrates; blackfly; fish; freshwater conservation; life history; water temperature

1. Introduction

Primary effects of global climate change will be reflected first and foremost as altered air temperatures and precipitation. While the former occurs as a continuous time series, and the latter as event-based, both variables have spatial and temporal patterns at a local scale that are projected to undergo changes. Further detail and examples of this are provided in Chapters 2 and 3. Analyses of air temperature and rainfall patterns across South Africa's national parks already indicate changes to both parameters across the country, over the past fifty years [1]. Such data would represent a fair surrogate of conditions across the country, given the spread of national parks across most of the major biomes. Changes indicate significant increases in air temperatures across parks, with changes being more rapid in the more arid regions [1]. Changes in rainfall patterns are more complex, but also reflect spatio-temporal changes in seasonality, with higher rainfall areas predicted to receive more rainfall, and lower rainfall regions predicted to receive less rainfall [2].

This has important implications for South Africa's river systems, where primary effects of climate change are amplified through the hydrological cycle, and reflected in secondary variables such as flow patterns and water temperatures. Of particular significance is that large parts of South Africa are already classified as arid – hyper-arid [3]. Fragmentation across a landscape compounds impacts on biota by restricting natural movements of species as an adaptation to climate change. Specifically for rivers as longitudinal systems within the landscape, environmental gradients are particularly pronounced and upstream/ downstream connection is critical.

A water temperature regime is the result of a complex interplay of variables at different spatial and temporal scales [4]. Incoming solar radiation is, however, the major variable influencing both air and water temperatures, with air temperatures acting on water temperatures via convective energy exchanges [5]. While air temperature is the variable of greatest leverage affecting water temperatures, ultimately a measured water temperature is a product of additional drivers, which are in turn acted upon by insulators and buffers [6, 7]. Here, drivers operate beyond the boundaries of the stream, and control the rate at which heat and water are delivered to the stream system; insulators influence the rate of heat exchange with the atmosphere; buffers store heat already in the system, and integrate the variation in flow and temperature over time. In general, as streams become larger, insulating processes become less effective and buffering processes become more important [7]. It is thus reasonable to view water temperature as the single variable that integrates much of what is happening within catchments.

Water temperatures affect the physical nature of water by, *inter alia*, changing its density, viscosity, and surface tension [8]. Temperature also affects the chemical reactions of solutes in water, both by changing the rate of chemical reactions, as well as the types of reactions [9-11]. A strong link exists between water temperatures and the physiology of aquatic organisms, since most are poikilothermic, being either stenothermic (species occupying a narrow temperature range), or eurythermic (species occupying a wide temperature range) [10]. Metabolic rates, survival rates, growth rates, and fecundity are temperature dependent [9, 10, 12-14]. The timing and magnitude of heating and cooling periods act as cues for different life history stages of fish and invertebrates, which tend to correspond with critical flows volumes, and availability of food, sexual partners and habitats [15]. Temperatures outside an organism's optimal range lead to thermal stress, and in such situations biota will attempt to move to more favourable refugia habitats [16]. Distributional patterns are the final manifestation of how individuals have been responding to environmental pressures. The integrative nature of rivers within catchments means that these are amongst the first systems to reflect changes in climate, as manifested by these being the most threatened globally [17].

Links between species distributions and climate variables have long-been recognised in the global and South African scientific community, where studies from the 1950s and 1960s linked particular aquatic macroinvertebrate communities to river longitudinal zones and hydrological regions [18]. Furthermore, within the thermal zones coincident with species distributions, the warm months are often the most important biologically, since it is during the summer months that the important life-history processes, such as breeding and growth, occur [19]. For example, when unpacked for particular river systems, ichthyological patterns observed were largely explained by thermal patterns, as was shown in the Sabie River system, one of the most species-rich systems in South Africa [20, 21], with the fish having evolved to be in equilibrium with the prevailing thermal regime.

Range shifts of aquatic macroinvertebrates have already been identified and highlighted in the scientific literature [22]. Whereas most aquatic insects, but not all aquatic macroinvertebrates, have a flighted adult stage allowing these species to more easily track change, obligate aquatic species ranging from algae, molluscs and fish are restricted to the river channel itself. Pathways for range shifts require understanding of impacts on species, based on fundamental research of individual specimens collected concurrently with water temperature data. For example, data on frequencies of ghost frog tadpoles within different length and mass classes provide an understanding of how water temperatures predict life history lengths [23]. Data from this study show that a doubling of heat units halves lifecycle length of tadpoles from two years to one year. Similarly, the caddisfly, *Chimarra ambulans*, showed a phenotypically plastic response to temperature, in that more generations (trivoltinism) were observed in warmer rivers, in comparison to univoltine populations in colder rivers [24]. At a regional-scale level, distribution models based on thermal thresholds for different species highlight not only that cool water species are likely to undergo considerable range contractions under scenarios of a 2°C increase in water temperatures, but also that small differences in thermal stress thresholds between species results in major differences in relative adaptability of different species to climate change [25]. Irrespective of which scale lens these studies are viewed through, the core lesson is that species adaptation becomes a function of river connectivity.

Water temperature has long been recognised as a primary abiotic process structuring biotic patterns in rivers, by influencing most of the physical, chemical and biological properties of water bodies [26, 27]. There is renewed interest, particularly in the United States and Great

Britain, in simulating the thermal regime of rivers and streams, in response to anticipated alterations to the natural thermal regime of many rivers as a result of impoundments [28], changes in land use, and climate change [29]. The advent of cost-effective, continuous temperature sensor technology has made it possible to collect fine resolution water temperature data with relative ease [30]. Human impacts change the amount (magnitude) or timing of the heat load delivered to the watercourse or by modifying the flow regime [7, 31, 32]. Additionally, streams differ in their sensitivity to modifications. Water temperatures at different times of the year may not be affected to the same extent by future climate change [26, 33]. Any reduction in the buffer efficiency leads to larger swings in cyclical response patterns, resulting in higher maxima and lower minima (daily and seasonal) [7].

The objectives of this chapter were to (i) provide an overview of WRC-funded projects over the past two decades to illustrate how investments in research have led to a broader understanding of river systems and how these will be impacted by climate change; (ii) illustrate selected tools available for assessing these changes; and (iii) provide some thoughts and perspectives on the impacts of such changes, gleaned from collective experience.

2. Materials and methods

This section is a high-level overview of methods used in extending the understanding of water temperatures responses to climate change impacts. Relevant reports are cited that contain more detailed information on the methods described here. Such research is not presented in chronological order, but rather as a logical framework that illustrates how investments in individual projects results in a greater overall understanding of river systems.

2.1. Understanding the stage: Abiotic and biotic patterns in freshwater habitats

Water temperature, next to flow patterns, is the most important abiotic variable in a river system. Water temperatures very spatially and seasonally, and it is important to gain insights on this variability. Additionally, disruptions to the downstream flow of energy in a river can have considerable impacts on biological communities; methods to quantify thermal regimes and describe river connectivity thus become important tools for prioritizing conservation efforts on river systems.

2.2.1. Understanding thermal signatures [34]

Water temperature is a continuous variable, varying throughout the day, and along a river's longitudinal axis. Recording such data at suitable time intervals is able to provide information on how water temperatures vary across seasons at a particular site, and between sites within the same river or different catchments.

- Programmable data loggers were installed across 100 sites encompassing major ecoregions and longitudinal zones of the Eastern and Western Cape Provinces [34] (Figure 1)
- Thermographs were statistically described in terms of the frequency, duration, magnitude and timing of defined thermal events.
- Sites were grouped into thermal types using multivariate techniques.

2.2.2. Understanding biotic patterns down river profiles [35-37]

Alpha diversity refers to the number of species at a particular site, while beta diversity describes how aquatic communities change between sites, and what the patterns in turnover are. An understanding of where diversity hotpots occur down a river's axis, and what natural rates of turnover are for different taxonomic groups (fish versus macroinvertebrates) provides a yardstick against which impacts of climate change on aquatic systems can be measured. Representative samples of biota collected relative to environmental gradients are important for measuring present distributions and predicting shifts in distribution of taxa in response to climate change or reduced river connectivity.

- Fish and aquatic macroinvertebrate species data for sites down the longitudinal axes of nine rivers in four provinces along the eastern side of South Africa were analysed in terms of species richness and turnover. Data represented longitudinal species patterns down longitudinal river axes;
- A method was developed to identify suitable river segments for sampling and monitoring changes in taxon diversity, where representative sampling sites were identified using a logistic regression model to predict the probability of site pairs that were more than 50% similar as a function of up-/downstream distance.

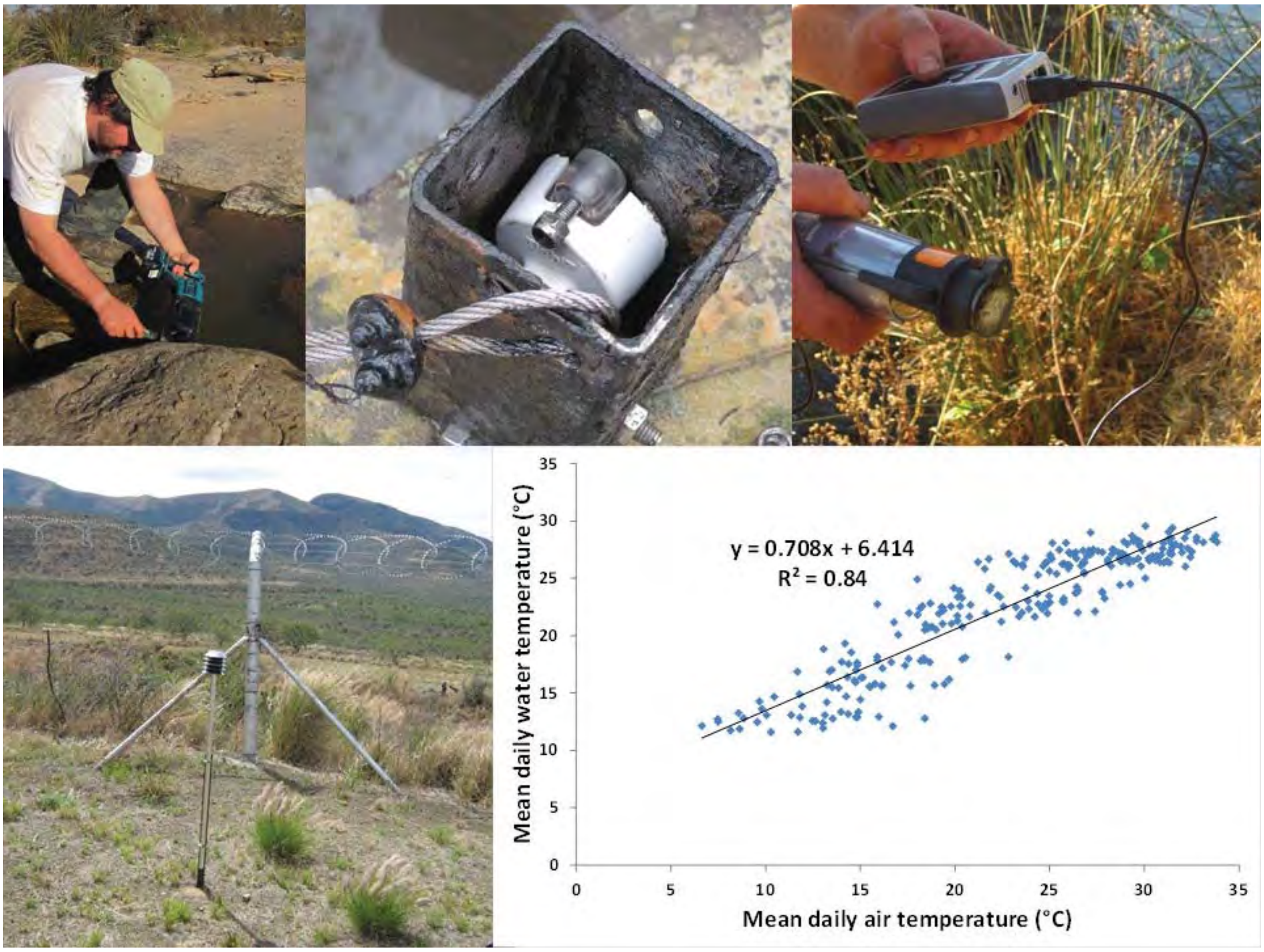


Figure 1. Installation and downloading are water temperature loggers, in association with collection of air temperature data from a logger inside a heat shield. Graph shows a typical association between air and water temperature data.

2.2.3. Characterising river connectivity [38-40]

River connectivity has a number of components: longitudinal connectivity describes the extent to which upstream/ downstream connections broken; lateral connectivity describes the extent to which overland flow through a catchment is uninterrupted; and temporal connectivity describes the extent to which flow or water temperature time series are natural and flow freely between seasons. Ecological processes in freshwater lotic systems are disrupted when upstream/ downstream connectivity is broken. Changes in catchment land use, catchment density of small dams, and instream impoundments result in changes to thermal and flow regimes, which in turn affect natural biological turnover patterns and rates, as well as organism exchange and dispersal.

- Longitudinal connectivity was defined for mainstem rivers in KwaZulu-Natal, with relative weights assigned to absoluteness of in-channel barriers. A cumulative score was calculated for each river, based on additive numbers, as well as the use of a reset distance
- A lateral connectivity index was calculated at quaternary catchment scale, based on landscape fragmentation and a small dams density score
- An overall connectivity index was calculated as the sum of lateral and longitudinal indices
- A practical application of this was applied by categorizing catchments according to conservation uniqueness and connectivity

2.2. Understanding biological responses to water temperatures

With the exception of mammals and birds that live in rivers, such as otters and waterfowl, all other freshwater organisms are described as “poikilothermic”, meaning that their internal temperatures vary in accordance with the environment they are in. In addition to this category, species may be defined as eurythermic (able to tolerate wide thermal ranges) or stenothermic (thermally sensitive, with onset of thermal stress outside of a narrow thermal envelope). Aquatic organisms may be even further classified as a warm-water eurytherm, or a cool-water stenotherm. All organisms have a preferred range of temperatures, often termed the ‘optimum thermal regime [15], at which optimal growth, reproduction and other measures of ‘health’ are greatest. This optimum range is bounded by the thermal tolerance range (i.e. the range over which a species may survive) with upper and lower tolerance limits demarcating the thermal extremes. Organisms of a given species may survive on either side of this optimal range, but as the tolerance limits are approached, signs of stress become evident. The first signs of thermal stress are usually behavioural, with avoidance of suboptimal conditions, followed by physiological stress (e.g., respiratory, metabolic or excretory rates may increase), reduction in egg and/or sperm production and hence in fecundity, and increased susceptibility to parasites and pathogens and also to food shortages.

This means that changes to natural thermal regimes may result in lethal effects, acute or chronic thermal stress, or sub-lethal effects [41]. It becomes important for aquatic ecologists to be able to know what these lethal and sub-lethal thresholds are, in order to understand when the onset of thermal stress begins. Lethal endpoints are commonly estimated using the Critical Thermal Method (CTM) or the Incipient Lethal Temperature (ILT) method [38, 42, 43]. Sub-lethal effects may include behavioural responses [38] or development effects such as egg development, hatching success and life history [24, 44].

While these thresholds (upper and lower lethal limits) are useful for studies considering particular life-history components relative to thermal stress, there is considerable merit in using an overarching (or integrating) thermal metric when determining the suitability of a species to a particular receiving environment. A commonly used chronic stress threshold is the Maximum Weekly Allowable Temperature (MWAT) threshold, which is calculated using experimental temperature data. MWAT is regarded as the best overall thermo-physiological integrator [45, 46], is species specific and is based on a combination of optimal and incipient lethal temperatures.

2.2.1. Thermal thresholds of aquatic invertebrates

Not all families of aquatic macroinvertebrates at a single site will respond in the same way to the onset of thermal stress. Certain species will be more sensitive to thermal stress than others, leading to differential species losses and gains within a river system. Knowledge on this is important for selecting indicator species for identifying climate change impacts.Two methods have been used to experimentally measure thermal stress of aquatic invertebrates, expressed as upper thermal limits, namely the critical thermal method (CTM) and the incipient lethal temperature method (ILT) (Figure 2). These complimentary methods were used to allow for estimation of both acute (CTM) and chronic (ILT) thermal limits, thereby providing insight into the influence of intensity and duration of thermal stress on survival [see 47].

- **Critical thermal method**: In the laboratory, the CTM is conducted over relatively short periods of time (1–2 h) and the thermal stress is short lived (given that the animal is removed from the experiment as soon as visible symptoms of heat stress are observed). CTM experiments involve heating an organism immersed in a chamber in a water bath at a constant rate of 0.34°C per minute using a circulating heater (JulaboTM). A predetermined critical thermal endpoint behavioural (CTE) response is triggered when locomotor activity becomes disorganised, for example, loss of grip, lying upside down and not moving [42]. At this point the organism is removed from the water into the recovery chamber. The temperature at an organism's CTE is recorded as the CT_{max} for each test organism [48]. For each species up to 30 individuals are tested to generate a median CT_{max} for a species.
- **Incipient lethal temperature method**: ILT experiments involve placing organisms in chambers in glass tanks filled with water heated to five to eight different temperatures, including one control temperature. Chambers are checked for survival every 24 h for 96 h and LT_{50} values (the temperature at which 50% of the sample survives in a specified time) determined and used to calculate the incipient lethal upper temperature (ILUT), which is the temperature survived by 50% of the population for 96 h.

- The ILUT can be used to calculate a biological threshold, expressed as Maximum Weekly Allowable Temperature (MWAT), using the formula: MWAT=OT+((ILUT-OT))/3, where OT is optimal temperature, and ILUT is the Incipient Lethal Upper Temperature.

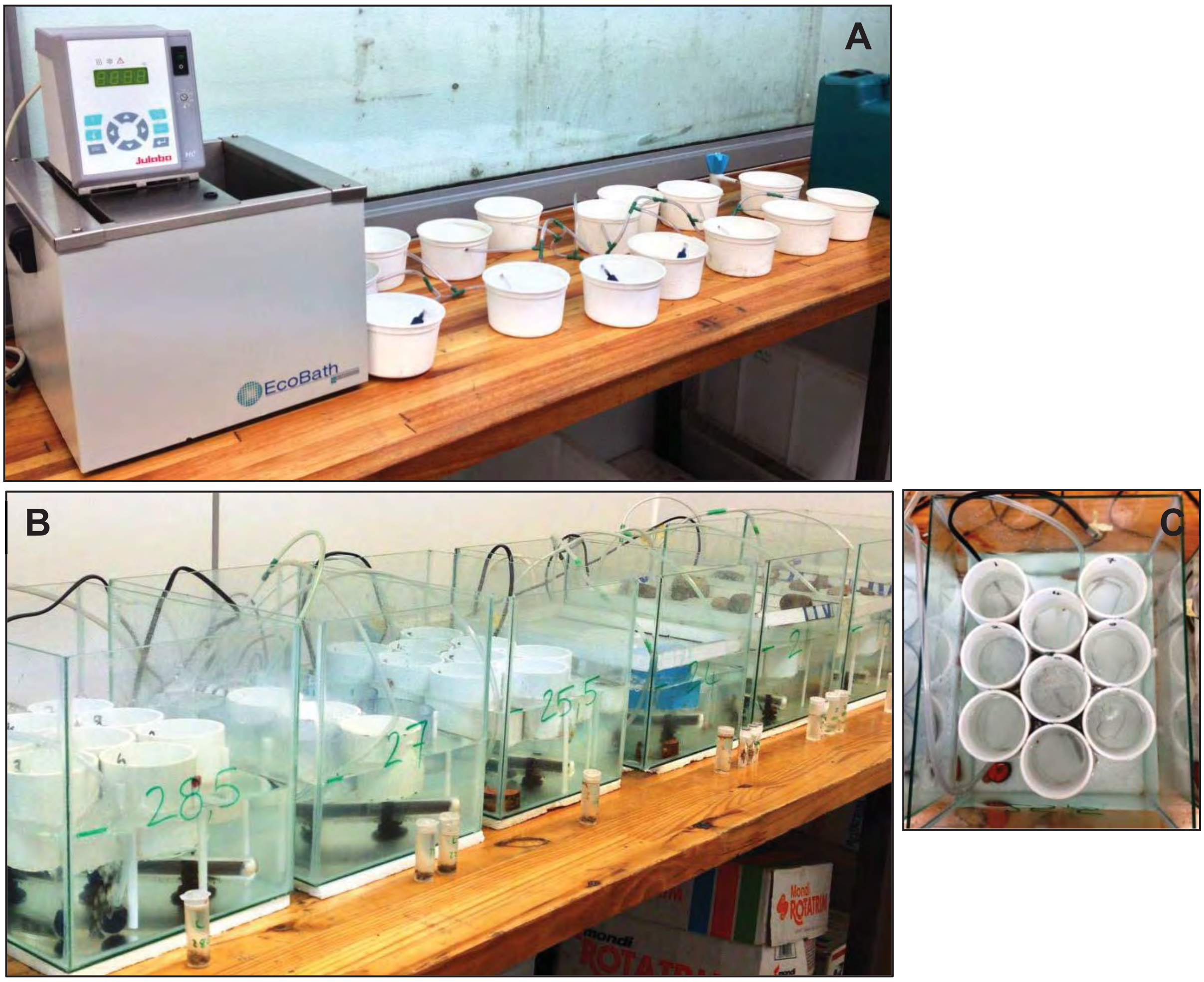


Figure 2. A: Water bath and immersion heater with recovery tubs for critical thermal method (CTM) experiments; B: aquaria tanks, immersion heaters and experimental chambers for incipient lethal temperature method (ILT) experiments; C: Experimental chambers.

2.2.2. Thermal preferences of aquatic invertebrates

Thermal preference experiments are choice experiments, by which the preferred temperature of a group of organisms can be determined. These experiments are undertaken using thermal gradient tanks (Figure 3), which allow for the estimation of temperatures completely avoided and those preferentially migrated to over time. In this way it provides insight into the range of temperatures that an organism is able to utilise allowing for comparison with sub-lethal and lethal effects.

- A horizonal thermal preference tank, which generated at 14° gradient, was designed with water temperature loggers, copper cooling pipes and aquarium heaters.
- Logged water temperatures in the thermal gradient tank were used to generate a “preference temperature” (Tp) for each organism following release and one hour of settling in the tank.

2.2.3. Sub-lethal effects of water temperature on egg development

This was investigated in three mountain stream insects, *Lestagella penicillata* (Ephemeroptera: Teloganodidae), *Aphanicercella scutata* (Plecoptera: Notonemouridae) and *Chimarra ambulans* (Trichoptera: Philopotamidae) from the winter rainfall Western Cape Province, South Africa. Eggs of each species were incubated after fertilisation at six temperature treatments across the range of 5 – 30 °C. Total development time required for 50% hatch, total hatch success, duration of the hatching period, upper and lower thermal limits for development, were calculated for each species [44].

2.2.4. Thermal thresholds of native fish from the Cape Fold Ecoregion (CFE)

The lack of physiological information on native fishes in the CFE is considered a major bottleneck in understanding their biology, ecology, distributions and behaviour [49], and constrains the understanding of the potential consequences of climate change for their survival [50]. The CTM method described in the sub-section 2.2.1 were applied to selected native fish species in the CFE.

- The CTM is appropriate for use with endangered species as alternative methods, such as the ILT, requires death of the test individual, and is thus not suitable for thermal experiments on native fish species.
- Target species were selected from the four major endemic fish families in the CFE, namely Anabantidae, Austroglanididae, Cyprinidae and Galaxiidae [50].
- The endpoint (CTE) of the experiment for an individual fish was the observed loss of righting response, where the individual lost complete ability to remain upright.

2.2.5. Thermal preferences of native fish from the Cape Fold Ecoregion (CFE)

The thermal preference method described in the sub-section 2.2.2 was applied to selected native fish species in the CFE (Figure 2.2).

- Fish were added to the thermal gradient tank and allowed to settle for 30 minutes, after which heating and cooling gradually established the thermal gradient over three hours. The experimental phase commenced with tanks checked at 10-minute intervals, with the number/frequency of fish in each 25cm thermal section recorded. Three experimental tanks were paired with three control tanks, which were used to discount stress effects on fish and where temperature remained constant. A thermal gradient of ±15 to 30^{o}C was established in the experimental tanks.
- Logged water temperatures in the thermal gradient tank were used to generate a “preference temperature” (Tp) for each fish.

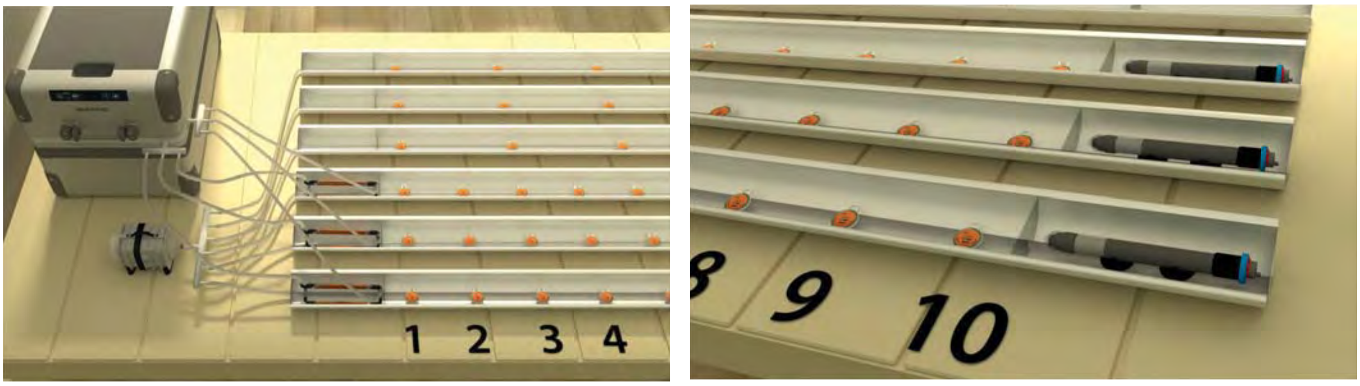


Figure 3: Diagram showing experimental setup for estimating thermal preference using thermal gradient tanks, with the cold pole (left) and the warm pole (right).

2.2.6. Spatial and seasonal plasticity between and within species of aquatic invertebrates and fish

The thermal history (i.e., thermal characteristics of an organism's environment) of an organism is an important measure of its relative resilience to climate change. Consequently, knowledge on the extent to which thermal thresholds vary between sites, and between seasons, for the same species, provides an indication of species-specific thermal plasticity. Spatial and temporal (seasonal) variability in upper thermal limits, expresses as CT_{max} and ILUT, was investigated as follows:

- Spatial variability in upper thermal limits for the mayfly, *Lestagella penicillata* (Teloganodidae), and the stonefly, *Aphanicerca capensis* (Notonemouridae), from six rivers in the Western Cape [57].
- Spatial variability in upper thermal limits for nine families (Notonemouridae, Perlidae, Heptageniidae, Leptophlebiidae, Teloganodidae, Tricorythidae, Philopotamidae and Blephariceridae) of aquatic invertebrates from 18 rivers in five geographical regions of South Africa, including the Western Cape, Southern Cape, Eastern Cape, Mpumalanga and KwaZulu-Natal [38].
- Spatial variability in upper thermal limits of one native CFE fish genus, *Pseudobarbus*, and two species, *Pseudobarbus phlegethon* and *Sandelia capensis*, from five, two and three rivers, respectively, in the CFE [50].
- Spatial and temporal variability in upper thermal limits of an endemic CFE fish species, the Cape Galaxias, *Galaxias zebratus*, from ten sites on six rivers on the Cape Peninsula, Western Cape [52].
- Temporal variability in upper thermal limits of two cold-adapted stenotherms: the amphipod, *Paramelita nigroculus* (Paramelitidae), and the mayfly, *Lestagella penicillata* (Teloganodidae), from two rivers in the Western Cape [48].
- Temporal variability in thermal preference of two native fish species, *Pseudobarbus burgi* and *Pseudobarbus afer*, from two rivers in the CFE [51] (Figure 4).

Figure 4. Fyke net set on the upper Berg River. (Photo: Helen Dallas)

2.3. Counting the potential cost

Biological thermal thresholds, when coupled with thermographs, provide the capability to develop ecological response models to simulate responses to changes in water temperature regimes under different scenarios. Models may take a variety of formats, with our focus being on life history or probability models. Such models have been applied over the WRC's blackfly research programme, and well as being integrated into a framework for assessing thermal risk and resilience.

2.3.1. Life history, probability and species distribution models

Successful completion of an organism's lifecycle is much more likely to happen when an organism is able to inhabit its optimal or preferred thermal niche. The progression from one lifecycle stage to another (for example, onset of pupation), hatching and breeding success and fecundity, are all dependent on water temperatures. Linking such events to thermal time series allows ecologists to not only better understand river systems, but also assess relative threats and risks to perturbations including global climate change.

- Laboratory-controlled hatching experiments of various aquatic macroinvertebrate species, to provide basic scientific information on critical thermal thresholds controlling hatching success and life cycle duration [24,38]
- Logistic regression models predicting the probability of hatching success or occurrence for selected species, based on thermal thresholds [53]
- Species distribution models for fish in the Cape Fold Ecoregion, using species presence data with a number of spatial predictor variables (hydrological, meteorological and topographic) [51]

2.3.2. Blackfly research

One of the ecological consequences of reduced river connectivity is where pest-level outbreaks of the blackfly *Simulium chutteri* has occurred downstream of major impoundments in a number of rivers in South Africa. While blackfly adult females cause the economic losses by requiring a blood meal from livestock for successful egg laying, it is the prevailing thermal and hydraulic conditions that determine the likelihood of an outbreak due to successful and prolific larval development. For the past thirty years, the WRC has funded a number of projects to better understand blackfly ecology and river conditions. Not only did this provide the science necessary for developing a successful blackfly control programme, but when integrated into ecological models, the capability exists to evaluate impacts under different climate change scenarios.

- Development of a Bayesian network probability model linking multiple environmental and ecological variables into a predictive tool to indicate probability of pest blackfly outbreaks under different thermal and flow conditions [54]
- Linking economic data on relative benefit-cost ratios and losses to the stock industry, to climate change scenarios
- Understanding the dynamics of system switches between clear and turbid states within the Orange River, by sampling 14 sites in the middle and lower Orange River for blackfly species and abundances, presence of benthic algae, and water quality and turbidity seasonally between November 2015 and December 2016. Data were applied to an event-based probability model to assess impacts of flow patterns and climate change on the number of switching events (= system resets) per annum [55]
- Three scenarios (increased water temperatures; increased flows and combined effects of flows and temperatures) were applied to existing outbreak probability models for both the Great Fish River and the Orange River

2.3.3. Tools and frameworks [56]

All of the research described in the previous sections is not always directly translatable into an applied product that dovetails with existing water legislation. Consequently, funded research was undertaken to assimilate these information and expertise into a framework for practitioners to apply the thermal knowledge to impact assessment and resource quality objectives.

- Development of a screening tool to assess whether thermal impacts should be assessed further or not. This included a risk matrix of thermal effects based on magnitude of impact and likelihood of occurrence. Relative potential ecosystem resilience was calculated for quinary catchments for all of South Africa, based on five important and spatially representable metrics (groundwater depth; natural vegetation cover; stream order; flow predictability and water stress)
- Frameworks and flowcharts of how to define reference water temperature thermographs using observed data, or to generate data from air temperature data.

3. Results

This section lists key findings of various studies in terms of thermal patterns and biological responses to thermal stresses.

3.1. Habitat template: abiotic patterns

3.1.1. Thermal signatures of rivers

Hourly water temperatures over at least a year can be statistically described and compared using 39 metrics based on the magnitude, frequency, duration and timing of thermal events:

- Correlation between many of the metrics was high, such that thermal time series can be described using a smaller suite of metrics
- Sites can be classified into thermal groups using this approach. For example, 82 sites from 48 rivers in ten catchments were classified into 11 thermal groups defined in terms of various thermal gradients
- Thermal groups reflect relative cool versus warm water conditions, groundwater inputs, and thermal variability
- The use of thermal groups provides the capacity to generate statistically robust thermal reference conditions for thermal types, and measure quantifiable departures from this in terms of changes of timing, frequency, magnitude and duration of thermal events

3.1.2. Biotic patterns down river profiles

Fish proved to be not useful for mapping biodiversity patterns, as measured by turnover, whereas aquatic macroinvertebrate species patterns exhibited predictable patterns of turnover with downstream distance:

- Alpha diversities peaked in the upper third of river lengths; beta diversities showed predictable exponential decay rates down river axes
- Average turnover rates could be decomposed into turnover of common ('core') species, which were accelerated by presence of rare and narrow-range species
- Disruptions to the river continuum impacted on the rate of turnover. Aquatic macroinvertebrate communities could be grouped into upland versus lowland assemblages, and also be defined by longitudinal zones
- Application of the model to a 370 km-long river indicated that 14 sites should be selected for sampling to capture overall biodiversity patterns.

3.1.3. River connectivity

A comprehensive connectivity index for rivers was generated, which can be used as a spatial product to prioritise areas of freshwater importance within the province of KwaZulu-Natal, South Africa:

- 275 instream barriers were found along a total river length of 7,900 km (stream order 2 and above; 1:500 000 scale) in KwaZulu-Natal, extending over four primary catchments and 214 quaternary catchments
- Fifty-six per cent of the overall river length was disturbed by one or more barriers, with only c. 25% of rivers with an average length of 45 km showing undisturbed free-flowing conditions, with most as tributaries

- River disconnectivity generally increased with increasing stream order
- Reduced connectivity had an impact on river time-series signatures.

3.2. Understanding biological responses to water temperatures

3.2.1. Thermal thresholds for aquatic macroinvertebrates

Based on thermal experiments on individual organisms across a range of aquatic macroinvertebrate families, thermal thresholds for CT_{max} were successfully calculated for 29 families, 54 genera and 30 species. ILUTs were calculated for 13 families, nine genera and nine species. Biological thresholds (MWAT) were determined for nine families, seven genera and five species [38].

- Most thermally sensitive taxa were in the order Amphipoda and the EPT taxa [in order of sensitivity: Plecoptera (stoneflies), Trichoptera (caddisflies) and Ephemeroptera (mayflies)], as well as the net-winged midges (Blephariceridae)
- Least thermally sensitive orders include the bugs, beetles, dragonflies and snails (Hemiptera, Coleoptera, Odonata and Gastropoda)
- Medium CT_{max} varied from 26.5°C (Blephariceridae) to 42.3°C (Gyrinidae)
- Median ILUT varied from 23.2°C (Plecoptera: *Aphanicerca capensis*) to 33.9°C (Aeshnidae)
- There was a significant positive linear relationship between ILUT and CT_{max} [42]
- MWAT thresholds varied amongst taxa and rivers ranging from 15.8°C to 20.9°C
- MWAT was significantly correlated with mean annual temperature (MAT) and thus MAT can be used to provide an estimate of MWAT with a medium confidence level
- Upper thermal limits, expressed as CT_{max}, were used to develop a prototype Thermal Sensitivity Index. A Thermal Sensitivity Weighting was assigned to each South African Scoring System (SASS) taxon, with the weighting derived from a combination of an estimate of thermophily and thermal limits [34]). This index provides an indication of the thermal sensitivity of taxa at a site and provides an indication of the vulnerability of the site, and its taxa, to climate warming.

3.2.2. Thermal preferences (Tp) of aquatic macroinvertebrates

Preliminary mean Tp was calculated for eleven families of aquatic invertebrates.

- Thermal preference varied from 15.5 to 20.2°C [38]
- Problems encountered included variability in the migration of organisms along the thermal gradient, which differed amongst taxa with some taxa very mobile and other less mobile
- Recommendations for future experiments included the inclusion of a control tank and further replicated trials to increase confidence in results

3.2.3. Sub-lethal effects of water temperature on egg development

- Successful egg development and hatching occurred between 10 and 20°C for *L. penicillata*, with highest percentage hatch (90%) at 10, 15 and 20°C treatments
- For *A. scutata* successful hatching also occurred between 10 and 20°C, but hatching success was reduced (~ 30%) at 20°C compared to ~ 80% hatching success at 10 and 15°C treatments
- For *C. ambulans*, successful development and hatching occurred over a wider range of temperatures (10 – 25°C) but with lower (5 – 20%) and more variable hatching success at all temperatures [44]

3.2.4. Thermal thresholds of native fish from the Cape Fold Ecoregion (CFE)

Based on thermal experiments on individual organisms across five rivers in the CFE, thermal thresholds for CT_{max} were successfully calculated for eight species of freshwater fish [51].

- Upper thermal limits varied significantly between species (Figure 5)
- Cape galaxias (*Galaxias zebratus)*, Breede River redfin (*Pseudobarbus burchelli)*, Berg River redfin (*Pseudobarbus burgi)*, Clanwilliam redfin (*Pseudobarbus calidus)* and fiery redfin (*Pseudobarbus phlegethon)* were the most thermally sensitive (CT_{max} = 29.8–32.8°C)
- Clanwilliam rock-catfish (*Austroglanis gilli)*, Eastern Cape redfin (*Pseudobarbus afer)* and Cape kurper (*Sandelia capensis)* were moderately sensitive (CT_{max} = 33.0–36.8 °C)
- It is important to note that the upper thermal limit, expressed as CT_{max}, represents an acute lethal limit, with fish exhibiting behavioural stress over a short time period of approximately 1 to 2 hours
- Thermal tolerance data demonstrate that resilience to climate warming follows a geographical cline and that within the CFE, the more sensitive western species and regions are conservation priorities
- Generally, thermal tolerance (and thermal preference) of CFE fish fell below those for warm-adapted non-native species (e.g. centrarchids), but above cold-adapted non-natives like trout (e.g. salmonids)

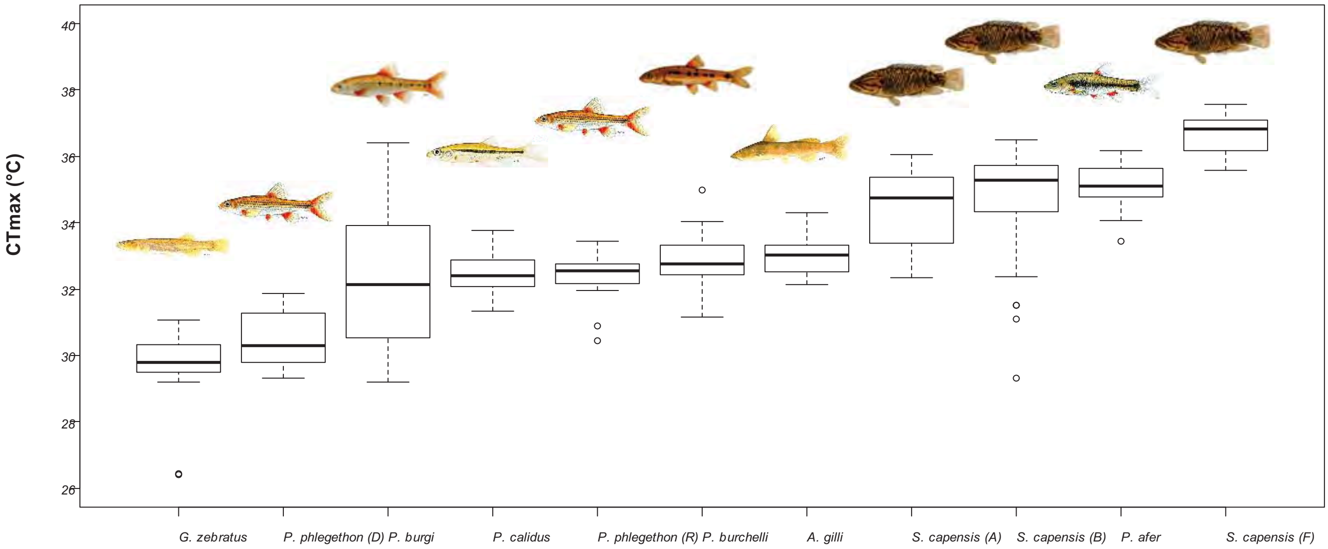


Figure 5. Boxplot showing median, quartiles and range of thermal tolerance, expressed as CT_{max}, for all species in the Western Cape ordered from most thermally sensitive to least thermally sensitive. (Rivers denoted as follows: D=Driehoek, R=Rondegat, A=Amandel, B=Berg and F=Fernkloof). All illustrations are ©NRF-SAIAB.

3.2.5. Thermal preferences of native fish from the Cape Fold Ecoregion (CFE)

Thermal preferences were estimated for seven species of native freshwater fish from five rivers in the CFE [51].

- Thermal preference varied significantly between species, with *G. zebratus* showing a preference for the coolest temperature (18.7°C), and *S. capensis* showing a preference for the warmest temperature (27.7°C) (Figure 6).
- Median CT_{max} and preferred temperature were correlated

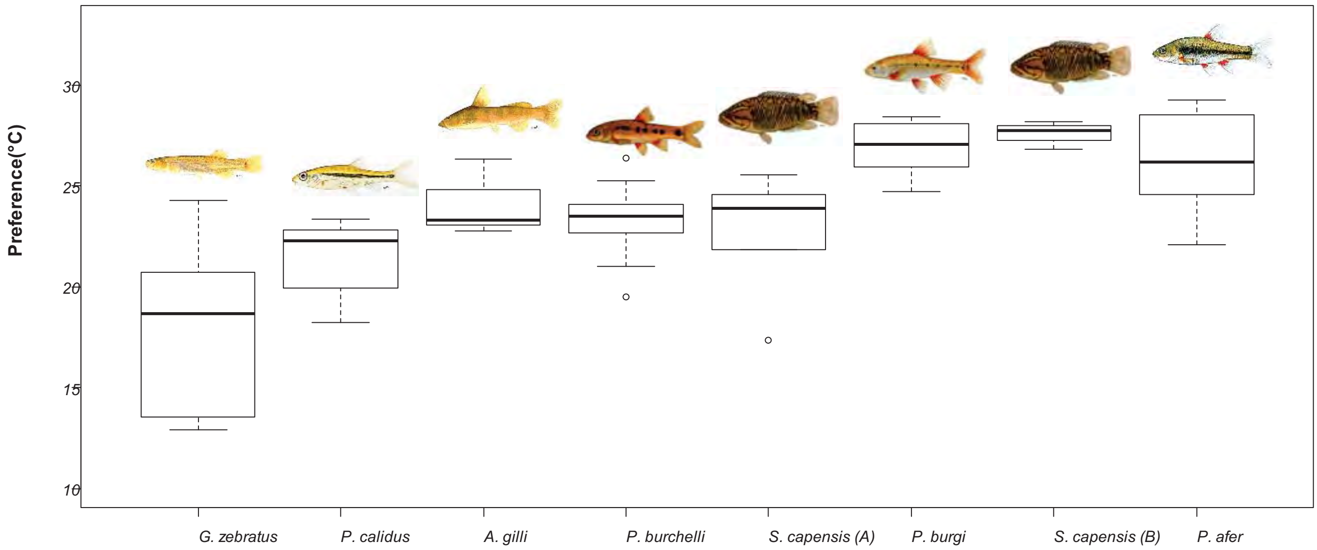


Figure 6. Boxplot showing median, quartiles and range of thermal preference for all species in the Western Cape from coolest to warmest preference. (Parentheses denote the River; A= Amandel, B= Berg). All illustrations are ©NRF-SAIAB.

3.2.6. Spatial and seasonal plasticity between and within species of aquatic invertebrates and fish

Thermal history of an aquatic organism reflects the antecedent *in situ* water temperature of the river, with upper thermal limits and preferences within a species varying from one river to another, and over time with season.

- Median CT_{max} and ILUT varied significantly amongst rivers for both *L. penicillata* (CT_{max}: 29.1 to 34.2; ILUT: 19.3 to 23.3°C) and *A. capensis* (CT_{max}:28.2 to 32.3°C; ILUT: 20.8 to 23.2°C) [57]
- Species specific thermal limits varied amongst rivers by as much as 5.7°C for CT_{max} and 4.0°C for 96 h ILUT. *A. capensis* had a lower MWAT threshold (17.0 °C) than *L. penicillata* (19.0°C) [57]
- CT_{max} values varied significantly amongst geographic regions for all families examined [38]. Differences were often evident amongst winter versus summer rainfall regions
- CT_{max} differed significantly among species within the genus *Pseudobarbus* (30.1 to 35.1°C) and within the species *P. phlegethon* (30.3 and 32.7°C) and *S. capensis* (34.8 to 36.8°C), with higher CT_{max} from species resident in streams with higher *in situ* water temperatures [51]
- Focusing on a single species, *G. zebratus*, upper thermal limits were strongly related to thermal history. Median CT_{max} values for *G. zebratus* ranged from 30.0°C to 32.5°C in spring/early summer 31.3°C to 33.4°C in late summer. Fish from warmer sites had higher upper thermal limits compared to fish from cooler sites; and fish generally had higher upper limits during the warmer late summer period (January to February) compared to the spring/early summer period (November to December) [52]
- Upper thermal limits varied significantly with season for the amphipod, *P. nigroculus*, and the mayfly, *L. penicillata*, confirming that seasonal acclimatisation of both species occurred. Greatest differences were observed between summer (highest upper limit) and winter (lowest upper limit) [48]
- The rate of change in water temperature influenced thermal stress, with *P. nigroculus* more vulnerable to rapid increases in temperature, compared to *L. penicillata*, which appears more vulnerable over longer durations. Thus, both the intensity and duration of thermal stress influence survival [48]
- The proportion of time within a 24-h period that chronic thermal stress thresholds are not exceeded provides a measure of monthly or seasonal chronic thermal stress and reflects the quantity of temporal thermal refugia for vulnerable organisms [48]
- Thermal preference of *Pseudobarbus burgi* and *Pseudobarbus afer* was significantly higher in summer in comparison to spring for *P. burgi* (27.0°C and 21.9°C respectively) and higher in summer in comparison to winter for *P. afer* (26.2°C and 21.6°C respectively) [51]

- From these thermal experiments it is clear that both spatial and temporal variation in upper thermal limits is evident across a range of aquatic invertebrate and fish species. The extent to which species thermal limits varies across sites and seasons, provides an important measure of its relative resilience to climate change.
- From a biological threshold perspective, these studies have demonstrated that upper thermal limits are related to one or more statistics used to summarise water temperature data.

3.3 Counting the potential cost

3.3.1. Life history, probability and species distribution models

Spreadsheet probability and logistic regression models showed that cold-adapted Gondwanaland relict species are likely to become increasingly vulnerable and range limited, whereas multivoltine pest species are likely to become more abundant under scenarios of increased water temperatures. There will be clear ecological “winners” and “losers”, where life-history trains help in predicting species responses. For example:

- The univoltine mayfly, *Lestagella penicillata*, noteworthy as a conservation species by being a Gondwanaland relict species, is likely to undergo significant range contraction, especially when water temperatures exceed its biological thermal threshold by 60 days per annum, and especially when this occurs as a successive number of days. This could occur through increased probability of breeding failure [53]
- The multivoltine pest species of blackfly, *Simulium chutteri*, is predicted to benefit from warmer water temperatures. This will be reflected in larger populations and more generations per annum [53]
- Cold-water fish species are expected to undergo substantial habitat reduction in response to warming water temperatures [25,51] (Figure 7). This has implications both for prioritising cold-water stenothermic native fish species for conservation, and management of non-native fish species ranked by thermal sensitivity [25]

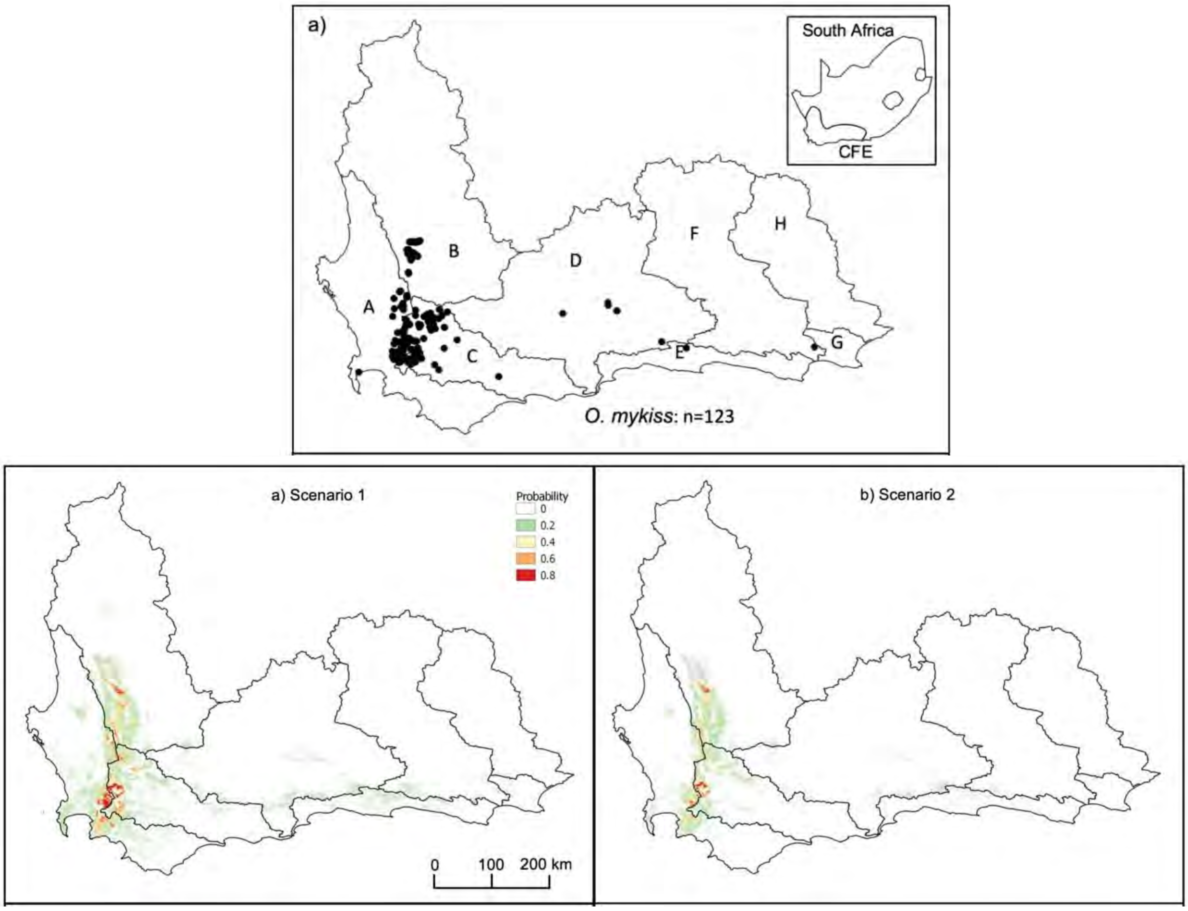


Figure 7. Occurrence data points for *O. mykiss* (top) in primary catchment areas in the Cape Fold Ecoregion (CFE). Primary river catchments included in the CFE are: A=Berg, B=Olifants-Doring, C=Breede, D=Gouritz, E=Coastal, F=Gamtoos, H=Sundays, G=Swartkops. The insert shows the location of the CFE in South Africa. The lower figures show predicted probabilities of occurrence for the *O. mykiss* for (a) present-day, (b) present-day +2 °C water temperature scenarios, based on species distribution models [51].

3.3.2. Blackfly research

Pest-level blackfly populations have not reached their upper ecological limit in terms of carrying capacity in the two river systems studied and that there remains additional niche space for blackfly expansion, presenting a problem that is likely to be exacerbated by predicted climate change:

- Logistic regression models, time series analyses, and multivariate ordinations showed that clearer water favours benthic algae and non-pest blackfly species, while high turbidity favours the major pest black fly species. These switches appear to be less frequent under post-impoundment conditions. Under an assumed 2°C increase in water temperatures, system switches are predicted to become even less frequent
- The current seasonal variation in the likelihood of pest outbreaks is replaced by high perpetual outbreak probabilities (Figure 8)
- Interactions between major environmental variables become synergistic, with major cost implications to regional economies
- Lessons from this study can be generalised and used as a means of predicting similar synergistic effects in other aquatic macroinvertebrate disease vectors (such as bilharzia vector snails and mosquitoes) in response to global climate change

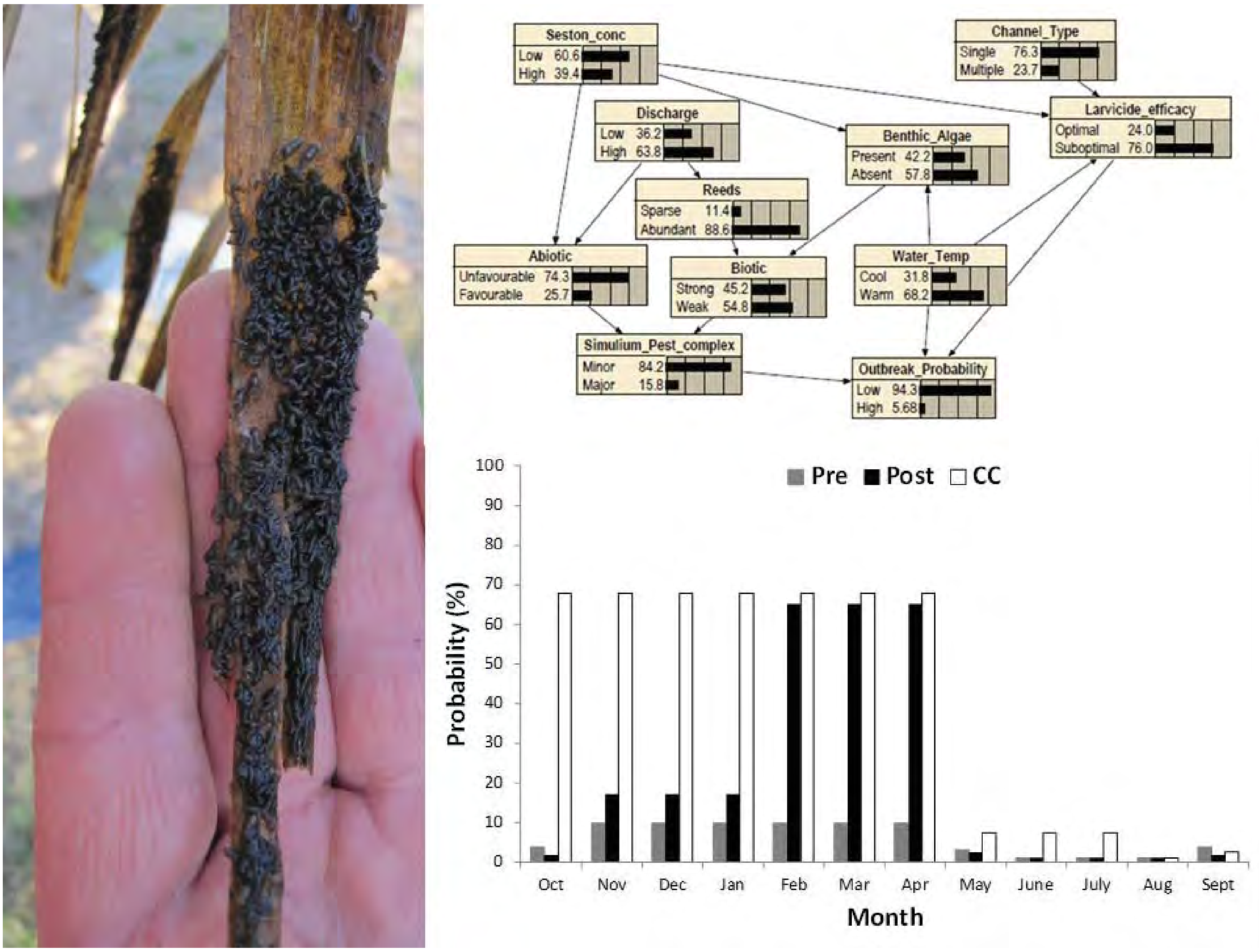


Figure 8. Larvae of pest blackfly at pest-level densities on a reed (left); schematic of Bayesian network predictive model for blackfly outbreaks based on system variables and their states; and monthly outputs as outbreak probabilities under pre-impoundment, post-impoundment (current) and future climate change scenarios [58].

3.3.3. Tools and frameworks [56]

Following extensive consultation with water resource practitioners via questionnaires, workshops and individually; there was a unanimous recognition that water temperature urgently needs to be routinely monitored in South African rivers. The following tools were provided within the framework:

- Recommended water temperature models based on whether site falls within an upland or lowland catchment (Figure 9)
- Key thermal impacts and their prevalence in South African rivers have been tabulated, and management and mitigation options outlined
- Biological effects of changes in water temperature (and flow) on river organisms are described and categorised as physiological, metabolic, phenological, reproductive, behavioural or ecological
- National maps of potential system resilience (Figure 10) and model accuracy

- A prototype Thermal Sensitivity Index (TSI) based on aquatic macroinvertebrates has been developed, whereby each taxon is assigned a Thermal Sensitivity Weighting based on a combination of an estimate of thermophily and thermal limits determined experimentally

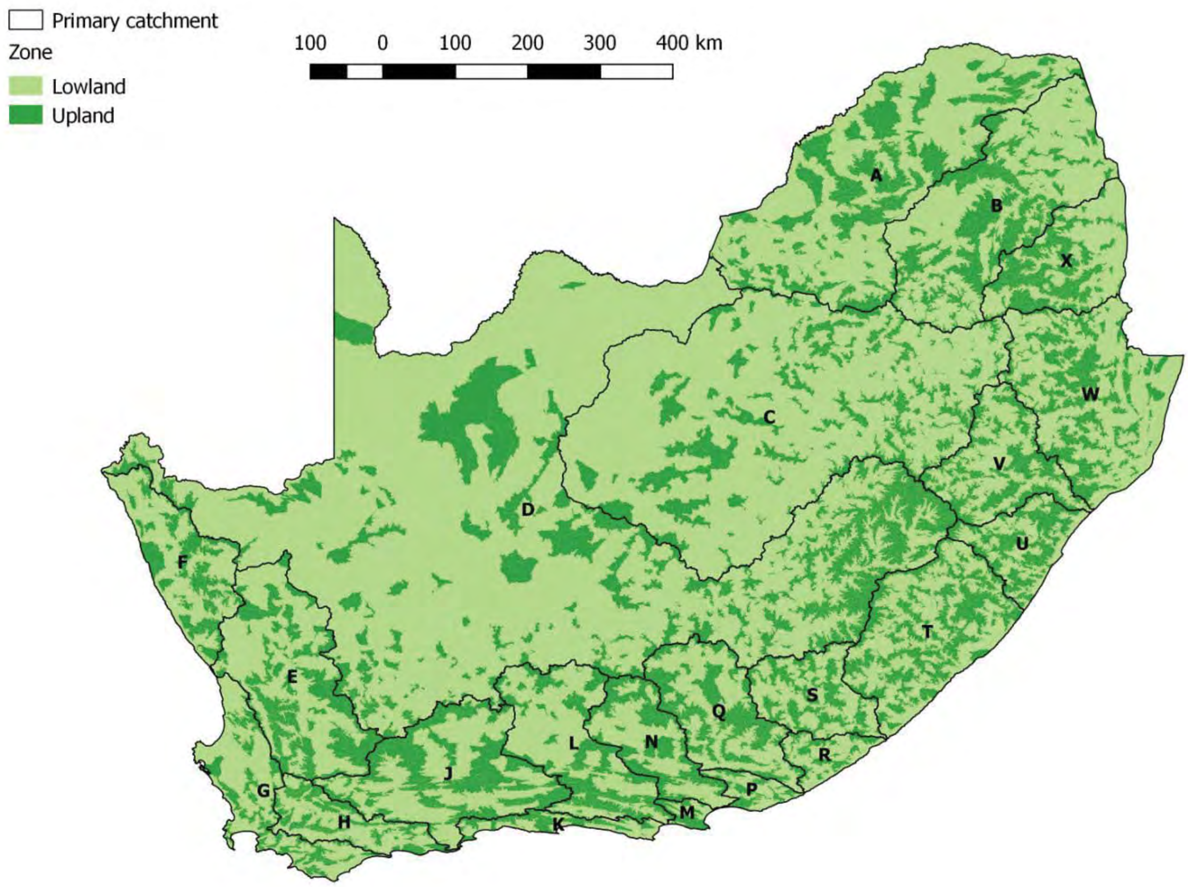


Figure 9. Lowland and upland regions of South Africa defined according to quinary sub-catchments, as a part of a thermal framework to assist in choosing water temperature models and assessing thermal risk to aquatic systems [56].

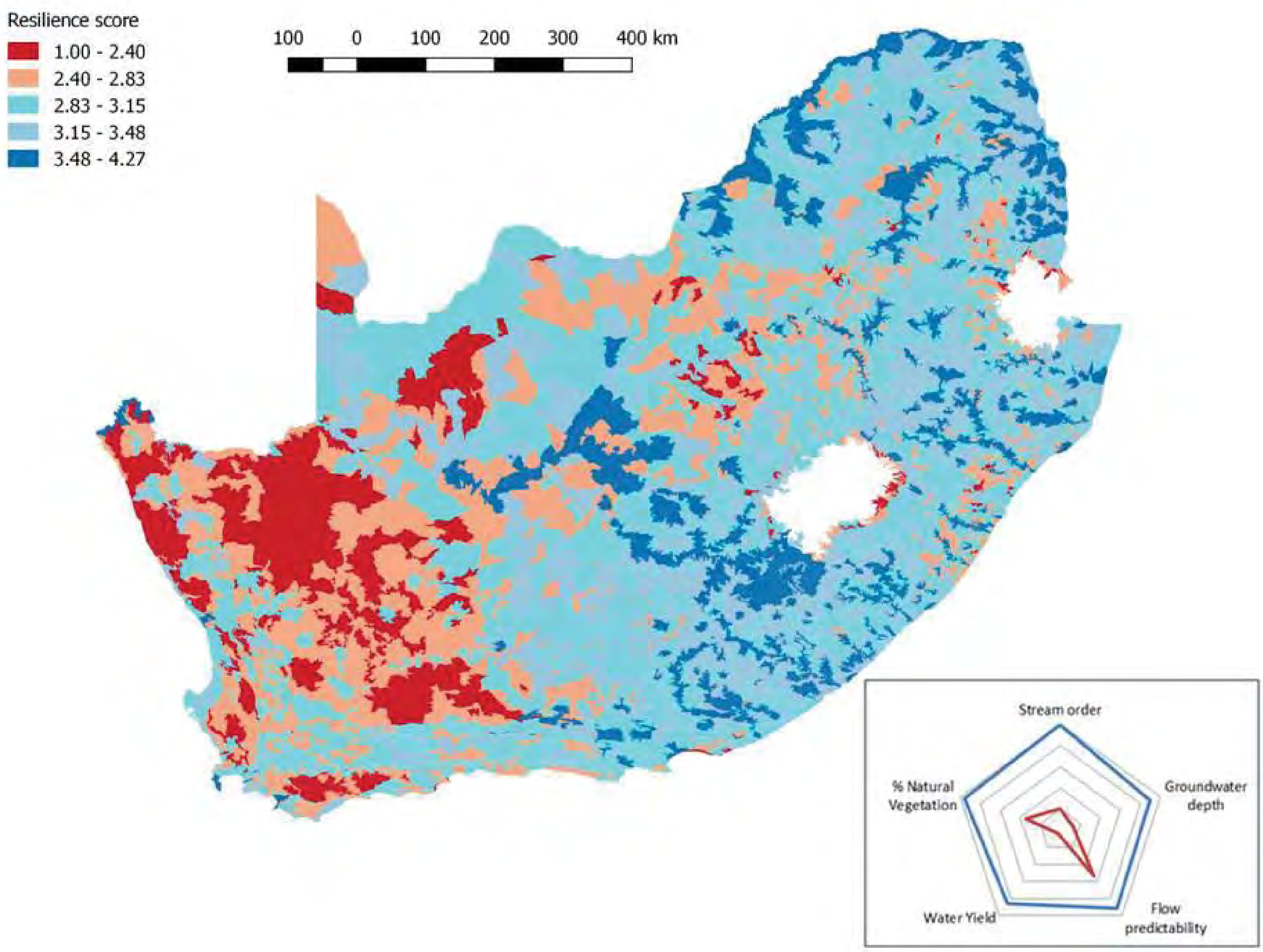


Figure 10. Map of Thermal Resilience giving Total Resilience Score (TRS) (low resilience = red; high resilience = blue). Inset shows a hypothetical radar plot of the relative importance of five site variables potentially affecting system resilience for a highly resilient site (blue) and a low-resilience site (red) [56]

4. Discussion

Water temperature is a fundamental index used to determine the nature of an aquatic environment [59], because of its role in the life histories of aquatic organisms. Furthermore, "temperature prediction may be used as a first step in predicting the effect of man's activity on the aquatic ecosystem of a body of water" [60]. Predicting water temperatures, and changes to water temperature regimes, is important for anticipating the potential impacts of temperature changes on the provision of ecosystem services, such as fisheries [13,61-63]. However, the general paucity of water temperature data, compared to river flow data, is a global problem, reflecting the later interest in water quality issues compared with water quantity issues. Data for Africa are particularly scarce [4,11], and river temperature data, where it does exist, may have been collected incidentally during other aquatic studies [64].

Mean daily water temperature is considered a poor ecological measure, and it is rather the accumulation of daily maximum temperatures above a critical threshold that affects fish condition and distribution [16,19,46,65]. The best predictor for presence or absence of trout (*Oncorhynchus kisutch*) was the number of days a site exceeded a critical temperature threshold

[66], and that single temperature values correlated poorly with fish presence and absence. The cumulative effect of daily maximum water temperatures has been shown to have the greatest effect on the distribution of aquatic species [16,19,46,65,67]. Therefore, a water temperature model that is appropriate to river ecologists, should predict ecologically significant water temperature characteristics, such as daily maximum water temperatures.

Water temperature simulation models are able to provide data for use in constructing thermographs for a river. The most common ecological use of these models is that the output can be used as inputs into plots of cumulative heat units, such as duration curves and degree curves. Temperature duration curves (percentage time versus temperature) are useful in comparing sites, while cumulative degree curves (hours, days) are useful in showing the sequence in which water is heated over time [68], thereby quantifying the cumulative warmth in a season at a particular location [16]. Cumulative degree curves are useful for evaluating the potential of a stream to achieve or maintain a temperature below a given threshold [16,68], and are a measure of average temperature reached and the time for which it is maintained [64]. Furthermore, degree units (days or hours) are a useful criterion for comparing temperature regimes between sites, and for relating field results to experimental data [64]. These curves take into account magnitude and duration of departure from a chosen threshold temperature [16]. Degree hour curves can be used for establishing threshold levels for population distributions [15,64], and have often been used to predict year-class strength of certain species of fish [69]. Growing degree days have been used extensively in crop yield modelling because they link a plant's growth stage to environmental cues rather than calendar days [70].

The extent to which drivers and buffers modify the thermal regime of rivers in South Africa is not known. The identification of the magnitude of selected thermal modifiers within the South Africa context would provide insight into management of thermal changes in river systems. Human alteration of insulators and buffers, for example changing groundwater dynamics, channel morphology and turbidity, are critical pathways of human influence on channel water temperatures [7]. What is known is that upper catchment river systems and their biota are most susceptible to climate change impacts [37]. This is due to a number of factors, including prevalence of cold-water stenothermic species and steep thermal gradients over narrow river lengths.

Ecological impacts are demonstrated using amphibians as a case study. Within the broader literature, amphibians have been shown to exhibit thermoregulatory behaviour, with increased mortality linked to increased deviation from preferred thermal optima [71]. On a global scale, impacts of climate change on amphibians have been highlighted to include, *inter alia*, not only range shifts, but also a number of direct and indirect effects, including changes in community structure, competitive interactions and pathogen–host interactions [72]. Given the wide altitudinal distribution range of Natal cascade frogs, it is unlikely that increased water temperatures in response to global climate change will result in rapid range shifts of these frogs, based on their aquatic stages. This study suggests that, instead of this occurring [(see, for example, 73,74], it is more likely that the duration of the aquatic tadpole stage will be reduced from two years to one year, with a possible gradual attrition on low-altitude populations resulting from diminished condition and fecundity. This has a number of possible implications, none of which can be tested without further data, but which have merit in forming hypotheses. These include reduced exposure to predation resulting from a shortened aquatic stage, which may impact positively or negatively on Natal cascade frog population sizes. A second unknown linked to predation relates to how climate change may impact on the distribution of predators, and in the absence of predators there may be an increase in abundance at higher altitudes. Notably, warmer water temperatures are detrimental to trout populations [75]. Unknowns resulting from the consequences of altered life-cycle length may relate to how adult frogs may cope with increased air temperatures; and how changes in water temperature translate into changes in body size and fecundity, since, certainly in aquatic macroinvertebrates, cooler water temperatures result in larger, more fecund individuals [76]. Two further unknowns, both of which advocate strongly for taking the precautionary approach of maintaining habitat connectivity and integrity, are the effects of climate change on stream hydrology and water velocities, and the potential for synergistic food web asynchronies to result from changes in lifecycle duration and timing, all of which are connected to periodicity and predictability. Practical management options could include mitigation of physical habitat loss due to sedimentation and altered flows through catchment management – e.g. control of alien vegetation and maintenance of riparian zones.

Expanding these outcomes into general principles, likely impacts of global change in South African rivers include homogenisation of aquatic communities, measurable as a loss of beta diversity; dominance by generalist species and loss of individual river species signatures [77,78]. Rare and narrow-range species will be the first to be lost, and will probably go unnoticed since turnover is driven by common species. However, given differential responses to thermal stress, and different levels of thermal stress plasticity, climate change is likely to result on substantial reorganization of aquatic communities, with a ripple effect through trophic levels. Implications are that pest species are likely to become worse, while less-common but high conservation value species could begin to drop out of ecological communities. Aside from the economic implications of such outbreaks, a shift towards more variable, event-driven river systems dominated by generalist species implies a loss of the uniqueness and resilience of our rivers. It becomes critical that river connectivity be maintained as far as possible so that river biota will be able to adapt. We propose management options that include maintaining river connectivity and dam re-operation as potential mitigation measures.

Given the limited resources for conservation actions, tools that allow identification of catchment “hotspots” for interventions assist with gaining maximum river system leverage for least cost. Such hotspots have been shown to be an effective catchment conservation approach [79]. The thermal resilience map provides one such hotpot identification tool, which, if combined with river connectivity spatial layers and species thermal tolerance data, creates an objective and repeatable approach to maximizing targeted conservation inputs. River connectivity is fundamental to resilience and persistence in aquatic ecosystems. Sadly, a recent study published in the journal *Nature* showed that only 37% of rivers > 1000 km long remain free-flowing globally [80]. While impoundment, channelisation and water abstraction of rivers are not new issues, the stakes have become higher in the past few decades. Indicator organisms for climate change monitoring include “detectors” and “sentinels”. The former are naturally occurring species that are suitable indicators of environmental change, while the latter are non-native organisms that are sensitive to environmental change, and have the potential to act as early warning “devices”. Responses may be measured in terms of changes in distribution, abundance, physiology and phenology. An example of a thermally sensitive “detector” species in the Western Cape is the Gondwanaland relict species *Lestagella penicillata* (Ephmeroptera: Telaganodidae). A suitable “sentinel” species is rainbow trout, which, while considered as an alien invasive species, nevertheless functions as a highly thermally sensitive species to warming temperatures in upper catchment streams.

Both indicator types are useful in climate change monitoring programmes, especially when they incorporate Citizen Science. This idea has already been pioneered in Australia in the early 2000s. Published studies are already available for South African rivers where response curves have been established for thermally sensitive species to changes in flows and water temperatures. These have the potential to be linked to selected catchments chosen on the basis of their flow regime type and conservation value. Given that there are high levels of data redundancy between sites in thermal data, monitoring networks can be optimized to provide maximum data for most efficient cost [81]. The scientific benefits of such a programme are also clear, because though a long-term monitoring programme where trend and system change can be detected in an early warning system, mitigatory interventions can be tested in an adaptive management approach.

5. Conclusions

Our rivers may already be at tipping point for an extinction debt to be paid. This will play itself out in the loss of specialist and/ or unique species, and replacement by generalist and opportunistic species, and heightened levels of alien invasions. The very real potential exists for riverscape to start to resemble agricultural landscapes, where biodiversity is homogenized at the expense of ecosystem resilience and provision of natural services. Single species dominance and proliferation of pest species are outcomes of this process. The only viable mechanisms of mitigating against this unrecorded process of attrition will be through carefully designed monitoring networks, and facilitating river connectivity wherever possible.

Funding: This research was funded by the WRC, under project numbers K8/689, K8/690, K5/1799, K5/2182, K5/2264, K5/2337, K5/2459, K5/2537.

Data availability statement: Data supporting reported results can be accessed by contacting the authors directly, or via the Freshwater Biodiversity Information System portal for selected datasets.

Acknowledgments: We gratefully acknowledge the support and contributions to our research over the years from the WRC and the research managers who have supported our projects (Dr Steve Mitchell; Mr Bonani Madikizela; Dr Brilliant Petja). We also wish to express gratitude to the many colleagues, post-graduate students and support staff that have supported and facilitated our research projects over the years.

References

1. van Wilgen, N.J.; Goodall, V.; Holness, S. ;Chown, S.L.; McGeoch, M.A.. Rising temperatures and changing rainfall patterns in South Africa's national parks. *Int. J. Climatol.* **2016**, 36, 706-721.
2. MacFadyen, S.; Zambatis, N.; Astrid, J. A.; Van Teeffelenb; Cang, H. Long-term rainfall regression surfaces for the Kruger National Park, South Africa: a spatio-temporal review of patterns from 1981 to 2015. *Int. J. Climatol.* **2018**, 38, 2506–2519.
3. Trabucco, A., & Zomer, R. *Global Aridity Index and Potential Evapotranspiration (ET0) Climate Database*. **2019.** https://classes.engr.oregonstate.edu/cce/spring2019/ce202/Data/global-ai_et0/ai_et0/Global%20AI_PET%20v2%20-%20Readme.pdf
4. Ward, J.V. Thermal characteristics of running waters. *Hydrobiologia* **1985**, 125, 31-46.
5. Johnson, S.L. Stream temperature: scaling of observations and issues for modelling. *Hydrol. Process.* **2003** (17), 497-499.
6. Bartholow, J.M. Stream temperature investigations: field and analytic methods. *Biological Reports* **1989**, 89(17).www.krisweb.com/biblio/general/usfws/bartholo.pdf
7. Poole, G.C.; Berman, C.H. Pathways of human influence on water temperature dynamics in stream channels. *Environ. Manage*, **27**(6), 787-802.
8. Gordon, N.D.; McMahon, T.A.; Finlayson, B.L. Stream Hydrology: An Introduction for Ecologists. John Wiley and Sons, Chichester, 1994.
9. Nikolsky, G.V. The Ecology of Fishes. Academic Press, London, 1963.
10. Allan, J.D. Stream Ecology: Structure and function of running water. Chapman and Hall, London, 1995.
11. Webb, B. W. Trends in stream and river temperature. *Hydrol. Process.* 1996, 10, 205-226.
12. Crisp, D.T.; Howson, G. Effect of air temperature upon mean water temperature in streams in the north Pennines and English Lake District. *Freshw. Biol.* 1982, 12, 359-367.
13. Hostetler, S.W. Analysis and modelling of long-term stream temperatures on the Steamboat Creek Basin, Oregon: Implications for land use and fish habitat. *Water Res. Bull,* **27**(4), 637-647.
14. Claska, M.E.; Gilbert, J.J. The effect of temperature on the response of *Daphnia* to toxic cyanobacteria. *Freshw. Biol.* 1998. 39, 221-232.
15. Vannote, R.L.; Sweeney, B.W. Geographic analysis of thermal equilibria: A conceptual model for evaluating the effect of natural and modified thermal regimes on aquatic insect communities. *Am. Nat*, **115**(5), 667-695.
16. Essig, D.A. The dilemma of applying uniform temperature criteria in a diverse environment: an issue analysis. **1998**. Idaho Division of Environmental Water Quality, Boise, Idaho. www.krisweb.com/biblio/general/misc/essigidahotemp.pdf
17. Dallas, H.F.; Rivers-Moore, N.A. Ecological consequences of global climate change for freshwater ecosystems in South Africa. *S. Afr. J. Sci*, **110** (5/6) Art. #2013-0274, 11 pages. http://dx.doi.org/10.1590/ sajs.2014/20130274.
18. Harrison, A.D. General statement on South African Hydrobiological Regions. Report No. 1, project 6.8H. Internal Report, National Institute for Water Research, Council for Scientific and Industrial Research, Pretoria. 12 pp. 1959.
19. Stuckenberg, B.R. Effective temperature as an ecological factor in southern Africa. *Zoologica Africana* **1969**, 4(2), 145-197.
20. Weeks, D.C.; O'Keeffe, J.H.; Fourie, A.; Davies, B.R. A pre-impoundment study of the Sabie-Sand River system, Mpumalanga, with special reference to predicted impacts on the Kruger National Park. Vol. I: The ecological status of the Sabie-Sand River system. WRC report no. 294/1/96. Water Research Commission: Pretoria.
21. Rivers-Moore, N.A.; Jewitt, G.P.W.; Weeks, D.C.; O'Keeffe, J.H. Water temperature and fish distribution in the Sabie River system: Towards the development of an adaptive management tool. WRC report no. 1065/1/04. Water Research Commission: Pretoria.
22. Sheldon A.L. Possible climate-induced shift of stoneflies in a southern Appalachian catchment. *Freshw. Sci.* **2012**, 31, 765–774.
23. Rivers-Moore, N.A.; Karssing, R.J. Water temperature affects life cycle duration of tadpoles of Natal cascade frogs in KwaZulu-Natal, South Africa. *Afr. J. Aquat. Sci.*, 39(2), 223-227.
24. Ross-Gillespie, V. Effects of water temperature on life history traits of selected South African aquatic insects. PhD Thesis, University of Cape Town, Cape Town, 2014.
25. Rivers-Moore, N.A.; Ellender, B.R.; Weyl, O.L.F. Modelling expected trout ranges under current and future water temperature regimes in the Eastern Cape, South Africa. *Afr. J. Aquat. Sci.* **2019**, 44, 35-42.
26. Webb, B. W.; Nobilis, F. Long-term perspective on the nature of the air-water temperature relationship: A case study. *Hydrol. Process.* **1997**, 11, 137-147.
27. Smith, K. River water temperatures - an environmental review. *Scott. Geogr. Mag.* **1972**, 88, 211-220.
28. Walters, C.; Korman, J., Stevens, L.E.; Gold, B. Ecosystem modeling for evaluation of adaptive management policies in the Grand Canyon. *Conserv. Ecol*, **4**(2), 1 [online].http://www.consecol.org/vol4/iss2/art1.

29. Mohseni, O.; Erickson, T.R.; Stefan, H.G. 1999. Sensitivity of stream temperatures in the United States to air temperatures projected under a global warming scenario. *Water Resour. Res*, **35**(12), 3723-3733.
30. Lewis, T. Stream Temperature Protocol. **1999**, Humboldt State University - Forest Science Project, Arcata, CA. <http://www.krisweb.com/stream/temp.htm>.
31. Rivers-Moore, N.A.; Dallas, H.F.; de Moor, F.C.; Barendse J. Relationships of water temperature and aquatic macroinvertebrate community structure with non-native riparian plant densities in the southern Cape, South Africa. *Afr. J.f Aquat. Sci.* **2018**, 43, 215-227.
32. Rivers-Moore, N.A.; Jewitt, G.P.W. Adaptive management and water temperature variability within South African rivers: What are the management options? *J. Environ. Manage.* **2007**, 82(1), 39-50.
33. Webb, B.W.; Hannah, D.M.; Moore, R.D.; Brown, L.E.; Nobilis, F. Recent advances in stream and river temperature research. *Hydrol. Process.* **2008**, 22, 902-918.
34. Dallas, H.F.; Rivers-Moore, N.A. Water temperatures and the ecological reserve. **2012**, WRC report no. 1799/1/12, Water Research Commission: Pretoria.
35. Rivers-Moore, N.A. Deriving conservation targets for rivers. WRC Report No. 1796/1/10, Water Research Commission: Pretoria.
36. Rivers-Moore, N.A. Turnover patterns in fish versus macroinvertebrates – implications for conservation planning. *Afr. J. Aquat. Sci.* **2012**, 37, 301-309.
37. Rivers-Moore, N.A.; de Moor F.C. Longitudinal species turnover rates are predictable and should guide location of sampling sites for South African river surveys to assess aquatic biodiversity. *Afr. J. Aquat. Sci,* 46(1), 45-53.
38. Dallas, H.F.; Rivers-Moore, N.A.; Ross-Gillespie, V.; Ramulifho, P.; Reizenberg, J. Adaptability and vulnerability of Riverine Biota to Climate Change – Developing Tools for Assessing Biological Effects. WRC report no. 2182/1/15. Water Research Commission: Pretoria.
39. Rivers-Moore, N.A.; Mantel, S.; Ramulifho, P.; Dallas, H. A disconnectivity index for improving choices in river protected area management. *Aquat. Conserv.: Mar. Freshw. Ecosyst.* **26** (Suppl. 1), 29-38.
40. Ramulifho, P.A.; Rivers-Moore, N.A.; Dallas, H.F.; Foord, S.H. A conceptual framework towards more holistic freshwater conservation planning through incorporation of stream connectivity and thermal vulnerability. *J. Hydrol* **2017**, 556, 173-181.
41. Dallas, H.F.; Ross-Gillespie, V. Sublethal effects of temperature on freshwater organisms, with special reference to aquatic insects. *Water SA*. **41**(5), 712-726.
42. Dallas, H.F.; Ketley, Z.A. Upper thermal limits of aquatic macroinvertebrates: Comparing critical thermal maxima with 96-LT50 values. *J. Therm. Biol.* **2011**, 36, 322–327.
43. Dallas, H.F.; Rivers-Moore, N.A. Critical thermal maxima of aquatic macroinvertebrates: towards identifying bioindicators of thermal alteration. *Hydrobiologia* **2012**, 679, 61-76.
44. Ross-Gillespie, V.; Picker, M.D.; Dallas, H.F.; Day, J.A. The role of temperature in egg development of three aquatic insects *Lestagella penicillata* (Ephemeroptera), *Aphanicercella scutata* (Plecoptera), *Chimarra ambulans* (Trichoptera) from South Africa. *J. Therm. Biol.* **2018**, 71, 158-170.
45. Brungs, W.A.; Jones, B.R. Temperature Criteria for Freshwater Fish: Protocol and Procedures. 1977, US Environmental Protection Agency Environmental Research Laboratory, Duluth, Minn. EPA-600/3-77-061.
46. Armour, C.L. Guidance for evaluating and recommending temperature regimes to protect fish. *Biological Reports*, 90(22): 13.www.krisweb.com/biblio/general/usfws/armour.pdf
47. Rezende, E.L.; Castañeda, L.E.; Santos, M. Tolerance landscapes in thermal ecology. *Funct. Ecol.* **2014**, 28, 799–809.
48. Dallas, H.F.; Rivers-Moore, N.A. Temporal thermal refugia and seasonal variation in upper thermal limits of two species of riverine invertebrates: the amphipod, *Paramelita nigroculus*, and the mayfly *Lestagella penicillata*. *Aquat. Ecol.* **2018**, 52, 333-349.
49. Ellender, B. R.; Wasserman, R. J.; Chakona, A.; Skelton, P.H.; Weyl, O.L. A review of the biology and status of Cape Fold Ecoregion freshwater fish. *Aquat Conserv.: Mar. Freshw. Ecosyst.* **27**(4), 867–879.
50. Reizenberg, J-L.; Bloy, L.E.; Weyl, O.L.; Shelton, J.M.; Dallas HF. Variation in thermal tolerances of native freshwater fishes in South Africa's Cape Fold Ecoregion: examining the east–west gradient in species' sensitivity to climate warming. *J. Fish Biol.* **94**(1), 103-112.
51. Dallas, H.; Shelton, J.; Paxton, B.; Weyl, O.; Reizenberg, J-L.; Bloy, L.; Rivers-Moore, N. Assessing the Effect of Climate Change on Native and Non-Native Freshwater Fishes of the Cape Fold Ecoregion, South Africa. WRC report no. TT 801/19, Water Research Commission: Pretoria.
52. Olsen, T.; Shelton, J.M.; Dallas, H.F. Does thermal history influence thermal tolerance of the freshwater fish *Galaxias zebratus* in a global biodiversity hotspot? *J. Therm. Biol.* **2021**, 97, 102890, https://doi.org/10.1016/j.jtherbio.2021.102890.
53. Rivers-Moore, N.A., Dallas, H.F.; Ross-Gillespie, V. Life history does matter in assessing potential impacts of thermal changes on aquatic macroinvertebrates. *River Res. Applic.* **2013**, 29, 1100-1109.

54. Rivers-Moore, N.A.; Hill, T.R. A predictive management tool for blackfly outbreaks on the Orange River, South Africa. *River Res. Appl.* **2018**, 34, 1197-1207.
55. Rivers-Moore, N.A.; Palmer, R. The influence of turbidity and water temperature on black fly species in the middle and lower Orange River, South Africa. *Can. J. Zool.* **96**(6), 614-621.
56. Dallas, H.F.; Rivers-Moore, N.A. Environmental Water Temperature Guidelines for Perennial Rivers in South Africa, Volume 1: Technical Report. WRC report no. TT 799/1/19; and Volume 2: A technical Manual for Setting Water Temperature Targets WRC report no. TT 799/2/19. Water Research Commission: Pretoria.
57. Dallas, H.F. The influence of thermal history on upper thermal limits of two species of riverine insects: the stonefly, *Aphanicerca capensis*, and the mayfly, *Lestagella penicillata*. *Hydrobiologia* **2016**, 781, 95-108.
58. Rivers-Moore, N.A.; de Moor, F.C. Climate-linked freshwater habitat change will have cost implications: Pest blackfly outbreaks in two linked South African rivers. *River Res. Appl.* **2020**, 37, 387-398.
59. Jewitt, G.P.W.; Görgens, A.H.M. Facilitation of interdisciplinary collaboration in research projects: lessons from a Kruger National park Rivers Research Programme project. *S. Afr. J. Sci.* **96**(8), 410-414.
60. Brown, G.W. Predicting temperatures of small streams. *Water Resour Res.* **5**(1), 68-75.
61. Morse, W.L. Stream temperature prediction model. *Water Resour. Res.* **6**(1), 290-302.
62. Eaton, J.G.; Scheller, R.M. Effects of climate on fish thermal habitat in streams of the United States. *Limnol. Oceanogr.* **41**(5), 1109-1115.
63. Graham, W.D.; Thorpe, J.E.; Metcalfe, N.B. Seasonal current holding performance of juvenile Atlantic salmon in relation to temperature and smolting. *Can. J. Fish. Aquat. Sci.* **1996**, 53, 80-86.
64. Appleton, C.C. Observations on the thermal regime of a stream in the Eastern Transvaal, with reference to certain aquatic Pulmonata. *S. Afr. J. Sci.* **1976**, 72, 20-23.
65. Caissie, D.; El-Jabi, N.; Satish, M.G. Modelling of daily maximum water temperatures in a small stream using air temperatures. *J. Hydrol.* **2001**, 251, 14-28.
66. Hines, D.; Ambrose, J. Evaluation of stream temperatures based on observations of juvenile coho salmon in northern California streams, **1998**, http://www.krisweb.com/biblio/general/misc/hinesambrose.pdf.
67. Sullivan, K.; Martin, D.J.; Cardwell, R.D; Toll, J.E.; Duke, S. An analysis of the effects of temperature on salmonids of the Pacific Northwest with implications for selecting temperature criteria. **2000**, Sustainable Ecosystems Institute, Portland, Oregon. www.sei.org/downloads/reports/salmon2000.pdf.
68. Webb, B.W.; Walling, D.E. Temporal variation of river water temperatures in a Devon river system. *Hydrol. Sci.* **30**(4): 449-464.
69. Nunn, A.D.; Cowx, I.G.; Frear, P.A.; Harvey, J.P. Is water temperature an adequate predictor of recruitment success in cyprinid fish populations in lowland rivers? *Freshw. Biol.* **2003**, 48, 579-588.
70. Schulze, R.E. Hydrology and Agrohydrology: A text to accompany the ACRU 3.00 agrohydrological modelling system. **1995**, WRC report no. TT69/95. Water Research Commission: Pretoria.
71. Catenazzi, A.; Kupferberg, S.J. The importance of thermal conditions to recruitment success in stream-breeding frog populations distributed across a productivity gradient. *Biol. Conserv.* **2013**, 168, 40–48.
72. Blaustein, A.R.; Walls, S.C.; Bancroft, B.A.; Lawler, J.J.; Searle, C.L., Gervasi, S.S. Direct and indirect effects of climate change on amphibian populations. *Diversity* **2010,** 2: 281–313.
73. Domisch, S.; Jahnig, S.C.; Haase, P. Climate-change winners and losers: stream macroinvertebrates of a submontane region in Central Europe. *Freshw. Biol.* **2011**, 56, 2009-2020.
74. Rivers-Moore, N.A.; Dallas, H.F.; Morris, C. Towards setting environmental water temperature guidelines: A South African example. *J. Environ. Manage.* **2013**, 82, 39-50.
75. Rieman, B.E.; Isaak, D.; Adams, S.; Horan, D.; Nagel, D.; Luce, C.; Myers, D. Anticipated climate warming effects on bull trout habitats and populations across the interior Columbia Basin. *Trans. Am. Fish. Soc.* **2007**, 136, 1552-1565.
76. de Moor, F.C. Determination of the number of instars and size variation in the larvae and pupae of Simulium chutteri Lewis 1965 (Diptera: Simuliidae) and some possible bionomical implications. *Can. J. Zool.* **1982**, 60, 1374–1382.
77. Eady, B.R.; Rivers-Moore, N.A.; Hill, T.R. Relationship between water temperature predictability and aquatic macroinvertebrate assemblages in two South African streams. *Afr. J. Aquat. Sci.* **2013**, 38, 163-174.
78. Eady, B.R.; Hill T.R.; Rivers-Moore, N.A. Shifts in aquatic macroinvertebrate community structure in response to perenniality, southern Cape, South Africa. *J. Freshw. Ecol.* **29**(4), 475-490.
79. Newson, M. Understanding 'hot-spot' problems in catchments: the need for scale-sensitive measures and mechanisms to secure effective solutions for river management and conservation. *Aquat. Conserv.: Mar. Freshw. Ecosyst.* **2010**, 20, 62–72.
80. Grill, G.; Lehner, B.; Thieme, M.; Geenen, D.; Tickner, D.; Antonelli, F. et al. Mapping the world's free-flowing rivers. *Nature* **2019**, 569, 215–221.
81. Isaak, D.J.; Luse, C.H.; Chandler, G.L.; Horan, D.L.; Wollrab, S.P. Principal components of thermal regimes in mountain river networks. *Hydrol. Earth Syst. Sci.* **2018**, 22: 6225-6240.

Chapter 6

Response of South African coastal wetlands to climate change

Janine Barbara Adams[1*], Johan Wasserman[1], Jacqueline Leoni Raw[1] and Lara Van Niekerk[1,2]

1 DSI/NRF Research Chair in Shallow Water Ecosystems, Department of Botany, Institute for Coastal & Marine Research, Nelson Mandela University
2 CSIR, PO Box 320, 7600, South Africa
* Corresponding author: Janine.adams@mandela.ac.za

Abstract: The South African coastline has 290 estuaries that span over four biogeographic zones and support seagrasses, salt marshes and mangroves. These coastal wetland habitats provide a multitude of ecosystem services, but these services are threatened by the impacts of climate change. Predicted effects include sea level rise, increased sea storms and wave height, increased flood intensity, droughts, closure of estuary mouths salinisation, and increased atmospheric CO_2 and temperature. These impacts alter key abiotic stressors such as inundation patterns, salinity gradients and sediment biogeochemistry. Sea level rise raises concerns of habitat loss due to coastal squeeze and macrophyte dieback due to mouth closure and the associated changes in salinity and inundation regimes. Droughts may also increase mouth closure and salinity leading to changes in coastal wetlands. More intense sea storms and flooding can lead to increased deposition of sediments resulting in the smothering of mangroves and salt marsh. Increased temperatures are expected to facilitate the encroachment of mangroves into salt marsh habitats. The biogeographical patterns observed along the South African coastline present an important opportunity for climate change research as the transition between subtropical and warm temperate regions and between cool temperate and warm temperate regions are expected to be significantly influenced. Conservation and management plans need to include future changes in climate to ensure the protection of estuarine ecosystems at the southern tip of Africa.

Keywords: Estuary, macrophyte response, multiple stressors, sea level rise, coastal storms

1. Introduction

The estuaries of South Africa host important coastal wetland habitats (seagrasses, salt marshes and mangroves) that provide a multitude of valuable ecosystem services. Estuaries are dynamic environments at the interface of the land and the sea, thus are subjected to multiple natural stressors. Coastal areas have also been historically heavily populated; thus estuaries are susceptible to anthropogenic activities associated with transformation and development. In South Africa, estuaries are under high anthropogenic pressure and most of the estuarine area has already been impacted to some extent [1]. The natural stressors acting on estuaries will be altered with climate change and acting synergistically with anthropogenic pressures, threaten estuarine habitats over a range of spatial extents and temporal periods [2,3]. An understanding of how climate change will affect coastal wetlands is necessary for producing realistic and achievable management and conservation strategies and plans.

The South African coastline, spanning roughly 3,000 km, covers four biogeographical regions. In the country's north-eastern corner lies the tropical region, which transitions into a subtropical region on the east coast, the warm temperate region on the southern coast, and the cool temperate region along the west coast. Furthermore, the variation in climatic, oceanographic and geological characteristics along the South African coast results in a diversity of estuarine ecosystems. The country's 290 estuaries have been classified into nine ecosystem types based on key ecological features and biogeographic settings [4,5]. The variation in estuary type and climate result in local and regional differences in abiotic stressors, which influences the distribution of macrophytes throughout South African estuaries [6]. The diverse climate and estuarine types of South Africa presents a unique opportunity to investigate the response of coastal wetland habitats to climate change.

Six distinct macrophyte habitat types occur in South African estuaries: submerged macrophytes, salt marsh, reeds and sedges, mangroves, swamp forests and macroalgae (Table 1, Figure 1) [6,7]. Submerged macrophytes such as the endangered seagrass *Zostera capensis* occur mainly in the country's permanently open estuaries [8]. The fresher and calmer conditions of temporarily closed estuaries (TCEs) and estuarine lakes often allow for the establishment of other submerged macrophyte species like *Ruppia cirrhosa* and *Stuckenia pectinata* [6]. Salt marshes occur in sheltered estuaries throughout South Africa with the greatest area occurring in the cool temperate and warm temperate regions, respectively [9]. Salt marsh plants occur in zones along a distinct tidal inundation gradient (Figure 2). Reeds and sedges (e.g. *Phragmites australis*, *Schoenoplectus scirpoides* and *Bolboschoenus maritimus*) are the most widespread and dominant (in terms of area cover) habitat type nationally and are typically found in fresh and brackish areas of estuaries across all biogeographical regions [6]. Mangroves grow in 32 sheltered estuaries along a 1800 km stretch of the east coast spanning from the warm temperate to the tropical bioregion [10]. Swamp forests are limited to the subtropical to tropical east coast [6]. Attached and free-floating macroalgae are common in estuaries throughout South Africa (Table 1), and filamentous macroalgal mats often form in nutrient-enriched systems in closed estuaries with calm and sheltered conditions [7]. Information on the extent and distribution of these various habitats have been collated and catalogued in a national Estuary Botanical Database [6,11].

Coastal wetland habitats will be influenced in multiple ways by anthropogenic climate change. Not only will the increased CO_2 levels directly influence the physiology of macrophytes, but the already dynamic abiotic environment of coastal wetlands will be changed by the multitude of consequent impacts. These impacts are not straightforward to predict, as they depend on the context of environmental conditions and anthropogenic activity, which can differ greatly among regions [12]. While many studies have speculated the response of estuaries to climate change in different parts of the world [2,13,14], local studies are needed that cover different region-specific contexts. This study aims to provide predictions on how climate change will impact seagrass, salt marsh and mangrove habitats in South African estuaries.

2. Study approach

This review synthesises available knowledge from peer-reviewed literature on the ecological responses of coastal wetland habitats to the predicted impacts of climate change. Focus was placed on increased atmospheric CO_2 concentrations, increased temperatures, changes in hydrological processes, floods, droughts, sea-level rise and increased sea storms and wave height. While the emphasis was on South African literature, studies from elsewhere in the world were also consulted.

3. Results and discussion

The key estuarine abiotic processes expected to be altered by climate change and the resultant biotic responses and expected habitat trends toward the year 2050 are summarised in Table 2. Salt marsh and mangrove area are expected to decrease overall. To date mangrove area has remained fairly stable due to increases and decreases in certain estuaries. Submerged macrophyte habitats are highly dynamic, but little overall change in habitat area is predicted, however, some increased fluctuations in biomass are expected in response to increased occurrence of extreme events such as floods and droughts.

Table 1. Summary of the biogeographical distribution of six macrophyte habitat types

Macrophyte habitat types	**Biogeographical Region**			
	Cool temperate	**Warm Temperate**	**Subtropical**	**Tropical**
Submerged Macrophytes	•	•	•	•
Salt Marsh	●	●	•	•
Reeds and Sedges	•	•	•	•
Mangroves		•	●	●
Swamp Forests			●	●
Macroalgae	•	•	•	•

Figure 1. Mangrove, salt marsh and seagrass habitats in the Nahoon Estuary.

Figure 2. Salt marsh zonation along a tidal inundation gradient at Knysna Estuary.

Table 2. Climate change stressors and predicted habitat trends by 2050 for submerged macrophytes, salt marsh and mangroves in South African estuaries (*italics* indicate abiotic changes and responses in temporarily closed estuaries)

Abiotic change	Ecological responses		
	Submerged macrophytes	**Salt marsh**	**Mangroves**
↑**CO_2** Higher C availability	Increase in plant growth and productivity ↑4%	Increase in plant growth and productivity ↑4%	Increase in plant growth and productivity ↑4%
↑**Temperature** Warming Higher aridity	Competition with more abundant macroalgae Decreased growth due to higher epiphyte cover ↓4%	Increase in plant growth and productivity, however distributional range shifts and change in habitat diversity, mangroves replace salt marsh Increase in invasive species. Change in salt marsh phenology and extinctions ↓3%	Increase in plant growth and productivity Distributional range shifts and change in habitat diversity, mangroves replace salt marsh. ↑4%
↑**Floods** ↑ Nutrient inputs & eutrophication ↑Sediment input *Scouring of estuary, decrease in salinity*	Submerged macrophyte loss due to scouring, sediment deposition and smothering ↓4%	Macroalgal growth, smothering of salt marsh *Loss of salt marsh cover, change in species composition* ↓4%	Mangrove loss due to scouring, sediment deposition and smothering ↓4%
↑**Droughts** ↑Salinity and aridity ↑*Closed mouth condition* ↑*Water level & inundation, loss of intertidal habitat*	Higher water level will allow an increase in submerged macrophyte cover Seagrass cover increases in response to higher salinity cover ↑4%	Change in species and community composition Decrease in productivity Loss of salt marsh cover. *Increase in water level, flooding and dieback of salt marsh. Loss of intertidal habitat and marine connectivity.* ↓5.5%	Decrease in productivity and cover *Flooding and die-back of mangroves* ↓5.5%
↓↑ **Stream flow** ↑↓ Closed mouth condition ↑↓ Salinity penetration	Shift in water level will cause changes in submerged macrophyte cover Higher/lower salinity will increase/decrease seagrass cover	Shifts in water level, flooding will cause an increase/decrease in intertidal habitat and marine connectivity. Changes in species composition NO OVERALL CHANGE	Changes in mangroves Inland / landward migration of mangroves Decrease/increase in productivity and cover
↑**Sea level rise** +1.5 – 2.7 $mm.yr^{-1}$ Inundation & waterlogging, coastal squeeze ↑*Open mouth condition* ↑*Saline conditions*	Increase in intertidal area for seagrass colonisation Seagrasses can become established further upstream ↑4%	Possible salt marsh subsidence or landward migration Die-back and loss Changes in species composition *Expansion of salt marsh on exposed sand/mudflats* NO OVERALL CHANGE	Expansion of mangroves in intertidal areas Inland / landward migration of mangroves ↑4%
↑**Sea storms & wave height** Erosion ↑*Sediment deposition, constricted mouth*	Removal of seagrass and submerged macrophytes ↓4%	Smothering and loss of salt marsh *Increase in water level, flooding and dieback of salt marsh* ↓4%	Smothering e.g. of pneumatophores by marine sediment Loss of mangroves ↓4%
Ocean acidification	Possible increase in seagrass production and seagrass carbon storage	Not likely to cause significant impacts	

3.1. Increased atmospheric CO_2

Enhanced productivity due to higher CO_2 levels will occur for both mangroves and salt marshes as a result of increased photosynthetic efficiency and water use efficiency [17 and references therein]. Mangrove productivity will especially be favoured as these trees utilise the C3 photosynthetic pathway. Climate-related warming and an increase in CO_2 are positive conditions for mangroves to expand their distribution to higher latitudes but this will depend on propagule dispersal between estuaries and the availability of suitable habitats [25]. Many of the small estuaries are temporarily closed to the sea for different periods of time thus limiting recruitment [10]. Increased CO_2 concentrations are also expected to change the species composition of salt marshes. Higher CO_2 availability will favour the growth of C3 salt marsh species (e.g. *Salicornia spp* and *Juncus spp*) over C4 species such as *Spartina* maritima. [74]. Elevated CO_2 concentrations will likely also increase the productivity of seagrasses and macroalgae, as they mostly appear to use the C3 photosynthetic pathway as well [37].

3.2. Increased temperature

Over the last 50 years, land-based air temperatures in southern Africa have been rising at twice the global average and are projected to continue increasing at 1.5 times that of the global rate. In general, South Africa will experience a warmer and drier climate in the future. Increased temperatures will directly affect the growth and reproduction of estuarine macrophytes. In salt marshes and mangroves, productivity will increase until an upper temperature threshold is reached [9,16]. However, increased temperatures can inhibit the germination of certain salt marsh species and this could counteract potential increases in productivity [17]. Seagrasses are also sensitive to increased temperatures and may die-back in response to warming [18]. Warmer temperatures will also alter plant phenological patterns and species composition in coastal wetlands [9,19].

Increased temperatures, in conjunction with elevated CO_2 levels, will also change the distribution of estuarine habitats. Rising temperatures are associated with the expansion of mangroves towards higher latitudes, often into salt marsh habitats, in a phenomenon known as 'tropicalization'. Such range shifts have been described for different regions around the world [20-22], including for our subtropical east coast of South Africa [23,24]. Temperature is not a limiting factor in the poleward expansion of mangroves on South Africa's east coast; instead successful colonization of new sites by mangroves will depend on the effectiveness of propagule dispersal between estuaries, the local geomorphology (including the estuary mouth being open), and the availability of suitable riparian habitats [10,25]. Mangrove encroachment into salt marshes will result in a decrease in salt marsh cover [26].

Rising temperatures and the associated evaporation can have dire impacts on the health of coastal wetlands. In extreme cases, estuaries can become highly desiccated and hypersaline leading to great declines or die-offs of flora and fauna [27]. The effects of warming will be most apparent in shallow estuaries, particularly those experiencing a prolonged phase of mouth closure [28]. South Africa's estuarine lakes will likely also be susceptible to increased evaporation. For example, St Lucia, the country's largest estuarine lake, persisted in a highly desiccated hypersaline state following an extended drought during a closed mouth phase, resulting in significant declines in biota [29]. Habitats such as submerged macrophytes and reeds and sedges are particularly susceptible to hypersalinity and desiccation [30-32]. Some salt marsh habitats can persist in extreme hypersaline environments, but increased evaporation would likely contribute to the threat of salt marsh desertification [9,33].

The effects of extended ocean heat waves have not been documented in South Africa but can have severe consequences. Above average temperatures for four months (2 - 4°C above average) caused 90% die-back of seagrass beds in Shark Bay, Western Australia [34]. In northern Australia the 2016 extreme El Niño event led to extensive dieback of mangroves in the Gulf of Carpentaria [35]. Ocean heat waves have increased notably in frequency and duration over the last century and are projected to become more common in the future [36]. These warming events will have profound impacts on species distributions and community structure [37,38]. In January to March 2021 South Africa's south and east coast experienced such a temperature anomaly due to meanders of the Agulhas current. Most of the impacts were only observed in the nearshore coastal environments, but should serve as a warning that could this become a more frequent occurrence in our estuaries.

3.3. Changes to hydrological process (streamflow)

The ecological functioning and health of estuaries depends strongly on freshwater inflows, which will change with climate change-driven alterations in rainfall patterns. The most widespread impact resulting from the predicted hydrological changes will be changes in the mouth dynamics of estuaries. Approximately 75% of South Africa's estuaries close to the sea for varying periods of time due to the formation of sand berms at the mouth resulting from high-wave energy, high sediment availability, and low tidal flows and fluvial inflows [4,27]. These temporarily closed estuaries will be susceptible to change in hydrological regimes, but in extreme cases even predominantly open estuaries can close to the sea as occurred at the Gamtoos Estuary, which closed for the first time in 49 years due to drought and freshwater abstraction [39]. Drier conditions and higher inter-annual variability in rainfall patterns are expected on the western coast of South Africa (Table 3) [41,42]. The frequency and duration of mouth closure are expected to increase in this region [42]. Along the rest of the coastline, extreme rainfall events are projected to increase in spring and summer but decrease in autumn and winter [40,41,43]. It is predicted that mouth dynamics will remain largely similar along the southern coast and that open mouth conditions will generally become more common further up the eastern coast due to increased freshwater flows and flooding [42].

Changes in mouth condition are likely to cause substantial changes in the extent and distribution of coastal wetland habitats and have been shown to cause shifts between macrophyte habitat types [44-46]. During periods of mouth closure, estuaries are unsuitable for the establishment of mangroves and intertidal salt marsh. Furthermore, extended periods of mouth closure can result in high water levels which cause inundation and die-back of intertidal salt marsh and mangroves [44,45,47]. Large mangrove die-back events have been recorded at the Kosi, Kobonqaba and St Lucia estuaries [48-50]. Elevated salinity levels during periods of mouth closure also lead to the loss of submerged macrophytes and the proliferation of opportunistic macroalgae [45,46]. Macroalgal blooms will be particularly concerning in closed estuaries susceptible to eutrophication as they can shade and smother submerged macrophytes and salt marsh habitats [51-53]. However, more frequent mouth closure may increase the resilience of salt marshes to sea level rise as these intertidal habitats have greater elevation gains and sediment accretion rates than those that maintain a permanent connection to the sea [54]. Increased open mouth conditions, in contrast, will facilitate the establishment of salt marshes and mangroves and create a favourable environment for the persistence of submerged macrophytes [8,10]. However, the periods of high productivity typical of closed mouth conditions will be decreased [55,56].

3.4 Droughts

In addition to altering mouth dynamics, changes in freshwater inflows (particularly extreme events like droughts and floods) will decrease the resilience of coastal wetlands to the impacts of climate change. Decreased freshwater inflows and drought will result in the salinisation and desiccation of macrophyte habitats. High salinity and low moisture content in sediments decrease salt marsh species composition, cover, and productivity [9]. Salinisation and desiccation will particularly place pressure on the country's arid west coast estuaries such as the Groot Berg, Olifants and Orange (Table 3) where the desertification of large areas of salt marsh has been recorded [9]. On the east coast, drought stress will affect the physiological processes in mangrove trees related to water uptake and water use efficiency, and will inhibit growth and expansion [57,58]. Recent large-scale mangrove die-back events have occurred in northern and western Australia under drought conditions in combination with low sea levels and low humidity as a consequence of an El Niño-Southern Oscillation (ENSO) event [35,59,60]. Prolonged droughts can lead to soil shrinkage, which would inhibit the ability of salt marshes and mangroves to maintain their elevation relative to rising sea levels [61,62]. Soil volumes, however, can recover after droughts have ended [62]. Droughts can also cause shifts in habitat type; for example, large scale drought-induced dieback of salt marsh at the Mississippi River Delta, USA resulted in mangrove encroachment until it became the dominant habitat type [63].

Lower freshwater inflows will also result in increased seawater penetration into estuaries, reducing the extent of the river-estuary interface and changing the distribution of habitats. Under these circumstances, a reverse estuary gradient is often formed. Increased salinity in the upper reaches of estuaries will facilitate an increase in seagrass biomass and distribution under clear-water conditions [64,65]. Prolonged periods of hypersalinity (salinity ≥ 75), however, will lead to the die-back of submerged macrophytes [30]. Reeds and sedges may die-back or persist only in brackish areas (salinity < 20) such as sites of freshwater seepage [32].

3.5 Floods

Flooding and increased freshwater inflows can also be detrimental to coastal wetlands in several ways. Floods will scour estuary banks, removing macrophytes in intertidal habitats. Such habitats may be able to re-establish, but this can take place slowly. For example, mangroves that were removed by flooding in the Mnyameni and Mzimvubu estuaries only re-established after 11 years [10]. Floods can also deposit sediments causing smothering and die-back of submerged macrophytes and mangroves. However, such deposition events can expand intertidal areas available for colonization by macrophytes. Submerged macrophytes respond particularly strongly to flooding – floods can completely remove them from estuaries as has occurred with *Z. capensis* habitats in Swartkops Estuary [66]. Recovery of submerged macrophytes after floods can have a lag period of up to three years [67]. Furthermore, increased siltation, turbidity and salinity changes associated with floods will influence the growth and distribution of submerged macrophytes [8]. Increased high intensity rainfall events and flooding will likely remove submerged macrophyte beds from estuaries, particularly along the east coast where floods are expected to increase (Table 3) [42]. The endangered *Z. capensis* is already absent from freshwater dominated estuaries in southern KwaZulu-Natal where flooding and highly turbid conditions are common [8].

Increased rainfall and runoff will contribute to the nutrient enrichment and eutrophication of estuaries, which is already a significant pressure on South African estuaries that will likely be exacerbated by climate change, especially in disturbed catchments [28,68]. Eutrophication can shift estuaries to an alternate state where algal blooms can outcompete, outshade and possibly exclude submerged macrophytes and smother salt marshes [51,52]. Nutrient enrichment leads to dense epiphytic growth on the leaves of submerged macrophytes reducing light availability and limiting growth, and epiphytic fouling will increase as temperatures rise [69]. Increased nutrient loading due to runoff, along with increased temperatures, will also result in the proliferation of invasive alien aquatic plants (IAAPs) which are already widespread in South African estuaries, especially along the KwaZulu-Natal coast [68]. Predictive models suggest that climate change over coming decades will facilitate the range expansion of several IAAP species along the South African coast [70]. The proliferation of IAAPs leads to the loss of native species and biodiversity with impacts across trophic levels, and alters aquatic environments by decreasing light penetration, flow and connectivity between rivers and estuaries [68,71]. IAAPs can also displace important nursery habitats, for example, the spread of water hyacinth along with turbid conditions displaced *Z. capensis* beds in the Swartkops Estuary [66]. Although increased freshwater inflow and floods will generally contribute to eutrophication, they will also be important in opening estuary mouths, flushing systems, reoxygenating the water column, re-establishing salinity gradients following periods of mouth closure, inundating floodplains and decreasing soil salinity, maintaining sediment structure and building habitat (accretion) [73].

3.6. Sea level rise

Current SLR rates differ along the South African coast, with an increase of 1.9 $mm.yr^{-1}$ on the west coast, 1.5 $mm.yr^{-1}$ on the south coast and 2.7 $mm.yr^{-1}$ on the east coast [80,81]. Sea-level rise will increase inundation and waterlogging altering sediment biogeochemistry, moisture and salinity. This is the predicted scenario; however, if salt marshes and mangroves build elevation at a sufficient rate then inundation and waterlogging may not increase [82]. Local topography and coastal development constrain the availability of areas for landward migration, but the rate of sedimentation determines the capacity of mangrove and salt marsh ecosystems to resist SLR through surface elevation gain [83,84]. Predictive models that incorporate landward migration and surface elevation processes have been used to estimate changes in blue carbon stocks under different SLR scenarios at the Knysna and Swartkops estuaries [85,86].

Higher sea levels would cause salt marshes to migrate landwards [87,88]. Plant ecophysiology studies have shown lower intertidal salt marsh species will be able to survive in upper intertidal zones, but upper intertidal species will not be able to persist in waterlogged conditions [47]. The tolerance of salt marsh species to inundation will determine their survival, and the availability of areas with suitable elevation will allow for the landward migration of salt marsh habitats [9,89]. However, many South African estuaries are impacted by development and urban encroachment, which leads to 'coastal squeeze' which limits the amount of suitable area for salt marsh migration [90]. Recent research has found that there is a deficit in elevation gain and local relative sea-level rise in South African intertidal salt marshes, and it will be necessary for accretion rates to increase for these salt marshes to persist in the long-term [91]. This is especially the case for the sediment starved estuaries fed by catchments dominated by Table Mountain Sandstone. Sea level rise modelling studies at the Swartkops Estuary have predicted that lower intertidal habitats characterised by the cordgrass *Spartina maritima* do not gain elevation at a rate sufficient to keep up with current and future sea-level rise, but these habitats would migrate landwards and replace habitats located higher in the tidal frame [85,92]. At the Knysna Estuary, the capacity of *S. maritima* habitats to build elevation is variable along the length of the estuary [86]. Most sites in the lower and middle reaches are subsiding and therefore will not persist under projected sea level rise without the potential for landward migration. This can only be facilitated by the removal of hard structures [86].

Sea-level rise may lead to an increase in open mouth conditions in temporarily closed estuaries creating favourable habitat for mangrove, salt marsh and seagrass colonisation in intertidal areas [10]. However, these positive effects may be counteracted by drought and a reduction in freshwater inflow that results in mouth closure, high water level flooding and die-back of mangrove and salt marsh. Nationally it is difficult to predict the future trajectory of change for the endangered seagrass *Zostera capensis.* Sea-level rise will increase salinity in estuaries and seagrass can expand upstream. However, an increase in high intensity rainfall events will likely remove submerged macrophyte beds [8].

3.7. Increased sea storms and wave height

South Africa's wave-dominated coast is sensitive to sea storminess that can result in erosion or sediment deposition and accretion [80]. More frequent and intense sea storms and wave action may further inhibit the ability of the mouth of estuaries to remain open [75]. The resultant increase in water levels within estuaries will cause prolonged inundation and waterlogging of intertidal areas, leading to the loss of macrophyte habitats. Sea storms can also deposit marine sediments onto habitats, smothering them and causing die-back. For example, a major storm at the Mbashe Estuary led to the die-back of mangroves, of which many died within three years and the area was subsequently colonised by salt marsh species [93]. However, increased wave action due to sea storms can erode the mouth area of estuaries increasing periods of open mouth conditions [76]. Salt marshes can be particularly sensitive to erosion, which has caused the loss of large areas of salt marsh in various parts of the world [94-96]. Salt marsh has already been lost to erosion in some South African estuaries and further losses are expected [97] (Figure 3). While some increase in the frequency and intensity of sea storms has been recorded along parts of the South African coast in recent decades, these have not yet been definitively linked to anthropogenically-driven climate change [98]. However, a global increase in sea storms has been projected [99], which will result in increased coastal erosion and the loss of estuarine habitats.

3.8. Ocean acidification

Ocean acidification is a concerning consequence of increased CO_2. Acidification will likely impact South Africa's permanently open estuaries, particularly those on the west coast where upwelling is prevalent (Table 3) [75]. Acidification impacts nutrient and carbon availability in aquatic environments, but the impacts of acidification on macrophytes are complex and requires species- and situation-specific investigations [76]. Acidification will impact calcifying fauna, possibly leading to indirect effects through species interactions – such changes in biotic controls – but these are also difficult to predict. Eutrophication and algal blooms, a widespread problem in South African estuaries, will exacerbate climate change-driven acidification [68]. This will particularly be an issue in eutrophic estuaries that are closed to the sea, especially since mouth closure is expected to increase with climate change in many of these systems in South Africa. During open mouth conditions, pH is regulated by tidal mixing but during closed mouth conditions, pH dynamics are dominated by *in situ* biological processes [78]. Closed estuaries that are susceptible to eutrophication will experience greater diurnal pH variability due to increased primary production by algal blooms [77]. When the algal blooms decay, remineralisation and aerobic respiration by bacteria decreases pH, particularly under the long water residence times experienced during a closed mouth phase [77,79]. These *in situ* processes are likely to be enhanced by increase temperatures.

4. Conclusions

Predicting the effect of multiple climate change stressors is difficult because of the natural variability of our coastal wetlands. Long-term monitoring is needed to support research findings. Monitoring of permanent plots and transects are necessary to identify changes such as salinisation and drying out of salt marshes. Synergistic interactions between climate change and human impacts need teasing out at a local scale so that we can understand the processes influencing the vulnerability and resilience of coastal wetlands. Long-term datasets are also needed to understand the change in the frequency and intensity of climatic cycles such as El Niño. Nationally we need policies and planning mechanisms to set aside buffers for landward migration of coastal wetlands in response to sea level rise. Estuary conservation and management plans need to include future changes in climate to ensure the protection of coastal wetlands. However successful management and restoration of coastal wetlands requires a socio-ecological systems approach to address the lack of alignment between ecosystem requirements, legislation, governance, implementation and social commitment.

Past research has identified patterns of change that allow for the prediction of potential future change. South Africa is an important outdoor laboratory as changes are occurring across different biogeographic zones i.e. subtropical to warm temperate and warm temperate to cool temperate. Our research makes an important contribution globally as little is known about the response of African coastal wetlands to climate change. Data sets inform range expansions of species at a southern continental limit and responses characteristic of a wave-dominated high-energy coastline.

Funding: The DSI/NRF Research Chair in Shallow Water Ecosystems (UID 84375) supported JBA. LvN was funded through the Coastal Systems, Council for Scientific and Industrial Research DSI Parliamentary Grant (PG). The Water Research Commission funded Project K5/2769/1/19 titled 'Climate change and South Africa's blue carbon ecosystems'.

Figure 3. Salt marsh erosion in the Knysna Estuary.

Table 3. Summary of key processes that will be impacted by climate change stressors and the broad direction of change per biogeographical region (Solid ● = increase; Hollow ○ = decrease; Large ⬤ = High degree of change, small ● small to moderate degree of change)

Key processes	Climate change stressors	Biogeographical Region			
		Cool temperate	Warm Temperate	Subtropical	Tropical
Atmospheric	CO_2	⬤	⬤	⬤	⬤
	Temperature	⬤	⬤	●	●
Hydrological	Floods	●	⬤	⬤	⬤
	Droughts	⬤	●	●	●
	Streamflow	◯	●	⬤	⬤
Oceanic	Sea level rise	⬤	⬤	⬤	⬤
	Sea storms & wave height	⬤	⬤	⬤	⬤
	Ocean Acidification	◯	○	○	○

References

1. Van Niekerk, L., Taljaard, S., Adams, J.B., Clark, B., Lamberth, S.J., MacKay, C.F., Weerts, S.P. Chapter 7: Condition of South Africa's estuarine ecosystems. In *South African National Biodiversity Assessment 2018: Technical Report. Volume 3: Estuarine Realm.* South African National Biodiversity Institute, Pretoria, **2019**; Report Number: SANBI/NAT/NBA2018/2019/Vol3/A.
2. Hallett, C.S., Hobday, A.J., Tweedley, J.R., Thompson, P.A., McMahon, K., Valesini, F.J. Observed and predicted impacts of climate change on the estuaries of south-western Australia, a Mediterranean climate region. *Reg. Environ. Change* **2018**, *18*, pp.1357-1373.
3. Lovelock, C.E., Reef, R. Variable impacts of climate change on blue carbon. *One Earth* **2020**, *3*, pp.195-211.
4. Whitfield, A.K. A characterization of southern African estuarine systems. *S. Afr.J. Aquat. Sci.* **1992**, *18*, pp.89-103.
5. Van Niekerk, L., Adams, J.B., James, N.C., Lamberth, S.J., MacKay, C.F., Turpie, J.K., Rajkaran, A., Weerts, S.P., Whitfield, A.K. An Estuary Ecosystem Classification that encompasses biogeography and a high diversity of types in support of protection and management. *Afr.J. Aquat. Sci.* **2020**, *45*, pp.199-216.
6. Adams, J.B., Veldkornet, D., Tabot, P. Distribution of macrophyte species and habitats in South African estuaries. *S. Afr. J. Bot.* **2016**, *107*, pp.5-11.
7. Adams, J.B., Bate, G.C., O'Callaghan, M. Primary producers. *Estuaries of South Africa.* Allanson, B., Baird, D., Eds.; *Cambridge University Press, Cambridge*, **1999**, pp.91-117.
8. Adams, J.B.. Distribution and status of *Zostera capensis* in South African estuaries—A review. *S. Afr. J. Bot.* **2016**, *107*, pp.63-73.
9. Adams, J.B. Salt marsh at the tip of Africa: patterns, processes and changes in response to climate change. *Estuar., Coast. Shelf Sci.* **2020**, *237*, p.106650.
10. Adams, J.B., Rajkaran, A. Changes in mangroves at their southernmost African distribution limit. *Estuar., Coast. Shelf Sci.* **2021**, *248*, p.107158.
11. Adams, J., Fernandes, M., Riddin, T. Chapter 5: Estuarine Habitat extent and trend. In *South African National Biodiversity Assessment 2018: Technical Report. Volume 3: Estuarine Realm.* South African National Biodiversity Institute, Pretoria, **2019**; Report Number: SANBI/NAT/NBA2018/2019/Vol3/A.
12. Day, J.W., Christian, R.R., Boesch, D.M., Yáñez-Arancibia, A., Morris, J., Twilley, R.R., Naylor, L., Schaffner, L. Consequences of climate change on the ecogeomorphology of coastal wetlands. *Estuaries Coast* **2008**, *31*, pp.477-491.
13. Scavia, D., Field, J.C., Boesch, D.F., Buddemeier, R.W., Burkett, V., Cayan, D.R., Fogarty, M., Harwell, M.A., Howarth, R.W., Mason, C., Reed, D.J. Climate change impacts on US coastal and marine ecosystems. *Estuaries* **2002**, *25*, pp.149-164.
14. Robins, P.E., Skov, M.W., Lewis, M.J., Giménez, L., Davies, A.G., Malham, S.K., Neill, S.P., McDonald, J.E., Whitton, T.A., Jackson, S.E., Jago, C.F. Impact of climate change on UK estuaries: A review of past trends and potential projections. *Estuar., Coast. Shelf Sci.* **2016**, *169*, pp.119-135.
15. Engelbrecht, C.J., Landman, W.A., Engelbrecht, F.A., Malherbe, J. A synoptic decomposition of rainfall over the Cape south coast of South Africa. *Clim. Dyn.* **2015**, *44*, pp.2589-2607.

16. Ellison, J.C. How South Pacific mangroves may respond to predicted climate change and sea-level rise. In *Climate change in the South Pacific: Impacts and responses in Australia, New Zealand, and small island states;* Gillespie, A., Burns, W.C.G., Eds. Springer, Dordrecht, **2000**; pp. 289-300
17. McKee, K., Rogers, K., Saintilan, N. Response of salt marsh and mangrove wetlands to changes in atmospheric CO_2, climate, and sea level. In *Global change and the function and distribution of wetlands*; Middleton, B.A., Ed. Springer, Dordrecht, **2012**; pp. 63-96
18. Marbà, N., Duarte, C.M. Mediterranean warming triggers seagrass (*Posidonia oceanica*) shoot mortality. *Glob. Change Biol.* **2010**, *16*, pp.2366-2375.
19. Ward, R.D., Friess, D.A., Day, R.H., MacKenzie, R.A. Impacts of climate change on mangrove ecosystems: a region by region overview. *Ecosyst. Health Sustain.* **2016**, *2*, p.e01211.
20. Saintilan, N., Wilson, N.C., Rogers, K., Rajkaran, A., Krauss, K.W. Mangrove expansion and salt marsh decline at mangrove poleward limits. *Glob. Change Biol.* **2014**, *20*, pp.147-157.
21. Osland, M.J., Day, R.H., Hall, C.T., Brumfield, M.D., Dugas, J.L., Jones, W.R. Mangrove expansion and contraction at a poleward range limit: climate extremes and land-ocean temperature gradients. *Ecology* **2017**, *98*, pp.125-137.
22. Cavanaugh, K.C., Osland, M.J., Bardou, R., Hinojosa-Arango, G., López-Vivas, J.M., Parker, J.D., Rovai, A.S.. Sensitivity of mangrove range limits to climate variability. *Glob. Ecol. Biog.* **2018**, *27*, pp.925-935.
23. Whitfield, A.K., James, N.C., Lamberth, S.J., Adams, J.B., Perissinotto, R., Rajkaran, A., Bornman, T.G. The role of pioneers as indicators of biogeographic range expansion caused by global change in southern African coastal waters. *Estuar., Coast. Shelf Sci.* **2016**, *172*, pp.138-153.
24. Peer, N., Rajkaran, A., Miranda, N.A.F., Taylor, R.H., Newman, B., Porri, F., Raw, J.L., Mbense, S.P., Adams, J.B., Perissinotto, R. Latitudinal gradients and poleward expansion of mangrove ecosystems in South Africa: 50 years after Macnae's first assessment. *Afr. J. Mar. Sci.* **2018**, *40*, pp.101-120.
25. Raw, J.L., Godbold, J.A., Van Niekerk, L., Adams, J.B. Drivers of mangrove distribution at the high-energy, wave-dominated, southern African range limit. *Estuar., Coast. Shelf Sci.* **2019**, *226*, p.106296.
26. Whitt, A.A., Coleman, R., Lovelock, C.E., Gillies, C., Ierodiaconou, D., Liyanapathirana, M. and Macreadie, P.I. March of the mangroves: Drivers of encroachment into southern temperate saltmarsh. *Estuar., Coast. Shelf Sci.* **2020**, 240, p. 106776.
27. Cooper, J.A.G. Geomorphological variability among microtidal estuaries from the wave-dominated South African coast. *Geomorphology* **2001**, *40*, pp.99-122.
28. James, N.C., Van Niekerk, L., Whitfield, A.K., Potts, W.M., Götz, A., Paterson, A.W. Effects of climate change on South African estuaries and associated fish species. *Clim. Res.* **2013**, *57*, pp.233-248.
29. Cyrus, D., Jerling, H., MacKay, F., Vivier, L. Lake St Lucia, Africa's largest estuarine lake in crisis: combined effects of mouth closure, low levels and hypersalinity. *Afr. J. Sci.* **2011**, *107*, pp.01-13.
30. Adams, J.B., Bate, G.C. The ecological implications of tolerance to salinity by *Ruppia cirrhosa* (Petagna) Grande and *Zostera capensis* Setchell. *Bot. Mar.* **1994**, *37*, pp.449-456.
31. Adams, J.B., Bate, G.C. The tolerance to desiccation of the submerged macrophytes *Ruppia cirrhosa* (Petagna) Grande and *Zostera capensis* Setchell. *J. Exp. Mar. Biol. Ecol.* **1994**, *183*, pp.53-62.
32. Adams, J.B., Bate, G.C. Growth and photosynthetic performance of *Phragmites australis* in estuarine waters: a field and experimental evaluation. *Aquat. Bot.* **1994**, *64*, pp.359-367.
33. Wooldridge, T.H., Adams, J.B., Fernandes, M. Biotic responses to extreme hypersalinity in an arid zone estuary, South Africa. *S. Afr. J. Bot* **2016**, *107*, pp.160-169.
34. Nowicki, R.J., Thomson, J.A., Burkholder, D.A., Fourqurean, J.W., Heithaus, M.R. Predicting seagrass recovery times and their implications following an extreme climate event. *Mar. Ecol. Prog. Ser.* **2017**, *567*, pp.79-93.
35. Duke, N.C., Kovacs, J.M., Griffiths, A.D., Preece, L., Hill, D.J., Van Oosterzee, P., Mackenzie, J., Morning, H.S., Burrows, D. Large-scale dieback of mangroves in Australia's Gulf of Carpentaria: a severe ecosystem response, coincidental with an unusually extreme weather event. *Mar. Freshw. Res.* **2017**, *68*, pp.1816-1829.
36. Oliver, E.C., Donat, M.G., Burrows, M.T., Moore, P.J., Smale, D.A., Alexander, L.V., Benthuysen, J.A., Feng, M., Gupta, A.S., Hobday, A.J., Holbrook, N.J. Longer and more frequent marine heatwaves over the past century. *Nat. Commun.* **2018**, *9*, pp.1-12.
37. Koch, M., Bowes, G., Ross, C., Zhang, X.H. Climate change and ocean acidification effects on seagrasses and marine macroalgae. *Global Change Biol.* **2013**, *19*, pp.103-132.
38. Smale, D.A., Wernberg, T. Extreme climatic event drives range contraction of a habitat-forming species. *Proc. Royal Soc. B: Biol. Sci.* **2013**, *280*, p.20122829.
39. Lemley, D.A., Adams, J.B. Physico-chemical and microalgal gradients change rapidly in response to mouth closure in a predominantly open estuary. *Afr.J. Aquat. Sci.* **2020**, 45, pp.11-21.
40. Engelbrecht, F.A., McGregor, J.L., Engelbrecht, C.J. Dynamics of the Conformal-Cubic Atmospheric Model projected climate-change signal over southern Africa. *Int. J. Climatol.* **2009**, *29*, pp.1013-1033.
41. Engelbrecht, C.J., Engelbrecht, F.A., Dyson, L.L. High-resolution model-projected changes in mid-tropospheric closed-lows and extreme rainfall events over southern Africa. *Int. J. Climatol.* **2013**, *33*, pp.173-187.
42. Van Niekerk, L, Lamberth SJ, James, N, Taljaard, S, Adams, JB, Theron, A, Krug, M. In prep. The vulnerability of South African estuaries to Climate Change: a review and synthesis. (in prep.).

43. Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.-T. Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr, A., Whetton, P. Regional Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Solomon, S., Ed. Cambridge University Press, Cambridge, **2007**, pp. 848-940.
44. Riddin, T., Adams, J.B. Influence of mouth status and water level on the macrophytes in a small temporarily open/closed estuary *Estuar., Coast. Shelf Sci.* **2008**, *79*, pp.86-92.
45. Riddin, T., Adams, J.B. The effect of a storm surge event on the macrophytes of a temporarily open/closed estuary, South Africa. *Estuar., Coast. Shelf Sci.* **2010**, *89*(1), pp.119-123.
46. Riddin, T., Adams, J.B. Predicting macrophyte states in a small temporarily open/closed estuary. *Mar. Freshw. Res.* **2012**, *63*, pp.616-623.
47. Tabot, P.T., Adams, J.B. Ecophysiology of salt marsh plants and predicted responses to climate change in South Africa. *Ocean Coast Manag.* **2013**, *80*, pp.89-99.
48. Breen, C.M., Hill, B.J. A mass mortality of mangroves in the Kosi Estuary. *Transactions of the royal society of South Africa* **1969**, *38*, pp.285-303.
49. Adams, J.B., Human, L.R.D. Investigation into the mortality of mangroves at St. Lucia Estuary. *S. Afr. J. Bot* **2016**, *107*, pp.121-128.
50. Mbense, S., Rajkaran, A., Bolosha, U., Adams, J. Rapid colonization of degraded mangrove habitat by succulent salt marsh. *S. Afr. J. Bot* **2016**, *107*, pp.129-136.
51. Burkholder, J.M., Tomasko, D.A., Touchette, B.W. Seagrasses and eutrophication. *J. Exp. Mar. Biol. Ecol.* **2007**, *350*, pp.46-72.
52. Nunes, M., Adams, J.B. Responses of primary producers to mouth closure in the temporarily open/closed Great Brak Estuary in the warm-temperate region of South Africa. *Afr.J. Aquat. Sci.* 2014, *39*, pp.387-394.
53. Human, L.R.D., Adams, J.B., Allanson, B.R. Insights into the cause of an *Ulva lactuca* Linnaeus bloom in the Knysna Estuary. *S. Afr. J. Bot.* **2016**, *107*, pp.55-62.
54. Thorne, K.M., Buffington, K.J., Jones, S.F., Largier, J.L. Wetlands in intermittently closed estuaries can build elevations to keep pace with sea-level rise. *Estuar., Coast. Shelf Sci.* **2021**, *257,* p.107386.
55. Nozais, C., Perissinotto, R., Tita, G. Seasonal dynamics of meiofauna in a South African temporarily open/closed estuary (Mdloti Estuary, Indian Ocean). *Estuar., Coast. Shelf Sci.* **2005**, *62*, pp.325-338.
56. Thomas, C.M., Perissinotto, R., Kibirige, I. Phytoplankton biomass and size structure in two South African eutrophic, temporarily open/closed estuaries. *Estuar., Coast. Shelf Sci.* **2005**, *65*, pp.223-238.
57. Buckney, R.T. Three decades of habitat change: Kooragang Island, New South Wales. In *Nature conservation, the role of remnants of native vegetation in Melbourne*, Saunders, D.A., Arnold, G.W., Burrbidge, G., Hopkins, A.G.M., Eds.; Surrey, Beatty and Sons, Sydney. **1987**; pp. 227–232.
58. Eslami-Andargoli, L., Dale, P.E.R., Sipe, N., Chaseling, J. Mangrove expansion and rainfall patterns in Moreton Bay, southeast Queensland, Australia. *Estuar., Coast. Shelf Sci.* **2009**, *85*, pp.292-298.
59. Lovelock, C.E., Feller, I.C., Reef, R., Hickey, S., Ball, M.C. Mangrove dieback during fluctuating sea levels. *Sci. Rep.* **2017**, *7*, pp.1-8.
60. Asbridge, E.F., Bartolo, R., Finlayson, C.M., Lucas, R.M., Rogers, K., Woodroffe, C.D. Assessing the distribution and drivers of mangrove dieback in Kakadu National Park, northern Australia. *Estuar., Coast. Shelf Sci.* **2019**, *228*, p.106353.
61. Rogers, K., Saintilan, N. and Cahoon, D. Surface elevation dynamics in a regenerating mangrove forest at Homebush Bay, Australia. *Wet. Ecol. Manag.* **2005**, *13*, pp.587-598.
62. Rogers, K., Saintilan, N. Relationships between surface elevation and groundwater in mangrove forests of southeast Australia. *J. Coast. Res.* **2008**, *24*, pp.63-69.
63. McKee, K.L., Mendelssohn, I.A., Materne, M. Acute salt marsh dieback in the Mississippi River deltaic plain: a drought-induced phenomenon?. Glob. Ecol. and Biogeogr. **2004**, *13*, pp.65-73.
64. Adams, J.B., Knoop, W.T., Bate, G.C. The distribution of estuarine macrophytes in relation to freshwater. *Bot. Mar.* **1992**, 37, pp. 449-456.
65. Adams, J.B., Talbot, M.M.B. The influence of river impoundment on the estuarine seagrass *Zostera capensis* Setchell. *Bot. Mar.* **1992**, *35*, pp.69-75.
66. Emmerson, W.D., Watling, H.R., Watling, R.J. A community analysis in the Kromme and the Swartkops estuaries and in the Algoa Bay region. *University of Port Elizabeth, Zoology Dept. Rep. Series* **1982**, 16, pp.1-128.
67. Talbot, M.M.B., Knoop, W.T., Bate, G.C. The dynamics of estuarine macrophytes in relation to flood/siltation cycles. *Bot. Mar.* **1990**, *33*, pp.159-164.
68. Adams, J.B., Taljaard, S., Van Niekerk, L., Lemley, D.A. Nutrient enrichment as a threat to the ecological resilience and health of South African microtidal estuaries. *Afr.J. Aquat. Sci.* **2020**, *45*, pp.23-40.
69. Mvungi, E.F., Pillay, D. Eutrophication overrides warming as a stressor for a temperate African seagrass (*Zostera capensis*). *PLOS ONE* **2019,** *14*, p.e0215129.
70. Hoveka, L.N., Bezeng, B.S., Yessoufou, K., Boatwright, J.S., Van der Bank, M. Effects of climate change on the future distributions of the top five freshwater invasive plants in South Africa. *S. Afr. J. Bot* **2016**, *102*, pp.33-38.

71. Hill, M.P., Coetzee, J.A., Martin, G.D., Smith, R., Strange, E.F. Invasive alien aquatic plants in South African freshwater ecosystems. In *Biological Invasions in South Africa*; van Wilgen, B., Measey, J., Richardson, D.M., Wilson, J.R., Zengeya, T.A., Eds.; Springer, Cham, **2020**; pp. 97-114.
72. Van Niekerk, L., Adams, A.B., Lamberth, S.J., Taljaard, S., MacKay, C.F., Bachoo, S. Parak, O., Murison, G., Weerts, S.P. Chapter 6: Pressures on the Estuarine Realm. *In South African National Biodiversity Assessment 2018: Technical Report. Volume 3: Estuarine Realm*. South African National Biodiversity Institute, Pretoria, **2019**; Report Number: SANBI/NAT/NBA2018/2019/Vol3/A.
73. Human, L.R.D., Snow, G.C., Adams, J.B. Responses in a temporarily open/closed estuary to natural and artificial mouth breaching. *S. Afr. J. Bot* **2016**, *107*, pp.39-48.
74. Arp, W.J., Drake, B.G., Pockman, W.T., Curtis, P.S., Whigham, D.F. Interactions between C 3 and C 4 salt marsh plant species during four years of exposure to elevated atmospheric CO_2. In *CO_2 and Biosphere*, Rozema, J., Lambers, H., Van de Geijn, S.C., Cambridge, S.L., Eds.; Springer, Dordrecht, **1993**; pp. 133-143.
75. Van Niekerk, L. Approaches to Detecting and Assessing Patterns, Processes and Responses to Change in South African Estuaries. PhD thesis. Nelson Mandela University, Port Elizabeth, **2018**.
76. Farmer, A.M. The effects of lake acidification on aquatic macrophytes — a review. *Environ. Pollut.* **1990**, *65*, pp.219-240.
77. Wallace, R.B., Baumann, H., Grear, J.S., Aller, R.C., Gobler, C.J. Coastal ocean acidification: The other eutrophication problem. *Estuar., Coast. Shelf Sci.* **2014**, *148*, pp.1-13.
78. Omarjee, A., Taljaard, S., Weerts, S.P., Adams, J.B. The influence of mouth status on pH variability in small temporarily closed estuaries. *Estuar., Coast. Shelf Sci.* **2020**, *246*, p.107043.
79. Snow, G.C., Taljaard, S. Water quality in South African temporarily open/closed estuaries: a conceptual model. *Afr.J. Aquat. Sci.* **2007**, *32*, pp.99-111.
80. Mather, A.A., Stretch, D.D. A perspective on sea level rise and coastal storm surge from Southern and Eastern Africa: A case study near Durban, South Africa. *Water* **2012**, *4*, pp.237-259.
81. Mather, A.A., Garland, G.G., Stretch, D.D. Southern African sea levels: corrections, influences and trends. *Afr. J. Mar. Sci.* **2009**, *31*, pp.145-156.
82. Rogers, K., Mogensen, L.A., Davies, P., Kelleway, J., Saintilan, N., Withycombe, G. Impacts and adaptation options for estuarine vegetation in a large city. *Landsc. Urban Plan.* **2019**, *182*, pp.1-11.
83. Lovelock, C.E., Cahoon, D.R., Friess, D.A., Guntenspergen, G.R., Krauss, K.W., Reef, R., Rogers, K., Saunders, M.L., Sidik, F., Swales, A., Saintilan, N. The vulnerability of Indo-Pacific mangrove forests to sea-level rise. *Nature* **2015**, *526*, pp.559-563.
84. Baustian, J.J., Mendelssohn, I.A. Sea level rise impacts to coastal marshes may be ameliorated by natural sedimentation events. *Wetlands* **2018**, *38*, pp.689-701.
85. Raw, J.L., Adams, J.B., Bornman, T.G., Riddin, T., Vanderklift, M.A. Vulnerability to sea-level rise and the potential for restoration to enhance blue carbon sequestration in salt marshes of an urban estuary. *Estuar., Coast. Shelf Sci.*, 260, p. 107495.
86. Raw, J.L., Riddin, T., Wasserman, J., Lehman, T.W.K., Bornman, T.G., Adams, J.B. Salt marsh elevation and responses to future sea-level rise in the Knysna Estuary, South Africa. *Afr.J. Aquat. Sci.* **2020**, *45*, pp.49-64.
87. Enwright, N.M., Griffith, K.T., Osland, M.J. Barriers to and opportunities for landward migration of coastal wetlands with sea-level rise. *Front. Ecol. Environ.* **2016**, *14*, pp.307-316.
88. Kirwan, M.L., Walters, D.C., Reay, W.G., Carr, J.A. Sea level driven marsh expansion in a coupled model of marsh erosion and migration. *Geophys. Res. Lett.* **2016**, *43*, pp.4366-4373.
89. Veldkornet, D.A., Adams, J.B., Potts, A.J. Where do you draw the line? Determining the transition thresholds between estuarine salt marshes and terrestrial vegetation. *S. Afr. J. Bot* **2015**, *101*, pp.153-159.
90. Veldkornet, D.A., Adams, J.B., Van Niekerk, L. Characteristics and landcover of estuarine boundaries: implications for the delineation of the South African estuarine functional zone. *Afr. J. Mar. Sci.* **2015**, *37*, pp.313-323.
91. Saintilan, N., Kovalenko, K.E., Guntenspergen, G., Rogers, K., Lynch, J.C., Cahoon, D., Lovelock, C., Friess, D.A., Ashe, E., Krauss, K., Cormier, N., Spencer, T., Adams, J.B., Raw, J., Ibanez, C., Scarton, F.W., Temmerman, S., Meire, P., Maris, T., Thorne, K., Brazner, J., Chmura, G., Bowron, T., Vishmie, P.G. Global patterns and drivers of tidal marsh response to accelerating sea-level rise. *Science* (Accepted).
92. Bornman, T.G., Schmidt, J., Adams, J.B., Mfikili, A.N., Farre, R.E., Smit, A.J. Relative sea-level rise and the potential for subsidence of the Swartkops Estuary intertidal salt marshes, South Africa. *S. Afr. J. Bot* **2016**, *107*, pp.91-100.
93. James, N.C., Adams, J.B., Connell, A.D., Lamberth, S.J., MacKay, C.F., Snow, G.C., Van Niekerk, L., Whitfield, A.K. High flow variability and storm events shape the ecology of the Mbhashe Estuary, South Africa. *Afr.J. Aquat. Sci.* **2020**, *45*, pp.131-151.
94. Cooper, N.J., Cooper, T., Burd, F. 25 years of salt marsh erosion in Essex: Implications for coastal defence and nature conservation. *J Coast. Conserv.* **2001**, *7*, pp.31-40.
95. Ravens, T.M., Thomas, R.C., Roberts, K.A., Santschi, P.H. Causes of salt marsh erosion in Galveston Bay, Texas. *Journal of Coastal Research* **2009**, *25*, pp.265-272.
96. Leonardi, N., Fagherazzi, S. How waves shape salt marshes. *Geology* **2014**, *42*, pp.887-890.
97. Riddin T, Adams JB. Salt marsh erosion in a microtidal estuary. *S.A.J.Mar. Sci.* (43(2), pp. 265- 273. DOI: 10.2989/1814232X.2021.

98. Guastella L, Rossouw J. Coastal vulnerability: are coastal storms increasing in frequency and intensity along the South African coast? *Reef Journal* **2012**, *2*, pp.129-139.
99. IPCC. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, Midgley, P.M., Eds.; Cambridge University Press, Cambridge, **2013**; 1535 pp.

Chapter 7

Evaluating the vulnerability of South Africa's estuarine lakes to climate change

Lara van Niekerk [1,2*], Susan Taljaard[1,2], Janine Adams[2,3], Stephen Lamberth[4], Daniel Lemley[2,3], Steven Weerts[1]

[1] CSIR
[2] Institute for Coastal & Marine Research, Nelson Mandela University
[3] DSI/NRF Research Chair in Shallow Water Ecosystems, Botany Department, Nelson Mandela University
[4] Department of Forestry and Fisheries and the Environment
* Corresponding author: lvnieker@csir.co.za

Abstract: Estuarine lakes numerically constitute 4% of estuaries in South Africa, but collectively they cover more than 60% of estuarine habitat. Their large surface area:volume ratios, low mean annual runoff, and intermitted connectivity to the sea; result in low flushing rates that increase the influence of *in situ* processes. This complexity is further compounded by the occurrence of a wide range of abiotic states that are observed over long timescales. Climate change is likely to add to and exacerbate existing pressures on estuarine lakes which motivated the need for a Climate Change Vulnerability assessment on these type of estuaries. This assessment specifically focused on terrestrial climatic and hydrological vectors associated with climate change and showed that the maximum potential shift in estuarine state varied between 9% and 22% from present functionality under the Representative Concentration Pathway (RCP) 4.5 and RCP8.5 Climate scenarios. In all cases, the maximum degree of change was induced by the RCP8.5 Far Future Scenario, impacting estuarine connectivity and related biotic productivity and composition. The responses to the RCP4.5 scenarios were generally grouped around the present state, with some scenarios even representing a shift towards natural conditions as a result of increased freshwater input in the mid-future scenarios. In all systems, except for Kosi, anthropogenic-induced change exceeded climate-induced shifts in estuary functioning; highlighting the degree of transformation estuarine lakes have already experienced. Present water quality was a good predictor of future resilience, with the condition of enriched systems more likely to decline further under hotter and/or drier future conditions. Relatively shallow lake systems, such as Verlorenvlei, Bot/Kleinmond and Heuningnes, tend to be more vulnerable to the impact of reduced flows and/or the impact of drought conditions. In this type of system, event-scale droughts tend to dry out a large part of the lake beds and surrounding estuarine vegetation. Depending on the degree of marine connectivity, this type of system may also develop extreme hypersalinity in portions of the system. This effect could be further amplified if the system were already subjected to enrichment, with harmful algal blooms often associated with extreme conditions. The development of the estuary abiotic and biotic conceptual models as an explicit step in the vulnerability assessment method allowed for the identification of commonalities and differences across systems and assisted with bridging data gaps and extrapolating findings. The selected assessment approach was sensitive to change and allowed for the detection of climate-induced shifts in estuary function and productivity. Future research priorities should include (1) the assessment of primary producers and estuarine fish to elevated temperatures, and (2) the development of coupled rainfall-runoff yield models specifically geared at resolving climate change projections on river flows.

Keywords: climate change, estuarine lakes, vulnerability assessment, rainfall, runoff, temperature, multiple stressors, ecosystem-scale response

1. Introduction

Estuaries form an interface between the land and sea and are strongly influenced by climatic, hydrological, and oceanic processes. Approximately 90% of South Africa's 290 estuaries are small, dynamic temporarily closed estuaries or seasonally driven predominantly open systems. However, a small percentage (< 4%) are large estuarine lake systems [1]. While these estuarine lakes constitute a small percentage of systems numerically, collectively they cover more than 60% of South Africa's estuarine habitat [2]. More than 84% of the country's estuarine lake area is already in a poor ecological state as a result of anthropogenic pressures [2]. Undoubtedly these systems face future climate change pressures, but very few have been the focal point of long-term biophysical research that could inform climate change response strategies.

Estuarine lakes typically have large surface area: volume ratios, comparatively low mean annual runoff, and intermittent connectivity to the sea (e.g. mouths can close for extended periods), resulting in relatively low flushing rates and a larger influence of *in situ* processes on estuarine characteristics relative to other estuary types [3]. They are therefore less resilient to change as their biophysical processes function over long time-scales (i.e. annual to decadal cycles) and their re-setting mechanisms are relatively weak in comparison with the smaller systems. Thus, estuarine lakes are vulnerable to catchment land-use and development pressures [4]. This also makes them vulnerable to the vectors of global change, including climate change (e.g., shifts in seasonal rainfall, intensification of drought cycles, increase in the occurrence of floods, as well as increasing temperatures and evaporation).

Ever-increasing anthropogenic impacts on estuarine systems already pose serious threats to the biodiversity and ecosystem services we derive from these ecosystems (e.g. carbon sequestration, flood attenuation, fisheries, provision of sustainable livelihoods, and eco-tourism). Climate change is likely to add to, and possibly exacerbate existing pressures, accelerating the degradation of estuaries. In fact, several estuarine lakes are already recognised as systems in transition from estuarine lakes to coastal lakes [5] due to human interferences such as reduction in freshwater inflows, barriers at their outlets and low-lying development. For example, Sibaya, Cubhu and Mzingazi, used to be lakes that were connected to the sea (i.e., estuarine lakes) but have evolved into coastal lakes through natural or anthropogenically induced loss of connectivity with the sea [5]. Timeous planning to mitigate and adapt to climate change is critical for sustaining these valuable ecosystem assets. Management and climate change strategies for these systems may require unique and dedicated interventions to ensure future resilience in the face of ongoing change.

Climate change is a measurable reality and South Africa is especially vulnerable to its impacts [6,7]. Globally, estuaries have been the focus of several comprehensive Climate Change Vulnerability Assessments [8-11]. Key drivers of change have been identified as: modification of terrestrial climatic (e.g., temperature and rainfall) and hydrological processes; changes in the oceanic circulation; ocean acidification; sea-level rise; and increased sea storminess [e.g., 12-18]. However, this study focused specifically on the critical *terrestrial climatic and hydrological vectors associated with climate change*, and their anticipated effects on the key processes in the estuarine lakes of South Africa, as well as the key biotic responses, and their consequences on the ecological health of these valuable systems.

2. Study area

Thirteen estuarine lakes systems occur in four biogeographical regions along South Africa's coast, namely Verlorenvlei, Zeekoevlei, Klein, Bot/Kleinmond, Heuningnes, Touw/Wilderness, Swartvlei, iMhlathuze, St Lucia, uMgobezeleni and Kosi (Figure 1) [4]. These lake systems mostly formed as a result of sea-level changes between the late Pleistocene and Holocene [5], some stemming from drowned river valleys (e.g. Swartvlei) and others from marine flooding (e.g. Wilderness) [5].

Estuarine lake connectivity ranges from near-permanently open (e.g. Kosi), through systems that are open on annual time scales (e.g. Swartvlei) [19], to predominantly closed (e.g. Bot/Kleinmond and St Lucia). The extent and duration of marine connectivity influence the salinity regime in these lake systems, which can range from fresh to hypersaline. As a result of restricted connectivity to the sea and low tidal amplitudes (15 to 20 cm) wind plays a more prevalent role than tides in mixing processes [4]. The low flushing rates and intermittent connection to the sea makes South Africa's estuarine lakes vulnerable to catchment and development pressures and contributes to more than 84% of estuarine lake habitat already being in a poor condition from catchment and development pressures [4]. This reduces their ability to provide key ecosystem services such as flood regulation, nutrient cycling, nursery habitat, and has compromised recreational and tourism benefits derived from these systems. Catchment development is increasing, resulting in reduced inflow (either surface or groundwater) into many lakes, with Kosi being a good example.

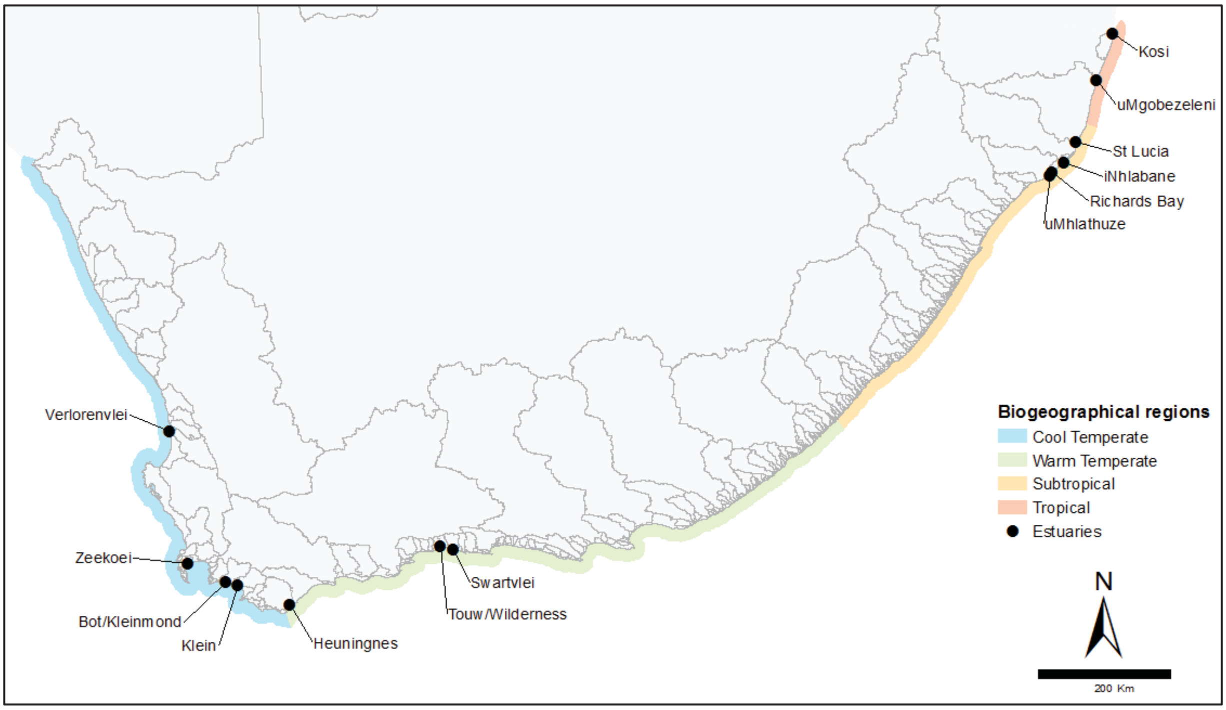


Figure 1. Location of South Africa's estuarine lakes.

Estuarine lakes have unique system-specific characteristics relating to connectivity, morphological complexity and salinity regimes (Table 1) [3,20-30]. Connectivity to the sea can occur via constricted inlet channels, fully functional estuaries, or in some cases, large estuarine lakes can be directly connected to the sea with no clearly defined channels (e.g. Klein).

Estuarine lakes can comprise single basins, or they can occur as a series of linked lake systems that are connected through several meandering channels. Kosi, for example, comprises four linked lakes that are connected to the sea by a large shallow estuary. Across the country's estuarine lakes, average depth varies from 2 m to more than 30 m, with most lakes typically 3 to 5 m deep. Most lake systems have more than one river feeding them, but two are fed nearly exclusively by groundwater. Salinity regimes vary from 0 to 35. Most lakes are brackish to fresh but some show a tendency to become hypersaline during dry periods (Tables 1 and 2).

This complexity is further compounded by the occurrence of a wide range of abiotic states that are observed in estuarine lake systems over long timescales. In total, seven open and five closed abiotic states were recognised in the lakes systems that largely maintain natural functionality. Table 2 provides a summary of typical abiotic conditions associated with each of these states, focusing on mouth state, salinity regime, and water levels as key distinguishing characteristics [3,20-30]. While there are differences amongst lakes in the states as a result of the interplay between bathymetry and freshwater input, some common features could be grouped into the 12 states.

Table 1. Overview of connectivity, morphological complexity and salinity regimes in South Africa's estuarine lakes under present conditions

ESTUARINE LAKE	CONNECTIVITY			MORPHOLOGICAL COMPLEXITY					SALINITY	
	# Mouths	Tidal exchange	Temporal scales	Inlet channel/ Estuarine zone	Lakes	Depth (m)	Connecting channels	Rivers	Inlet/ Estuarine zone	Lakes
Verlorenvlei	1	Perched	1-4 yrs	Inlet channel	1	2.5 m (Max: 5)	-	1	0-110	Fresh
Zeekoevlei	1	Perched	Open (100%)	Canalised	2		2	2	0 - 100	Fresh
Bot/Kleinmond	2	Tidal/ Constricted	1-4 yrs	Estuarine zone (Kleinmond)	1 (Bot)		1 (Rooisand)	2/1	0-35 (Kleinmond)	0 – 45 Bot
Klein	1	Tidal	1-2 yrs	-	1	3 (Max: 2)	-	2	-	0-40
Heuningnes	1	Tidal	Open (95%)	Estuarine zone	1			2	0-45	0-6
Touw/Wilderness	1	Tidal	1-3 yrs	Estuarine zone (Touw)	3 (Wilderness)	4 - 6 (Max:7)	3	1/2	0-35	0 -20
Swartvlei	1	Tidal	1-4 yrs	Estuarine zone	2	5 (Max: 17)		3	0-35	5-12
St Lucia/uMfolozi	2 (during floods)	Tidal	1-10 yrs	Estuarine zone (Narrows)	3	1/1 (Max: 3 /2)	1	5 / 2	0-35	0-250
uMhlathuze	2	Tidal/Tidal	Open (100%)	-	2	1/12 (Max: 2/20)	2	2/3	- -	0-35 35
iNhlabane	1	Constricted	>1 yr	Estuary	1	2 (Max: 5)		1	0-35	0
uMgobezeleni	1	Constricted	Open (99%)	Inlet channel	2	3 (Max: 5)	2	Ground-water + 2		Fresh
Kosi	1	Tidal	Open (99%)	Estuarine zone	4+1 (Zilonde)	3 (Max: 31)	4	Ground-water + 3	0-35	0-20

Table 2. Description of generic abiotic states occurring in South Africa's estuarine lake systems

ESTUARY	OPEN ABIOTIC STATES							CLOSED ABIOTIC STATES					
	Fresh	Marine/ Fresh	Gradient	Marine/ Brackish	Marine	Marine/ Hypersaline	Hypersaline	Fresh	Brackish	Gradient	Marine/ Brackish	Marine	Hypersaline
Verlorenvlei	●							●	●				
Zeekoevlei	●												
Bot/Kleinmond					●			●	●			●	●
Klein	●		●		●				●			●	
Heuningnes	●		●		●		●		●				●
Touw/Wilderness	●		●					●	●		●		
Swartvlei	●		●						●	●		●	
St Lucia/uMfolozi					●	●	●	●		●			●
iNhlabane	●							●					
uMhlathuze			●		●								
uMgobezeleni	●							●					
Kosi	●	●	●	●							●		

ABIOTIC STATE		STATE DESCRIPTION
OPEN	Fresh	Mouth is open and the system is (nearly) fresh throughout. Average water levels. Can have elevated water levels due to flooding for short periods.
	Marine/ Fresh	Mouth is open with limited salinity penetration in lower reaches (estuarine zone), while lakes are generally fresh. Average water levels.
	Gradient	Mouth is open and full salinity gradient is observed throughout the system. Average water levels.
	Marine/ Brackish	Mouth is open and salinity varies from marine (near mouth) to brackish. Average water levels.
	Marine	Mouth is open and a marine salinity regime is observed throughout the system. Average water levels.
	Marine/ Hypersaline	Mouth is open and the salinity regime varies from marine to hypersaline in parts of the system. Average to low water levels. Some parts of the system may become isolated.
	Hypersaline	Mouth is open and the majority of lake system is hypersaline. Very low water levels.
CLOSED	Fresh	Mouth is closed and the system is nearly fresh throughout. High to very high water levels.
	Brackish	Mouth is closed and the system is brackish throughout. High water levels.
	Gradient	The mouth is closed and partial longitudinal salinity gradient is observed. High water levels.
	Marine/ Brackish	Mouth is closed and salinity regime varies from marine to brackish in parts of the system. Low water levels.
	Marine/ Hypersaline	Mouth is closed and salinity regime varies from marine to hypersaline in parts of the system. Very low water levels, some littoral habitats may be exposed or parts of lakes isolated from larger system.

South Africa’s estuarine lakes are already subject to extensive anthropogenic pressures that go beyond the influence of climate change. The key pressures acting on each of the country’s estuarine lake systems are indicated in Table 3, as per [4].

Table 3. Key anthropogenic pressures on South Africa’s estuarine lakes

SYSTEM	PRESSURE																
	Overall Pressure Level	Reduced base flows	Reduced floods	Reduced groundwater input	Poor water Quality: Stormwater / floodplain drainage	Poor water quality : River water quality	Poor water quality: WWTWdischarges	Reduced connectivity/ hydrodynamic functioning	Artificial mouth management/breaching	Loss/degraded riparian areas/ wetlands	Alien vegetation	Grazing (sheep, cattle, goats)	Mangrove harvesting	Recreational activities impacting birds	High fishing pressure/ bait collection	Alien or translocated fish	Mining
Verlorenvlei	H			●		Agric		●	●	●		●			●*	●	
Zeekoevlei	VH	●			Urban	Urban	●	●	●		●			●		●	
Bot/Kleinmond	M	●				Agric	●		●		●			●	●	●	
Klein	M	●			Urban	Agric	●		●		●			●	●*	●	
Heuningnes	H	●			Agric	Agric		●	●	●	●	●		●	●	●	
Touw/ Wilderness	M	●						●	●		●			●	●	●	
Swartvlei	L	●				Agric		●	●		●			●			
uMhlathuze	VH	●	●		Agric	Agric/ Urban		●	●	●	●		●	●	●*	●	●
iNhlabane	VH	●	●					●		●	●	●			●*		●
St Lucia/ uMfolozi	H	●	●					●			●		●		●*		
uMgobezeleni	M			●	Agric/ Urban			●	●				●		●*		
Kosi	L	●		●							●		●		●*		

**Ilegal gillnetting impacting nursery function & food security*

3. Approach and methods

The vulnerability assessment, specifically focused on terrestrial climatic and hydrological vectors associated with climate change, did not consider highly modified estuarine lake systems, such as Richards Bay/uMhlathuze, impacted by port development, and Zeekoevlei and iNhlabane, which are impacted by weirs to the extent that they no longer function as estuarine lake systems. It also did not include the St Lucia/uMfolozi system which has been the focus of a previous vulnerability assessment but was considered in the development of conceptual models to allow for a holistic view of major processes and responses across lakes.

3.1 Climate change scenarios and vectors of change

While global *temperatures* have increased by about 0.8°C over the last century in response to the enhanced greenhouse effect, recent analyses indicate that South Africa has been warming at more than twice the global rate over the past five decades [31-35]. The mean temperature of coastal waters has increased by 0.1°C per decade since the early 1970s [36], although the trend is not uniform. Increases along the KwaZulu-Natal coast are among the highest in the Western Indian Ocean [37], while localised areas along the west and south coasts are cooling seasonally as a result of changes in upwelling patterns [38,37]. Climate change in southern Africa will change precipitation patterns, which in turn will affect the quantity, quality, and seasonality of hydrological flows to estuaries and exacerbate existing human modifications of river inflows [39- 43]. Climate change may also manifest through changes in the frequency of severe weather events. On the subtropical and warm temperate coasts, the combination of generally wetter conditions and increased intensity of precipitation events will result in increased runoff. An anticipated decrease in rainfall in the cool temperate region, with a minor increase in inter-annual variability, will result in a decrease in freshwater flows and an intensification of the wet-dry cycles, as shifts in precipitation are strengthened in the hydrological cycle in most instances [44-47,41]. An increase in extreme events is projected for the Southern, Eastern Cape and KwaZulu-Natal coasts during spring and summer, with a reduction projected for winter and autumn [e.g. 48,45,49].

An ensemble of high-resolution climate model simulations of present-day climate and projections of future climate change over South Africa has been performed as part of the “Green Book” project. Simulations were developed using a regional conformal-cubic atmospheric model (CCAM) developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) [50,51,52]. Six simulations of the Coupled Model Intercomparison Project Phase Five (CMIP5) and Assessment Report Five (AR5) of the Intergovernmental Panel on Climate Change (IPCC) [53], obtained for the emission scenarios described by Representative Concentration Pathways 4.5 and 8.5 (RCP4.5 and 8.5) were first downscaled to 50 km resolution globally and then further to 8 km resolution for South Africa. The simulations span the period 1960-2100, with the period 1960 to 1990 representing the baseline, 2021-2050 (mid future) and 2070-2099 (Far future). RCP4.5 is a high mitigation scenario, whilst RCP8.5 is a low mitigation scenario. For the period 2021-2050 (mid future) relative to the baseline, under low mitigation (RCP8.5), temperature increases of 1 to 3°C may plausibly occur over the coastal regions. For RCP8.5 far future relative to baseline, temperature increases of 3 to 4°C are plausible to occur over coastal regions, with some months projected as high as 5°C (Figure 1.3). Under RCP4.5 temperature increases may still be significantly reduced, estimated between 1 and 2.5°C. Under RCP8.5 Mid future, rainfall is projected to increase over the central interior and east coast, while the western interior, northeastern parts and the winter rainfall region of the southwestern Cape are projected to become generally drier. The projected changes in rainfall patterns under RCP4.8 and RCP8.5 are very similar. For RCP8.5 Far future, rainfall is projected to decrease over the central interior and east coast of South Africa.

Since measured inflow data into estuaries are typically not available due to sparse observation networks, rainfall-runoff models were used to simulate hydrological data. The advantage of applying these modelling techniques is that natural flow regimes and future regimes can be simulated to assist in determining the sensitivity of ecological responses to changes in flow. No new hydrological modelling was undertaken as part of this study, and available simulated data for Reference (i.e. prior to any anthropogenic or climate change pressures) and Present (i.e. accounting for existing anthropogenic pressures, but not climate change pressures) were sourced from the literature) [20-30,3]. Given that the climate model ensemble outputs do not span the required >70-year simulation periods, available simulated monthly present inflows were scaled according to the predicted relative shifts in monthly rainfall for the catchments and directly onto the estuaries using a delta-change approach. These broad extrapolations were further moderated with the outputs of Cullis et al. [54]. For example, large floods are not transformed to the same degree as average only flows, so factors were applied to moderate the impact on inflows that only occur for 5 to 10% of the time in the simulated sequence.

3.2 Selection of key abiotic and biotic indicators

For this study, four abiotic indicators (water level, mouth state, salinity, and water quality [nutrients]), and three biotic indicators (microalgae, macrophytes and fish) were selected to assess the responses of estuarine lakes to climate change. These were primarily selected based on their suitability and sensitivity to the selected climate change vectors, but also based on the availability of data across these systems. Temperature was used as a driver of changes and not as an indicator. Table 4 provides a summary of the rationale for the selection of the indicators. *Microalgae* form the base of food chains in estuaries and were considered an important indicator from that perspective [55]. Lake systems support very valuable *macrophyte* habitats. Macrophyte habitats provide important ecosystem services such as filtering and bank stabilisation. They cycle nutrients by taking them up and releasing them again through decomposition processes. Salt marsh, mangrove, reed and sedge wetlands protect the land from floods and sea storms, sequester carbon and serve as a source of raw materials for humans. Submerged aquatic vegetation provides critical habitat for fish and invertebrates, thus supporting a valuable ecosystem service in the form of the provision of nursery areas [56]. Estuarine habitats are extremely important for *fish* in southern Africa. The vast majority of coastal habitat in this region very exposed to the open ocean, so its estuaries are disproportionately important relative to other parts of the world, in that they constitute the bulk of the sheltered, shallow water inshore habitat in the region [57,58]. There are at least 100 species that show a clear association with estuaries in South Africa [56]. The response of estuarine fish assemblages to environmental and ecological change makes them good indicators of anthropogenic stress [57,59,60].

Table 4. Summary of the rationale for the selection of abiotic and biotic indicators

INDICATOR	RATIONALE
Water level	An increase/decrease in rainfall and associated runoff will result in a related increase/decrease in lake water levels driven by catchment inputs and direct rainfall on the lake surface areas.
Mouth state	An increase/decrease in rainfall and associated runoff will result in a related impact on breaching frequencies and the duration of open mouth conditions. Mouth state is also a direct indicator of land-sea connectivity.
Salinity	Salinity responds to increase rainfall and runoff, as well as mouth state (frequency and duration of open and closed conditions). It is also a key indicator of biotic community composition and/or abundance.
Water quality (nutrients)	Although it was not expected for the selected vectors of climate change to necessarily have a direct influence on nutrients, enrichment is a major anthropogenic pollution pressure in many estuarine lakes [61,62]. It was, therefore, important to include this indicator to account for the cumulative impacts of climate changes and nutrient enrichment.
Microalgae	Microalgae are a major food source for higher trophic levels in estuaries (e.g., zooplankton, fish). The dynamics of microalgae (especially phytoplankton) are largely influenced by nutrient availability and residence time [55]. The latter is influenced by, for example, mouth state which, in turn, is affected by shifts in river runoff. Temperature increases can also stimulate primary production in estuaries.
Macrophytes	Macrophyte habitats provide important ecosystem services. Mouth state is a key driver of tidal inundation/water levels and salinity. Water levels (e.g. flooding, standing, fluctuating), in turn, is a key determinant of macrophyte habitats, with any changes in water level resulting in vegetation changes. Salinity also influences macrophyte habitats and may lead to die back under extreme conditions or change community composition. Increased temperature will increase primary production.
Fish	Estuarine fish assemblages are economically important and good stress indicators [59,57,60] Mouth state governs connectivity, recruitment and community composition. Water levels fluctuations can lead to loss of critical habitats, e.g., intertidal areas. Salinity is a primary driver of fish distribution in estuarine lakes. High temperatures decrease tolerance to environmental perurbation and may influence sex ratios.

3.3 Ecosystem-based assessment method

For this assessment, an ecosystem-based approach was adopted whereby conceptual models, of typical biophysical patterns in each of the estuarine lakes were constructed from the generic seven open and five closed abiotic states (Table 2). These conceptual models distinguished between dominant open-closed cycles, and drought and flood events (if persistent state), as illustrated in Figure 2.

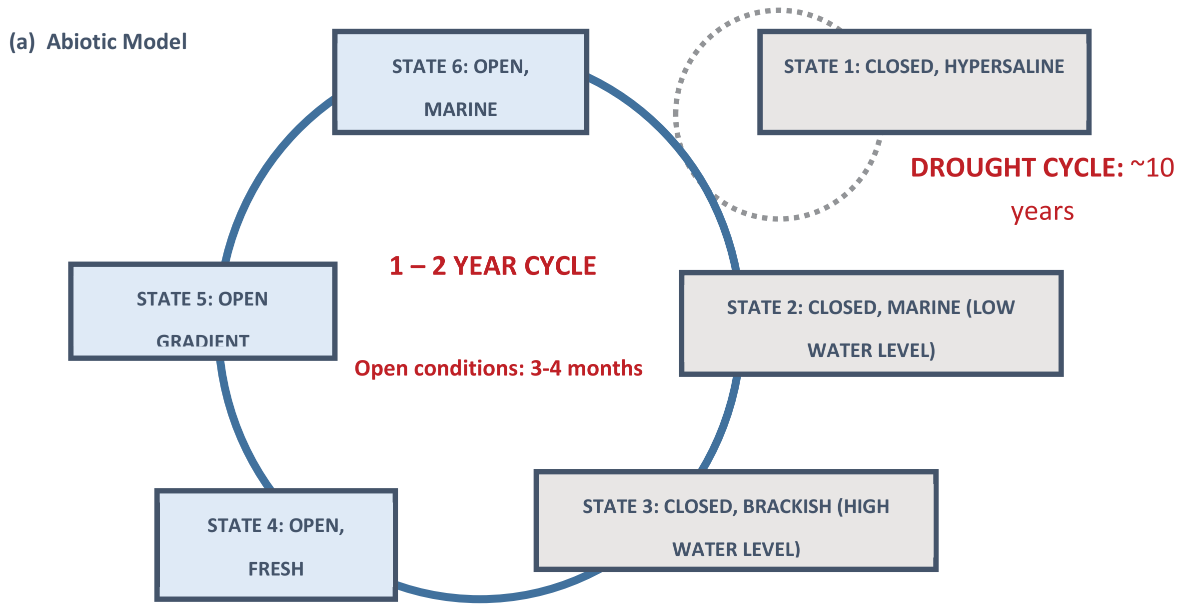


Figure 2. Example of an abiotic conceptual model for estuarine lakes.

Using the simulated runoff scenarios (Reference, Present and Climate Change) as input data, shifts in the occurrence and frequency distribution of *various abiotic states* in each of the systems were derived by either using a water balance model or direct correlation with flow (whichever was considered most appropriate). Given the relatively large surface areas of the lake systems in comparison with their relative low inflow, in most cases, water balance models [e.g. 63] were considered the most appropriate tool for this national-scale assessment. Specifically, *water levels* and *mouth state* were used where measured data were not available. The simple equation for the volume of water in the estuary at time t [64], is given as:

$$V_t = V_{t-1} + V_{\inf low} + V_{precip} + V_{evap} + V_{seepage} + V_{overwash} + V_{artificial} + V_{ground}$$

Estuarine lake systems typically remain closed until their basins fill up to a level equal to the height of the sand berm across the mouth. Any additional water added to the estuary basin after this will cause breaching (assuming that inflow exceeds the outflow from the estuary). The foremost assumption in the development of a water balance model for these type of systems is therefore that breaching will occur when the water level (WL) in the estuary basin equals, or is greater than the height of the berm (B_c). This results in the algebraic inequality which states that a breach occurs if [64]:

$$WL(t) \geq B_c(t)$$

Given the complexity in calculating the effects of increased temperature on evaporation, this aspect was not systematically factored into this assessment. Evaporation rates were kept similar to present in the water balance models but assumed to have a compounding impact on drought conditions. Increased evapotranspiration rates were also not systematically included, but factored in as a contributing factor under extreme drought conditions in systems predicted to have high exposure and vulnerability (e.g. shallow bathymetry). In larger systems where water levels fluctuate more slowly over time (i.e., annual or seasonal scales) water level data were calculated and reported on independently from other variables, such as mouth state. In more simplified applications of the model, water level estimates were linked directly to river flow ranges through either in-situ measurements or area-volume relationships [64].

Salinity distribution patterns were sourced from available literature or inferred from water level and mouth state measurements or estimates. For example, longitudinal salinity distribution patterns are linked to open or closed mouth conditions and, in turn, can be used to predict changes in average salinity concentrations under certain hydrological or hydrodynamic conditions.

Temperature ranges were derived from available literature or field data and broadly adjusted for predicted changes under climate change conditions. Given that most lakes are weakly connected to the sea, an assumption was made that lake temperatures would broadly follow that of terrestrial prediction. For example, if predicted changes were 2 to 3°C, the study would assume that lake temperatures would increase by 1 to 3°C in unstratified systems. Bottom waters of stratified systems were deemed less sensitive.

It has been shown that in South African estuaries – including estuarine lakes – nutrients are the major driver of *water quality* status [61,62]. Based on this, dissolved inorganic nitrogen (DIN) was selected as a proxy to assess shifts in water quality status. Nutrient data were sourced from available literature [3,20-30] and, where data were not available, the experiential knowledge of the project team on estuarine water quality was used to derive the best estimates. Using a box model approach [e.g. 61], shifts in water quality condition were estimated from the predicted distribution of abiotic states, which, in turn were estimated from the simulated runoff scenarios.

Changes in microalgae were primarily organised into changes in phytoplankton and benthic microalgal biomass, and the presence/absence of harmful algal blooms (HABs) (Figure 3a). Information on the present status of microalgae data were sourced from available literature [3,20-30]. Where data were not available, the experiential knowledge of the project team on microalgal behaviour was used to derive the best estimates. The eutrophication classification system developed by Lemley et al. [65] was used to rate microalgal condition. The best available knowledge was used in predicting the probability of the occurrence of HABs.

Present conditions for macrophyte habitats were derived from available studies [3,20-30]. Where appropriate aerial photographs or Google Earth images were available, these were also used to assess the distribution of macrophyte habitats. Present assessments were refined by more detailed vegetation inundation modelling under different water level conditions for some systems (i.e. Klein, Bot and

Verlorenvlei). Projected response to climate change was expressed as change in the estuary habitat types, focusing on salt marsh, reeds and sedges and submerged macrophytes, as illustrated in Figure 3b. Whitfield [60,66] has developed a detailed classification system of estuary-associated fishes in southern Africa, recognizing five major categories of estuary-associated fish species ranging from estuarine-dependent to marine and freshwater species.

Following detailed review of unpublished and unpublished data, a species list was compiled for each lake system and fish categorised according to the above classification.

Figure 3 below shows an example of microalgae (a), macrophyte (b) and fish (c) conceptual models for estuarine lakes.

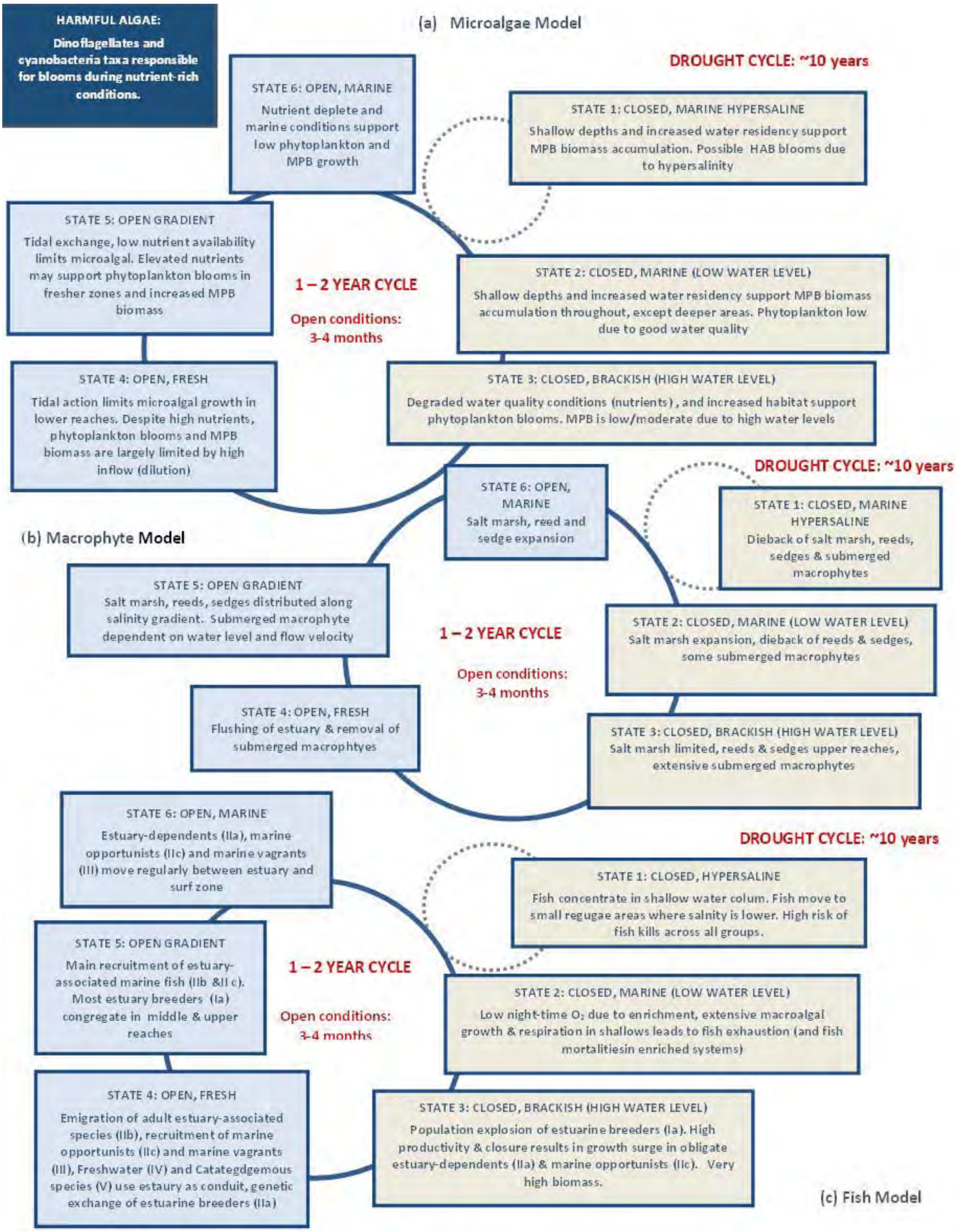


Figure 3. Example of microalgae (a), macrophyte (b) and fish (c) conceptual models for estuarine lakes.

Known life-history characteristics of the fish, as well as predicted changes in abiotic factors which influence the abundance and diversity of estuarine-associated fishes were then used to predict changes in fish abundance and/or community composition. Feeding guilds were also considered to express changes in the fish conceptual models. Possible responses of fish to shifts in abiotic states are illustrated in Figure 3c.

3.4 Integration of assessment results

To ensure alignment with existing estuarine health assessments conducted for South African estuaries (e.g. NBA 2018) [4], the country's official Estuary Health Index (EHI), developed under the National Water Act [67,68] was used to integrate assessment results in a compatible format. The index adopts an ecosystem-based approach that considers an array of abiotic (hydrology, hydrodynamics and mouth condition, sediment processes and water quality) and biotic (microalgae, macrophytes, invertebrates, fish and birds) components. For this study, the abiotic components were simplified to three indicators, namely hydrology, hydrodynamics (mouth state and water level), and water quality (including salinity and nutrients), while the biotic indicators were simplified to three, namely microalgae, macrophytes and fish. For each of the abiotic and biotic components, the predicted state was estimated as a percentage (0% – 100%) of the natural state. Weighted averages for the abiotic and biotic indicators were then applied to attain a habitat and biotic health score, respectively. Finally, these habitat and biotic health scores were combined into a final health score, weighted equally (Table 5).

As with the original index, these indicators were each categorised from natural (A) to critically modified (F) based on expected changes under each of the climate change scenarios. Of note is that the A to F scale represents a continuum and that the boundaries between categories are conceptual points along the continuum as loss of estuarine functionality happens along a continuum [2]. This integration of assessment to determine the present state and each system's future sensitivity to climate-induced shifts in the abiotic and biotic processes was performed during a virtual workshop attended by a group of estuarine scientists using available information and their expertise on estuaries, including estuarine lakes.

Table 5. Estuary health scoring system indicating the relationship between the six Ecological Categories and the loss of ecosystem condition and functionality [adapted from 2].

Condition (% of natural)	≥91%	90-75	75 - 61	60 - 41	40-21	≤20
Ecological condition Category	A Natural	B Largely natural / few changes	C Moderately modified	D Largely modified	E Highly degraded	F Extremely degraded
Ecological State	NATURAL	NEAR NATURAL	MODERATE	HEAVILY	SEVERE/CRITICAL	
Functionality	Retain Process & Pattern (Representation)		Some loss of Process & Pattern	Significant loss of Process & Pattern	Little remaining Process & Pattern	

Category	Description
A	**Unmodified, approximates natural condition.** The natural abiotic processes should not be modified. The characteristics of the resource should be determined by unmodifed natural disturbance regimes. There should be no human induced risks to the abiotic and biotic processes and function.
B	**Near natural with few modifications**. A small change in natural habitats and biota may have taken place, but the ecosystem functions are essentially unchanged.
C	**Moderately modified**. A loss and change of natural habitat and biota have occurred, but the basic ecosystem functions are still predominantly unchanged.
D	**Heavily modified**. A large shift natural processes and ecosystem functions and/or loss of habitat, biota have occurred.
E F	**Severely modified.** The loss of natural habitat, biota and basic ecosystem functions is extensive. **Critically modified**. Modifications have reached a critical level and the system has been modified completely with an almost complete loss of natural abiotic processes and associated biota. In the worst instances the basic ecosystem functions have been destroyed and the changes are irreversible.

4. Results and discussion

4.1 Vulnerability to Climate Change

4.1.1 Sensitivity of abiotic and biotic indicators

Evaluating the different indicator responses to climate change highlights some of the regional responses. Table 6 summarises the impacts climate may have on key abiotic and biotic processes in estuarine lakes.

Hydrology: Depending on the predicted degree of change in precipitation, and in which part of the rainfall regime (low flow or high flow season) these changes occur, runoff changes could be negligible (e.g. RCP4.5 Mid future) or severe (RCP8.5 Far Future). The most change was projected for the cool temperate regions, with systems such as the Bot/Kleinmond showing a severe decline in indicator condition (~ 20%), i.e., from a B category to a C/D category. While lake systems in the warm temperate region (Heuningnes, Touw/Wilderniss and Swartvlei) saw a smaller decline overall and even incremental improvement in hydrology under mid- future conditions. The least impacted were the tropical systems (Mgobozeleni and Kosi).

Mouth state*:* Most systems showed some sensitivity to changes in mouth state and marine connectivity, with most declining by half a category or a full category. Bot/Kleinmond and Klein in the warm temperate region showed the most sensitivity to this indicator.

Water levels*:* Lake levels fluctuate annually and inter-annually as a natural response to local climate and rainfall events. These fluctuations are expected to amplify under climate change as rainfall reduces and abstraction for human consumption increases. An increase in temperature is likely to increase evaporation rates and decrease lake water levels during the closed phase due to high evaporative losses (and thus also decrease opportunities for open mouth conditions). This will be a problem particularly during drought conditions (e.g., Verlorenvlei, Bot). However, given the high variability in water level over long time scales, this indicator was the least sensitive to predicted climate change, with the Verlorenvlei system being the most likely to respond to future climate change conditions.

Salinity*:* Rising temperatures and evaporation rates may lead to hypersalinity developing in some lakes systems (e.g., Klein), or increase the duration and intensity of existing hypersalinity cycles (e.g., St Lucia). However, in some systems, like the Bot/Kleinmond, it could lead to a freshening of the lake system under prolonged closed conditions due to seepage losses and outflow through Kleinmond. Overall, average salinity regimes shifted significantly over longer time scales with the Heuningnes and Bot/Kleinmond system showing the greatest sensitivity to future climate conditions (e.g., RCP8.5 Far Future).

Water quality (Nutrients): As expected, the water quality did not change much as a result of climatic conditions with less than a 5% change observed under most scenarios. No significant shifts in condition categories were observed.

Microalgae responses*:* The dynamics of microalgae (especially phytoplankton) is largely influenced by nutrient availability and residence time [55]. During the open state, previously submerged sand and/or mud banks become exposed (weeks to years). The exposure of previously inundated sediments has a profound impact on the available microphytobenthic habitat within a lake system [69,70]. Salinity drives distinct microalgae community shifts in both phytoplankton and microphytobenthos. The relative contribution of either of these two communities in an estuarine lake system is dependent on the hydrodynamics (e.g., mouth state and freshwater inflow). Increases in temperature and nutrient loading can stimulate primary production, occasionally supporting high microalgal biomass. Vertical stratification in nutrient-rich estuarine lakes is likely to support flagellate-dominated phytoplankton communities (e.g., dinoflagellates, raphidophytes [71].

Extended periods of low runoff and limited, or no, tidal exchange in a nutrient-rich system will accelerate the process of eutrophication, resulting in an organic-rich and oxygen-poor environment that can support a cyanobacterium dominated microalgal community. Phytoplankton was the most sensitive of the algae groups, with notable responses observed under the RCP8.5 scenario for all systems, while benthic microalgae were the least responsive. Harmful algal blooms were a key concern in enriched systems, such as the Klein, Swartvlei, and Mgobozeleni; while the blooms in Kosi were largely attributed to natural processes but needs further investigation. Increased temperature was a major driver of change in this component under RCP 8.5Far Future conditions.

Table 6: Summary of responses of abiotic and biotic indicators to climate change scenarios (RCP4.5 and RCP8.5)

Estuary	Scenario	Hydrology	Mouth State	Water levels	Salinity	Water Quality	Abiotic Sensitivity	Phytoplankton	Benthic Microalgae	Harmful Algal Blooms	Macrophytes	Fish (-Fishing impacts)	Biotic Sensitivity	Estuary Sensitivity
Verloren	Present	B/C	A/B	B/C	A	E	B/C	D	C	C/D	D	D/E	D	C
	1: RCP4.5Mid	C	B	C	A	E	B/C	D	C	C/D	D	E	D	C/D
	2: RCP4.5Far	C	B	C	A	E	B/C	D	C	C/D	D	E	D	C/D
	3: RCP8.5Mid	C	B/C	C	A	E	C	D	C	C/D	D	E	D	C/D
	4: RCP8.5Far	C/D	B/C	C	A	E	D	D/E	C/D	C/D	D	E	D/E	D
Bot/ Kleinmond	Present	B	B	A/B	A/B	D	B	B	A/B	A/B	B	B/C	B	B
	1: RCP4.5Mid	B/C	C/D	A/B	A	D	C	B/C	A/B	B	B	B/C	B	B/C
	2: RCP4.5Far	C	C/D	A/B	A	D	C	B/C	A/B	B	B	B/C	B	B/C
	3: RCP8.5Mid	C	D	A/B	A	D	C	B/C	A/B	B	B	B/C	B	C
	4: RCP8.5Far	C/D	C/D	A/B	A	D	D	B/C	A/B	B	B	C	B/C	C
Klein	Present	B/C	C	A	A/B	D/E	B/C	C	B/C	B/C	C	C	C	B/C
	1: RCP4.5Mid	B/C	C	A	A/B	D/E	B/C	C	B/C	B/C	C	C	C	C
	2: RCP4.5Far	B/C	B/C	A	A/B	D/E	B/C	C	B/C	B/C	C	C	C	C
	3: RCP8.5Mid	C	C/D	A	A/B	D/E	C	C	B/C	B/C	C	C/D	C	C
	4: RCP8.5Far	C	D	A	A/B	D/E	D	C/D	B/C	C	C/D	D	D	D
Heuningnes	Present	B	B	A/B	D/E	C	B/C	B	B/C	A	C/D	C/D	C	C
	1: RCP4.5Mid	B	B/C	B	D/E	C	B/C	B	B/C	A	C/D	C/D	C	C
	2: RCP4.5Far	B	B/C	B	E	C	B/C	B	B/C	A	C/D	C/D	C	C
	3: RCP8.5Mid	A/B	B/C	B	D/E	C	C	B	B/C	A	C/D	C/D	C	C
	4: RCP8.5Far	B/C	B/C	B	E	C	D	B/C	B/C	A/B	D	D	C/D	D
Touw/ Wilderness	Present	C	C/D	B	B	B	C	A/B	C/D	A/B	B/C	C	C	C
	1: RCP4.5Mid	A/B	C	B	B	B	B	A/B	C/D	A	B/C	C	C	B/C
	2: RCP4.5Far	B	C/D	B	B	B	C	A/B	C/D	A/B	B/C	C	C	C
	3: RCP8.5Mid	B/C	D	B	B	B	C	A/B	C/D	A/B	B/C	C/D	C	C
	4: RCP8.5Far	C	D	B	B	B	D	B	C/D	A/B	B/C	D	C/D	D
Swartvlei	Present	C	B	B	C	B	B/C	B/C	A/B	B	B/C	B/C	B/C	B/C
	1: RCP4.5Mid	C	B	B	C	B	B/C	B/C	B	B	B/C	B/C	B/C	B/C
	2: RCP4.5Far	C	B/C	B	C	B	C	B/C	A/B	A/B	C	C	C	C
	3: RCP8.5Mid	C	A	B	C	B	C	B/C	B	B	B/C	B	B/C	B/C
	4: RCP8.5Far	C/D	B	B	B/C	B	C/D	C	B	B/C	B/C	B/C	C	C
Mgoboze-leni	Present	A/B	A/B	A	A	B/C	A/B	B	A	C	B	C	C	B
	1: RCP4.5Mid	B	A/B	A	A	B/C	A/B	B	A	C	B	C	C	B
	2: RCP4.5Far	A	A	A	A	B/C	A	B	A	C	B	C	C	B
	3: RCP8.5Mid	B	A	A	A	B/C	B	B	A	C	B	C	C	B
	4: RCP8.5Far	A	B	A	A	B/C	B/C	C	A	C/D	B/C	C	C	C
Kosi	Present	A/B	A	A	A	A/B	A	B	B/C	A/B	A/B	A/B	B	A/B
	1: RCP4.5Mid	B	A	A	A	A/B	A	B	B/C	A/B	A/B	A/B	B	A/B
	2: RCP4.5Far	A	A	A	A	A/B	A	B	B/C	A/B	A/B	A/B	B	A/B
	3: RCP8.5Mid	A	A	A	A	A/B	A	B	B/C	A/B	A/B	B	B	A/B
	4: RCP8.5Far	A/B	A	A/B	A	A/B	B	B/C	C	B	C	B	C	B

Macrophyte responses*:* High water levels result in flooding of macrophyte habitats. Macroalgae and submerged macrophytes flourish in this state, while mangroves and swamp forest are sensitive to flooding, standing water and anoxic conditions and will not survive prolonged inundation (months) [72]. Lakeshores are ecotones (a transitional zone between terrestrial and aquatic habitats) characterized by fluctuations in water levels. Any rapid changes in water level will result in vegetation changes. Stable water levels can also cause an expansion of macrophytes, such as reeds and sedges. Increased temperature will increase primary production. Open mouth states create intertidal habitat, with salt marsh species occurring along a tidal inundation gradient. Closed states promote the growth and proliferation of macroalgae. Prolonged mouth closure could result in the dieback of intertidal salt marsh species [73]. A change in salinity will influence the macrophyte habitats, e.g., reeds and sedges grow better in brackish water whereas salt marsh and seagrass grow better in salinity close to seawater. Reeds and sedges are sensitive to increases in salinity but can survive if their roots and rhizomes are located in salinity less than 20. However, if freshwater seepage is reduced then it may lead to die back. Freshwater inflow prevents hypersaline conditions in sediments of salt marshes. Hypersaline sediments caused by evaporation and infrequent flooding will result in dry bare patches in the supratidal areas [74]. Macrophyte conditions decline between 3 and 10% under future climate conditions, but in most cases remain in the present condition category. Bot/Kleinmond and Klein were the most sensitive to change as a result of a change in mouth state and water levels.

Fish responses*:* Mouth state governs connectivity between estuarine lake habitats and the sea. Mouth closure prevents recruitment of marine spawned larval and juvenile fish into a system, and may also prevent movement and migration of fishes during spawning periods [75]. It also results in a loss of salinity gradients that govern fish (as well as their prey and habitat) distributions [76]. Under closed conditions, intertidal area already limited in most lakes, is lost, with implications for the productivity of intertidal habitats and trophic effects to the fish community. Increased open-states, stimulating microphytobenthic production to the benefit of components of the fish assemblage (e.g. Mugilidae), but to the detriment of others either through direct loss of habitat (e.g. loss of shallow submerged vegetation such as *Zostera capensis* beds as preferred or even critical [i.e., pipefish, seahorses] habitat) and/or through trophic effects (e.g., loss of benthic invertebrate productivity, sand prawns) [77]. Salinity is a primary driver of fish distribution in estuarine lakes, either directly as different species have different salinity preferences, or indirectly, through affecting prey and habitat distribution. Most estuarine-associated marine fishes and estuarine resident species are tolerant of low rather than high salinity and several freshwater species can tolerate slight (or even marked) elevations in salinity [60]. High temperatures decrease tolerance to hypoxia and low salinities and increase risk of mass mortality [78]. Sex ratios can be skewed in fish where sex-determination is temperature related [79]. Temperature increases tend to skew towards males [79]. Different life history stages may be more susceptible to temperature and other stressors which may be mitigated by transgenerational plasticity [79]. This is especially true of estuary-associated fish that experience a diversity of stressors in their lifetime. One example is *Atherina* where males seem to be few (e.g. [80]), and non-existent in some populations (Lamberth unpublished data). One possibility is that the consequences of female skewed sex-ratios may be mitigated by it being a parthenogetic species. Consequently, climate change influences on temperature could have a profound impact on fish populations. Growth rates and gonadal development tend to decrease on either side of the optimal temperatures for individual species. Shallow marginal areas tend to be warmer than deeper channel areas and are thus favourable for metabolic processes. Juveniles and small adults also use shallow water as a predation refuge. Submerged aquatic macrophytes are also important for some estuarine-associated species (e.g., pipefishes and seahorses, gobies, blennies and sparids such as stumpnose) [60]. These habitats, in estuarine lakes, are typically shallow subtidal. Intertidal habitats are limited, but where they occur are important for estuarine dependent marine species. Deeper intertidal habitat is used as a refuge from predation [81,82]. Very deep subtidal areas in estuarine lakes are likely to have quite distinct water quality characteristics, including low oxygen levels, that might preclude use by fishes. A decrease /increase in floods will have a related impact on the fluvially dependant nearshore marine habitats that rely on river inflow for salinity and turbidity fronts, nutrient input, sediment supply and detritus (organic matter). Changes in flood behaviour will also have an impact on migratory signals and fish recruitment to estuaries [83,84]. Most systems reflected sensitivity to future climate change conditions (between 5 and 25%), with the biggest shift observed in the Klein reflecting the cumulative impact of climate change and nutrient enrichment. Systems such as the Touw/Wilderness and Swartvlei was also sensitive to the combination of changes in rainfall/runoff, mouth state, warmer conditions and enrichment.

Droughts and floods*:* An increase in future occurrence of drought conditions is very likely to decrease marine connectivity (less open mouth conditions) and/or decrease lake water levels. Drastically reduced lake levels are likely to isolate parts of the estuarine lake systems from each other (e.g., Rondevlei), thus impacting lake connectivity. Droughts are also likely to increase the likelihood of hypersalinity developing in some systems (e.g., Klein), or increase the duration and intensity of hypersalinity cycles (Heuningnes). However, in some systems prolonged periods of closure may lead to freshening of the lake system such as the case of the Bot/Kleinmond system. An increase in floods will increase opportunities for mouth breaching – and vice versa - which, in turn, will change connectivity with the marine environment. Changes in flood regimes will also change the sediment equilibrium in lake systems. In many cases, lakes are sediment sinks and thus sensitive to increased sediment input. Larger floods may deposit more sediments.

During a flood event, salinities can be fresh or nearly fresh. However, after a flood event, salinities tend to increase significantly due to increased tidal amplitude and related seawater intrusion. Thus, an increase in floods and related scouring of the mouth area, can result in an increased salinities subsequent to a flood event. Systems such as Swartvlei may thus experience an increase in the maximum salinity achieved during the open cycle if floods were to intensify. Low tide levels can be dramatically lower after a flood event, reducing subtidal habitat and causing dieback /desiccation of submerged vegetation that is now exposed. Thus, reduction in habitat can impact on biota such as fish.

4.1.2 Overall sensitivity of estuarine lakes

One of the key findings that emerged from the Estuarine Lake Vulnerability Assessment was that the maximum potential shift in estuarine state varied between 9% and 22% from present functionality under the RCP4.5 and RCP8.5 Climate scenarios (see Figure 3). In all cases, the maximum degree of change was induced by the RCP8.5 Far Future Scenario. RCP8.5 Far Future conditions were *very likely* to cause major impacts on estuarine connectivity and associated functioning, with related impacts on biotic productivity and composition.

The responses to the RCP4.5 scenarios were generally grouped around the present state, with some scenarios even representing a shift towards natural conditions as a result of increased freshwater input in the mid-future scenarios. In most cases, the estuarine lakes were somewhat buffered against slight shifts in connectivity, water levels or salinity regimes as they are generally weekly connected to the sea and subjected to long periods of closure.

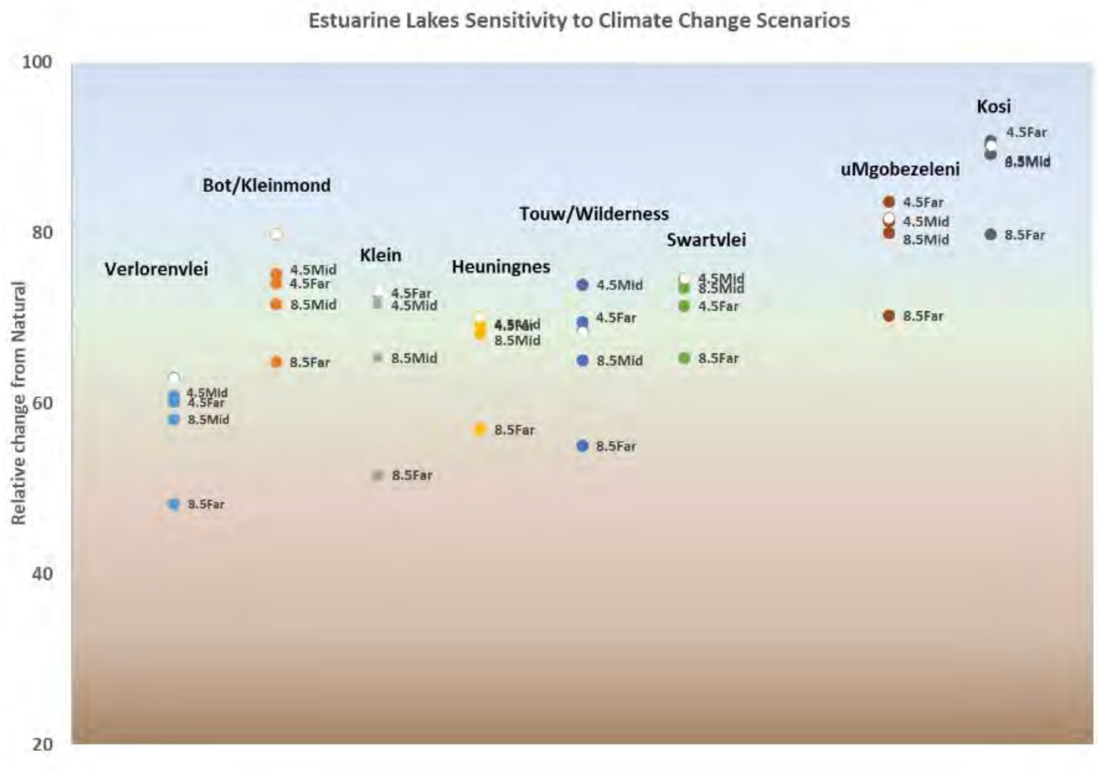


Figure 3. Relative sensitivity of the estuarine lakes of South Africa to RCP4.5 and RCP8.5 Climate Change Scenarios.

4.2 Climate change versus anthropogenic change

An important finding of the assessment was that in all systems assessed, except for Kosi, anthropogenic-induced change exceeded climate-induced shifts in estuary functioning (see Figure 4); highlighting the degree of transformation the estuarine lakes have already experienced. In the case of Kosi (near-natural in its present state), the relative shifts were similar in magnitude.

Given that estuarine lakes are nutrient sinks, that cannot be flushed by floods like other systems, the present water quality was a good predictor of future resilience, with enriched systems more likely to decline further in condition under hotter and/or drier future conditions. For example, the Klein that receives continuous wastewater input, is expected to become significantly more degraded under warmer climatic conditions. Increased mouth closure, lower water levels and warmer temperatures are *very likely* to drive an increase in harmful algal blooms and concomitant lower oxygen levels. Thus, *very likely* to increase the occurrence of fish kills in the system. In contrast, Kosi with near-natural water quality, mostly only responded to shifts in water levels and salinity regimes.

Relatively shallow lake systems, such as Verlorenvlei, Bot/Kleinmond and Heuningnes tend to be more vulnerable to the impact of reduced flows and/or the impact of drought conditions. In this type of system, event-scale droughts tend to dry out a large part of the lake beds and surrounding estuarine vegetation. Depending on the degree of marine connectivity, this type may also develop extreme hypersalinity in some parts of the system. This effect could be further amplified if the system was already subjected to enrichment, with harmful algal blooms often associated with this type of conditions. In some systems like Verlorenvlei, blue-green algal blooms are associated with fish developing lesions during the breeding season. While in Botvlei and Soetedalsvlei (Heuningnes) drought conditions are associated with extensive reed die-off due to low water levels and hypersalinity.

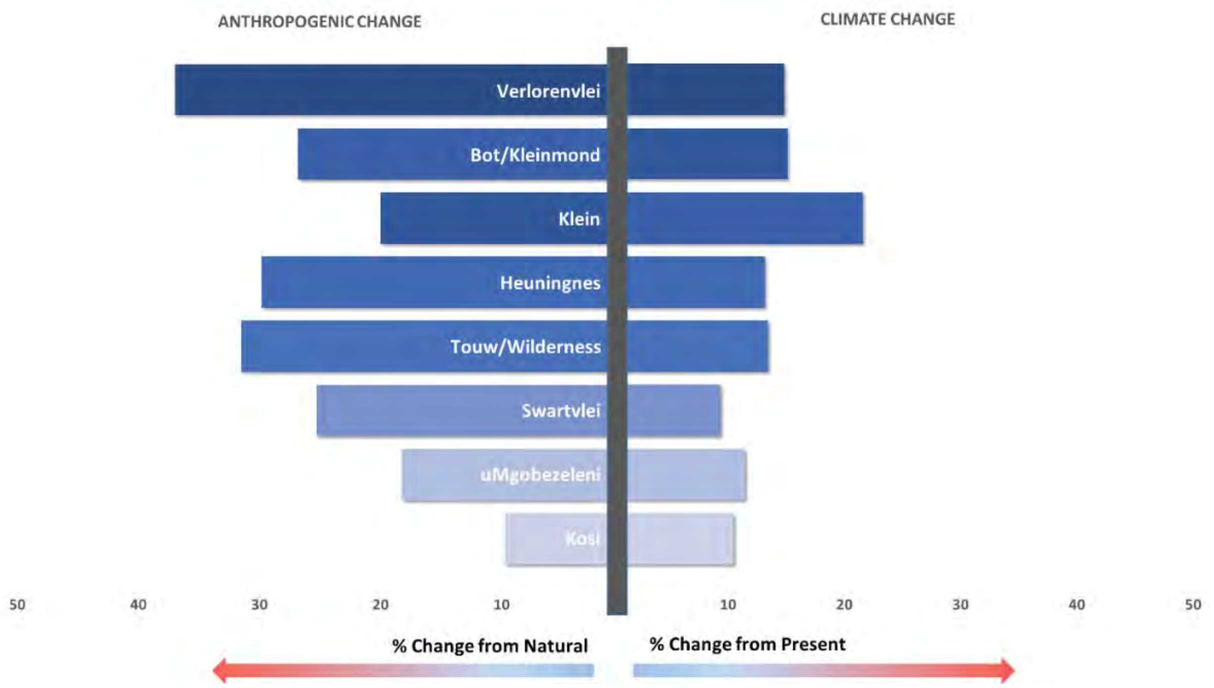


Figure 4. Graphic representation of the degree of anthropogenically-induced versus climate-induced change in the Estuarine Lakes of South Africa.

5. Conclusions and recommendations

The development of the abiotic and biotic conceptual models as an explicit step in the vulnerability assessment method allowed for the identification of commonalities and differences across estuarine lake systems and assists with bridging data gaps and extrapolating findings. The selected assessment approach was sensitive to change and allowed for the detection of climate-induced shifts in estuary function and productivity.

The impact of droughts is of special concern. More effort should be made to develop measures that reflect the increase in the occurrence and duration of droughts explicitly (some broad measures were included in this estuarine lakes study). It is also recommended that all estuary conceptual models in future explicitly develop a ‘drought state’ (even if only based on theoretical understanding and/or extrapolated from similar systems). This will assist with developing a more informed understanding of the impact and risk associated with severe droughts on estuaries moving forward.

The impact of increasing temperatures on primary producers (e.g., algae and macrophytes) is not well understood and thus poorly coupled to predictions of change, especially under the RCP8.5 far-future scenarios. This results in a low confidence assessment. More research needs to be done to inform predictions. Similarly, more research is needed on the impact of elevated temperatures on estuarine fish and the protection deeper refugia offer in the face of rising temperatures.

More effort should be made to develop coupled rainfall-runoff yield models specifically geared to better resolve climate change projections on river flows. Given the high degree of flow modification many estuary catchments are subjected to at present, it is not appropriate to merely superimpose climate change impacts on natural flow regimes. The impact of climate change needs to be reflected in conjunction with present levels of use (i.e., exploitation). Given the importance of evaporation in the development of water balance models for large water bodies such as the estuarine lakes, ongoing efforts in this regard should be supported. Groundwater is often ignored in these assessments, but under a hotter climate, this relative stable input parameter may change and needs to be considered in future studies as it plays a key role in maintaining lake levels in drought conditions. Given that many of the tools utilised in the estuarine lake vulnerability assessment have been set up and automated, e.g., estimating a change in mouth state, water quality and microalgae; should more detailed runoff, evaporation rates, or groundwater input datasets become available; it is recommended that the predicted abiotic state shifts be re-evaluated, and if need be, the vulnerability assessment workshop repeated.

The concomitant impact of sea level rise was not included in this estuarine vulnerability assessment. It is recommended that where detailed topographical (e.g., LiDAR) information is available more systematic evaluation be undertaken of the impact of sea level rise on key estuarine habitats, such as mangroves and salt marsh, similar as to what was done in the Knysna Estuary [85]. Finally, it is recommended that the approach adopted in this study for estuarine lakes be expanded to other estuarine types in South Africa (e.g.

predominantly open and temporarily closed systems) to assess vulnerability to climate change at the country-level for all estuarine types.

References

1. Van Niekerk, L., Adams, J.B., James, N., Lamberth, S., Mackay, F., Rajkaran, A., Turpie, J., Weerts, S., Whitfield, A.K. An Estuary Ecosystem Classification that encompasses biogeography and a high diversity of types in support of protection and management. *Afr.J. Aquat. Sci.* **2020**, 45, pp.199-216.
2. Van Niekerk, L., Adams, J.B., Bate, G.C., Forbes, A.T., Forbes, N.T., Huizinga, P., Lamberth, S.J., MacKay, C.F., Petersen, C., Taljaard, S., Weerts, S.P., Whitfield, A.K., Wooldridge, T.H. Country-wide assessment of estuary health: An approach for integrating pressures and ecosystem response in a data-limited environment, *Estuar., Coast. Shelf Sci.* **2013**, 130, pp.239-251.
3. Taljaard, S., Van Niekerk, L., Lemley, D.A. A glimpse into the littoral nutrient dynamics of a lake system connected to the sea. *Water SA* **2018**, 44, pp.65-74.
4. Van Niekerk, L., Adams, J.B., Lamberth, S.J., MacKay, F., Taljaard, S., Turpie, J.K., Weerts, S., Raimondo, D.C., (eds). South African National Biodiversity Assessment (NBA) 2018: Technical Report. Volume 3: Estuarine Realm. CSIR report number CSIR/SPLA/EM/EXP/2019/0062/A. South African National Biodiversity Institute, Pretoria, **2019;** Report Number: http://hdl.handle.net/20.500.12143/6373.
5. Whitfield, A.K., Weerts, S.P., Weyl, O. A review of the influence of biogeography, riverine linkages, and marine connectivity on fish assemblages in evolving lagoons and lakes of coastal southern Africa. *Ecology and Evolution* **2017,** 7, pp.7382-7398.
6. Department of Environmental Affairs (DEA). South Africa's second National Communication under the United Nations Framework Conversion on Climate Change. Department of Environmental Affairs, Pretoria, South Africa, **2010**; p.271.
7. Department of Environmental Affairs (DEA). Long-Term Adaptation Scenarios Flagship Research Programme (LTAS) for South Africa. Climate Change Implications for Marine Fisheries in South Africa. Pretoria, South Africa. Department of Environmental Affairs, Pretoria, South Africa, **2013**; p.60.
8. Day, J.W., Christian, R.R., Boesch, D.M., Yáñez-Arancibia, A., Morris, J., Twilley, R.R., Naylor, L., Schaffner, L., Stevenson, C. Consequences of climate change on the ecogeomorphology of coastal wetlands. *Estuaries and Coasts* **2008**, 31, pp.477-491.
9. Day, J.W., Yáñez-Arancibia, A., Rybczyk, J.M. Climate Change: Effects, Causes, Consequences: Physical, Hydromorphological, Ecophysiological, and Biogeographical Changes. *Treatise on Estuarine and Coastal Science* Vol. 8.11. Academic Press, London, **2011**; pp.303-312.
10. Gillanders, B.M., Elsdon, T.S., Halliday, I.A., Jenkins, J.P., Robins, J.B., Valesini, F.J. Potential effects of climate change on Australian estuaries and fish utilising estuaries: a review. *Marine and Freshwater Research* **2011**, 62, pp.1115-1131.
11. Newton, A., Icely, J.,Cristina, S., Brito, A., Cardoso, A.C., Colijn, F., Riva, S.D., Gertz, F., Hansen, J.W., Holmer, M., Ivanova, K., Leppäkoski, E., Canu, D.M., Mocenni, C., Mudge, S., Murray, N., Pejrup, M., Razinkovas, A., Reizopoulou, S., Pérez-Ruzafa, A., Schernewski, G., Schubert, H., Carr, L., Solidoro, C., Pierluigi, V., Zaldívar, J.M. An overview of ecological status, vulnerability and future perspectives of European large shallow, semi-enclosed coastal systems, lagoons and transitional waters. *Estuar., Coast. Shelf Sci.* **2014**, 140, pp.95-122.
12. Duarte, C.M., Hendriks, I.E., Moore, T.S., Olsen, Y.S., Steckbauer, A., Ramajo, L., Carstensen, J., Trotter, J.A., McCullochIs, M. Ocean Acidification an Open-Ocean Syndrome? Understanding Anthropogenic Impacts on Seawater pH. *Estuaries and Coasts* **2013**, 36, pp.221-236.
13. Vizzini, S., Di Leonardo, R., Costa, V., Tramati, C.D., Luzzu, F., Mazzola, A. Trace element bias in the use of CO2 vents as analogues for low pH environments: implications for contamination levels in acidified oceans. *Estuar., Coast. Shelf Sci.* **2013**, 134, pp.19-30.

14. Kerfahi, D., Hall-Spencer, J.M., Tripathi, B.M., Milazzo, M., Lee, J., Adams, J.M. Shallow water marine sediment bacterial community shifts along a natural CO_2 gradient in the Mediterranean Sea off Vulcano, Italy. *Microbial Ecology* **2014**, 67, pp.819-828.
15. Milazzo, M., Rodolfo-Metalpa, R., San Chan, V.B., Fine, M., Alessi, C., Thiyagarajan, V., Hall-Spencer, J.M., Chemello, R. Ocean acidification impairs vermetid reef recruitment. *Scientific Reports* **2014**, 4, p.4189.
16. Ge, C., Chai, Y., Wang, H., Kan, M. Ocean acidification: One potential driver of phosphorus eutrophication. *Marine Pollution Bulletin* **2017**, 115, pp.149-153.
17. Rees, A.P., Turk-Kubo, K.A., Al-Moosawi, L., Alliouane, S., Gazeau, F., Hogan, M.E., Zehr, J.P. Ocean acidification impacts on nitrogen fixation in the coastal western Mediterranean Sea. *Estuar., Coast. Shelf Sci.* **2017***,* 186, pp.45-57.
18. Laurent, A., K. Fennel, K., Cai, W.C., Huang, W.H., Barbero, L., Wanninkhof, A.R. Eutrophication induced acidification of coastal waters in the northern Gulf of Mexico: Insights into origin and processes from a coupled physical-biogeochemical model. *Geophysical Research Letters* **2017**, 44, pp.946-956.
19. Russell, I.A., Randall, R.M. Effects of prolonged elevated water salinity on submerged macrophyte and waterbird communities in Swartvlei Lake, South Africa. *Water SA* **2017,** 43, pp. 666-672.
20. CSIR. Wilderness Report No. 1. Evaluation of prototype data and the application of a numerical model to the Wilderness lakes and Touw River floodplain, **1981**; CSIR Report C/SEA 8113.
21. CSIR. Development of the Verlorenvlei estuarine management plan: Situation assessment. Report prepared for the C.A.P.E. Estuaries Programme. Stellenbosch, **2009**; CSIR Report No. CSIR/NRE/CO/ER/2009/0153/B.
22. Department of Water Affairs and Forestry (DWAF). Sandveld Preliminary (Rapid) Reserve Determinations. Langvlei, Jakkals and Verlorenvlei Rivers. Olifants-Doorn WMA G30. *Surface Volume 1: Final Report Reserve Specifications,* **2003**; DWAF Project Number: 2002-227.
23. Department of Water Affairs and Forestry (DWAF). Determination of the Preliminary Ecological Reserve on a Rapid Level for the St. Lucia Estuary. Prepared by L. Van Niekerk of CSIR, **2004**; CSIR Report pp. 105.
24. Van Niekerk, L., Van Der Merwe, J.H., Huizinga, P. The hydrodynamics of the Bot River Estuary revisited. *Water SA* **2005**, 31, pp.73-86.
25. Department of Water Affairs (DWA). Resource Directed Measures: Reserve Determination studies for selected surface water, groundwater, estuaries and wetlands in the Outeniqua catchment: Ecological Water Requirements Study. Estuarine RDM Report: Swartvlei. Edited by Dr Paterson, A (SAEON), for Scherman Colloty & Associates, **2009a**; Report no. RDM/K40-50/00/CON/0407.
26. Department of Water Affairs (DWA). Resource Directed Measures: Reserve Determination studies for selected surface water, groundwater, estuaries and wetlands in the Outeniqua catchment: Ecological Water Requirements Study. Estuarine RDM Report: Swartvlei. Edited by Dr Paterson, A (SAEON), for Scherman Colloty & Associates, **2009b**; Report no. RDM/K50/00/CON/0407.
27. Department of Water and Sanitation (DWS). Reserve Determination Studies for Surface Water, Groundwater, Estuaries and Wetlands in the Gouritz Water Management Area: Estuaries RDM Report – Rapid Assessment, Volume 2 (Wilderness System). Prepared by the Council for Scientific and Industrial Research (CSIR) for Scherman Colloty and Associates cc. **2014**; Report no. RDM/WMA16/04/CON/0713, Volume 2.
28. Department of Water and Sanitation (DWS). Resource Directed Measures: Reserve determination study of selected surface water and groundwater resources in the Usutu/Mhlathuze Water Management Area. *Kosi Estuary Rapid Environmental Water Requirements Determination*. Report produced by CSIR on behalf of Tlou Consulting (Pty) Ltd. **2016**; Report no: RDM/WMA6/CON/COMP/2613.
29. Anchor Environmental Consultants (Anchor) Determination of the Ecological Reserve for the Klein Estuary. Report prepared for the Breede-Gouritz Catchment Management Agency, **2015,** p.197.

30. Anchor Environmental Consultants (Anchor) Determination of the Ecological Reserve for the Heuningnes Estuary. Report prepared for the Breede-Gouritz Catchment Management Agency, **2018**.
31. Jones, P. D., Lister, D. H., Osborne, T. J., Harphan, C., Salmon, M., Morice, C. P. Hemispheric and large-scale land-surface air temperature variations: an extensive revision and an update to 2010. *Journal of Geophysical Research* **2012**, 117, D05127.
32. Kruger, A.C., Sekele, S. Trends in extreme temperature indices in South Africa: 1962 – 2009. *International Journal of Climatology* **2012**, 33, pp.661-676.
33. MacKellar, N., New, M., Jack, C. Observed and modelled trends in rainfall and temperature for South Africa: 1960–2010. *South African Journal of Science* **2014**, 110 (7/8) pp.1-13.
34. Engelbrecht, F.A., Adegoke, J., Bopape, M.M., Naidoo, M., Garland, R., Thatcher, M., McGregor, J., Katzfey, J., Werner, M., Ichoku, C., Gatebe, C. Projections of rapidly rising surface temperatures over Africa under low mitigation. *Environmental Research Letters* **2015,** 10(8), p.085004.
35. Kruger, A.C., Nxumalo, M. Surface Temperature Trends from Homogenised Time Series in South Africa: 1931 – 2014. *International Journal of Climatology* **2016**, 37, pp.2364-2377.
36. Schlegel, R. W., Smit, A. J. Climate change in coastal waters: time series properties affecting trend estimation. *Journal of Climate* **2016**, 29(24), pp.9113-9124.
37. Lima, F. P. Wethey, D. S. Three decades of high-resolution coastal sea surface temperatures reveal more than warming, *Natural Communications* **2012**, 3, pp.1-13.
38. Rouault, M., Pohl, B., Penven, P. Coastal oceanic Climate Change and variability from 1982 to 2009 around South Africa. *Afr. J. Mar. Sci.* 2010, 32, pp.237-246.
39. Alber, M. A conceptual model of estuarine freshwater inflow management. *Estuaries.* **2002,** 25, pp.1246-1261.
40. USEPA. Synthesis of Adaptation Options for Coastal Areas. Environmental Protection Agency, Climate Ready Estuaries Program, EPA 430-F-08-024, Washington DC, U.S. **2009.**
41. James, R., Washington, R. Changes in African temperature and precipitation associated with degrees of global warming. *Climatic Change* **2013,** 117, pp.859-872.
42. Bunn, S.E. Grand challenge for the future of freshwater ecosystems. *Frontiers in Environmental Science* **2016,** 4, p.21.
43. South African Weather Services (SAWS). A Climate change Reference Atlas based on CMIP5 – CORDEX downscaling. Water Research Commission Report. Pretoria, **2017**.
44. Hewitson, B.C., Crane, R.G. Consensus between GCM climate change projections with empirical downscaling: precipitation downscaling over South Africa. *Int J Climatol.* **2006**, 26, pp.1315-1337.
45. Engelbrecht, F.A., McGregor, J.L., Engelbrecht, C.J. Dynamics of the conformal-cubic atmospheric model projected climate-change signal over southern Africa. *Int J Climatol.* **2009**, 29, pp.1013-1033.
46. Engelbrecht, F.A., Landman, W.A., Engelbrecht, C.J., Landman, S., Bopape, M.M., Roux, B., McGregor, J.L., Thatcher, M. Multi-scale climate modelling over Southern Africa using a variable-resolution global model. *Water SA* **2011**, 37, pp.647–658.
47. Lumsden, T.G., Schulze, R.E., Hewitson, B.C. 2009. Evaluation of potential changes in hydrologically relevant statistics of rainfall in Southern Africa under conditions of climate change. *Water SA* **2009**, 35, pp.649-656.
48. Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W-T., Laprise, R., Magana Rueda, V., Mearns, L., Menendez, C.G., Raisanen, J., Rinke, A., Sarr, A., Whetton, P. Regional climate projections. In: *Climate change 2007: the physical science basis*. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, A.B., Tignor, M., Miller, H.L. (eds). Contribution of Working Group I to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change. Cambridge University Press, Cambridge, **2007.**
49. Engelbrecht, C.J., Engelbrecht, F.A., Dyson, L.L. High-resolution model projected changes in mid-tropospheric closed-lows and extreme rainfall events over southern Africa. *Int J Climatol.* **2013**, 33, pp.173-187.
50. McGregor, J.L. *C-CAM*: Geometric aspects and dynamical formulation. CSIRO Atmospheric Research Tech. Paper No 70, **2005;** p.43.

51. McGregor, J.L., Dix, M.R. The CSIRO conformal-cubic atmospheric GCM. In: *Proc. IUTAM Symposium on Advances in Mathematical Modelling of Atmosphere and Ocean Dynamics*; Hodnett, P.F. (ed.) Kluwer, Dordrecht, **2001,** pp.197-202.
52. McGregor, J.L, Dix, M.R. An updated description of the Conformal-Cubic Atmospheric Model. In: *High Resolution Simulation of the Atmosphere and Ocean*; Hamilton, K. and Ohfuchi, W. (eds.). Springer Verlag, **2008**, pp.51-76.
53. (IPCC) Niang, I., Ruppel, O.C., Abdrabo. M., Essel, A., Lennard, C., Padgham, J., Urquhart, P., Adelekan, I., Archibald, S., Barkhordarian, A., Battersby, J., Balinga, M., Bilir, E., Burke, M., Chahed, M., Chatterjee, M., Chidiezie, C.T., Descheemaeker, K., Djoudi, H., Ebi, K.L., Fall, P.D., Fuentes, R., Garland, R., Gaye, F., Hilmi, K., Gbobaniyi, E., Gonzalez, P., Harvey, B., Hayden, M., Hemp, A., Jobbins, G., Johnson, J., Lobell, D., Locatelli, B., Ludi, E., Otto Naess, L., Ndebele-Murisa, M.R., Ndiaye, A., Newsham, A., Njai, S., Nkem, Olwoch, J.M., Pauw, P., Pramova, E., Rakotondrafara, M-L., Raleigh, C., Roberts, D., Roncoli, C., Sarr, A.T., Schleyer, M.H., Schulte-Uebbing, L., Schulze, R., Seid, H., Shackleton, S., Shongwe, M., Stone, D., Thomas, D., Ugochukwu, O., Victor, D., Vincent, K., Warner, K., Yaffa, S. *IPCC WGII AR5*, **2014**, 22, pp.1-115.
54. Cullis, J., Alton, T., Arndt, C., Cartwright, A., Chang, A., Gabriel, S., Gebretsadik, Y., Hartley, F., de Jager, G., Makrelov, K., Robertson, G. *An uncertainty approach to modelling climate change risk in South Africa*. No. 2015/045. WIDER working paper, **2015.**
55. Lemley, D.A., Adams, J.B., Bate, G.C. A review of microalgae as indicators in South African estuaries. *S. Afr. J. Bot.* **2016**. 107, pp.12-20.
56. Whitfield, A.K., Weerts, S.P., Weyl, O. A review of the influence of biogeography, riverine linkages, and marine connectivity on fish assemblages in evolving lagoons and lakes of coastal southern Africa. Ecology and Evolution 2017, 7, pp.7382-7398.
57. Field, J.G., Griffiths, C.L. Littoral and sublittoral ecosystems of southern Africa. In: *Intertidal and Littoral Ecosystems*. Mathieson AC & Nienhuis PH (Eds), Elsevier, Amsterdam, **1991**, pp.323–346.
58. Potter I.C., Beckley L.E., Whitfield A.K., Lenanton R.C.J. (1990) Comparisons between the roles played by estuaries in the life cycles of fishes in temperate Western Australia and South Africa. Environmantal Biology of Fishes 28: 143-178.
59. Whitfield, A.K., Wooldridge, T.H. Changes in freshwater supplies to southern African estuaries: some theoretical and practical considerations. In: *Changes in fluxes in estuaries: implications from science to management*; Dyer, K.R., Orth, R.J. (eds). Olsen & Olsen, Fredensborg, Denmark. **1994**. pp.41-50.
60. Whitfield, A.K. Fishes of Southern African Estuaries: From Species to Systems. *Smithiana Monograph No. 4* **2019,** p. 495.
61. Taljaard, S., Slinger, J.H., Van Niekerk, L. A screening model for assessing water quality in small, dynamic estuaries. *Ocean. Coast. Manag.* **2017**, 146, pp.1-14.
62. Adams, J.B., Taljaard, S., Van Niekerk, L., Lemley, D.A. Nutrient enrichment as a threat to the ecological resilience and health of South African micro-tidal estuaries. *Afr.J. Aquat. Sci.* **2020,** 45 (1-2), pp.23-40.
63. Smakhtin, V., Revenga, C., Döll, P. Taking into account environmental water requirements in global-scale water resources assessments. *Comprehensive Assessment Research Report 2*. Colombo, Sri Lanka: Comprehensive Assessment Secretariat, **2004.**
64. Van Niekerk, L., Taljaard, S., Huizinga, P. An evaluation of the ecological flow requirements of South Africa's estuaries from a hydrodynamic perspective. *Water Research Commission Report K8/797*, Pretoria, South Africa, **2012.**
65. Lemley, D.A., Adams, J.B., Taljaard, S., Strydom, N.A. Towards the classification of eutrophic condition in estuaries. *Estuar., Coast. Shelf Sci.* **2015**, 164, pp. 221-232.
66. Whitfield, A.K. An estuary-association classification for the fishes of southern Africa. *S. Afr. J. Sci.* **1994b**, 90, pp.411-417.
67. Department of Water Affairs and Forestry (DWAF). Water resource protection and assessment policy implementation process. Resource directed measures for protection of water resource: Methodology for the determination of the ecological water requirements for estuaries. Version 2.1. Department of Water Affairs, Pretoria, **2008**.

68. Turpie, J.K., Taljaard, S., Van Niekerk, L., Adams, J.B., Wooldridge, T., Cyrus, D., Clark, B., Forbes, N. The Estuary Health Index: a Standardised Metric for Use in Estuary Management and the Determination of Ecological Water equirements. Water Research Commission, Pretoria, South Africa, **2012**; WRC Report No. 1930/1/12.
69. Perissinotto, R., Pillay, D., Bate, G.C. Microalgal biomass in the St Lucia Estuary during the 2004 to 2007 drought period. *Marine Ecology Progress Series* **2010**, 405, pp.147-161.
70. Nunes, M., Adams, J.B., Bate, G.C., Bornman, T.G. Abiotic characteristics and microalgal dynamics in South Africa's largest estuarine lake during a wet to dry transitional phase. *Estuar., Coast. Shelf Sci.* **2017**, 198, pp. 236-248.
71. Lemley, D.A., Adams, J.B., Rishworth, G.M. Unwinding a tangled web: a fine-scale approach towards understanding the drivers of harmful algal bloom species in a eutrophic South African estuary. *Estuaries and Coasts* **2018**, 41, pp.1356-1369.
72. Adams, J.B, Veldkornet, D.A., Tabot, P. Distribution of macrophyte species and habitats in South African estuaries. *S. Afr. J. Bot.* **2016,** 107, pp.5-11.
73. Adams, J.B., Van Niekerk, L. Ten principles to determine environmental flow requirements for temporarily closed estuaries. *Water* **2020,** 12, p.1944.
74. Adams, J.B. Salt marsh at the tip of Africa: Patterns, processes and changes in response to climate change. *Estuar., Coast. Shelf Sci.* **2020,** 237, p.106650.
75. James, N.C., Cowley, P.D., Whitfield, A.K., Lamberth, S. Fish communities in temporarily open/closed estuaries from the warm- and cooltemperate regions of South Africa - A review. *Reviews in Fish Biology & Fisheries* **2007,** 17, pp.565-580.
76. Whitfield, A.K., Taylor, R.H., Fox, C., Cyrus, D.P. (2016) Fish and salinities in the St Lucia estuarine system – a review. Rev Fish Biol Fisheries **2016**. 16: 1-20.
77. Von der Heyden, S., Toms, J.A., Teske, P.R., Lamberth, S.J., Holleman, W. Contrasting signals of genetic diversity and historical demography between two recently diverged marine and estuarine fish species. *Mar. Ecol. Prog. Ser.* **2015**, 526, pp.157-167.
78. McBryan, T.L., Anttila, K., Healy, T.M., Schulte, P.M. Responses to Temperature and Hypoxia as Interacting Stressors in Fish: Implications for Adaptation to Environmental Change. *Integrative and Comparative Biology* **2013,** 53 (4), pp.648-659.
79. Geffroy, B., Wedekind, C. Effects of global warming on sex ratios in fishes. *J. Fish. Biol.* **2020**; 97 (3), pp.596-606.
80. Ratte, T.W. Population structure, production, growth, reproduction and the ecology of Atherina breviceps Valenciennes. 1935 (Pisces: Atherinidae) and Gilchristella aestuaria (Gilchrist. 1914) (Pisces: Clupeidae) from two southern Cape coastal lakes. Ph.D. thesis. 1989. University of Port Elizabeth. South Africa. 319 pp.
81. Paterson, A.W. and Whitfield, A.K., Do shallow-water habitats function as refugia for juvenile fishes?. Estuarine, *Coastal and Shelf Science* **2000**, 51(3), pp.359-364.
82. Keur, R., James, N., Rajkaran, A. A tale of two habitats: preliminary comparison of fish and abundance and diversity between salt marsh and mangrove dominated creeks in the Nahoon Estuary, South Africa. *Afr.J. Aquat. Sci.*, **2019**, 41:449-454.
83. Nodo, P., James, N.C., Childs, A.-R., Nakin, M.. Response of demersal fish assemblages to an extreme flood event in a freshwater deprived estuary, South Africa. *Marine and Freshwater Research* **2018**, 69: 253–266.
84. James, N.C., Adams, J.B., Connell, A.D., Lamberth, S.J., MacKay, C.F., Snow, G.C., Van Niekerk, L., Whitfield, A.K. High flow variability and storm events shape the ecology of the Mbhashe Estuary, South Africa, *Afr.J. Aquat. Sci.* **2020***,* 45 (1-2), pp.131-151.
85. Raw, J.L., Riddin, T., Wasserman, J., Lehman, T.W.K., Bornman, T.G., Adams, J.B. Salt marsh elevation and responses to future sea-level rise in the Knysna Estuary, South Africa. *Afr.J. Aquat. Sci.* **2020**, 45, pp. 49-64.

Chapter 8

Impact of climate change on crop water requirements in the Luvuvhu River Catchment, South Africa

Rachel Makungo[1]* and Tinyiko Rivers Nkuna[1]

[1] University of Venda
* Corresponding author: rachel.makungo@univen.ac.za

Abstract: The impacts of climate change on crop water requirements were investigated for Luvuvhu River Catchment (LRC). The LRC is of paramount importance since it is a commercial hub for agricultural production in the Limpopo Province. Historical temperature data and climate projections from Conformal Cubic Atmospheric Model (CCAM) were used to estimate crop water requirements for banana, maize and tomatoes. The period considered for the estimation ranged from 2010 – 2099. The results showed increase in crop water requirements for banana, maize and tomatoes. Highest crop water requirements were obtained from the most downstream station (Tshanzhe) with values ranging from 5.40-24.65, 17.10-25.87, and 5.00-22.97 mm/day for maize, tomato and banana for the periods 2010 – 2019, 2050 – 2059 and 2090 – 2099. Increased crop water requirements will have negative consequences on agriculture and livelihoods of the communities and subsistence farmers. Similar studies in other catchments and covering more crops are essential to further contribute knowledge on climate change impacts.

Keywords: CCAM, climate change; crop water requirement; water availability

1. Introduction

South Africa is a semi-arid to arid country characterised by a highly variable and unpredictable climate with constrained water resources [1]. This is worsened by the changes in temperatures, rainfall and climate extremes as indicated by the climate projections. Engelbrecht et al. [2] projected a general decrease in rainfall over southern Africa under enhanced anthropogenic forcing while increase in temperature is expected to exceed 3°C over the northern parts of South Africa. DEA [3] projected significant reductions in rainfall in the future, with the pattern of drying projected to increase over time and annual average temperature increase of 3 – 6°C. These changes in climate are expected to impact on available water resources as well as irrigation water requirements. At national level, preliminary results suggest between 20% reduction to 60% increase of runoff under an unconstrained greenhouse gas emissions scenario in South Africa [3]. It has also been projected that median irrigation demand will increase by possibly more than 12% in South Africa under unconstrained global emissions path [4]. An increase in daily temperature by 2°C will result to 5 – 13% increase in potential evapotranspiration [5].

Studies have used outputs from global climate models (GCMs) to assess impact climate change on future crop water requirements. Schulze and Taylor [6] used climate projections from coordinated regional climate downscaling experiment (CORDEX) to project irrigation water requirements of an all-year crop under various climatic scenarios in South Africa. The projections indicated that more than 6% water will be required to satisfy irrigation requirements in semi-arid areas while more than 25% will be the wetter eastern parts of the country compared with those of the period 1976-2005. The crop water requirements for 2020 and 2050 were estimated based on CROPWAT based on outputs from HadCM3 GCM in a study by Rao [7]. The results indicated increase in water requirements for wheat, maize, sorghum and millet crops between 2020 and 2050 when compared to 1990 to 2020 with maize having the highest crop water requirements. Water Evaluation Allocation and Planning-MAitrise des Besoins d'Irrigation en Agriculture (WEAP-MABIA) model driven by six CORDEX climate change data for RCPs4.5 and 8.5 was used to quantify the effect of climate change on maize, soya beans, dry beans and sunflower in the Olifants catchment by Olabanji et al. [8]. The findings indicated steady increase in crop water requirements for both RCPs which were linked to increased temperature and decreased precipitation during planting seasons.

Midgely et al. [9] and DEA [3] indicated the economics of climate change impacts on crops. In Ethiopia, Deressa [10] indicated that there would be crop net revenue per hectare by the year 2100. The study further indicated that if the impacts are not reduced, there would be severe impacts for different crops. In South Africa, Singels [11] indicated that there have been significant moves with regards to modelling the impacts of climate change on water requirements. The study showed how different models can predict the impacts. Zimmermann et al. [12] showed that climate change affected crop yield, land use, and environment in response to crop sowing dates and thermal time requirements. Common approaches employed in estimating crop water requirements globally include SAPWAT, CROPWAT, amongst others. CROPWAT is the most widely used method due to its accessibility and data requirements. Some of the studies that used CROPWAT include [13], [14], [15]. [16] indicate that apart from estimating crop water requirements, CROPWAT can also be used to manage irrigation scheduling particularly in areas where water availability may be an issue. Although the results are generally accepted, it is important to note that there is a greatest level of uncertainty attached to the estimation of water requirements [17]. Gong et al. [18] shows that uncertainties are inevitable in crop water requirement estimation.

This study is aimed at determining the impact of climate change on crop water requirements. Agriculture serves as a source of food, employment, income and foreign exchange earning in Limpopo Province [19], and it is hence substantial in improving economic growth and sustaining livelihoods in the province including the Luvuvhu River Catchment (LRC). The upper third of the LRC is mainly utilised for commercial agriculture. Climate change will, therefore, impact on economic growth and livelihoods in the catchment. Studies that have been done in Limpopo Province including the study area mainly focused on perceptions of climate variation and the community's ability to adapt to climate change [20], climate-risk management strategies [21] and [22], how small-scale farmers employed adaptation strategies in response to climate variability and change [23], perceived effects of climate change on crop production of smallholder farmers [24]. There is therefore for lack of knowledge on impact of climate change on crop water requirements. In addition, the study used Conformal-Cubic Atmospheric Model (CCAM) projections for estimating which are at higher resolution (8 km) as compared to climate projections used in the reviewed studies. It therefore provides an assessment of climate change impacts based on high resolution projections.

2. Materials and methods

This section deals with the methodology followed in executing the study including data collection. Three crops were selected for crop water requirements estimation, i.e. banana, maize and tomato.

2.1.1 Study area

The LRC covers an area of approximately 5,941 km^2 and is situated between the longitudes 29°49'46.16''E and 31°23'32.02''E and latitudes 22°17'33.57''S and 23°17'57.31''S in the Limpopo Province of South Africa (Figure 1). The rainfall received in the area during the summer season averages 450 mm per annum to more than 1200 mm in the mountainous area. The predominant topographical feature in the LRC is the Soutpansberg Mountain range which has a profound effect on the hydrology of the catchment. Some parts of the catchment like Entabeni around the Soutpansberg area receive up to 2,000 mm of rainfall per annum. This makes the upstream of LRC a strategic water resource area for both domestic and agricultural water supply in the catchment. The average daily temperature is 28°C. Some areas of the catchment towards the downstream with very low rainfall and high temperature can be described as semi-arid to arid. Commercial and subsistence (small scale) farming of diverse crops are common within the LRC. Some of the common crops include mangoes, avocadoes, guavas, macadamia nuts, tomatoes and bananas. Odiyo et al. [25] has identified crops that were prioritised for inclusion in the Vhembe District Municipality Agri-Park programme. The programme was aimed at eradication of rural poverty as part of the 2011 Green Paper on Land Reform policy review and reformulation process. The crops were prioritised based on biophysical (climatic, soil and resilience to weed, pest and disease and adaptability to adverse conditions); transport, market access and demand; strategy, payback and profitability; human, physical and financial capital, linkages and processing opportunities, job creation (direct on-farm job creation), local development, global competitiveness and trade, political and institutional issues; social issues, and food security and sustainability factors.

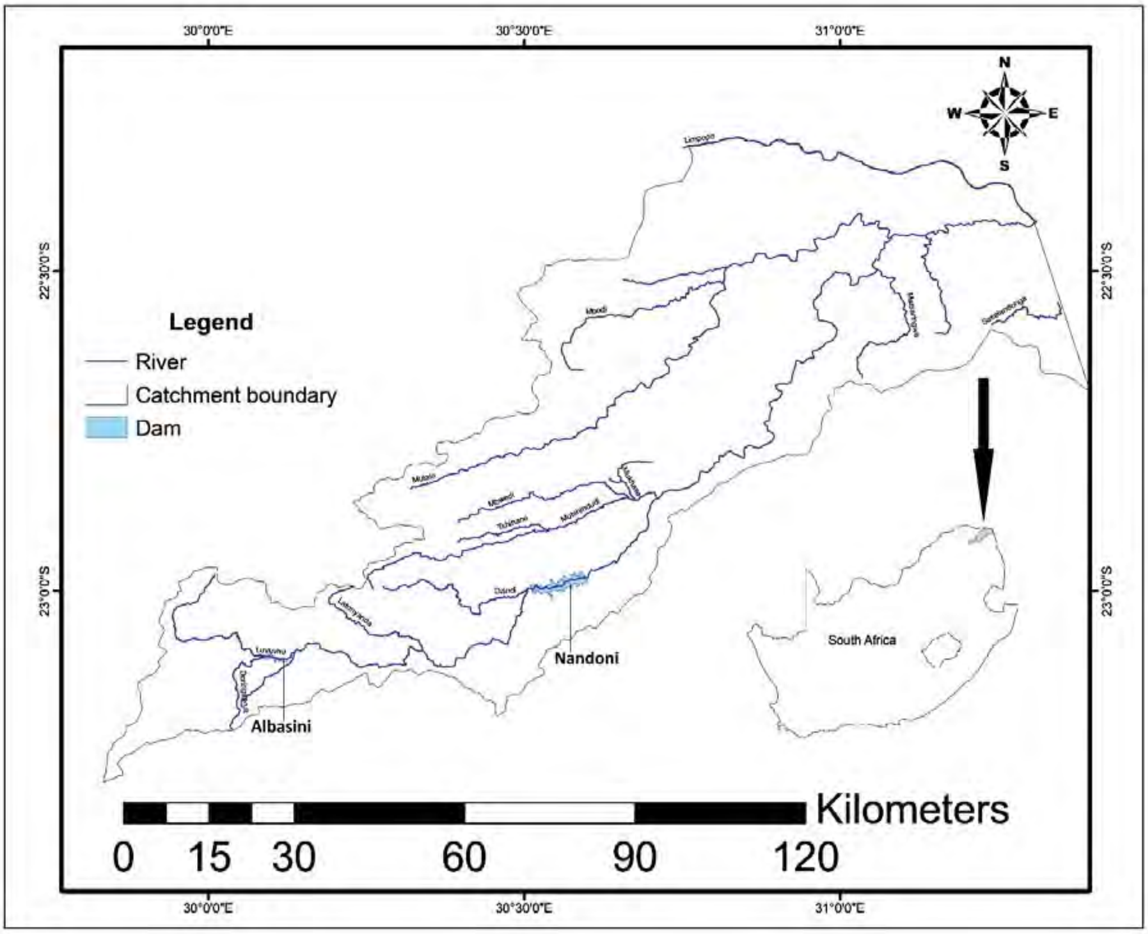


Figure 1. Location of the study area.

2.1.2 Data

Daily temperature data was obtained from high resolution CCAM projections of present-day climate and projections of future climate change over South Africa generated by CSIR [2]. The procedure for generating the CCAM data involved downscaling climate projections from 6 GCM simulations of the CMIP5 and Assessment Report Five (AR5) of the Intergovernmental Panel on Climate Change (IPCC) for the emission scenarios described by Representative Concentration Pathways 4.5 and 8.5 (RCP4.5 and 8.5) at 50 km resolution [2]. A multiple-nudging strategy was then used to obtain an integrated stretched-grid mode at a resolution of about 8 km (0.08° degrees in latitude and longitude) over South Africa [2]. The 8 km projections are ideal for Luvuvhu River Catchment with distinct topographical features including the Soutpansberg Mountain. The CCAM future temperatures were for the period 1961/01/01 to 2099/12/31. Figure 2 indicates an overview of CCAM temperature data used in the study. These are average temperatures for the periods 1991/01/01 – 2021/12/31, 2022/01/01 – 2052/12/31 and 2053/01/01 – 2083/01/01 which were considered to be historic, near future and far future, respectively.

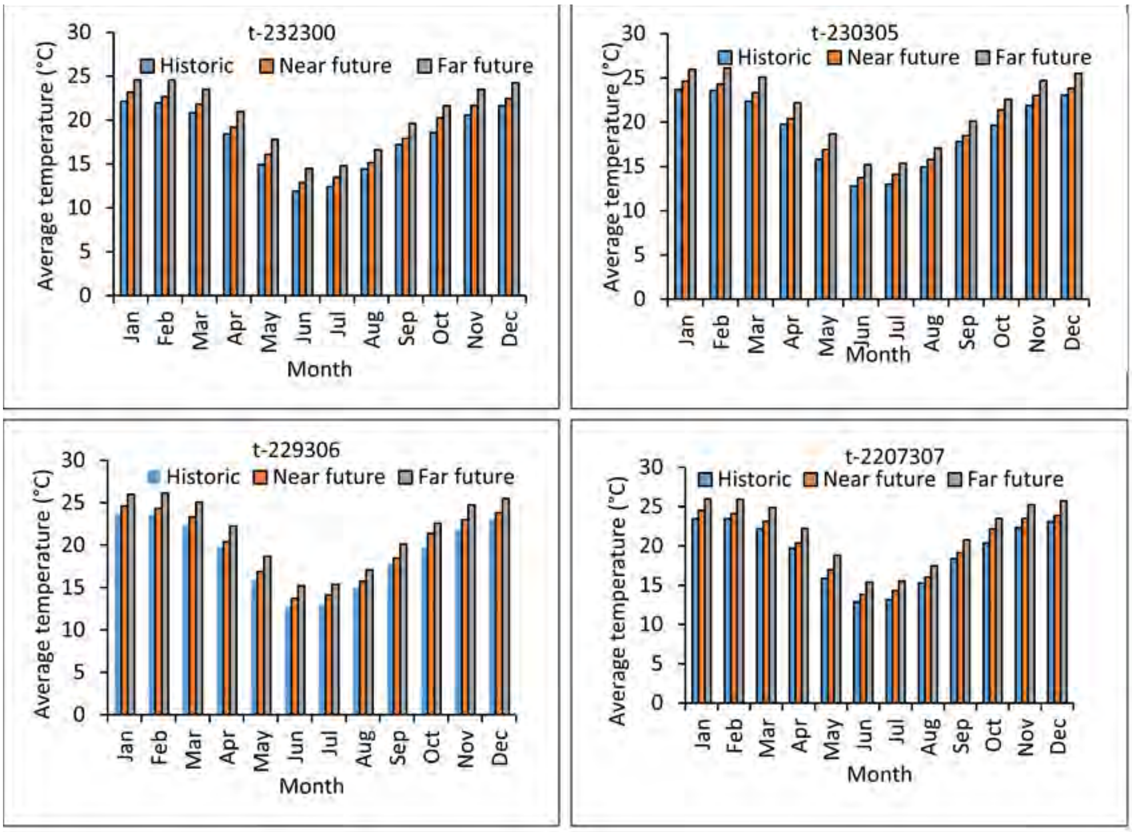


Figure 2. CCAM temperature data.

2.1.3 Projections of crop water requirements

Evapotranspiration was used in the estimation of crop water requirements for selected crops within the LRC under changing climatic conditions. Temperature data from CCAM stations t-232300, t-232305, t-229306 and t-2207307 were used in the estimation of evapotranspiration for the period 2010-2099. In this manuscript, the stations are referred to based on the name of the village located close to them for simplicity (Figure 3). Stations t-232300, t-232305, t-229306 and t-2207307 are henceforth referred to as Vleifontein, Maniini, Malamangwa and Tshanzhe, respectively. The selection of the stations was done such that the estimations covered areas in the upstream, midstream and towards the downstream of the LRC (Figure 3). Crop water requirements for selected crops within LRC were estimated based on reference crop evapotranspiration, duration of different growth stages and estimated reference evapotranspiration (Equation 2.1).

$$ET_{crop} = K_c \times ET_o, \tag{2.1}$$

where ET_{crop} = the water requirement of a given crop in mm/day, Kc = the crop factor and ETo = the reference crop evapotranspiration in mm/day. Reference evapotranspiration was estimated based on the Hargreaves equation below (Equation 2.2) [26]:

$$ET_o = 0.0023 R_a TD^{0.5} (T_a + 17.8), \tag{2.2}$$

where R_a is extraterrestrial radiation (mm/day), TD is the difference between the daily maximum and minimum temperatures, Ta is the mean daily temperature and Ra was computed as (Equation 2.3):

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r \left[\omega s \sin(\phi)\sin(\delta) + \cos(\phi)\cos\delta \sin(\omega s)\right], \tag{2.3}$$

where G_{sc} is the solar constant, dr is the inverse relative distance Earth-Sun, ωs is the sunset hour angle, ϕ is the latitude and δ is the solar declination. Equations for calculating these variables are found in [27]. Estimated ET_o for the period 2010 – 2019 were divided by a pan coefficient of 0.7 to convert them into evaporation to enable comparison with observed pan evaporation. This was done to verify the estimated values and could only be done for CCAM temperature stations (Vleifontein, Maniini and Malamangwa) which were within the vicinity of pan evaporation stations. Evaporation data for stations A9E002 and A9E004 were compared with evaporation estimated based on Hagreaves method [26]. The data periods used corresponded to the period when pan evaporation data was available. A9E002 and A9E004 had data for the periods 1961/01/01 to 2019/09/01 and 2009/11/30 to 2019/07/01, respectively. Figure 4 indicates the crop coefficients (K_c) and stages of development for selected crops (maize, banana and tomato) used in the study. These were obtained from CROPWAT model and based on data from Allen et al. (1998). The planting dates of 15 October, 1 December and 1 September were considered in the study.

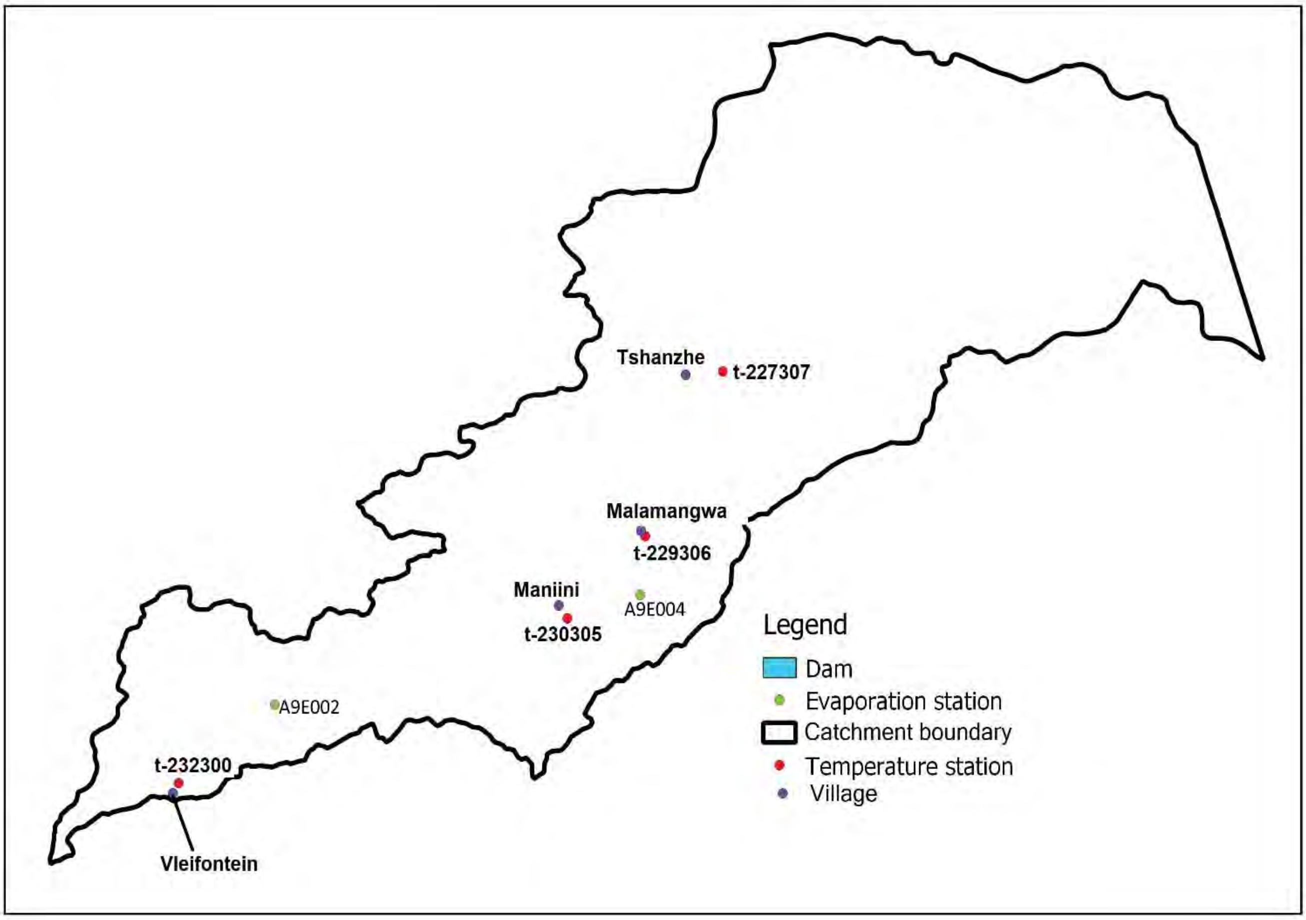


Figure 3. Distribution of stations and neighbouring villages.

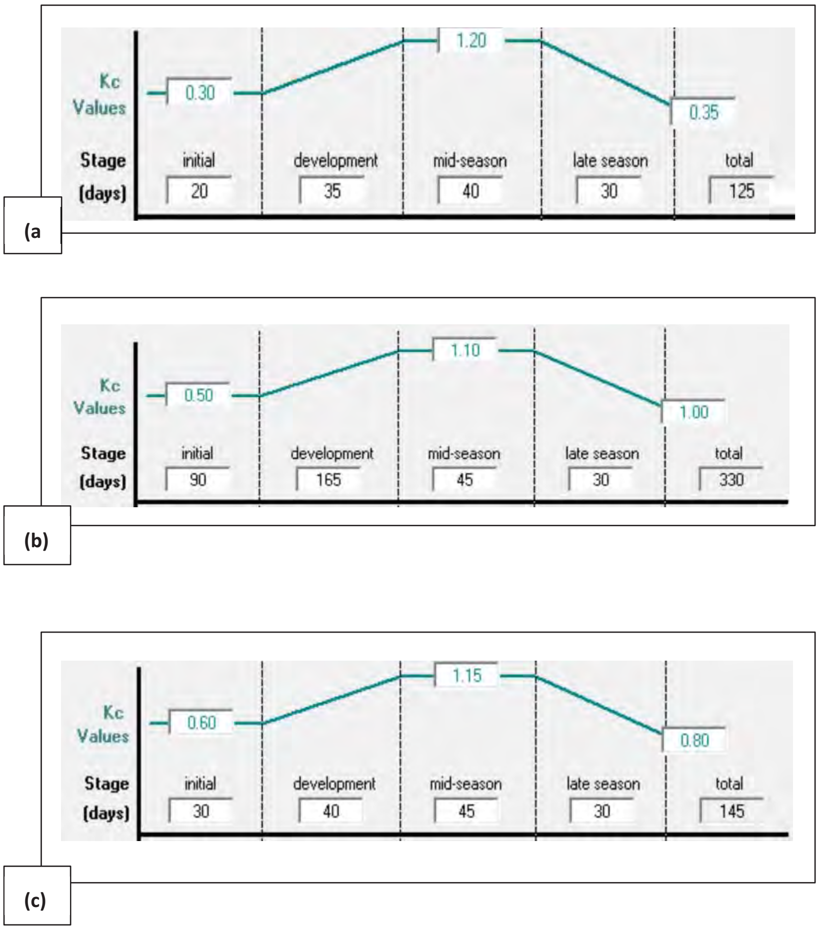


Figure 4. Crop coefficients (K_c) and stages of development for (a) maize, (b) banana and (c) tomato.

3. Results

Comparisons of observed and estimated evaporation indicated similar behaviour (pattern) though evaporation was overestimated in some of the periods (Figure 5). The results presented are for 3 years to show a clear view of the comparison between observed and estimated values. Figure 6 indicate the average crop water requirements for three selected crops (banana, maize and tomato) for the periods 2010 – 2019, 2050 – 2059 and 2090 – 2099. These have been used as examples to indicate the crop water requirements under changing climatic conditions. There was a general increase in water requirements for all crops in the periods 2010 – 2019, 2050 – 2059 and 2090 – 2099 (for the 3 crop types). Tomato had the highest average crop water requirements with a range of 10.38 mm/day in September (Malamangwa) to 25.87 mm/day in November (Tshanzhe). Crop water requirements for banana steadily increased in the months of October, November and December for all the periods. The crop water requirements for maize were relatively high in December and January while those of tomato were high in November and December. Average crop water requirements increased moving downstream of the catchment indicated by the increases in the estimates for Vleifontein, Malamangwa and Tshanzhe (Table 1). This indicates the spatial variation in crop water requirements moving towards downstream. Highest crop water requirements were obtained from the most downstream station (Tshanzhe) with ranges of 5.40-24.65, 17.10-25.87, and 5.00-22.97 mm/day for maize, tomato and banana for the periods 2010 – 2019, 2050 – 2059 and 2090 – 2099 (Table 1).

Table 1. Ranges of average crop water requirements

Crop	Period	Vleifontein	Malamangwa	Tshanzhe
Maize	2010-2019 2050-2059 2090-2099	2.70-9.39 6.17-19.41 7.28-22.03	5.09-17.06 6.32-19.03 7.22-21.82	5.40-15.98 6.71-19.95 7.57-24.65
Tomato	2010-2019 2050-2059 2090-2099	10.46-19.19 10.77-21.39 12.73-25.17	10.38-18.77 10.66-20.90 12.72-25.16	17.14-21.59 17.10-21.82 19.79-25.87
Banana	2010-2019 2050-2059 2090-2099	4.42-18.84 4.46-21.24 5.16-23.99	8.17-19.68 7.87-21.06 9.04-24.76	5.00-15.15 4.96-22.97 5.77-24.59

Figure 7 indicates the changes in crop water requirements computed as the difference between the requirements for the periods (A) 2050 – 2090 and 2010 – 2019, (B) 2090 – 2099 and 2050 – 2090 and the overall period (C) 2090 – 2099 and 2010 – 2019, with period (C) having the highest positive changes in crop water requirements. There were slight negative changes in crop water requirements for banana in the months of June and September for Vleifontein and Tshanzhe in period A. The months of February, May-July and September for Malamangwa also had slight negative change in crop water requirements for banana the same period. The average crop water requirements for banana for these months in the period 2010 – 2019 were higher than those in the period 2050 – 2090 resulting to negative changes. The changes in average crop water requirements for maize the periods A, B and C ranged from 0.46 to 11.02, 0.10 to 4.76, and 0.27 to 4.70 mm/day for Vleifontein, Malamangwa and Tshanzhe, respectively. For banana, the changes in average crop water requirements for the periods A, B and C ranged from -0.17 to 7.04, -0.001 to 7.14 and -013 to 7.5 mm/day for Vleifontein, Malamangwa and Tshanzhe, respectively. The changes in average crop water requirements for tomato for the periods A, B and C ranged from 0.28-4.86, 1.55-5.59 and -0.04 to 5.35 mm/day for Vleifontein, Malamangwa and Tshanzhe, respectively. The results indicated dominant positive changes confirming increase in on crop water requirements for all crops in the study area.

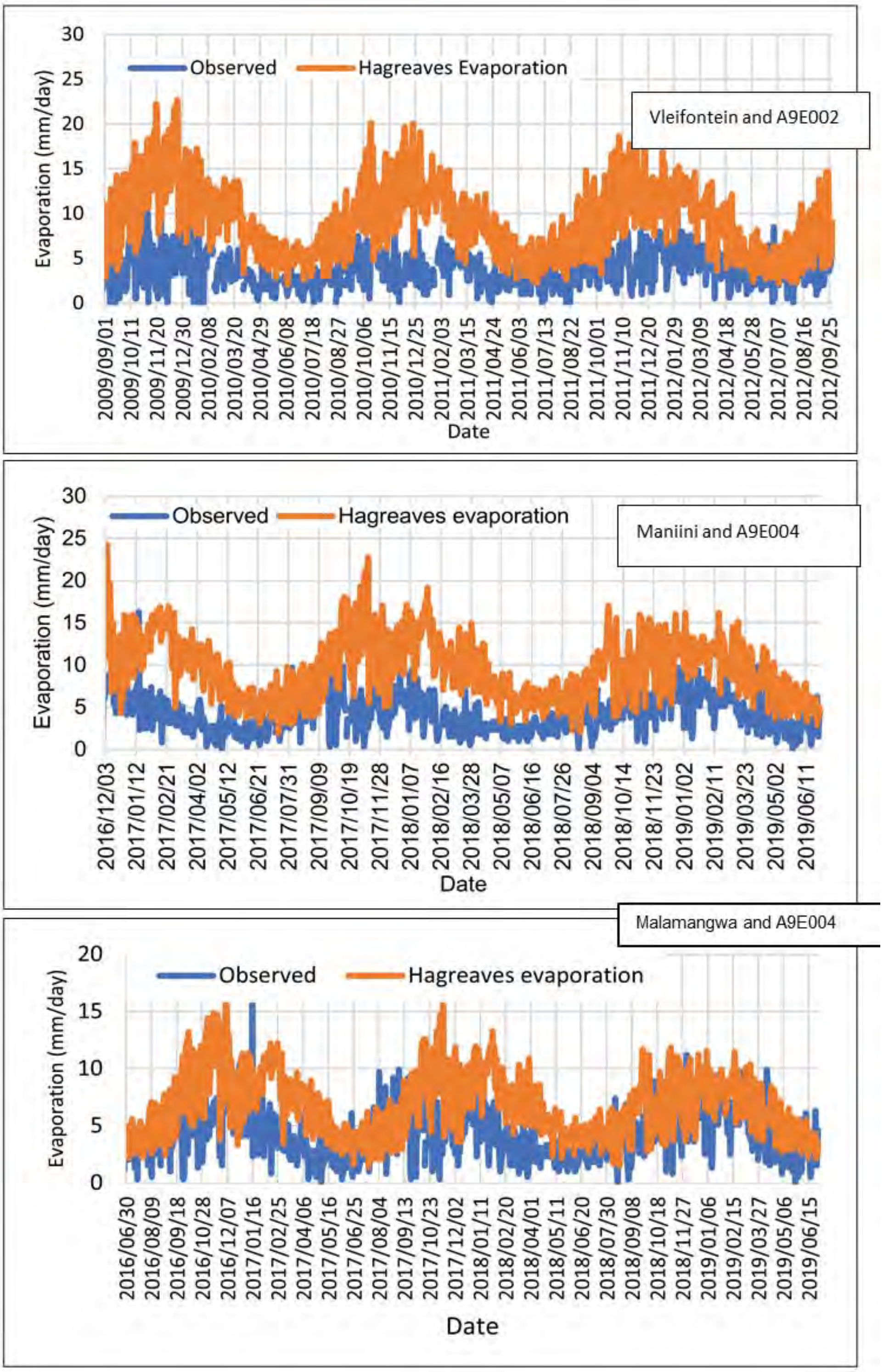


Figure 5. Observed and estimated evaporation.

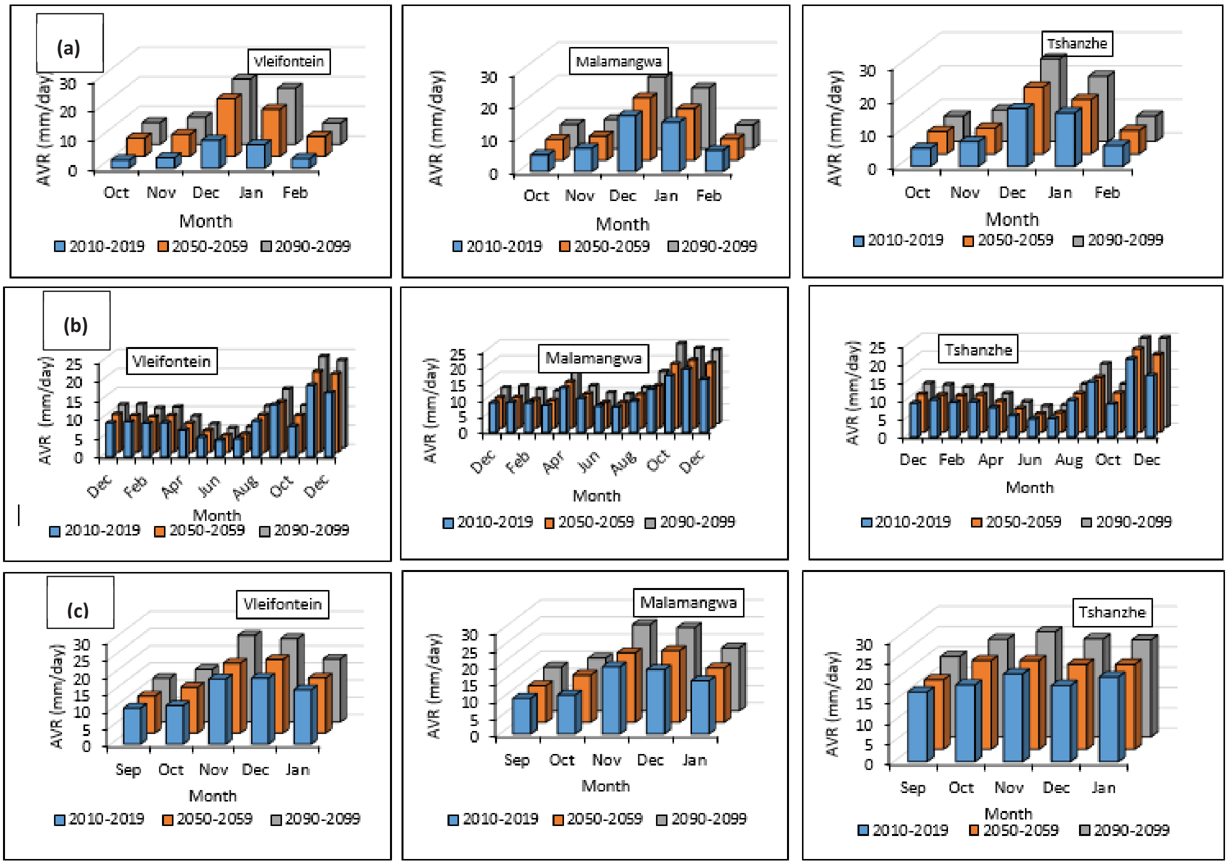


Figure 6. Average crop water requirements (Row: (a) maize (b) banana (c) tomato)).

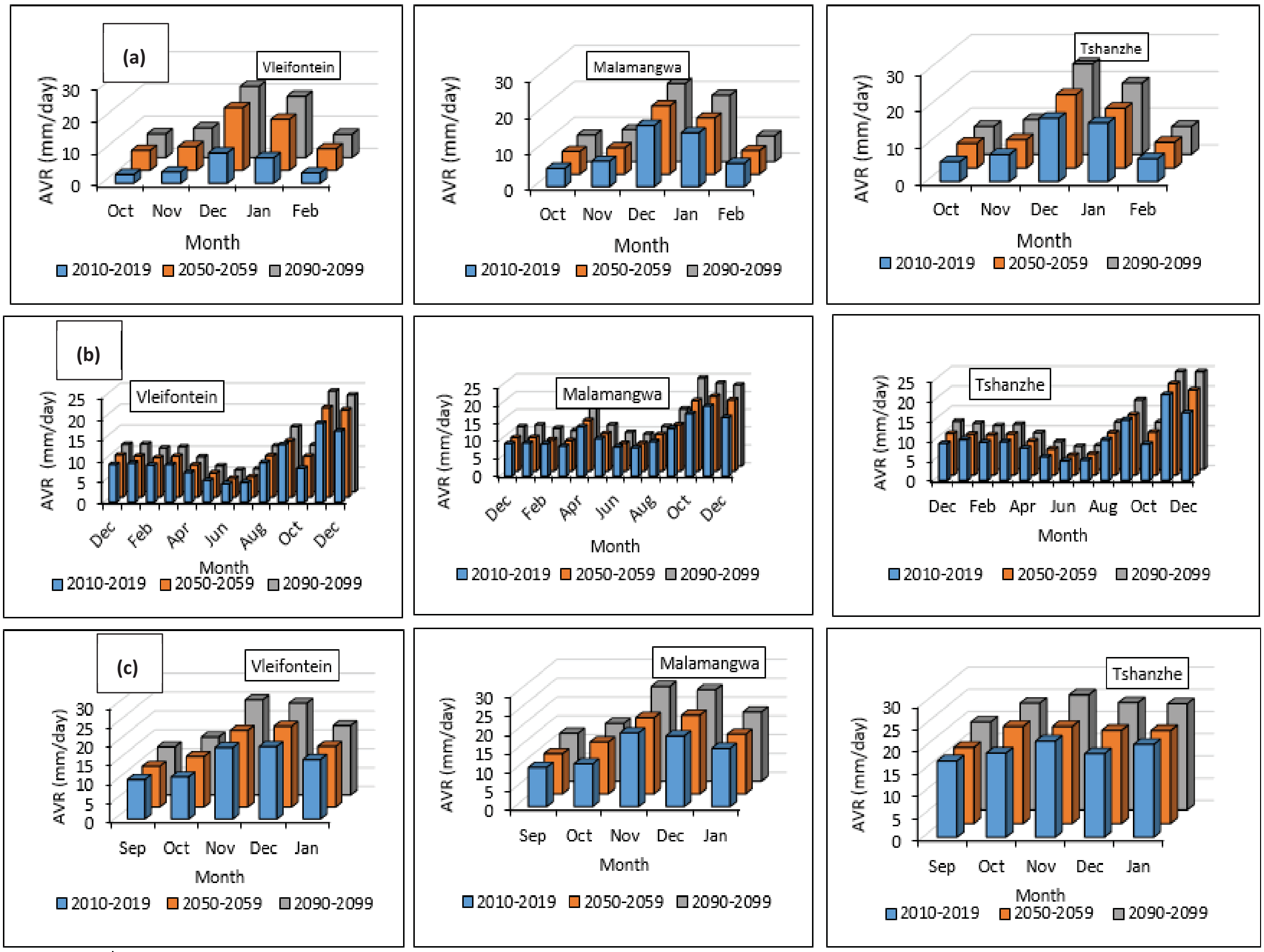


Figure 7. Change in average crop water requirements (Row: (a) maize (b) banana (c) tomato)).

4. Discussion

The increase in crop water requirements for the three crops is related to the expected increase in future temperatures (Figure 6). Previous studies have also projected increase in crop water requirements related to climate change. The studies by Parekh et al. [28] and Chowdhury [29] also reported increased future water requirements for maize and tomato which were linked to increased temperature due to climate change. In their study, [8] indicated that crop water requirements for maize in the Olifants River Catchment will increase and this will result to decline in crop yield. The LRC is expected to have increased temperatures in the future as reported in [30]. Projections of temperature rises of between 3-5°C were also forecasted under low mitigation for Limpopo Province where the study area is located. An increase in daily temperature by 2°C increase in daily temperature will result to 5–13% increase in potential evapotranspiration [31]. Based on this, the rise in temperatures is therefore expected to increase potential evapotranspiration by more than 13% in the study area. The crop water requirements vary due to the highly variable climate of LRC as noted in Odiyo et al. [30] and Mukwada et al. [32]. The downstream area within the vicinity of Tshanzhe is typically dominated by subsistence rainfed agriculture. The increase in water requirements will have negative consequences on rainfed agriculture and livelihoods of the communities and subsistence farmers. This will be exacerbated by decreased rainfall patterns which have been projected by

Engelbrecht et al. [2] and Odiyo et al. [25]. The average crop water requirements for maize, tomato and banana for the entire study period ranged from 2.70 to 24.65, 10.38 to 25.87 and 4.42-24.59 mm/day, respectively. The water requirements for banana are ideally in the range of 3.0 – 6.3 mm/day during the growth and production cycle [33]. Actual irrigation water for tomato crop may be recommended between 4.1 and 5.6 mm/day [34]. Maize needs 450 to 600 mm of water per season [35] which is equivalent to a range of 3.6 to 4.8 for a crop growth duration of 125 days considered on this study. The average crop water requirements for maize, tomato and for 2010 – 2019, 2050 – 2059 and 2090 – 2099 estimated in this study are mostly higher than the standard water requirements for these crops and this is linked to climate change. Tomato is the second most important and popular vegetable crop which is cultivated commercially and commonly grown by subsistence, resource poor farmers and home gardeners in South Africa [36] while maize is a staple food for most of the communities in LRC. The high crop water requirements may result to crop failure and/or reduced crop yields as rainfall is also expected to decrease in the future. The reduced yields will threaten livelihood and food security for the communities in the study area.

5. Conclusions

This study demonstrated the impact of climate change on crop water requirements in the LRC. Climate change projections from CCAM model were used in projecting near future and far future crop water requirements. There was an increase in projected crop water requirements. The semi-arid nature and highly variable rainfall distribution within the LRC will exacerbate the impact of climate change on agriculture due to increased crop water requirements. This will significantly pose major implications for subsistence and commercial farmers as well as food security for local communities. The study has shown the potential impact of climate change on crop water requirements with negative implications. The study has shown the potential impact of climate change on water requirements for different crops, particularly those considered staple food.

Funding: This research was funded by WRC, project number K2271.

Acknowledgments: Prof Francois Engelbrecht is acknowledged for providing rainfall data used in this study.

References

1. Botai, C.M., J.O. Botai, and A.M. Adeola, *Spatial distribution of temporal precipitation contrasts in South Africa.* South African Journal of Science, 2018. **114**(7-8): p. 70-78.
2. Engelbrecht, F., et al., *Green Book. Detailed projections of future climate change over South Africa. Pretoria: CSIR*. 2019.
3. DEA, G., *Long-Term Adaptation Scenarios Flagship Research Programme (LTAS) for South Africa. Summary for Policy-Makers*, E. Affairs, Editor. 2013.
4. UNU-WIDER, *Climate change effects on irrigation demand and crop yields in South Africa*. 2016, UNU-WIDER: Helsinki, Finland.
5. Warburton, M.L., R.E. Schulze, and G.P. Jewitt, *Confirmation of ACRU model results for applications in land use and climate change studies.* Hydrology and Earth System Sciences, 2010. **14**(12): p. 2399-2414.
6. Schulze, R., Taylor, MA, *Net Irrigation Demands in South Africa and Climate Change.* Schulze, R.E. Handbook for Farmers, Officials and Other Stakeholders on Adaptation to Climate Change in the Agriculture Sector within South Africa. Section H: Irrigation in South Africa and Climate Change, Chapter H2., 2016.

7. Rao, V., et al., *Impact of climate change on crop water requirements and adaptation strategies*, in *Challenges and Opportunities in Agrometeorology*. 2011, Springer. p. 311-319.
8. Olabanji, M.F., T. Ndarana, and N. Davis, *Impact of Climate Change on Crop Production and Potential Adaptive Measures in the Olifants Catchment, South Africa.* Climate, 2021. **9**(1): p. 6.
9. Midgley, G., R. Scholes, and J. Blignaut, *Scoping of the approximate climate change adaptation costs in several key sector for South Africa up to 2050. Department of Environmental Affairs, Pretoria.* 2011.
10. Deressa, T.T. and R.M. Hassan, *Economic impact of climate change on crop production in Ethiopia: Evidence from cross-section measures.* Journal of African economies, 2009. **18**(4): p. 529-554.
11. Singels, A., et al., *Modelling crop growth and crop water relations in South Africa: Past achievements and lessons for the future.* South African Journal of Plant and Soil, 2010. **27**(1): p. 49-65.
12. Zimmermann, A., et al., *Climate change impacts on crop yields, land use and environment in response to crop sowing dates and thermal time requirements.* Agricultural Systems, 2017. **157**: p. 81-92.
13. Smith, M., D. Kivumbi, and L. Heng, *Use of the FAO CROPWAT model in deficit irrigation studies*, in *Deficit irrigation practices*. 2002.
14. Surendran, U., et al., *Modelling the crop water requirement using FAO-CROPWAT and assessment of water resources for sustainable water resource management: A case study in Palakkad district of humid tropical Kerala, India.* Aquatic Procedia, 2015. **4**: p. 1211-1219.
15. Tsakmakis, I.D., et al., *Impact of irrigation technologies and strategies on cotton water footprint using AquaCrop and CROPWAT models.* Environmental Processes, 2018. **5**(1): p. 181-199.
16. Gabr, M.E. and E.M. Fattouh, *Assessment of irrigation management practices using FAO-CROPWAT 8, case studies: Tina Plain and East South El-Kantara, Sinai, Egypt.* Ain Shams Engineering Journal, 2021. **12**(2): p. 1623-1636.
17. Nkomozepi, T. and S.-O. Chung, *Assessing the trends and uncertainty of maize net irrigation water requirement estimated from climate change projections for Zimbabwe.* Agricultural Water Management, 2012. **111**: p. 60-67.
18. Gong, X., et al., *Optimization allocation of irrigation water resources based on crop water requirement under considering effective precipitation and uncertainty.* Agricultural Water Management, 2020. **239**: p. 106264.
19. Oni, S., et al., *Executive summary of a study of agricultural industry of Limpopo Province.* South Africa: Centre for rural development: department of soil science, 2012.
20. Rankoana, S.A., *Perceptions of climate change and the potential for adaptation in a rural community in Limpopo Province, South Africa.* Sustainability, 2016. **8**(8): p. 672.
21. Maponya, P. and S. Mpandeli, *Perception of farmers on climate change and adaptation in Limpopo Province of South Africa.* Journal of Human Ecology, 2013. **42**(3): p. 283-288.
22. Mpandeli, S., *Managing climate risks using seasonal climate forecast information in Vhembe District in Limpopo Province, South Africa.* Journal of Sustainable development, 2014. **7**(5): p. 68.
23. Kom, Z., et al., *Determinants of small-scale farmers' choice and adaptive strategies in response to climatic shocks in Vhembe District, South Africa.* GeoJournal, 2020: p. 1-24.
24. Ubisi, N.R., et al., *Smallholder farmer's perceived effects of climate change on crop production and household livelihoods in rural Limpopo province, South Africa.* Change and Adaptation in Socio-Ecological Systems, 2017. **3**(1): p. 27-38.
25. Odiyo, J.O., et al., *Hydrological modelling of climate change impacts for development of adaptation strategies: The case of Luvuvhu River Catchment, Limpopo, South Africa*. 2020, Water Research Commission Report No. 2771/1/20 Pretoria
26. Hargreaves, G.H. and Z.A. Samani, *Reference crop evapotranspiration from temperature.* Applied engineering in agriculture, 1985. **1**(2): p. 96-99.
27. Allen, R., et al., *FAO Irrigation and drainage paper No. 56. Rome: Food and Agriculture Organization of the United Nations.* 1998.

28. Parekh, F. and K.P. Prajapati, *Climate change impacts on crop water requirement for Sukhi reservoir project.* Int. J. Innov. Res. Sci. Eng. Technol, 2013. **2**(9): p. 2-10.
29. Chowdhury, S., M. Al-Zahrani, and A. Abbas, *Implications of climate change on crop water requirements in arid region: an example of Al-Jouf, Saudi Arabia.* Journal of King Saud University-Engineering Sciences, 2016. **28**(1): p. 21-31.
30. Odiyo, J.O., R. Makungo, and T.R. Nkuna, *Long-term changes and variability in rainfall and streamflow in Luvuvhu River Catchment, South Africa.* South African Journal of Science, 2015. **111**(7-8): p. 1-9.
31. Schulze, R. and S. Schütte, *Climate zones and climate change.* Handbook for farmers, officials and other stakeholders on adaptation to climate change in the agriculture sector within South Africa Section B: Agriculture's natural capital in South Africa: A climate change perspective, 2016.
32. Mukwada, G., et al., *Can Famine Be Averted? A Spatiotemporal Assessment of the Impact of Climate Change on Food Security in the Luvuvhu River Catchment of South Africa.* Land, 2021. **10**(5): p. 527.
33. Schulze, R. and D. Dlamini, *Case study 3: Potential impacts of a hypothetical, but plausible, climate change scenario on within country reservoir management for irrigation, and out-of-country flow obligations in the Mbuluzi catchment, Swaziland.* Climate change and water resources in Southern Africa: Studies on scenarios, impacts, vulnerabilifies and adaptafion, 2005: p. 249-254.
34. Salokhe, V., M. Babel, and H. Tantau, *Water requirement of drip irrigated tomatoes grown in greenhouse in tropical environment.* Agricultural water management, 2005. **71**(3): p. 225-242.
35. Du Plessis, J., *Maize Production, Department of Agriculture, Pretoria, South Africa*. 2003.
36. Bozo, T., et al., *Comparative studies on yield and quality response of soil and soilless grown tomatoes: the case study of Masiphathisane Community Project and Bathurst Experimental Farm.* South African Journal of Agricultural Extension, 2019. **47**(4): p. 75-85.

Chapter 9

The current policy situation as an enabler for water sector climate change response to increase resilience

Chris Moseki, [1,*] Gabriel Lekalakala [1] and Brilliant Petja [2]

[1] Department of Water and Sanitation
[2] Water Research Commission
* Corresponding author: mosekic@dws.gov.za

Abstract: In this chapter we investigate whether a policy environment would be enabling for the South African Water sector to effectively respond to the climate crisis. The limited water resources face increasing pressures attributed to fast growing population, economic development, and urbanisation. These pressures are projected to be further exacerbated by changes in climate. Together the pressures, coupled with gaps in government policies, and the lingering past-apartheid institutionalized segregative water allocation and rights policies, together with the chronic gender disparity calls for an urgent response to climate crises. The approach employed in this assessment was to review the water governance framework and past experiences on the policy environment in responding to prevailing challenges and this was used to infer if the sector is likely to respond to climate change based on current policy environment. The challenges owing to increasing pressure and climate change as said are to be addressed through adequate governance of the available water resources. The water governance is driven by the political, social, economic, and administrative systems that influence the use and management of water. This is essentially about equitable allocation of water resources and other rights to it, its related services, and their benefits. These challenges require a paradigm shift in approaches employed by water managers and planners that consider complexities, introduced by highly variable and unpredictable conditions, in addressing water resources management. South African governance's framework aligns with international and regional best practices, and it is said to have some of the world's best policies; however, the main challenges to their success stems from low adaptive capacity and limited translation of good policies into practice. These lead to lack of implementation and investment in the development of the water systems to meet the growing demands. This chapter demonstrates the importance of not only good water policy environment but also good governances to meeting the demands.

Keywords: Policy environment; governance; climate change; resilience; systems; adaptive capacity

1. Introduction

Climate change is no longer a projection, and its impacts to some extent on systems are evident and well documented in the recent Inter-governmental Panel of Climate Change (IPCC) Assessment Report. The report calls for urgent action on water and climate. Moreover, the report confirms that people around the world are experiencing devastating consequences – climate change is intensifying the water cycle, including its variability, global precipitation and severity of heat and cold as well as dry and wet events [1]. Most of scientific evidence is based on field observations from long-term monitoring networks that shows [2] that climate change is occurring. Climate change has altered the already highly variable weather patterns, leading to more incidents of extreme weather events, unpredictable water availability, exacerbating water scarcity and contaminating water supplies. The extreme weather events associated with climate change reveal existing underlying threats to water security [1]. Some of the most noticeable impacts result from the way climate change intensifies the water cycle, bringing more intense rainfall and associated flooding, as well as more intense drought in many regions. In South Africa, climate change poses a significant threat to the already highly variable and erratic rainfall patterns, high temperature with associated double evaporative demand as opposed to rainfall received, and the limited and unevenly distributed water resources.

Water is the primary vehicle through which we feel the impacts of climate change. Water is crucial for development, especially in a region such as Southern Africa where water access remains a challenge and tops local leader political agendas [1]. This is evidently demonstrated by the fact that water is a catalyst and essential for all developments and sustain livelihoods. Water management under the changing climate is a serious challenge facing water managers and decision makers worldwide. Over the years water managers and planners have been contending with climate variability and its impact on water resources and supply. The water policy practices with respect to climate have and still markedly are such that predictions on future status of water assume stationary climatic conditions [3]. However, intransient conditions typically prevail under climate change.

In South Africa, climate change poses significant threats to the country's water resources, food security, health, infrastructure, as well as its ecosystem services and biodiversity. These plausible impacts are exacerbated by an already vulnerable system, characterised by high levels of poverty and inequality, thus posing critical challenges for national development [4]. These projected impacts are alarming and are of immediate societal relevance. For example, a change in available water supply and its predictability in South Africa would have major implications in most sectors of the economy, especially for urban and agricultural demands. The economies of developing countries including South Africa depend on climate sensitive sectors [5] such as agriculture and water. However, South Africa is a water scare country with almost half the World's average in rainfall [6] and very high evaporation rate due to high temperature under natural conditions (i.e. prior to factoring climate change effects). The country is also highly variable in terms of climate. Various stress factors such as water pollution, unsustainable water use and climate change exacerbate the water situation. To address a number of these and other water related challenges it is necessary to ensure enhanced adaptive capacity and access to the means of adaptation.

The strategic plan of the Department of Water and Sanitation (DWS) asserts that for South Africa to achieve water security, a strong regulation in terms of water quality, balancing demand and supply, ensuring the safety of dams, and being resilient to climate change impacts [7] are imperative. The second edition of the National Water Resource Strategy and the Water and Sanitation Sector Policy on Climate Change are both strategic documents of the DWS that underpin policies and strategies for mainstreaming climate change in the operational plans [8,9]. However, to guide and inform the implementation of policies the Climate Change Response Strategy for the Water Sector was developed. This chapter therefore assess and review the policy environment as an enabler to the resilient response to the changing climate over and above practical and physical measures that improves the adaptive capacity.

2. Review and Analytical Approach

The review follows a desktop study based on information that is available in the public domain. As a point of departure, water related governance frameworks were reviewed, that is, both National and International best practice are considered to develop an understanding of how the policy environment enables or act as a barrier to climate change adaptation in the water space. That climate is changing is no longer a debate since evidence of change is observable and encountered in various situations. Much of scientific evidence is based on field observations from long-term monitoring networks that show [2] that climate change is occurring. This is further endorsed by several researchers [10,11,12,13,14] who acknowledge the fact that climate change impacts will mostly be realized and felt through water. This is evidently demonstrated by the fact that water is a catalyst and essential for all developments and sustain livelihoods.

3. Water Governance and Policy

The South African water governance framework includes the Constitution of the Republic of South Africa [15], legislation; national, regional and global policy directives; governance structures in national, provincial and local spheres of government, as well as the country's regional and international commitments in the water sector. The Department of Water and Sanitation is mandated to ensure that the country's water resources are protected, managed, used, developed, conserved and controlled through regulating and supporting the delivery of effective water supply and sanitation. To this end, the work of the Department is funded through the national budget (Vote 41). The purpose of the Vote is to ensure the availability of water resources, facilitate equitable and sustainable socio-economic development, and ensure universal access to water and sanitation services.

3.1. Legislation

In South Africa, the legislative framework that regulates access to and availability of water resources includes the Constitution; the National Water Act (NWA; Act No. 36 of 1998); and the Water Services Act (WSA; Act No. 108 of 1997). These pieces of legislation aim to enable Government, through the work of the Department of Water and Sanitation, to deliver on citizens' right to sufficient food and water, grow the economy and eradicate poverty.

- Constitution – Section 27(1)(b) guarantees for everyone the right to have access to sufficient food and water. It obliges Government to take reasonable legislative and other measures, within its available resources, to ensure the progressive realisation of this right.
- National Water Act – The purpose of the Act is to ensure that the country's water resources are protected, used, developed, conserved, managed and controlled in ways that take into account factors such

as promoting equitable access to water; meeting the basic human needs of present and future generations; and promoting the efficient, sustainable and beneficial use of water in the public interest.

- Water Services Act – Some of the main objectives of the Act are to provide for the right of access to basic water supply and the right to basic sanitation necessary to secure sufficient water and an environment not harmful to human health or well-being; the accountability of water services providers; and the promotion of effective water resource management and conservation.
- Climate Change Bill – The Bill is currently undergrounding the Parliamentary review process before it is sent to will be enacted into law. In its draft form is seeks to enable for the development of an effective climate change response and a long-term just transition to a low-carbon and climate-resilient economy and society for South Africa in the context of sustainable development, through provision of legislative mandates for different climate sensistive sectors, Departments and across the different spheres of government.

3.2. Policy

South Africa's approach to ensuring access to and availability of water resources is underpinned by the strategic imperatives relating to water and sanitation at national (National Development Plan 2030 and Medium-Term Strategic Framework 2019-2024); regional (African Union Agenda 2063: The Africa We Want); and global (2030 United Nations Agenda for Development (SDGs)) levels. The relevant provisions contained in these documents are summarised in Table 1 below.

Section 24 (b) of the Constitution of South Africa, stipulates that everyone has the right to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that among other, to secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development [15]. In order to give effect to the Constitutional prescripts in this regard, the State is obliged to act to achieve the intended result, and the legislative measures will invariably have to be supported by appropriate, well-directed policies and programs that are reasonable both in their conception and their implementation [5]. The Constitution also stipulates that everyone has the right to sufficient food and water, while the state must take legislative and other measures within its available means to ensure attainment of these rights.

The legislative and financing instruments and institutions should synergistically be put it into practice to achieve sustainable, equitable and climate-resilient water management the policy [16]. In this regard, strong policies backed by sound technical understanding and operational capacity would yield the best form of adaptation to climate change [17] to deal with the general development challenges in sectors. The South African Water Policy was developed prior to the Water Law. That is appropriately in line with good international practice since the policy development represents the first aspect of an enabling environment [16]. The South African National Water Policy (adopted in 1997) hinges on the three (3) fundamental objectives; namely: achieving equitable access to water, sustainable use of water as well as efficient and effective water use. These objectives underpin the National Water Act (Act No. 36 of 1998) for management of water resources in South Africa. The Policy and the Act together with the National Water Resource

Strategy created an enabling environment for sustainable management and use of water, thus ensuring resilience building of the resource against various stress factors including climate change.

The second edition of the National Water Resource Strategy (NWRS 2) is among other outlined strategic actions that need to be taken to ensure climate change considerations in water management and planning. The actions primarily entail water governance, infrastructure development, operation, and maintenance as well as sustainable water management. These are important ingredients for creation of the enabling environment for transformation of the water sector into resilient and adaptive institutions.

The set of environmental policies and guidelines (Table 1) enables a low carbon transition within the context of the NDP, SDGs and Agenda 2063, with a focus on water resources. The policy framework links together South Africa's international commitments, national policies, and legislation.

Table 4. A set of environmental policies and guidelines

National Development Plan 2030	Medium Term Strategic Framework 2019-2024	Agenda 2063 Goals	Sustainable Development Goals (SDGs)

Chapter 4 Economy infrastructure – The foundation of social and economic development:
  Access to water and sanitation
  Water resources and services
	Priority 1: Economic transformation and job creation
	 Priority 4: Spatial integration, human settlements and local government
		Goal 7: Environmentally sustainable and climate resilient economies and communities.
		
		 Priority Areas:
		 • Bio-diversity, conservation and sustainable natural resource management.
		 • Water security
		 • Climate resilience and natural disasters preparedness
			SDG 6: Ensure availability and sustainable management of water and sanitation for all.

Chapter 5. Environmental sustainability: An equitable transition to a low-carbon economy: • Sustaining South Africa's ecosystem and using natural resources efficiently • Building sustainable communities • Responding effectively to climate change: adaptation • Managing a just transition • Enhancing governance systems and capacity			

Various countries worldwide took various policy positions to ensure enhanced resilience to climate change. [14] Resilience is expected to transform the social-ecological systems to shift to a socially desirable and sustainable regime in the European Union [14], thus calling for societal shifts from greenhouse gas intensive economy to a low-carbon one. In a similar vein South Africa's National Development Plan 2030

[17] also called for a transition from carbon intensive technology dependency to low carbon economy. The National Development Plan (NDP) aims to ensure that climate change is effectively addressed and mainstreamed in every department, as an essential component of a broader national development strategy. The national aspiration is that by 2030 South Africa's transition to an environmentally sustainable, climate-change resilient, low-carbon economy and just society would be well under way. In this regard, the country's approach [17] will essentially be strengthening the economic and societal resilience to climate change that include decreasing poverty and inequality, creating employment, improving education and promoting skills development, improving health care and maintaining the integrity of ecosystems.

The National Climate Change Response Strategy for the Water Sector aims to guide and inform the mainstreaming of climate change considerations into water management and planning. The overall objective of the Strategy is to ensure effective management of climate change impacts as well as extreme events on the country's water and sanitation through interventions that build and sustain South Africa's social, economic and environmental resilience and emergency response capacity. The recently developed Climate Change Bill, under consideration in Parliament, seeks to translate policies and associated response frameworks at local scale, and through sector specific approach to ensure that no vulnerable groups or sectors are missed in the strategy and implementation.

3.3. International and regional commitments

South Africa is party to a number of international agreements that provide for, among others, the protection and sustainable utilisation of freshwater resources. These include:

• Conventions – South Africa ratified the Convention on Biological Diversity (CBD) on 2 November 1995. The Convention promotes the conservation and sustainable use of biodiversity, especially through the protection of ecosystems, whilst respecting countries' sovereign rights over biological resources within their own territories.

• Furthermore, the United Nations Convention to Combat Desertification (UNCCD) requires States to promote the restoration, conservation, and sustainable management of land and water, and to cooperate with each other for the protection of those resources. It also requires neighbouring countries to work together in developing action programmes, which may include the joint sustainable management of transboundary water resources. South Africa ratified the UNCCD on 30 September 1997.

• Paris Agreement 2015 – is an agreement within the United Nations Framework Convention on Climate Change (UNFCC) that addresses greenhouse-gas-emissions mitigation, adaptation, and finance. The agreement was negotiated at the UNFCC's 21st Conference of Parties talks in France on 12 December 2015, and South Africa ratified it in 2016. The agreement entered into force on 4 November 2016. The agreement is a legally binding instrument that guides the process for universal action on climate change. It strengthens the global response to the threat of climate change by bringing all nations into a common cause of acting collectively, within the context of sustainable development and efforts to eradicate poverty, to hold the increase in global average temperature to well below 2°C and pursuing efforts to limit global temperature increase to 1.5°C [18].

- Southern African Development Community (SADC) Protocol on Shared Watercourse Systems, 2000 – SADC initially passed its Protocol on Shared Watercourses on 28 August 1995, and thereafter revised it on 7 August 2000. The Protocol aims to foster closer cooperation among Member States for protection, management, and use of shared watercourses in the region. Member States agreed to cooperate on projects and exchange information on shared watercourses, consulting with each other and collaborating on initiatives that balance development of watercourses with conservation of the environment [19]. For example, the Lesotho Highland Water Project, which gets its water from the Senqu/Orange river, a shared river between Lesotho, South Africa and Namibia.
- African Ministers' Council on Water (AMCOW) – was formed in 2002 in Abuja Nigeria, primarily to promote cooperation, security, social and economic development and poverty eradication among member states through the effective management of the Continent's water resources and provision of water supply services. In 2008, at the 11th ordinary session of the AU Assembly in Sharm el-Sheikh, Heads of State and the AU agreed on commitments to accelerate the achievement of water and sanitation goals in Africa. They mandated AMCOW to develop and follow up with an implementation strategy for these commitments. AMCOW has also been accorded the status of a Specialised Committee for Water and Sanitation in the African Union.

3.4. National, sub-national and local government structures

In South Africa, the Department of Water and Sanitation is the custodian of water resources, with the primary responsibility for the formulation and implementation of policy governing the sector. The Department ensures that all South Africans gain access to clean water and dignified sanitation. It also promotes effective and efficient water resources management to ensure sustainable economic and social development. The National Government manages water resources through the 15 Water Boards. The three Largest Water Boards are Rand Water in Gauteng Province, Umgeni Water in Kwazulu Natal Province and Overberg Water in the Western Cape. They operate dams, bulk water supply infrastructure, some retail infrastructure and wastewater systems. Some also provide technical assistance to municipalities. Through their role in the operation of dams, they also play an important role in water resource management. The Water Boards report to the Department of Water and Sanitation. Municipalities are responsible for the delivery of water and sanitation services to communities and must develop plans for delivery. These plans take into account effective delivery of services to informal communities, as stipulated in the National Water Act of 1998 and related regulations that ensure that every citizen is entitled to receive a minimum of 25 litres of water per day within a 200-meter walking distance.

3.5. Water resource access and availability

Water access in South Africa should be considered within the context of the various factors that shaped it, most notably separate development under the system of Apartheid, which resulted in levels of water inequality. For example, Apartheid spatial planning and governance created a system that ensured certain groupings in communities and sectors enjoyed priority to the limited water resources. The spatial architecture of the Apartheid government policies, characterised by marginal agricultural land, uneven distribution of resources and access to water is still reflective and has influenced the industry, national parks, population groups and agricultural sectors [20] .

The pre-democratic water laws were directed towards allocating and regulating water use for commercial farming as key water user, in particular irrigation, while subsistence farming had no official rights, as the land was under communal laws [21]. The growing demands or competition for the limited water resources, even with reforms in water laws, makes it difficult for additional water users to be allocated in the current water system, thus making irrigation unattainable for subsistence farmers, thereby contributing to their inability to cope with climate-related risks. The post-Apartheid Government, in redressing past injustices through policy reforms and expanding services, failed to review the available water resources and implement the necessary water infrastructure for the growing water demands. Further, informal settlements and new water users (such as farmers, industry, amongst others) across the landscape are still excluded from water access.

South Africa has access to surface water (77% of total use), groundwater (9% of total use), and recycled water (14% of total use). However, the population's dependence on water is not evenly distributed. Due to a lack of water infrastructure in rural settlements, 74% of all rural people are entirely dependent upon groundwater (i.e. local wells and pumps [22]). In South Africa the scarce fresh water is decreasing in quality because of an increase in pollution and the destruction of river catchments, caused by urbanisation, deforestation, damming of rivers, destruction of wetlands, industry, mining, agriculture, energy use, and accidental water pollution. As the human population increases, there is an increase in pollution and catchment destruction. South Africa needs to reduce water demand and increase supply for a growing population and economy to ensure water security by 2030. This is envisaged through the National Water and Sanitation Master Plan, which details the requirements for appropriate investment in water resources and services and sets targets for adequate water conservation and demand management.

4. Climate change and water

4.1. Projected change in precipitation

South Africa’s climate is highly variable under natural conditions with relatively low rainfall (of about 500 mm per annum on average) and high temperature with resultant high evaporation rate. This high degree of spatial variation in rainfall across southern Africa is attributed to the influence of the ocean currents and prevailing winds [23]. The rainfall is also projected to decrease [1] in the Mediterranean, the Western parts of West Africa, and Southern Africa, regions which are already prone to droughts. Additionally, in recent studies [23] for South Africa decreases in rainfall and the number of rainfall days over parts of the country have been detected. Also, evidence from other studies indicates that inter-annual rainfall variability over southern Africa has increased since the late 1960s and that droughts have become more intense and widespread in the region. These climatic changes are most likely to impact negatively on water availability in South Africa, particularly as a developing state with water related challenges already. On one hand, nature remain unsympathetic with only 9% of rainfall feeding rivers as runoff while only 4% recharges groundwater storage, while on the other unsustainable use of water country wide remains a high risk.

4.2. Projected change in temperature

Southern Africa has a warm climate, with the greater part of the region experiencing an average annual temperature above 17°C, and studies are also indicative of drastic increases in surface temperature [23], in the order of twice the global rate of temperature increase. The downscaled climate change projections projected the increase in annual-average surface temperature to range between 4 and 6 °C in the African and between 3 and 5 °C in the African tropics [24]. This future further increase in temperature is likely to exacerbate the water scarcity in the country.

4.3. Water sector implications

South Africa is indeed a water is a scarce country under natural conditions, due to among other, low rainfall and high temperature. The situation is exacerbated by unsustainable use of the limited resource, the escalating demand due to economic and population growth, urbanisation and rising standards of living, unsustainable use and high levels of wastage and loss, and increasing pollution which renders water not fit for use [6]. Additionally, the degradation of wetlands, climate change driven variation in rainfall patterns and increasing temperatures are also contributing to reduced security of supply. Undoubtedly, the non-climatic stress factors overshadow the climate change impacts. In other words, climate change is most likely to aggravate the already dire water situation.

The water sector in response need to develop additional water sources to make up for the shortfall in supply. However, it is quite clear that although surface water is South Africa's major source contributing about 77% of the total water use, this water resource mix type is oversubscribed, and development potential thereof is somewhat limited albeit it is still an economically viable option as well. On the other hand, other alternative yet relatively unconventional sources such as groundwater, return flows and desalinated water have great potential subject to appropriate assessment. Hence, the National Water and Sanitation Master Plan requires the diversification of the water resource mix [6] wherein surface water contribution will progressively reduce to 63% by 2040 while other alternative sources increase. For instance, groundwater contribution to water resource mix is planned to increase from the current 9% to 12% by 2040. Water conservation programs that seek to improve water use efficiency through education and awareness campaigns also need to be strengthened to reduce the need for water restrictions during drought, to delay the need for developing new water supplies that are relatively more costly. The nonrevenue water, particularly for domestic use in Local sphere of Government also need to be reduced. It is also crucial to manage demands for water among users, by various innovative approaches.

The strategic plan of the Department proposed adapting to climate change imperatives as well as taking advantage of the technological advances in line with the 4th industrial revolution [7]. In fact, to ensure water security the strategic plan calls for regular balancing of water requirements and supply, to inform reduction in water demand, and augmentation of supply for a growing population and support the economy. The Planning division of the Department currently undertakes reconciliation studies that entail water balances taking climate change into account.

4.4. Policy recommendation and adaptive strategies

To address these challenges the systems and tools as well as appropriate adaptation measures are necessary and essential. In other words, it is worthwhile to enhance capacity of implementing institutions and to ensure availability of requisite tools to those responsible for implementation. The poorer countries are not able to manage their current climate variability, due to lack of the means of implementation rather than lack of clarity regarding requisite strategies [25]. Indeed, making adaptation strategies available to vulnerable communities without necessary funding or even prior training on how tools can be used is a futile exercise. A case study in South Africa revealed that a shortage of capacity to deal with climate change and related policies within the Government stems from limited human and financial resources, and a shortage of relevant expertise and skills [26]. The other findings in the study were that growing complexity of work involved in designing and implementing sectoral and multisector decarbonisation and resilience policies made matters worse.

Hydrological and climate monitoring data and information underpin all analysis, modelling, projections, and decision-making processes in water management and planning. For instance, [2] emphasised that data from long-term monitoring networks is required to detect hydrologic changes for establishing baseline conditions and then record any changes over time. Additionally, good water management hinges on long-term hydrological and meteorological monitoring networks that provide sound, accurate, timely, and consistent data that can be used readily to develop and assess decision making tools needed to quantify uncertainty, forecast change, and create the multiphase, multilevel climate scenarios that will provide reasonable and relevant management [2]. This demonstrates the importance of monitoring data and information in the adaptation process. In South Africa, however, the typical scenario encountered is invariably patchy data observation coverage in time and space. To address this challenge, the National Water and Sanitation Master Plan requires that hydrological monitoring network should be improved to ensure that the climate change impacts are evaluated and considered in the analysis of water resources [6]. This directive has since been taken up; and plans are afoot to initiate the process of enhancing the national water monitoring network.

South Africa has developed through coordinate efforts the National Climate Change Adaptation Strategy (NCCAS). NCCAS provides as a strategic policy, a common vision of climate change adaptation and climate resilience for the country, drawing from the National Development Plan, the National Strategy for Sustainable Development, the adaptation commitments included in its Nationally Determined Contributions, sector adaptation plans, provincial adaptation plans and municipality adaptation plans. It acts as a common reference point for climate change adaptation efforts in South Africa in the short to medium term, providing guidance for all levels of government, sectors and stakeholders affected by climate variability and change. It provides a policy instrument which articulates South Africa’s national climate change adaptation objectives to provide overarching guidance to all sectors of the economy and facilitates the degree to which development initiatives at different levels of government and business integrate and reflect critical climate change adaptation priorities, and thus inform resource allocation by the various stakeholders towards climate change resilience. It also guides a strong, coherent and coordinated approach to climate change adaptation activities between different institutions and levels of government while supporting South Africa’s efforts in meeting its international obligations by defining the country’s vulnerabilities, and its plans to reduce these vulnerabilities and leverage opportunities. NCCAS further recognises that adaptation to climate change presents South Africa with an opportunity to transform the health and the economy, in order to strengthen the social and spatial fabric, and to become more competitive in the global marketplace. This would however require systematic changes that would require important considerations of social and economic changes together with technological adjustments amongst others in order to make the significant change that would improve the resilience and minimize risks. The National Climate Change Adaptation

Strategy (NCCAS) therefore provides a common vision of climate change adaptation and climate resilience for the country, and outlines priority areas for achieving this [27].

5. Impediments and barriers in the water sector

The South African Water Sector faces compounding challenges, wherein water availability is often not spatially well distributed to meet the growing demand and needs, or of the quality not conducive for use, due to unpredictable rainfall, limited infrastructure, the misuse of financial resources, and poor management – aggravated by corruption. The corruption watch report [28] gives examples of the corruption in South Africa's sector, its consequences, and a way forward, while the State Capture Report [29] provides more details on the systemic mechanisms behind corruption in the water sector. This led to the failure in the systems to provide basic services, as contracts for planned projects were not completed – owing to poor workmanship, budgetary constraints as money had been channelled out of the system and deployment of unskilled individuals, amongst others.

The impact of corruption in the water sector can be measured by the number of failed water projects, growing water supply and sanitation issues related to poorly maintained and inefficient infrastructure to support the growing population – crosscutting throughout the three spheres of government. It can also be attributed to failure to enforce laws meant to protect water sources from encroachment and pollution, resulting in discriminatory outcomes in water flows and irrigation patterns, leading to poor quality water and impacting the infrastructure that affects access to water. Moreover, the programme of water allocation and management reforms had been carried out since 1994 with institutional changes in the policy, legal and organizational dimensions. This was at some stage hailed as one of the world's best. However, these reforms are still not realised owing to institutionalized misappropriation of funds and inequitable water distribution as some of the barriers. All these impediments coupled with a low adaptive capacity, make climate change a significant threat to the water sector. However, current policy interventions, leadership, reprioritization of infrastructure development and addressing immediate past failures promises a revival of the sector and actions towards resilience despite a rise in extreme events.

6. Conclusions

Water is one of the pathways through which climate change and its associated risks (such as floods, drought, erratic rainfall, and others) will affect people, ecosystems and socio-economic activities. Climate change, within the South African context, with ongoing challenges around water availability and access to all users, adds more complexities for water resource management. This has been shown in the recent IPCC report, which points to projected intensification in the water cycle. This in addition to the already unequal access to and distribution of water resources across South Africa, thus translating into peoples' livelihoods being under threat. This particularly affects the poorest and most vulnerable of societies who rely on rain-fed agriculture and who live in areas that have limited resources for adaptive activities.

Over the years water managers and planners have been contending with climate variability and its impact on water resources and supply. For South Africa, a water scare country with highly variable climate under natural conditions climate change is likely to exacerbate an already vulnerable system that needs enhanced adaptive capacity and access to the means of adaptation. To address challenges, the Department developed tools such as the National Water and Sanitation Master Plan to guide and inform appropriate response and to ensure water security and safe sanitation for the country. The fact that everyone has the right to sufficient food and water, while the state must take legislative and other measures within its available means to ensure attainment of these rights is South Africa's Constitutional mandate makes the policy environment conducive to increasing the resilience and improving the adaptive capacity.

In addition, the South African national water policy hinges on the three (3) fundamental objectives; namely: achieving equitable access to water, sustainable use of water as well as efficient and effective water use. Yet, due to among other lack of requisite resources, the State does not always have the means adequate and fit for use to make water available and accessible to everyone who needs it. The other tool is the National Climate Change Response Strategy for the Water Sector that aims to guide and inform the mainstreaming of climate change considerations into water management and planning. In terms of climate, the rainfall is projected to decrease in the Southern Africa, region while temperature is predicted to increase thus exacerbating the water situation in the country. These tools are currently being implemented to address water, climate and sanitation related challenges. A potential game changer in the policy landscape is the introduction of the Climate Change Bill, which seeks to coordinate and harmonize climate change efforts across all organs of state, through their various policies, plans, programmes, decisions and decision-making processes. This Bill has potential to guide South African effort towards sustainable development pathways through systems approach and reducing conflicting interventions and thus maladaptation.

South Africa seems to have among the world's best policy and governance frameworks which align well with international governance frameworks and treaties. However, challenges persist in efforts to address water related challenges. The recent Zondo commission reports point to decay in state governance and control systems of which were attributed to lack of political will and institutionalisation of corruption. These two issues need to be addressed to ensure that South Africa is prepared and has the necessary tools and measures to address the growing water demands, owing to climate crises and growing population (development). Attempts to correct this structural and system failures in the current situation shows a promising future.

Funding: No funding was solicited for this article.

Acknowledgments: We acknowledge the WRC for encouragement and support thus enabling completion of this work. The views expressed in this paper are of the authors and not their respective affiliated organizations.

References

1. Intergovernmental Panel on Climate Change. (2021). Climate change African Perspective 6th IPCC Special Report on Africa
2. Brekke, L.D., Kiang, J.E., Olsen, J.R., Pulwarty, R.S., Raff, D.A., Turnipseed, D.P., Webb, R.S., and White, K.D., (2009) Climate change and water resources management—A federal perspective: U.S. Geological Survey Circular 1331, 65 p.
3. Pittock, J. (2011). National climate change policies and sustainable water management: conflicts and synergies. *Ecology and Society* **16**(2): 25. [online] URL: http://www.ecologyandsociety.org/vol16/iss2/ art25/
4. Department of Environmental Affairs, DEA (2011). South Africa's Second National Communication under the United Nations Framework Convention on Climate Change. Pretoria, South Africa: Department of Environmental Affairs, Republic of South Africa (RSA).

5. Van der Bank, M. and Karsten, J. (2020). Climate Change and South Africa: A Critical Analysis of the Earth-life Africa Johannesburg and Another v Minister of Energy and Others 65662/16 (2017) Case and the Drive for Concrete Climate Practices. Air, Soil and Water Research Volume 13: 1–11
6. Department of Water and Sanitation (2018). National Water and Sanitation Matter Plan, Volume 2 – Plan to Action Version 4.2
7. Department of Water and Sanitation (2021). Revised Strategic Plan (2020/21 – 2024/25)
8. Department of Water Affairs (2013). National Water Resource Strategy 2nd Edition. South Africa
9. Department of Water and Sanitation (2017). Water and Sanitation sector policy on climate change
10. Water and climate coalition (2010). Placing water resources management at the heart of global policy responses to climate change. Water and Climate Roadmap: Securing a Work Programme on Water and Climate Change under the UNFCCC.
11. Calow, R.; Bonsor, H.; Jones, L.; O'Meally, S.; MacDonald, A. and Kaur, N. (2011) Climate change, water resources and WASH: A scoping study. Working Paper 337. ODI; British Geological Survey. ISBN 978 1 907288 50 0. 59p
12. Asia-Pacific Water Forum (2012) Framework Document on Water and Climate Change Adaptation. For Leaders and Policymakers in the Asia-Pacific Region. tkoike@hydra.t.u-tokyo.ac.jp
13. Stuart-Hill, S.I. (2015). Mainstreaming adaptation to climate change into decision making in the water sector: Concepts and case studies from South Africa. Unpublished PhD thesis in the School of Agricultural, Earth and Environmental Sciences, Discipline of Hydrology; University of KwaZulu-Natal Pietermaritzburg. 235p
14. Puharinen, S.-T. (2021). Good Status in the Changing Climate? —Climate Proofing Law on Water Management in the EU. Sustainability 13, 517. https://doi.org/10.3390/su13020517
15. Constitution of the Republic of South Africa, No 108 of 1996
16. Capnet (2020) Climate change adaptation and Integrated Water Resource Management www.cap-net.org
17. National Planning Commission of RSA (2011) National Development Plan 2030 Our Future – Make it Work ISBN: 978-0-621-41180-5
18. United Nations Framework Convention on Climate Change, UNFCC. (2022).The Paris Agreement. Available from: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement [internet]
19. Southern African Development Community, SADC. (2000). Revised Protocol on Shared Watercourses Southern African Development Community. Available from: Revised Protocol on Shared Watercourses - 2000 - English.pdf (sadc.int) [Internet]
20. Lévite, H. Sally, H., van Koppen, B. and Cour, J. 2003. Olifants River Basin, South Africa. IWMI Africa Regional Program, [Internet]. South Africa, Available from http://portal.unesco.org/.
21. Turton, A. and Henwood, R. 2002. Hydropolitics in the Developing World: A Southern African Perspective. African Water Issues Research. Pretoria, RSA. Unit. ISBN: 0-0620-29519-8.
22. United Nations Water (2006). Water a Shared Responsibility. Retrieved from http://unesdoc.unesco.org/images/0014/001454/145405e.pdf#page=519
23. Davis-Reddy, C.L. and Vincent, K. (2017): Climate Risk and Vulnerability: A Handbook for Southern Africa (2nd Ed), CSIR, Pretoria, South Africa.
24. Francois Engelbrecht, F., Adegoke, J. Bopape, M-J., Naidoo, M., Garland, R., Thatcher, M., McGregor, J., Katzfey, J., Werner, M., Ichoku, C. and Gatebe, C. (2015). Projections of rapidly rising surface temperatures over Africa under low mitigation. Environmental Research Letters

25. Muller, M. (2007) Adapting to climate change: Water management for urban resilience. Environment & Urbanization Copyright © 2007 International Institute for Environment and Development (IIED). Vol 19(1): 99–113. DOI: 10.1177/0956247807076726 www.sagepublications.com
26. Averchenkova A, Gannon KE, Patrick C (2019) *Governance of climate change policy: A case study of South Africa*. London: Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London School of Economics and Political Science
27. Department of Forestry, Fisheries and the Environment (2020) National Climate Change Adaptation Strategy: Republic of South Africa. Department of Forestry, Fisheries and the Environment, Pretoria.
28. Erasmus, J. (2020). Money down the Drain: corruption in South Africa's water sector. Available from: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.corruptionwatch.org.za/wp-content/uploads/2020/03/water-report_2020-single-pages-Final.pdf. [Internet]
29. Zondo, R.M.M Justice. 2022. Judicial Commission of Inquiry into allegations of State Capture, Corruption and Fraud in the Public Sector including Organs of State.

WATER
RESEARCH
COMMISSION