SCENARIO BUILDING FOR FUTURE WATER MANAGEMENT IN LIMPOPO PROVINCE, SOUTH AFRICA

Report
to the Water Research Commission

by

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EXECUTIVE SUMMARY

BACKGROUND AND RATIONALE

Located in the north-eastern part of South Africa, Limpopo Province is named after a transboundary river basin which forms the northern boundaries of the country between Botswana, Zimbabwe, and Mozambique. The arid to semi-arid climate of the province influences the seasonal variability in available water, leading to water challenges across the province's five districts.

In recent years, Limpopo Province has been experiencing an increasing demand for water due to population growth, changes in socio-economic conditions, changes in consumption patterns, dilapidating infrastructure, water leakages, agricultural intensification and expansion, and an increase in mining and industrial activities. These complexities of water supply and demand make water estimation and management a challenging task for the province.

Climate change further exacerbates current water challenges across the Limpopo Province by affecting rainfall patterns, distribution, timing, and intensity, leading to extreme climate events such as floods and droughts. This impinges on water availability, distribution, quality, and management, resulting in widespread water scarcity, stresses, and diverse environmental impairments.

To date, there has been a dearth of research that provides a panoptic view of the nature and extent of the impact of climate change on the spatio-temporal variability in rainfall in the province, nor the consequential impact on water availability for achieving shared vision or developmental goals. Nor has the communication of such findings to the relevant authorities responsible for water resource management of the province been prioritised.

Conventional approaches in water resources management lack an effective climate change perspective and inclusion in water demand planning phases. With increasing climate change impacts, Limpopo's residents are expected to be exposed to a decrease in renewable water resources. The omission of the potential impact of climate change in the conventional water demand and supply forecasting for the province may, therefore, hasten the need for effective climate change early warning systems and adaptation responses. This is to limit vulnerability to variations in water availability across sectors and exposure to extreme water-related events.

To inform the improvement in water management in the Limpopo Province, this project from a climate change, water availability, risk management and preparedness perspective, considered the following:

- the need for a comprehensive assessment of the water situation in the province,
- increasing stakeholder and relevant authorities' awareness of current and future climate risks and constraints, and
- the need for adequate preparedness and responses across all five districts in the province.

These types of assessments and improvements are necessary in the face of increasing climate variability, change, and extremes so as to inform the choice of innovative technologies, economic incentives, financial instruments, institutional arrangements, and management approaches to deploy to limit water-related vulnerabilities and risks in the province.

Water stress across the regions of the province is diverse, affecting the developmental sectors in different ways. Water is considered a primary constituent in development, upon which other sectors depend. Climate change, current water management approaches, unsustainable and inefficient use, ineffective policies, and deteriorating water quality threaten water availability needed to support the livelihoods of people, to support major economic sectors, and to facilitate current and future developmental goals within the Limpopo Province.

This project, in addition to offering a comprehensive assessment of changes in the rainfall patterns of the province, contributes to the development of tools and methodologies to support better planning, adaptive management, and improved water governance in the province. This is to support communities, drive sustainable development solutions, and inform policy and decision-making. The project enabled a significant level of stakeholder participation to improve the level of ownership. Therefore, this research supports the principles of Integrated Water Resource Management (IWRM) in the Limpopo Province.

PROJECT AIMS

The overall project aims include:

1. To undertake a water resource assessment in Limpopo Province (document analysis and interviews).
2. To undertake a comprehensive analysis of all rainfall data measured in the province suitable for the study of long-term variability and trend, including frequencies and scale of droughts, changes and variability in the intensity of rainfall.
3. To determine the impacts of climate change on water availability through GIS application and modelling (numerical and statistical).
4. To undertake a future water resource assessment in Limpopo Province (scenario building).
5. To examine the possible future trends of water management, and the impact these trends are likely to have on the possibility of achieving a shared vision (scenario building).
6. To determine developmental implications of the various scenarios developed in the study and recommend appropriate adaptation options.

PROJECT TEAM

The University of Limpopo was awarded a research grant by the Water Research Commission (WRC), to lead research on climate change impacts and how climate change perspectives can be incorporated into water resource management in the province.

To achieve the project's aims, the University of Limpopo has partnered with the Council for Scientific and Industrial Research (CSIR), Motlole & Associates, and the South African Weather Service (SAWS) to conduct the research in well-defined phases, organised into work packages (WP). The project, which was implemented between 2021-2023, achieved all set objectives.

METHODOLOGY

To undertake a water resource assessment in Limpopo Province, a combination of national, provincial, and district or local government documents analysis was undertaken. This was followed by key and knowledgeable informant interviews and interactions in order to contextualise the water situation in Limpopo Province and to track the previous and present developmental changes in the water sector, as well as its current and future developmental plans. A systematic document analysis approach was, therefore, used to review both printed and/ or electronic material so as to establish the strategic interventions of the district municipalities, resource availability, condition of infrastructure, social demand, and pertinent aspects concerning water management. Interviews with high-level knowledgeable officials in the municipalities were undertaken to fill the gaps in knowledge from the document analysis.

To undertake a comprehensive analysis of all rainfall data measured in the province suitable for the study of long-term variability and trend, including frequencies and scale of droughts, changes and variability in the intensity of rainfall, the South African Weather Service conducted an audit of all data suitable for long-term rainfall analysis to assess trends and variability in rainfall across all the district municipalities in the province. Analysis periods were not fixed but variable according to data availability. Similarities between rainfall statistics per station enabled the statistical inference of past rainfall where measurements were not necessarily made. The availability of rainfall data was considered in conjunction with the homogeneous rainfall districts in the province, which were developed by SAWS in the 1970s, and consist of monthly averages of rainfall of all the SAWS rainfall stations which recorded rainfall during the month. Average monthly data of the rainfall districts were used to establish long-term trends and the severity of dry episodes. An important aspect of the analyses was the frequencies and scales of drought and trends thereof. This revealed that the scale, intensities, and lengths of droughts have become more extreme and frequent in different regions of the province. A second important aspect is the analysis of shorter time-scale rainfall intensities and intermittent dry periods in order to answer the question whether the rainfall season has become more extreme in terms of intensity, and whether rainfall has become more inconsistent and unreliable.

The development of reliable future rainfall climate scenarios for the province, with analysis similar to that of the historical data from the above assessment, was conducted. Eight individual and ensemble of Global Circulation Models (GCMs) that participated in the Fifth Phase of Coupled Model Inter-comparison Project (CMIP5) were dynamically downscaled to a finer spatial resolution (0.44° x 0.44°) using the Rossby Centre regional (RCA4) model. The RCA4 simulated projections formed part of the Coordinated Regional Climate Downscaling Experiment (CORDEX). The performance of the individual and ensemble models was evaluated by using the Taylor diagram technique, which was quantified in terms of the correlation (R), the centred root-mean-square-error (RMSE), and the amplitude of the standard deviations (Std). Consequently, projections for rainfall amount, precipitation extreme indices from the Expert Team on Climate Change Detection and Indices (ETCCDI), and drought indices such as the Standardized Precipitation Evapotranspiration Index (SPEI) and Standardized Precipitation Index (SPI) under climate change scenarios of the Representative Concentration Pathways (RCPs) 4.5 and 8.5, were generated.

To examine the potential impact of climate change on water resources and to work towards a shared vision through scenario building, the ACRU model was selected for application in the study, given its more process-based nature and the availability of a single configuration of the model for the large study area. The advantage of the ACRU model is that it is more process-based and better suited for assessing climate change impacts, where changes in daily rainfall patterns may result in different hydrological responses to what has been typical in the past. Projected changes in mean annual streamflow were analysed for the larger river systems In Limpopo. Future scenarios of water availability based on the Sixth Phase of the Coupled Model Inter-comparison Project (CMIP6), were developed. As part of this deliverable, both virtual and face-to-face workshops were held to get stakeholders' input into the scenario development.

To determine the developmental implications of the various scenarios developed above and to recommend appropriate adaptation options, a review of the socio-economic conditions in the province was undertaken, followed by an examination of the developmental strategies in the province and the challenges posed by water scarcity in the pursuit of Limpopo's development agenda. Water requirements and availability from existing and planned supply infrastructures were captured. Current and planned development projects in the province requiring significant amounts of water were identified. Their water requirements were then analysed in the context of the projected changes in climate and water availability assessed in previous components of the project. Finally, strategic interventions and adaptation options were presented considering the findings of the analysis.

RESULTS AND DISCUSSION

Analysis of the current water situation in the province showed that water services and their accessibility for the more than 6 million people dependent on them in Limpopo Province are insufficient. It suggests that the total water service system yield in the province has to be augmented with water from other sources, such as groundwater, water recovery and harvesting, amongst others, to meet part of the current water demands in the province.

The analysis of long-term daily rainfall for the period 1921 to 2023 showed historical trends in rainfall patterns over the Limpopo Province. The drought analysis with the 12- and 24-month SPI values showed that most of the province underwent drying to various degrees, with the central and western parts showing drying over the last century. Drier conditions over the eastern parts of the province have become more prevalent over the last 50 years. The SPEI index, applied to individual climate stations with records longer than 30 years, indicated similar trends to the SPI analysis. However, there are clear signals that recent longer-term droughts were more severe than what the SPI alone indicates. Findings conclude that the rainfall climate in Limpopo Province has become drier to various degrees, exhibiting more extremes on a sub-seasonal basis, as reflected in trends of daily extreme indices.

Effects of climate change on water availability through GIS application and modelling of rainfall indices indicate that the province is expected to experience a decrease in precipitation across the three projection periods under both RCP4.5 and RCP8.5. The south-eastern parts of Sekhukhune District Municipality, and the central (South-Eastern Capricorn, Western Mopani, and Central Waterberg), and northern (Central Vhembe) parts of the province are expected to experience notable reductions in rainfall. Increased rainfall is expected in the south-western part (Western Waterberg) under the RCP 4.5 scenario. Localised spatial variations were observed across the analysed precipitation extreme indices over the projected periods. The number of heavy (and very heavy) precipitation days is likely to decrease for most parts of the province for all projection periods under both RCP scenarios. The number of consecutive wet days is projected to decline in the southern and northern parts, and increase in the south-western parts of the province. Consecutive dry days and the maximum number of CDD periods are projected to significantly increase during the analysed periods under both RCP4.5 and RCP8.5 scenarios. Negative trends in drought indicators are detected across the analysed 3-, 6-, and 12-month timescales, suggesting that the province is likely to continue experiencing drought conditions over the projected periods. While persistent drought is expected in most parts of the province, the conditions are projected to mostly last for approximately 3-5 months, and be less severe over a given time.

Results of the assessments of potential impacts of climate change on water resources showed that at the median percentile for the SSP245 emissions scenario, there were mixed responses with some rivers showing decreases in flows (of up to 5 per cent) and others showing increases (of up to 25 per cent). For the SSP585 scenario, all rivers were projected to experience increases in flows (of up to 25 per cent). At the 10th percentile of the climate model ensemble (dry end), most rivers are projected to experience reductions in flows for both emission scenarios (of up to 15 per cent). An exception to this is the Olifants River, where small increases were projected (7 per cent). At the 90th percentile of the climate model ensemble (wet end), most rivers are projected to experience increases in flows for both emission scenarios (of up to 65 per cent). For the SSP245 scenario, two rivers are projected to experience negligible change.

The assessment of development implications found that most of the developments considered are in water-stressed areas and, as such, are already vulnerable to climate impacts. The Limpopo Province is found to be water-stressed and riddled with severe and frequent droughts, excessively high temperatures, as well as reduced rainfall. Additionally, the climate change-driven extreme events, particularly drought and floods, negatively impact water-dependent economic development projects such as agriculture production and mining. In general, water scarcity and unsustainable water use are identified as limiting factors for water-dependent developments. For instance, some of the non-climatic stress factors such as increased non-revenue water, degradation of water quality, over-exploitation of groundwater and unsustainable water use, as well as poor water management, render the system vulnerable to climate change. The water resources schemes planned by the Department of Water and Sanitation aim to address deficits in various areas, while the district municipalities and the private sector (e.g., mines) develop local resources to augment their water requirements. Hence, the recommended interventions and adaptation options aim to ensure the reduction of vulnerability and enhanced resilience.

CONCLUSION AND RECOMMENDATIONS

With increasing water demands in the Limpopo Province, there is a need to intensify the integrated water management of water resources in the province. All perspectives of water management ought to be considered.

Expanding water requirements reflecting increasing and diverse water demands, the need for development, and the impacts of climate change, all serve to put immense pressure on available water resources in the Limpopo Province. This is influencing the developmental potential of the residents of the province.

The rainfall and streamflow analyses carried out in this project indicate that the Limpopo Province's climate is changing, and is evidenced by changing rainfall patterns, as reflected in rainfall indices measuring droughts and floods. These have translated into projected changes in stream flow across the different major basins in the province.

This project concludes that climate change is affecting the spatial and temporal distribution and pattern of rainfall in the Limpopo Province. This is putting pressure on available water resources and the ability to plan and manage available resources sustainably. There is a need for a conscientious consideration of changes in future water availability due to climate change in the province in future resource planning, to effectively close the gaps in current and projected water demands, including the requirements for future provincial developmental goals.

The following recommendations are made based on the outcomes of the project and its conclusions:

- Under the auspices of the WMO, a relatively new suite of extreme climate indices has been developed and is calculable with the WMO ClimPact software. The trends of these sector-relevant indices can be determined for both historical periods and future periods, depending on data availability. The impacts of climate change in areas or regions of particular concern can be further investigated through these indices, which in many cases can be refined by the user, for example, in terms of threshold values. In this regard, the impacts of the changing rainfall climate could be assessed for specific sectors and industries in the province.
- The ISIMIP climate projections should be analysed in terms of changes in rainfall extremes (droughts, extreme precipitation indices) to assess how well they correspond with the CORDEX projections. This will further help to relate the streamflow projections to the other climate-related analyses conducted in the project. In addition, other available climate models in the ISIMIP dataset (for SSP585) should be assessed to determine whether they indicate future drying or wetting. The inclusion of these models may shift the overall outlook of the ISIMIP projections to be more in line with the greater CMIP6 envelope and the CORDEX models used in the project.
- Adaptive interventions should focus on building resilience to climate extremes (droughts and floods) given that the trend for these events to increase in severity/frequency is associated with greater certainty than the changes in mean conditions. The robustness of water resources infrastructure is also tested to a greater degree during extreme conditions than under “mean” conditions.
- Assess whether stochastic flow sequences conventionally used as input to the DWS yield/planning models have sufficient extremes represented in them to represent any future condition that may be experienced under climate change. This would require research to develop valid stochastic flow sequences conditioned on future climate change projections, for comparison with stochastic flow sequences conditioned on historical flow records.
- The impact of climate change on groundwater should be considered in future research since groundwater has been identified as a key resource to achieving future water security in Limpopo.
- The impact of climate change on water quality should be considered in future research.
- Efforts to maintain and improve sewage networks and wastewater treatment facilities should be given top priority, given the severe risk that failing sanitation infrastructure poses to water security.
- Other measures to conserve water resources, such as the reduction of non-revenue water and the improvement of irrigation efficiency, should be prioritised to ensure water security in a changing climate.
- Greater awareness should be raised of the need to consider water availability in future development projects to ensure the success of these developments and the security of water supplies. Consideration should be given to water requirements early in the planning phase to avoid later problems in the approvals and implementation of these projects.
- There should be ongoing engagement between researchers and DWS to ensure climate change is adequately factored into water resources planning.

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The project team would like to thank the following Reference Group members for their contributions to the project:

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS & ABBREVIATIONS

AsgiSA	Accelerated and Shared Growth Initiative for South Africa
CDD	Consecutive Dry Days
CDO	Climate Data Operator
CMIP5	5th Phase of the Coupled Model Intercomparison Project
CORDEX	Coordinated Regional Downscaling Experiment
CSIR	Council for Scientific and Industrial Research
CWD	Consecutive Wet Days
DD	Drought Duration
DM	District Municipality
DS	Drought Severity
DWS	Department of Water and Sanitation
DEA	Department of Environmental Affairs
ETCCDI	Expert Team on Climate Change Detection and Indices
FAO	Food and Agriculture Organization
GCM	Global Climate Model
GIS	Geographical Information System
GRIP	Groundwater Resource Information Project
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
IPCC	Intergovernmental Panel on Climate Change
LEIP	Limpopo Eco-Industrial Park
MAP	Mean Annual Precipitation
MCWAP	Mokolo and Crocodile West Water Augmentation Project
MMSEZ	Musina-Makhado Special Economic Zone
MK	Mann-Kendall
NRW	Non-revenue water
NWP	Numerical Weather Prediction
PET	Potential Evapotranspiration
PRCPTOT	Precipitation Total
QCD	Quinary Catchments Database
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
R&D	Research and Development
SAWS	South African Weather Service
SDII	Simple Daily Intensity Index
SMA	Simple Multi-model Averaging

SSP	Socio-Economic Pathways
SPEI	Standardised Precipitation-Evapotranspiration Index
SPI	Standardised Precipitation Index
SSA	Sub-Saharan Africa
WMA	Water Management Area
WMO	World Meteorological Organisation
WP	Work Packages
WRC	Water Research Commission

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Climate change has become one of the greatest challenges facing mankind, due to the far-reaching implications it has on the functioning of ecological, social, and economic systems. There is overwhelming evidence that the climate is rapidly changing at various spatio-temporal scales. According to the Intergovernmental Panel on Climate Change (IPCC) reports, global climate and its extremes are changing, with observations indicating increases in global average air and ocean temperatures, widespread melting of snow and ice, changes in rainfall patterns, as well as rising global average sea level (Allen et al., 2018; Liu et al., 2024). Africa is one of the most vulnerable continents to climate change and variability, due to the continent's high dependence on agriculture and natural resources, the aridity found on parts of the continent, warmer baseline climates, low annual precipitation, and low climate change adaptive capacity (Kurukulasuriya and Mendelsohn, 2008; Hassan and Nhemachena, 2008; Thornton et al., 2008; Mensah et al. 2024; Adeola et al., 2024). Furthermore, the type and patterns of extreme events have shifted over the years, with alternating flood and drought regimes noted (Ebi and Bowen, 2016). Sub-Saharan Africa (SSA), including South Africa, has been identified by the IPCC as being the most vulnerable region to the increase in extreme events such as storms, floods, droughts, heatwaves, wildfires, and landslides (CDKN, 2014).

In recent decades, Limpopo Province has experienced an increasing water demand, mainly due to population growth but also due to changes in socio-economic conditions (with changes in consumption patterns), and increased mining and industrial activity. This increasing demand for water is occurring against the backdrop of the increasing impact of climate change. According to Müller et al. (2014), the geographical location of South Africa is in one of the three regions of the African continent that is likely to suffer more adverse impacts from climate change than elsewhere. This is because South Africa is climatically sensitive and already water stressed. Much of the country is arid or semi-arid and the whole country is subject to relatively frequent droughts and floods. Any variation in the rainfall or temperatures would thus exacerbate the already stressed environment. Most South African crops are grown in areas that are only just climatically suitable and with limited water supplies (Africa, 2009). Climate change research indicates that the region within which Limpopo Province is located will face a potential increase in temperatures, and the region is likely to experience greater variability in rainfall and will almost certainly witness an increase in evaporation rates (DEA, 2015), implying a drier future even in the presence of greater rainfall and heavy rainfall events (DEA, 2013).

Up to now, however, there has not been comprehensive research conducted to ascertain the exact nature of the changes in rainfall, both spatially and temporally; nor has such detailed information been effectively communicated to stakeholders within the province, e.g., local authorities and water resource management.

Given the above context, the main objective of the proposed research was to address one of the deficiencies in the approach to water resource management, which is the consideration of a detailed climate change perspective in the water resources planning phase in the Limpopo Province. This gap may consequently jeopardise the opportunity to put in place effective early warning systems and implement adaptive interventions to variations in water availability and extreme water-related events. The project aims to contribute, from a climate and water availability perspective to risk management and preparedness; to improve strategy development by making stakeholders more aware of risks and constraints; to find a number of possible alternatives and raise awareness for possible future scenarios; and to assist water end-users in the Limpopo Province to prepare for situations of low water availability due to anticipated decreased and more erratic rainfall. As climate change and variability becomes more extreme, newer, more innovative technologies, economic incentives and financial instruments and institutional arrangements will have to be introduced.

1.2 PROJECT AIMS

The specific aims of the project (as reflected in the contract) were defined as follows:

1. To undertake a water resource assessment in Limpopo Province (document analysis and interviews).
2. To undertake a comprehensive analysis of all rainfall data measured in the province suitable for the study of long-term variability and trend, including frequencies and scale of droughts, changes and variability in the intensity of rainfall, and so forth. This analysis will be used as input in the bias correction of climate models for the development of more reliable future rainfall scenarios.
3. To determine the impacts of climate change on water availability through (Geographic Information Systems) application and modelling (numerical and statistical).
4. To undertake a future water resource assessment in Limpopo Province (scenario building).
5. To examine the possible future trends of water management and the impact these trends are likely to have on the possibility of achieving a shared vision (scenario building).
6. To determine the developmental implications of the various scenarios developed in the study, and recommend appropriate adaptation options.

1.3 SCOPE AND LIMITATIONS

As the title of the project implies, the geographical domain of the study covers the Limpopo Province. Thus, the various components of the study (historical rainfall analysis, analysis of climate projections, water resources assessment and scenario building, and exploration of development implications) were undertaken across the province. As there are river systems that flow through Limpopo, which have their source outside the province, the water resources assessment was expanded to include the headwater regions located outside the province. Given the large catchment areas involved in the study (total area of 184 314 km^2) and the complex land and water use patterns found in the province, a high-level approach was adopted in the water resources assessment. The approach emphasised the representation of a variety of climate models and scenarios, given that the project was essentially a climate change impact study. It was a requirement of the project that more than one emission scenario be considered. Stakeholder engagement was focused on key stakeholders, than an exhaustive consultation exercise.

1.4 OVERVIEW OF APPROACH ADOPTED

The components of the research were divided by the project team into a series of work packages (WP) as follows:

- WP1: Description of the study area, including the characterisation of its climate, water resources, and socio-economic conditions.
- WP2: Analysis of historical (measured) rainfall data.
- WP3: Analysis of projected future rainfall.
- WP4: Modelling of future water resources for Limpopo Province and scenario building.
- WP5: Exploration of developmental implications given the projected changes in water resources.
- WP6: Production of the final report.

Each of the consortium partners had the responsibility to lead a particular work package, while other organisations played a supporting role. The process of organising the research into work packages with assigned leads became important following the departure of some members of the original project team from the project.

ABOUT THE CONSORTIUM PARTNERS AND ROLE

PARTNER 1: UNIVERSITY OF LIMPOPO (LEAD)

The University of Limpopo is one of South Africa’s institutions of higher learning, located in Polokwane, Limpopo Province. The University emerged following the merger between the former Medical University of Southern Africa and the University of the North, which merger occurred on 01 January 2005. The Department of Water and Sanitation at the University of Limpopo was leading the consortium team, coordinating the project, providing technical guidance, and requisite administrative support on the implementation of the project.

PARTNER 2: COUNCIL FOR SCIENTIFIC AND INDUSTRIAL RESEARCH (CSIR)

The Council for Scientific and Industrial Research (CSIR) is an entity of the Department of Science and Innovation, and South Africa's central and premier scientific research and development organisation. It was established by an act of parliament in 1945 and is situated on its campus in the city of Pretoria.

One of the key pillars of the CSIR is the SMART Places Cluster, within which is the Holistic Climate Change Impact Area. This strategic division of the CSIR undertakes directed climate change research that supports integrative climate change responses, with tangible impacts for low-carbon, resilient development across Southern Africa. One of its strategic imperatives is to play a leading role in developing appropriate modelling tools to facilitate integrated resource planning for cross-cutting themes such as Water Energy Food Nexus, which feeds directly to this project for scenario building for future water management. The CSIR led the hydrological component through coupling climate change projections with provincial surface water resources and facilitated the stakeholder engagement.

PARTNER 3: SOUTH AFRICAN WEATHER SERVICES (SAWS)

The South African Weather Service (SAWS) is a Section 3(a) public entity under the Ministry of Environmental Affairs, and is governed by a Board. The organisation became a public entity on 15 July 2001 in terms of the South African Weather Service Act (No. 8 of 2001), as amended in 2013. It is an authoritative voice for weather and climate forecasting in South Africa, and as a member of the World Meteorological Organization (WMO), it complies with international meteorological standards. As an Aviation Meteorological Authority, SAWS is designated by the State to provide weather services to the aviation industry, marine and a range of other identified clients, and to fulfil a range of international obligations of the government. It provides two distinct services, namely public good services that are funded by government, and paid-for commercial services. In this project SAWS led the historical rainfall analysis as well as the future projections of rainfall, extreme indices, and drought.

PARTNER 4: MOTLOLE & ASSOCIATES
Motlole and Associates is a privately owned company responsible for leading the scope of work on assessing the developmental implications of the projected future changes in water resources for Limpopo Province.

1.5 OUTLINE OF REPORT

Following this introductory Chapter 1, which describes the study context and institutional arrangements, Chapter 2 describes the study area and characterises it in terms of climate, water resources and socio-economic conditions (WP1). Chapter 3 details the analysis of historical rainfall (WP2) while the analysis of projected future rainfall is presented in Chapter 4 (WP3). Chapter 5 presents the assessment of future water resources and scenario building (WP4), while Chapter 6 explores the implications of projected changes in water resources on key development projects in the province (WP5). In Chapter 7, the stakeholder engagement workshops are briefly described, and the outcomes and implications are summarised. Finally, in Chapter 7, overall conclusions from the work are drawn, and recommendations are made.

1.6 CONCLUSION

This chapter has provided the background to the project and has defined the project aims. It has also outlined the scope of the work and highlighted some limitations applied to ensure the achievement of the project aims. Finally, the approach adopted to tackling the work, namely the delineation of the research into work packages, has been explained.

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CHAPTER 2: DESCRIPTION OF STUDY AREA

2.1 INTRODUCTION

Water is one of the main limiting resources upon which smart, sustainable economic development and investments should be focused (Scholes, 2001; Daly and Farley, 2004; Aronson et al., 2006). Water use in South Africa, given the supply constraints now and in the future, cannot continue to grow at current rates. If it continues, more parts of the country might have to deal with Day Zero conditions such as those experienced in Cape Town in early 2018 (Maxmen, 2018; Wolski, 2018; Booysen et al., 2019; Pascale et al., 2020). This situation is worsened by projected decreases in water availability due to changes in climatic conditions and socio-economic and demographic pressures, which increase the demand for potable water for household use and water required for value-added industries.

This chapter describes the study area and characterises it in terms of climate, water resources and socio-economic conditions. This description provides the background for the research conducted in the study.

2.2 GEOGRAPHICAL LOCATION, FEATURES, AND DISTRICT MUNICIPALITIES OF LIMPOPO

The Limpopo Province is South Africa's northernmost province, which shares borders with Mozambique, Zimbabwe, and Botswana - making it a gateway to Africa (Ladzani and Netserwa 2009). Named after the great Limpopo River that flows along its northern border, this province is rich in wildlife, spectacular scenery, and a wealth of historical and cultural treasures. The province is divided into five district municipalities (Figure 2.1): Waterberg (44 913 km^2), Capricorn (21 705 km^2), Vhembe (25 596 km^2), Mopani (20 011 km^2) and Sekhukhune (13 528 km^2). Each district municipality is, in turn, subdivided into four or five local municipalities (Figure 2.1).

2.3 CLIMATE

South Africa can be clustered according to regions with similar climatic conditions (Blignaut et al., 2009). The climate controls and the topography of the region largely determine the delineation of the country into what can be called different climate regimes. Table 2.1 shows clusters of provinces in South Africa, classified according to the levels of mean annual temperature and total annual rainfall. The cluster, which comprises Gauteng, Mpumalanga, and KwaZulu-Natal, receives the highest annual rainfall (>700mm) on average, while the cluster with the Northern Cape and North-West provinces receives the least rainfall per annum of less than 550mm. The rest of the provinces form the last cluster, which receives annual rainfall ranging from 550mm to 700mm.

According to the Köppen method of climate classification (Köppen, 1900), South Africa can be divided into climate-based regions, i.e. BW: Desert (arid); BS: Steppe (semi-arid); Csa: winter rain with hot summers; Csb: winter rain with cool summers; Cwa: summer rain with hot summers; Cwb: summer rain with cool summers; Cfa: all-year rain with hot summers; and Cfb: all-year rain with cool summers. These climatic regions are shown in Figure 2.2. The Koppen classification approach or a modified version of it (Geiger, 1954; Peel et al., 2007) has been used for South Africa in the past (Engelbrecht and Engelbrecht, 2016; Wichman et al., 2017). This method of classification divides a region based on seasonal precipitation and temperature patterns.

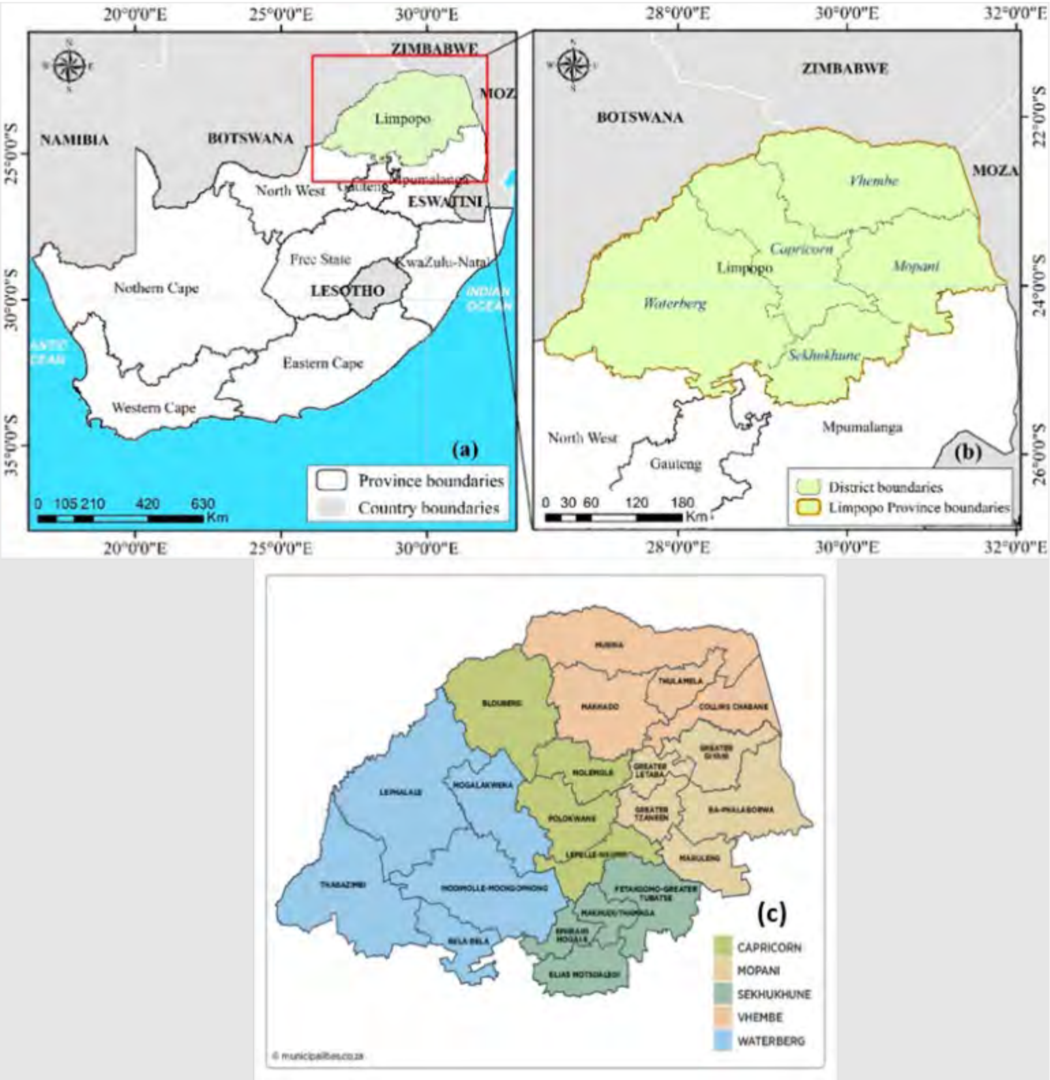

Figure 2.1 Geographical location of the Limpopo Province (a), with its districts (b) and local (c) municipalities shown

Table 2.1 Classification of South Africa's nine provinces based on temperature and rainfall data, with percentage changes between 1970–1979 and 1997–2006 (Blignaut et al., 2009)

Mean annual rainfall by region		Mean annual temperature by region		Final clustering	% Change in rainfall	% Change in temperature
<550 mm	Northern Cape	>25°C	Limpopo	**Hot and arid**		
	North West		North West	Northern Cape	–21.4%	1.7%
			Northern Cape	North West	–11.3%	2.3%
550–700 mm	Western Cape	24.5–25°C	Western Cape	**Hot and semi-arid**		
	Free State		Free State	Limpopo	–1.4%	3.8%
	Limpopo		Mpumalanga			
	Eastern Cape			**Temperate & semi-arid**		
				Western Cape	0.3%	1.5%
>700 mm	Gauteng	<24.5°C	KwaZulu-Natal	Free State	–3.5%	1.7%
	Mpumalanga		Gauteng	Mpumalanga	–5.7%	–2.1%
	KwaZulu-Natal		Eastern Cape			
				Temperate & non-arid		
				Gauteng	–7.1%	4.0%
				Eastern Cape	–4.8%	2.8%
				KwaZulu-Natal	–5.8%	2.1%
				South Africa	**–6.0%**	**2%**

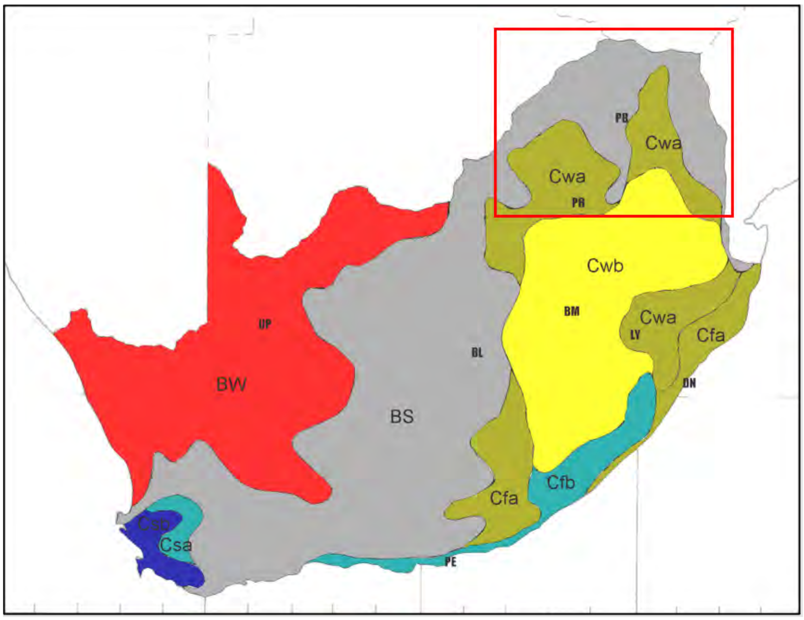

Figure 2.2 The Köppen Climatic Classification of South Africa: BW: Desert (arid), BS: Steppe (semi-arid), Csa: Winter rain with hot summers, Csb: Winter rain with cool summers, Cwa: Summer rain with hot summers, Cwb: Summer rain with cool summers, Cfa: All-year rain with hot summers, Cfb: All-year rain with cool summers. Limpopo is in the northernmost part of South Africa, lying in the Cwa and BS climatic regions (Kruger, 2004). The red box shows the geographical area where the Limpopo Province lies.

Based on an analysis of long-term climate data, the Limpopo Province lies in the Cwa (summer rain with hot summers) and the BS (Semi-arid) climatic regions. Specifically, the province consists mainly of the Cwa on the escarpment and higher-lying regions and BS conditions elsewhere, as shown in Figure 2.2. In the province, the BS region has semi-arid or steppe climatic conditions, while the areas with Cwa climatic conditions have dry winters with at least ten times as much rain in the wettest month of summer as in the driest month of winter. The warmest month in summer has an average temperature of more than 22ºC. Furthermore, the Limpopo Province experiences some of the warmest temperatures in the country and is also projected to have amongst the highest decreases in annual rainfall of all South African provinces in mid- and far-future climate scenarios (IPCC, 2021, Engelbrecht and Engelbrecht, 2016). Semi-arid regions are especially vulnerable to climatic instability and frequent droughts (Oni et al., 2011).

Factoring in vegetation types in the delineation of regions adds more value and is more informative than basing the classification on only climate conditions. It is expected that there should be a relationship between the vegetation biomes in South Africa and the Köppen climate boundaries. Therefore, using this relationship, the South African Weather Service (SAWS) developed a more detailed system of climate region classification. This SAWS vegetation-based delineation of regions in South Africa is presented in Figure 2.3. Using this classification, the climate of Limpopo Province is relatively diverse, consisting of five distinct climate regions. These regions are (1) Northern Arid Bushveld, (2) Central Bushveld, (3) Lowveld Bushveld, (5) Lowveld Mountain Bushveld, and (14) Eastern Mountain Grassland (see Figure 2.3).

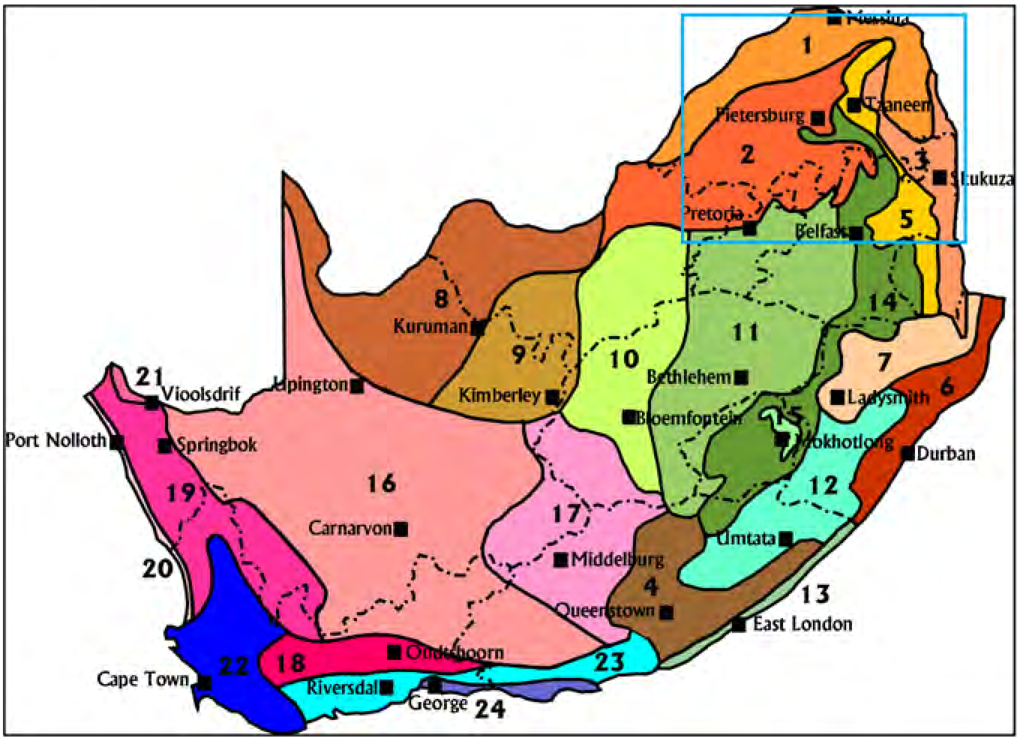

Figure 2.3 The Climatic Regions of South Africa: 1. Northern Arid Bushveld 2. Central Bushveld 3. Lowveld Bushveld 4. South-Eastern Thornveld 5. Lowveld Mountain Bushveld 6. Eastern Coastal Bushveld 7. KwaZulu-Natal Central Bushveld 8. Kalahari Bushveld 9. Kalahari Hardveld Bushveld 10. Dry Highveld Grassland 11. Moist Highveld Grassland 12. Eastern Grassland 13. South-Eastern Coast Grassland 14. Eastern Mountain Grassland 15. Alpine Heathland 16. Great and Upper Karoo 17. Eastern Karoo 18. Little Karoo 19. Western Karoo 20. West Coast 21. North-Western Desert 22. South-Western Cape 23. Southern Cape 24. Southern Cape Forest (Kruger, 2004). The blue box shows the geographical area where the Limpopo Province lies.

There are five climate types that are found within the boundaries of the Limpopo Province. Table 2.2 presents the five district municipalities and the respective climate regions included within their boundaries.

Table 2.2 Limpopo district municipalities and climate types

District Municipality	Climate Regions
Vhembe	Northern Arid Bushveld, Central Bushveld, Lowveld Bushveld, Lowveld Mountain Bushveld
Capricorn	Northern Arid Bushveld, Central Bushveld, Eastern Mountain Grassland
Mopani	Northern Arid Bushveld, Eastern Mountain Grassland, Lowveld Bushveld, Lowveld Mountain Bushveld.
Waterberg	Northern Arid Bushveld, Central Bushveld
Sekhukhune	Central Bushveld, Eastern Mountain Grassland

2.4 WATER RESOURCES

Through the longstanding and active involvement of the Water Research Commission (WRC), the South African water sector is well-supported and receives considerable research and development (R&D) investments (Bhagwan, 2010). With the IPCC assessment reports and published articles noting a decrease in rainfall over most parts of South Africa (Christensen et al., 2007; IPCC, 2013; Nangombe et al., 2018; IPCC 2021), research on water resources in both the present and future is of paramount importance. This is particularly so for millions in rural populations found in KwaZulu-Natal, Limpopo, Eastern Cape, and the Free State (DoA, 2007) where rain-fed agriculture is a mainstay of people's livelihoods (Blignaut et al., 2009). Water is a very important resource in South Africa as noted by the Water Services Act (RSA, 1997) and the National Water Act (RSA, 1998), especially in semi-arid and water-stressed regions like the Limpopo Province where the climate is generally characterized by high temperatures, low rainfall, and high evaporation rates (Blignaut et al., 2009). The Limpopo Province experiences particularly severe conditions, with its annual temperatures being among the highest in the country. The hydrology of the province is dominated by the Limpopo (A) and Olifants (B) primary drainage regions, which drain the entire province and some parts of the neighbouring provinces (RSA, 1998). These regions coincide with the Limpopo and Olifants Water Management Areas and form part of the larger Limpopo River Basin, which encompasses portions of Botswana, South Africa, Zimbabwe, and Mozambique. The boundaries of primary catchments A and B and the river network within them are shown in Figure 2.4, along with the boundaries of the five district municipalities. The boundaries of the secondary catchments are also shown (e.g. A4, B5, B7). There are inter-basin transfers of water into primary catchments A and B from the neighbouring Vaal and Inkomati-Usuthu Water Management Areas (not shown).

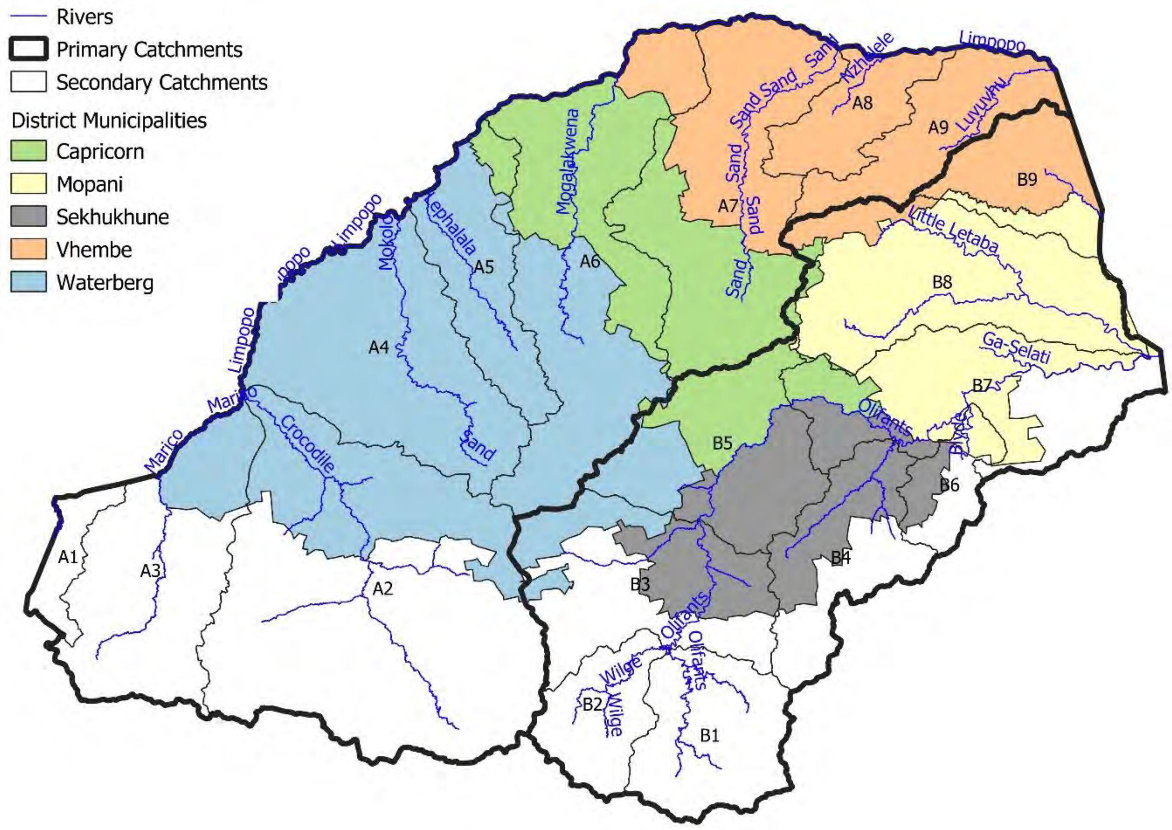

Figure 2.4 Primary and secondary catchments draining the five district municipalities of the Limpopo Province

Due to the fundamental role that water plays in socio-economic activities, the country has invested in the development of large-scale water infrastructure, including dams and transfer schemes. In the Limpopo Province, there are dams of various sizes and uses in each district, as shown in Table 2.3.

Table 2.3 Characteristics of dams in the Limpopo Province (information sourced from DWS (2021) and Bailey and Pitman (2015))

District	Dam	Storage Capacity (10^6 m^3)	River	Water Usage
Vhembe	Albasini	28.2	Luvuvhu	Water supply to Louis Trichardt
	Luphephe	14	Luphephe	Irrigation water supply to the Nwanedzi River catchment
	Nandoni	166.2	Luvhuvhu	Water supply to the villages of ha-Mutoti and ha-Budeli and ha-Mphego
	Nwanedzi	5.2	Nwanedzi	Irrigation, coal mining, domestic water to the Nwanedzi River catchment
	Vondo	30.5	Mutshindudi	Irrigation
	Mutshedzi	2.4	Mutshedzi	Water supply to the Nzhelele River catchment
	Nzhelele	51.3	Nzhelele	Irrigation, coal mining
Capricorn	Glen Alpine	18.9	Mogalakwena	Irrigation supply to Mokgalakwena river catchment, platinum mining
	Flag Boshielo	185.2	Olifants	Potable water supply to Polokwane, Lepelle Nkumpi and Lebowakgomo municipality.
	Houtrivier	6.7	Hout	Water supply for domestic use in Seshego, Ga-Mamadilla and Moletji
Mopani	Dap Naude	2	Broederstroom	Irrigation water supply to Polokwane
	Ebenezer	69.2	Groot-Letaba	Irrigation, water supply to Haenertsburg (Mopani District) and Polokwane Local Municipality.
	Magoebaskloof	4.9	Politsi	
	Middel-Letaba	172	Middel-Letaba	Domestic water supply to Giyani
	Tzaneen	114.3	Groot-Letaba	Domestic water to Polokwane and Tzaneen, irrigation
	Nsami	21.9	Nsama	Tourism
Waterberg	Doorndraai	43.8	Sterk	Domestic and irrigation water supply to the Mogalakwena municipality, platinum mining
	Mokolo	145.8	Mokolo	Water supply to the Matimba Power Station, coal mining, irrigation
	Warmbad	0.6	Buffelspruit	
Sekhukhune	De Hoop	348.7	Steelpoort	Mining, water supply to towns, industries and communities in Sekhukhune
	Rust De Winter	28.2	Elands	Irrigation
	Tonteldoos	0.2	Tonteldoos	

Overall, the major uses of the dams in the five districts of Limpopo include urban water supply, irrigation, and mining activities (Groenewald, 2012; Ololade, 2018). The differences in population sizes, urbanisation, and economic development in the various districts affect the water demand. As a result, water transfer schemes were implemented as a means to address the expanding water demand. For example, the Capricorn District is home to the capital city and economic hub of the Limpopo Province, Polokwane. As a result, it comprises the largest population and highest water demand, hence the development of rural-to-urban water transfer schemes from the Mopani District to the Capricorn District to address water shortages. In Mopani District, there are several main rivers which include the Groot Letaba, Politsi, Broederstroom, Selati, Thabina, and Letsitele Rivers. There are also some tributaries; and most of these rivers flow across the Kruger National Park where they join the Lepelle River (Olifants River) upstream of the Mozambique border (MDM, 2021). The Olifants River is part of the southern boundary of the Mopani District, while the Shingwedzi River is part of the northern boundary (DWAF, 2001).

2.5 SOCIO-ECONOMIC CONTEXT

As is the case in many other regions, the development and general wellbeing of the people of Limpopo Province is strongly based on three main aspects, i.e., environmental, social, and economic aspects. An examination of measures of the quality of life and the standard of living will allow for a perspective to emerge on the socio-economic aspects. The environmental conditions in the Limpopo Province have been detailed in earlier sections of this chapter, which covered the province's climatic conditions and water resources.

On the social aspect, a large number of people in South Africa are living without proper housing, without affordable and sustainable energy sources, with poor quality of education and training, without access to portable water and sanitation, and with poor and inaccessible health services (SSA, 2016). Although South Africa was ranked 40th on the list of 105 countries that are most food secure according to a Global Food Security Index (EIU, 2012), food insecurity and malnutrition are, however, high in some South African provinces with large rural populations such as KwaZulu-Natal, Limpopo, Eastern Cape and the Free State (Department of Agriculture, 2007). A Water Research Commission-funded study also identified the Limpopo Province as one of the poorest provinces in the country (Hendricks et al., 2016). In this study, one of the reasons the Limpopo Province was selected as a study area was due to its socio-economic status. The issues of food insecurity and poverty are intertwined into the same destructive cycle on livelihoods, where poverty is a main cause of food insecurity; and food insecurity plays a big role in poverty levels (Oni et al., 2011).

According to the ‘Reviewed Integrated Development Plan’ document produced by the Mopani Municipality, released in May 2021 (MDM, 2021), the Limpopo Province is the second poorest province in South Africa. The same report notes that around 77 per cent of the population in the Limpopo Province lives below the poverty/income datum line. It is also the most rural province out of the country’s nine provinces, where specifically 89 per cent of its population is rural, and the unemployment rate is 46 per cent (Statistics South Africa, 1996, 2000). Socio-economically at national level, the main significant problems bedevilling South Africa are issues of unemployment (45 per cent) and rural poverty (71 per cent), which consequently bares direct effects on other multifaceted social challenges such as crime, health (e.g. AIDS), income, and even food-security (Aliber, 2002). Since the Limpopo Province is one of the poorest and most rural provinces, the two major problems just mentioned and the consequent social ills are even more widespread and severe in this province compared to other provinces. This makes Limpopo Province an ideal and worthwhile study area to assess the current and future water resources management. For water management to be effective, the socio-economic aspects need to be considered as well, in a systematic manner, especially since most livelihoods in the province are agriculture-based.

Socio-analytic reflections of the people in the Limpopo Province in the form of indices per municipal district are shown in Table 2.4. The literacy level in the Limpopo Province is quite low; amongst the adult population (over 20 years of age in 2016), over 10 per cent have not received any form of schooling. Mopani, Sekhukhune, Vhembe, Capricorn, and Waterberg have 17.1 per cent, 16 per cent, 14.4 per cent, 12.4 per cent, and 7.1per cent of their adult population with no form of schooling, respectively. The districts with the highest number of adult people with no formal schooling are also the districts with the highest unemployment rates. Specifically, Sekhukhune, Mopani, Vhembe, Capricorn, and Waterberg districts have unemployment rates of 50.9 per cent, 39.4 per cent, 38.7 per cent, 37.2 per cent, and 28.1 per cent, respectively. Even though the absolute number of unemployed people has gone down, the percentage of people with no income in some districts like Mopani is still higher than that of the Limpopo Province in general (MDM, 2021). In terms of the dependency ratio, there are no big differences amongst the districts, with all ratios falling between 57 and 65, whereas there is substantial contrast amongst the districts in having piped water inside the house as well as access to flush toilets connected to sewerage. Sekhukhune has the least number of houses with piped water inside, and the least number of flush toilets connected to sewerage, i.e., 4.6 per cent and 5.9 per cent, respectively.

Table 2.4: Socio-economic indices for Limpopo's district municipalities based on household characteristics in terms of some of the Rose and Charlton (2002) categories. The unemployment rate figures are based on the 2011 data, while the rest are based on 2016 data.

Socio-economic factors	Capricorn	Vhembe	Sekhukhune	Waterberg	Mopani
Population size	1 330 436	1 393 949	1 169 762	745 758	1 159 185
Population growth (% per yr)	1.21	1.68	1.88	2.125	1.35
Unemployment rate (%)	37.2	38.7	50.9	28.1	39.4
Higher education (%)	11.4	9.6	6.4	9	8.1
Dependency ratio (per 100)	65	63.8	61	65.4	56.5
No schooling (%)	12.4	14.4	16	7.1	17.1
Average household size	3.5	3.6	4	3.5	3.4
Piped water inside house (%)	12.5	7.4	4.6	24.4	12.8
Flush toilet connected to sewerage (%)	30.4	16	5.9	43.5	14.1

For the economic aspects within the Limpopo Province, the Capricorn district is considered the major economic engine of the province (MDM, 2021). In terms of the main economic sectors in the Limpopo Province, finance contributes 27.6 per cent, 14.6 per cent, and about 12 per cent in Capricorn, Mopani, and Sekhukhune, respectively, whereas trade contributes 17 per cent, 14.6 per cent, and 14 per cent in Sekhukhune, Mopani, and Capricorn, respectively (Table 2.5). Capricorn and Mopani districts have vibrant community services contributing 30.9 per cent and 22.6 per cent to the economy, respectively. Eco-tourism was identified by the Limpopo Provincial Government as the official tourism product of the province (LPG, 1999). Tourism development in rural areas provides numerous opportunities for rural development and economic growth (Mahony and Van Zyl, 2002). On eco-tourism in Limpopo, Mopani District Municipality has a comparative advantage compared to other districts due to its closeness to the world-renowned Kruger National Park, which is an eco-tourism hotspot of international importance (MDM, 2021). This is convenient and a welcome development since Mopani District is the poorest in the province and has the highest percentage of people receiving income below the poverty datum line per month (Ladzani and Netswera, 2009; Gumede, 2010). The district is considered the home of the 'Big Five' largely due to part of the Kruger National Park being located inside the district area.

Table 2.5 Main economic sectors found in Limpopo's district municipalities

District Municipality	Main economic sectors
Capricorn	Community services (30.9%), finance (27.6%), trade (14%), transport (13.2%), manufacturing (4.3%), construction (3.3%), agriculture (3.1%), electricity (2.9%)
Mopani	Mining (30.1%), community services (22.6%), trade (14.6%), finance (14.6%), transport (8.2%), agriculture (3.2%), electricity (2.8%), construction (2%)
Vhembe	Mining, community services, finance
Sekhukhune	Community services, mining (15-20%), trade (17%), financial and business services (10-12%), agriculture (9.7%)
Waterberg	Mining, agriculture, tourism

More detailed socio-economic data for each district of Limpopo may be found in Appendix A.

Limpopo Province is characterised by the predominance of rural and township communities, and is one of South Africa's provinces with the highest amount of water shortages (Matlakala et al., 2023). According to the National Water Services Knowledge System, as of April 2023, the province had a service population of more than 5.9 million people, of which almost a quarter of the service population do not have access to potable water (24 per cent) (https://ws.dws.gov.za/wsks/theme.aspx). Only about half of the population of the province (2.7 million) is served with water. Total system water volume is estimated at about 301.3 million m³/annum (2021), and an average system loss of 168.2 million m³/annum (55.8 per cent) is recorded annually in the province (National Water Services Knowledge System, DWS 2021). There is, therefore, an extensive use of groundwater resources in the province to cater for the gap in water service (Mutileni et al., 2023, Murie et al., 2022), accounting for more than 70 per cent of rural domestic water supply (du Toit., 2012), contributing about 40 per cent of the local water supply and agricultural water use (DWS, 2018).

2.6 CONCLUSION

This chapter has described the study area of Limpopo Province in terms of its climate, water resources, and socio-economic conditions. This description has referenced the five district municipalities and contrasted the characteristics of these. At the extremes of this contrast, Mopani District represents the poorest and most rural part of Limpopo, while Capricorn, as the capital and commercial hub of Limpopo, represents the more developed part of the province. These districts also have different climatic characteristics, with Mopani District having a hotter and wetter climate compared to Capricorn which is drier and less hot.

The description of the study area provides a platform for analysing projected changes in climate and the impact this will have on water resources. Furthermore, the description will aid in exploring the implications of the projected changes on development projects in the province.

Having described the study area in this chapter, the next chapter delves into a detailed analysis of historical rainfall patterns based on measured data collected in the province.

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CHAPTER 3: HISTORICAL RAINFALL ANALYSIS

3.1 INTRODUCTION

In this chapter, a comprehensive analysis of rainfall data measured in the province is presented. This analysis makes use of data that are suitable for the study of long-term variability and trends, including frequencies and scales of droughts, changes, and variability in the intensity of rainfall, and similar analyses. It is noted here that historical temperature analysis is not included in this work as the project focuses on rainfall and associated water management scenarios. However, it follows that the expected general warming of the country, which is already observed and predicted, will exacerbate any drying trends that are found.

3.2 DATA USED IN THE ANALYSIS

3.2.1 The SAWS homogeneous rainfall districts

The availability of rainfall data should be considered in conjunction with the homogeneous rainfall districts, which were developed by SAWS in the 1970s (Kruger and Nxumalo, 2017). Rainfall district data consist of the monthly averages of rainfall of all the SAWS rainfall stations which recorded rainfall during the month. The rainfall districts are presented in Figure 3.1.

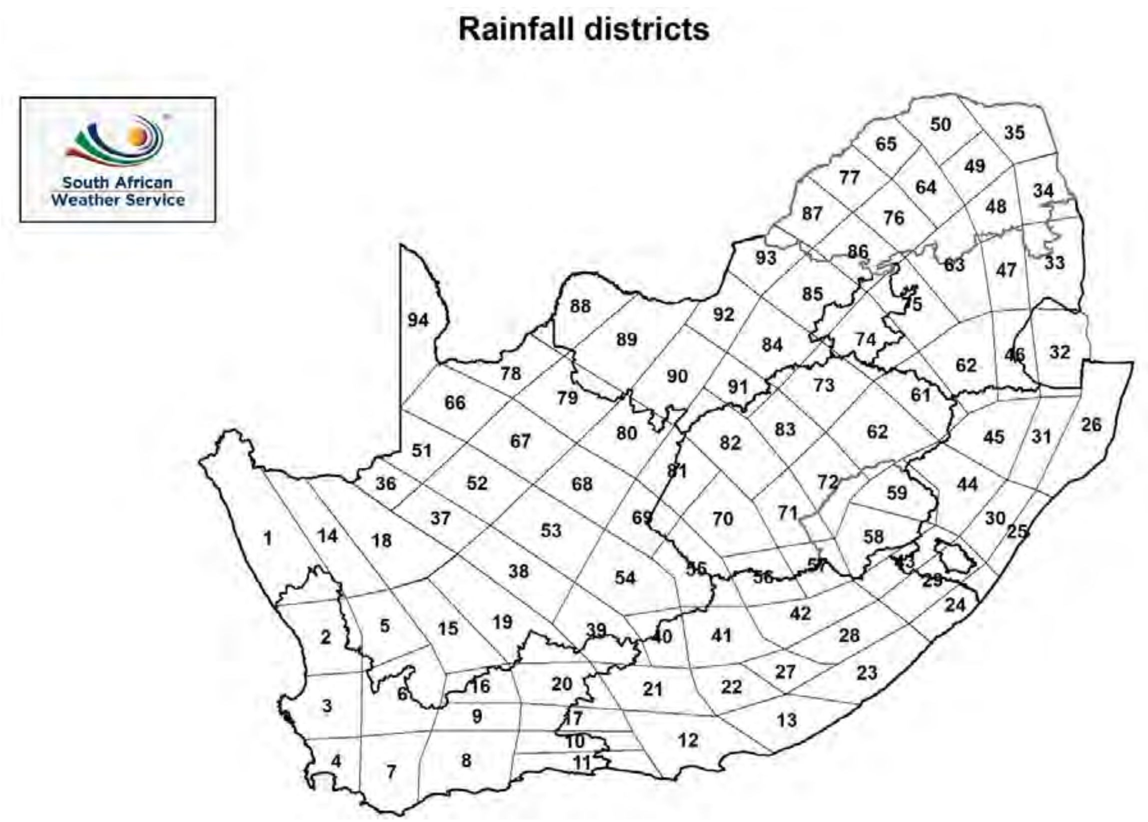

Figure 3.1 The homogeneous rainfall districts of South Africa developed by SAWS

There are 10 rainfall districts in Limpopo Province. The average monthly data of the rainfall districts are used to establish long-term trends and severity of dry episodes, i.e. significant droughts.

3.2.2 Higher-resolution data at station level

Monthly data cannot be used to determine trends in short-term extremes, for which point data of at least a daily resolution is required. Therefore, an audit was done in each of the districts to assess the availability of long-term data at station level. Below is a list of all 54 available rainfall stations with relatively long rainfall data sets, i.e. 30 years or longer, divided into each of the rainfall districts in Limpopo Province (Table 3.1). The name of the station, position, and date the station was opened are listed. It should be noted that those stations with start dates of January 1921 will probably have records stretching further back, but a starting date for analysis had to be selected, also being the start date of available rainfall district data. The starting date for the rainfall district and the station data is, therefore, the same. Also note that most of the stations are still open; therefore, for most stations, the analysis end date will be the date when the actual analysis of the data is done, which is the end of 2021.

3.3 LONG-TERM DROUGHT ANALYSIS

3.3.1 Methodology

It is expected that some parts of the province will become drier in the medium to long-term future, and previous analysis has already shown some signals of drying (Kruger and Nxumalo, 2017). Significant droughts are characterised by one to multi-year rainfall deficits. The magnitudes of the deficits and temporal persistence of below-normal rainfall largely determine the severity of particular droughts.

An approach to determine whether there is a historical tendency towards more frequent drought-like conditions is to apply a drought index to historical time series and determine whether there are significant trends in the drought index values. Here we applied the 12- and 24-month SPI (Standardised Precipitation Index) to the historical monthly rainfall values. The SPI is the most widely used drought index due to its simplicity to apply and the fact that it only requires rainfall data as input. This index is also used by SAWS in its monthly drought bulletin (https://www.weathersa.co.za/Documents/Climate/nr_drought.pdf). The interpretation of the SPI values is presented in Table 3.2 and should be assessed considering the time period over which the index value is calculated. For example, a 12-month SPI value of -1.23 indicates that over the previous year, a moderate drought was experienced, in comparison with the base period of 1991-2020 selected in this analysis.

Table 3.1 Long-term daily rainfall data in Limpopo Province according to rainfall districts (districts as in Figure 3.1)

Rainfall District	Station Name	Latitude	Longitude	Start Date
34	Letaba Mooiplaas	-23.51	31.4	1973/01/12
	Olifantskamp	-24.01	31.74	1973/01/12
	Letaba Mahlangeni	-23.82	31.09	1986/01/10
35	Shingwedzi Vlakteplaas	-22.87	31.22	1983/01/04
	Punda Maria	-22.68	31.02	1924/01/02
	Letaba Woodlands	-23.22	31.21	1983/01/01
	Krugerwildtuin Shangoni ARS	-23.17	30.94	1957/01/11
48	Hans Merensky	-23.79	30.13	1927/01/12
	New Agatha Bos	-23.95	30.13	1940/01/01
	Tubatse Agric	-24.58	30.33	1979/01/11
	Wolkberg	-24.05	30.01	1971/01/12
	Phalaborwa Excellence	-24.18	30.84	1978/01/03
49	Haenertsburg	-23.93	29.93	1921/01/01
	Wood Bush	-23.80	29.97	1921/01/01
	Letaba District	-23.73	30.10	1921/01/01
	Zwartrantjes	-23.23	29.86	1921/01/01
	Palmaryville	-22.99	30.43	1921/01/01
50	Hanglip	-23.02	29.92	1921/01/01
	UNA-ARG	-23.12	29.63	1947/01/07
	MARA POL	-23.09	29.39	1947/01/02
	MARA	-23.08	29.42	1936/01/09
	Vreendeling	-22.96	30.02	1972/01/10
	Platjan Grensbos	-22.47	28.83	1983/01/02
	Pontdrift	-22.22	29.14	1965/01/11
63	Laersdrif Police ARS	-25.38	29.85	1923/01/09
	Mable Hall	-24.97	29.3	1939/01/01
64	Bergzicht	-23.78	29.16	1921/01/01
	Pietersburg-Hosp	-23.89	29.46	1921/01/01
	Kalkfontein	-23.9	29.58	1921/01/01
	Dendron	-23.37	29.33	1971/01/06
	Syferkuil	-23.85	29.72	1948/01/12
65	Tolwe	-23.15	28.55	1969/01/10
76	Naboomspruit	-24.52	28.72	1921/01/01
	Nylsvley	-24.65	28.67	1921/01/01
	Palmer estate	-24.35	29.04	1924/01/03
	Jonkmansdrift	-24.18	28.54	1984/01/08
	Sterkrivier	-24.16	28.74	1979/01/03

Rainfall District	Station Name	Latitude	Longitude	Start Date
	Moorddrift	-24.27	28.95	1921/01/01
	Doornfontein	-24.33	29.07	1926/01/08
	Verdoornsdraai	-23.95	28.63	1941/01/01
	Bakenberg	-23.86	28.75	1986/01/04
	Dorset-Pol	-24.06	28.16	1935/01/06
	Grootgeluk-MYN	-23.66	27.56	1976/01/09
77	Ellisras-Pol	-23.68	27.68	1967/01/09
	Villa Nora-Pol	-23.53	28.13	1921/01/01
	Stockpoort-Pol	-23.42	27.33	1925/01/05
	Leeupoort-Mun	-24.92	27.72	1921/01/01
	Nylstroom-Mun	-24.71	28.42	1949/01/05
86	Rus de Winter-IRR	-25.2	28.61	1953/01/05
	Warmbad Towoomba	-24.9	28.32	1937/01/01
	Rankins Pass-Pol	-24.53	27.91	1921/01/01
	Buffeldoorns ARS	-24.57	27.12	1934/01/03
87	Rooidam	-24.72	27.32	1981/01/11
93	Swartklip Nooitgedacht	-24.89	27.15	1979/01/08

Table 3.2 Standardised Precipitation Index categories

SPI	SPI category
>= 2	Extremely wet
1.50 to 1.99	Severely wet
1.00 to 1.49	Moderately wet
0 to 0.99	Mildly wet
-0.99 to 0	Mild drought
-1.00 to -1.49	Moderate drought
-1.99 to -1.50	Severe drought
<= -2.00	Extreme drought

Significance of trend is determined by Student's t-test, whereby it can be established whether r is significant or not. The following equation was used for the table:

$$r = \frac{t}{\sqrt{n-2+t^2}} \quad [1]$$

Where r = correlation factor test value, t = the value from the t-table corresponding to the 95 per cent level of confidence in this case and n-2 degrees of freedom and n the number of values (years). For a 100-year period, a value of $R^2 > 0.04$ is deemed significant at the 95 per cent level of confidence.

In addition to the SPI the SPEI (Standardised Precipitation-Evapotranspiration Index) is also applied to consider the impact of surface temperature (and, therefore, potential evapotranspiration). The SPEI index is considered to be a more effective index in the estimation of drought severity, but, as it requires temperature data in addition to rainfall data, its use in the determination of drought severity from observed data is limited.

3.3.2 Data considerations

The data that the SPI is applied to is the homogeneous rainfall district data set as developed by SAWS (see delineation in Figure 3.1). This data set consists of the average monthly rainfall totals of all stations that reported in a particular district that is considered homogenous in terms of rainfall. In some instances, this criterion is not fully justifiable, e.g. in areas or regions which are topographically complex, but the number of stations usually makes up for this shortcoming. A total of 13 rainfall district time series were analysed with the SPI drought index, calculated over 12- and 24-month periods. The analysis period covers 1921 to the present. The districts are shown in Figure 3.2.

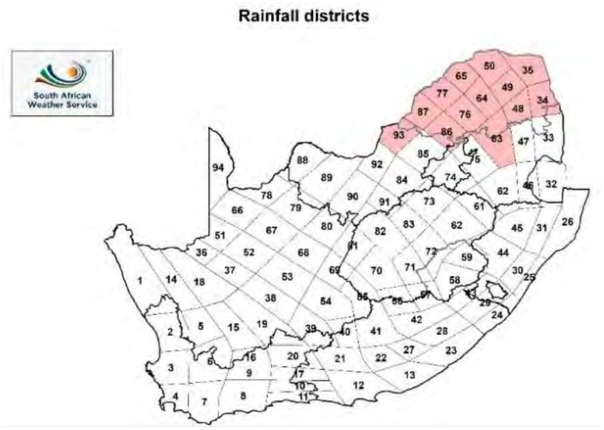

Figure 3.2 The 94 homogeneous rainfall districts in South Africa. The highlighted districts covering Limpopo were analysed for trends in drought.

The SPEI cannot be applied to rainfall district data and, therefore, the application was limited to eight locations with rainfall and surface temperature data with records longer than 30 years. In some cases, a number of nearby stations' time series were combined, but it is assumed that this will not make any significant impact on the determination or estimation of drought conditions. The station details are presented in Table 3.3.

Table 3.3 Long-term daily rainfall and temperature time series in Limpopo Province according to rainfall districts (districts as in Figure 3.1)

Rainfall District	Station Name	Latitude	Longitude	Start Date
35	Musina	-22.27	29.90	1933/10/01
49	Levubu	-23.08	30.28	1964/02/01
	Tshivhasie Tea Estate	-22.96	30.35	1989/12/21
50	Mara	-23.08	29.42	1982/01/11
63	Oudestad	-25.18	29.34	1975/10/04
64	Polokwane	-23.85	29.46	1952/10/01
86	Warmbad Towoomba	-24.90	28.32	1937/01/01
87	Thabazimbi	-24.62	27.40	1983/07/01

3.3.3 Results

A 12-month SPI/SPEI value indicates the relative rainfall conditions over the previous year, compared to all years in the base period of 1991-2020. A 24-month SPI value indicates the same but for the preceding two years. Figures 3.3 to 3.15 present the 12- and 24-month SPI graphs for rainfall districts 34, 35, 48, 49, 50, 63, 64, 65, 76, 77, 76, 87, and 93, respectively. In these plots, the black lines indicate the linear trend over the analysis period (1921 to 2021). Blue shading indicates wet conditions and red shading indicates dry conditions.

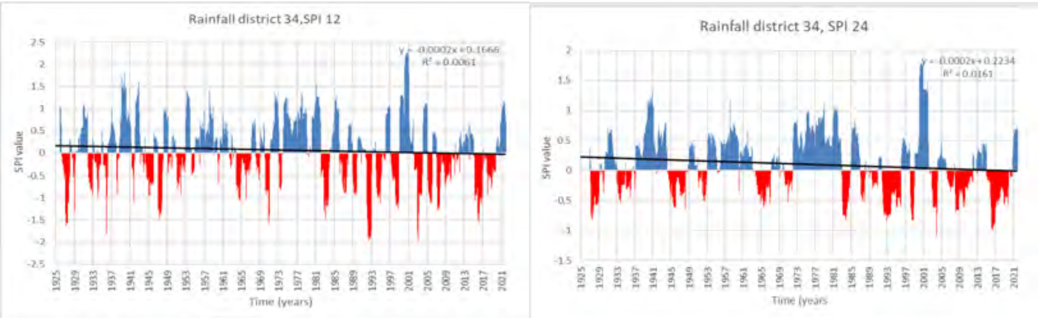

Figure 3.3 Drought analysis for Homogeneous Rainfall District 34 over 12 (left) and 24 (right) month periods

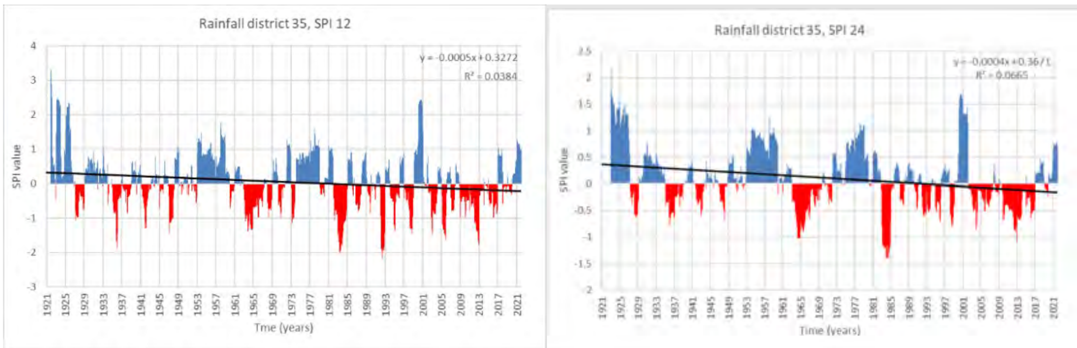

Figure 3.4 Drought analysis for Homogeneous Rainfall District 35 over 12 (left) and 24 (right) month periods

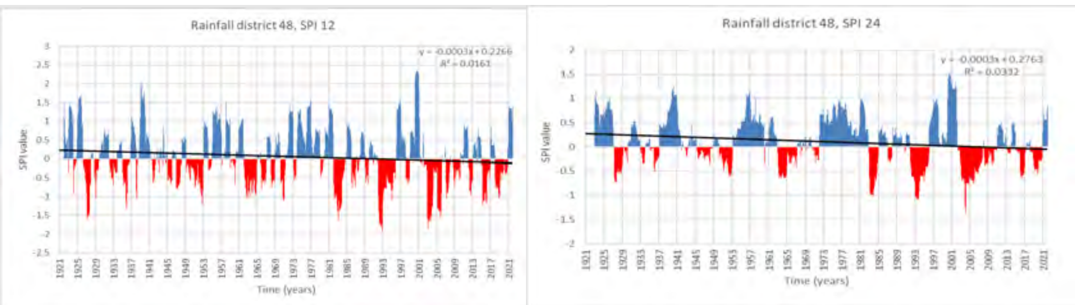

Figure 3.5 Drought analysis for Homogeneous Rainfall District 48, over 12 (left) and 24 (right) month periods

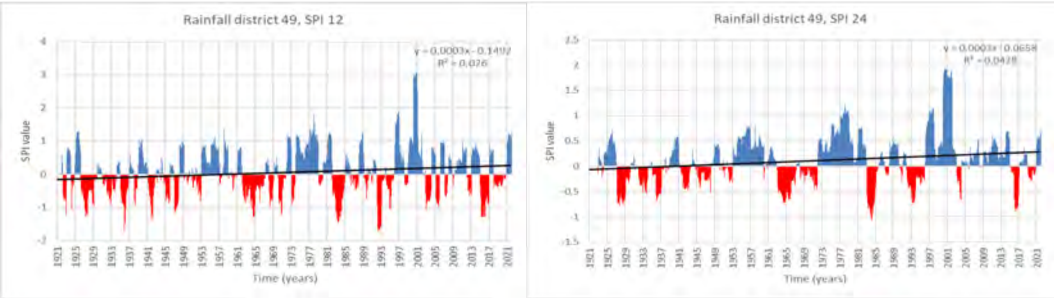

Figure 3.6 Drought analysis for Homogeneous Rainfall District 49 over 12 (left) and 24 (right) month periods

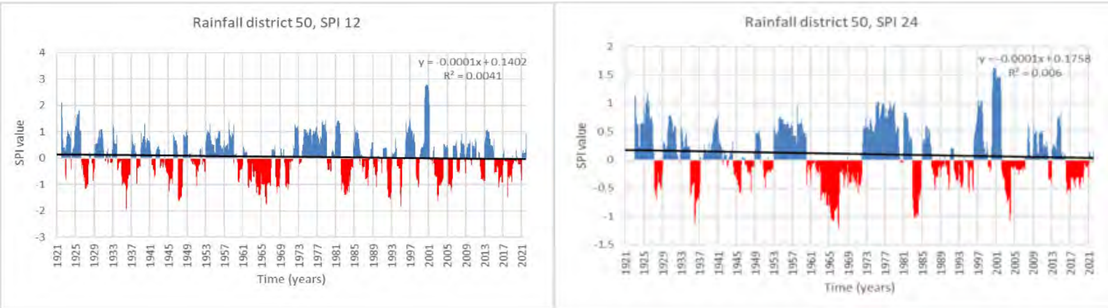

Figure 3.7 Drought analysis for Homogeneous Rainfall District 50 over 12 (left) and 24 (right) month periods

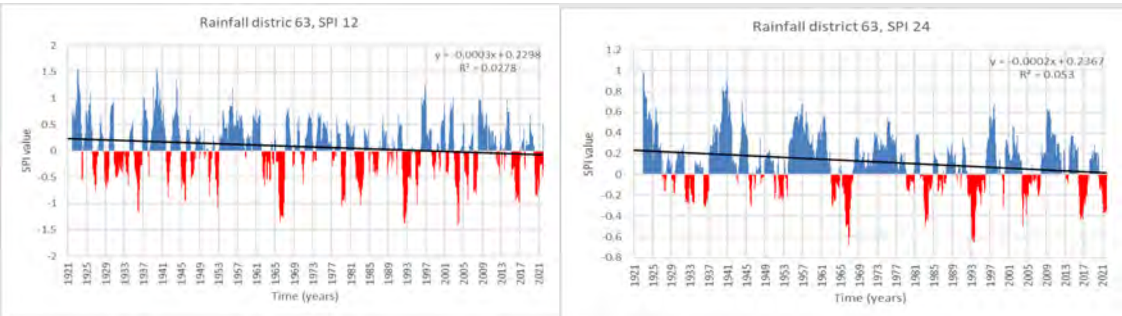

Figure 3.8 Drought analysis for Homogeneous Rainfall District 63 over 12 (left) and 24 (right) month periods

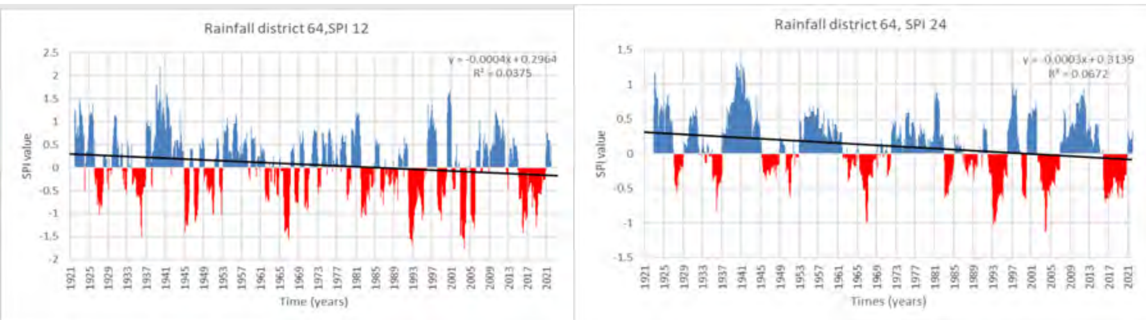

Figure 3.9 Drought analysis for Homogeneous Rainfall District 64 over 12 (left) and 24 (right) month periods

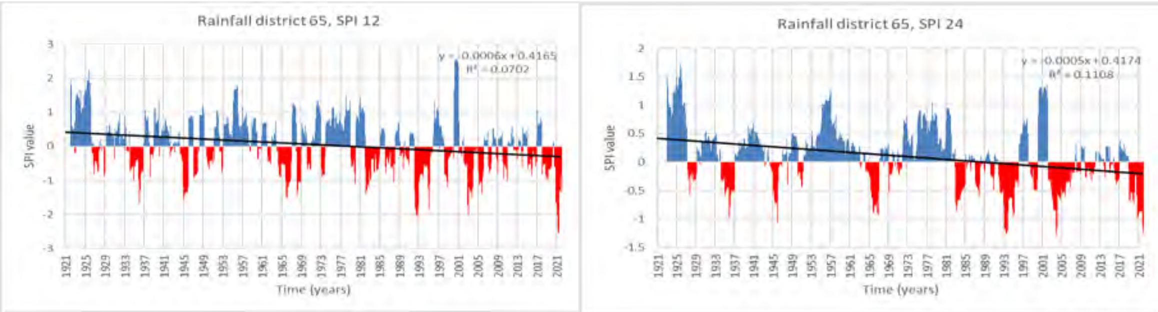

Figure 3.10 Drought analysis for Homogeneous Rainfall District 65 over 12 (left) and 24 (right) month periods

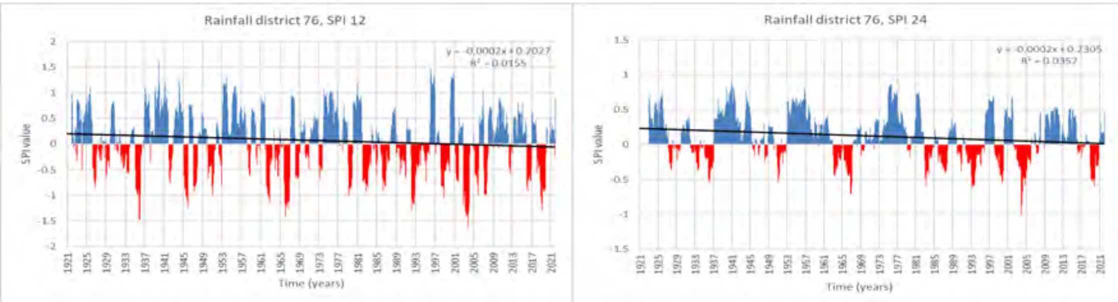

Figure 3.11 Drought analysis for Homogeneous Rainfall District 76 over 12 (left) and 24 (right) month periods

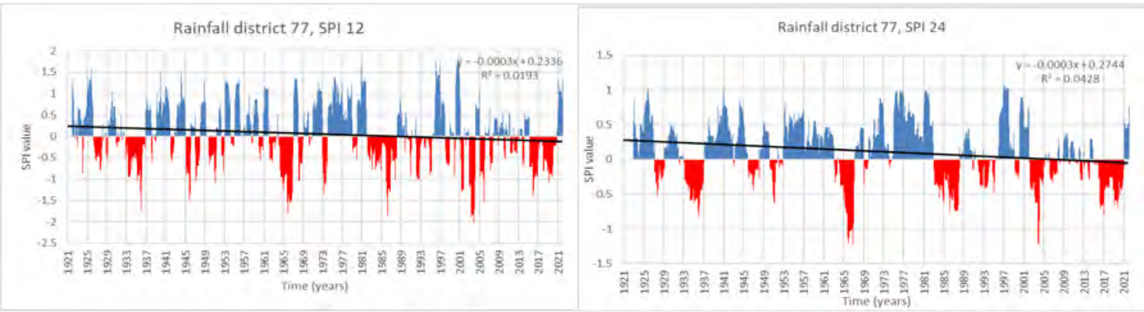

Figure 3.12 Drought analysis for Homogeneous Rainfall District 77 over 12 (left) and 24 (right) month periods

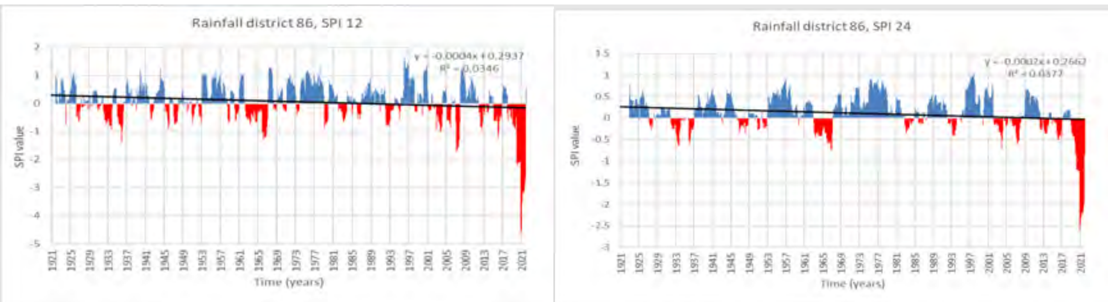

Figure 3.13 Drought analysis for Homogeneous Rainfall District 86 over 12 (left) and 24 (right) month periods

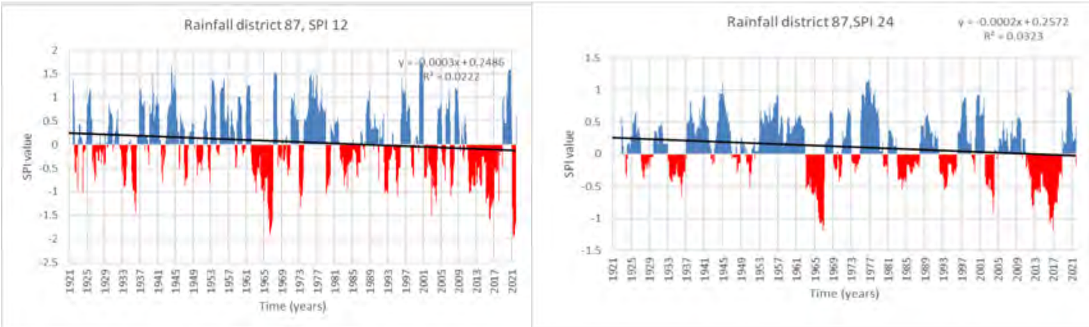

Figure 3.14 Drought analysis for Homogeneous Rainfall District 87 over 12 (left) and 24 (right) month periods

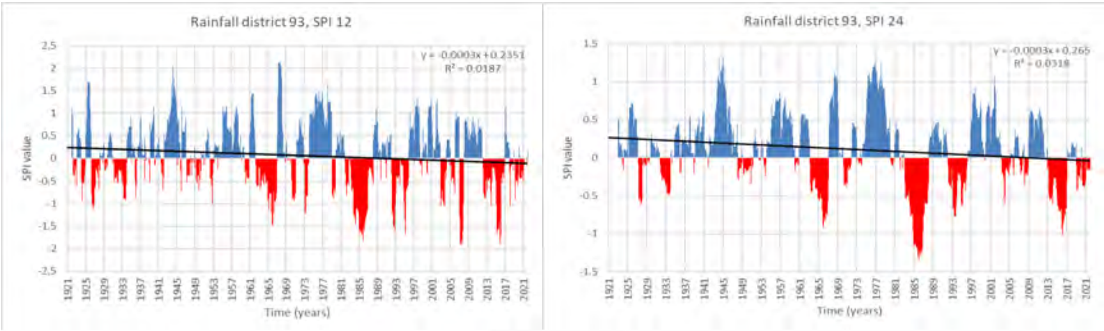

Figure 3.15 Drought analysis for Homogeneous Rainfall District 93 over 12 (left) and 24 (right) month periods

Except for Rainfall District 49 and 50 in the central and northern parts, a decreasing trend is evident at all the districts at both time scales, which comprises most of the province. However, confidence in long-term trends in the climate is usually established at the 5 per cent level. Longer-term droughts seem to become more prevalent, with 24-month SPI negative trends showing statistical significance for Districts 35, 63, 64, 65, and 77 (shaded in Figure 3.16). For District 65 trends in the 12-month SPI are also significant.

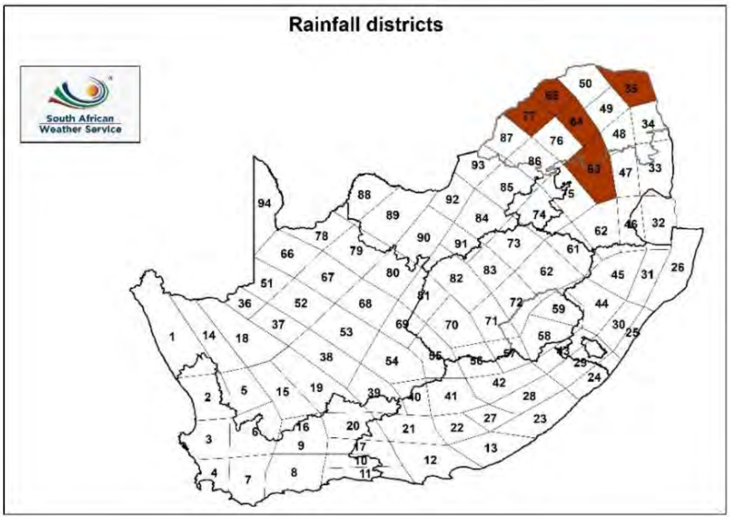

Figure 3.16 Homogeneous rainfall districts over Limpopo Province showing significantly negative trends in 24-month SPI drought index values over the period 1921–2021

Examining the results from the rainfall districts indicates that the Capricorn District Municipality (i.e. Rainfall Districts 64 and 65) has experienced gradual drying over the last century, but the Mopani District Municipality (DM) has not significantly (Rainfall Districts 34 and 48). However, the evaluation of climatological long-term trends, especially rainfall, is highly dependent on the period of analysis. The 24-month SPI analysis for Rainfall Districts 34 and 48 indicates significant drying over the last 50 years, starting in 1971 (the analysis for District 48 is presented in Figure 3.17). This is because of the periodic behaviour that rainfall exhibited until the turn of the last century. Starting the analysis at the beginning of a wet 'cycle', tends to produce results which indicate significant drying, which might be a spurious result. Applying the same period to all the districts for the 24-month SPI shows that over the last 50 years, a large part of the Capricorn DM, as well as the Mopani DM, experienced significant negative trends in the 24-month SPI (Figure 3.18), pointing to a higher likelihood of extended dry conditions.

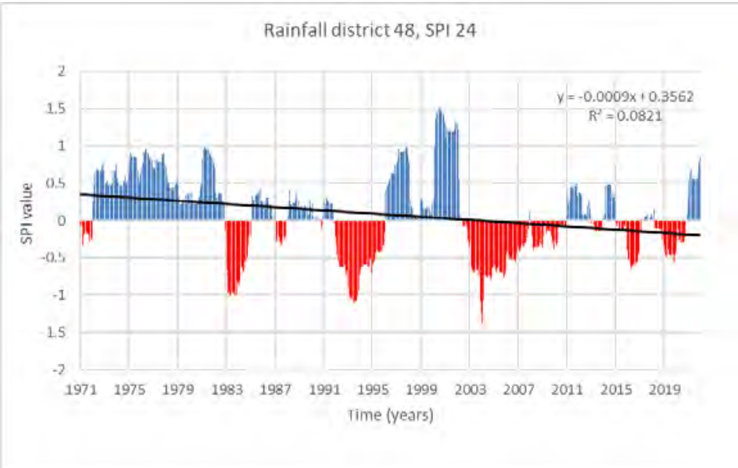

Figure 3.17 Drought analysis for Homogeneous Rainfall District 48 over 24 months. The black line indicates the linear trend over the analysis period (1971 to 2021).

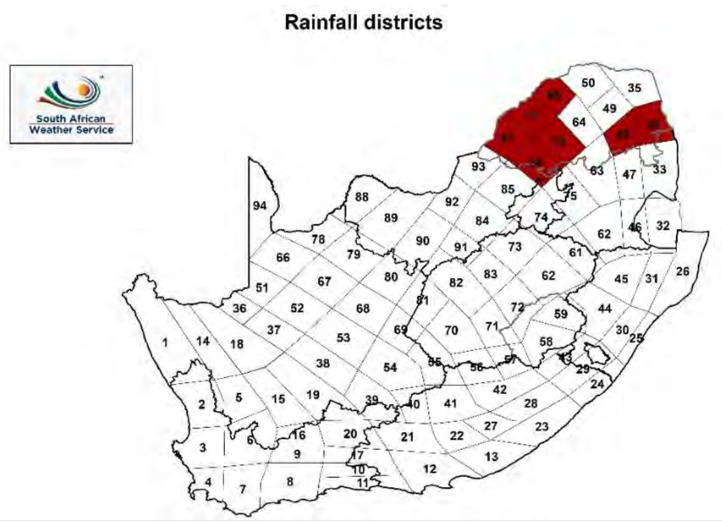

Figure 3.18 Homogeneous rainfall districts over Limpopo Province showing significantly negative trends in 24-month SPI drought index values over the period 1971–2021

From the above results, one can conclude with high confidence that there are signs of general drying in the province over the very long term, particularly over the Capricorn District Municipality. However, over the last 50 years, drying signals have also become evident in the Mopani District Municipality.

The SPEI index analysis can provide indications of whether the drought trends are more severe than the SPI analysis indicates. Figures 3.19 to 3.26 present the 12- and 24-month SPEI trends for the stations in numerical (station number) order as listed in Table 3.3. As before, the black line in the plots indicates the linear trend over the analysis period (1921 to 2021). Blue and red shading indicates wet and dry conditions, respectively.

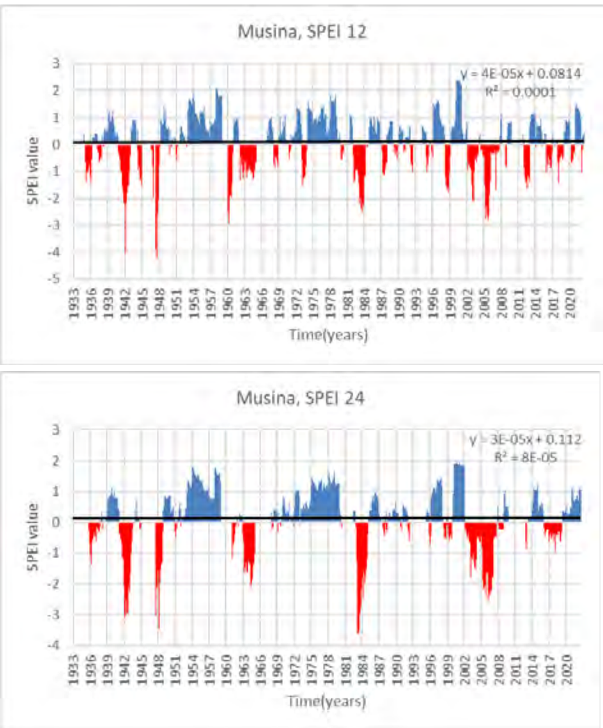

Figure 3.19 SPEI drought analysis for Musina (Rainfall District 35) over 12 (left) and 24 (right) month periods

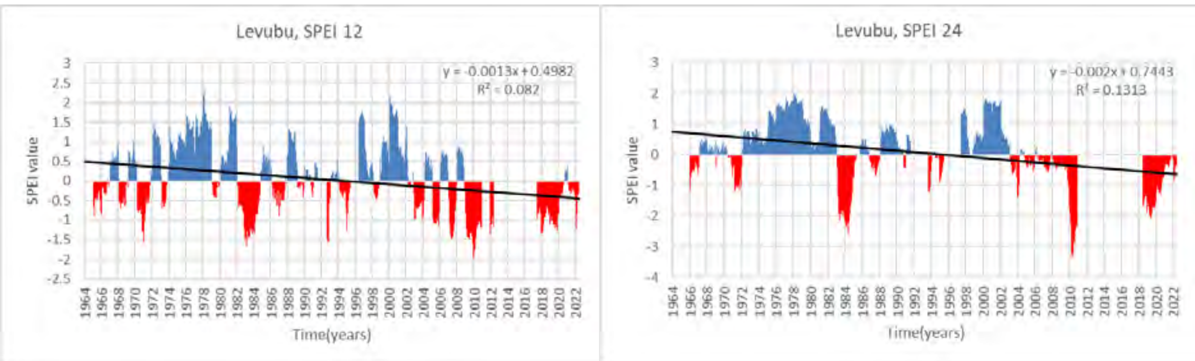

Figure 3.20 SPEI drought analysis for Levubu (Rainfall District 49), over 12 (left) and 24 (right) month periods

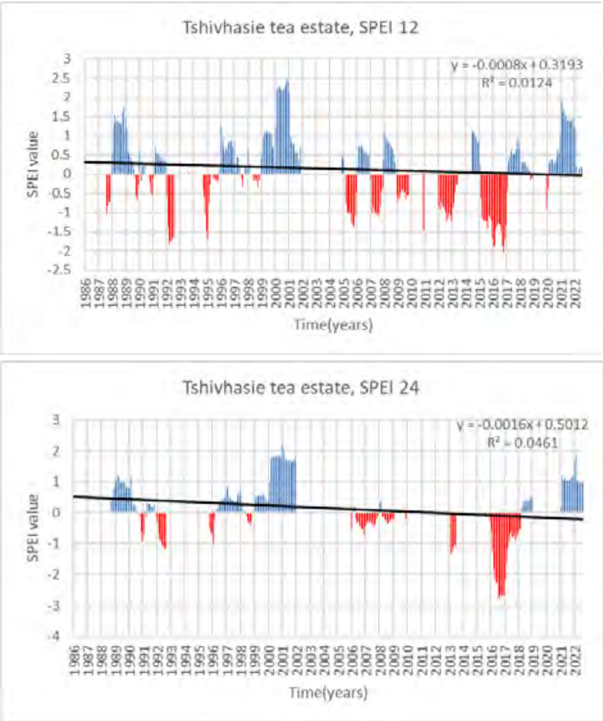

Figure 3.21 SPEI drought analysis for Tshivhasie Tea Estate (Rainfall District 49) over 12 (left) and 24 (right) month periods

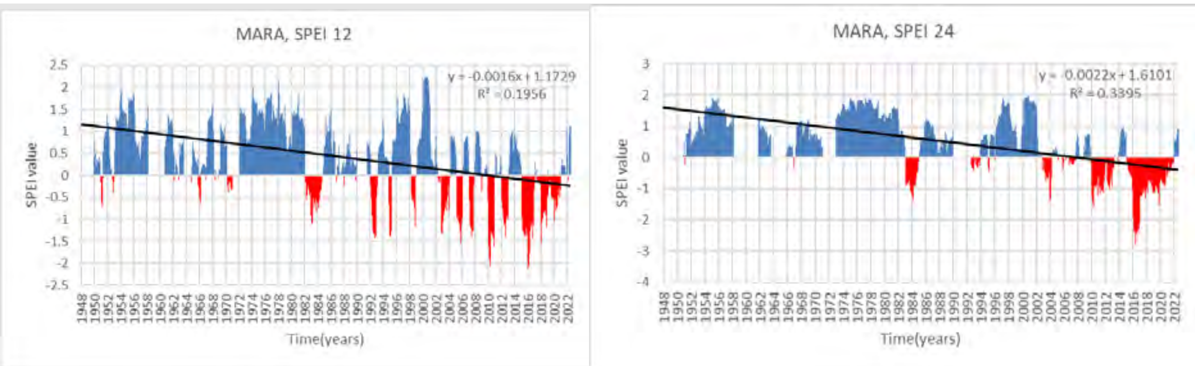

Figure 3.22 SPEI drought analysis for Mara (Rainfall District 50) over 12 (left) and 24 (right) month periods

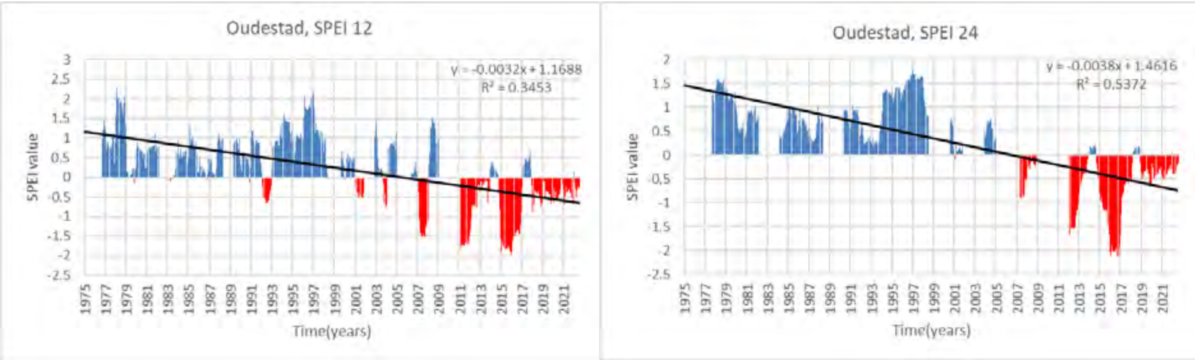

Figure 3.23 SPEI drought analysis for Oudestad (Rainfall District 63) over 12 (left) and 24 (right) month periods

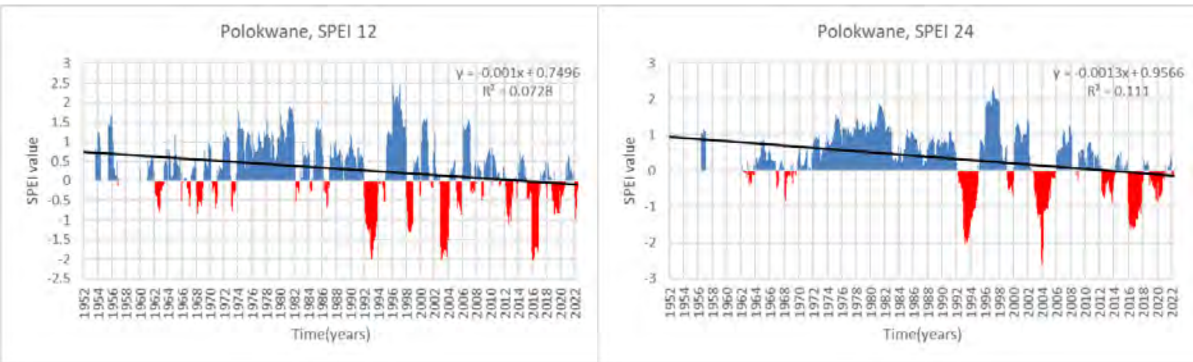

Figure 3.24 SPEI drought analysis for Polokwane (Rainfall District 64) over 12 (left) and 24 (right) month periods

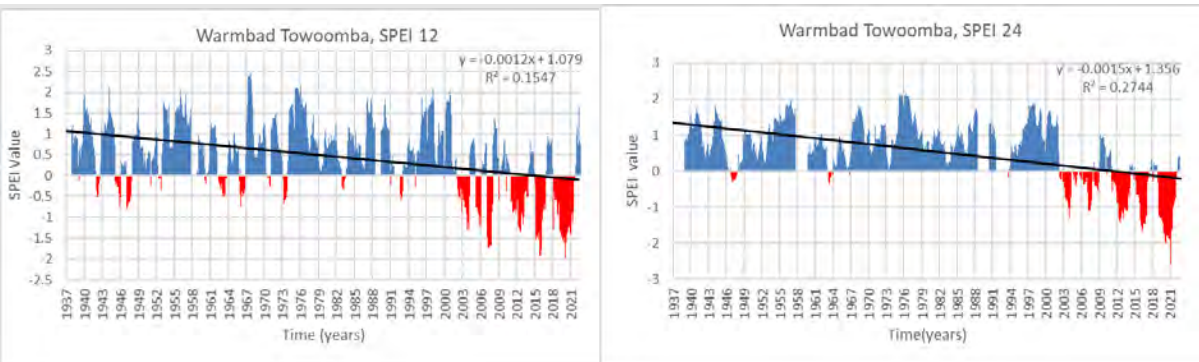

Figure 3.25 SPEI drought analysis for Warmbad Towoomba (Rainfall District 86) over 12 (left) and 24 (right) month periods

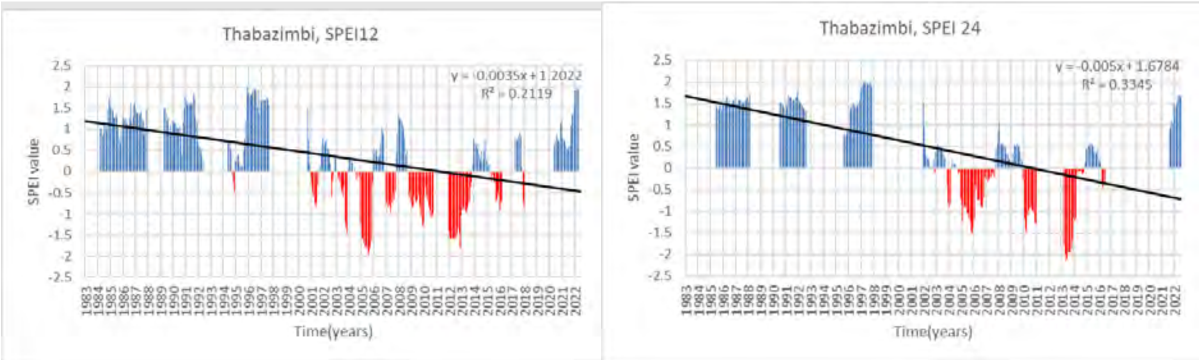

Figure 3.26 SPEI drought analysis for Thabazimbi (Rainfall District 87) over 12 (left) and 24 (right) month periods

Regarding the results of the SPEI analysis, it is critical to take the analysis periods into account. For Musina (Rainfall District 35) in the far north, the analysis from 1933 can be comparable to the SPI rainfall district analysis from 1921 onwards. Interestingly, and contrary to what is expected due to the general warming trend across South Africa, there is no evidence of significant trends in the SPEI, while the 24-month SPI trend showed significant drying in the district. These contradictory results illustrate how critical the analysis period is, as the decade of the 1920s, which was not included in the SPEI analysis, was generally wet across the district.

For Levubu and Tshivhasie Tea Estate in Rainfall District 49 in the north-east, the analysis spans from 1964 and 1986, respectively. The SPI Rainfall District analyses (Figure 3.6) showed no significant trend. However, for Levubu, there is a significant negative trend for the 24-month SPEI analysis (Figure 3.20). The relatively short period for Tshivhasie Tea Estate exhibits no significance in trend (Figure 3.21).

The SPI trends for Rainfall District 50 are not statistically significant. However, the SPEI analysis for District 50 (1948-present) shows a significantly negative trend with relatively wetter conditions up to around 2000, and drier thereafter (Figure 3.22). Oudestad (Rainfall District 63 in the south) essentially shows a similar trend pattern (Figure 3.23).

Polokwane (Rainfall District 64) shows significantly negative trends for the SPEI analysis period from 1952 (Figure 3.24), which confirms the results of the SPI analysis since 1921.

Warmbad Towoomba in the far south also experienced relatively dry conditions during recent decades, with significantly negative trends in the SPEI analysis from 1937 (Figure 3.25). Thabazimbi in the south-west did not experience these dry conditions (Figure 3.26). Nevertheless, the SPEI analysis from 1983 showed significantly negative trends due to a prolonged dry period from 2000 to 2015.

From the SPEI analysis of individual stations, it is evident that recent decades were relatively dry, especially in the central and southern parts of the province. Depending on the analysis period, these dry conditions caused a drying signal in the long-term rainfall patterns. The results largely mirror those of the SPI analysis, which indicated significant drying over a large part of the province over different time scales.

As the SPEI takes surface temperature and thus evapotranspiration into account, in addition to rainfall, one would expect that recent dry conditions would result in the SPEI indicating more severe conditions when compared to the SPI due to the general long-term increase in surface temperature across South

Africa. Except for Rainfall District 86, this is indeed the case, with SPI reaching negative values between -1 and -1.5 in the recent past, but with SPEI reaching values lower than -2 for some stations, especially in the case of the 24-month SPEI index. These results point to an expectation of an increased likelihood of severe drought due to a general increase in surface temperature, the effects of which would be exacerbated by dry conditions.

3.4 ANALYSIS OF RAINFALL EXTREMES

3.4.1 Methodology

In most historical climatological analyses, the basis of the evaluation of trends in extremes is the WMO-developed extreme indices developed by the Expert Team on Climate Change Detection and Indices (ETCCDI). The extremes are divided into surface temperature and precipitation extremes. As the focus of this project is on rainfall, the details of the relevant precipitation indices are presented in Table 3.4. The first index is *prcptot*. The trend of this index provides information on long-term change in the annual total precipitation on wet days, i.e. when the daily precipitation is >= 1 mm. Trends in *prcptot* should, therefore, reflect the trends in the SPI analysis in Section 3.3.

Table 3.4 List of relevant ETCCDI indices utilized in the assessment of precipitation trends (Kruger and Nxumalo, 2017)

Index	Description	Unit
prcptot	Annual total precipitation in wet days, i.e., days with precipitation≥1 mm	mm
r95p	Annual total precipitation from daily precipitation > 95th percentile	mm
r99p	Annual total precipitation from daily precipitation > 99th percentile	mm
rx1day	Annual maximum 1-day precipitation	mm
r10mm	Annual count of days when precipitation ≥ 10mm	days
r20mm	Annual count of days when precipitation ≥ 20mm	days
r25mm	Annual count of days when precipitation ≥ 25mm	days
SDII	Simple Daily Intensity Index, annual mean of daily precipitation intensity	mm
CWD	Annual maximum length of wet spell, maximum number of consecutive days with precipitation ≥ 1mm	days
CDD	Annual maximum length of dry spell, maximum number of consecutive days with precipitation < 1mm	days

The *r95p* and *r99p* indices are the annual totals from daily values greater than the 95th and 99th percentile (based on the 1991-2020 period). The trends in these indices reflect whether precipitation is derived from more extreme daily rainfall events.

The *rx1day* precipitation is the annual maximum daily precipitation. This index is important for general return period estimations since these statistics are usually based on the annual maximum values. An increase in *rx1day* will, in most cases, lead to an increase in the maximum daily rainfall values to be expected over a specific period.

The indices *r10mm*, *r20mm* and *r25mm* indicate the number of days per year with rainfall equal to or above the specified thresholds.

SDII indicates the mean rainfall on a daily basis per year. An increase in *SDII* will indicate that, in general, more rainfall can be expected on a rainy day, i.e. the intensity of daily rainfall increases.

CWD indicates the longest wet spell, i.e. the largest number of consecutive days with rainfall >= 1 mm. *CDD* is the annual maximum length of dry days. In the Limpopo Province under study, the *CDD* will always fall in the winter months, and will indicate the longest period in winter when no daily rain >= 1mm has been recorded.

3.4.2 Results per homogeneous rainfall district

The extreme precipitation indices were evaluated per rainfall district using the station data outlined in Table 3.1. Selected plots of these indices are presented below per rainfall district. Trend statistics for all indices and stations can be found in Appendix B.

Rainfall District 34 (extreme Eastern Limpopo)

Three rainfall stations were selected for analysis, i.e. Letaba Mahlangeni (1987-2017), Letaba Mooiplaas (1974-2020), and Olifantskamp (1974-2021), all situated in the Kruger National Park. The *prcptot* index shows decreasing trends for all stations but none are statistically significant. Therefore, one can state that over the very long-term, there is a decreasing trend in rainfall (according to the SPI analysis), but not so in the recent 40 to 50 years. Figure 3.27 presents the trend in *prcptot* for Olifantskamp and reflects no significant linear trend.

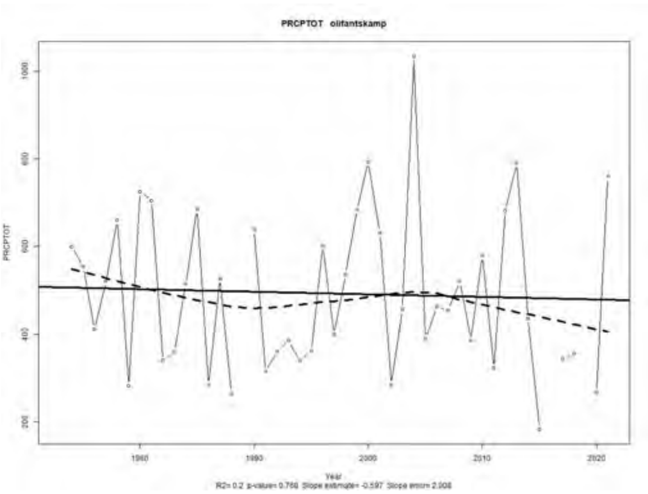

Figure 3.27 Trend in *prcptot* for Olifantskamp (1974-2021)

Trends in *r95p and r99p* show whether precipitation is derived from more extreme daily rainfall events. All stations show increases over their recording periods, but not at significant levels. Trends in *rx1day* also show increasing trends but not at a significant level.

Trends in daily rainfall above the specific thresholds *r10mm*, *r20mm*, and *r25mm* show mostly decreasing non-significant trends. Rainfall above these thresholds is not unusual and, therefore, this could be why these trends reflect the general rainfall trends.

SDII shows non-significant increasing and decreasing trends. *CWD* shows almost no or non-significant negative trends.

CDD shows non-significant increasing trends, reflecting the general decline in *prcptot*, but these trends are also not significant.

Rainfall District 35 (extreme north-east of Limpopo)

Four rainfall stations were selected for analysis, i.e. Krugerwildtuin Shangoni ARS (1958-2021), Letaba Woodlands (1983-2021), Punda Maria (1925-2021), and Shingwedzi Vlakteplaas (1984-2021), all situated in the Kruger National Park. The *prcptot* index shows that the longer-term stations have decreasing trends with none being statistically significant, while the shorter-term stations show essentially no trend. Therefore, one can state that over the very long term, there is a decreasing trend in rainfall (mostly due to high rainfall in the 1970s), but not so in the more recent decades. Figure 3.28 presents the trend in *prcptot* for Punda Maria, reflecting a decreasing, but non-significant linear trend.

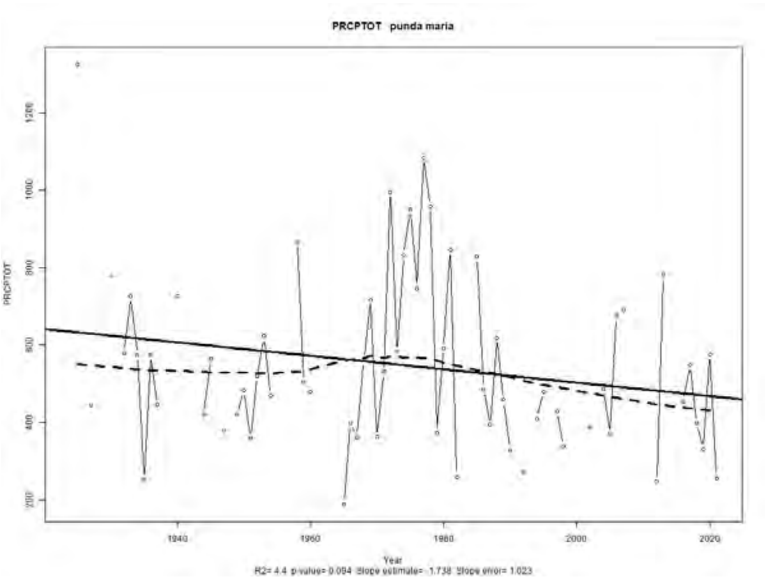

Figure 3.28 Trend in *prcptot* for Punda Maria (1925-2021)

Trends in *r95p and r99p* show whether precipitation is derived from more extreme daily rainfall events. Long-term stations show decreasing trends, while there is almost no trend for the shorter-term stations. Trends in *rx1day* also show decreases or increases, but the trends are not significant. Trends in daily rainfall above the specific thresholds *r10mm*, *r20mm*, and *r25mm* (Figure 3.29) show mostly decreasing non-significant trends. Rainfall above these thresholds is not unusual, and, therefore, this could be why these trends reflect the general rainfall trends.

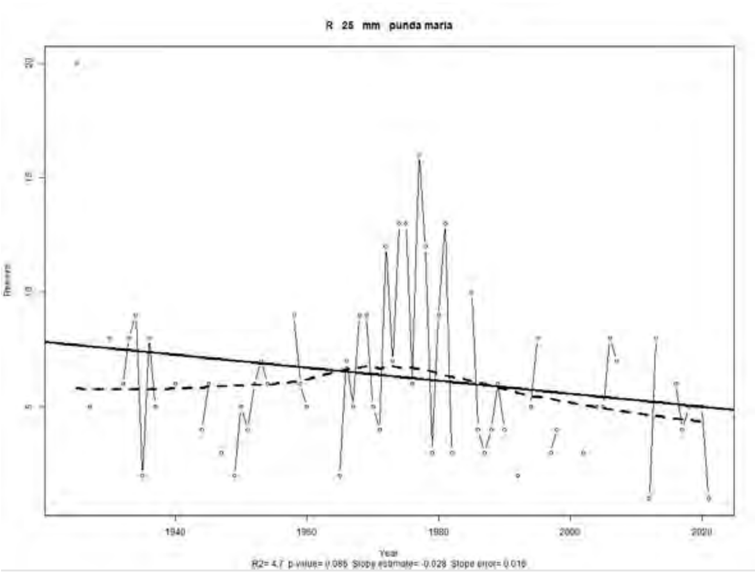

Figure 3.29 Trend in *r25mm* for Punda Maria (1925-2021)

SDII shows non-significant increasing and decreasing trends, with the short-term stations showing increases. *CWD* shows almost no or non-significant negative trends. *CDD* shows increasing trends, reflecting the general decline in *prcptot* over the long term. Most of these trends are not significant, except for Shingwedzi Vlakteplaas (presented in Figure 3.30) which experienced a significantly positive trend. This signals that during the last 40 years, the dry period length has probably increased in the region.

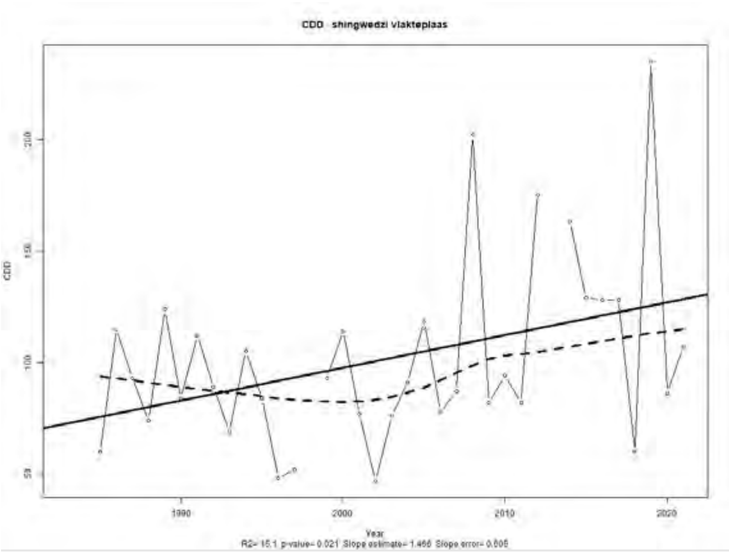

Figure 3.30 Trend in *CDD* for Shingwedzi Vlakteplaas (1984-2021)

Rainfall District 48 (South-Eastern Limpopo)

Five rainfall stations were selected for the analyses, i.e. Hans Merensky (1927-2021), New Agatha (1940-2021), Tubatse (1979-2021), Wolkberg (1971-2021), and Phalaborwa Excellence (1978–2021). The *prcptot* index shows no clear trend for most stations. Therefore, one can state that in this district, the total rainfall received has remained fairly consistent historically.

Trends in *r95p* and *r99p* show whether precipitation is derived from more extreme daily rainfall events. Long-term stations show decreasing trends, while there is almost no trend for the shorter-term stations, and none are statistically significant. The same applies to *rx1day* with no significant trends.

Trends in daily rainfall above the specific thresholds *r10mm*, *r20mm*, and *r25mm* show mostly decreasing but non-significant trends. *SDII* shows non-significant increasing and decreasing trends, but a significant increase at New Agatha. This is due to very low values close to the start of the time series and can be indicative of data problems (underreporting of rainfall). *CWD* shows almost no or non-significant negative trends. *CDD* shows positive, but non-significant trends for the shorter-term stations. However, as with District 35, this signals that during the last 40 years, the dry period length has probably increased in some parts. Figure 3.31 presents the trend in *CDD* for Tubatse.

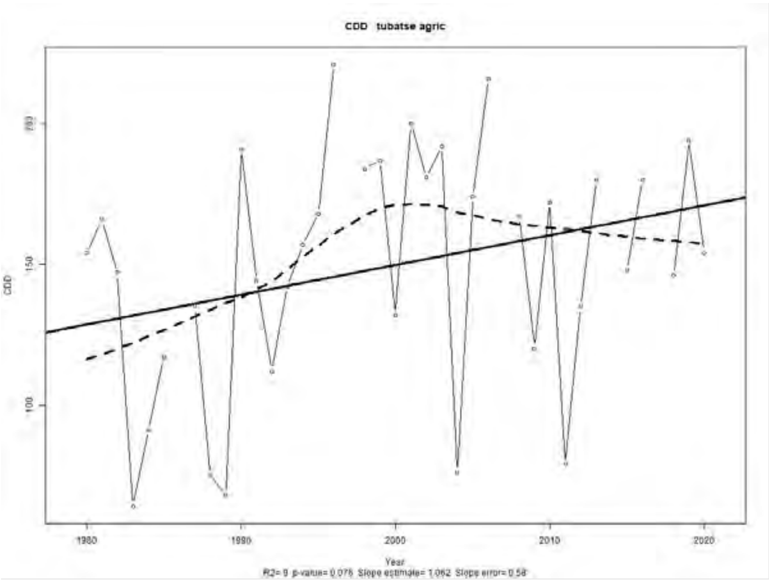

Figure 3.31 Trend in *CDD* for Tubatse (1979-2021)

Rainfall District 49 (Central/Eastern Limpopo)

Five rainfall stations were selected for analysis, i.e. Haenertsburg (1921-2021), Wood Bush (1921-2021), Letaba District (1921-2021), Zwartrantjes (1921-2021), and Palmaryville (1921-2021). All these stations are situated in the Letaba District and usually receive relatively high rainfall, being situated on the escarpment. The *prcptot* index shows negative trends for most stations, except Zwartrantjes, with Palmaryville significant. Therefore, one can state that in this district the total rainfall received is generally less over the long-term period. Figure 3.32 presents the trend in prcptot for Palmaryville.

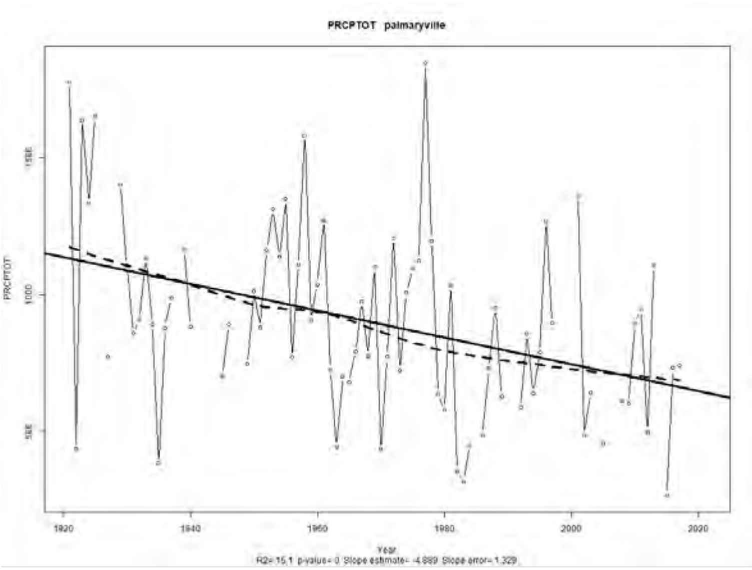

Figure 3.32 Trend in *prcptot* for Palmaryville (1921-2021)

Trends in *r95p* and *r99p* show whether precipitation is derived from more extreme daily rainfall events. The long-term stations show mostly increases, but are non-significant. The same applies to *rx1day* with no significant trends.

Trends in daily rainfall above the specific thresholds *r10mm*, *r20mm*, and *r25mm* show mostly decreasing trends and are mostly significant, except for Zwartrandjes. Figure 3.33 presents the trend in *r10mm* for Haenertsburg. These trends reflect the general decrease in annual rainfall totals and imply that, in general, significant rainfall events have decreased.

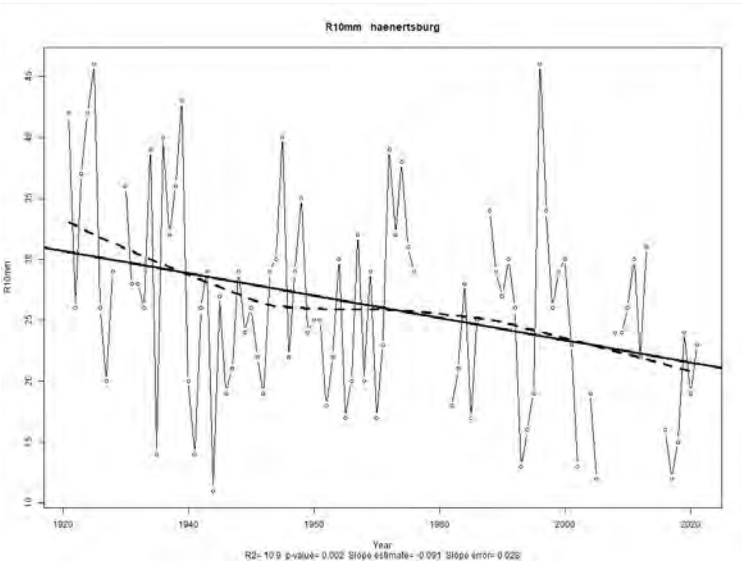

Figure 3.33 Trend in *r10mm* for Haenertsburg (1921-2021)

SDII shows mostly decreases and is significant for Wood Bush (Figure 3.34). *CWD* shows significantly negative trends, as indicated in Figure 3.35 for Haenertsburg.

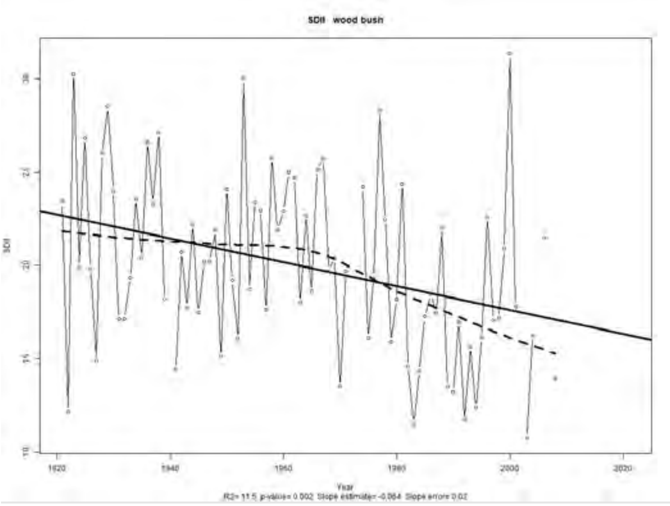

Figure 3.34 Trend in *SDII* for Wood Bush (1921-2006)

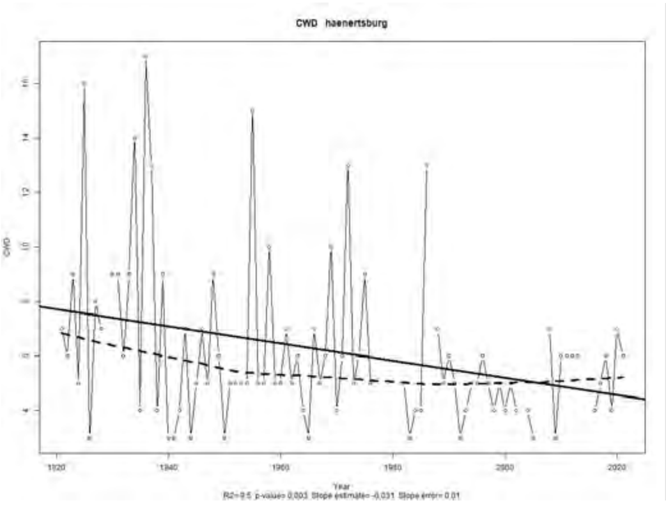

Figure 3.35 Trend in *CWD* for Haenertsburg (1921-2021)

CDD shows mainly negative trends and is significant for Letaba District (Figure 3.36). This indicates that the winter dry period has reduced significantly in some places.

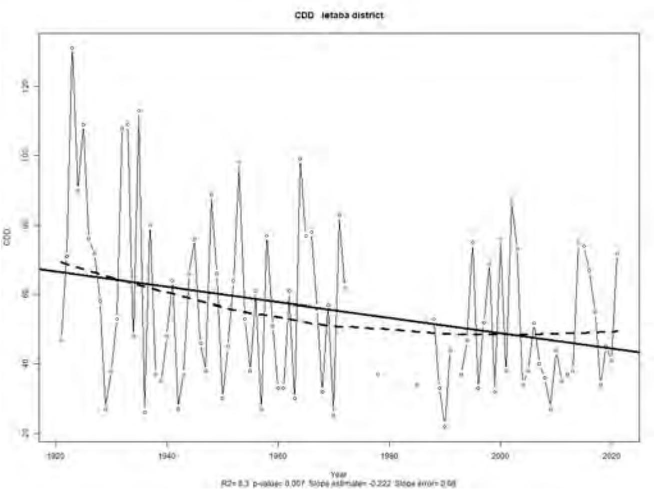

Figure 3.36 Trend in *CDD* for Letaba District (1921-2021)

Rainfall District 50 (Northern Limpopo)

Six rainfall stations were selected for analysis, i.e. Hanglip (1921-2021), Mara (1937-2021), Platjan Grenspos (1984-2021), Pontdrift (1966-2021), Una Agr (1948-2021), and Vreemdeling (1973-2021). The *prcptot* index shows negative trends for most stations, with Pontdrift significant. Therefore, one can state that in this district, the total rainfall received is generally less over the long term. Figure 3.37 presents the trend in *prcptot* for Pontdrift.

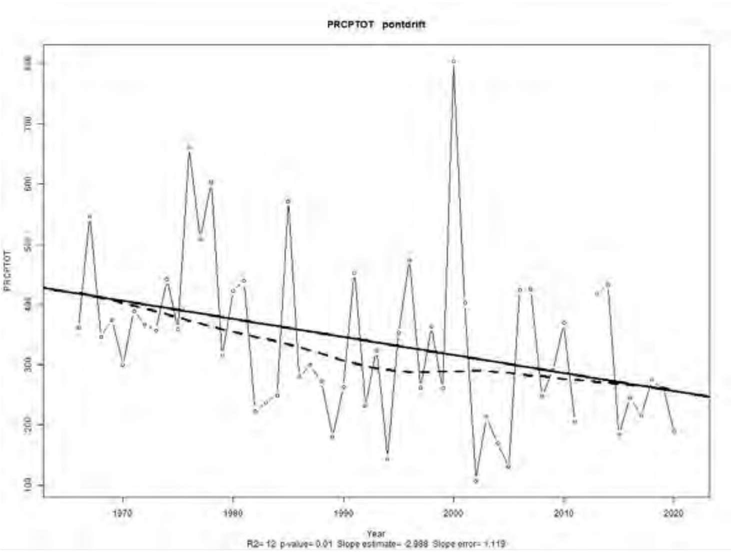

Figure 3.37 Trend in *prcptot* for Pontdrift (1966-2021)

Trends in *r95p* and *r99p* show whether precipitation is derived from more extreme daily rainfall events. All the stations show only weak, non-significant trends. The same applies to *rx1day* with no significant trends.

Trends in daily rainfall above the specific thresholds *r10mm*, *r20mm*, and *r25mm* show mostly decreasing trends, and are mostly significant, except for Platjan Grenspos. Figure 3.38 presents the trend in *r10mm* for Hanglip. These trends reflect the general decrease in annual rainfall totals and imply that, in general, significant rainfall events have decreased.

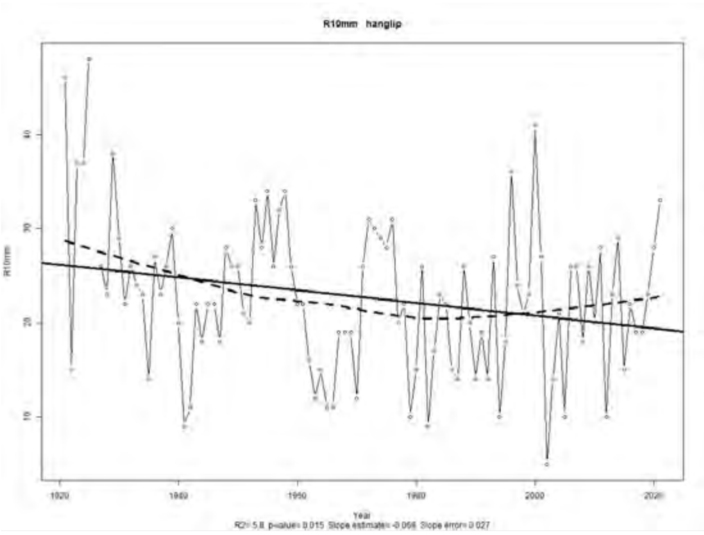

Figure 3.38 Trend in *r10mm* for Hanglip (1921-2021)

SDII shows increases and decreases, depending on the recording period of the station. The very long-term stations show decreases, e.g. Mara presented in Figure 3.39. Also, *CWD* shows significantly negative trends for the long-term stations, as presented for Hanglip in Figure 3.40.

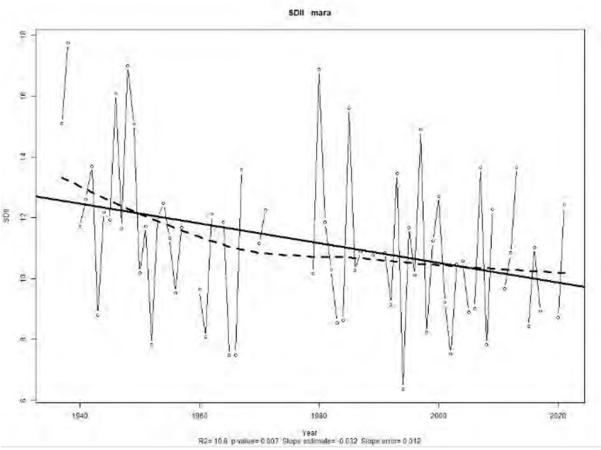

Figure 3.39 Trend in *SDII* for Mara (1937-2021)

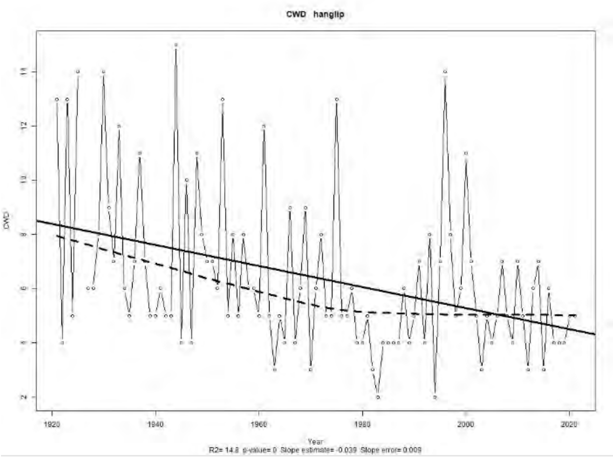

Figure 3.40 Trend in *CWD* for Hanglip (1921-2021)

CDD shows mainly positive trends and is significant for most stations (e.g. for Pontdrift in Figure 3.41). This indicates that the winter dry period has increased significantly in most places, especially over the long term.

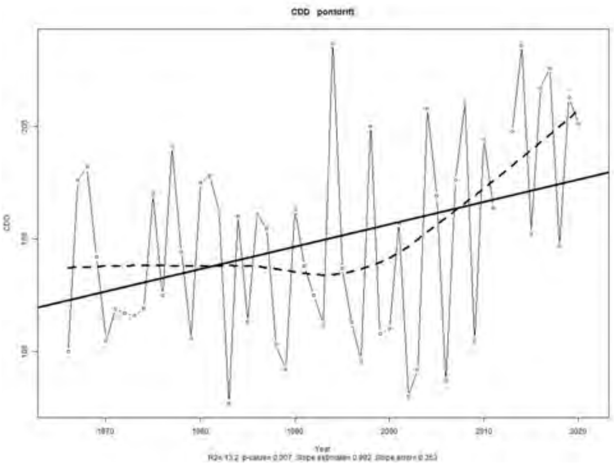

Figure 3.41 Trend in *CDD* for Pontdrift (1966-2021)

Rainfall District 63 (Southern Limpopo)

Two rainfall stations were selected for analysis: Laersdrift (1924-2021) and Marble Hall (1939-2021). The *prcptot* index shows a significantly negative trend for Laersdrift (Figure 3.42), but positive and non-significant trends for Marble Hall. A comparison with the SPI analysis indicates that the drying signal over the very long term is convincing.

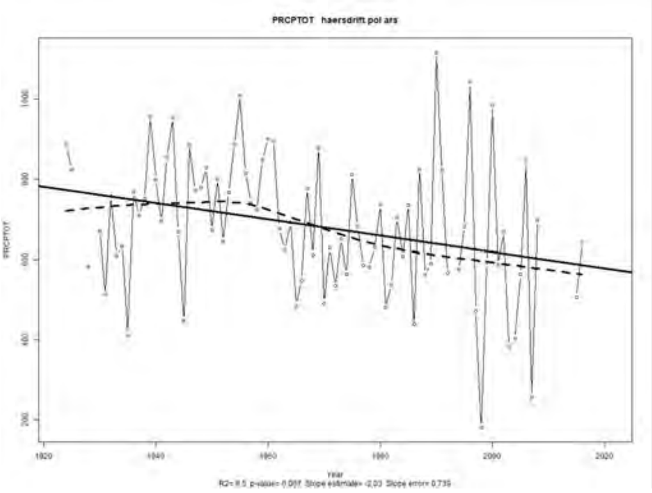

Figure 3.42 Trend in *prcptot* for Laersdrift (1924 – 2021)

Both stations show positive trends for *r95p* and *r99p*, with Laersdrift having a significantly positive trend in *r99p* (Figure 3.43). The same applies to *rx1day*, but with no significant trends. Trends in daily rainfall above the specific thresholds *r10mm*, *r20mm*, and *r25mm* show both increasing and decreasing trends, but are only significant for *r10mm* for Laersdrift, which also experienced a long-term drying trend. Figure 3.44 presents the trend in r10mm for Laersdrift.

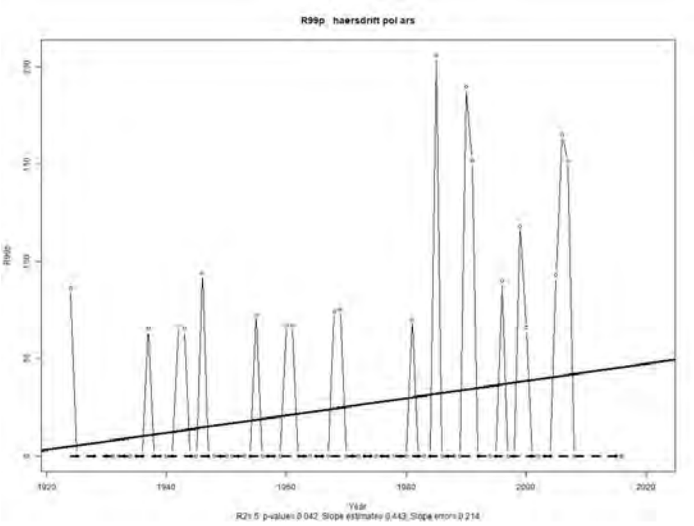

Figure 3.43 Trend in *r99p* for Laersdrift (1924-2021)

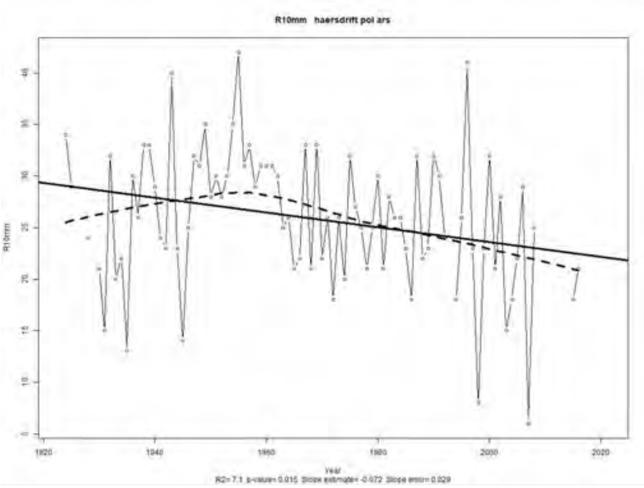

Figure 3.44 Trend in *r10mm* for Laersdrift (1924-2021)

SDII shows increases and decreases and is significantly positive for Laersdrift (Figure 3.45), while *CWD* shows a significantly negative trend for Laersdrift, as shown in Figure 3.46.

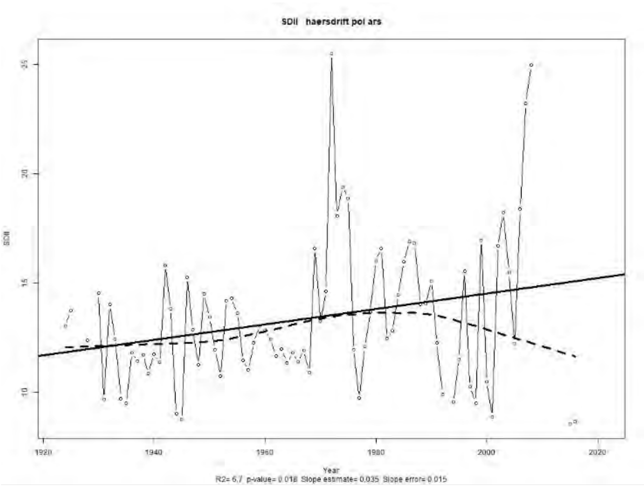

Figure 3.45 Trend in *SDII* for Laersdrift (1924-2021)

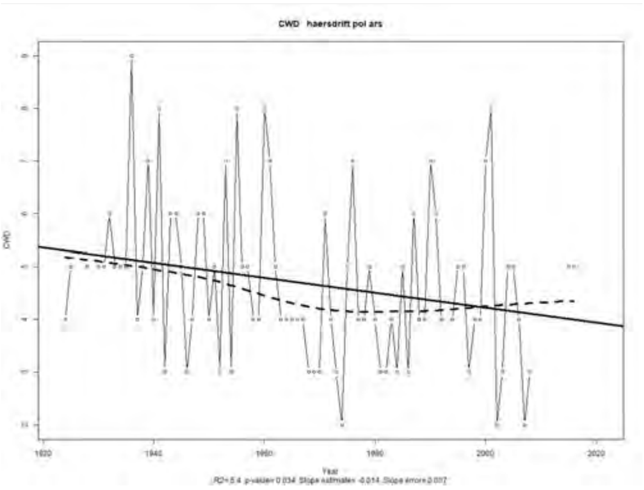

Figure 3.46 Trend in *CWD* for Laersdrift (1924-2021)

CDD shows a significantly positive trend for Laersdrift (Figure 3.47), which indicates that the winter dry period has increased significantly, especially over the long term.

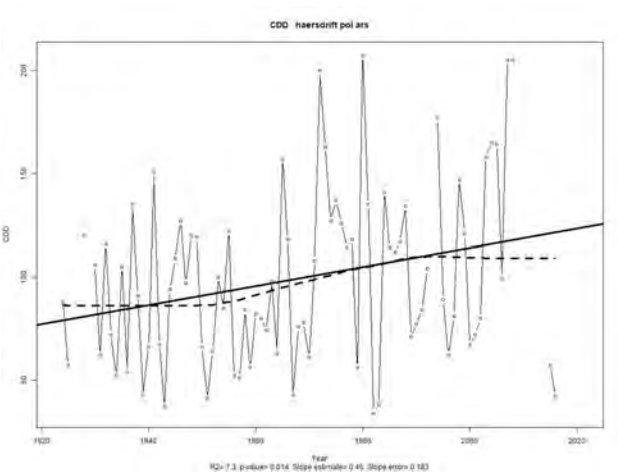

Figure 3.47 Trend in *CDD* for Laersdrift (1924-2021)

Rainfall District 64 (Central Limpopo)

Five rainfall stations were selected for analysis: Bergzicht (1921-2021), Pietersburg-Hosp (1921-2021), Kalkfontein (1921-2021), Dendron (1971-2021), and Syferkuil (1948-2021). All these stations are close to or in the capital city of Polokwane. The *prcptot* index shows trends slightly negative or close to zero for all stations, and, therefore, they are all non-significant (e.g. Figure 3.48 for Pietersburg-Hosp). A comparison with the SPI analysis indicates that there are drying signals for the long-term SPIs, nonetheless.

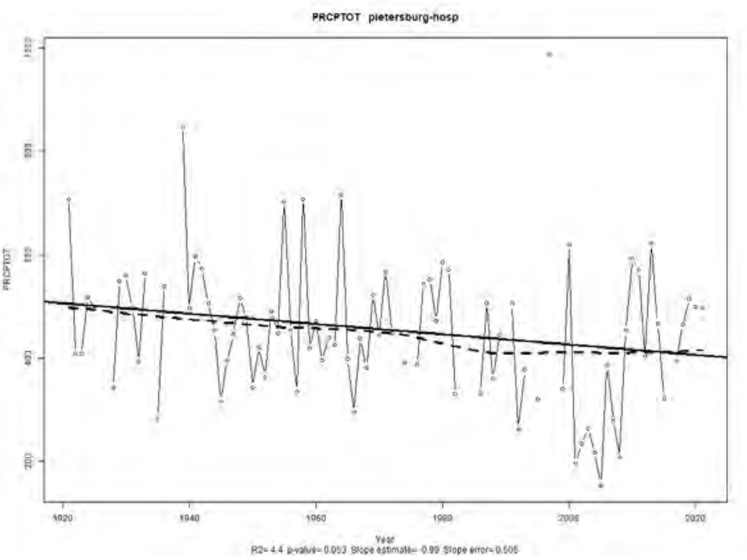

Figure 3.48 Trend in *prcptot* for Pietersburg - hosp (1921-2021)

Most stations show positive trends in *r99p* due to an increase in extreme daily rainfall events occurring in the last few decades. However, no stations show statistically significant trends. For *rx1day* near-zero trends were observed. Trends in daily rainfall above the specific thresholds *r10mm*, *r20mm*, and *r25mm* show mostly increasing but non-significant trends. However, trends are significant for *r20mm* for some stations. Figure 3.49 presents the trend in *r20mm* for Kalkfontein.

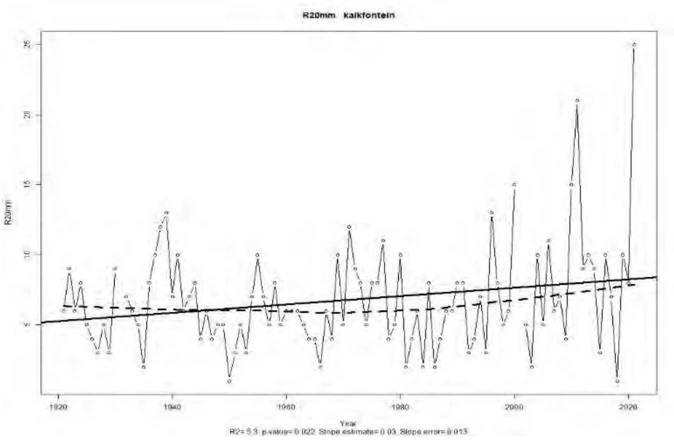

Figure 3.49 Trend in *r20mm* for Kalkfontein (1921-2021)

Following on from the trends in the results above, most stations show increases for *SDII*, with some being significant, e.g., for Pietersburg-hosp presented in Figure 3.50. The *CWD* shows almost no trend for some stations, while it is significantly negative for others, e.g., for Dendron presented in Figure 3.51.

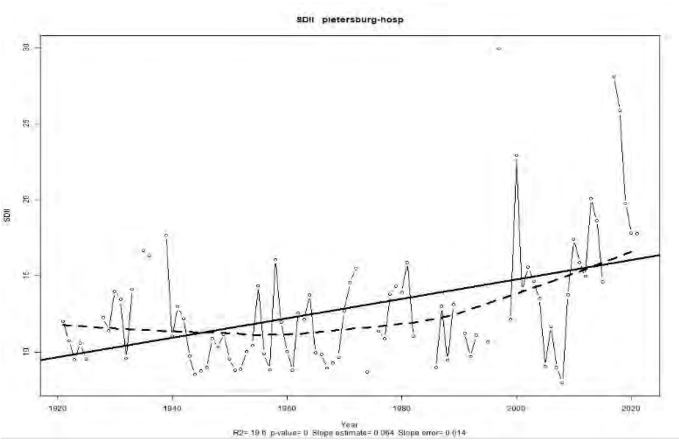

Figure 3.50 Trend in *SDII* for Pietersburg-hosp (1921-2021)

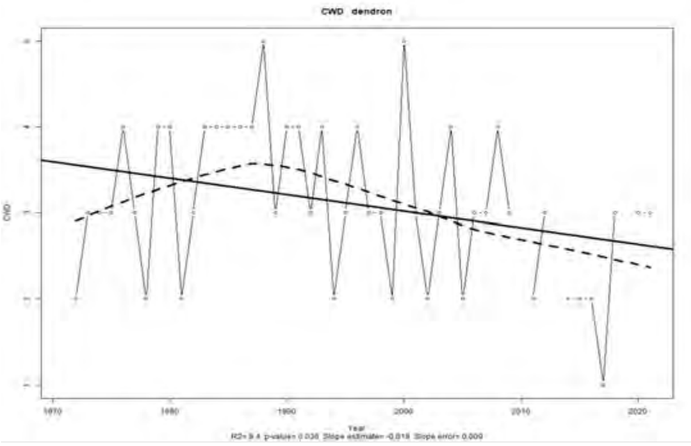

Figure 3.51 Trend in *CWD* for Dendron (1972-2021)

CDD shows mostly positive trends with some trends being significant, e.g. for Kalkfontein (Figure 3.52), which indicates that the winter dry period has increased significantly over the long term.

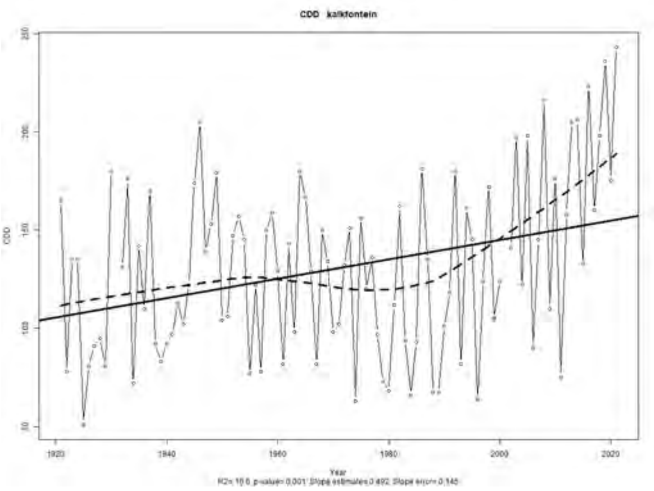

Figure 3.52 Trend in *CDD* for Kalkfontein (1921-2021)

Rainfall District 65 (Northern Limpopo)

One rainfall station was selected for analysis, i.e. Tolwe (1969-2021). The *prcptot* index shows a non-significant decrease, which confirms the findings of the SPI analysis. The extreme indices of *r95p and r99p* show almost no and somewhat negative trends, respectively. This is also the case for *rx1day*. Trends in daily rainfall above the specific thresholds *r10mm*, *r20mm*, and *r25mm* show mostly flat trends, but are significantly negative for *r10mm*, as presented in Figure 3.53.

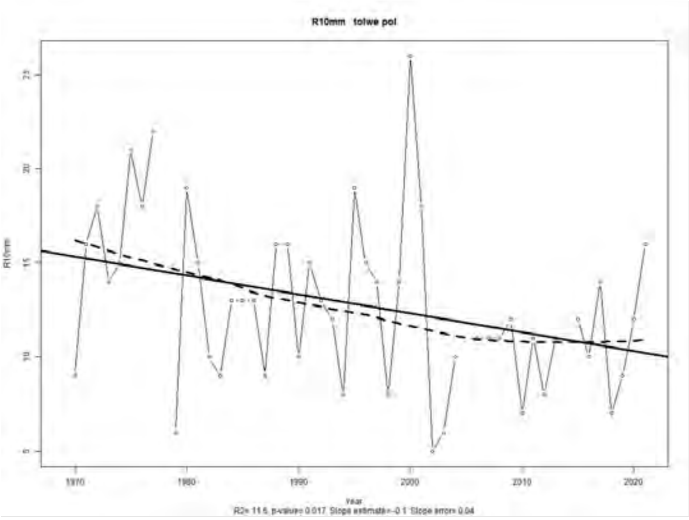

Figure 3.53 Trend in *r10mm* for Tolwe (1970-2021)

Following on from the trends above, Tolwe shows a significant increase for *SDII* (presented in Figure 3.54). The *CWD* exhibits a significantly negative trend, as shown in Figure 3.55.

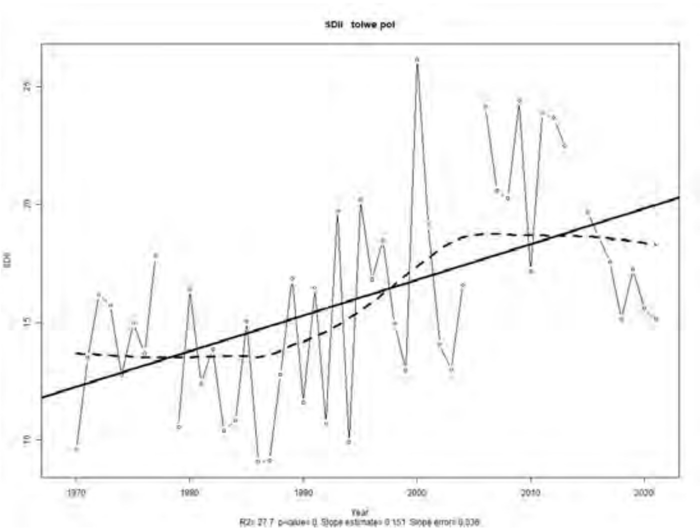

Figure 3.54 Trend in *SDII* for Tolwe (1970-2021)

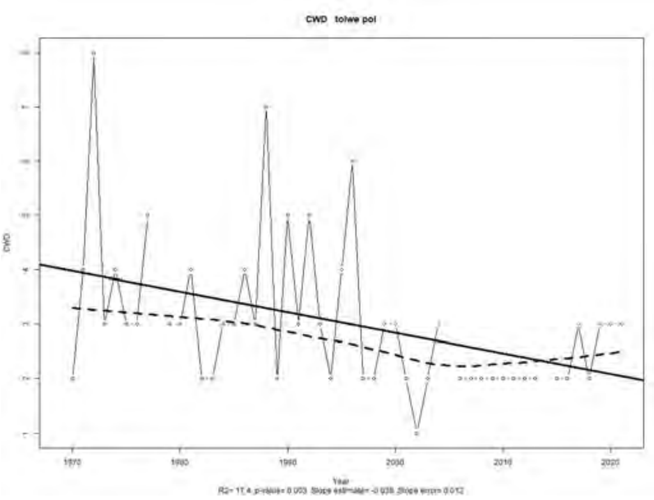

Figure 3.55 Trend in *CWD* for Tolwe (1970-2021)

CDD shows a significantly positive trend (Figure 3.56), which indicates that the winter dry period has increased significantly over the long-term.

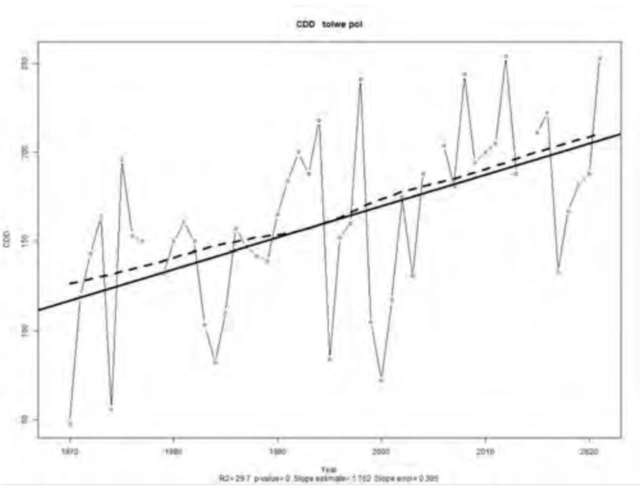

Figure 3.56 Trend in *CDD* for Tolwe (1970-2021)

Rainfall District 76 (Southern Limpopo)

Nine rainfall stations were selected for analysis, i.e. Naboomspruit (1921-2021), Nylsvley (1921-2021), Palmer Estate (1924-2021), Jonkmansdrift (1984-2021), Sterkrivier (1979-2021), Moorddrift (1921-2021), Doornfontein (1926-2021), Verdoornsdraai (1941-2021), and Bakenberg (1986-2021). For all the very long-term stations, the *prcptot* index shows non-significant trends, which does not confirm the results of the SPI analysis, which indicates an increase in long-term dry conditions.

Trends in *r95p and r99p* are variable. While most very long-term stations show increases, Moorddrift shows a significant decrease. For *rx1day* most stations show non-significant increases. Trends in daily rainfall above the specific thresholds *r10mm*, *r20mm*, and *r25mm* show mostly positive trends, but are non-significant.

Following on from the trends above, most stations show non-significant increases for *SDII*, except for Palmer Estate and Nylsvley (the latter is shown in Figure 3.57). *CWD* shows variable trends but is significantly negative for Nylsvley (Figure 3.58).

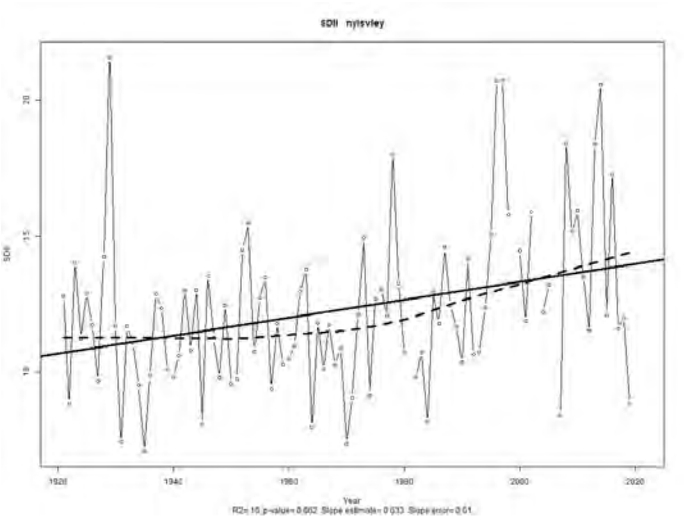

Figure 3.57 Trend in *SDII* for Nylsvley (1921-2021)

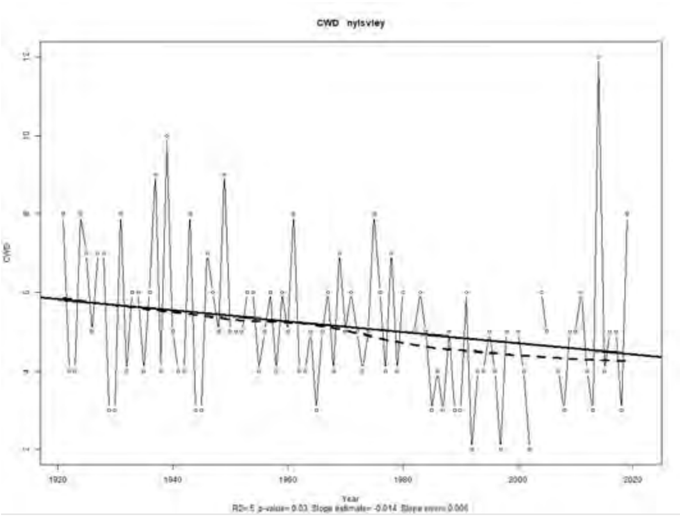

Figure 3.58 Trend in *CWD* for Nylsvley (1921-2021)

CDD shows a significantly positive trend for most very long-term stations, e.g. Palmer Estate (Figure 3.59), which indicates that the winter dry period has increased significantly over the long term.

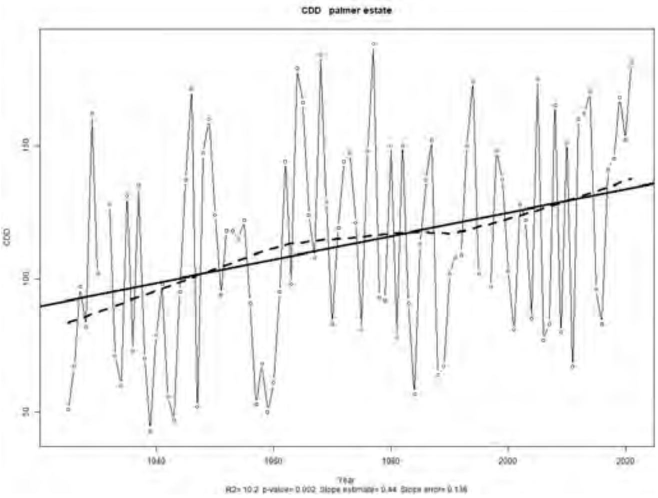

Figure 3.59 Trend in *CDD* for Palmer Estate (1921-2021)

Rainfall District 77 (Western Limpopo)

Five rainfall stations were selected for analysis, i.e., Dorset-Pol (1935-2021), Grootgeluk-MYN (1976-2021), Ellisras-Pol (1967-2021), Villa Nora-Pol (1921-2021), and Stockpoort-Pol (1921-2021). For the very long-term stations, the *prcptot* index shows significant negative trends (Villa Nora presented in Figure 3.60), which confirms the results of the SPI analysis, indicating an increase in long-term dry conditions.

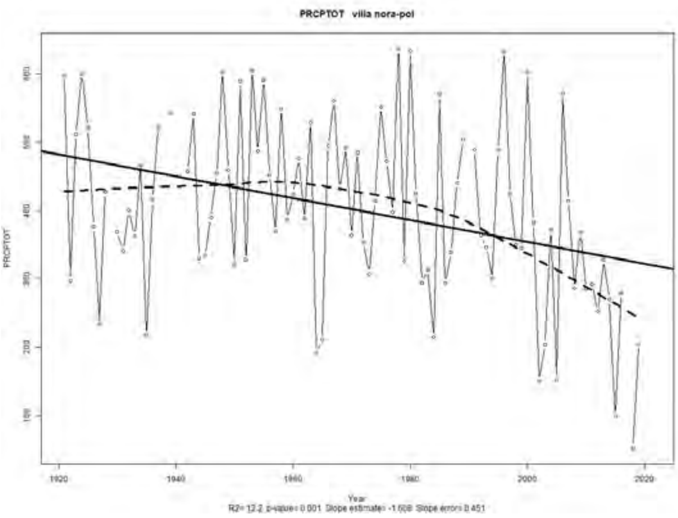

Figure 3.60 Trend on *prcptot* for Villa Nora (1921-2021)

Trends in *r95p and r99p* are variable. Decreases in *r95p* are evident at the very long-term stations (e.g. for Villa Nora presented in Figure 3.61). For *rx1day* most stations show non-significant trends, and mostly decreases. These results confirm the generally negative trends in rainfall amounts.

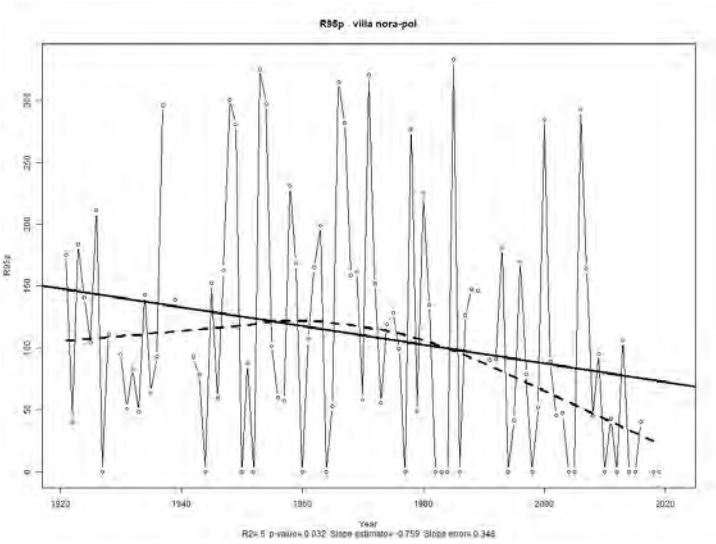

Figure 3.61 Trend in *r95p* for Villa Nora (1921-2021)

Trends in daily rainfall above the specific thresholds *r10mm*, *r20mm*, and *r25mm* show mostly negative trends, but are mostly non-significant. Some indices show significance for the very long-term stations, e.g. *r25mm* for Villa Nora (Figure 3.62).

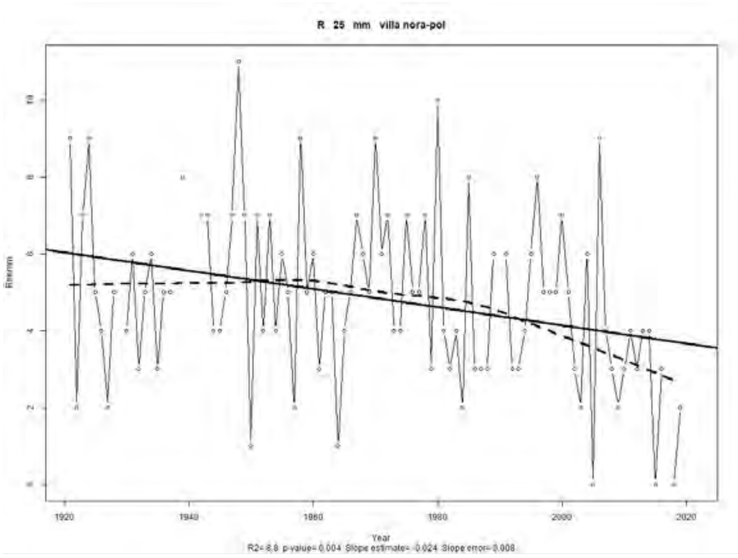

Figure 3.62 Trend in *r25mm* for Villa Nora (1921-2021)

Following on from the trends above, most very-long term stations show significant decreases for *SDII* (e.g. Villa Nora presented in Figure 3.63). *CWD* shows variable trends but is significantly negative for Villa Nora (Figure 3.64).

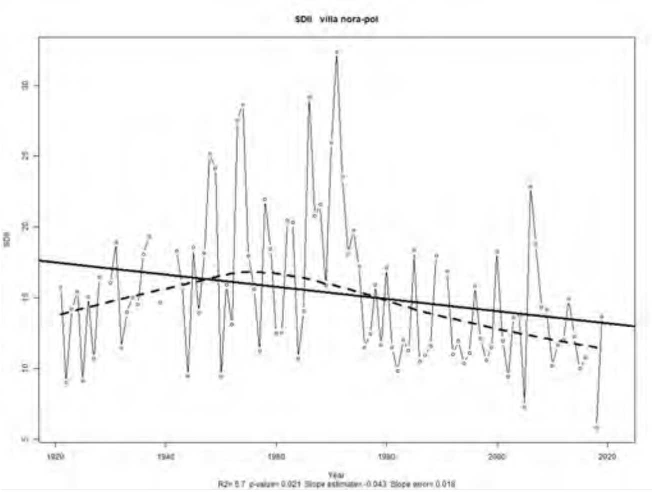

Figure 3.63 Trend in *SDII* for Villa Nora (1921-2021)

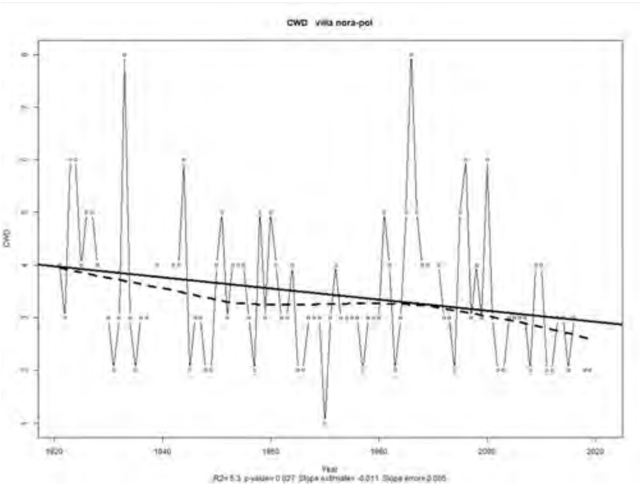

Figure 3.64 Trend in *CWD* for Villa Nora (1921-2021)

CDD shows a significantly positive trend for some very long-term stations, e.g. Dorset (Figure 3.65), which suggests that the winter dry period has probably increased over the long term.

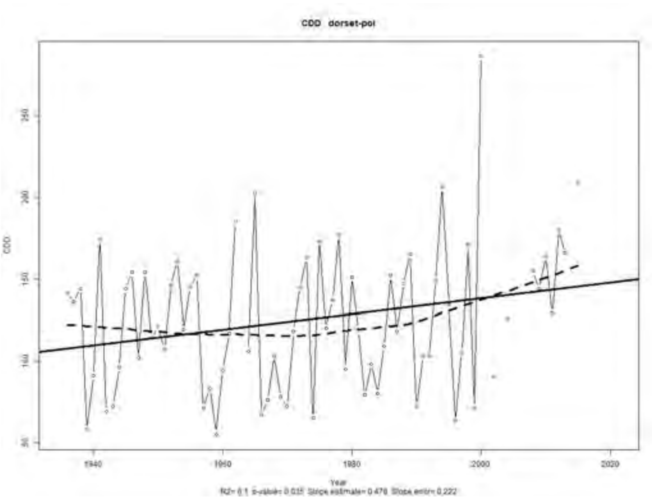

Figure 3.65 Trend in *CDD* for Dorset (1921-2021)

Rainfall District 86 (Southern Limpopo)

Five rainfall stations were selected for analysis, i.e. Leeupoort-Mun (1921-2021), Nylstroom-Mun (1949-2021), Rust de Winter-IRR (1953-2021), Warmbad-Towoomba (1937-2021), and Rankins Pass-Pol (1921-2021). For the very long-term stations, the *prcptot* index shows decreasing but non-significant trends and confirms the results of the SPI analysis, which indicates an increase in long-term dry conditions. Trends in *r95p* and *r99p* show mostly positive trends. Figure 3.66 presents *r99p* for Rankins Pass. For *rx1day* most stations show non-significant increases.

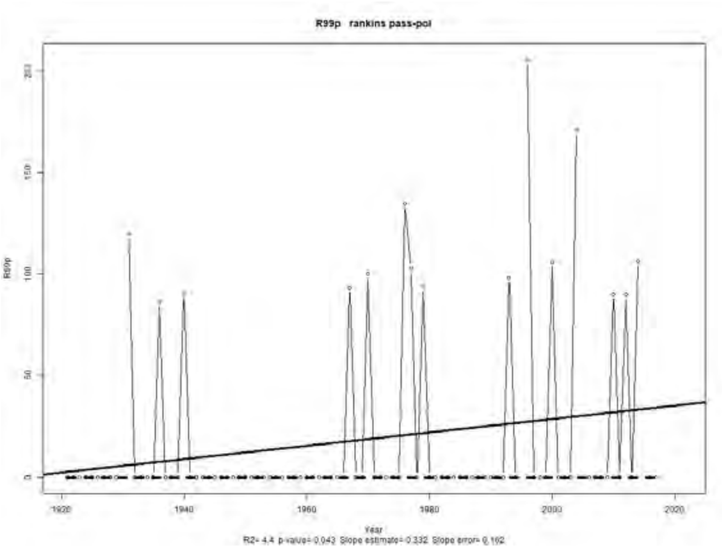

Figure 3.66 Trend in *r99p* for Rankins Pass (1921-2018)

Trends in daily rainfall above the specific thresholds *r10mm*, *r20mm,* and *r25mm* show mostly positive trends, but are non-significant. Most stations show increases for *SDII* and in the case of Rankins Pass are significant (Figure 3.67). *CWD* shows variable trends but is significantly negative in some cases (e.g. for Rankins Pass, Figure 3.68).

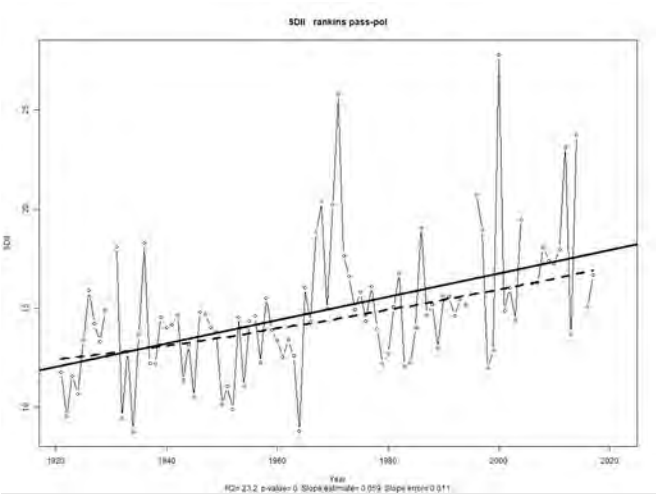

Figure 3.67 Trend in *SDII* for Rankins Pass (1921-2018)

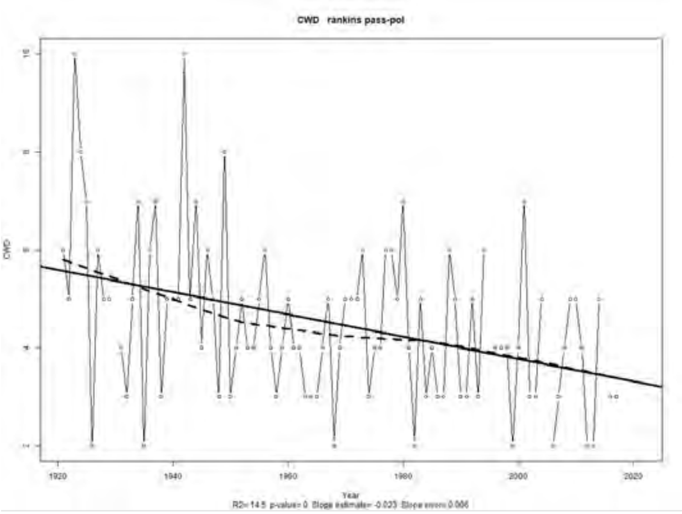

Figure 3.68 Trend in *CWD* for Rankins Pass (1921-2018)

CDD shows a significantly positive trend for most very long-term stations (e.g. Rankins Pass in Figure 3.69), which indicates that the winter dry period has increased significantly over the long term.

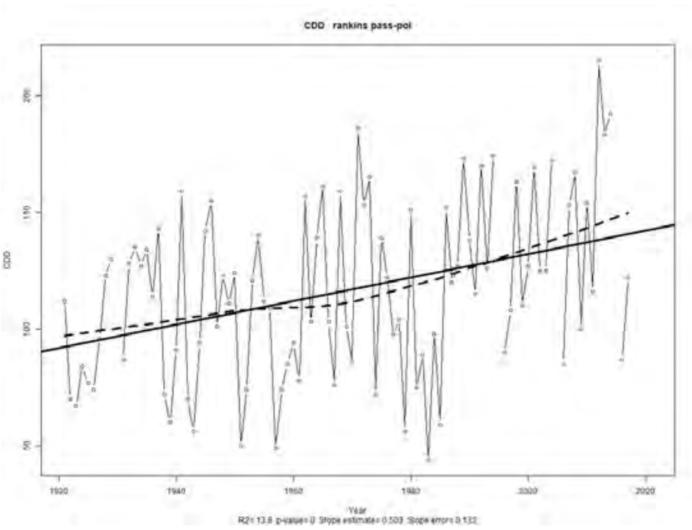

Figure 3.69 Trend in *CDD* for Rankins Pass (1921-2018)

Rainfall District 87 (South-Western Limpopo)

Two rainfall stations were selected for analysis, i.e. Buffeldoorns ARS (1934-2021) and Rooidam (1981-2021). The stations show consistency in terms of *prcptot* decreasing, although this decrease is not significant. This somewhat confirms the results of the SPI analysis, which indicated an increase in long-term dry conditions. However, the data sets are relatively short or incomplete for confident deductions to be made regarding long-term trends.

Trends in *r95p* and *r99p* are variable and non-significant. The same applies for the *rx1day*, *r10mm*, *r20mm, r25mm, SDII*, and *CWD* indexes. *CDD* shows positive trends and is significant for Rooidam (Figure 3.70). The recording period for this station is relatively short; however, considering the consistency in results with the other station (Buffeldoorns ARS), one can confidently assume that the winter dry period has lengthened over the long term.

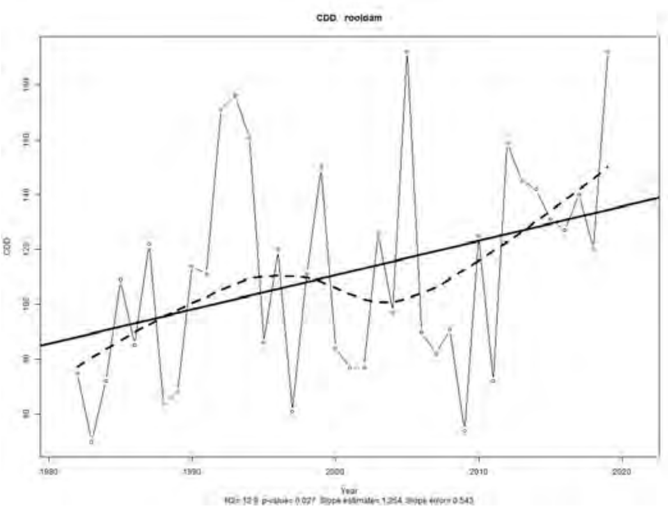

Figure 3.70 Trend in *CDD* for Rooidam (1981-2021)

Rainfall District 93 (South-Western Limpopo)

One rainfall station could be selected for analysis, i.e. Swartklip-Nooitgedacht (1979-2021). No significant trend for any of the extreme indices was noted. Therefore, no assessment of rainfall over the very long term could be made for this rainfall district.

Below, a discussion of the extreme precipitation index trends that is limited to just those stations with very long time series (i.e. 1921-2021, included in Table 3.1), is presented. These stations do not uniformly cover the Limpopo Province and are more concentrated around Polokwane and surrounding areas.

Total precipitation

The index *prcptot* calculates the annual total precipitation based on wet days (daily precipitation >= 1 mm). Figure 3.71 presents the results for *prcptot*. There are 15 stations with sufficient data, with 10 showing negative trends and five showing positive trends. Six of the stations with negative trends are statistically significant, while none of the stations with positive trends are significant. A clear drying signal is thus evident over the very long term.

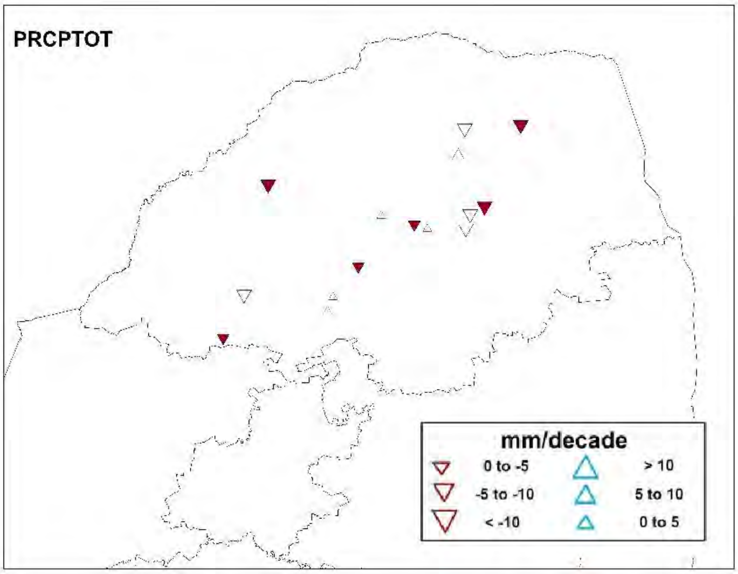

Figure 3.71 Trend in *prcptot* for 15 very long-term rainfall stations (1921-2021)

Annual total precipitation from wet and very wet days

The *r95p* and *r99p* indices are defined as the annual total precipitation from daily precipitation greater than the 95th and 99th percentiles, respectively, in mm. Therefore, the index provides the annual total precipitation derived from wet and very wet days. In a drying climate, as overwhelmingly indicated by historical precipitation trends over the province, a decrease in wet and very wet days will be expected, if rainfall is not becoming more extreme in general. However, this is not the case, with clear signals of more extreme rainfall, particularly in the analysis of *r95p* (Figure 3.72). Of the 15 stations, nine show increasing trends (seven significant) while six show negative trends (two significant). For *r99p*, only two stations have significant trends, with both being positive and in the south of the province (Figure 3.73).

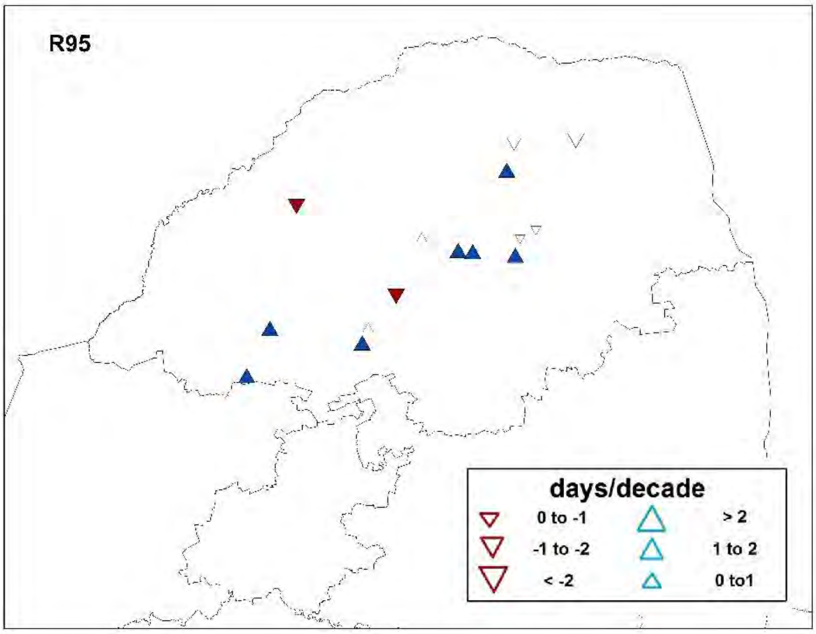

Figure 3.72 Trend in *r95p* for 15 very long-term rainfall stations (1921-2021)

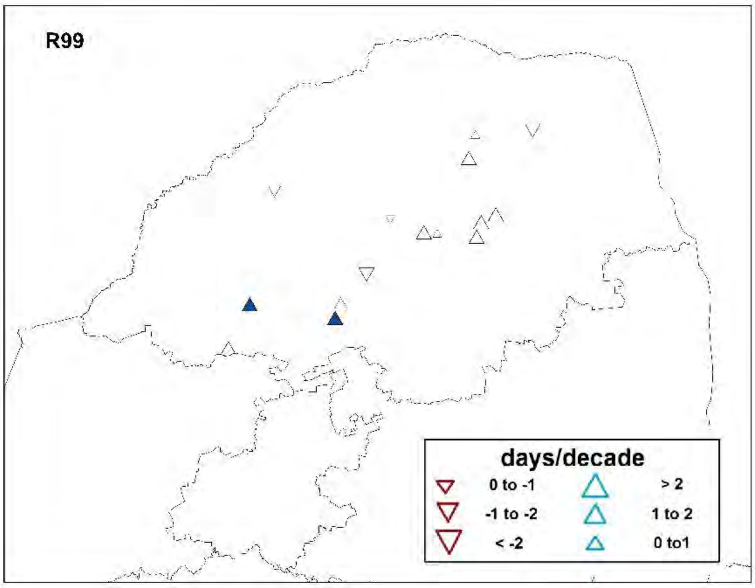

Figure 3.73 Trend in *r99p* for 15 very long-term rainfall stations (1921-2021)

Annual maximum daily precipitation

The annual maximum 1-day precipitation, *rx1day*, is important in the sense that it can indicate whether there could have occurred a change in the maximum daily precipitation to be expected per year, or over specific return periods. Figure 3.74 presents the trends in *rx1day,* and while most stations indicate positive trends (highest daily rainfall per annum increasing; 12 stations decrease vs. 3 stations increase), only one station indicates a significantly positive increase.

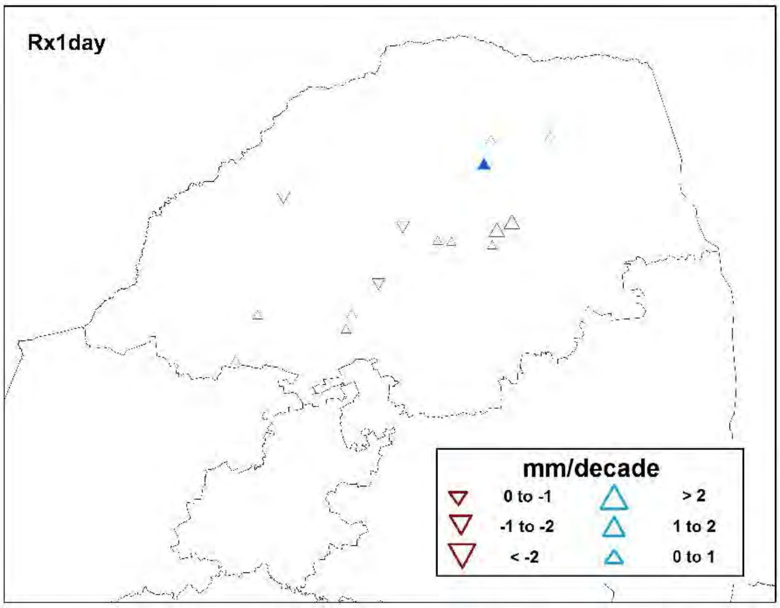

Figure 3.74 Trend in *rx1day* for 15 very long-term rainfall stations (1921 – 2021)

Rainfall days with totals exceeding specific thresholds

In climate regions that become drier, it is expected that the number of days with rainfall above relatively low thresholds (which cannot be considered extreme) will decrease as well. However, if the rainfall climate is becoming more extreme, the number of days with rainfall exceeding relatively high thresholds can increase or decrease. Figure 3.75, Figure 3.76, and Figure 3.77 present the trends in *r10mm*, *r20mm*, and *r25mm*, respectively. For *r10mm*, most stations (11 vs. 4) show negative trends, with seven being significantly negative. This can be viewed as a direct reflection of the general decline in rainfall experienced over most parts of the province. For *r20mm* the number of stations with significantly positive trends increased from one to three, but most stations still show negative trends. This was also the case for *r25mm*.

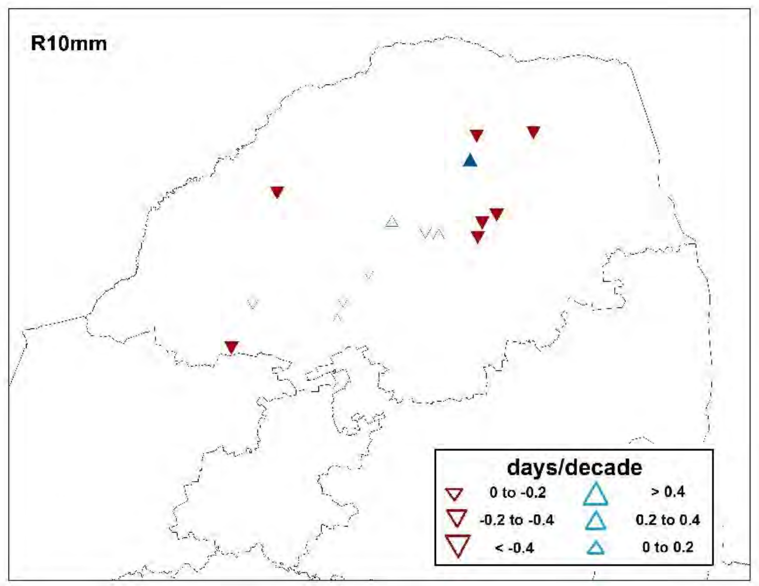

Figure 3.75 Trend in *r10mm* for 15 very long-term rainfall stations (1921-2021)

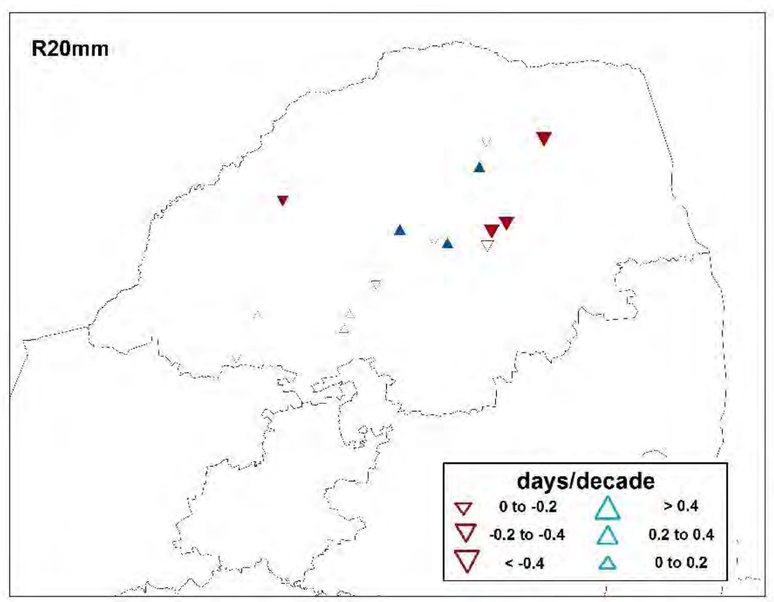

Figure 3.76 Trend in *r20mm* for 15 very long-term rainfall stations (1921-2021)

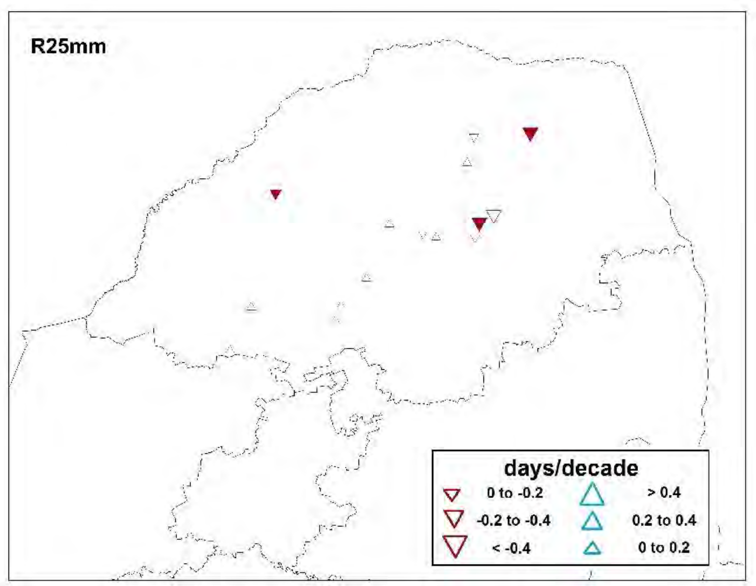

Figure 3.77 Trend in *r25mm* for 15 very long-term rainfall stations (1921-2021)

Daily intensity of rainfall

As noted in the results of the previous indices, one can conclude that although total rainfall is declining in most parts of the province, there are signals that rainfall is becoming more extreme. The *SDII*, the Simple Daily Intensity Index, is defined as the annual mean of daily precipitation intensity. Figure 3.78 presents the trends in *SDII,* and it confirms the trend results from the previous extreme indices that rainfall is becoming more extreme. Of the 15 long-term stations, eight show positive trends, which are all statistically significant.

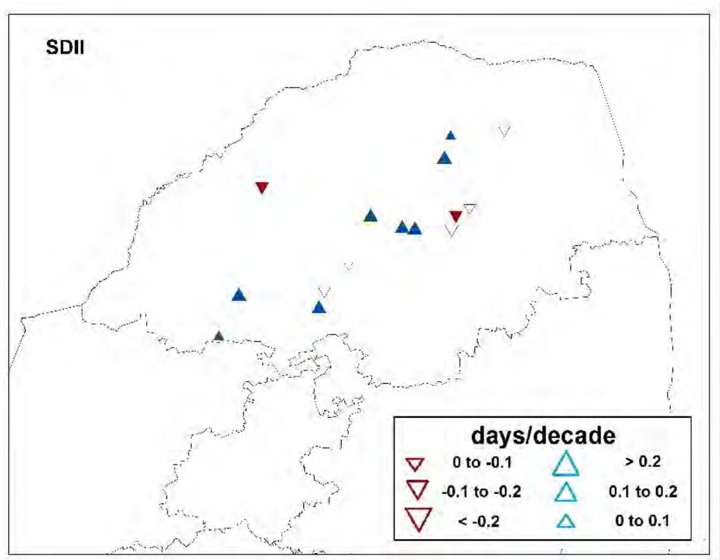

Figure 3.78 Trend in *SDII* for 15 very long-term rainfall stations (1921-2021)

Longest wet spell per year

The *CWD* index is defined as the annual maximum length of a wet spell, i.e. the annual maximum number of consecutive days with precipitation >= 1 mm. Figure 3.79 presents the trend results of *CWD* and confirms what can be expected in a drying climate. Of the 15 stations 12 show negative trends, with nine significant.

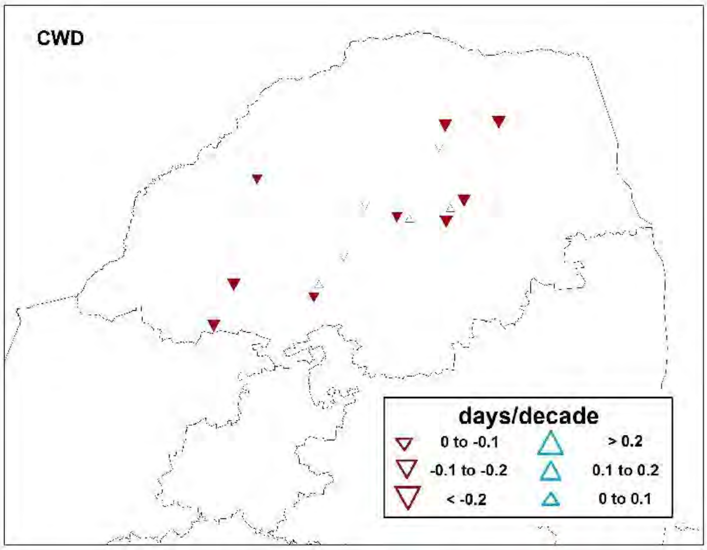

Figure 3.79 Trend in *CWD* for 15 very long-term rainfall stations (1921-2021)

Longest dry spell per year

The Limpopo Province falls in the summer rainfall region of South Africa and, therefore, the longest dry period is usually experienced in winter, when very little rainfall is received (almost no rainfall occurs in the central and western parts). The *CDD* index is defined as the annual maximum length of dry spell, i.e. the maximum number of consecutive days per year with precipitation < 1 mm. Again, reflecting the previous results, the trends in *CDD* (Figure 3.80) show results expected from a drying climate, with 11 stations showing increases in the annual maximum dry spell length (six stations with significant trends). Interestingly, stations with negative trends, although not significant, are clustered in the east, which can be an indication or confirmation of the SPI results that, closer to the eastern escarpment, the drying signal is not as pronounced as over the remainder of the province.

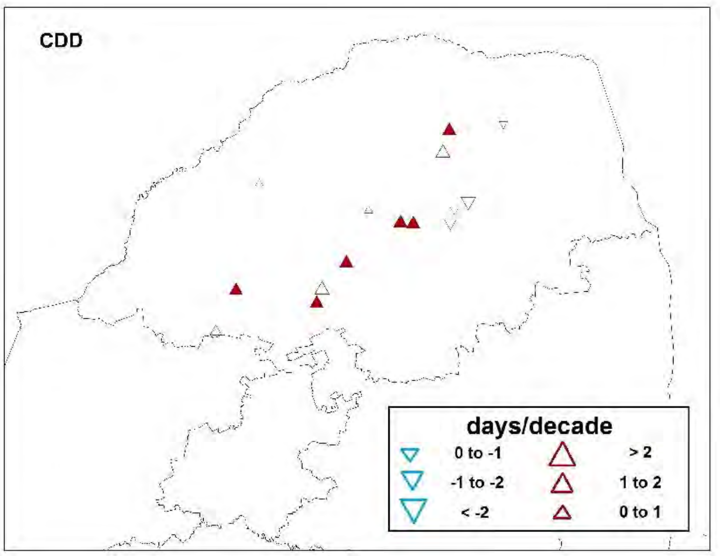

Figure 3.80 Trend in *CDD* for 15 very long-term rainfall stations (1921-2021)

3.5 CONCLUSION

The analysis of long-term daily rainfall for the period 1921 to the present provides a comprehensive overview of historical trends in rainfall in the Limpopo Province. The drought analysis with the 12- and 24-month SPI values as indicators indicates that most of the province underwent drying to various degrees. While the central and western parts show drying over the last century, drier conditions over the eastern parts of the province have become more prevalent over the last 50 years.

The SPEI index, applied to individual climate stations with records longer than 30 years, indicates similar trends to the SPI analysis. However, there are clear signals that recent longer-term droughts were more severe than what the SPI alone indicates. The Limpopo Province, just like the country and the globe as a whole, has experienced significant warming in the recent past, with the effect that, due to relatively more evapotranspiration, droughts have the potential to be more severe.

Most extreme indices indicate a positive trend calculated from individual station data. For example, the amounts of annual rainfall derived from days considered very wet, i.e., falling in the highest 5 per cent of daily rain totals historically, have increased significantly for most stations with very long-term data since 1921. However, due to the general drying trend in the province, the longest periods per year without rainfall have increased, while the longest wet spells per year have largely decreased.

In summary, the rainfall climate in Limpopo Province has become drier to various degrees, but also more extreme on a sub-seasonal basis, as reflected in trends of daily extreme indices.

3.6 REFERENCES

KRUGER AC, and NXUMALO MP, (2017) Historical rainfall trends in South Africa: 1921–2015. Water SA. 43(2): 285 – 297. http://dx.doi.org/10.4314/wsa.v43i2.12

CHAPTER 4: FUTURE PROJECTIONS OF RAINFALL, EXTREME INDICES, AND DROUGHT

4.1 INTRODUCTION

Climate-related extremes have been the main causes of natural disasters over the past few decades in Southern Africa (Shongwe et al., 2009). Significant trends in temperature and precipitation extremes were also identified by New et al. (2006). In South Africa, the Limpopo Province experiences very high temperatures during the austral summer season (Kruger and Shongwe, 2004). Extreme weather events are also common in Limpopo during summertime and often coincide with mature phases of the El Niño Southern Oscillation (Sikhwari et al., 2022). Understanding, modelling, and predicting weather and climate extremes is identified as a major area necessitating further progress in climate research (Sillmann et al., 2017). This includes evaluating the drivers and specific processes at local to regional scales, the temporal variability, and the evolution of extreme events. Reliable predictions of extremes are needed on short and long timescales to inform local and national climate change adaptation plans as well as other policies, to reduce potential risks and damages that result from weather and climate extremes (IPCC, 2012).

Having analysed historical trends in droughts and precipitation extremes in the previous chapter, this chapter proceeds to characterize future precipitation projections for Limpopo. Given the importance of understanding and predicting extremes (outlined above), the projections are applied to evaluate potential changes in future drought (SPEI and SPI) and extreme precipitation indices for the province. As before, the focus of this investigation covers the Limpopo Province with its five district municipalities.

4.2 DATA AND METHODS

4.2.1 CORDEX models

The spatial resolution of the Global Climate Model (GCM) grid squares is relatively coarse, especially when applied to produce South African provincial-scale climate change projections. Therefore, to address the spatial scale limitations posed by the GCM fields, the Coordinated Regional Downscaling Experiment (CORDEX) dynamically downscaled simulations over the African domain (grid spatial resolution of 0.44°x 0.44°) were used. The Rossby Centre regional model (RCA4), forced across its lateral boundaries by the GCM models (Table 4.1) of the 5th phase of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012) was used. RCA4 was the version used in the downscaling of CMIP5 simulations for CORDEX. The CORDEX simulations, with predefined regions, grids, experiment protocols, output variables, and output format, facilitate easier analysis of possible future regional climate changes, not only by the scientific community but also by end-user communities at regional and local levels (Giorgi et al., 2009). The RCA4 is a coupled ocean-atmosphere Regional Climate Model (RCM) based on the Numerical Weather Prediction (NWP) model HARLAM (Undén et al., 2002). For the climate change projections, outputs from the historical or reference period (1976-2005), and three projected time intervals, spanning the current climate from 2006-2035; the near-future, defined as the period starting from 2036-2065; and the distant future, spanning from 2066-2095 were considered. The CORDEX-Africa model simulations under the Representative Concentration

Pathway (RCP) 4.5 and RCP8.5 emissions scenarios across the selected time intervals were used for the climate change projections.

Multi-model ensembles, i.e., models produced by combining multiple model ensemble members, are often described as 'ensembles of opportunity' (Tebaldi and Knutti, 2007). This is attributed to the way they are created, which involves the combination of information from all participating models (Pincus et al., 2008). Multi-model ensembles are believed to increase the skill, reliability, and consistency of output (Cantelaube and Terres, 2005), and are often found to out-perform single models (Duan and Phillips, 2010; Miao et al., 2012). This has previously been demonstrated in a part of Limpopo by Adiola et al. (2022). In this study, multi-model ensembles refer to a set of model simulations from eight different CORDEX-Africa models (Table 4.1). These model ensembles were characterised by use of the Simple Multi-model Averaging (SMA) technique (Georgakakos et al., 2004). The SMA approach can be described as:

$$(Q_{SMA})_t = \overline{Q_{obs}} + \sum_{i=1}^{N} \frac{(Q_{sim})_{i,t} - \overline{(Q_{obs})}_i}{N} \quad [2]$$

where $(Q_{SMA})_t$ is the multi-model variable (e.g. precipitation, minimum, or maximum temperature) simulations from CORDEX-Africa models derived using SMA at time *t*, $(Q_{SMA})_{i,t}$ corresponds to the i^{th} model variable simulation for time *t*, $\left(\underline{Q_{sim}}\right)_{i,t}$ is the time average of the i^{th} model variable simulation, $\underline{Q_{obs}}$ corresponds to the observed average variable and *N* represents the number of models under consideration.

Table 4.1 List of the Global Circulation Models (GCMs) used in the study

Model name	Country	Resolution	Literature
CanESM2m	Canada	2.8° x 2.8°	Arora et al. (2011)
CNRM-CM5	France	1.4° x 1.4°	Voldoire et al. (2013)
CSIRO-Mk3	Australia	1.9° x 1.9°	Jeffrey et al. (2013)
IPSL-CM5A-MR	France	1.9° x 3.8°	Hourdin et al. (2013)
MIROC5	Japan	1.4° x 1.4°	Watanabe et al. (2011)
MPI-ESM-LR	Germany	1.9° x 1.9°	Giorgetta et al. (2013)
NorESMI-M	Norway	1.9° x 2.5°	Tjiputra et al. (2013)
GFDL-ESM2M	USA	2.0° x 2.5°	Dunne et al. (2012)

It is recognised that the CORDEX simulation data used in the analysis of drought and extreme rainfall indices will, like any climate model output, have systematic errors (bias) inherent in the data. However, the data were not subjected to a bias correction procedure in this context since it is believed that the multi-model ensemble averaging technique employed will tend to cancel out the error found in individual climate models. In addition, by comparing the index values of future periods to a reference period and analysing the relative changes, the influence of bias (present in both periods) is further reduced or largely eliminated.

4.2.2 Precipitation extreme indices

In this study, selected precipitation extreme indices from the original 27 core climate indices developed by the Expert Team (ET) on Climate Change Detection and Indices (ETCCDI) (Peterson, 2005) were analysed. These precipitation indices were selected based on their relevance to the climatology and hydrology of the Limpopo Province. The indices are mostly the same as the indices used in the historical rainfall analysis (Chapter 3), and are defined again in Table 4.2 for ease of reference. Eight precipitation extreme indices were analysed to assess the projected changes in precipitation in the province. The indices were calculated from daily precipitation CORDEX ensemble data (ensemble average) using Climate Data Operator (CDO). For detailed information on the calculation of climate extreme indices, the reader is referred to the following website, http://etccdi.pacificclimate.org/list_27_indices.shtml. The climate change indices relating to precipitation were calculated for both the reference (1976-2005) datasets and the projection datasets across the three time intervals. The results were then inter-compared with the reference period to assess the projected change in precipitation extremes over time, in relation to the historical period.

Table 4.2 Selected precipitation extreme indices used in this study

Precipitation Extreme Indices		
rx1day	Maximum 1-day precipitation amount	Maximum 1-day precipitation Let RR_{ij} be the daily precipitation amount on day *i* in period *j*. The maximum 1-day value for period *j* are: $rx1day_j = \max(RR_{ij})$
rx5day	Maximum 5-day precipitation amount	Maximum consecutive 5-day precipitation Let RR_{kj} be the precipitation amount for the 5-day interval ending $_k$, period *j*. Then maximum 5-day values for period *j* are: $rx5day_j = \max(RR_{kj})$
SDII	Simple Daily Intensity Index	Total precipitation divided by the number of wet days Let RR_{wj} be the daily precipitation amount on wet days, $w\ (RR \geq 1mm)$ in period *j*. If *W* represents number of wet days in *j*, then: $SDII_j = \frac{\sum_{w=1}^{W} RR_{wj}}{W}$
CDD	Consecutive Dry Days	Maximum number of consecutive days with *Pre* < 1 mm Let RR_{ij} be the daily precipitation amount on day *i* in period *j*. Count the largest number of consecutive days where: $RR_{ij} < 1mm$ *CDD>5day* is the number of CDD periods with more than 5days per time period
CWD	Consecutive Wet Days	Maximum number of consecutive days with *Pre* ≥ 1 mm Let RR_{ij} be the daily precipitation amount on day *i* in period *j*. Count the largest number of consecutive days where: $RR_{ij} \geq 1mm$ *CWD>5day* is the number of CWD periods with more than 5days per time period
r10mm	Number of heavy	The annual count of days when *Pre* ≥ 10 mm

	precipitation days	Let RR_{ij} be the daily precipitation amount on day *i* in period *j*. Count the number of days where: $RR_{ij} \geq 10mm$
r20mm	Number of heavy precipitation days	The annual count of days when *Pre* ≥ 20 mm Let RR_{ij} be the daily precipitation amount on day *i* in period *j*. Count the number of days where: $RR_{ij} \geq 20mm$
r95p	Very wet days	Annual total precipitation when *Pre* > 95th percentile Let RR_{wj} be the daily precipitation amount on a wet day *w (RR ≥ 1.0mm)* in period *i* and let $RR_{wn}95$ be the 95th percentile of precipitation on wet days for any period used as a reference. If *W* represents the number of wet days in the period, then: $R95p_j = \sum_{w=1}^{W} RR_{wj}$ where $RR_{wj} > RR_{wn}95$

4.2.3 Calculation of SPI and SPEI

Projected drought over the Limpopo Province was characterised based on the Standardized Precipitation Index (SPI) (McKee et al., 1993; Edwards and McKee, 1997) and Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) drought indices. As mentioned in Chapter 3, the simplicity of data requirements in computing the SPI has made it the most commonly used and recommended indicator by the World Meteorological Organization for detecting and monitoring droughts (Chen et al., 2013). The concept of the SPI is described in detail by Edwards and McKee (1997). In general, SPI is computed monthly for a moving window of *n* (e.g., rainfall accumulation period from 1-48) months of interest. In this regard, the SPI-*n* for each projected timescale under the RCP4.5 and RCP8.5 was calculated by fitting a gamma distribution to projected rainfall and estimating corresponding probability distribution parameters (i.e., shape and scale). The estimated parameters of the gamma distribution are used to derive the cumulative probability of rainfall accumulation, which is then transformed to the standard distribution with satisfying conditions of a mean SPI value of zero and a variance of one. The resulting SPI consists of both negative and positive values, which represent drought/dry (i.e., a period having negative/below zero values) and non-drought/wet (i.e., a period with positive/above zero values) events, respectively.

Calculation of SPEI follows a similar concept to SPI. An important aspect is that SPEI requires both precipitation and potential evapotranspiration (PET), which is estimated based on projected monthly mean temperature and latitude. In this study, SPI/SPEI were computed for 3-, 6-, and 12-month accumulation periods and categorized using the classification criteria of SPI, recommended by the World Meteorological Organization standards (WMO, 2012).

4.2.4 Drought duration and severity

The resulting SPEI calculated across the 3-, 6- and 12-month accumulation periods and RCPs were used to compute Drought Duration (DD) and Drought Severity (DS) over the Limpopo Province. A drought event (epoch) was determined when 2 or more consecutive months exhibited negative SPEI values. The DS was computed as the absolute sum of the SPEI as shown in Equation 3,

$$DS_e = \left|\sum_{j=1}^{DD} SPEI_j\right| \quad [3]$$

In Equation 3, *j* represents a drought month, and *DD* corresponds to the duration (in months) of a drought event *e*. The median and trends were calculated to determine basic characteristics of the projected drought duration and severity.

4.2.5 Mann-Kendall trend analysis

Trends analysis for projected rainfall, drought and the selected drought features was carried out by using the original form of the Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975). The MK is a non-parametric test that is flexible with all distributions, i.e., the data does not have to conform to a certain distribution nor follow the presumption of normality (Wang et al., 2019). According to Mann (1945) and Kendall (1975), the MK test statistic (S) is calculated using Equation 4

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \quad [4]$$

where *n* represents the number of datasets, and x_i and x_j are the ranks for the i^{th} (i = 1, 2, 3, …, n–1), and j^{th} ($j = i$+1, 2, …, n) datasets. The sign function, *sgn*, is calculated using Equation 5,

$$sgn\,(x_j - x_i) = \begin{cases} 1; & \text{if } (x_j - x_i) > 0 \\ 0; & \text{if } (x_j - x_i) = 0 \\ -1; & \text{if } (x_j - x_i) < 0 \end{cases} \quad [5]$$

The variance [*Var(S)*] is calculated as given by Equation 6

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{P} t_i(t_i-1)(2t_i+5)}{18} \quad [6]$$

where *P* is number of tied groups, Σ is the summation over all tied groups and t_i represents the number of data values in the i^{th} group with i = 1, 2, 3, …, n. The standardized MK test is computed using Equation 7,

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}; & \text{if } S > 0 \\ 0; & \text{if } S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}; & \text{if } S < 0 \end{cases} \quad [7]$$

In this study, the computed trends were considered statistically significant when the *p*-value is less or equal to 0.05 (i.e., 95% confidence level).

4.3 RESULTS

4.3.1 Historical and projected precipitation for the Limpopo Province

The average historical CORDEX ensemble mean annual precipitation (MAP) for the reference period (1976-2005) is presented in Figure 4.1. Limpopo Province has experienced a high spatial variation in annual total precipitation amount received during the reference period (1976-2005). The MAP varied from a minimum of 300 mm to a maximum of 1500 mm for some parts of the province, with a mean MAP of 740 mm during the reference period. As shown in Figure 4.1, very high annual total precipitation (> 1200 mm) was observed for the southern (South-Eastern Sekhukhune), central (South-Eastern Capricorn, Western Mopani, and Central Waterberg), as well as the northern (Central Vhembe) parts of the province.

Projected changes in MAP (mm) for Limpopo Province with reference to the baseline period (1976-2005) for the three projection time periods under RCP4.5 and RCP8.5 scenarios are depicted in Figure 4.2. Overall, the results indicate that MAP (mm) is projected mostly to decrease over the province for all the projection periods under both RCPs 4.5 and 8.5. Under the RCP 4.5 scenario, a maximum decrease of 210 mm (2006-2035) to 335 mm (2066-2095) was noted, with mean projected decline of 17 mm (2006-2035), 36 mm (2036-2065), and 54 mm (2065-2099) for the province (Figure 4.2a, c, and e). These projected highest reductions in MAP are more pronounced for the areas that receive higher annual rainfall (Figure 4.1), including the southern (South-Eastern Sekhukhune), central (South-Eastern Capricorn, Western Mopani, and Central Waterberg), and northern (Central Vhembe) parts of the province. However, MAP is projected to increase slightly (40 mm) for the south-western part (Western Waterberg) of the province under the RCP 4.5 scenario.

For the RCP 8.5 scenario, MAP is also projected to decrease with a higher magnitude in the near to far future periods over most parts of the province, compared to RCP 4.5 (Figure 4.2). A maximum projected decline in MAP of 350 mm (2036-2065) to 510 mm (2066-2095) were observed under this RCP, with mean projected decreases of 19 mm (2006-2035), 54 mm (2036-2065), and 85 mm (2065-2099) for the province (Figure 4.2b, d, and f). Similarly, the highest reductions in MAP are more pronounced for the southern (South-Eastern Sekhukhune), central (South-Eastern Capricorn, Western Mopani, and Central Waterberg) parts of the province (Figure 4.2d and f).

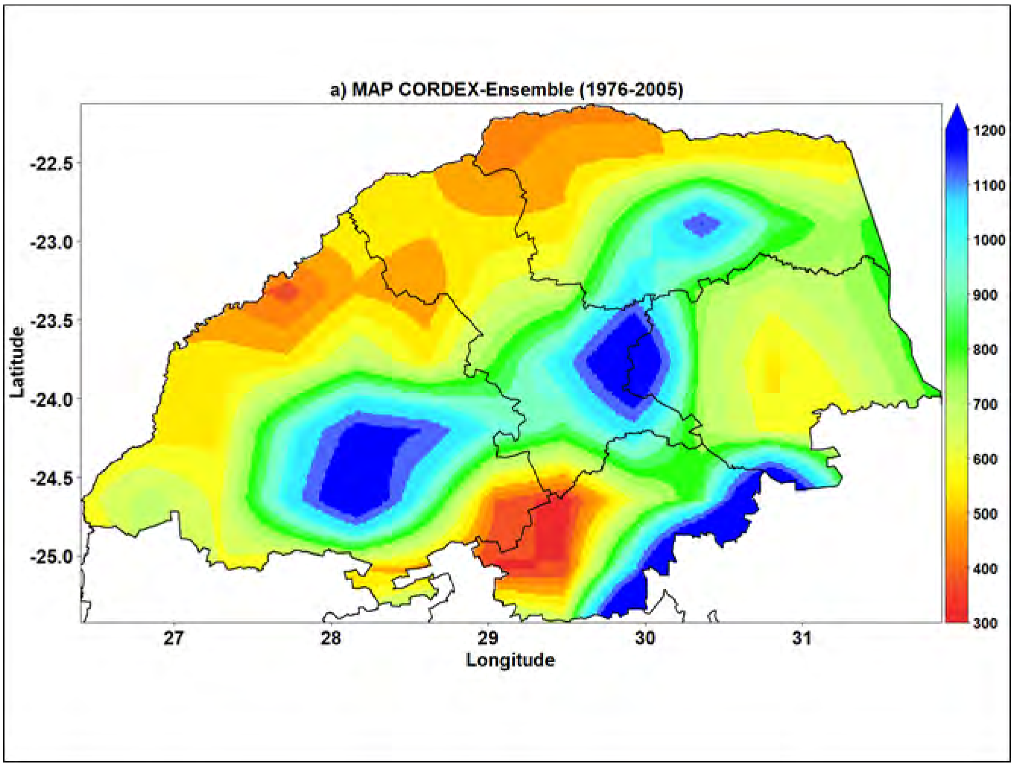

Figure 4.1 Average historical CORDEX ensemble mean annual precipitation (MAP) in mm for the Limpopo Province (1976-2005)

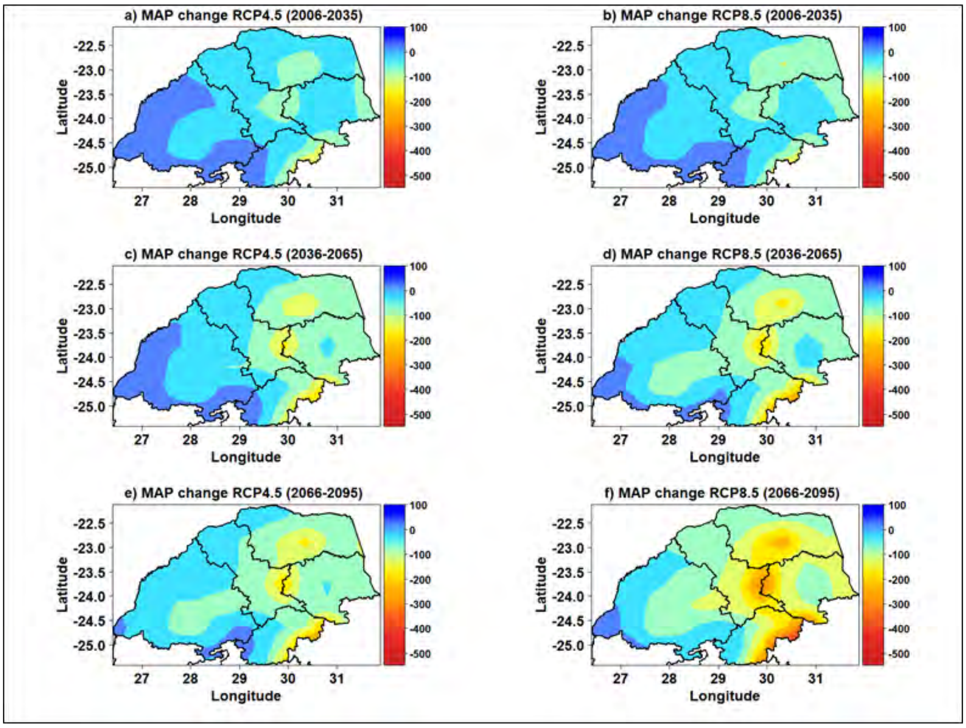

Figure 4.2 Projected changes in mean annual precipitation (MAP) in mm for Limpopo Province with reference to 1976-2005 for three projection time periods, based on RCP4.5 (a, c and e) and RCP8.5 (b, d and f) scenarios

4.3.2 Precipitation extreme indices for the Limpopo Province

4.3.2.1 Maximum 1-day Precipitation per Time Period

The highest one-day precipitation amount per time period (*rx1day*) for the reference period (1976-2005) varied from a minimum of 20 mm to a maximum of 70 mm for the province, with a mean value of 41 mm (Figure 4.3). The *rx1day* projections are presented in Figure 4.4 for the Limpopo Province under both RCP 4.5 and 8.5 scenarios. The maximum *rx1day* is projected to increase under RCP 4.5, with a mean increase of 2 mm for the period 2066-2095 (Figure 4.4e) compared to the reference period. For the RCP 8.5, rx1day projections ranged from a minimum of 20 mm to a maximum of 90 mm (Figure 4.4b, d, and f). The mean *rx1day* projections for the province show increases of 4 mm (2036-2065) and 8 mm (2066-2095) under RCP 8.5 scenario (Figure 4.4d and f). As shown in Figure 4.4, the north and eastern parts of the province are projected to receive the highest 1-day precipitation under both RCP4.5 and 8.5 scenarios for all periods including some central parts (South-Eastern Capricorn, Western Mopani, and Central Waterberg) in 2036-2065 (Figure 4.4d) and 2066-2095 (Figure 4.4f).

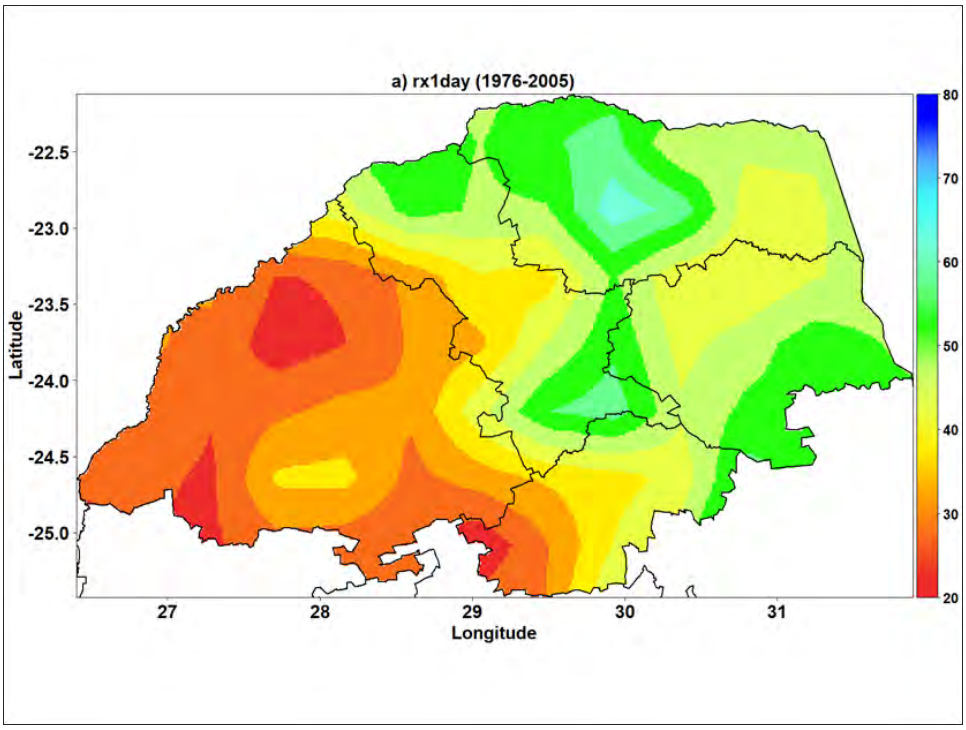

Figure 4.3 Maximum 1-day precipitation, *rx1day* (mm) climatology over the reference period (1976-2005) for Limpopo Province

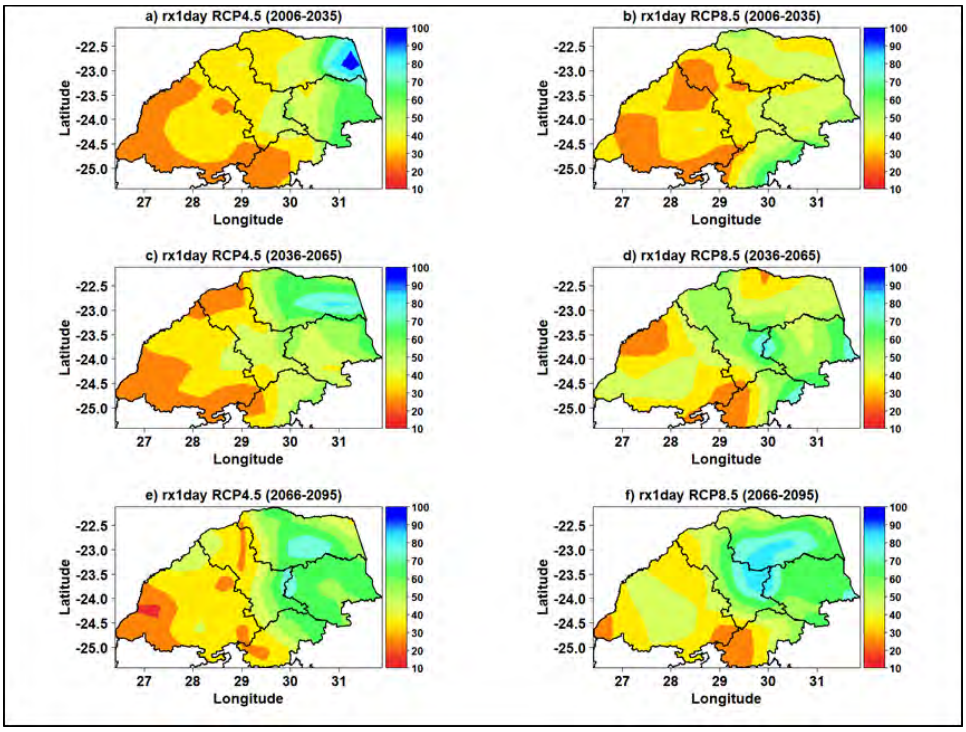

Figure 4.4 Highest 1-day precipitation (*rx1day*, mm) for the three projection time periods under RCP4.5 (a, c and e) and RCP8.5 (b, d and f) scenarios for Limpopo Province

4.3.2.2 Maximum 5-day Precipitation per Time Period

The highest five-day precipitation amount (*rx5day*) for the reference period (1976-2005) varied from a minimum of 40 mm to a maximum of 175 mm for the province, with a mean value of 90 mm (Figure 4.5a). The number of 5-day heavy precipitation periods for the reference period (1976-2005) ranged widely from a minimum of 0 to a maximum of 722 for the province, as shown in Figure 4.5b. The *rx5day* results indicate that the northern (Vhembe), central (South-Eastern Capricorn, Western Mopani, and Central Waterberg), and the southern (South-Eastern Sekhukhune) parts of the province have received the highest 5-day precipitation amount (Figure 4.5a) and the highest number of 5-day heavy precipitation during the reference period (Figure 4.5b).

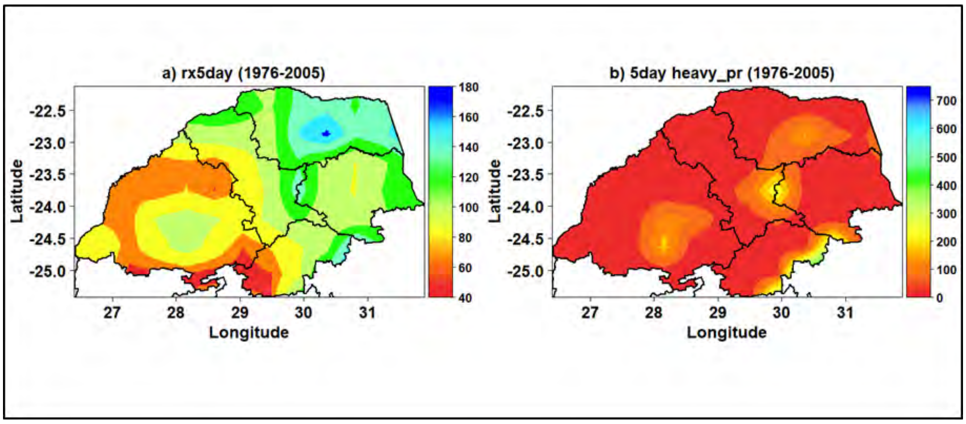

Figure 4.5 Five-day reference period (1976-2005) precipitation climatology (*rx5day*) for Limpopo Province including a) Highest five-day precipitation amount per time period (mm), and b) Number of 5-day heavy precipitation periods per time period

The projected *rx5day* 'highest five-day precipitation amount per time period (mm)' and projected changes with reference to the baseline period of the 'number of 5-day heavy precipitation periods per time period' for the three time periods under RCP4.5 and RCP8.5 scenarios are depicted in Figure 4.6 and Figure 4.7, respectively. The highest projected *rx5day* varied from a minimum of 34 mm to a maximum of 250 mm for the province, with mean values ranging from 85 to 90 mm across the three projection periods under both RCPs 4.5 and 8.5 scenarios (Figure 4.6). As shown in Figure 4.7, the north and western part of the province is projected to receive the highest number of 5-day heavy precipitation events under both RCP4.5 and 8.5 scenarios for all periods. The projections indicate a significant decrease in both the highest 5-day precipitation amount per time-period and the number of 5-day heavy precipitation periods per time period for most parts of the province, with the exception of some parts in the north and western parts of the province (Figure 4.7).

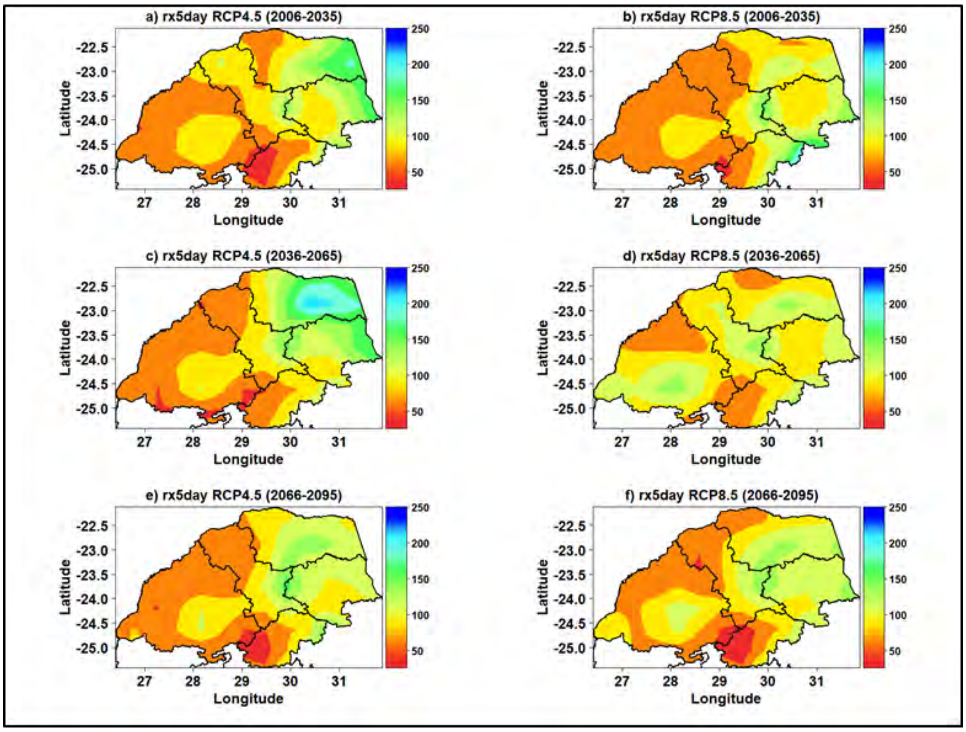

Figure 4.6 Highest 5-day precipitation (*rx5day, mm*) for the three projection time periods under RCP4.5 (a, c and e) and RCP8.5 (b, d and f) scenarios for Limpopo Province

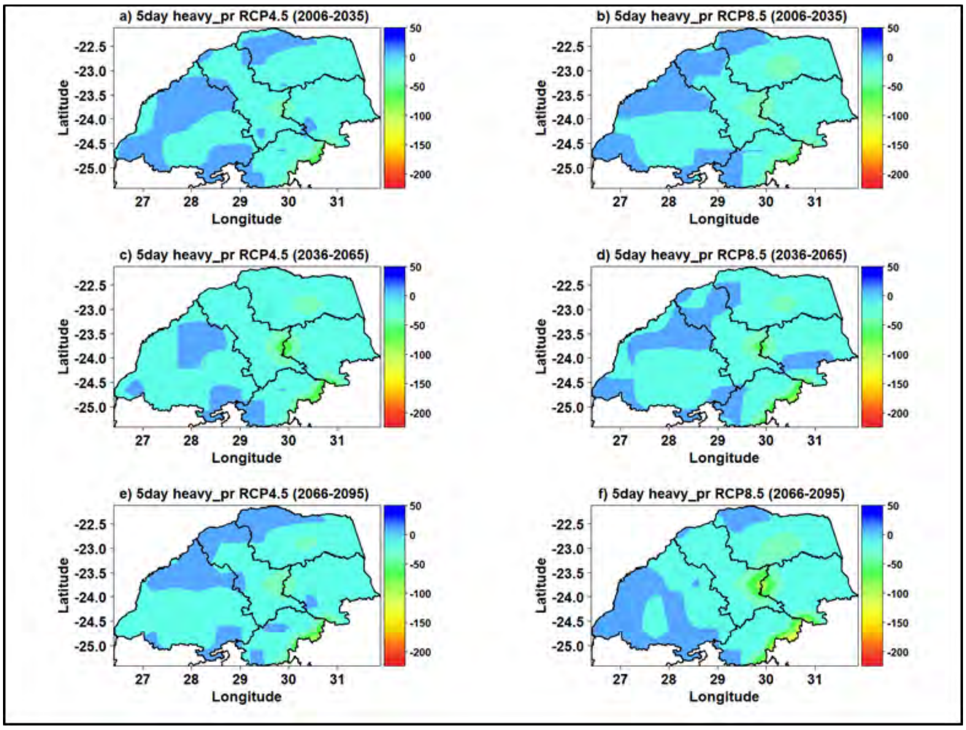

Figure 4.7 Projected changes in the number of 5-day heavy precipitation amount events per time period for the three projection time periods with reference to the 1976-2005 period under RCP4.5 (a, c and e) and RCP8.5 (b, d and f) scenarios for Limpopo Province

4.3.2.3 Simple Daily Intensity Index (SDII)

Simple Daily Intensity Index (*SDII*) values for the Limpopo Province for the reference period (1976-2005) and the three projection periods are shown in Figure 4.8 and Figure 4.9, respectively. The *SDII* is defined as the ratio of time series total precipitation to the number of rainy days (precipitation ≥ 1 mm/day). As shown in Figure 4.8 and Figure 4.9, the northern (Vhembe), central (South-Eastern Capricorn and Western Mopani), western (Central Waterberg), and southern (South-Eastern Sekhukhune) parts of the province have higher *SDII* values. The *SDII* values ranged from a minimum of 2.68 to a maximum of 9.74 for the province, with mean values ranging from 4.15 to 4.29 for the reference and all three projection periods under both RCP 4.5 and 8.5 scenarios (Figure 4.8 and Figure 4.9). There is no significant difference in *SDII* between the reference period and the three projection periods under both RCPs 4.5 and 8.5; however, mean *SDII* for the province is projected to decrease slightly (<0.1) under both RCP4.5 and 8.5 for all three projection periods (Figure 4.9).

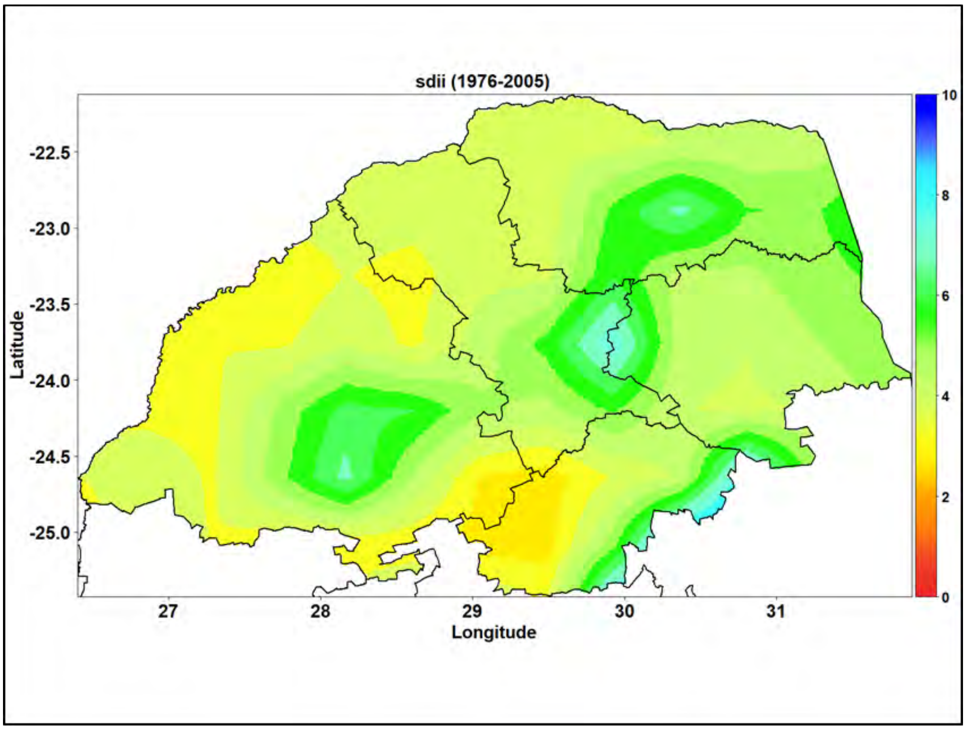

Figure 4.8 Simple Daily Intensity Index (*SDII*) for Limpopo Province over the reference period (1976-2005)

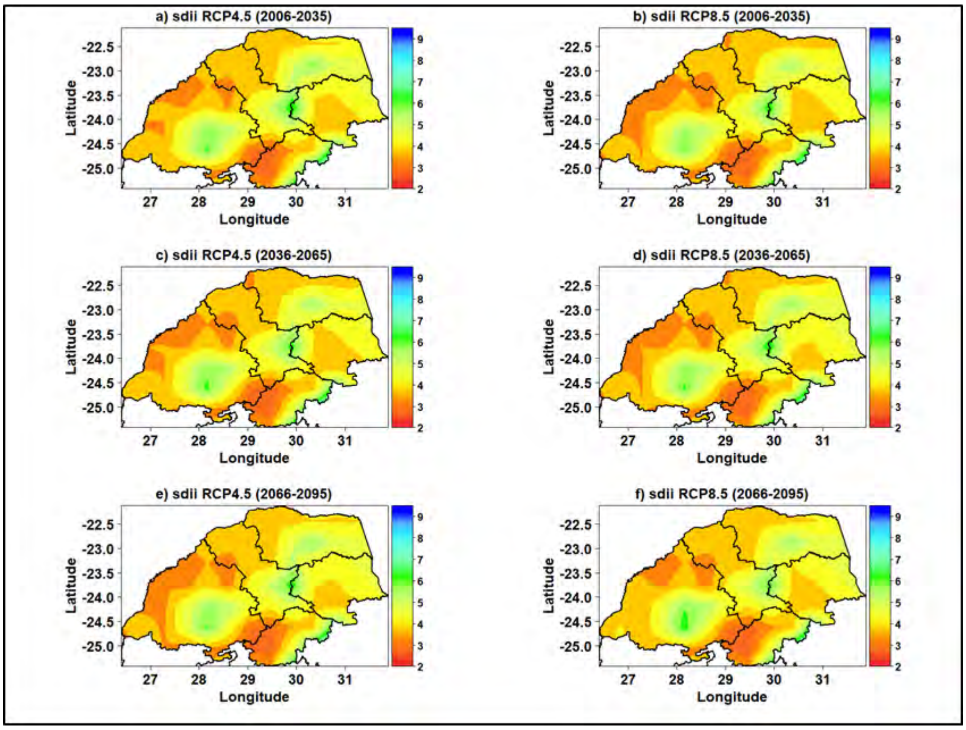

Figure 4.9 Simple Daily Intensity Index (*SDII*) for the three projection time periods under RCP4.5 (a, c and e) and RCP8.5 (b, d and f) scenarios for Limpopo Province

4.3.2.4 Number of Heavy Precipitation Days (rx10mm)

The number of heavy precipitation days index per time period (*r10mm*) for the reference period (1976-2005) and the projected changes in *r10mm* under RCP 4.5 and 8.5 for Limpopo Province are presented in Figure 4.10 and Figure 4.11, respectively. The number of heavy precipitation days with precipitation amount higher than 10 mm (*r10mm*) for the reference period (1976-2005) ranged widely from a minimum of 45 to a maximum of 3160 for the province, as shown in Figure 4.10. The mean value of *r10mm* for the province is 400. The *r10mm* results indicate that the highest values were observed for the northern (Vhembe), central (South-Eastern Capricorn and Western Mopani), western (Central Waterberg), and southern (South-Eastern Sekhukhune) parts of the province (Figure 4.10).

As illustrated in Figure 4.11, the numbers of heavy precipitation days with precipitation amount higher than 10 mm (*r10 mm*) are projected to decrease for most parts of the province for all projection periods under both RCP4.5 and 8.5 scenarios. These results indicate that areas which receive higher amounts of rainfall in the province are projected to have a maximum decline in *r10mm* (750 days) for the far future period (2066-2095) under RCP 8.5 (Figure 4.11f). However, a slight increase in *r10mm* (40-70 days) is projected for some areas in the south-western parts of the province (South and Western Waterberg) as shown in Figure 4.11.

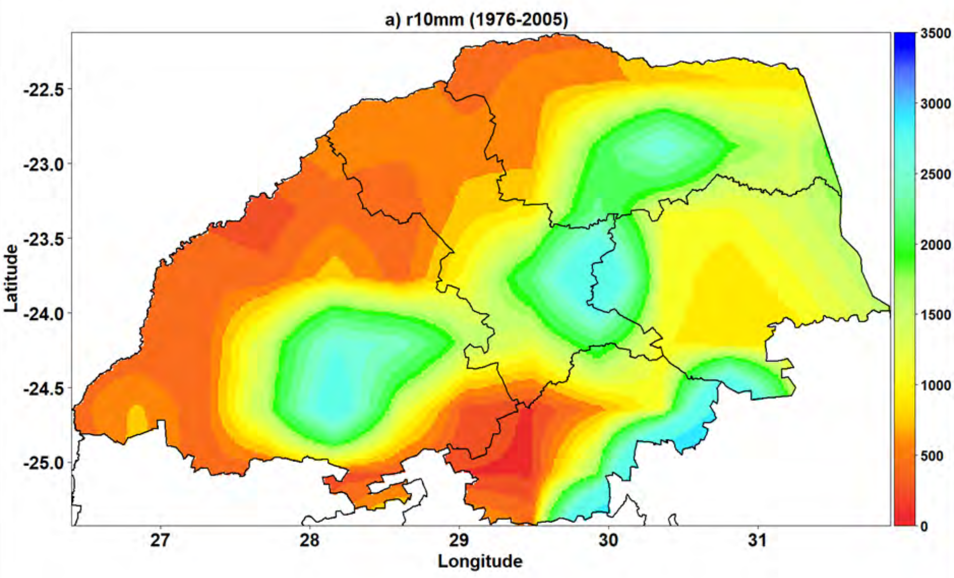

Figure 4.10 Heavy precipitation days index per time period (*r10mm*) for Limpopo Province for the reference period (1976-2005)

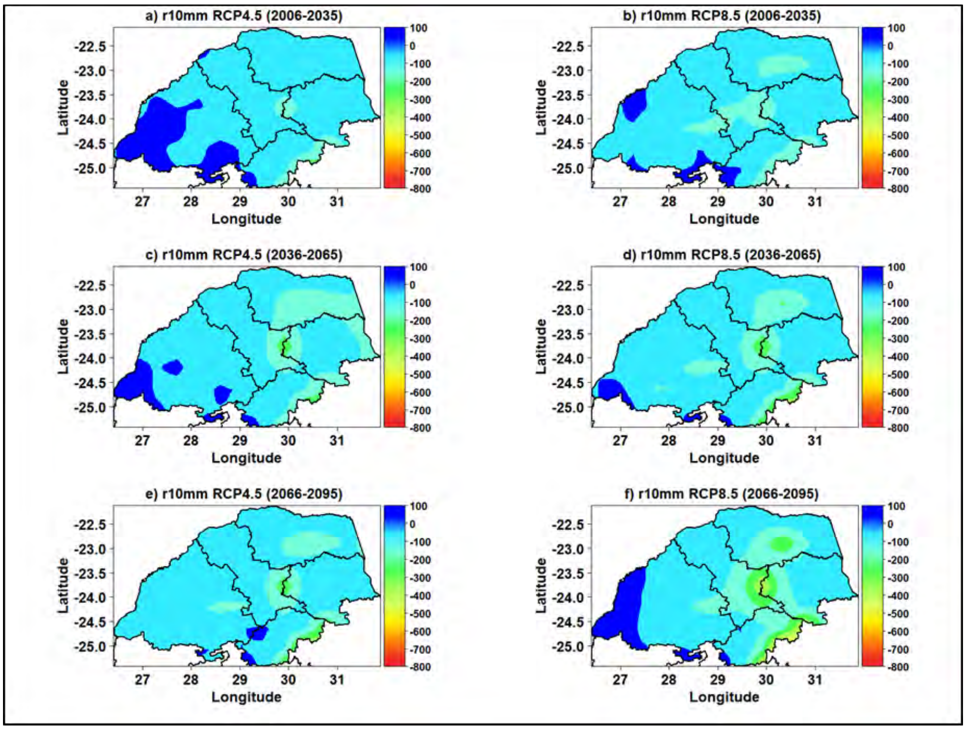

Figure 4.11 Projected changes in the number heavy precipitation days index per time period (*r10mm*) for the three projection time periods with reference to the 1976-2005 period under RCP4.5 (a, c and e) and RCP8.5 (b, d and f) scenarios for Limpopo Province

4.3.2.5 Number of Very Heavy Precipitation Days (rx20mm)

The number of heavy precipitation days index per time period (*r20mm*) for the reference period (1976-2005) is shown in Figure 4.12. The number of very heavy precipitation days with precipitation amount higher than 20 mm (*r20mm*) for the reference period (1976-2005) varied from a minimum of 1 to a maximum of 830, with mean value of 55 for the province (Figure 4.12). Similar to the *r10mm* (Figure 4.11), the *r20mm* results indicate that the highest values were observed for the northern (Vhembe), central (South-Eastern Capricorn and Western Mopani), and western (Central Waterberg), and southern (South-Eastern Sekhukhune) parts of the province (Figure 4.12).

The projected changes in *r20mm* under RCP 4.5 and 8.5 scenarios for Limpopo Province are presented in Figure 4.13. As shown in Figure 4.13, the number of heavy precipitation days with precipitation amount higher than 20 mm *(r20mm*) are also projected to decrease for most parts of the province for all projection periods under both RCP4.5 and 8.5 scenarios. Some areas which receive a higher amount of rainfall in the province are projected to have a maximum decline in *r20mm* (260 days) for the near and far future periods under RCP 8.5 (Figure 4.13). However, a slight increase in *r20mm* (2-20 days) is projected for some areas in the south-western parts of the province (South and Western Waterberg and Sekhukhune) as shown in Figure 4.13.

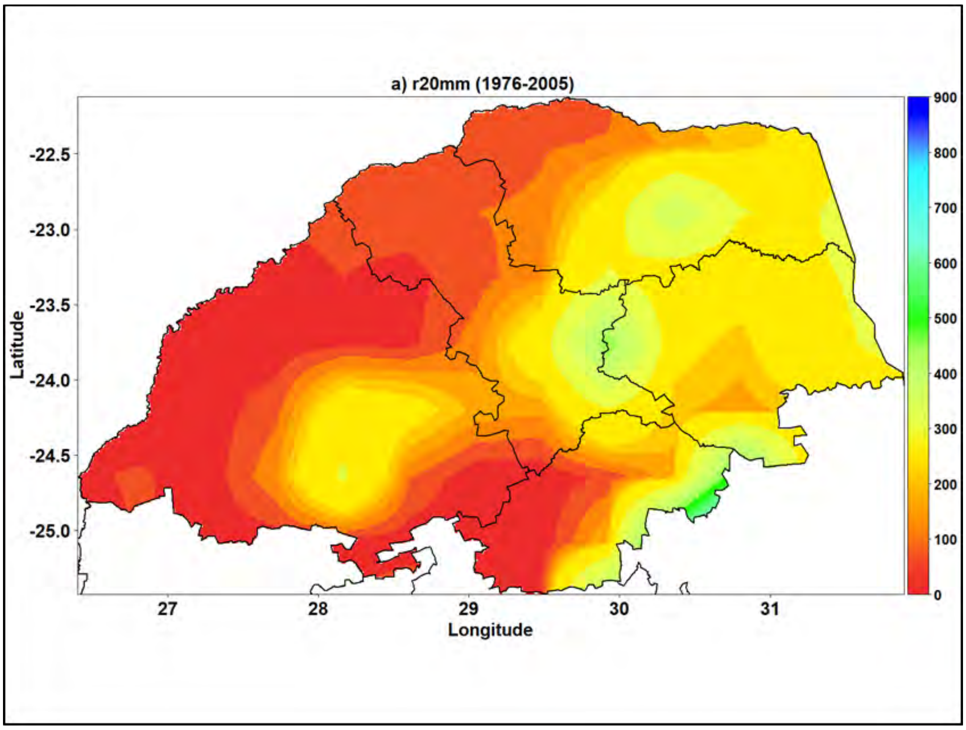

Figure 4.12 Very heavy precipitation days index per time period (*r20mm*) for Limpopo Province for the reference period (1976-2005)

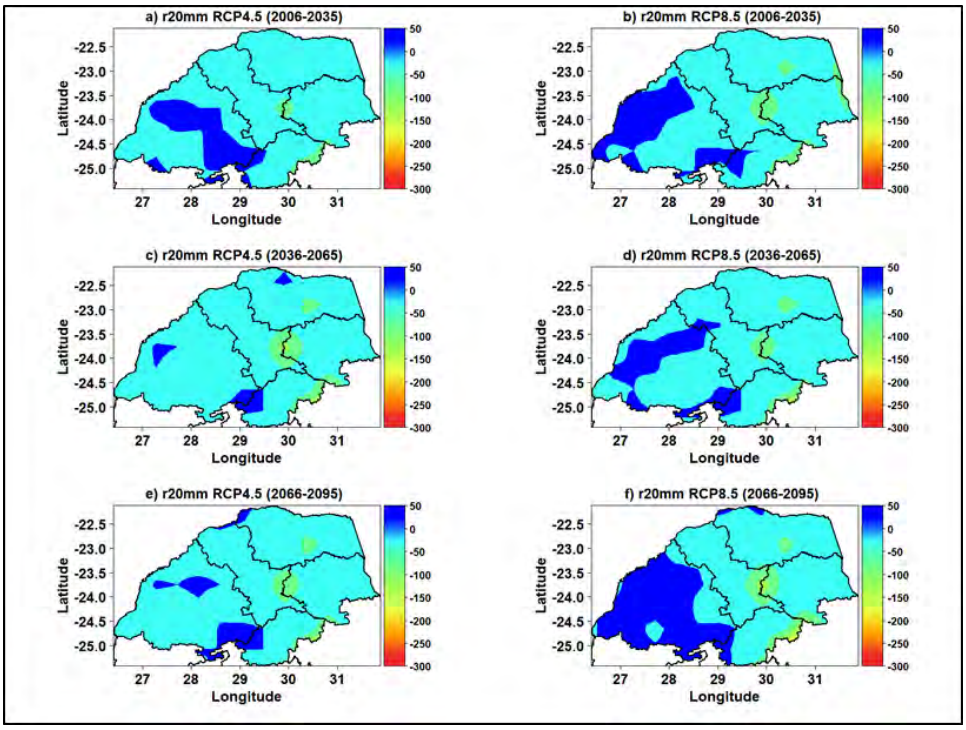

Figure 4.13 Projected changes in the number of very heavy precipitation days index per time period (*r20mm*) for the three projection time periods with reference to the 1976-2005 period under RCP4.5 (a, c and e) and RCP8.5 (b, d and f) scenarios for Limpopo Province

4.3.2.6 Consecutive Dry Days (CDD)

The number of consecutive dry days index (CDD) per time period for the reference period (1976-2005) varied from a minimum of 30 to a maximum of 185 for the province, with a mean value of 120 (Figure 4.14a). The number of CDD periods with more than 5 days per time period ranged from a minimum of 120 to a maximum of 307 for the province as shown in Figure 4.14b. The north-western (Vhembe, Capricorn, and Waterberg) and the southern (South-Western Sekhukhune and South-Eastern Waterberg) parts of the province have experienced the highest number of CDD (maximum length of dry spells) during the reference period (Figure 4.14a). However, the highest number of CDD periods with more than 5 days per time period was observed for the north-eastern parts (Vhembe and Mopani) of the province (Figure 4.14b).

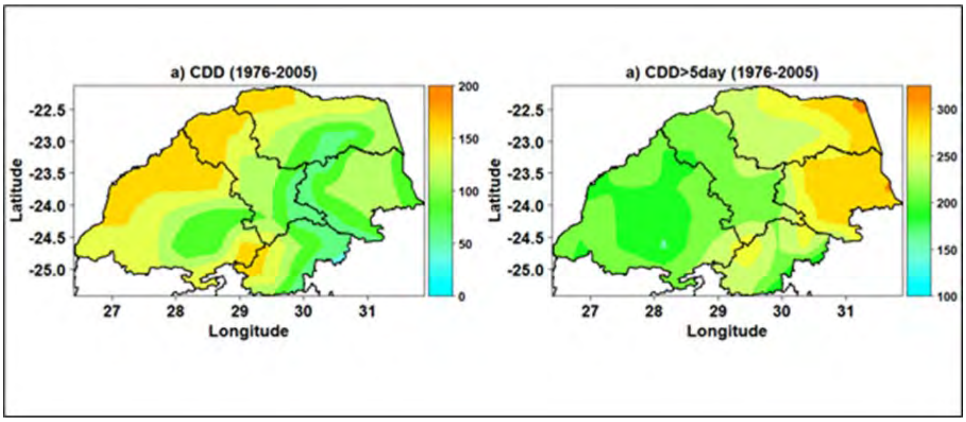

Figure 4.14 Consecutive dry days index (CDD) for Limpopo Province including a) Number of consecutive dry days (CDD) per time period for the reference period (1976-2005), and b) Number of CDD periods with more than 5days per time period for the reference period (1976-2005)

The projected changes in consecutive dry days index per time period (CDD), as well as the CDD periods with more than 5 days per time period, are shown in Figure 4.15 and Figure 4.16 for Limpopo Province, respectively. Based on the results, CDD (based on days of rainfall with less than 1mm) is projected to increase for most parts of the Limpopo Province except for the western (parts of Waterberg District) and the north-eastern (Vhembe and Mopani) parts of the province under both RCPs 4.5 and 8.5 (Figure 4.15). The projected CDD for the province is likely to increase by a maximum of 45 to 85 days under both RCP4.5 and RCP8.5 compared to the reference period. The mean number of CDD periods with more than 5 days per time period will decrease by 1 to 4 days under RCP4.5 and by 8 to 26 days under RCP8.5 compared to the reference period (Figure 4.16). However, the maximum values of the number of CDD periods with more than 5 days per time period for the province will increase by 40 to 75 days under both RCP4.5 and RCP8.5 compared to the reference period (not included in this report).

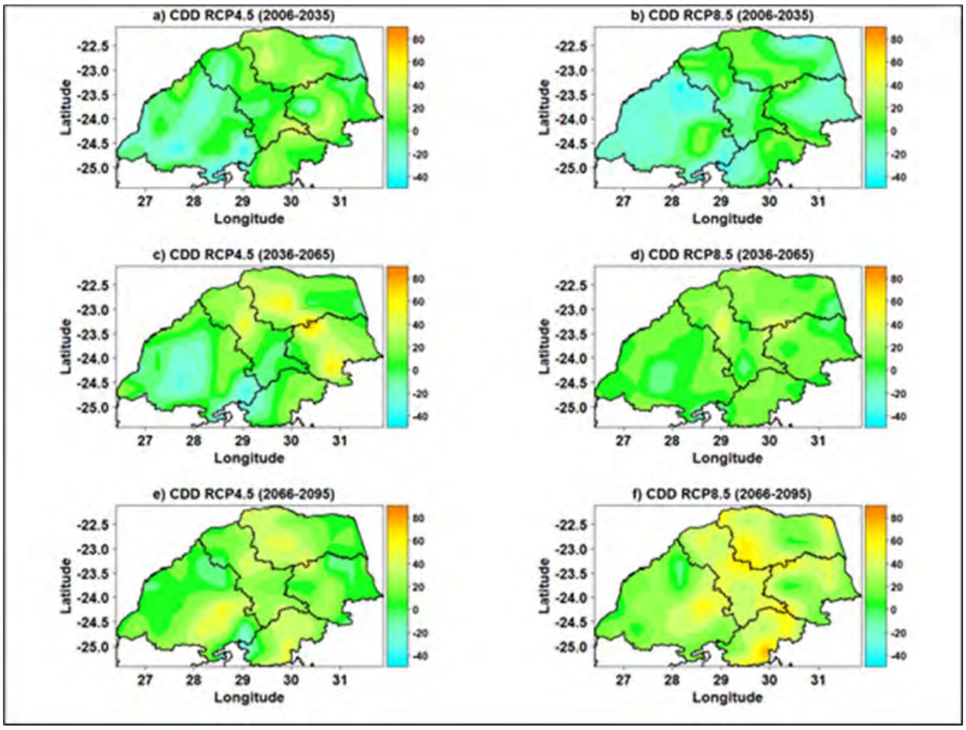

Figure 4.15 Projected changes in the number consecutive dry days index per time period (CDD) for the three projection time periods with reference to the 1976-2005 period under RCP4.5 (a, c and e) and RCP8.5 (b, d and f) scenarios for Limpopo Province

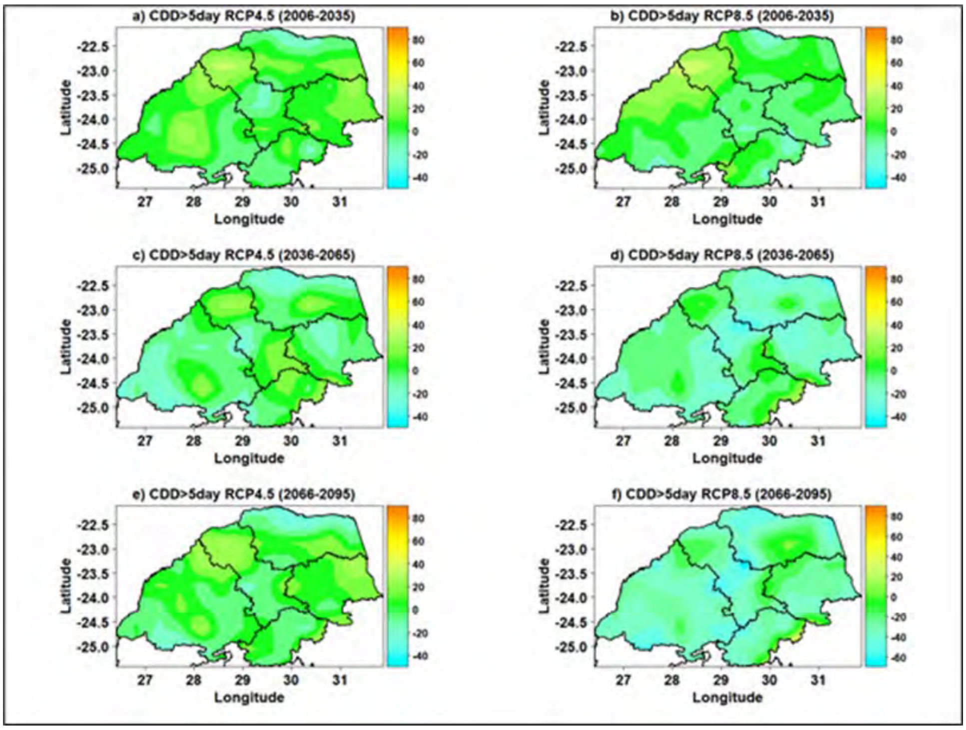

Figure 4.16 Projected changes in the number of CDD periods with more than 5 days per time period for the three projection time periods with reference to the 1976-2005 period under RCP4.5 (a, c and e) and RCP8.5 (b, d and f) scenarios for Limpopo Province

4.3.2.7 Consecutive Wet Days (CWD)

The number of consecutive wet days index (CWD) per time period for the reference period (1976-2005) varied from a minimum of 20 to a maximum of 205 for the province, with a mean value of 60 (Figure 4.17a). The number of CWD periods with more than 5 days per time period ranged from a minimum of 91 to a maximum of 300 for the province, as shown in Figure 4.17b. The CWD results show that the northern (Vhembe), central (South-Eastern Capricorn, Western Mopani, and Central Waterberg), and the southern (South-Eastern Sekhukhune) parts of the province have experienced the highest CWD for the reference period (Figure 4.17a). As shown in Figure 4.17b, the highest number of CWD periods with more than 5days per time period is observed for the central parts of the Limpopo and during the reference period (1976-2005).

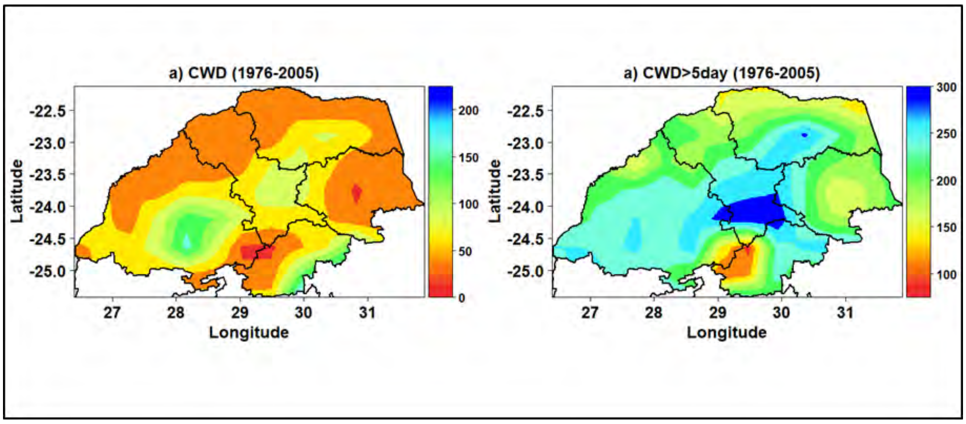

Figure 4.17 Consecutive wet days index (CWD) for Limpopo Province including a) Number of consecutive wet days (CWD) per time period for the reference period (1976-2005), and b) Number of CWD periods with more than 5 days per time period for the reference period (1976-2005)

Projected changes in the number of CWD per time period and the number of CWD periods with more than 5 days per time period with reference to the baseline period (1976-2005) for the Limpopo Province under RCP4.5 and RCP8.5 scenarios are shown in Figure 4.18 and Figure 4.19, respectively. The projections indicate a decrease in both the number of CWD per time period and the number of CWD periods with more than 5 days per time period for most parts of the province, as shown in Figure 4.18 and Figure 4.19. A maximum decline in the number of CWD (70 days) is noticed for the southern and northern parts of the province under RCP 8.5 for the far future period (Figure 4.18). However, the number of CWD periods with more than 5 days per time period is projected to increase for the southern and south-western parts of the province under both RCPs 4.5 and 8.5 (Figure 4.19).

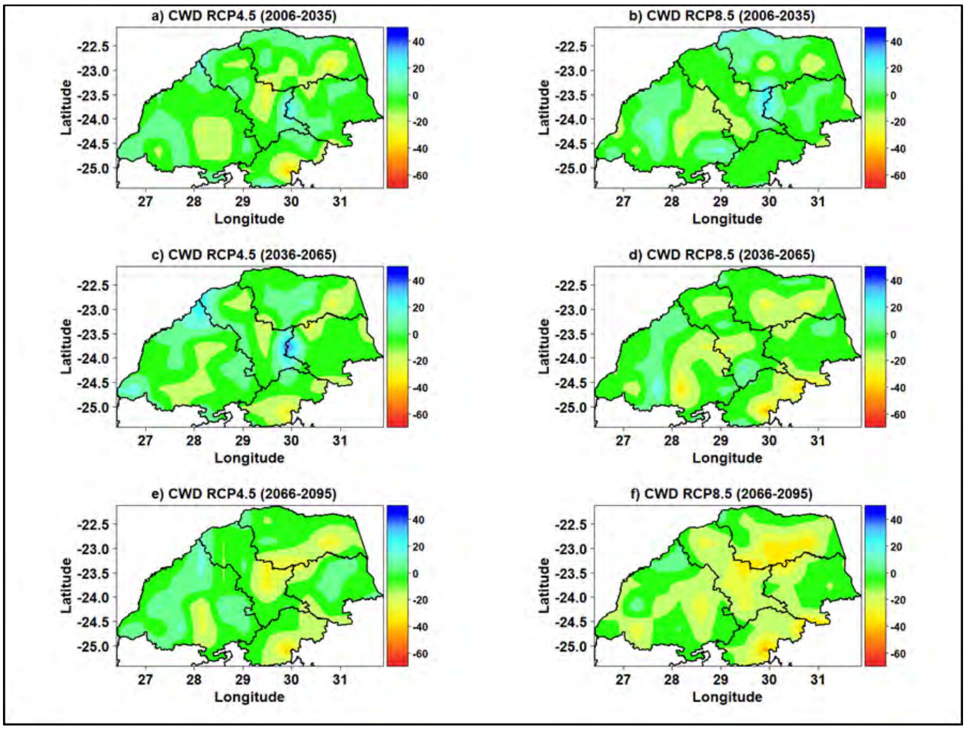

Figure 4.18 Projected changes in the number consecutive wet days index per time period (CWD) for the three projection time periods with reference to the 1976-2005 period under RCP4.5 (a, c and e) and RCP8.5 (b, d and f) scenarios for Limpopo Province

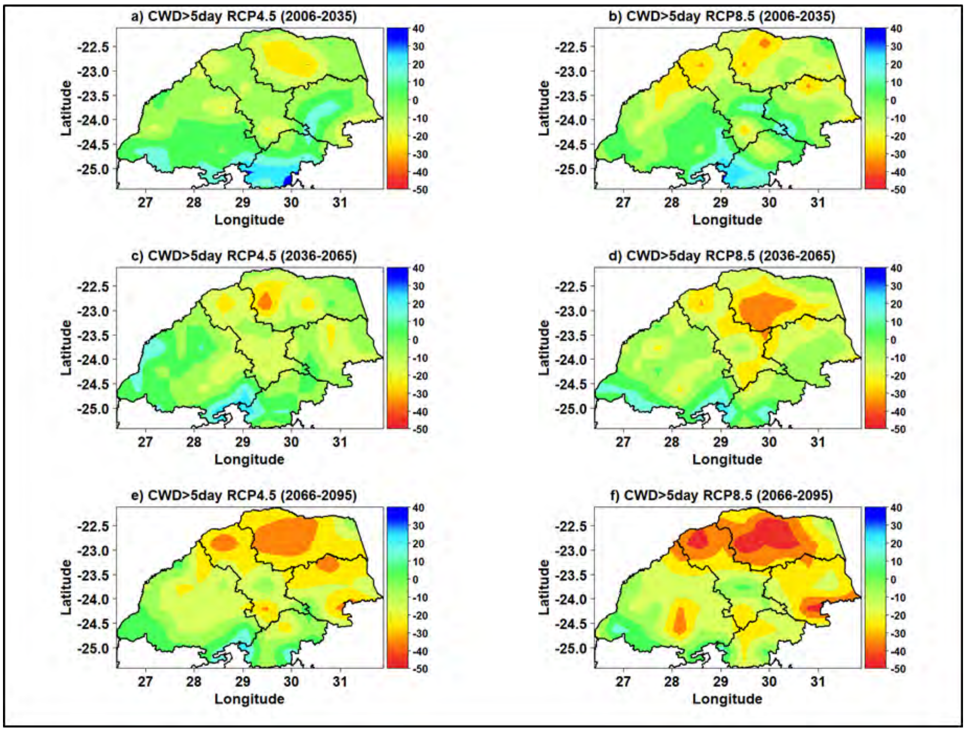

Figure 4.19 Projected changes in the number of CWD periods with more than 5 days per time period for the three projection time periods with reference to the 1976-2005 period under RCP4.5 (a, c and e) and RCP8.5 (b, d and f) scenarios for Limpopo Province

4.3.2.8 Very Wet Days (r95p)

The *r95p* index is defined as the percentage of wet days where the daily precipitation amount is greater than the 95th percentile of the daily precipitation amount on wet days for any given reference period. The projections for the very wet days with respect to the 95th percentile of the reference period (*r95p*) under RCP4.5 and RCP8.5 for Limpopo Province are shown in Figure 4.20. The percentage of wet days where the daily precipitation amount is greater than the 95th percentile of the daily precipitation amount at wet days for the reference period (*r95p*) varied between 4 to 10 under RCP 4.5 as shown in Figure 4.20a, c, and e. Similarly, the range of *r95p* values for Limpopo Province under RCP8.5 was between 3 and 11 for all projection periods (Figure 4.20b, d, and f). The highest percentage increase in *r95p* is noticed for some areas of the northern (North-Western Vhembe), western (Western Waterberg), and southern (Southern Sekhukhune) parts of the province.

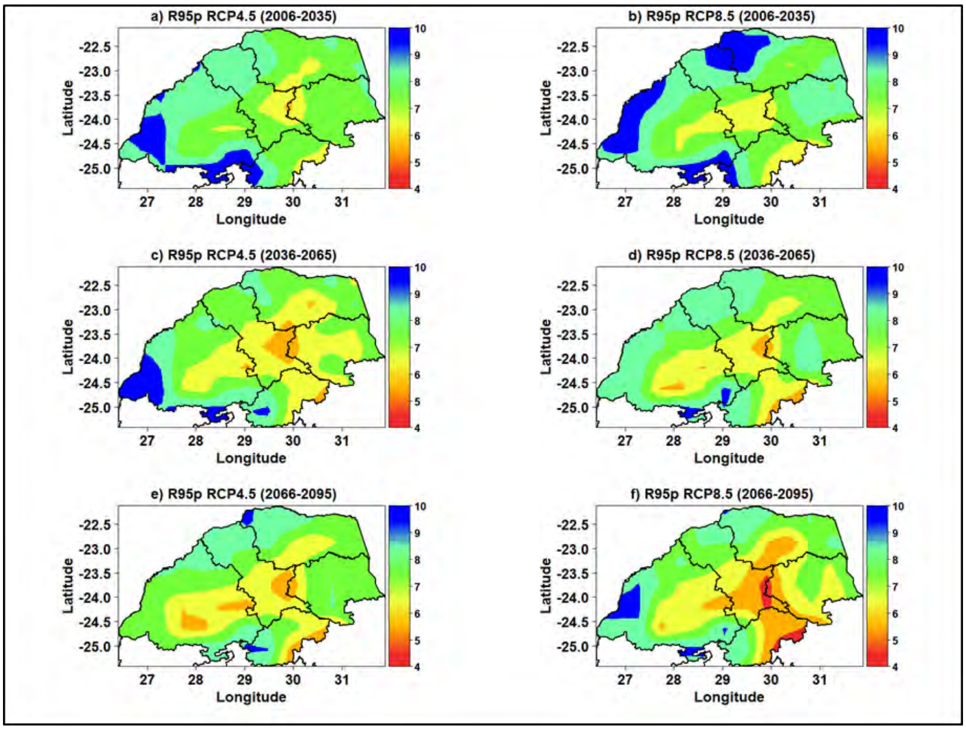

Figure 4.20 Projected changes in very wet days (*r95p*) for the three projection time periods with reference to the 1976-2005 period under RCP4.5 (a, c and e) and RCP8.5 (b, d and f) scenarios

4.3.3 Characteristics of drought in Limpopo Province

4.3.3.1 Drought trends based on SPI and SPEI

The SPEI and SPI trends computed across the three projected periods under the RCP4.5 and 8.5 scenarios are presented in Figure 4.21 to Figure 4.26. In each figure, the SPEI and SPI trends are presented on the top and bottom panels, respectively. Negative trends indicate that the province is likely to experience increased drought conditions over the projected period, due to various factors such as delayed or reduced rainfall, coupled with hot temperatures, as well as human-induced climate factors such as land use/land cover and deforestation, among others. Positive trends signal wet conditions over the province, which provide a good opportunity for groundwater and other reservoirs to recharge. Such conditions may cause flooding, particularly in areas prone to floods.

In general, the projected trends presented in this study fluctuate between the two (SPI and SPEI) drought indicators, across the projected (i.e., 2006-2035, 2036-2065, and 2066-2095) and accumulation periods (i.e., 3-, 6- and 12-month) as well as the RCP pathways. In particular, negative trends in SPEI under both the RCP4.5 and 8.5 scenarios are observed across all three accumulated (3-, 6- and 12-month) periods for the three projected (current, near- and distant) epochs. However, this is with the exception of SPEI trends for the far-future under the RCP4.5 scenario, which is dominated by subtle positive trends over most of the Limpopo Province. In addition, negative trends in SPI under RCP8.5 are observed across the projected and accumulation periods. Simulations under RCP4.5 scenario depict a decreasing and increasing trend towards the south-eastern and the western parts of the province, respectively, for both the current and near-future epochs. Projections for the far future under RCP4.5 depict positive trends across the Limpopo Province.

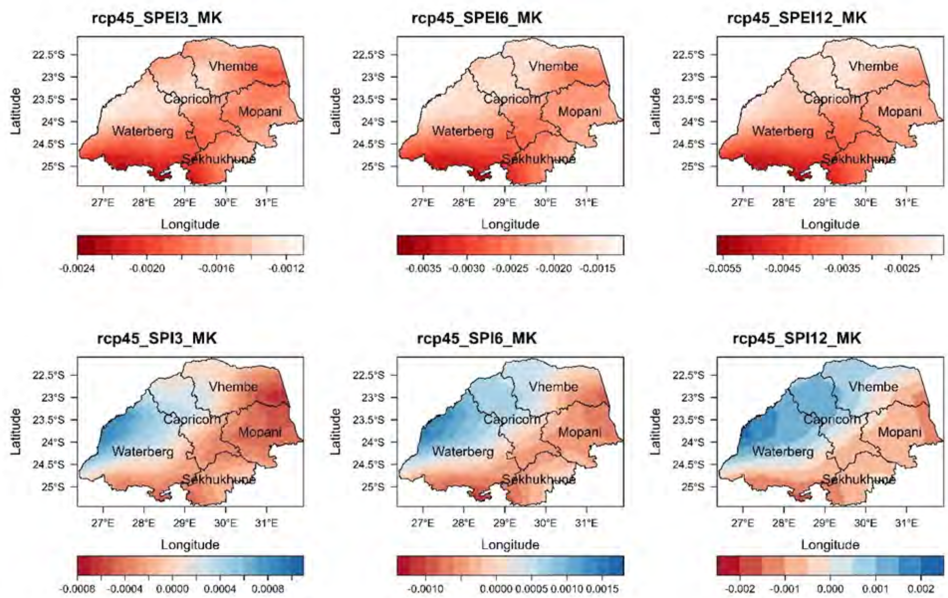

Figure 4.21 Projected trends in SPEI and SPI across accumulation periods for 2006-2035 projections based on RCP4.5 scenario

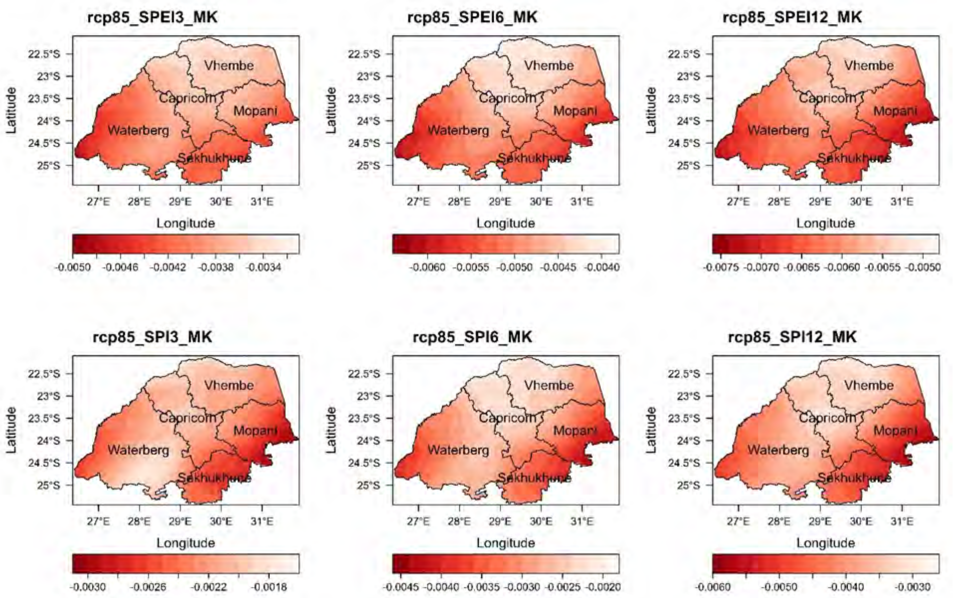

Figure 4.22 Projected trends in SPEI and SPI across accumulation periods for 2006-2035 projections based on RCP8.5 scenario

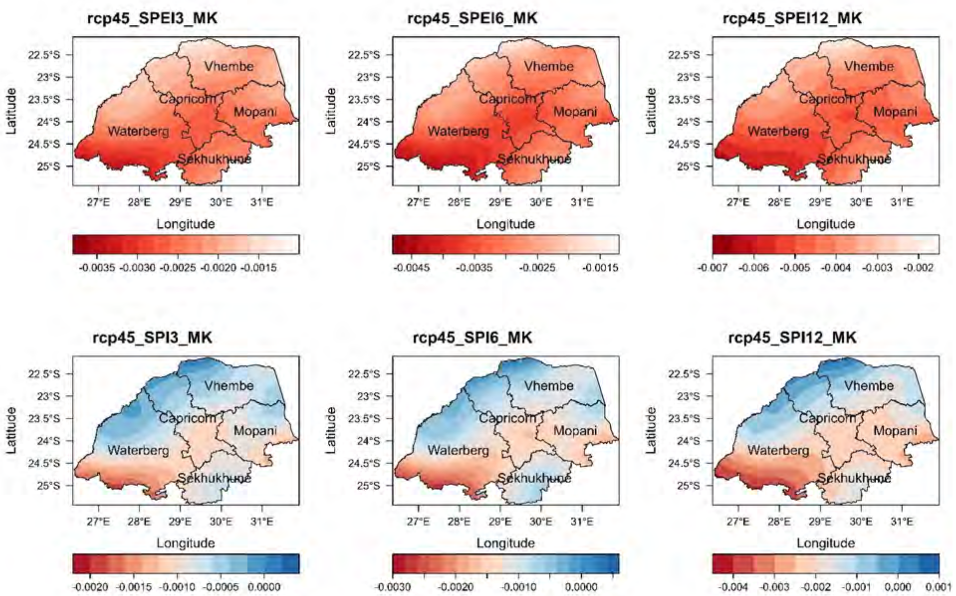

Figure 4.23 Projected trends in SPEI and SPI across accumulation periods for 2036-2065 period based on RCP4.5 scenario

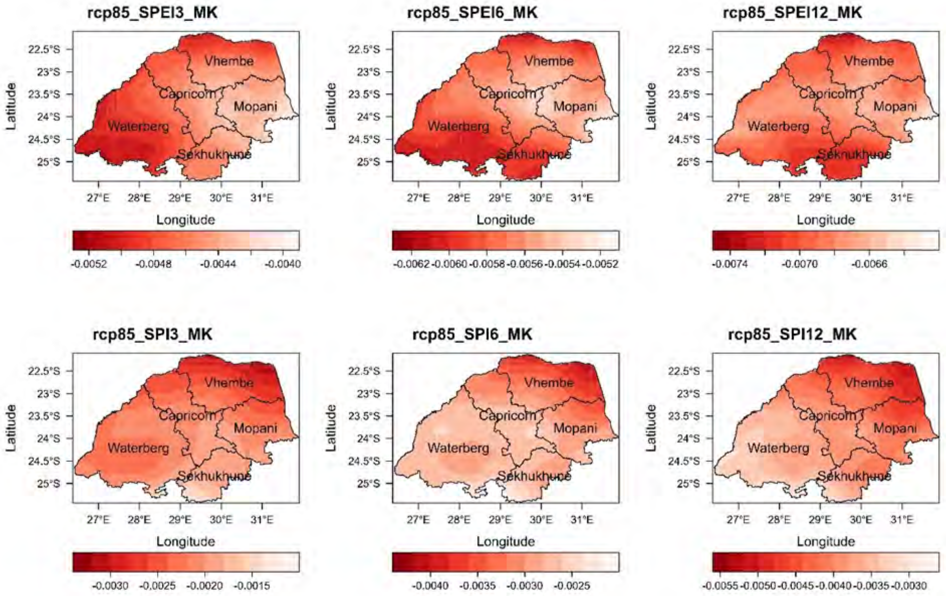

Figure 4.24 Projected trends in SPEI and SPI across accumulation periods for 2036-2065 period based on RCP8.5 scenario

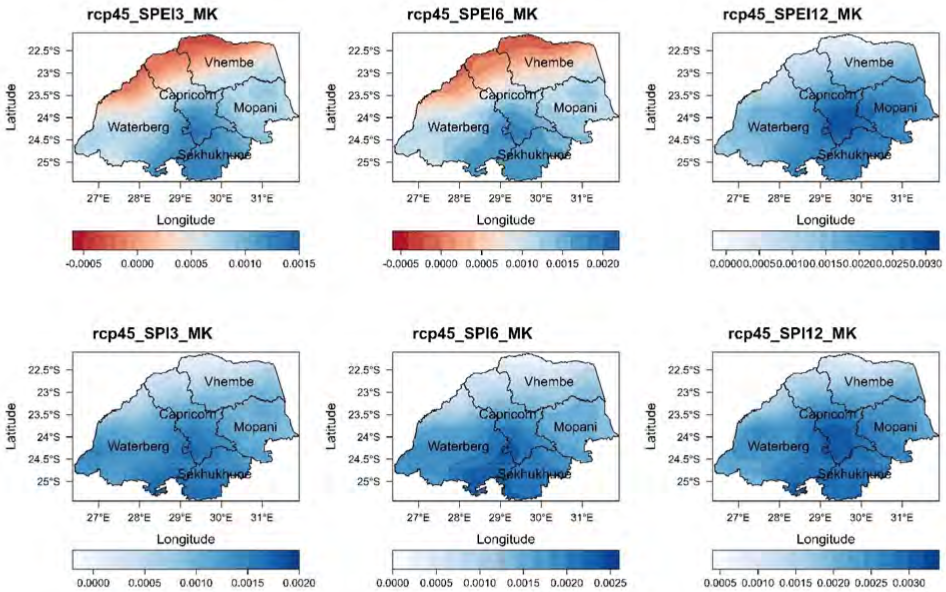

Figure 4.25 Projected trends in SPEI and SPI across accumulation periods for 2066-2095 period based on RCP4.5 scenario

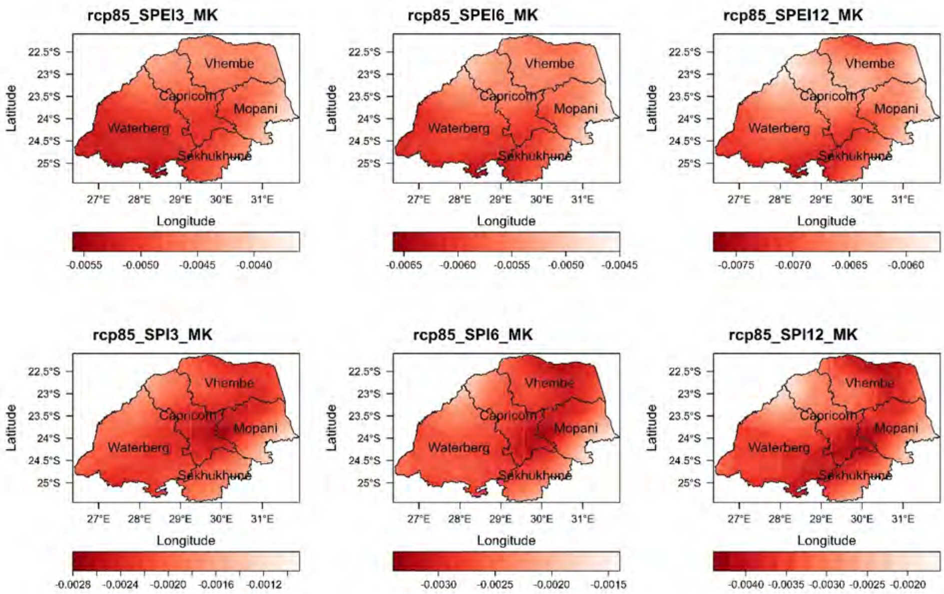

Figure 4.26 Projected trends in SPEI and SPI across accumulation periods for 2066-2095 period based on RCP8.5 scenario

4.3.3.2 Variability and trend characteristics in drought duration and severity

Statistical characteristics of Drought Duration (DD) and Duration Severity (DS) across the three projected epochs under the RCP4.5 and RCP8.5 are presented in this section. The analysis of DD and DS characteristics is studied and described in terms of spatial median values and trends, both calculated using projected SPEI 3-, 6- and 12-month values across the Limpopo Province. In each figure, under each RCP scenario simulation, the first and second columns from the left depict the spatial distribution of the median values and trends of DD or DS across the 3-, 6- and 12-month accumulation timescales. The spatial distribution of the median and trends in DD under RCP4.5 and 8.5 for 2006-2035 period are shown in Figure 4.27 and Figure 4.28, respectively.

In general, the projected results show positive trends in DD over the Limpopo Province across the three accumulated timescales and under both RCP4.5 and RCP8.5 scenarios. In particular, a large area of the province presents a strong positive duration trend for higher timescales (6- and 12-month) under both RCP scenarios. Trends in most parts of the province were statistically significant at the 0.05 significance level (results not shown). Projected drought duration varies across the timescales and scenarios. Persistent and longer droughts are observed for higher timescales, with parts of Vhembe, Waterberg, and the northern part of Capricorn District Municipalities reaching maximum drought duration. Projections for RCP8.5 indicate a spatial shift in DD, particularly for 6- and 12-month accumulation periods.

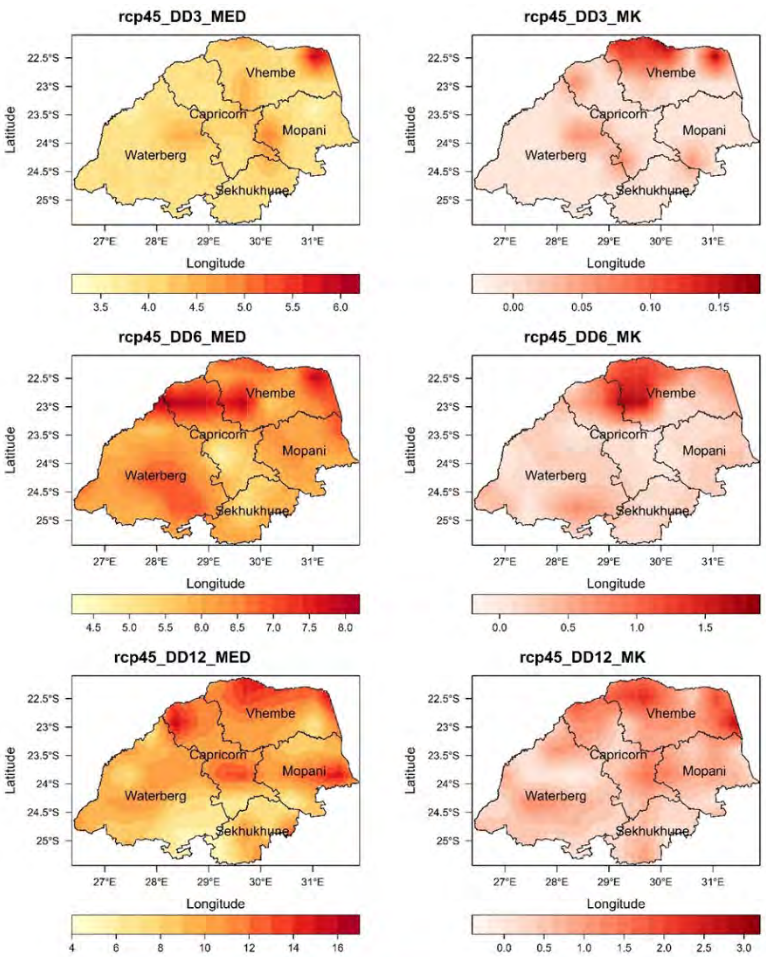

Figure 4.27 Spatial distribution of drought duration median (1st column) and trends (2nd column) computed from SPEI 3-, 6- and 12-month timescales for 2006-2035 projections under RCP4.5 scenario

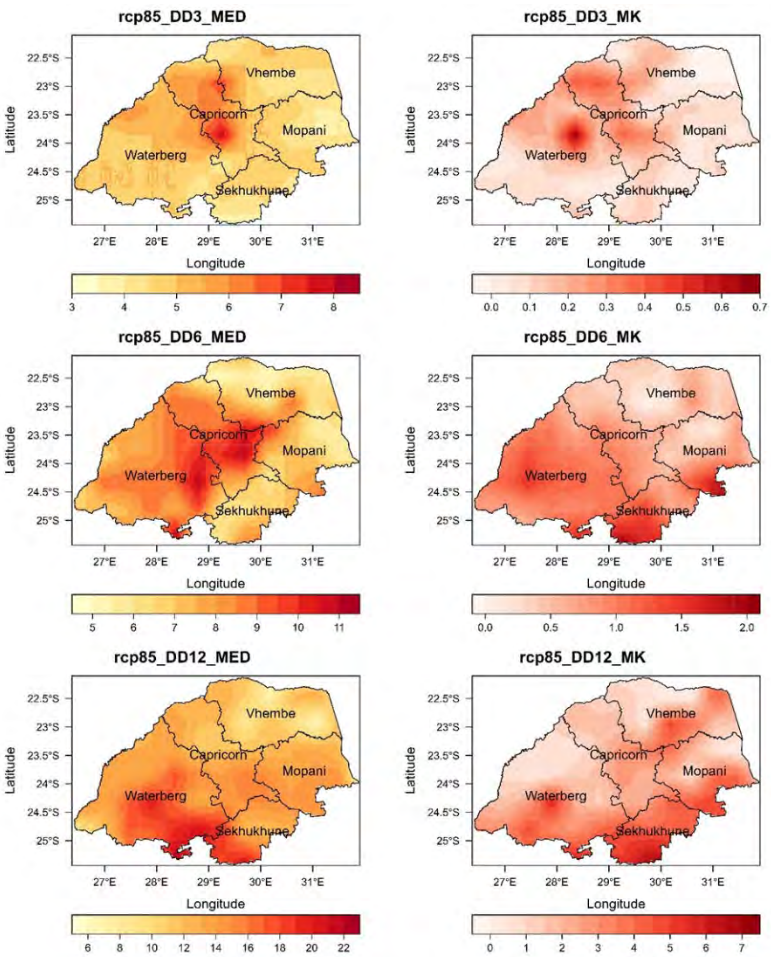

Figure 4.28 Same as Figure 4.27 but for RCP8.5 scenario

Figure 4.29 and Figure 4.30 depict spatial distribution of median DS, and trends under the RCP4.5 and 8.5 scenarios, respectively, for 2005-2036 projected period. The results indicate that drought is less severe in the current climatology for most parts of the province, particularly when considering SPEI 3 under RCP4.5 and 8.5 scenarios. There is a spatial shift in maximum severity based on SPEI at 6- and 12-month timescales under both RCP scenarios. Results also show negative and positive trends in DS, particularly under RCP4.5, for 3- and 12-month timescales. In general, positive trends in DS dominate over large parts of the Limpopo Province across the RCP4.5. and 8.5 scenarios.

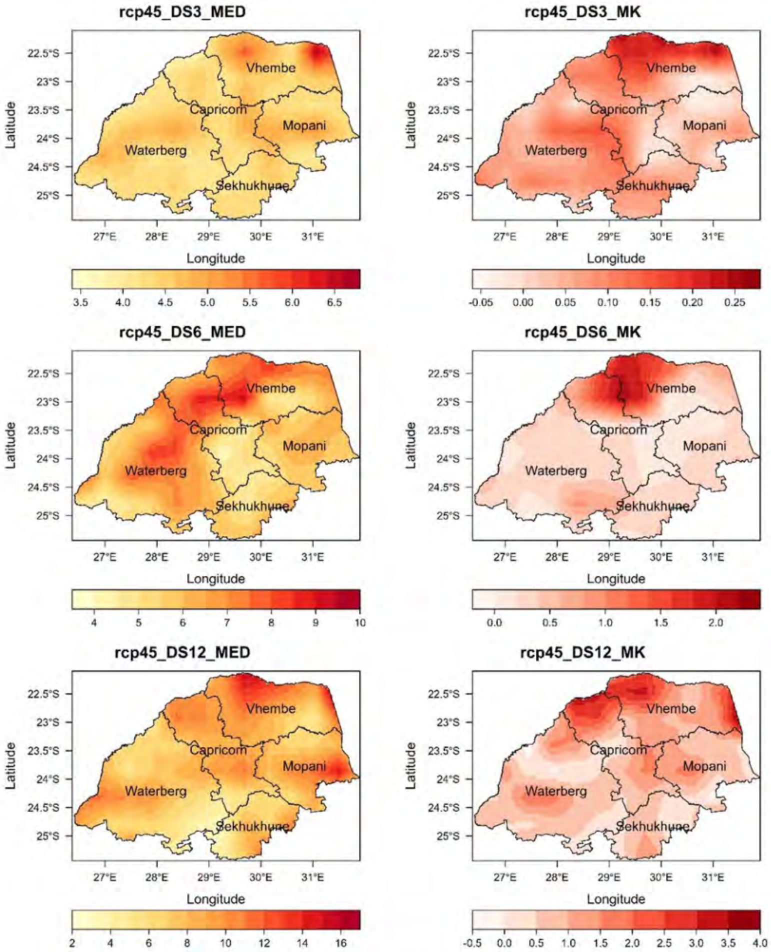

Figure 4.29 Spatial distribution of drought severity median (1st column) and trends (2nd column) computed from SPEI 3-, 6- and 12-month timescales for 2006-2035 projections under RCP4.5 scenario

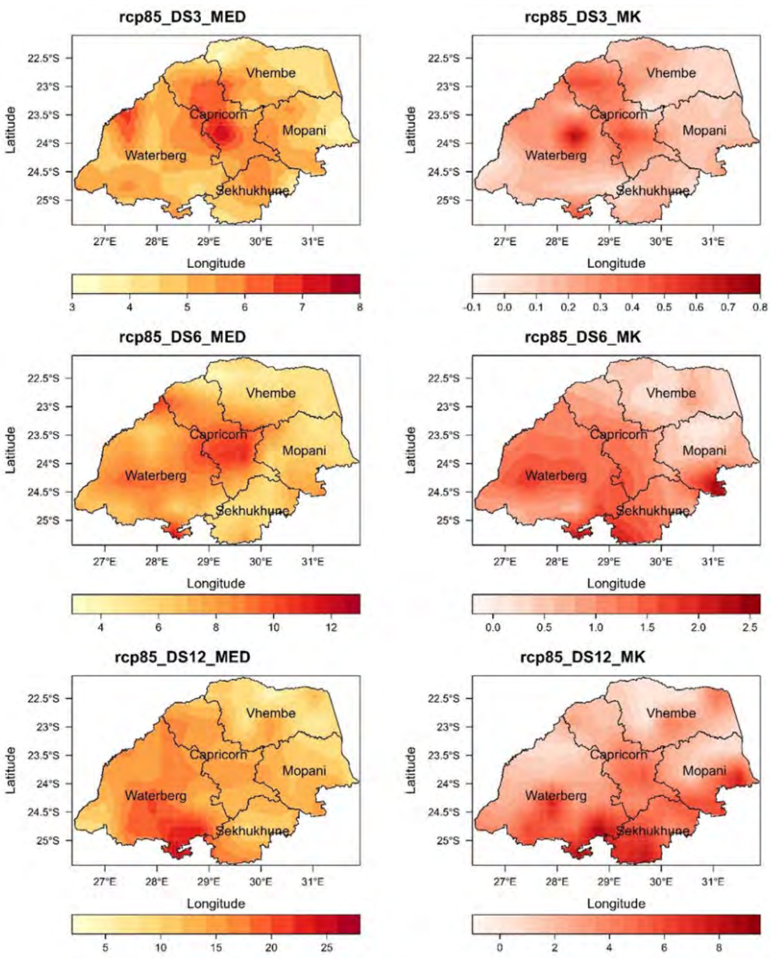

Figure 4.30 Same as Figure 4.29 but for RCP8.5 scenario

Results for near-future DD projections are shown Figure 4.31 and Figure 4.32 for RCP4.5 and 8.5, respectively. Projected median DD ranges between approximately 3 to 5 months for 3-month, 4-8 months for 6-month and 4-14 months for the 12-month accumulated period under RCP4.5. Projection results for 3-month accumulation periods indicate that drought will last longer in the central parts of Capricorn and the southern regions of the Waterberg District Municipalities. Maximum DD is also projected for the 12-month accumulation period in the southern parts of Capricorn and Mopani District Municipalities. Simulations under RCP8.5 depict a slight increase in DD, particularly for 6- and 12-month accumulation periods. Drought is expected to last longer in parts of Vhembe and Waterberg District Municipalities, based on a 12-month accumulation period. Projections for RCP8.5 indicate a spatial shift in longer DD, particularly for 6- and 12-month accumulation periods. Most parts of the Limpopo Province depict positive trends across the timescales and RCP scenarios, suggesting increased drought duration.

According to projection results presented in Figure 4.33 (RCP4.5) and Figure 4.34 (RCP8.5), drought is expected to be less severe in most parts of the province. There is a spatial shift in drought severity under both RCP4.5 and 8.5 scenarios. While results for RCP4.5 depict highly variable severity, projections under RCP8.5 depict consistent spatial distribution in drought severity. Drought is projected to be more severe in pocket areas of the following district municipalities: Capricorn and Waterberg for a 3-month, Vhembe for a 6-month, and Mopani for a 12-month accumulation period, under RCP4.5. Similarly, RCP8.5 simulations depict high DS in pocket areas of Vhembe and Waterberg, Vhembe, Mopani, and Waterberg, as well as Vhembe and Waterberg District Municipalities for 3-, 6-, and 12-month accumulation periods, respectively. Positive trends dominate across the Limpopo Province under both RCP4.5 and 8.5 scenarios, suggesting that DS is projected to increase during the 2036-2065 projected period.

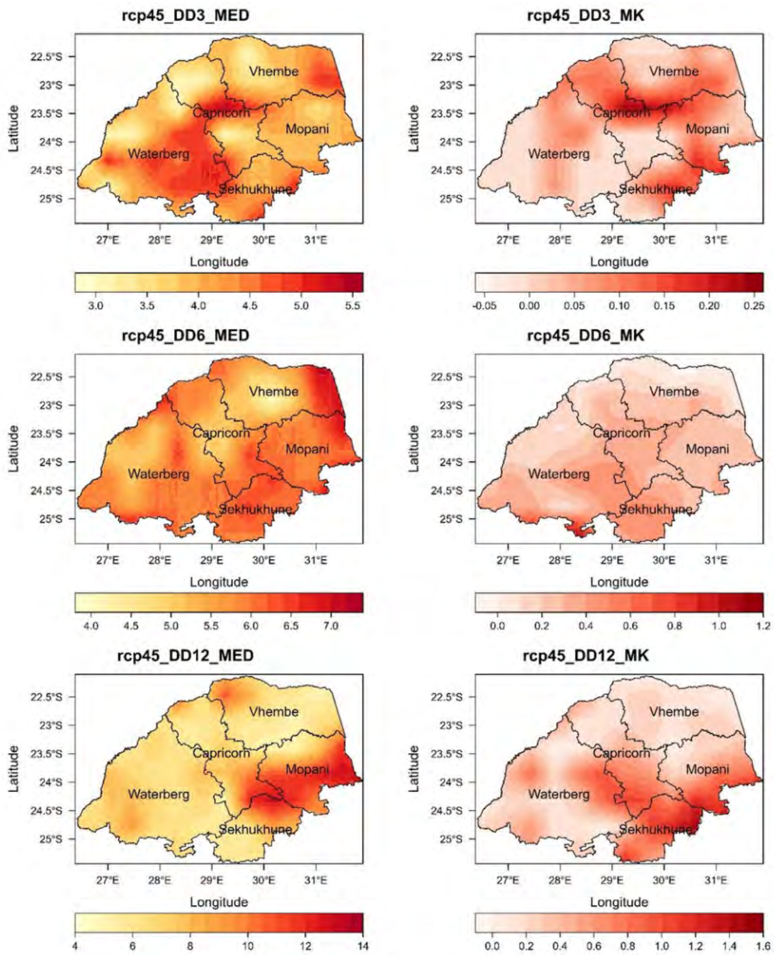

Figure 4.31 Spatial distribution of drought duration median (1st column) and trends (2nd column) computed from SPEI 3-, 6- and 12-month timescales for 2036-2065 projections under RCP4.5 scenario

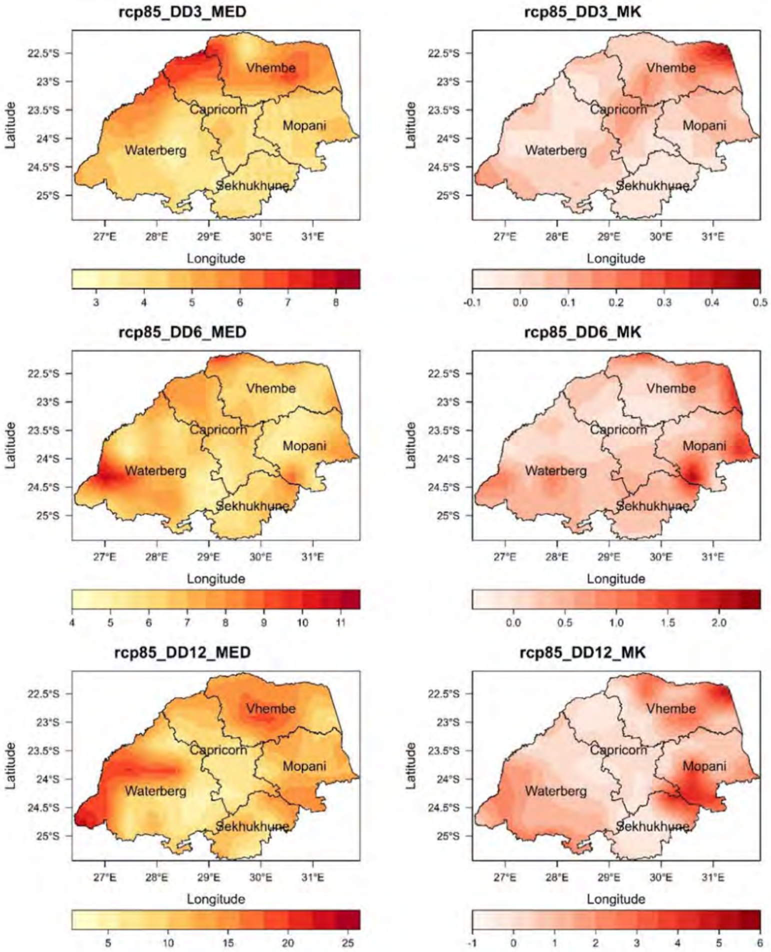

Figure 4.32 Same as Figure 4.31 but for RCP8.5 scenario

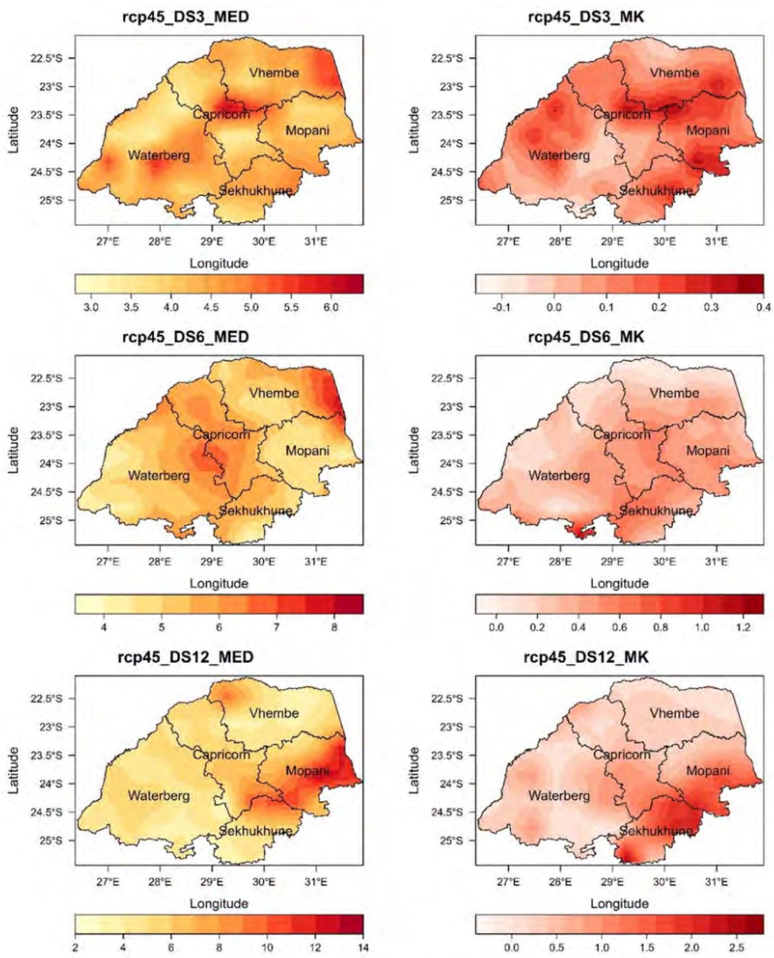

Figure 4.33 Spatial distribution of drought severity median (1st column) and trends (2nd column) computed from SPEI 3-, 6- and 12-month timescales for 2036-2065 projections under RCP4.5 scenario

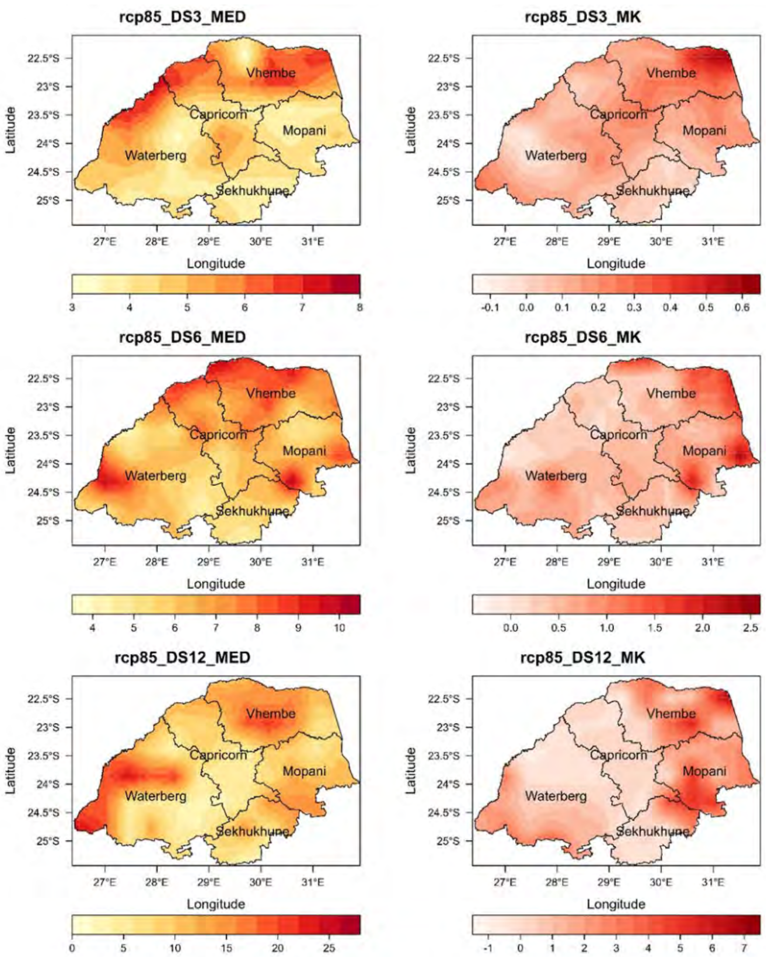

Figure 4.34 Same as Figure 4.33 but for RCP8.5 scenario

Drought duration, ranging from approximately 3 months up to 16 months under RCP4.5 and 35 months under RCP8.5, is projected across the province for the far-future period (Figure 4.35 and Figure 4.36). In general, projection results for the far-future are similar to those for 2006-2035 and 2036-2065, with the only differences being slight shift in spatial DD distribution. Waterberg is the only district municipality that consistently depicts maximum drought duration across the analysed accumulation periods and RCPs. In contrast to current climatology and near-future projections, negative and positive trends in DD are notable for all the analysed timescales under RCP4.5 as well as for 6- and 12-month periods under RCP8.5 scenarios.

Regarding the projected severity, the drought is expected to be less severe in most parts of the Limpopo Province, for 3- and 6- and 12-month accumulation timescales, under RCP4.5 (Figure 4.37). Similar results are observed for RCP8.5 simulations, with exceptions for Waterberg where drought is likely to be more severe. Concerning trends, both increasing and decreasing patterns are observed for 3- and 12-month periods under RCP4.5, whereas positive trends dominate across the province under RCP8.5.

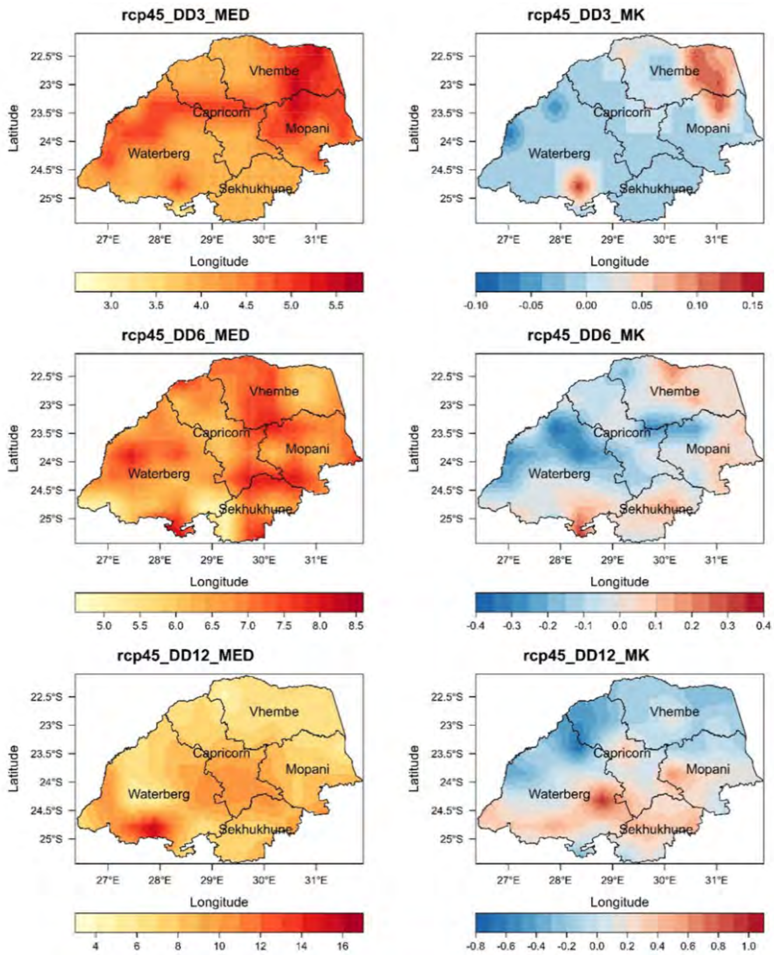

Figure 4.35 Spatial distribution of drought duration median (1st column) and trends (2nd column) computed from SPEI 3-, 6- and 12-month timescales for 2066-2095 projections under RCP4.5 scenario

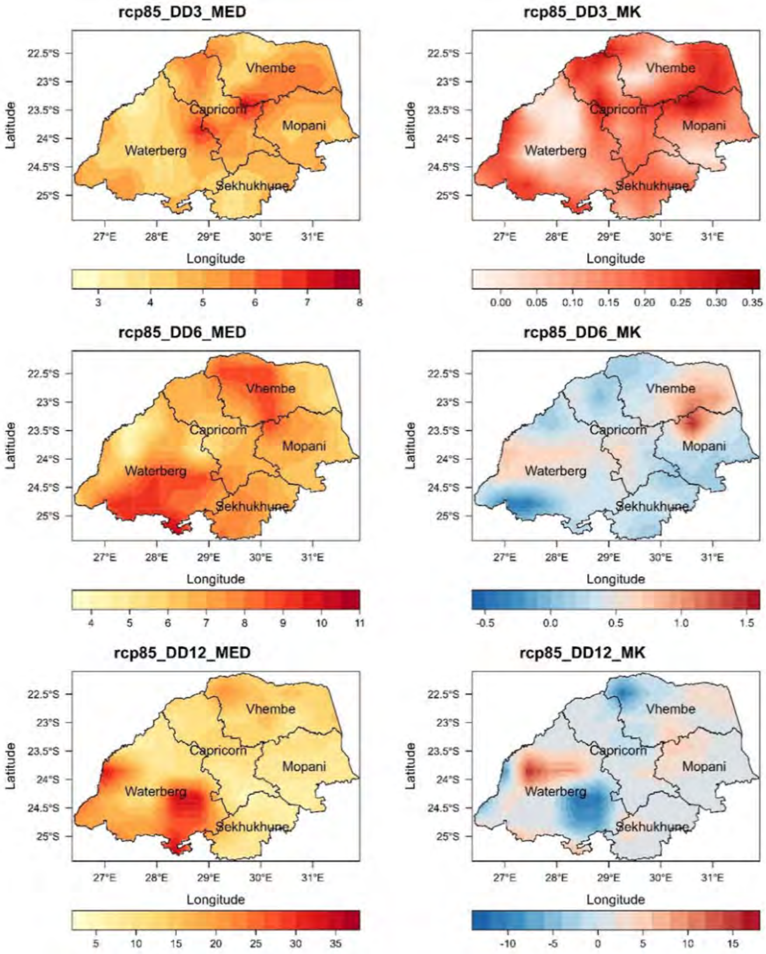

Figure 4.36 Same as Figure 4.35 but for RCP8.5 scenario

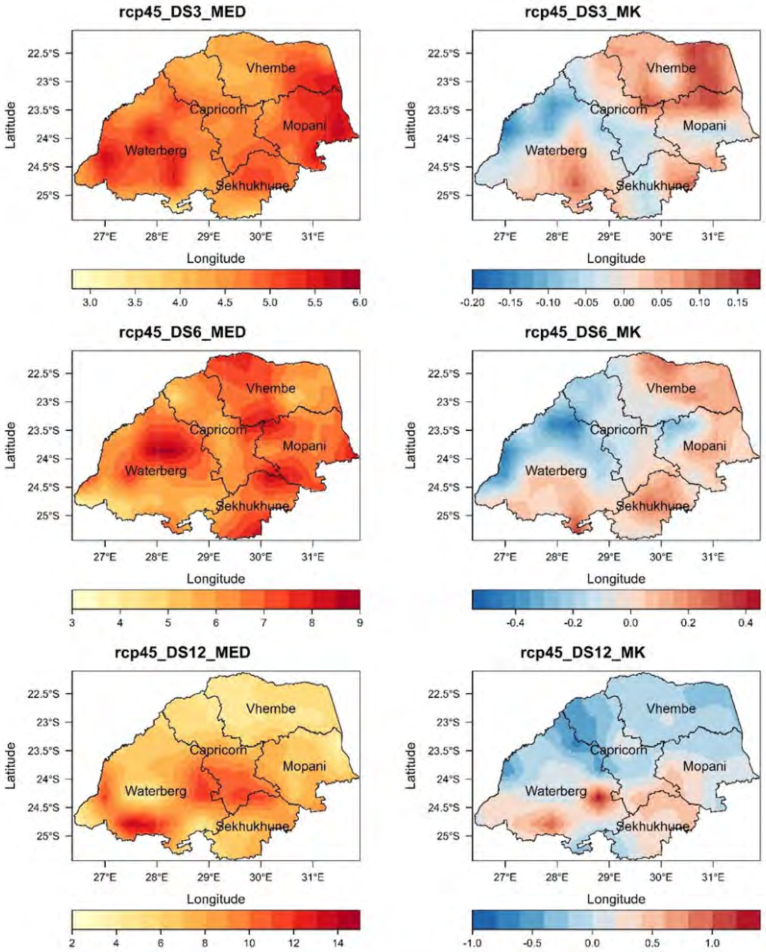

Figure 4.37 Spatial distribution of drought severity median (1st column) and trends (2nd column) computed from SPEI 3-, 6- and 12-month timescales for 2066-2095 projections under RCP4.5 scenario

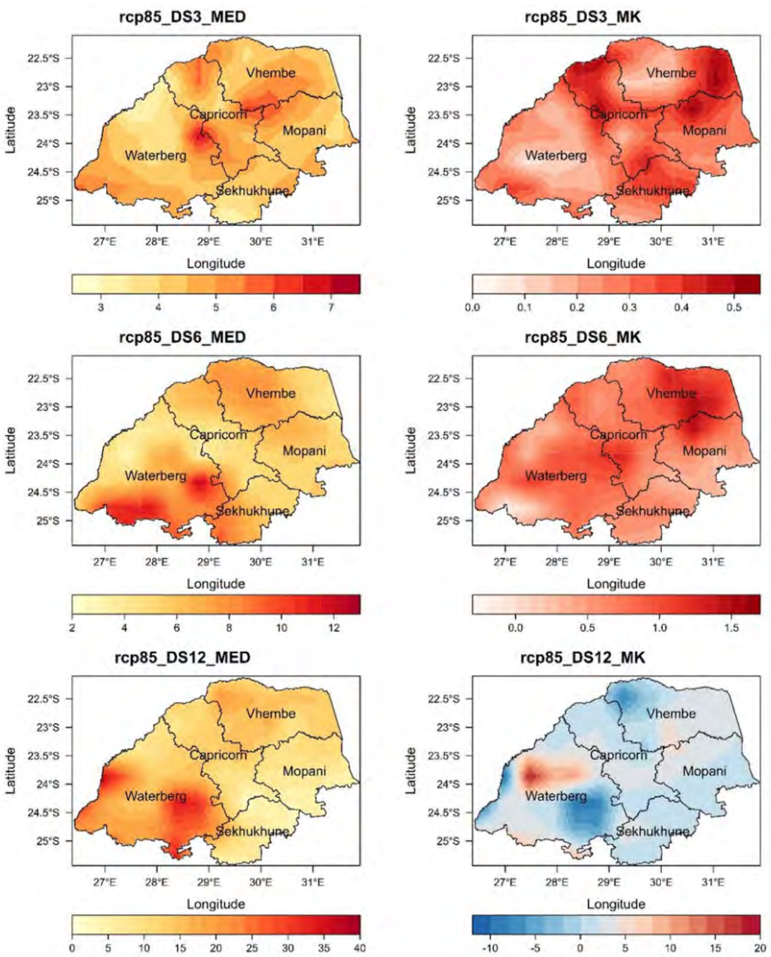

Figure 4.38 Same as Figure 4.37 but for RCP8.5 scenario

4.4 IMPLICATIONS FOR WATER RESOURCES

The Limpopo Province covers mostly the South African part of the Limpopo River Basin, which over time has attracted interest from stakeholders such as in-country and transboundary hydro-governance structures and institutions, the science community, and society. Most parts of the province are arid to semi-arid, with water availability and accessibility being one of the dominating factors affecting the socio-economic development and livelihoods in the province (LBPTC, 2010). Like many regions in South Africa, water demand in the province has increasingly surpassed the supply over the years due to factors such as climate change, coupled with population growth, urbanization, industrial development, and increasing agricultural activities (Van der Zaag et al., 2010). Ongoing increases of such factors are likely to exacerbate the strain on water resources in the Limpopo Province, with its impacts manifested in cross-cutting sectors highly dependent on water. It will also impact socially and economically disadvantaged groups, who depend directly on these resources for their livelihoods.

Climate change is by far one of the factors expected to influence annual variations in precipitation and changing temperature patterns within the Limpopo Province, resulting in more frequent droughts and floods. Projections indicate that precipitation will decrease, and extreme precipitation events will be more frequent and severe. These projected changes in precipitation will potentially have negative impacts on water resources, agriculture, and ecosystems such as: decline in water quality; risk of flooding/drought; decrease in water availability; potential damage to crops; soil erosion leading to loss of soil fertility; reduced hydropower potential; migration; increased energy demand; declining wildlife populations leading to both a loss of biodiversity and decreased revenue from tourism; increased poverty and food insecurity; increased societal vulnerability; disruption of settlements; and increased costs for disaster response. In tandem, these potentially affect the developmental potential of communities in a province that is predominantly rural and dependent on natural resources.

This chapter has shown that the province is projected to experience various states of drought conditions during the 2006-2035 period. The observed negative trends in both SPI and SPEI under RCP4.5 and 8.5 scenarios across the three projected epochs are a clear indication of the recurrence of drought in the province, which is likely to progress into the far-distant period. These findings corroborate the results reported by Zhu and Ringle (2010) and Botai et al. (2020), although both studies focused on streamflow and hydroclimatic extreme projections. Projections also indicate that most parts of the province are expected to experience drought, i.e. mostly lasting less than 5 months at a given future time period. In addition, while recurring drought episodes are expected over the projected period, conditions are likely to be less severe across most parts of the province, with the exception of the Waterberg District Municipality. The projected drought in Limpopo Province will not only be detrimental to water resources but will influence other health aspects such as diseases, including nutrition-related, water-related, airborne, and dust-related diseases, as well as mental health disorders (IWMI, 2018). In addition, persistent drought in the province is likely to be a stumbling block towards the attainment of some of the Sustainable Development Goals, including: 1 (No Poverty), 2 (Zero Hunger), 3 (Good Health and Wellbeing), and 6 (Clean Water and Sanitation), among others.

4.5 CONCLUSION

This chapter aimed to assess future changes in mean precipitation, precipitation extremes, and drought over the Limpopo Province. Findings from this assessment can be summarised as follows:

- The province is expected to experience a decrease in precipitation across the three projection time periods under both RCP4.5 and RCP8.5. Reductions are more notable in the south-eastern parts of Sekhukhune District Municipality, the central (South-Eastern Capricorn, Western Mopani, and Central Waterberg), and northern (Central Vhembe) parts of the province. Increased rainfall is also expected in the south-western part (Western Waterberg) of the province under RCP 4.5 scenario.
- Localised spatial variations are observed across the analysed precipitation extreme indices over the projected periods. The number of heavy (and very heavy) precipitation days are likely to decrease for most parts of the province for all projection periods under both RCP scenarios. The number of CWD is projected to decline in the southern and northern parts and increase in the south-western parts of the province. Consecutive dry days and the maximum number of CDD periods are projected to significantly increase during the analysed periods under both RCP4.5 and RCP8.5 scenarios.
- Negative trends in drought indicators are detected across the analysed 3-, 6-, and 12-month timescales, suggesting that the province is likely to continue experiencing drought conditions over the projected periods. While persistent drought is expected in most parts of the province, the conditions are projected to mostly last for approximately 3-5 months and be less severe over a given time.

The results presented in this study can contribute to and support provincial efforts to effectively plan and manage water resources under the changing climate. The results may also contribute towards enhancing the ability of farmers, catchment management agencies, and extension services within the province to develop sustainable adaptation strategies that can be used to alleviate the impacts of climate change.

The work presented in this chapter has helped in understanding the potential future changes in drought and flooding risks in Limpopo through the analysis of a range of relevant precipitation indices. This work lays a good foundation for the next chapter, which involves conducting a future water resources assessment through the application of climate projections and hydrological modelling.

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CHAPTER 5: MODELLING OF FUTURE WATER RESOURCES AND SCENARIO BUILDING

5.1 INTRODUCTION

This chapter provides an assessment of the future water resources of Limpopo Province. This assessment is a precursor to defining future scenarios of water resources availability. These scenarios will serve to support future water resources planning in the province.

The future water resources assessment was conducted by coupling future climate projections with a hydrological model. The modelling enabled future projections of runoff and streamflow to be developed for the province. These projections were analysed across an ensemble of climate models, and for two different emissions scenarios. From these projections, a set of scenarios is proposed for use in water resources planning.

The chapter begins with a section describing the selection of climate projections for use in the assessment. This is followed by a section detailing the development of the hydrological projections, including the configuration of the selected hydrological model, the data sources used, and the analysis of the outputs produced. The following section then defines the future scenarios. Finally, a postgraduate case study on assessing land use change in the Letaba catchment and its potential impact on water resources is presented.

5.2 SELECTION OF CLIMATE PROJECTIONS FOR HYDROLOGICAL MODELLING

The approach to developing hydrological projections required the selection of a set of climate projections. Consideration was initially given to the use of the Coordinated Regional Downscaling Experiment (CORDEX) projections applied in the analysis of drought and extreme rainfall indices reported in Chapter 4. In that work, the set of 8 climate models (downscaled to 0.44 degrees) was processed into an ensemble mean before being analysed. While the data of the individual models was not bias corrected, it is believed that by calculating an ensemble mean, the bias in the individual models would have tended to be cancelled out, as explained previously.

For daily hydrological modelling, however, it is not advisable to use an ensemble mean since the daily rainfalls in the individual models are not synchronised and, when averaged, result in a time series with a large number of rain days having small rainfall amounts. From a hydrological modelling perspective, this is problematic since the threshold for producing runoff (after initial abstractions have been satisfied) will tend not to be met, and thus, low runoff will be modelled. Consideration was then given to applying the time series of the individual climate models in hydrological modelling. However, before doing this, it was important to consider the bias which may be present in the individual models, given that they were not subjected to a bias correction procedure.

At the same time as evaluating the individual climate models in the set of CORDEX projections, a set of projections from the Inter-sectoral Impact Model Intercomparison Project (ISIMIP) was also considered as an alternative for application in the hydrological modelling (Lange and Buchner, 2021; Lange et al., 2023). The advantage of using these daily level projections is that they have been developed for the express purpose of being used in impact modelling and are based on newer CMIP6 global climate models applied in the latest IPCC Assessment Report (IPCC, 2021). They are downscaled to a 0.5-degree resolution (a similar resolution to the CORDEX models) and have been bias-corrected using a quantile mapping approach for several key climate variables. Data are available for five climate models and two emissions scenarios: SSP2-4.5 (intermediate level of emissions) and SSP5-8.5 (high level of emissions).

Both sets of projections were compared with observed rainfall extracted from the Quinary Catchments Database (Schulze et al., 2011) to assess how well they perform at catchment-scale for a historical period. This database is compiled from observed station data and provides a unique time series of rainfall for all quinary catchments in the country. The comparative analysis was conducted for all quinary catchments in the study area and covered a period for which both climate model data and observed data were available (1976 to 1999).

Since the CORDEX data were not bias-corrected, data were only considered for the two climate models in the ensemble considered to be the most representative of the study area, based on the experience of the SAWS project team, who applied them in Chapter 4 and other projects. Each set of climate projections was compared with the observations in terms of:

- Annual mean rainfall (mm)
- Variability in annual rainfall (Coefficient of Variation, CV, %)
- Average annual counts of daily rainfalls across a range of thresholds: 0 mm, 0–2 mm, 2–10 mm, 10–20 mm, 20–50 mm, 50–100 mm, >100 mm

The comparisons are presented in the form of scatter plots of modelled versus observed rainfall (each point in the plots represents a quinary catchment). The correlation between the datasets (coefficient of determination, r^2) is indicated in the plots along with a 1:1 line representing a perfect fit. Plots for annual statistics are presented in Figure 5.1 for the CORDEX models and in Figure 5.2 for the ISIMIP models. Perusal of Figure 5.1 and Figure 5.2 reveals that the mean annual rainfall of the ISIMIP models is better correlated with the observations than the CORDEX models. The correlations for annual rainfall variability are comparable for the two sets of projections. Both sets of models tend to under-simulate rainfall variability. This is a common trend in climate modelling.

Plots were also made for monthly means and variability of rainfall (not presented here). These plots also revealed that the correlations of the ISIMIP models were better for the monthly means. For some months of the year, the CORDEX models better represented monthly variability.

Plots of average annual counts of daily rainfalls across a range of thresholds are presented in Figure 5.3 for the CORDEX models and Figure 5.4 for the ISIMIP models. The significance of daily rainfall thresholds is that they relate to the intensity of the rainfall. If rainfall tends to fall in frequent small amounts, as opposed to infrequent large amounts, the hydrological response is different.

Perusal of Figure 5.3 and Figure 5.4 reveals that the ISIMIP models tend to have higher correlations with observations than the CORDEX models for the various thresholds considered. The ISIMIP models also tend to better follow the slope of the 1:1 line. Both sets of models over-simulate the number of very small events (0–2 mm).

In summary, the ISIMIP models better represent observations than the CORDEX models in terms of the quantities that were assessed. Another advantage of this set of models is that they are downscalings of newer CMIP6 global climate models (GCMs), as opposed to the CORDEX models, which are based on older CMIP5 GCMs (the ISIMIP projections were not available at the time of analysing changes in drought and extreme precipitation indices). Furthermore, there was also a larger number of climate models available than the two CORDEX models, which were provided by the SAWS team for consideration (these models were selected based on the SAWS experience of using them previously). The ISIMIP models were also subjected to a relatively sophisticated bias correction procedure (quantile mapping) for a number of key variables in their original development. This procedure attempts to correct bias across the distribution of a variable and does not only focus on monthly means, as some simpler procedures do. The use of bias-corrected climate projections in hydrological modelling would lend greater confidence to the future application of the hydrological model output in other water resources models (e.g. yield and/or planning models) should there be an interest from stakeholders in doing so.

Before selecting the ISMIP climate projections for use in hydrological modelling, the future trends in projected rainfall were compared to the trends projected by the CORDEX models. This was done so as to be able to relate the analysis of projected changes in climate indices (Chapter 4) with the hydrological projections reported in this chapter. A comparison of projected changes in mean annual precipitation revealed similarities between the two sets of projections, with both showing increased wetting in the south-west of the study area, and either negligible change or slight decreases in rainfall elsewhere.

Based on all the above assessments, it was decided to select the ISIMIP climate projections for application in developing hydrological projections.

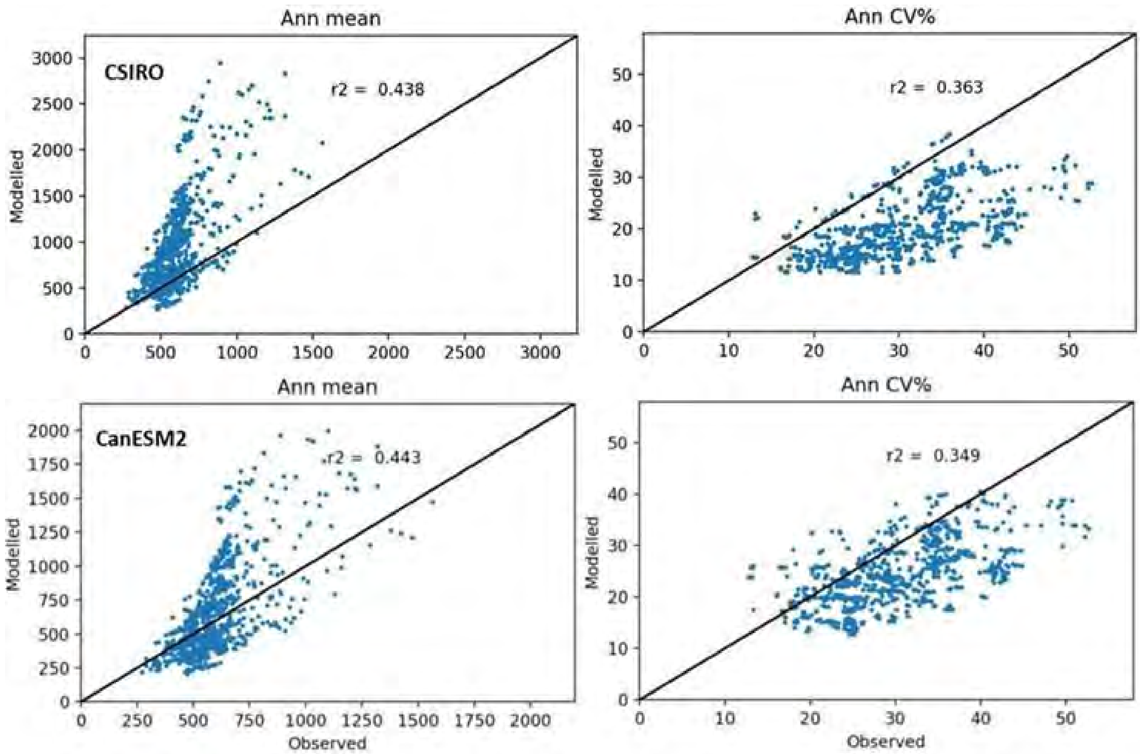

Figure 5.1 Scatterplots showing the relationship between modelled and observed rainfall in terms of average annual counts of daily rainfalls across a range of thresholds for the CORDEX climate models

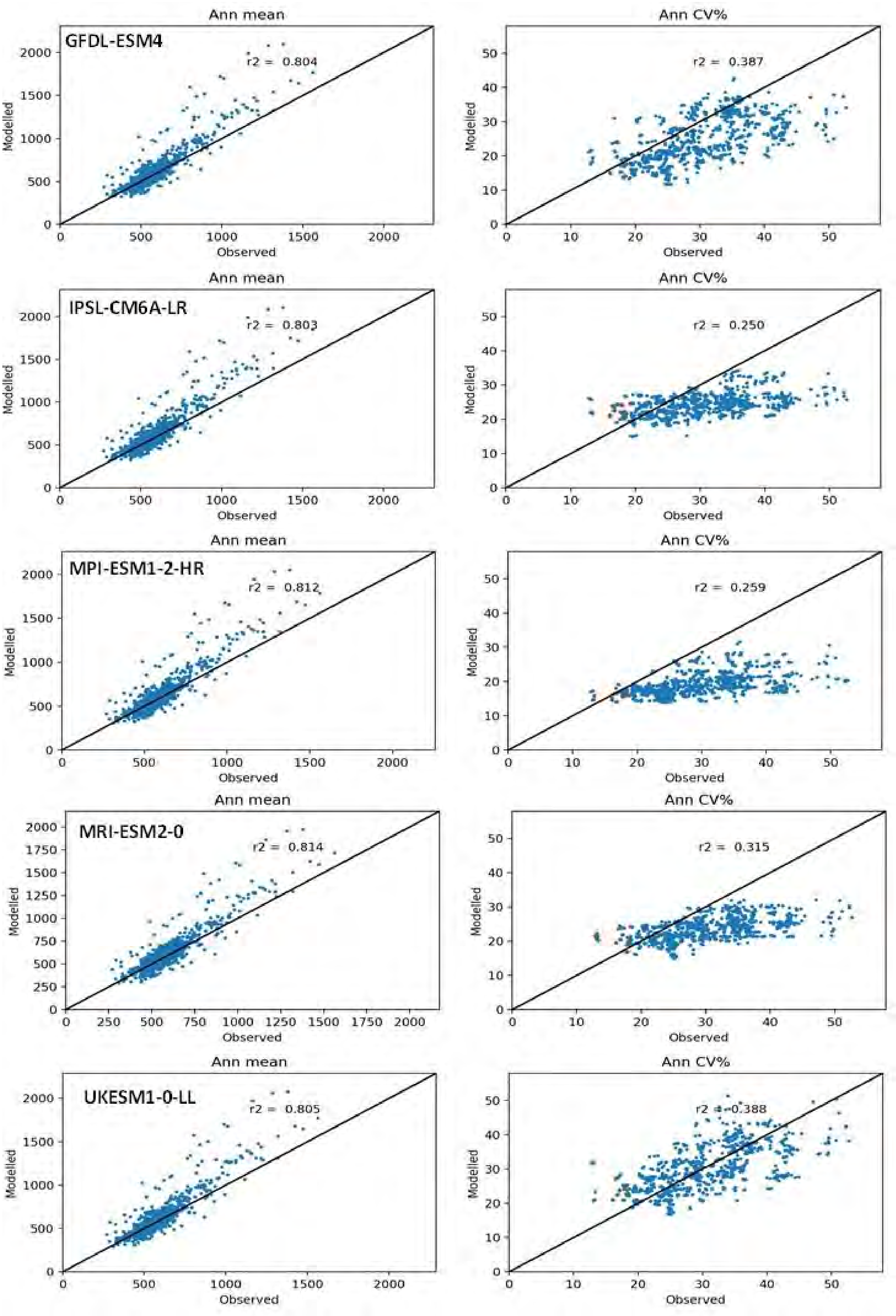

Figure 5.2 Scatterplots showing the relationship between modelled and observed rainfall in terms of mean annual precipitation in mm (left) and the coefficient of variation in annual precipitation as % (right) for the ISIMIP climate models

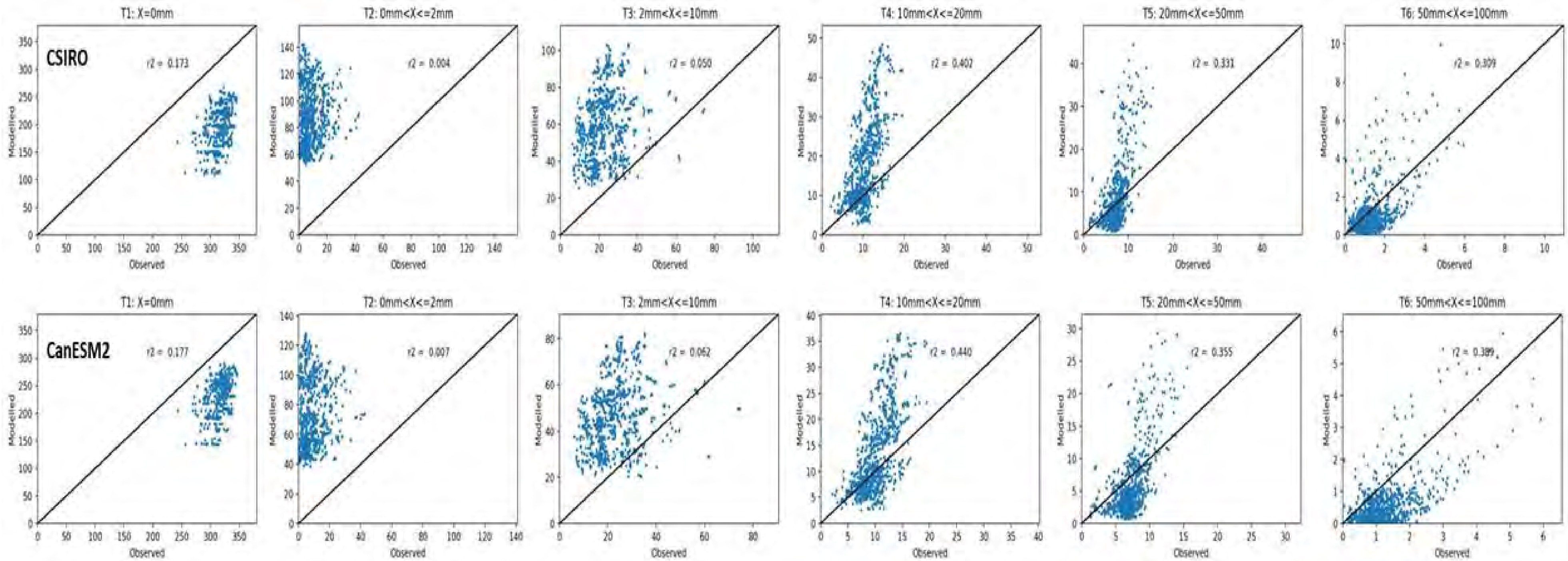

Figure 5.3 Scatterplots showing the relationship between modelled and observed rainfall in terms of average annual counts of daily rainfalls across a range of thresholds for the CORDEX climate models

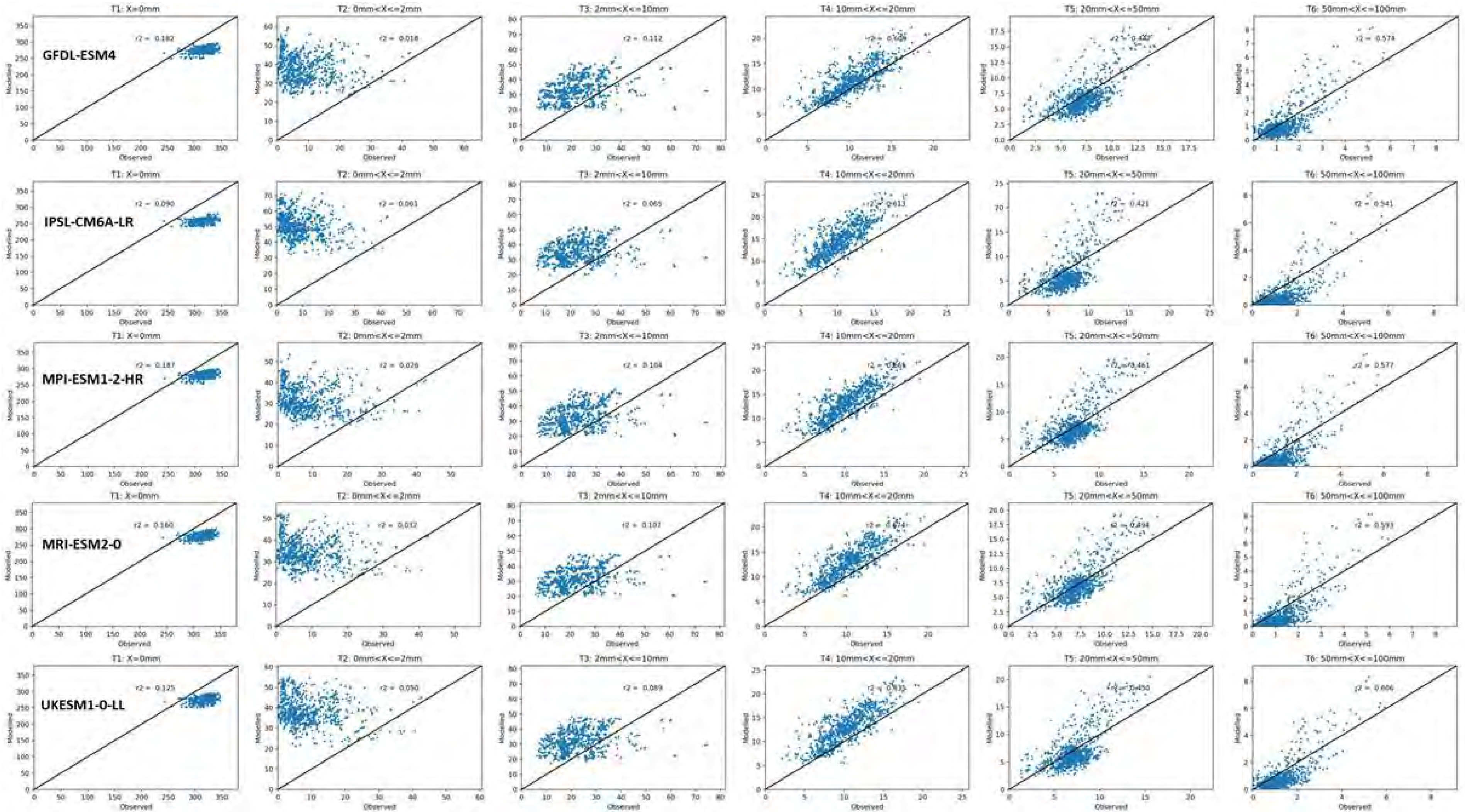

Figure 5.4 Scatterplots showing the relationship between modelled and observed rainfall in terms of average annual counts of daily rainfalls across a range of thresholds for the ISIMIP climate models

5.3 HYDROLOGICAL MODELLING AND PROJECTIONS

5.3.1 Overview of study area

The study area includes the five district municipalities of the Limpopo Province. It also extends to include source catchment areas outside of Limpopo (Figure 5.5) that feed rivers flowing through the province (i.e., Primary drainage regions A and B). Region A consists of the tributaries of the Limpopo River (along the northern border), while Region B is drained by the Olifants River to the southeast. Much of the Limpopo Province receives between 400 and 600 mm of rainfall. The exceptions to this include the far north, where lower rainfall occurs (200-400 mm), and the mountainous areas towards the east of the province (Soutpansberg, Wolkberg, Magoebaskloof), where rainfall can be more than 1200 mm (Schulze and Lynch, 2007)

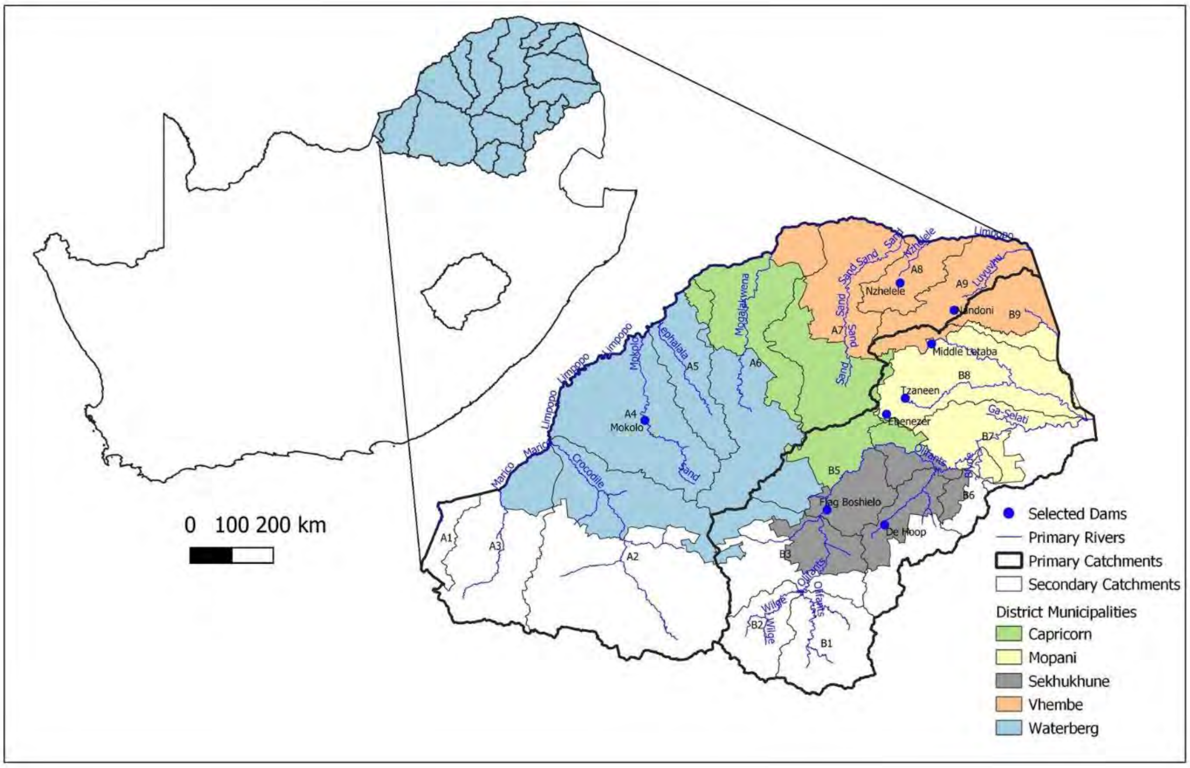

Figure 5.5 Locality map of the Limpopo Province with its four district municipalities, catchments, rivers, and selected dams. The modelled area also extends to include source catchment areas outside of Limpopo that feed rivers flowing through the province (Primary drainage regions A and B).

5.3.2 Methodology

5.3.2.1 Selection of hydrological model

As outlined in the introduction, the development of hydrological projections involved coupling climate projections with a hydrological model. Consideration was given to two models as possible candidates for this purpose. These include the Pitman model (Pitman et al., 2015) and the ACRU model (Schulze, 1995; Smithers et al., 2004). The advantage of the Pitman model is that it is used by the Department of Water and Sanitation (DWS), which is a key stakeholder in this work. The advantage of the ACRU model is that it is more process-based and thus suited to assessing climate change impacts where changes in rainfall patterns may result in different hydrological responses to what has been typical in the past. For example, if rainfall patterns show a shift to having fewer rain days and larger amounts (i.e., more intense rainfall), the ACRU model will respond to such a trend, while the monthly level Pitman model may not respond to this change in rainfall patterns.

Both the models considered have existing configurations for the study area (Bailey and Pitman, 2015; Schulze et al., 2010). However, in the case of the Pitman model, the configuration is fragmented, while for ACRU, it is consolidated into one configuration. From a practical point of view, this consolidated configuration has an advantage in climate change impact studies where numerous repetitive simulation runs are required to reflect the different climates considered (in this study, 10 climates are considered i.e., 5 climate models x 2 emissions scenarios).

As the main focus of this study is on assessing climate change impacts, the ACRU model was selected, given its more process-based nature and the availability of a single configuration of the model for the study area.

5.3.2.2 Configuration of the hydrological model

The configuration of ACRU for the study area was developed from the Quinary Catchments Database (QCD), a database that supports hydrological modelling over large areas. A set of model inputs is available for all quinary catchments in the country. This implies that the model runs at the scale of the quinary catchments, a subdivision of the quaternary catchments used operationally by DWS. The QCD configuration is based on a natural vegetation cover and excludes dams and non-natural water use. The simulated streamflow thus represents natural flow conditions. It has been shown in a previous WRC study that assessing *relative* changes in hydrological responses due to climate change is similar whether the assessment is done based on a natural vegetation land cover or actual (current) land cover (Schütte et al., 2023).

Apart from land cover inputs, other core inputs required by the model include climate, soils, and catchment characteristics. These data were all sourced from the QCD. With regards to climate, it was necessary to create new climate input files based on the ISIMIP climate model data. A set of input data files was created for each of the 10 climate futures considered in the study.

5.3.2.3 Approach to analysing model output

Both incremental runoff simulated by the model for each quinary catchment and the accumulated streamflow generated in the main river systems (at their outlets) were analysed in terms of the climate change impacts. The time periods considered in the analysis were as follows:

- Baseline period: 1976-2005
- Future period: 2036-2065

These time periods were consistent with time periods analysed in the analysis of climate indices (Chapter 4). Other future periods were also considered in Chapter 4, namely a current future period

(2006-2034) and a far future period (2066-2095). The current future period was not considered here since for the ISIMIP simulations, the period from 2006 to 2014 is driven by observed emissions, while for 2015 to 2034 they are driven by scenario-based emissions. The period 2036-2065 is still partly within the planning horizon of DWS (for example, the reconciliation strategy for Limpopo Water Management Area (WMA) North extends out to 2040), and also represents a target period for a net-zero transition.

The changes in runoff and streamflow were considered in terms of ratios of change, where the future value is divided by the baseline value. In this context, a ratio of 1 implies that there is no change in the quantity being assessed, while a ratio of greater than 1 implies the quantity (e.g., runoff) is increasing. Similarly, a ratio of less than 1 implies that the variable is decreasing. Once ratios of change were calculated for the simulations derived from each climate model, the median (50^{th} percentile) ratio of the climate model ensemble was calculated. To reflect that there is a range in ratios derived from the climate model ensemble, the 10^{th} (lower values) and 90^{th} (higher values) percentile ratios were also calculated and reflected in the analysis of results.

5.3.3 Results

To aid the interpretation of the hydrological impacts, maps of projected changes in mean annual rainfall (according to the ISIMIP projections) are presented in Figure 5.6. The median of the climate model ensemble shows some wetting (5-10 per cent) in the south-west and drying (510 per cent) in the north-east under the SSP245 scenario. Under the SSP585 scenario, there is a negligible change shown. For the 10^{th} percentile of the ensemble range, there is drying of up to 15 per cent in the south-west and north-east (not in the south-west for SSP245). For the 90^{th} percentile of the ensemble range, there is wetting in the south of up to 15 per cent for both emission scenarios and wetting of up to 10 per cent in the north and north-east for the SSP585 scenario.

The relative magnitude of the river flows in the province is shown in Figure 5.7. These are simulated flows that are based on observed climate and are presented to contextualise the projected change in flows that are to be analysed. The rivers with the largest flows include the Olifants, Letaba, and Crocodile rivers.

Projected changes in mean annual incremental runoff are presented in map form for the SSP245 and SSP585 scenarios (Figure 5.8). The 10^{th}, 50^{th}, and 90^{th} percentiles of the range in the climate model ensemble are again presented. The differences between the emissions scenarios (SSP245 and SSP585) are relatively small for the time period considered and are indicative of the relatively similar levels of warming at this point. Beyond this time period, the level of warming diverges significantly. The median of the climate model ensemble indicates both increases and decreases in runoff (of small magnitude) for the two emissions scenarios. At the 10^{th} percentile level, most areas experience reductions in runoff (up to 40 per cent in some cases). At the 90^{th} percentile level, most areas experience increases in runoff, with more marked increases projected in selected areas in the centre and south-west of the province. These divergent trends at different percentiles of the model ensemble range indicate that there is a high degree of uncertainty in projected rainfall and the resulting simulated runoff.

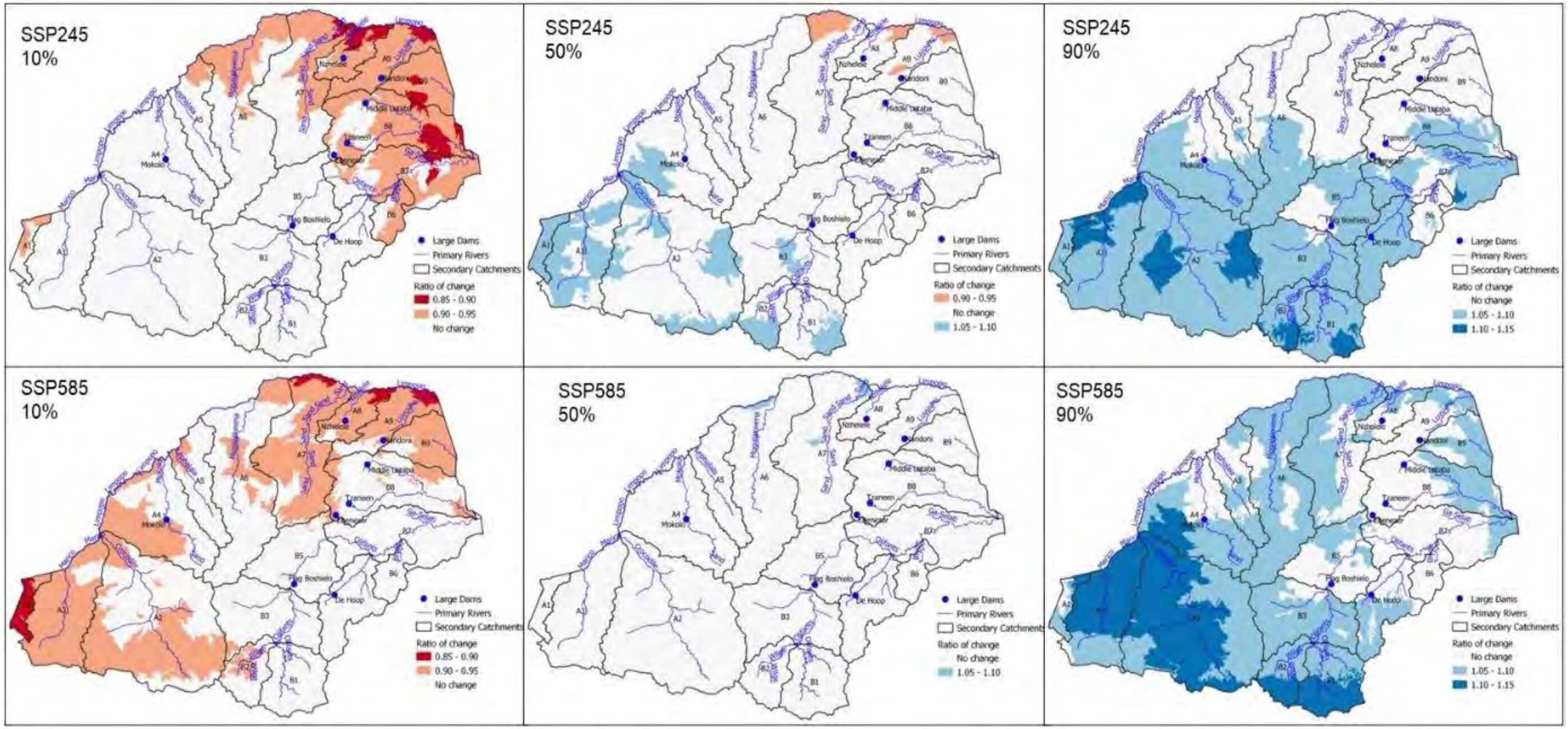

Figure 5.6 Projected change in mean annual precipitation under the under SSP245 and SSP585 emissions scenarios. The 10th, 50th, and 90th percentiles of the range in the climate model ensemble are shown.

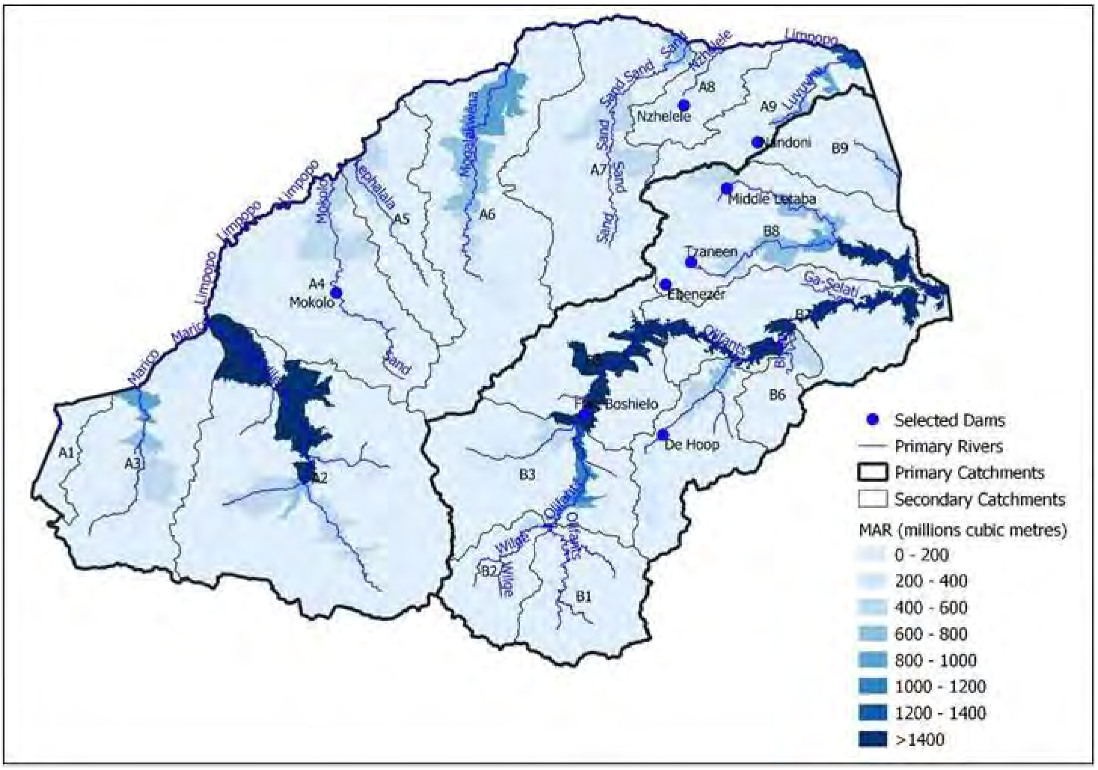

Figure 5.7 Simulated mean annual streamflow under observed climate

Projected changes in mean annual streamflow were analysed for the larger river systems in Limpopo. The analyses are presented in the form of a bar plot for each river, where the projected change for both emissions scenarios and the three percentile levels (reflecting the range in the climate model ensemble) are plotted. The projected changes are presented in Figure 5.9 and Figure 5.10 for the rivers in drainage regions A and B, respectively. Red dotted lines in the plots indicate a ratio of change equal to 1 (associated with no change). In Figure 5.9 and Figure 5.10, it is evident that the range of responses within the climate model ensemble is generally larger than the range between the two emission scenarios. For primary Region A, the dry end of the ensemble (10th percentile) tends to reduce flows (10-15 per cent), while the median of the ensemble is neutral or increasing by approximately 10 per cent. The wet end of the ensemble shows increases in streamflow ranging from approximately 0 per cent to 50 per cent. For primary Region B, the dry end of the ensemble shows neutral or reduced flows (up to 10 per cent), while the median of the ensemble is neutral or increasing by up to 25%. The wet end of the ensemble shows increases in flows ranging from 8 per cent to 64 per cent. These relatively large changes in streamflow reflect the non-linearity of the hydrological system, where relatively small changes in rainfall are amplified in the runoff response. For both Region A and Region B, it appears that flows in rivers in the eastern parts (e.g. for the Sand, Nzhelele, Luvuvhu, Letaba, and Shingwidzi rivers) tend to exhibit a larger difference between the two emissions scenarios than occurs elsewhere in the province (the higher emissions scenario, SSP585, results in more extreme responses). The eastern parts of the province are exposed to tropical weather systems making landfall, and might account for the bigger difference between the emissions scenarios in this part of the province (greater warming of sea surface temperatures in the Indian Ocean would create more conducive conditions for the formation of tropical cyclones). However, the climate projections were not analysed in terms of the occurrence of tropical weather systems to verify this as a causative mechanism.

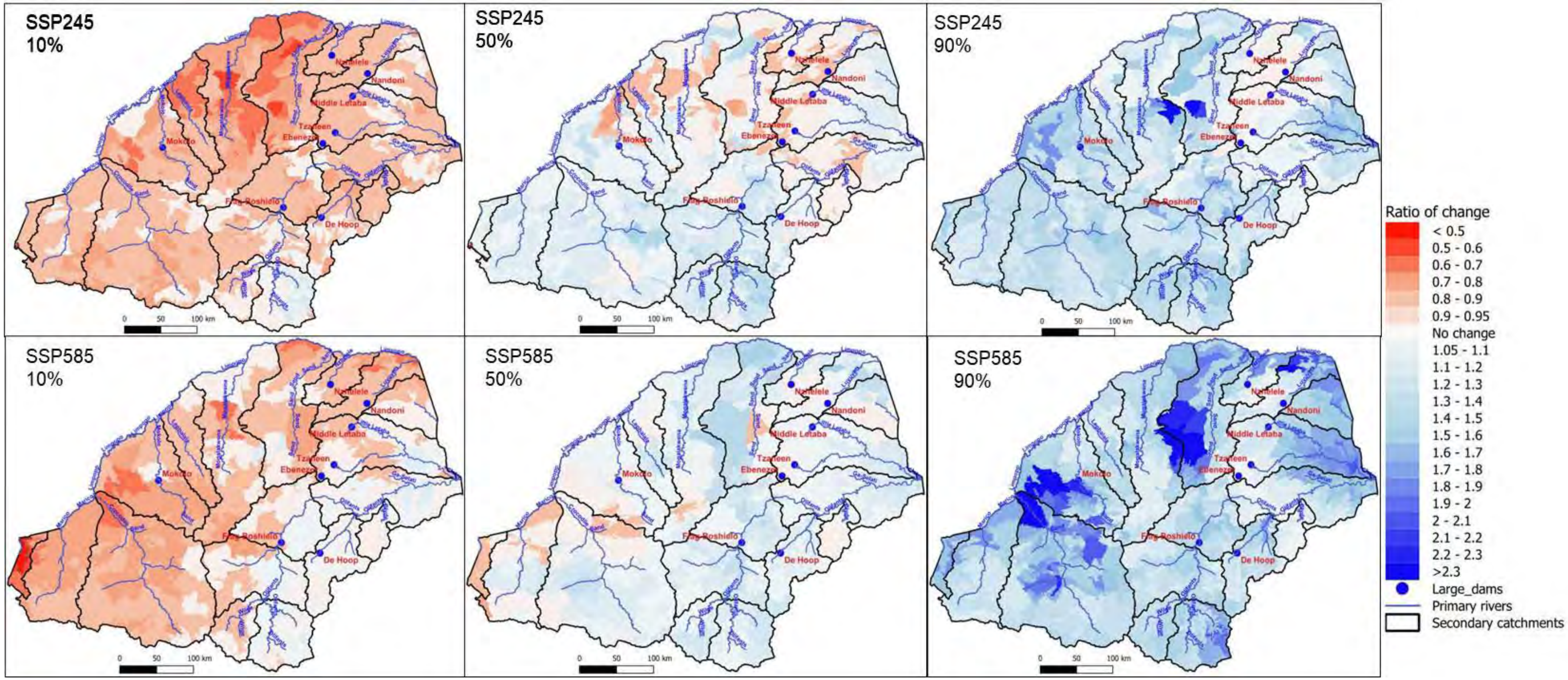

Figure 5.8 Projected change in mean annual runoff under the under SSP245 and SSP585 emissions scenarios. The 10th, 50th, and 90th percentiles of the range in the climate model ensemble are shown.

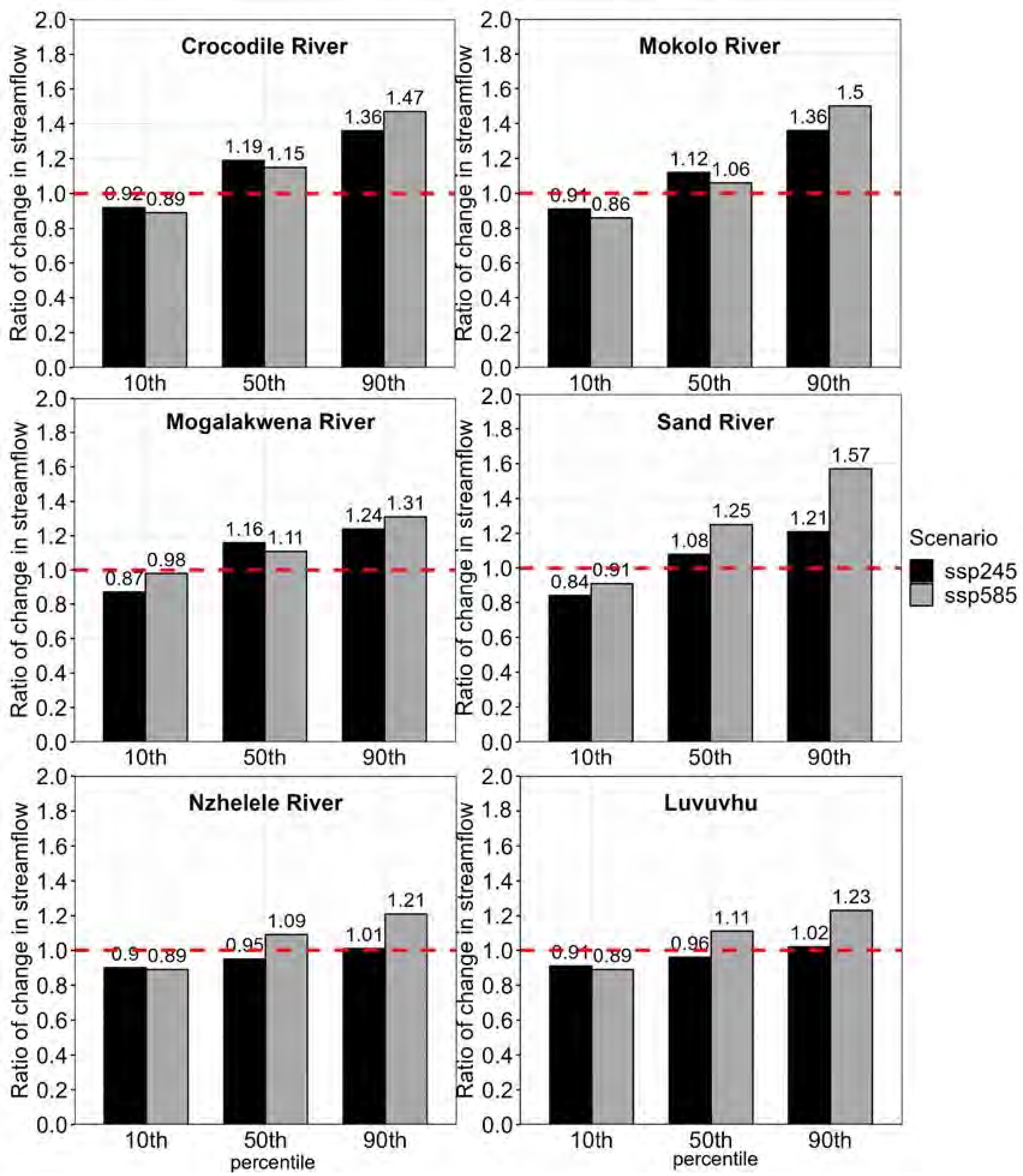

Figure 5.9 Projected change in mean annual streamflow for larger rivers in primary drainage Region A under SSP245 and SSP585

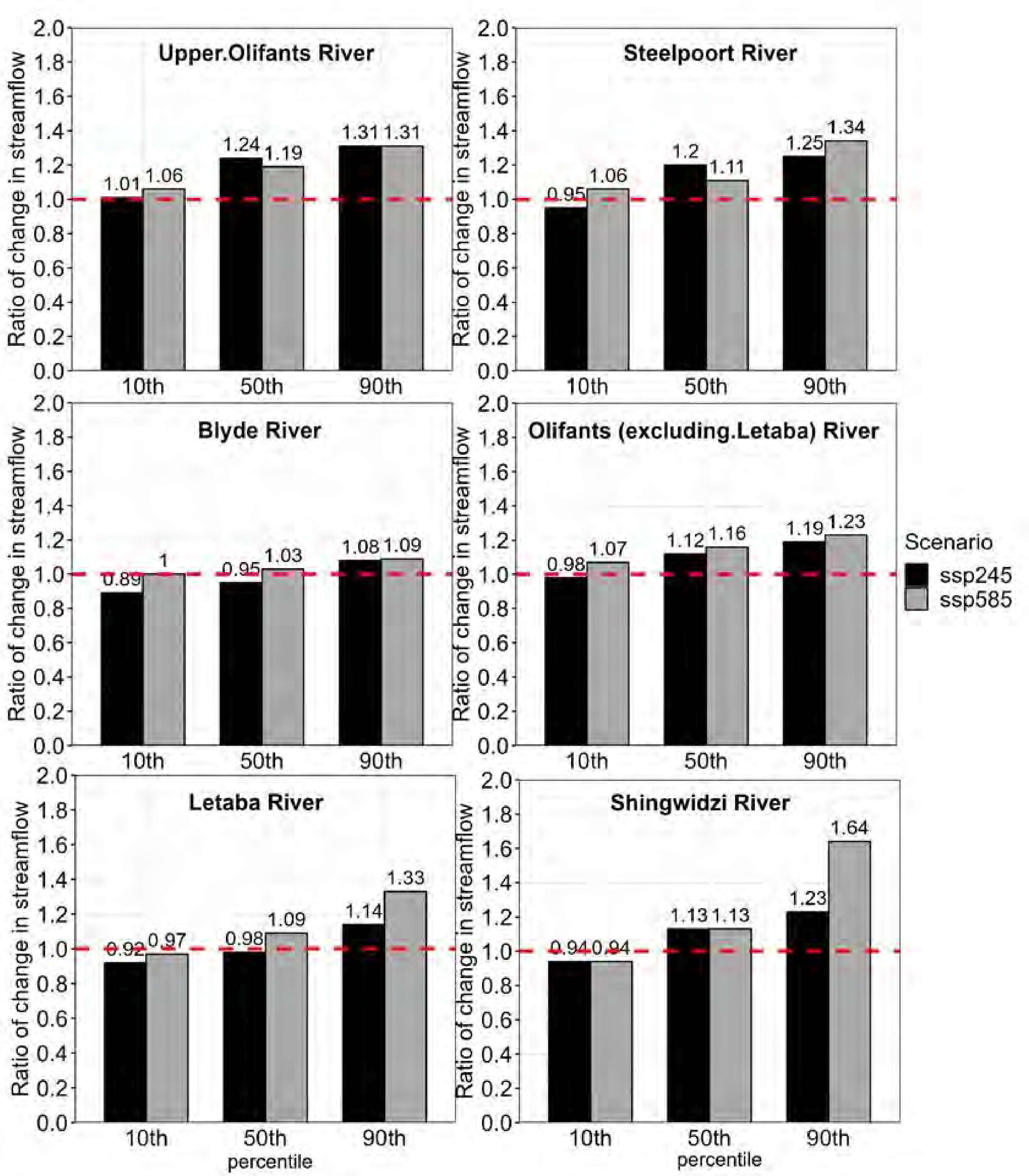

Figure 5.10 Projected change in mean annual streamflow for larger rivers in primary drainage Region B under SSP245 and SSP585

5.4 DEFINING SCENARIOS FOR WATER RESOURCES PLANNING

The analyses of projected changes in rainfall, runoff, and streamflow have indicated a fairly wide range of potential impacts on water availability, with both increases and decreases projected. It is recognised that different sources of climate projections will not produce identical patterns of change, and will likely only have commonalities at a broad, general level. This was evident during the selection of climate projections for the modelling when comparing projected rainfall patterns in the CORDEX projections to those found in the ISIMIP projections.

For water resources planning purposes, it is necessary to define a robust set of scenarios of water resources availability. Given this context, the approach adopted was to consider the overall projected change across all river systems as a guide to defining a set of scenarios. Here, the ratio of change for the two emissions scenarios and the three percentile levels was determined across all rivers using two methods. First, the relevant ratios of change were determined as an arithmetic mean of the values calculated for each river. Secondly, the same ratios were determined as a flow-weighted mean, where the response of the larger rivers would have more weight in the calculation of the mean ratios. These ratios are presented in Table 5.1. Also presented in Table 5.1 are the most extreme ratios of change found across the individual rivers assessed. This latter set of ratios gives an idea of how much change might be experienced in an individual location in extreme cases.

Table 5.1 Ratios of change in streamflow for all rivers (according to two methods) and the most extreme ratios found at the level of individual rivers. Ratios are tabulated for the two emission scenarios and the three percentile levels.

	SSP245			SSP585		
	10%	50%	90%	10%	50%	90%
All rivers (arithmetic mean)	0.91	1.10	1.23	0.94	1.12	1.38
All rivers (flow weighted)	0.95	1.10	1.15	1.03	1.11	1.26
Most extreme (individual rivers)	0.84	1.24	1.53	0.78	1.25	1.95

Given the aim of defining a robust set of scenarios and using the ratios of change in Table 5.1 as a guide, the following set of scenarios are proposed for consideration in planning in Limpopo Province:

Low scenario: 15 per cent reduction in available water resources
Baseline scenario: no change in available water resources
Medium-high scenario: 10 per cent increase in available water resources
High scenario: 20 per cent increase in available water resources

These scenarios were presented in stakeholder engagements to discuss the future of water resources in Limpopo and the implications for development projects.

5.5 CONSIDERATIONS REGARDING LAND USE CHANGE

While the hydrological modelling reported in this chapter has been based on an assumption of static land use, which does not change in future, it is recognised that in reality land use does change over time. Given this context, a study was conducted as part of a postgraduate project to assess how land use changed in a case study catchment in Limpopo to understand the associated hydrological impacts. A summary of the work conducted is provided in this section.

The dynamic interaction between people and the biophysical environment has an impact on a wide range of temporal and spatial scales, changing how land is used and covered (Tamm et al., 2018). To manage water resources sustainably, it is necessary to examine the impact of changes in land use and land cover on the hydrology (Abuelaish and Olmedo, 2016). Access to remotely sensed data with improved spectral and spatial resolutions, as well as temporal and multiscale explanations, has sparked interest in establishing a proper relationship between associated changing climate and Land Use Land Cover (LULC) changes (Gintamo et al., 2021) and how these affect both surface and groundwater quality and quantity.

For illustrative purposes, an assessment of land use land cover was done for the greater Letaba catchment. The Groot Letaba River and its major tributaries, the Molototsi River, Middle Letaba, Klein Letaba, and Letsitele drain the watershed (Department of Water and Forestry, 2006). The Groot Letaba basin has more than 20 significant streambed dams and irrigation canals that have been built (Kifanyi et al., 2019). The Letaba River catchment system is the primary source of freshwater for Tzaneen town's neighbouring settlements (and other towns such as Letsitele) and farming land.

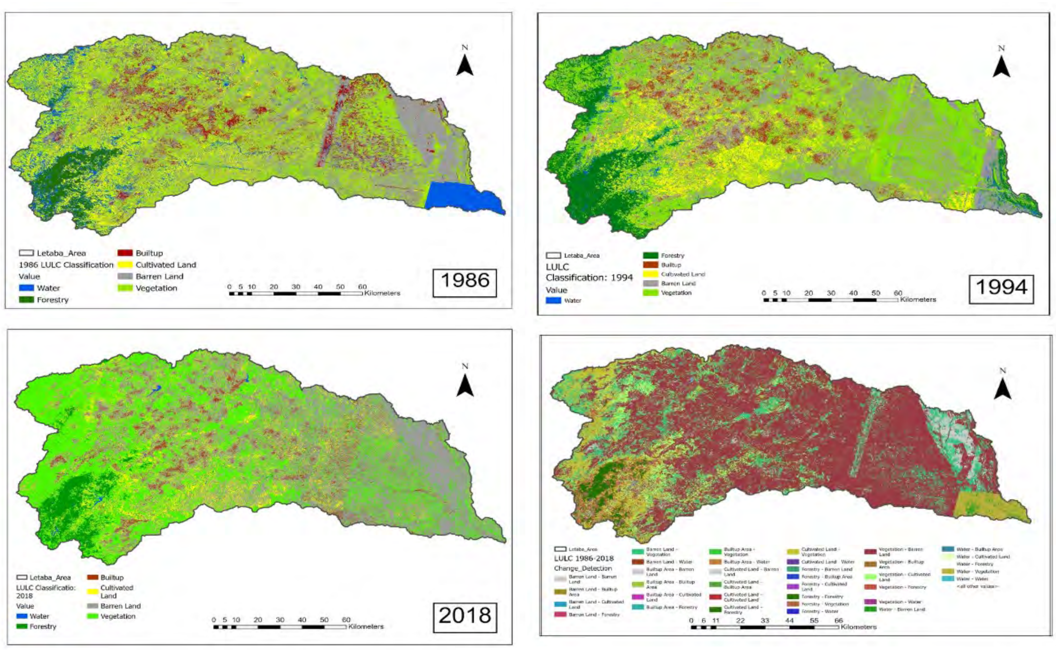

Figure 5.11 Shift in land use and land cover classes for three different periods (1986, 1994, and 2018)

Between 1986 and 2018 there has been a major shift in many significant land use and land cover classes, as illustrated in Figure 5.11. This has a net effect on water drainage during the rainfall seasons and, particularly in the context of climate extremes, results in floods.

5.6 CONCLUSION

In this chapter, a set of hydrological projections were developed and presented for the Limpopo Province. These projections were developed by coupling a set of climate projections with a hydrological model. Based on these results a set of scenarios of future water availability have been proposed for use in water resources planning.

The results of the hydrological modelling showed a large range in projected streamflows across the climate model ensemble. The results can be summarized as follows:

- At the median percentile for the SSP245 emissions scenario, there were mixed responses with some rivers showing decreases in flows (of up to 5 per cent) and others showing increases (of up to 25 per cent). For the SSP585 scenario, all rivers were projected to experience increases in flows (of up to 25 per cent).

- At the 10th percentile of the climate model ensemble (dry end), most rivers are projected to experience reductions in flows for both emission scenarios (of up to 15 per cent). An exception to this is the Olifants River where small increases are projected (7 per cent).

- At the 90th percentile of the climate model ensemble (wet end), most rivers are projected to experience increases in flows for both emission scenarios (of up to 65 per cent). For the SSP245 scenario, two rivers are projected to experience negligible change.

The above findings indicate a large degree of uncertainty regarding future changes in mean flows. This results from the uncertainty associated with rainfall projections when considering overall (mean) changes. Due to non-linearity in the hydrological system, relatively small changes in rainfall are amplified in the hydrological responses. This further contributes to the uncertainty regarding future changes in flows.

For the most part, the differences between emissions scenarios were relatively small in terms of the hydrological responses for the time period considered (2036-2065). The differences between the scenarios were largest in the eastern parts of the province. In the more distant future, the differences between the scenarios would be expected to grow as the impact of greater mitigation measures for SSP245 is felt.

Based on the analysis of projected changes in rainfall conducted in Chapter 4, more extreme conditions (dry, and in some areas wet) are likely in the province. This will cascade, though, to hydrological responses in the form of droughts and floods. While a different set of climate projections was used for the hydrological modelling in this chapter, it is likely that these projections would also indicate increases in extremes as this is a robust trend emanating from climate change research.

Projected increases in droughts and floods are of significance since these events test the limits of water resources infrastructure (e.g., dams). Droughts test the ability of dams to supply enough water, while floods test the ability of infrastructure to withstand damage. Increasing droughts may be challenging to manage, even if a region becomes wetter overall in terms of mean rainfall and streamflow.

A case study investigation in the Letaba catchment revealed that there have been significant shifts in land cover and land use over time. These shifts are likely to have had impacts on water quantity and quality. Such changes in land cover and use are likely to continue and will interact with climate changes and add complexity to understanding and predicting future changes in hydrological responses.

Having assessed potential changes in water availability in this chapter, the next chapter considers the implications of these changes on future development in Limpopo. This investigation of development implications draws on findings from all the analyses presented in the various chapters of this report.

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CHAPTER 6: EXPLORING DEVELOPMENTAL IMPLICATIONS

6.1 INTRODUCTION

This chapter assesses the future scenarios of water resource availability in the province, drawing insights from the preceding chapters (especially Chapters 3, 4, and 5), and considers the implications for current and planned developments in the Limpopo Province (encompassing its five districts). The chapter commences with a brief review of socio-economic conditions in the province, the strategy for development and the challenges posed by water scarcity in the pursuit of the development agenda. Thereafter, the water requirements and availability of water (from supply infrastructure) is presented per water management area or major water supply system in the province. This information is mainly drawn from water resources reconciliation strategies for the province. The next section then identifies current and planned development projects in the province (for projects requiring significant amounts of water to be viable) and lists their water requirements. These water requirements are analysed in the context of the projections of changes in climate and water availability made in this project. Finally, strategic interventions and adaption options are discussed considering the findings of the analysis.

6.2 LITERATURE REVIEW

The Limpopo Province's population of 5 941 439 (SSA, 2022) is distributed over its five (5) district municipalities. The district municipalities, Vhembe, Capricorn, Sekhukhune, Mopani and Waterberg, comprise of 24.3 per cent, 22.2 per cent, 20.4 per cent, 20.3 per cent, and 12.8 per cent of the provincial population, respectively (LPG, 2023).

The province has over the years, not only experienced excessive high temperatures, low rainfall, and frequent drought, but it is also characterised by poor socio-economic conditions associated with high unemployment, poverty, low economic growth, and poor infrastructure. Provincial socio-economic analysis shows a significant increase in unemployment rate from 33.7 per cent in 2016 to 41.7 per cent in 2021 (LPG, 2023) at an average annual growth rate of 4.7 per cent. Thus, an increased poverty rate is realized since there is a causal link between unemployment and poverty. According to Thought Leadership (2022) an increase of 1 per cent in unemployment yields a 0.4-0.7 per cent increase in poverty rates, while a 10 per cent increase in minimum wage yields a 2 per cent decrease in poverty rates.

The operation and maintenance needs analysis indicate that more than 70 per cent of Limpopo's water infrastructure requires medium to high refurbishment (LPG, 2023), and that the water infrastructure functionality challenges negatively impact many households, particularly those in rural communities in the province. To address these challenges, the Limpopo Development Plan was designed to inform and to guide the process. Among identified priorities in the Limpopo Development Plan is the integrated and sustainable socio-economic infrastructure development that aims to unlock the economic potential of the province and to improve people's quality of life (Limpopo Development Plan 2020-2025). The province then resolved, as part of implementation of the plan, to implement the strategic infrastructure development projects.

Water should be an enabler and not a limiting factor to socio-economic development (NPC, 2020; DWS, 2023). However, limited water availability often limits the envisaged support to economic development. Unsuccessful implementation of water-dependent developments is often attributed to water stress or limited access to water.

Planning economic developments without due consideration of water availability is also unhelpful. A macro-economic model used by Blignaut and van Heerden (2009) to analyse the possible effects of Accelerated and Shared Growth Initiative for South Africa (AsgiSA) on water demands showed that planning and design of economic development strategies in isolation from considering natural resource constraint is futile. Donnenfeld et al. (2018) asserted that water scarcity may limit South Africa's chances for economic progress and human development. According to Mnisi (2020), the UN's Food and Agriculture Organization (FAO) defines physical water scarcity as not having enough water available to meet all demands, or when natural water resources are insufficient to meet a region's demand. In this regard, FAO defines four drivers of physical water scarcity as: a) demand-driven water scarcity, b) population-driven water scarcity, c) climate-driven water scarcity and, d) pollution-driven water scarcity. South Africa in general, and the Limpopo Province in particular, are subject to all these water scarcity drivers. Resource poor communities are the hardest hit as they experience water scarcity markedly, due to their socio-economic conditions. A key challenge that is seldom factored in is that South Africa's water related problems are not only driven by physical, economic, population, and climate related water scarcity, but in addition South Africa is burdened by how this limited resource is used and managed. In this regard, MacAlister et al. (2023) indicated that in times of water scarcity, the value of water and the prioritization of water use can either speed up or slow down economic development because the economic valuation of water is a key factor in both social and economic development, and is related to how water use by different sectors is handled.

Baseline information clearly shows that the Limpopo Province is water stressed (Shikwambana et al., 2021), as shown by severe and frequent droughts, excessively high temperatures, and reduced rainfall. Tshiala et al. (2011) conducted thorough assessments of trends in annual and seasonal minimum and maximum temperatures as well as the diurnal temperature range over Limpopo Province, covering the years 1950 to 1999. Their findings revealed an increase of 0.12°C per decade in the mean annual temperature for the 30 catchments over the 50-year period, a negative trend in temperature for 13 per cent of the catchments, while 87 per cent showed positive trends in their annual mean temperature. Additionally, 20 per cent of catchments showed negative trends, while 80 per cent of catchments showed positive trends in their diurnal temperature range. The seasonal trends showed variability in mean temperature increase of about 0.18°C per decade in winter, and 0.09°C per decade in summer. Climate change effects are superimposed on and exacerbate the situation in the already vulnerable province.

The climate change-driven extreme events, particularly drought, impact negatively on water-dependent economic development projects such as agriculture production. Ferreira et al. (2023) determined how climate change is anticipated to affect maize production in the Univen and Syferkuil districts of the Limpopo Province using the Shared Socio-Economic Pathways (SSP) climate scenarios based on the CMIP6. Data from the models considered the historical period (1981-2010), the future medium period (2021-2050), and the far future period (2051-2080) for the SSP1-2.6, SSP3-7.0, and SSP5-8.5 scenarios. The worst drought conditions and corresponding highest reduction in yield and lowest absolute yields were found under the SSP5-8.5 (2051-2080) scenario. Additionally, Shikwambana et al. (2021) also observed an increase in temperature and a drop in yearly rainfall that caused droughts to occur in the Limpopo districts over the period 1960 to 2018. The results of the analysis indicated an increased recurrence of drought and rainfall variability, which resulted in water scarcity and food insecurity.

The probability of long-term droughts has increased over most parts of the Limpopo Province (Chapter 3), while the extreme indices signals indicate a rainfall climate that has become more extreme, with significantly positive trends in very wet and extremely wet days. This implies that whilst the province is likely to continue being water stressed, there is also a likelihood of flooding in areas that receive extreme rainfall. Assessment of future changes in precipitation, precipitation extreme indices, and drought characteristics over the Limpopo

Province (Chapter 4) indicated that most of the Limpopo Province will experience a decline in precipitation over the projected period under both RCP4.5 and RCP8.5 scenarios, while the precipitation extremes exhibit spatial and localised variability across the projected epochs. These results confirm the findings from Chapter 3, which point to a continuation of recent trends towards a more extreme climate with a resultant increase in the probability of extended dry periods. The climate model ensemble used in hydrological modelling (Chapter 5) shows some wetting (5-10 per cent) in the south-west and drying (5-10 per cent) in the north-east under the SSP245 scenario. This finding is similar to the future rainfall analysis results (Chapter 4) that projected a slight (40 mm) increase for the south-western part (Western Waterberg) of the province under RCP 4.5 scenario. Considering the above, it can be concluded that water management strategies should take into account a more erratic rainfall climate, which already has negative consequences for the reliability of water supply to various sectors.

6.3 WATER REQUIREMENTS AND AVAILABILITY FOR THE LIMPOPO PROVINCE

6.3.1 Olifants River Water Supply System

Table 6.1 illustrates the (2010/11) water balance of the Olifants Water Supply System. The figures beyond 2010 for this water supply system are not available. The Upper Olifants is excluded from water that is earmarked for Limpopo Province since it supplies Mpumalanga. Hence, the total water requirement (i.e., from Middle and Lower Olifants) is 407 Mm^3/a.

The corresponding water availability is 433 Mm^3/a, including the groundwater contribution that amounts to 38 Mm^3/a. Table 6.2 represents the water availability, including groundwater, transfers, and other sources.

Table 6.1 Current water balance of the Olifants River Water Supply System (DWA, 2011)

Sub-catchment	Water requirements (Mm^3/a)	Water resource (Mm^3/a)	Losses (Mm^3/a)	Comp. release (Mm^3/a)	Water balance (Mm^3/a)	
Upper Olifants	609	630	0		21	
Middle Olifants	187	185	0	(19)	(21)	
Lower Olifants	220	248	(5)		23	
Total	**1 016**	**1 063**	**(5)**	**(19)**	**23**	

Table 6.2 Summary of the 2010 water resource availability of the Olifants River Water Supply System (DWA, 2011)

Sub-catchment	Major dams (Mm^3/a)	Diffuse source (Mm^3/a)	Transfers in (Mm^3/a)	Other sources (Mm^3/a)	Groundwater (Mm^3/a)	Total (Mm^3/a)
Upper Olifants	272	104	230	4	20	630
Middle Olifants	110	32	8	0	35	185
Lower Olifants	199	43	3	0	3	248
Total	**581**	**179**	**241**	**4**	**58**	**1 063**

However, the total future (projected) water availability (Table 6.3) of the Olifants is 532 Mm^3/a, including anticipated water transfers**.** This estimated total projected (to 2035) water availability is the sum of Lower and Middle Olifants (from the Final Reconciliation Strategy Report for the Olifants River Water Supply System). The estimate assumes no intervention and high growth.

Table 6.3 Summary of the future (2035) water resource availability in the Olifants River Water Supply System (DWA, 2011)

Sub-catchment	Yield from Major Dams (1:50/yr) (Mm^3/a)	Yield from Farm Dams and Diffuse Sources (Mm^3/a)	Transfers in (Mm^3/a)	Other sources (Mm^3/a)	Groundwater (Mm^3/a)	Total (Mm^3/a)
Upper Olifants	272	104	241	4	20	641
Middle Olifants	209	32	8	0	35	284
Lower Olifants	199	43	3	0	3	248
Total	**680**	**179**	**252**	**4**	**58**	**1 173**

6.3.2 Limpopo WMA North

The current (2020/21) total water requirement for the Limpopo North WMA is 717.7 Mm^3/a while the projected (2030/31) water requirement is 824.6 Mm^3/a (Table 6.4).

Table 6.4 Limpopo North WMA - Total water requirement (DWS, 2016)

Sector or water user	Water requirements (million m^3/a)						
	2011	2015	2020	2025	2030	2035	2040
Irrigation	464.8	464.8	464.8	464.8	464.8	464.8	464.8
Domestic	102.1	105.6	109.0	115.8	122.6	128.3	134.0
Mining, industries and power generation	45.0	64.0	111.4	157.9	204.7	237.3	249.1
Livestock	23.4	23.4	23.4	23.4	23.4	23.4	23.4
IAP and commercial forestry	9.1	9.1	9.1	9.1	9.1	9.1	9.1
TOTAL	**644.4**	**666.8**	**717.7**	**771.0**	**824.6**	**862.9**	**880.4**

The surface water available for the Limpopo North is 633.7 Mm^3 /a, (refer to Table 6.5) while supply from groundwater is 327.9 Mm^3 /a (refer to Table 6.6). Hence, the total amount of available water from the Limpopo North WMA is 961.6 Mm^3 /a. It is worth noting that water use by irrigated agriculture in the Sand Catchment is excessive and almost depletes the resource.

Table 6.5 Limpopo North WMA - surface water availability (DWS, 2016)

Catchment	Water requirement (exclude stream flow reducers) (M m^3 /a)	Water availability (M m^3 /a)	Water balance (Mm^3 /a)
Matlabas	7.0	7.0	0
Mokolo	61.6	61.2	-0.4
Lephalale	75.1	77.3	2.3
Mogalakwena	156.8	152.3	-4.5
Sand	292.6	287.8	-4.7
Nzhelele	39.4	48.1	8.7
Total	**632.5**	**633.7**	**1.4**

Table 6.6 Limpopo North WMA - Limpopo WMA North: Groundwater exploitation potential and utilisation (DWS, 2016)

Catchment	Calculated Exploitation Potential from (Baron, Seward & Seymour, 1998 (Mm^3/a)	Water use (Mm^3/a)	Utilisation of exploitable potential (Mm^3/a)
Matlabas	50.70	2.32	5%
Mokolo	93.74	3.95	4%
Lephalale	65.97	29.70	45%
Mogalakwena	211.34	85.93	41%
Sand*	126.28	195.75	155%
Nzhelele	25.15	9.25	37%
Total	**573.19**	**327.90**	**57%**

*The Sand River Catchment's groundwater resource is almost depleted. The red figure signifies that this is the only area where water use exceeds available amount by more than 50%.

6.3.3 Crocodile West Water Supply System

Current (2020/21) water requirement supplied from the Crocodile West River Catchment (Table 6.7) for domestic, irrigation, and mining/power/industry respectively is 1 165 Mm^3/a, while the future (2030/31) projected water demands is 1 287 Mm^3/a.

Table 6.7 Water requirements per sector for the Crocodile West River Catchment (DWA, 2012)

Water use sector	Water requirements (Mm^3/a)						
	2010	2015	2020	2025	2030	2035	2040
Domestic	674	694	766	820	885	927	970
Irrigation	268	268	268	268	268	268	268
Mining, power, and industry	93	116	131	133	134	134	133
Total	**1 035**	**1 078**	**1 165**	**1 221**	**1 287**	**1 328**	**1 371**

Water re-use from the Crocodile West is planned to be transferred to Limpopo WMA North through the Mokolo and Crocodile West Water Augmentation Project (MCWAP) (from the current amount of 75 Mm^3/a to 211 Mm^3/a by 2050). The Crocodile West River catchment will in the future continue to be supplied from the Vaal River System (562.7 Mm^3/a in 2015 to 1 076.7 Mm^3/a by 2050), with additional water to be from reuse (387.9 Mm^3/a in 2015 to 656.7 Mm3/a by 2050). Therefore, water availability for Crocodile is 950.6 Mm^3/a (i.e., 562.7 + 387.9) Mm^3/a. The projected increase is planned to be 1 733.4 Mm^3/a by 2050.

6.3.4 Luvuvhu and Letaba Water Management Areas

Total water requirement from the Luvuvhu and Letaba Water Management Areas (Table 6.8) is currently (2020/21) 764.27 Mm^3/a. The demand is projected to increase to 806.63 Mm^3/a by 2030/31.

Table 6.8 Luvuvhu and Letaba WMAs: Total high growth water requirements (DWA, 2014)

Catchment & Description	User description	Demand projection (Mm^3/a)						
		2010	2015	2020	2025	2030	2035	2040
Groot Letaba	All users	332.7	338.7	345.1	351.9	355.4	358.9	362.7
Klein Letaba	All users	129.7	135.9	142.6	149.8	152.9	156.1	159.5
Luvuvhu/Shingwedzi	All users	126.4	132.9	176.6	191.4	196.6	201.0	204.3
Mutale	All users	8.2	8.9	9.5	10.2	10.6	11.1	11.6
Total Demand		596.70	616.31	673.73	703.27	715.53	727.04	738.06
Total study area	Reduction in runoff due to IAP	11.3	11.3	11.3	11.3	11.3	11.3	11.3
Total study area	Forestry reduction in runoff	79.7	79.7	79.7	79.7	79.7	79.7	79.7
Total demand and runoff reduction requirements		**687.70**	**707.31**	**764.73**	**794.27**	**806.53**	**818.04**	**829.06**

The latest figure for surface water is currently not available. However, the surface water availability at 98% assurance level is 529.1 Mm^3/a **(**DWA, 2003**)** while the groundwater amount is estimated to be 80 Mm^3/a (DWS, personal communication). Hence, the total water availability is about 609.1 Mm^3/a.

6.3.5 Consolidated water requirement and availability for the Limpopo Province

There's currently no official estimation of the total water availability or requirement for the Limpopo Province. However, the estimated figure below is based on the main known sources of water in the province. The current (2000/21) total water requirement for the Limpopo Province is 3 054.43 Mm^3/a, which is projected to increase to 3 450.13 Mm^3/a by 2030/31. The current water availability at 98 per cent assurance level is 2 988.46 Mm^3/a. Table 6.9 depicts the total water requirement and availability for the province.

Table 6.9 Estimated total water requirement and availability for Limpopo Province

Water supply system / WMA	Total water requirements (Mm^3/a)		Total water available (Mm^3/a)	
	Current (2000/21)	Projected (2030/31)	Current (2000/21)	Comments (references)
Olifants River Water Supply System	407	532	433	DWA (2011)
Limpopo North WMA	717.7	824.6	961.6	DWS (2016)
Crocodile West Water Supply System	1 165	1 287	950.6	DWA (2012)
Luvuvhu and Letaba Water Management Areas	764.73	806.53	609.1	DWAF (2003)
Total water transfers into the province			34.16	DWS (2016)
Total	**3 054.43**	**3 450.13**	**2 988.46**	

The Limpopo Province and its districts are mainly supplied with water from the Olifants River Water Supply System, Crocodile West Water Supply System, Limpopo North Water Management Area, Luvuvhu, and Letaba Water Management Areas as well as by transfers from other areas outside the province.

6.4 ANALYSIS OF CURRENT AND PLANNED DEVELOPMENT PROJECTS, ESTIMATED WATER REQUIREMENT, WATER AVAILABILITY AND THE IMPLICATIONS OF THE FUTURE SCENARIOS OF WATER AVAILABILITY ON DEVELOPMENTS

Increased water demands worldwide are driven by a combination of factors. The National Intelligence Council's Strategic Futures Group (2021) attributes a projected increase in water demand during the next 20 years to population growth, changes in lifestyles, and developments among others, and further projected increase of 20 to 50 per cent in water use by 2050, with agriculture being the largest user.

At a national level, there are seven (7) major water use sectors, namely: agriculture, domestic, mining, industrial, power generation, livestock, and afforestation (DWS, 2023). In the Limpopo Province, water plays a central role in all sectors that include agriculture, energy, mining, industry, tourism, urban growth, and rural development (DWS, 2023). Given these competing priorities, demand for water increases over time. WWF-SA (2017) predicted that by 2030, water demand in South Africa is expected to exceed supply by 17 per cent.

The Department of Water and Sanitation (2023) estimates South Africa's domestic water use to be about 237 litres per person per day compared to the global average of 173 litres per person per day, despite the fact that the country is water stressed. Water use among various sectors differs according to their respective demands. Agriculture, including afforestation and livestock watering, comprises 66 per cent of total water use, followed by municipal and domestic use (including industrial and commercial users supplied by municipal systems) at 27 per cent. The remaining 12 per cent is divided between power generation, mining, and bulk industrial use, livestock and conservation, and afforestation (DWS, 2023).

In spite of increasing demands, most of the water is wasted or lost, while very little results in beneficial use. The non-revenue water (i.e., lost or unaccounted for water) in the country has historically been rising and is now at unacceptably high levels. In 2012, the non-revenue water (NRW) was recorded as 36.8 per cent (Mckenzie et al., 2012); then it grew to 41 per cent in 2016 (DWS, 2018) and to 46.4 per cent in 2022 (Odendaal, 2023), exceeding the international average of 30 per cent.

As one of the hottest provinces in South Africa, Limpopo Province experiences regular and severe droughts as a result of its high temperatures and unpredictable rainfall (Maponya and Mpandeli, 2016; Ferreira et al., 2023). Water availability becomes a challenge due to persistent drought or the resultant high evaporation rate and unreliable rainfall. Matimolane et al. (2023) noted that the majority of rural areas in the Limpopo Province have poor infrastructure, inadequate water supply, and limited access to water. Climate scenarios in this study also indicate the probability of increases in long-term droughts over most parts of the Limpopo Province. Rural areas are often the hardest hit under drought conditions due to their dependence on climate-sensitive sectors for sustenance, such as agriculture.

Various development and strategic infrastructure projects that are planned or implemented in the Limpopo Province (e.g., in the mining, agriculture, electricity generation, and industrial sectors) require significant amounts of water. In the following sections, each of the planned major economic activities or developments is assessed, and then the final scenarios from the study are examined to determine their implications on current and planned developments in the Limpopo Province and its districts. The water development projects are also planned to address water shortages in some parts of the Limpopo Province.

6.4.1 Development of water resources to address deficits

The following water development projects are planned to address water requirements in various areas of the Limpopo Province (DWS, 2023b). A dam with a potential capacity of 130 Mm^3 is proposed to be built along the Mutale River to store at least 50 Mm^3/a of water for use in the Luvuvhu-Letaba Catchment, and for transfer to the Musina area. The feasibility study has been initiated, and the dam is currently planned to be operational by 2035. Plans are also afoot to withdraw water from the Limpopo River and pump it into two (2) storage dams within the Sand River, upstream of the confluence with the Limpopo River called Musina Dam and Sand River Dam, with a capacity of 78 Mm^3 and 405 Mm^3, respectively. The expected yield is 100-150 Mm^3/a. The Vhembe District Municipality drilled 6 boreholes, while the Venetia Mine drilled 10 boreholes as part of groundwater development to augment water demands in the Musina area. Additionally, negotiations between the South African and the Zimbabwe governments are ongoing to transfer 15 Mm^3/a of water through a 20 km pipeline from the Zhovhe dam in Zimbabwe across Beitbridge to Musina.

Other water development initiatives include the construction of the bulk pipelines to supply water to Sekhukhune, Capricorn, and Mogalakwena District Municipalities as part of the Olifants River Water Resource Development. Designs are completed to construct the Nwamitwa Dam in the Great Letaba River to provide water for the ecological reserve, domestic, and irrigation requirements in the Mopani District Municipality. In the Crocodile West River System, water is to be transferred from the Crocodile River to the Lephalale area through the Mokolo Crocodile West Water Augmentation Project (MCWAP). The Department of Water and Sanitation also aims to raise the dam wall of the Tzaneen Dam by 3 meters to increase the yield, in order to address water shortages in Tzaneen and the surrounding area within the Groot Letaba Water Supply System.

6.4.2 The Special Economic Zones

The Musina-Makhado and the Fetakgomo-Tubatse Special Economic Zones are the two major initiatives that are in the process of being implemented by the Limpopo Province to boost economic activity. The Musina-Makhado comprises two sites located between Musina and Makhado in the Vhembe District, while the Fetakgomo-Tubatse is in the Fetakgomo Tubatse Local Municipality within the Sekhukhune District. The former is intended to concentrate on light industry, agro-processing dry ports, metallurgical and mineral beneficiation, as well as possibly petrochemicals, while the latter is proposed to jump-start industrialization and is intended to deal with platinum-group metals beneficiation and mining input supplies. The Limpopo Provincial Government (2023) asserted that in order to improve the effectiveness of the logistics system and boost economic activity in Limpopo, it is anticipated that the Musina-Makhado and proposed Fetakgomo-Tubatse special economic zones will guide and inform the implementation of the industrialization program in collaboration with other sector departments in the Economic Cluster. Additionally, it is anticipated that the projected mining and beneficiation outlook of the Platinum Group of Metals in South Africa will be the driving force behind the proposed Fetakgomo-Tubatse Special Economic Zone.

It is estimated that the Musina-Makhado Special Economic Zone (MMSEZ) requires about 30 Mm^3 /a of water for the construction phase, while the projected total amount of water that will be required for operation is 123 Mm^3/a (Munnik, 2020). The combined water requirements for both the MMSEZ and the Limpopo Eco-Industrial Park (LEIP) are projected to be 100-150 Mm^3/a, although this demand has not yet been allocated. The likely main source of water for the special economic zones is the Limpopo River, while negotiations between South Africa and Zimbabwe towards obtaining water from the Zhovhe Dam in the Mzingwane Catchment are ongoing (Munnik, 2020).

The Vhembe District Municipality, in which the Musina-Makhado special economic zone is located, is currently experiencing issues of water scarcity (Promethium Carbon, 2019). At the same time, Vhembe is also home to the Sand River catchment which is the driest catchment in the area. These unfavourable conditions and the fact that the energy and metallurgical industries that will be located in the special economic zones are water-intensive imply that the implementation of the economic zone is likely to encounter viability-related challenges. Climate change impact is superimposed on these water-related challenges that render the Vhembe District Municipality vulnerable. For instance, the future projections of rainfall, extreme indices and drought (Chapter 4) climate scenario analysis indicate under RCP- 4.5 that drought is projected to be more severe in pocket areas of the Vhembe District Municipality for 6-month accumulation period, while in the Capricorn and Waterberg it will be for 3-month accumulation period, and in the case of Mopane it is expected to be for the 12-month accumulation period. Additionally, Promethium Carbon (2019) contends that as drought in the Musina and Makhado areas is expected to worsen between 2035 and 2064 under the no mitigation scenario RCP 8.5, a longer drought would affect the special economic zones' ability to obtain water for operations, which is especially concerning for the thermal and ferrochromium plants that depend heavily on water. However, the future (2035-2065) hydrological projections (Chapter 5) indicate that in the Vhembe District Municipality under the SSP245 and SSP585 emission scenarios, the streamflow is most likely to increase by more than 10 per cent. This projected general increase in streamflow, as well as the planned water resource developments in the area, may bring relief to the drought-stricken area and the envisaged economic developments in terms of water supply.

6.4.3 Mining

Mining is a major source of revenue in the Limpopo Province. In each of the five districts of the province some form or the other of mining activity is ongoing. For instance, platinum, coal, copper, chrome, and diamonds are mined in the Capricorn, Waterberg, Mopani, Sekhukhune, and Vhembe District Municipalities, respectively (LPG, 2023). However, the viability of mining operations also depends on the availability of water. Schoderer and Ott (2022) showed in their study on high-intensity water and conflicts that although extractive industries usually operate in water-scarce locations, they nonetheless require a lot of fresh water. This does not bode well for the likes of the Capricorn and Mopani District Municipalities that, as indicated by the historical rainfall analysis (Chapter 3), experienced negative trends in drought indices over the last 50 years, which implies drought conditions that may impact mining operations have become increasingly likely. However, the future hydrological projections (Chapter 5) under the SSP245 and SSP585 scenarios indicate increases in stream flow of 11 per cent to 15 per cent. If the planned construction of the bulk pipeline to bring water into the Capricorn District Municipality is successful, then at least part of the future water demands by the mining industry would also be addressed.

Table 6.10 depicts the mining sector water requirements for various mineral commodities in different district municipalities. The total water requirements for the mining sector are projected to increase from 159.8 Mm^3/a (in 2020/21) to 253 Mm^3/a (in 2030/31).

Munnik (2020) and DWS (2018) observed that the development of new mines in water-scarce areas requires proper planning that includes arrangements for the transfer of water and the development of new sources. However, developments seem to invariably precede good planning, probably overly driven by economic dictates and imperatives. Yet mining and related activities require significant quantities of water, and often have undesirable environmental impacts.

The climate scenarios (Chapter 4) indicate that Capricorn and Mopani District Municipalities are among the district municipalities that are projected to experience an increase in the number of heavy precipitation days index (*r20mm*), which implies the probability of flooding and may thus negatively impact on the mining operations.

Table 6.10 The water requirements for the mining sector (LPG, 2023)

District	Local Municipality	Commodity	Mining sector water demand (Mm3.a)				
			2015	2020	2025	2030	2045
Capricorn	Polokwane	Platinum Smelter	0.8	0.8	1	1.5	2
Capricorn	Polokwane	Silicon & Other	0.5	1	1.5	1.5	2
Capricorn	Polokwane (Aganang)	Platinum	0	0	0	5	5
Mopani	Phalaborwa	Copper & Sulphate	20	20	20	20	20
Sekhukhune	Tubatse	Platinum & Chrome	17	24	34	40	46
Sekhukhune	Fetakgomo	Platinum	6	6	6	6	6
Vhembe	Musina	Diamond	5	5	5	5	5
Vhembe	Makhado & Musina	Coal	0	7	14	18	18
Waterberg	Lephalale	Coal & Power Stations	30	70	100	120	150
Waterberg	Thabazimbi	Platinum	9	10	11	12	13
Waterberg	Mogalakwena	Platinum & Other	10	16	20	24	30
Total			**98.3**	**159.8**	**212.5**	**253**	**297**

6.4.4 Agriculture

Agriculture is viewed by the Provincial Government of Limpopo Province as having the ability to significantly contribute to the province's economy. The goal is to promote food security and economic growth through sustainable agricultural development (DARD, 2020). Reviving agriculture and agro-processing and fostering a supportive environment for farmers' access to markets are listed as priorities for achieving development of skills and training, as well as bringing about change (i.e., giving effect to transformation) for historically disadvantaged people and those with limited resources (DARD, 2020). Various scales of agriculture are practised in each district municipality of Limpopo. The agriculture industry's current strength is realised in Limpopo, with Mopani and Vhembe districts taking the lead, Capricorn displaying increasing strength, while Sekhukhune and Waterberg trail (LPG, 2023).

Table 6.11 presents the irrigation requirements according to different sources for various catchments of the Limpopo WMA North. In the Sand Catchment, much of the water resource is overexploited. Groundwater indicated earlier (Table 6.6) is overused by more than half of the available amount. It is also in the Sand Catchment where illegal water use is greater than anywhere else in the province (DWS, 2016), followed by the Mogalakwena and Lephalale River catchments.

Table 6.11 Irrigation water requirements for the Limpopo WMA North (DWS, 2016)

River Catchment	Irrigation water requirements (million m^3 /a)							
	Surface water				Groundwater			TOTAL
	Run-off-river and dams	*Schemes	Limpopo River	Total	Groundwater	Limpopo River aquifers	Total	
Matlabas	0.6	0.0	1.8	2.4	2	0.3	2.3	**4.7**
Mokolo	30.9	6.1	0.0	37	3.2	0.0	3.2	**40.2**
Lephalale	38.5	0.0	4.4	42.9	0.7	26.2	26.9	**69.8**
Mogalakwena	25.4	7.9	6.1	39.4	43.2	16.8	60.0	**99.4**
Sand	9.9	0.0	43.7	53.6	126.8	41.3	168.1	**221.7**
Nzhelele	0.8	18.7	5.7	25.2	3.8	0.1	3.9	**29.1**
Total	**106.2**	**32.7**	**61.7**	**200.6**	**179.7**	**84.7**	**264.4**	**464.8**

*Run of the river and dams

The total estimated water requirements for irrigation (Table 6.12) across the five municipal districts of the Limpopo Province is 1 268.3 Mm^3/a (LPG, 2023). These estimates are based on a rate of application of 8000 $m^3/ha/a$.

Table 6.12 Agricultural water demand in the municipal districts of the Limpopo Province (LPG, 2023)

Municipal district	Irrigated area (ha)	Main crops under irrigation	2015 water demand (8000 $m^3/ha/a$) Mm^3/a
Capricorn	12 185	Citrus, potatoes, pastures, maize, vegetables	97.5
Mopani	44 456	Citrus, subtropical fruit, tomatoes, vegetables	355.6
Sekhukhune	31 338	Citrus, grapes, maize, grains, vegetables	250.7
Vhembe	24 616	Nuts, citrus, subtropical fruit, tomatoes, vegetables	196.9
Waterberg	45 937	Citrus, grapes, grains, vegetables	367.5
Total	**158 530**		**1 268.3**

The projected climate scenarios indicate decrease in precipitation that will negatively impact water resources and agriculture. Projections in Chapter 4 showed that reductions in mean annual precipitation are more pronounced in at least four district municipalities, including the South-Eastern Sekhukhune, South-Eastern Capricorn, Western Mopani, and Central Waterberg. This will exacerbate the drought conditions in those districts, thus negatively impacting the economic developments in general, and exacerbating food insecurity in particular. The projected future (2035-2065) increases in streamflow of 10 per cent to 15 per cent (Chapter 5) under the SSP245 and SSP585 scenarios in the Mopani and Vhembe District Municipalities (that are leading in agricultural activities), is a welcome relief given the expected drought that would be dominating these areas.

6.4.5 Power generation

The vast majority of South Africa's electricity is generated in coal fired power stations (Mostert and Van Heerden, 2015). Additionally, Pierce and Le Roux (2022) noted that coal still dominates and provides about 80 per cent of electricity generated with continued high use of diesel, while renewables (excluding hydro) accounts for only 7 per cent. There is a symbiotic relationship between power stations and coal mines. For instance, according to Munnik (2020), eight (8) new coal-fired power stations linked to new coal mines were planned in the Limpopo Province. Matimba and Medupi Power stations were built near Grootegeluk coal mine that extracts the Waterberg coal deposit which is acknowledged to be the second largest coal reserve in South Africa, second only to Emalahleni.

Large amounts of water are used in the production of electricity for purposes of cooling in fossil-fuel and nuclear-based electricity generation, and spinning the turbines in hydroelectricity generation (Li et al., 2022). The fact that power generation also requires significant amounts of water is a huge conundrum for the water and energy sector. As projections (Chapter 4) show that all district municipalities are most likely to become drier and consequently experience reduced availability of water, this implies that these developments will also be negatively affected. Under both RCP4.5 and RCP8.5 scenarios, Waterberg is one of the district municipalities that are projected to experience a significant decrease in precipitation. That is most likely going to negatively impact power generation in the area. However, most power stations in Limpopo also receive water that is transferred from outside the study area to augment demand. The future (2035-2065) streamflow is projected (Chapter 5) to increase in the Waterberg District Municipality by 5 per cent to 15 per cent under the SSP245 and SSP585 scenarios. This is also in line with what was indicated earlier that the future rainfall analysis results (Chapter 4) projected a slight rainfall increase for the south-western part of Waterberg.

6.5 STRATEGIC INTERVENTIONS AND APPROPRIATE ADAPTATION OPTIONS

Each of the three spheres of Government (viz, at national, provincial, and local levels) should collaboratively implement strategic interventions to address climate change impacts, while on the other hand water users (i.e., those who are undertaking water intensive developments such as irrigators) should take appropriate adaptation actions to develop resilience and to reduce vulnerabilities.

Government-led interventions need to be put in place to address the national estimated figure of the non-revenue water that increased from 41 per cent in 2016 to 46.4 per cent in 2022, to reduce the vulnerability of the water supply systems to climate change-induced effects. Similar actions need to be taken by the local Government to reduce municipal water losses of about 1 660 Mm³/a from NRW, that is estimated in monetary terms to be in the order of about R9.9 billion each year (DWS, 2018). The Limpopo Province has the highest NRW percentage of 56.7 per cent (equivalent to 168.8 Mm³/a), in which water losses account for 56.5 per cent (DWS, 2023a). It is also reported that the Infrastructure Leakage Index of the province is 5.7, which is classified as poor performance on the No Drop scorecard. This means water conservation and demand management across the board are necessary and essential. Practical actions should include automated leak detection and leak repair, proper metering, effective billing, and improved cost recovery.

The institutional capacity of district municipalities should be strengthened, and their adaptive capabilities built to enable them to effectively deal with challenges that can potentially be addressed. For instance, Vhembe District Municipality could have addressed the problem of over-exploitation of groundwater in the Sand River if the institutional capacity thereof had been strengthened with appropriate skill sets, as well as the capacity to enforce compliance among irrigators in the area under their jurisdiction. Sustainable use of the limited water resources is possible if users comply with the operating rules or refrain from the withdrawal of groundwater at rates that exceed the safe yield of the resource.

Given that the surface water resources are over-subscribed in the province and various district municipalities, diversification of the water resource mix that entails a progressive paradigm shift from over-reliance on surface water to increased use of unconventional sources (such as groundwater, water re-use, or desalination of saline water) is essential. Regarding groundwater, the Limpopo Province is relatively advantaged since the Groundwater Resource Information Project (GRIP) data (Du Toit et al., 2012) is available for use to optimally develop groundwater sources. Another related adaptation strategy is using Managed Aquifer Recharge techniques to artificially recharge and later retrieve groundwater, and then conjunctively use it with other sources. There are ample lessons to be learnt in this regard, particularly from areas such as Polokwane (DWA, 2009; Tleane and Ndambuki, 2020), where Managed Aquifer Recharge has been used over the years for water augmentation purposes.

Considering water stress in the Limpopo Province and that agriculture is the largest water user, the Department of Water and Sanitation (2016) made a decision to refrain from increasing total water allocations for irrigation in successive years up to 2040. It was resolved that enhanced water use efficiency of irrigation systems is proposed, and rather than the envisaged expansion in agricultural production (DARD, 2020) should be achieved through use of the same amount of water allocated for irrigation (i.e., there will be no increase in water allocation during the set period). That is the strategic intervention of government on one hand, and adaption (i.e., water use efficiency in irrigation) by the water users on the other.

It is also recommended that the proponents of developments that require significant amounts of water, especially where demands far exceed availability of water within the districts, should consider seeking augmentation through development of local water sources (e.g., groundwater borehole field development). It is essential for water users to use water sparingly, sustainably, and efficiently through water conservation and water demand management approaches.

The resource-poor rural communities who are most vulnerable to the impacts of climate change and who often experience the scarcity of water access should be prioritized for water allocation by national government and be supported (resource wise) by both the provincial and local governments.

Where feasible, water transfers from areas with excess to those with deficit should also be considered.

6.6 CONCLUSION

This chapter assessed the projections from the study and determined the implications for current and planned developments in the Limpopo Province (in particular, those projects requiring significant water to be viable). The analyses conducted in Chapters 3, 4, and 5 were examined and the implications of those analyses on developments determined. The findings were that most of the developments are in water stressed areas and are as such already vulnerable to climate change impacts. The Limpopo Province is found to be water stressed and riddled with severe and frequent droughts, excessive high temperatures, as well as reduced rainfall. Additionally, the climate change driven extreme events, particularly drought and floods, impact negatively on water dependent economic development projects such as agriculture production and mining. In general, water scarcity and unsustainable water use are identified as limiting factors to water-dependent developments. For instance, some of the non-climatic stress factors such as increased non-revenue water, degradation of water quality, over-exploitation of groundwater and unsustainable water use, as well as poor water management, render the system vulnerable to climate change. The water resources schemes planned by the Department of Water and Sanitation address deficits in various areas, while the district municipalities and the private sector (e.g., mines) develop local resources to augment their water requirements. Hence, the recommended interventions and adaptation options aim to ensure reduction of vulnerability and enhanced resilience.

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CHAPTER 7: SUMMARY OF STAKEHOLDER ENGAGEMENTS

A series of three workshops was held during the course of the project to share details of the project with key stakeholders, and to receive their feedback to ensure the relevance and impact of the work. The first workshop was held in June 2023, while the second and third workshops were held in October and November 2023, respectively. A detailed account of each workshop, including the programmes, are given in Appendix C. A summary of the workshops, including their key findings and the implications for the project, are presented in this chapter.

7.1 FIRST STAKEHOLDER WORKSHOP

7.1.1 Overview of workshop

The first workshop was a hybrid (physical / virtual) workshop held on 30 June 2023 at the CSIR International Convention Centre. The workshop was mainly attended by national and provincial representatives of the Department of Water and Sanitation (DWS), and the partner organisations of the project (including team members and people not involved in the project). The opening session included presentations by the Water Research Commission (on their strategic vision), the project leader, who provided a project overview, the national director of Water Resources Planning, and a Limpopo representative of DWS who gave perspectives on water resource planning in the province. This was followed by two sessions on project progress, where members of the project team gave presentations on the methodology and results (where available) relating to the historical and projected future rainfall analysis, the hydrological modelling component, and the component devoted to exploring the development implications of projected future climate and water resources. A fourth session was devoted to students (one PhD and two MSc) working on the project, who gave presentations on their research.

7.1.2 Key findings of workshop

Key findings of the workshop included the following:

- Valuable insights on the current status of water resources in Limpopo, and the strategies in place to meet future water demands were obtained.
- There is a need for knowledge in the water sector (including on climate change issues) that can inform policy and practice. The complexity of water resources policy is increasing as water demands increase.
- The incorporation of climate change perspectives into water resources planning is needed and will be achieved through collaboration between DWS and researchers.
- Capacity building and the exchange of ideas is needed to empower communities.
- The need for capacity building of students and the development of water professionals to ensure water security in Limpopo and elsewhere in the country was highlighted.
- The drivers of water demand include natural population growth, economic growth, and migration. It is important that these demands are managed in a way that seeks to address inequality, poverty, and unemployment.
- Re-allocation of water is critical to ensure sustainable and equitable distribution of water.
- Reconciliation strategies are key to ensuring water security and increasingly require a broadening of the water resources mix to achieve their aims.

- The importance of groundwater as a resource in future planning in Limpopo was highlighted. The need for greater monitoring and the determination of sustainable extraction rates was also highlighted.

7.2 SECOND STAKEHOLDER WORKSHOP

7.2.1 Overview of workshop

The second stakeholder workshop was held on 30 October 2023 in the form of an online seminar. The workshop was mainly attended by Limpopo provincial representatives of the Department of Water and Sanitation (DWS), and the partner organisations in the project (including team members and people not involved in the project). The programme was mainly devoted to a presentation on preliminary results of coupling the climate projections with the hydrological model as part of the future water resources assessment. There was also a presentation in response which considered the development implications of the future water resources assessment. These presentations were followed by discussion and exchange of ideas on the results and the implications for planning.

7.2.2 Key findings of workshop

Key findings of the workshop included the following:

- The reasons for the selection of the hydrological model were discussed. The need to be able to link the outputs of the model to the planning models and processes used by DWS was highlighted. Ongoing engagement is required to achieve this.
- It was emphasised by DWS participants that the output of any model be critically evaluated to ensure that it represents reality, and that its outputs are not simply accepted at face value.
- It was believed by some that the large number of stochastic streamflow sequences (conditioned on historical records) incorporated into DWS planning models would be able to represent the range in future climate, without the need for future climate projections.
- DWS planners require a very strong motivation to adopt a particular scenario when offered a range of possible scenarios. They will typically develop plans that encompass all possible scenarios.
- If an additional future period were to be considered, a near future period (leading up to the one considered in the hydrological modelling, i.e., 2036-2065) would be of more interest to planners than a distant future period at the end of the century.
- The impact of changing land use on water resources was also highlighted as an additional factor to consider in future assessments.

7.3 THIRD STAKEHOLDER WORKSHOP

7.3.1 Overview of workshop

The third workshop was a hybrid (physical / virtual) workshop held on 6 November 2023 at a conference venue in Polokwane. The workshop was mainly attended by provincial representatives of the Department of Water and Sanitation (DWS), and the partner organisations of the project (including team members and people not involved in the project). The workshop commenced with opening remarks by the relevant head of department at the lead organisation (University of Limpopo) and the Chief Director of the Limpopo Department of Water and Sanitation. This was followed by an overview of the project (given by the project leader) and presentations by team members on the results of the project including the historical and projected future rainfall analysis, the hydrological modelling component, and the component devoted to exploring the development implications of projected future climate and water resources. A presentation was also given by an MSc student on a case study in the Letaba Catchment concerning the impact of land use and land cover on water quality. In the afternoon session, a presentation was given by a DWS representative on current and planned water supply augmentation projects in the province. Time was allocated to questions and discussion after each session. In the final session, a DWS representative provided overall feedback on the work, based on the presentations and subsequent discussions.

7.3.2 Key findings of workshop

Key findings of the workshop included the following:

- The importance of groundwater in various parts of the province both currently and as an adaptation in the future was highlighted, given that the modelling only accounted for surface water resources.
- The Olifants Catchment is highly stressed and the demand for water continues to grow. The water sector needs to continue highlighting this deficit to users. Municipalities need to be included in this discussion as their Integrated Development Plans often do not appreciate the impact of water scarcity in the region.
- Water quality is a key issue in Limpopo and it follows that the impact of climate change on water quality should also be investigated.
- A major limitation to implementing augmentation projects and other interventions is a lack of adequate funding. Given this context, economic modelling should also be factored into future water resource assessments to aid in planning.
- The plans for special economic zones in the Olifants WMA and Musina area are very concerning given that these locations are already water stressed.
- It is recognised that wastewater treatment plants are failing and are polluting the country’s water resources. This issue needs to be addressed as a top priority, even before climate change.
- The issue of where to incorporate climate projections in the planning process needs to be clarified or investigated.
- The importance of capacity building in the form of postgraduate training (and in other forums) was emphasised.

7.4 CONCLUSION

The stakeholder engagement workshops provided valuable opportunities for the sharing of knowledge between the project team and DWS representatives. Specifically, the DWS representatives were able to learn about the project methodology and results, and how climate change is projected to impact the province, while the project team gained a better understanding of existing planning for ensuring water security. Importantly, the project team was also able to receive feedback on the project methodology and results. This feedback was incorporated where possible, while other actions were identified for future recommendations. It was recognised that ongoing collaboration between researchers and DWS is needed to ensure the incorporation of climate change into planning processes and policy.

CHAPTER 8: CONCLUSION & RECOMMENDATIONS

8.1 DISCUSSION AND CONCLUSION

The analyses of rainfall indices conducted in the study projected more frequent droughts in future (based on SPI and SPEI), while extreme precipitation indices mostly showed reductions in the indices quantifying wet conditions and increases in the indices quantifying dry conditions (suggesting a pattern of overall drying). An exception to this pattern was in the south-west of the province which exhibited a wetting trend. The analysis of changes in rainfall indices was based on a multi-model averaging approach and, thus, did not indicate the range of responses that would have been present across the different climate models considered.

The analysis of change in streamflow focused on assessing changes in mean annual conditions, and showed a large range in responses across the driving climate models. In summary, the median of the climate model ensemble showed both decreases and increases in flows (location-dependent), while the wet end of the ensemble (90th percentile) generally showed increases in flows (some very large). The dry end of the ensemble generally showed reductions in flows, with an exception to this being the Upper Olifants Catchment in the south of the province where small increases were projected. Projected changes were similar for the lower and higher emissions scenarios, especially when considering the median of the climate model ensemble.

It is important to note that the streamflow projections were based on a different set of climate projections (ISIMIP) to the analysis of rainfall indices (CORDEX). The reasons for this were explained in Chapter 5 and included the considerations that the ISIMIP projections were newer (based on CMIP6 vs CMIP5 global climate models), had been bias corrected using a relatively sophisticated technique, and were available for a selection of climate models and emission scenarios. The ISIMIP climate projections were not available to the project team at the time of analysing changes in rainfall indices.

As there were more rivers indicating an increase in streamflow (than a decrease) for the median of the climate model ensemble (Chapter 5), and the degree of wetting at the 90th percentile was greater than the degree of drying at the 10th percentile, it can be concluded that the ISIMIP models tended to project a wetter future than the CORDEX models. The ISIMIP models are derived from CMIP6 global climate models (through a process of downscaling and bias correction). When looking at the average of all CMIP6 global models, the projected changes in annual rainfall indicate drying over South Africa including Limpopo (Lee et al., 2021). However, at the level of individual models, there are both drying and wetting patterns found with 50 per cent of the models in a 30-model ensemble indicating wetting over Limpopo for the summer rainfall season (Hamp et al., 2022). This suggests that the models indicating drying do so to a greater degree than those indicating wetting (given that the multi-model average of annual rainfall shows drying). The tendency of the ISIMIP models towards wetting suggests that the five models assessed in this project were wetter in nature than others available in the CMIP6 ensemble. The five models applied in this project were those for which data were available for both SSP245 and SSP585 scenarios. There are an additional five CMIP6 global models that were downscaled in the ISIMIP project; however, they were only downscaled for SSP585. It would be instructive to assess these additional five models to see if they have a greater tendency towards drying. Such a trend would be more in line with the trends found in historical rainfall (Chapter 3), the analysis of future rainfall indices based on CORDEX data (Chapter 4), and the experience and perceptions of many stakeholders (Chapter 6).

The projected changes in mean rainfall are associated with relatively high uncertainty (Chapter 5). This uncertainty is amplified in runoff responses due to non-linearity in the hydrological system. While the projected changes in mean conditions are associated with a relatively high uncertainty, the projected increases in rainfall extremes (Chapter 4, i.e., drought and in certain areas heavy rainfall events) are a robust finding that is common in climate change studies. It is the changes in extremes that will likely test the water resources infrastructure (e.g., dams) in the province (rather than changes in the means), with droughts being of concern to the provision of an adequate supply of water, and large rainfalls testing the resilience of infrastructure to flooding. Building resilience to the projected changes in extremes is thus the priority in adaptative interventions.

The future projections of streamflow were assimilated into a set of four plausible future scenarios (low, baseline, medium-high, high) by considering the average change across all key rivers in the province (Chapter 5). This process considered the two emissions scenarios and the three calculated percentiles of the climate model ensemble. Each scenario was considered to be possible in any location of the province, even though this pattern of change might not have been observed in the streamflow simulations in this project. This approach recognizes that different sources of projections do not necessarily indicate the same patterns of change (for example, Schutte et al*.* (2023) projected drying in the west and wetting in the east, i.e., the opposite pattern to that found in this project). However, the magnitudes of change in the proposed scenarios are typical of what was found in this study and elsewhere.

In discussion with DWS stakeholders, it was found that some assumed the streamflow outputs from this project would be used as input to the yield and planning models used by DWS. This would represent a more quantitative approach to incorporating climate change information into planning. An alternative, more qualitative approach, would be to infer a direction (and possibly magnitude) of change in yield based on a percentage change in input flow derived from the scenarios produced in this project.

Flow simulations from the Pitman model are typically used by DWS as input to their yield and planning models. A caution to the application of the quantitative approach outlined in the paragraph above is that naturalised flows in the Pitman model are not identical in nature to ACRU-simulated flows under natural vegetation conditions. Naturalised flows in Pitman are determined by removing the influence on flows of key, explicitly accounted for land uses (e.g., irrigation, mining, afforestation), while the influence of other land uses (e.g., dryland crops) on flows remains. This contrasts with ACRU-simulated flows under natural vegetation conditions which represent a more pure, natural condition. Hence, if the ACRU natural flows are input to the yield/planning models and the influence of the land uses that are normally explicitly accounted for in Pitman are then added, the influence of other land uses (e.g., dryland crops) on the simulated flows will still be missing.

In consultations with stakeholders, it was found that some believe that the large number of stochastic flow sequences conventionally used as input to the DWS yield/planning models would have sufficient extremes represented in them to represent any future condition that may be experienced under climate change. These stochastic flow sequences (which may be hundreds or thousands in number to ensure robustness) are generated by a stochastic model that is conditioned on the statistical properties of historical flow records. The above belief should be tested by comparing the worst drought conditions found in sequences generated in this manner, with conditions found in projected future climate. A challenge in this regard would be to find techniques that can generate comparative stochastic flow sequences conditioned on future climate projections when these projections do not represent stationary datasets (a requirement for the application of commonly used stochastic flow models).This challenge of generating valid stochastic flow sequences conditioned on future climate projections would also represent another challenge to adopting the quantitative approach to incorporating climate change information into planning models discussed in the previous sections.

Consultation with stakeholders revealed the importance of groundwater as a resource to satisfy growing water demands in the province. The need to assess the impact of climate change on this resource, and to build it into adaptation planning, was stressed. The reduction of non-revenue water as an intervention was also highlighted in the research and by stakeholders.

The importance of water quality was also highlighted in stakeholder consultations. While it would be valuable to understand the potential impact of climate change on water quality, stakeholders stressed that the first priority is to improve the maintenance of sewage networks and wastewater treatment facilities. This is true in Limpopo and elsewhere in the country, since failing sanitation infrastructure is polluting water resources and poses a serious risk to future water security.

The exploration of the impact of projected future climate on development in the province highlighted that several large development projects have been proposed without adequate consideration of water availability. Most of these developments are in water stressed areas and are, as such, already vulnerable to climate impacts. This is very concerning and prompted discussion during stakeholder engagements. It was agreed in these engagements that more awareness needed to be raised regarding the importance of considering water availability in spatial planning. This should also extend down to municipal level, where spatial development plans often do not give adequate attention to issues of water availability.

8.2 RECOMMENDATIONS

The following recommendations are made based on the outcomes of the project and the conclusions above:

- Under the auspices of the WMO, a relatively new suite of extreme climate indices has been developed and are calculable with the WMO ClimPact software. The trends of these sector-relevant indices can be determined for both the historical periods and future periods, depending on data availability. The impacts of climate change in areas or regions of particular concern can be further investigated through these indices, which in many cases can be refined by the user in terms of, for example, threshold values. In this regard, the impacts of the changing rainfall climate can be assessed for specific sectors and industries.
- The ISIMIP climate projections should be analysed in terms of changes in rainfall extremes (droughts, extreme precipitation indices) to assess how well they correspond with the CORDEX projections. This will further help to relate the streamflow projections to the other climate-related analyses conducted in the project. In addition, other available climate models in the ISIMIP dataset (for SSP585) should be assessed to determine whether they indicate future drying or wetting. The inclusion of these models may shift the overall outlook of the ISIMIP projections to be more in line with the greater CMIP6 envelope, and the CORDEX models used in the project.
- Adaptive interventions should focus on building resilience to climate extremes (droughts and floods) given that the trend for these events to increase in severity/frequency is associated with greater certainty than the changes in mean conditions. The robustness of water resources infrastructure is also tested to a greater degree during extreme conditions than under mean conditions.
- Assess whether stochastic flow sequences conventionally used as input to the DWS yield/planning models have sufficient extremes represented in them to represent any future condition that may be experienced under climate change. This would require research to develop valid stochastic flow sequences conditioned on future climate change projections, for comparison with stochastic flow sequences conditioned on historical flow records.
- The impacts of climate change on groundwater should be considered in future research since groundwater has been identified as a key resource to achieving future water security in Limpopo.
- The impacts of climate change on water quality should be considered in future research.

- Efforts to maintain and improve sewerage networks and wastewater treatment facilities should be given top priority given the severe risk that failing sanitation infrastructure poses to water security.
- Other measures to conserve water resources such as the reduction of non-revenue water and the improvement of irrigation efficiency should be prioritised to ensure water security in a changing climate.
- Greater awareness should be raised of the need to consider water availability in future development projects to ensure the success of these developments and the security of water supplies. Consideration should be given to water requirements early in the planning phase to avoid later problems in the approvals and implementation of these projects.
- There should be ongoing engagement between researchers and DWS to ensure climate change is adequately factored into water resources planning.

8.3 REFERENCES

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APPENDIX A: ADDITIONAL SOCIO-ECONOMIC DATA FOR LIMPOPO DISTRICTS

CAPRICORN DISTRICT

Main economic sectors: Community services (30.9 per cent), finance (27.6 per cent), trade (14 per cent), transport (13.2 per cent), manufacturing (4.3 per cent), construction (3.3 per cent), agriculture (3.1 per cent), electricity (2.9 per cent).

Socio-economic data for 2011 and 2016

Statistic	2016	2011
Population	1 330 436	1 261 463
Age Structure		
Population under 15	33.6%	33.6%
Population 15 to 64	60.6%	59.9%
Population over 65	5.8%	6.6%
Dependency Ratio		
Per 100 (15-64)	65.0	67.0
Sex Ratio		
Males per 100 females	88.7	87.9
Population Growth		
Per annum	1.21%	n/a
Labour Market		
Unemployment rate (official)	n/a	37.2%
Youth unemployment rate (official) 15-34	n/a	47.4%
Education (aged 20 +)		
No schooling	12.4%	13.2%
Matric	29.9%	24.9%
Higher education	11.4%	13.1%
Household Dynamics		
Households	378 301	342 838
Average household size	3.5	3.6
Female headed households	49.1%	49.9%
Formal dwellings	93.2%	92.0%
Housing owned	69.8%	58.1%
Household Services		
Flush toilet connected to sewerage	30.2%	26.6%
Weekly refuse removal	30.4%	29.7%
Piped water inside dwelling	19.5%	23.3%
Electricity for lighting	95.2%	87.4%

MOPANI DISTRICT

Main economic sectors: Mining (30.1 per cent), community services (22.6 per cent), trade (14.6 per cent), finance (14.6 per cent), transport (8.2 per cent), agriculture (3.2 per cent), electricity (2.8 per cent), construction (2 per cent).

Socio-economic data for 2011 and 2016

Statistic	2016	2011
Population	1 159 185	1 092 507
Age Structure		
Population under 15	31.5%	33.8%
Population 15 to 64	63.9%	60.5%
Population over 65	4.6%	5.7%
Dependency Ratio		
Per 100 (15-64)	56.5	65.3
Sex Ratio		
Males per 100 females	87.1	84.9
Population Growth		
Per annum	1.35%	n/a
Labour Market		
Unemployment rate (official)	n/a	39.4%
Youth unemployment rate (official) 15-34	n/a	51.4%
Education (aged 20 +)		
No schooling	17.1%	21.2%
Matric	24.8%	20.7%
Higher education	8.1%	8.2%
Household Dynamics		
Households	338 427	296 320
Average household size	3.4	3.6
Female headed households	49.2%	50.9%
Formal dwellings	90.7%	92.2%
Housing owned	71.5%	55.6%
Household Services		
Flush toilet connected to sewerage	14.1%	15.8%
Weekly refuse removal	15.6%	16.9%
Piped water inside dwelling	12.8%	16.8%
Electricity for lighting	94.5%	88.7%

SEKHUKHUNE DISTRICT

Main economic sectors: Community services, mining (15-20 per cent), trade (17 per cent), financial and business services (10-12 per cent), agriculture (9.7 per cent).

Socio-economic data for 2011 and 2016

Statistic	2016	2011
Population	1 169 762	1 076 840
Age Structure		
Population under 15	32.5%	36.0%
Population 15 to 64	62.1%	57.3%
Population over 65	5.3%	6.7%
Dependency Ratio		
Per 100 (15-64)	61.0	74.7
Sex Ratio		
Males per 100 females	88.3	85.9
Population Growth		
Per annum	1.88%	n/a
Labour Market		
Unemployment rate (official)	n/a	50.9%
Youth unemployment rate (official) 15-34	n/a	60.6%
Education (aged 20 +)		
No schooling	16.0%	20.9%
Matric	24.3%	21.0%
Higher education	6.4%	6.1%
Household Dynamics		
Households	290 527	263 802
Average household size	4.0	4.0
Female headed households	51.2%	52.9%
Formal dwellings	87.6%	88.7%
Housing owned	74.9%	58.2%
Household Services		
Flush toilet connected to sewerage	5.9%	6.3%
Weekly refuse removal	9.0%	8.2%
Piped water inside dwelling	4.6%	9.3%
Electricity for lighting	89.6%	85.9%

VHEMBE DISTRICT

Main economic sectors: Mining, community services, finance.

Socio-economic data for 2011 and 2016

Statistic	2016	2011
Population	1 393 949	1 294 722
Age Structure		
Population under 15	34.2%	34.9%
Population 15 to 64	61.0%	58.9%
Population over 65	4.7%	6.3%
Dependency Ratio		
Per 100 (15-64)	63.8	69.9
Sex Ratio		
Males per 100 females	85.8	84.1
Population Growth		
Per annum	1.68%	n/a
Labour Market		
Unemployment rate (official)	n/a	38.7%
Youth unemployment rate (official) 15-34	n/a	50.6%
Education (aged 20 +)		
No schooling	14.4%	17.7%
Matric	25.0%	21.6%
Higher education	9.6%	9.9%
Household Dynamics		
Households	382 357	335 276
Average household size	3.6	3.8
Female headed households	51.0%	52.6%
Formal dwellings	86.3%	87.7%
Housing owned	76.9%	64.0%
Household Services		
Flush toilet connected to sewerage	16.0%	13.9%
Weekly refuse removal	16.5%	13.7%
Piped water inside dwelling	7.4%	15.4%
Electricity for lighting	94.6%	87.2%

WATERBERG DISTRICT

Main economic sectors: Mining, agriculture, tourism.

Socio-economic data for 2011 and 2016

Statistic	2016	2011
Population	745 758	679 336
Age Structure		
Population under 15	34.4%	29.9%
Population 15 to 64	60.5%	64.3%
Population over 65	5.1%	5.8%
Dependency Ratio		
Per 100 (15-64)	65.4	55.5
Sex Ratio		
Males per 100 females	104.7	102.1
Population Growth		
Per annum	2.12%	n/a
Labour Market		
Unemployment rate (official)	n/a	28.1%
Youth unemployment rate (official) 15-34	n/a	35.5%
Education (aged 20 +)		
No schooling	7.1%	12.4%
Matric	27.6%	23.2%
Higher education	9.0%	9.0%
Household Dynamics		
Households	211 471	179 866
Average household size	3.5	3.4
Female headed households	40.9%	42.7%
Formal dwellings	85.0%	87.0%
Housing owned	63.6%	47.7%
Household Services		
Flush toilet connected to sewerage	43.8%	43.6%
Weekly refuse removal	44.4%	44.2%
Piped water inside dwelling	24.4%	30.7%
Electricity for lighting	86.1%	86.7%

APPENDIX B: TREND STATISTICS FOR ALL INDICES AND STATIONS CONSIDERED IN THE HISTORICAL EXTREME RAINFALL ANALYSIS

Rainfall District 34

Letaba Mahlangeni

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1986	2021	0.109	0.872	-
rx5day	1986	2021	0.113	0.927	-
sdii	1986	2021	0.046	0.529	-
r10mm	1986	2021	-0.091	0.398	-
r20mm	1986	2021	-0.015	0.829	-
R25mm	1986	2021	-0.036	0.562	-
cdd	1986	2021	1.035	0.125	-
cwd	1986	2021	-0.024	0.469	-
r95p	1986	2021	0.465	0.823	-
r99p	1986	2021	-0.015	0.99	-
prcptot	1986	2021	-2.116	0.562	-

Letaba Mooiplaas

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1973	2021	0.388	0.295	-
rx5day	1973	2021	0.515	0.524	-
sdii	1973	2021	-0.062	0.142	-
r10mm	1973	2021	-0.073	0.184	-
r20mm	1973	2021	-0.063	0.133	-
R25mm	1973	2021	-0.039	0.258	-
cdd	1973	2021	0.022	0.958	-
cwd	1973	2021	-0.005	0.792	-
r95p	1973	2021	1.638	0.278	-
r99p	1973	2021	0.936	0.24	-
prcptot	1973	2021	-1.186	0.605	-

Olifantskamp

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1973	2021	0.678	0.23	86
rx5day	1973	2021	0.82	0.326	102.1
sdii	1973	2021	0.032	0.55	19
r10mm	1973	2021	-0.036	0.499	25
r20mm	1973	2021	-0.05	0.165	12
R25mm	1973	2021	0.013	0.681	10
cdd	1973	2021	0.507	0.292	86
cwd	1973	2021	-0.023	0.116	4
r95p	1973	2021	1.57	0.232	228
r99p	1973	2021	0.878	0.448	0
prcptot	1973	2021	-0.597	0.768	760.5

Rainfall District 35

Krugerwildtuin Shangoni ARS

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1957	2021	-0.52	0.051	-
rx5day	1957	2021	-0.849	0.19	-
sdii	1957	2021	-0.012	0.641	12.7
r10mm	1957	2021	-0.031	0.524	20
r20mm	1957	2021	-0.03	0.366	7
R25mm	1957	2021	-0.032	0.292	5
cdd	1957	2021	0.47	0.138	68
cwd	1957	2021	0.004	0.81	5
r95p	1957	2021	-0.814	0.465	212.8
r99p	1957	2021	-1.109	0.106	0
prcptot	1957	2021	-1.987	0.26	623

Letaba Woodlands

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1983	2021	-0.119	0.871	69
rx5day	1983	2021	0.028	0.978	109.7
sdii	1983	2021	0.088	0.133	15.2
r10mm	1983	2021	-0.001	0.983	16
r20mm	1983	2021	0.011	0.797	10
R25mm	1983	2021	0.011	0.758	8
cdd	1983	2021	0.99	0.092	79
cwd	1983	2021	-0.02	0.411	3
r95p	1983	2021	0.069	0.972	136
r99p	1983	2021	-0.202	0.878	0
prcptot	1983	2021	-0.051	0.985	624.6

Punda Maria

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1924	2021	0.189	0.384	-
rx5day	1924	2021	0.182	0.677	-
sdii	1924	2021	-0.023	0.106	11.1
r10mm	1924	2021	-0.049	0.075	11
r20mm	1924	2021	-0.03	0.117	5
R25mm	1924	2021	-0.028	0.086	1
cdd	1924	2021	-0.041	0.816	167
cwd	1924	2021	-0.006	0.616	4
r95p	1924	2021	-0.643	0.281	0
r99p	1924	2021	-0.376	0.396	0
prcptot	1924	2021	-1.738	0.094	256

Shingedzi Vakteplaas

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1983	2021	0.267	0.568	125.5
rx5day	1983	2021	0.212	0.854	157.5
sdii	1983	2021	0.087	0.136	16.2
r10mm	1983	2021	-0.035	0.573	12
r20mm	1983	2021	0.008	0.872	9
R25mm	1983	2021	0.008	0.872	7
cdd	1983	2021	1.466	0.021	107
cwd	1983	2021	-0.034	0.1	5
r95p	1983	2021	0.601	0.789	392.5
r99p	1983	2021	0.04	0.972	209.5
prcptot	1983	2021	-0.66	0.816	630.4

Rainfall District 48

Hans Merensky N.S

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1927	2021	-0.144	0.381	-
rx5day	1927	2021	-0.269	0.38	-
sdii	1927	2021	-0.087	0	17.9
r10mm	1927	2021	-0.024	0.306	14
r20mm	1927	2021	-0.017	0.23	8
R25mm	1927	2021	-0.017	0.186	7
cdd	1927	2021	-0.063	0.707	195
cwd	1927	2021	0.001	0.846	4
r95p	1927	2021	-0.342	0.599	419
r99p	1927	2021	0.032	0.931	92
prcptot	1927	2021	-0.548	0.536	645.1

New Agatha Bos

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1940	2021	0.759	0.048	172
rx5day	1940	2021	0.892	0.205	308.5
sdii	1940	2021	0.085	0.004	34
r10mm	1940	2021	0.035	0.548	33
r20mm	1940	2021	0.064	0.121	26
R25mm	1940	2021	0.059	0.089	21
cdd	1940	2021	-0.089	0.567	74
cwd	1940	2021	-0.024	0.162	4
r95p	1940	2021	2.57	0.13	911.2
r99p	1940	2021	1.669	0.145	172
prcptot	1940	2021	2.952	0.25	1665

Phalaborwa Excellence

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1978	2021	0.275	0.592	-
rx5day	1978	2021	-0.417	0.552	-
sdii	1978	2021	0.048	0.217	-
r10mm	1978	2021	-0.137	0.054	-
r20mm	1978	2021	-0.061	0.229	-
R25mm	1978	2021	-0.034	0.438	-
cdd	1978	2021	0.94	0.083	-
cwd	1978	2021	-0.024	0.225	-
r95p	1978	2021	0.835	0.553	-
r99p	1978	2021	0.495	0.548	-
prcptot	1978	2021	-3.588	0.124	-

Tubatse Agric

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1979	2021	-0.431	0.477	-
rx5day	1979	2021	-1.525	0.18	-
sdii	1979	2021	-0.04	0.665	-
r10mm	1979	2021	-0.01	0.893	-
r20mm	1979	2021	0.007	0.896	-
R25mm	1979	2021	0.015	0.746	-
cdd	1979	2021	1.062	0.076	-
cwd	1979	2021	-0.022	0.148	-
r95p	1979	2021	-0.89	0.599	-
r99p	1979	2021	-0.979	0.371	-
prcptot	1979	2021	-0.532	0.833	-

Wolkberg

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1971	2021	0.072	0.856	117
rx5day	1971	2021	0.478	0.459	306.5
sdii	1971	2021	-0.025	0.317	12.6
r10mm	1971	2021	-0.132	0.052	28
r20mm	1971	2021	-0.057	0.228	14
R25mm	1971	2021	-0.03	0.445	12
cdd	1971	2021	0.088	0.753	141
cwd	1971	2021	-0.036	0.172	12
r95p	1971	2021	0.455	0.764	306.5
r99p	1971	2021	-0.104	0.909	0
prcptot	1971	2021	-1.986	0.396	117

Rainfall District 49

Haenertsburg

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1921	2021	0.123	0.484	-
rx5day	1921	2021	-0.168	0.58	-
sdii	1921	2021	-0.022	0.118	10.2
r10mm	1921	2021	-0.091	0.002	23
r20mm	1921	2021	-0.025	0.171	11
R25mm	1921	2021	-0.018	0.248	10
cdd	1921	2021	-0.167	0.243	53
cwd	1921	2021	-0.031	0.003	6
r95p	1921	2021	0.362	0.563	325.4
r99p	1921	2021	0.475	0.236	129.2
prcptot	1921	2021	-1.157	0.254	965.2

Letaba District

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1921	2021	0.39	0.142	125
rx5day	1921	2021	-0.424	0.297	327
sdii	1921	2021	-0.01	0.582	18.7
r10mm	1921	2021	-0.105	0	32
r20mm	1921	2021	-0.058	0.011	19
R25mm	1921	2021	-0.056	0.006	18
cdd	1921	2021	-0.222	0.007	72
cwd	1921	2021	-0.054	0	5
r95p	1921	2021	-0.061	0.945	410.5
r99p	1921	2021	0.655	0.284	0
prcptot	1921	2021	-3.027	0.028	1349.4

Palmaryville

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1921	2021	0.009	0.971	-
rx5day	1921	2021	-0.63	0.086	-
sdii	1921	2021	-0.015	0.49	-
r10mm	1921	2021	-0.098	0.004	-
r20mm	1921	2021	-0.068	0.003	-
R25mm	1921	2021	-0.083	0	-
cdd	1921	2021	-0.073	0.635	-
cwd	1921	2021	-0.03	0.003	-
r95p	1921	2021	-1.407	0.054	-
r99p	1921	2021	-0.584	0.19	-
prcptot	1921	2021	-4.889	0	-

Wood Bush

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1921	2021	0.562	0.147	-
rx5day	1921	2021	0.51	0.468	-
sdii	1921	2021	-0.064	0.002	-
r10mm	1921	2021	-0.117	0.036	-
r20mm	1921	2021	-0.127	0.003	-
R25mm	1921	2021	-0.125	0.001	-
cdd	1921	2021	-0.056	0.462	-
cwd	1921	2021	0.004	0.777	-
r95p	1921	2021	-0.075	0.966	-
r99p	1921	2021	0.309	0.779	-
prcptot	1921	2021	-4.405	0.11	-

Zwartranjes

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1921	2021	0.244	0.036	56
rx5day	1921	2021	0.341	0.053	113
sdii	1921	2021	0.053	0	13.9
r10mm	1921	2021	0.04	0.033	21
r20mm	1921	2021	0.026	0.037	12
R25mm	1921	2021	0.012	0.208	6
cdd	1921	2021	0.369	0.015	194
cwd	1921	2021	-0.006	0.355	4
r95p	1921	2021	0.85	0.045	56
r99p	1921	2021	0.362	0.158	0
prcptot	1921	2021	0.812	0.192	597

Rainfall District 50

Hanglip

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1921	2021	0.044	0.683	75
rx5day	1921	2021	-0.052	0.829	163
sdii	1921	2021	0.014	0.215	15.8
r10mm	1921	2021	-0.068	0.015	33
r20mm	1921	2021	-0.01	0.58	18
R25mm	1921	2021	-0.009	0.516	15
cdd	1921	2021	0.253	0.011	55
cwd	1921	2021	-0.039	0	5
r95p	1921	2021	-0.192	0.752	286
r99p	1921	2021	0.072	0.856	149
prcptot	1921	2021	-1.617	0.086	1071.8

MARA

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1936	2021	0.061	0.686	-
rx5day	1936	2021	0.304	0.15	-
sdii	1936	2021	-0.032	0.007	12.4
r10mm	1936	2021	-0.023	0.264	20
r20mm	1936	2021	-0.017	0.199	9
R25mm	1936	2021	-0.006	0.604	6
cdd	1936	2021	-0.281	0.139	120
cwd	1936	2021	0	0.963	4
r95p	1936	2021	0.283	0.548	151.8
r99p	1936	2021	0.105	0.718	84.4
prcptot	1936	2021	-0.116	0.862	597

MARA-POL

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1947	2021	-0.282	0.082	57
rx5day	1947	2021	0.026	0.92	214
sdii	1947	2021	0.114	0	21.6
r10mm	1947	2021	0.014	0.636	23
r20mm	1947	2021	0.016	0.416	16
R25mm	1947	2021	0.004	0.817	14
cdd	1947	2021	1.415	0	232
cwd	1947	2021	-0.018	0.077	6
r95p	1947	2021	-0.443	0.347	109
r99p	1947	2021	-0.388	0.116	0
prcptot	1921	2020	1.028	0.06	713.9

Platjan Grensbos

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1983	2021	-0.066	0.853	70
rx5day	1983	2021	0.044	0.936	110
sdii	1983	2021	0.035	0.6	14.5
r10mm	1983	2021	0.068	0.261	12
r20mm	1983	2021	0.066	0.177	10
R25mm	1983	2021	0.049	0.207	6
cdd	1983	2021	0.514	0.446	170
cwd	1983	2021	0.008	0.7	3
r95p	1983	2021	-0.025	0.987	70
r99p	1983	2021	-0.533	0.529	0
prcptot	1983	2021	1.617	0.459	434.1

Pontdrift

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1965	2021	-0.28	0.577	-
rx5day	1965	2021	-0.189	0.584	-
sdii	1965	2021	-0.09	0.001	-
r10mm	1965	2021	-0.103	0.859	-
r20mm	1965	2021	-0.056	0.317	-
R25mm	1965	2021	-0.047	0.293	-
cdd	1965	2021	0.992	0.042	-
cwd	1965	2021	-0.003	0.003	-
r95p	1965	2021	-1.483	0.464	-
r99p	1965	2021	0.243	0.518	-
prcptot	1965	2021	-2.988	0.978	-

Una Agr

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1945	2021	-0.033	0.878	80
rx5day	1945	2021	-0.163	0.509	95.1
sdii	1945	2021	0.104	0	13.5
r10mm	1945	2021	-0.028	0.18	16
r20mm	1945	2021	0.002	0.878	7
R25mm	1945	2021	-0.005	0.664	5
cdd	1945	2021	0.574	0.015	129
cwd	1945	2021	-0.039	0	4
r95p	1945	2021	0.243	0.61	80
r99p	1945	2021	0.097	0.75	0
prcptot	1921	2020	1.039	0.081	484.4

Vreemdeling

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1972	2021	0.404	0.348	177
rx5day	1972	2021	-0.187	0.866	255
sdii	1972	2021	0.2	0.001	24.6
r10mm	1972	2021	-0.103	0.125	23
r20mm	1972	2021	-0.046	0.366	14
R25mm	1972	2021	-0.046	0.33	10
cdd	1972	2021	0.644	0.13	76
cwd	1972	2021	-0.069	0.001	4
r95p	1972	2021	2.463	0.163	452
r99p	1972	2021	0.414	0.702	177
prcptot	1972	2021	-3.838	0.228	958.5

Rainfall District 63

Haersdrift Pol ARS

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1923	2021	0.173	0.118	-
rx5day	1923	2021	0.339	0.01	-
sdii	1923	2021	0.035	0.018	-
r10mm	1923	2021	-0.072	0.015	-
r20mm	1923	2021	-0.015	0.342	-
R25mm	1923	2021	0.001	0.957	-
cdd	1923	2021	0.46	0.014	-
cwd	1923	2021	-0.014	0.034	-
r95p	1923	2021	0.205	0.626	-
r99p	1923	2021	0.443	0.042	-
prcptot	1923	2021	-2.03	0.007	-

Marble Hall

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1939	2021	0.068	0.541	-
rx5day	1939	2021	0.104	0.461	-
sdii	1939	2021	-0.026	0.054	-
r10mm	1939	2021	-0.01	0.697	-
r20mm	1939	2021	0.009	0.606	-
R25mm	1939	2021	0.009	0.507	-
cdd	1939	2021	0.188	0.328	-
cwd	1939	2021	0.001	0.908	-
r95p	1939	2021	0.558	0.227	-
r99p	1927	2020	0.287	0.467	-
prcptot	1927	2020	-1.7	0.053	-

Rainfall District 64

Bergzicht

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1921	2021	-0.067	0.326	68
rx5day	1921	2021	0.016	0.891	138
sdii	1921	2021	0.037	0.008	20.2
r10mm	1921	2021	0.027	0.134	22
r20mm	1921	2021	0.025	0.037	13
R25mm	1921	2021	0.007	0.48	7
cdd	1921	2021	0.058	0.737	195
cwd	1921	2021	-0.008	0.138	3
r95p	1921	2021	0.029	0.911	68
r99p	1921	2021	-0.062	0.671	0
prcptot	1921	2021	0.27	0.587	565.3

Dendron

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1971	2021	0.062	0.863	55
rx5day	1971	2021	-0.535	0.276	96
sdii	1971	2021	0.082	0.084	20.4
r10mm	1971	2021	-0.048	0.301	22
r20mm	1971	2021	0	0.994	13
R25mm	1971	2021	-0.007	0.805	10
cdd	1971	2021	1.445	0.003	229
cwd	1971	2021	-0.019	0.036	3
r95p	1971	2021	0.306	0.724	109
r99p	1971	2021	0.076	0.877	0
prcptot	1971	2021	-1.123	0.431	611.7

Kalkfontein

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1921	2021	0	0.996	50
rx5day	1921	2021	0.132	0.25	161
sdii	1921	2021	0.03	0.019	23.3
r10mm	1921	2021	0.02	0.269	33
r20mm	1921	2021	0.03	0.022	25
R25mm	1921	2021	0.004	0.683	16
cdd	1921	2021	0.492	0.001	243
cwd	1921	2021	0.004	0.37	6
r95p	1921	2021	0.51	0.101	290
r99p	1921	2021	0.058	0.628	0
prcptot	1921	2021	0.301	0.581	932

Pietersburg-Hosp

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1921	2021	0.011	0.887	57.3
rx5day	1921	2021	-0.086	0.509	75.3
sdii	1921	2021	0.064	0	17.8
r10mm	1921	2021	-0.023	0.166	18
r20mm	1921	2021	-0.001	0.957	11
R25mm	1921	2021	0	0.972	8
cdd	1921	2021	0.498	0.002	195
cwd	1921	2021	-0.018	0.004	3
r95p	1921	2021	0.314	0.301	57.3
r99p	1921	2021	0.245	0.174	0
prcptot	1921	2021	-0.99	0.053	497.5

Syferkuil

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1948	2021	0.104	0.323	72.5
rx5day	1948	2021	0.215	0.223	91.5
sdii	1948	2021	-0.015	0.348	14.5
r10mm	1948	2021	0.007	0.805	20
r20mm	1948	2021	0.015	0.362	10
R25mm	1948	2021	0.01	0.452	5
cdd	1948	2021	0.459	0.059	188
cwd	1948	2021	0.003	0.614	4
r95p	1948	2021	0.28	0.536	194.5
r99p	1948	2021	0.241	0.253	0
prcptot	1948	2021	0.721	0.328	609

Rainfall District 65

Tolwe Pol

Indices	**Start Year**	**End Year**	**Slope**	**P Value**	**2021 value**
rx1day	1969	2021	-0.015	0.949	60
rx5day	1969	2021	-0.561	0.121	69
sdii	1969	2021	0.151	0	15.1
r10mm	1969	2021	-0.1	0.017	16
r20mm	1969	2021	0.013	0.617	10
R25mm	1969	2021	0.003	0.907	3
cdd	1969	2021	1.762	0	253
cwd	1969	2021	-0.038	0.003	3
r95p	1969	2021	0.004	0.996	60
r99p	1969	2021	-0.396	0.317	0
prcptot	1969	2021	-2.325	0.087	408.8

Rainfall District 76

Bakenberg

Indices	**Start Year**	**End Year**	**Slope**	**P Value**	**2021 value**
rx1day	1986	2021	-0.281	0.683	134.5
rx5day	1986	2021	-0.994	0.255	134.5
sdii	1986	2021	0.167	0.04	27.8
r10mm	1986	2021	-0.051	0.593	17
r20mm	1986	2021	0.04	0.575	12
R25mm	1986	2021	0.017	0.766	8
cdd	1986	2021	1.701	0.066	193
cwd	1986	2021	-0.04	0.082	2
r95p	1986	2021	1.171	0.619	439
r99p	1986	2021	1.451	0.352	330
prcptot	1986	2021	-0.517	0.867	779.6

Doornfontein

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1926	2021	-0.022	0.755	72
rx5day	1926	2021	0.052	0.624	126
sdii	1926	2021	0.015	0.085	18.9
r10mm	1926	2021	0.01	0.612	24
r20mm	1926	2021	0.005	0.684	16
R25mm	1926	2021	0.016	0.14	14
cdd	1926	2021	0.238	0.1	142
cwd	1926	2021	-0.007	0.243	4
r95p	1926	2021	-0.193	0.533	284.5
r99p	1926	2021	-0.158	0.408	72
prcptot	1926	2021	-0.018	0.971	811

Jonkmansdrift

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1984	2021	0.853	0.003	119
rx5day	1984	2021	0.889	0.074	193.7
sdii	1984	2021	0.123	0	14.5
r10mm	1984	2021	0.025	0.724	27
r20mm	1984	2021	0.138	0.004	14
R25mm	1984	2021	0.151	0	12
cdd	1984	2021	1.033	0.086	103
cwd	1984	2021	-0.026	0.197	6
r95p	1984	2021	3.888	0.003	207.2
r99p	1984	2021	1.936	0.039	119
prcptot	1984	2021	3.425	0.109	871.2

Moorddrift

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1921	2021	-0.067	0.424	126
rx5day	1921	2021	-0.247	0.055	154
sdii	1921	2021	-0.009	0.339	18.4
r10mm	1921	2021	-0.01	0.525	23
r20mm	1921	2021	-0.005	0.688	11
R25mm	1921	2021	0.006	0.517	11
cdd	1921	2021	0.319	0.021	192
cwd	1921	2021	-0.003	0.609	4
r95p	1921	2021	-0.652	0.046	287
r99p	1921	2021	-0.373	0.091	126
prcptot	1921	2021	-0.782	0.082	771.5

Naboomspruit

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1921	2021	0.029	0.669	85
rx5day	1921	2021	0.078	0.557	152.3
sdii	1921	2021	-0.014	0.232	8.2
r10mm	1921	2021	-0.009	0.641	12.6
r20mm	1921	2021	0.01	0.48	12
R25mm	1921	2021	0.007	0.537	8
cdd	1921	2021	0.257	0.076	152
cwd	1921	2021	0.002	0.711	5
r95p	1921	2021	0.027	0.931	234
r99p	1921	2021	0.106	0.59	85
prcptot	1921	2021	0.161	0.781	795.2

Nylsvley

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1921	2021	0.155	0.075	-
rx5day	1921	2021	0.17	0.172	-
sdii	1921	2021	0.033	0.002	-
r10mm	1921	2021	0.007	0.713	-
r20mm	1921	2021	0.018	0.125	-
R25mm	1921	2021	0.014	0.18	-
cdd	1921	2021	0.361	0.006	-
cwd	1921	2021	-0.014	0.03	-
r95p	1921	2021	0.762	0.033	-
r99p	1921	2021	0.466	0.027	-
prcptot	1921	2021	0.248	0.645	-

Palmer Estate

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1924	2021	-0.044	0.629	74.5
rx5day	1924	2021	-0.024	0.818	92.5
sdii	1924	2021	0.018	0.037	17.9
r10mm	1924	2021	-0.015	0.389	22
r20mm	1924	2021	0.003	0.752	11
R25mm	1924	2021	0.003	0.712	10
cdd	1924	2021	0.44	0.002	181
cwd	1924	2021	-0.008	0.125	4
r95p	1924	2021	0.141	0.629	301
r99p	1924	2021	0.081	0.692	143.5
prcptot	1924	2021	-0.409	0.372	698.5

Sterkrivier

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1979	2021	0.662	0.008	68.5
rx5day	1979	2021	0.726	0.032	120.3
sdii	1979	2021	0.14	0	14.5
r10mm	1979	2021	-0.034	0.632	27
r20mm	1979	2021	0.111	0.008	12
R25mm	1979	2021	0.076	0.033	10
cdd	1979	2021	0.683	0.159	104
cwd	1979	2021	-0.027	0.086	5
r95p	1979	2021	2.778	0.024	222
r99p	1979	2021	0.925	0.112	68.5
prcptot	1979	2021	1.527	0.429	797

Verdoornsdraai

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1941	2021	-0.044	0.721	45
rx5day	1941	2021	-0.268	0.174	90
sdii	1941	2021	-0.012	0.524	19.8
r10mm	1941	2021	-0.017	0.51	31
r20mm	1941	2021	-0.025	0.114	14
R25mm	1941	2021	-0.013	0.328	11
cdd	1941	2021	0.092	0.671	155
cwd	1941	2021	-0.009	0.342	3
r95p	1941	2021	0.023	0.962	0
r99p	1941	2021	-0.213	0.474	0
prcptot	1941	2021	-0.586	0.416	771.5

Rainfall District 77

Dorset-Pol

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1935	2021	-0.12	0.357	-
rx5day	1935	2021	-0.05	0.816	-
sdii	1935	2021	-0.004	0.846	-
r10mm	1935	2021	-0.053	0.114	-
r20mm	1935	2021	-0.034	0.093	-
R25mm	1935	2021	-0.038	0.008	-
cdd	1935	2021	0.478	0.035	-
cwd	1935	2021	-0.009	0.286	-
r95p	1935	2021	-1.246	0.013	-
r99p	1935	2021	0.027	0.911	-
prcptot	1935	2021	-2.411	0.007	-

Ellisras-Pol

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1967	2021	-0.273	0.158	81
rx5day	1967	2021	-0.106	0.761	103.1
sdii	1967	2021	-0.099	0.005	11.6
r10mm	1967	2021	-0.04	0.299	15
r20mm	1967	2021	-0.035	0.188	7
R25mm	1967	2021	-0.031	0.176	7
cdd	1967	2021	0.018	0.966	102
cwd	1967	2021	0.037	0.001	4
r95p	1967	2021	-0.924	0.166	177.2
r99p	1967	2021	-0.237	0.538	81
prcptot	1967	2021	-1.113	0.35	498.4

Grootgeluk MYN

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1976	2021	-0.041	0.916	-
rx5day	1976	2021	-0.23	0.592	-
sdii	1976	2021	0.061	0.077	19.2
r10mm	1976	2021	-0.018	0.672	17
r20mm	1976	2021	0.01	0.77	12
R25mm	1976	2021	0.022	0.476	10
cdd	1976	2021	0.777	0.134	156
cwd	1976	2021	-0.011	0.418	3
r95p	1976	2021	0.412	0.728	284.2
r99p	1976	2021	0.297	0.69	0
prcptot	1976	2021	-0.542	0.731	595.8

Stockpoort-Pol

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1925	2021	0.164	0.222	82.5
rx5day	1925	2021	0.168	0.295	117.5
sdii	1925	2021	0.106	0	35.5
r10mm	1925	2021	-0.002	0.93	10
r20mm	1925	2021	0.01	0.398	7
R25mm	1925	2021	0.008	0.43	7
cdd	1925	2021	0.545	0.004	234
cwd	1925	2021	-0.015	0.005	2
r95p	1925	2021	0.723	0.04	219.5
r99p	1925	2021	0.366	0.078	0
prcptot	1925	2021	-0.249	0.66	426.5

VIlla Nora-Pol

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1921	2021	-0.143	0.233	-
rx5day	1921	2021	-0.253	0.123	-
sdii	1921	2021	-0.043	0.021	-
r10mm	1921	2021	-0.04	0.01	-
r20mm	1921	2021	-0.021	0.034	-
R25mm	1921	2021	-0.024	0.004	-
cdd	1921	2021	0.08	0.619	-
cwd	1921	2021	-0.011	0.027	-
r95p	1921	2021	-0.759	0.032	-
r99p	1921	2021	-0.125	0.607	-
prcptot	1921	2021	-1.608	0.001	-

Rainfall District 86

Leeupoort-Mun

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1921	2021	0.105	0.359	-
rx5day	1921	2021	0.071	0.681	-
sdii	1921	2021	0.018	0.098	-
r10mm	1921	2021	-0.045	0.029	-
r20mm	1921	2021	-0.009	0.556	-
R25mm	1921	2021	0.004	0.765	-
cdd	1921	2021	0.131	0.424	-
cwd	1921	2021	-0.028	0	-
r95p	1921	2021	0.805	0.056	-
r99p	1921	2021	0.301	0.12	-
prcptot	1921	2021	-0.725	0.295	-

Nylstroom_Mun

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1949	2021	0.413	0.037	-
rx5day	1949	2021	0.272	0.418	-
sdii	1949	2021	0.129	0	-
r10mm	1949	2021	0.019	0.629	-
r20mm	1949	2021	0.049	0.051	-
R25mm	1949	2021	0.044	0.033	-
cdd	1949	2021	0.777	0.022	-
cwd	1949	2021	-0.018	0.088	-
r95p	1949	2021	1.575	0.032	-
r99p	1949	2021	0.655	0.033	-
prcptot	1949	2021	0.856	0.413	-

Rankins Pass-Pol

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1921	2021	0.111	0.156	-
rx5day	1921	2021	0.149	0.252	-
sdii	1921	2021	0.059	0	-
r10mm	1921	2021	-0.04	0.054	-
r20mm	1921	2021	0.001	0.955	-
R25mm	1921	2021	0.009	0.415	-
cdd	1921	2021	0.503	0	-
cwd	1921	2021	-0.023	0	-
r95p	1921	2021	0.252	0.438	-
r99p	1921	2021	0.332	0.043	-
prcptot	1921	2021	-1.174	0.06	-

Rus de Winter-IRR

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1953	2021	0.017	0.896	58
rx5day	1953	2021	0.23	0.243	114.7
sdii	1953	2021	0.014	0.359	15.6
r10mm	1953	2021	-0.039	0.238	27
r20mm	1953	2021	-0.019	0.39	9
R25mm	1953	2021	-0.007	0.682	7
cdd	1953	2021	0.658	0.008	154
cwd	1953	2021	0	0.977	10
r95p	1953	2021	0.059	0.923	196.8
r99p	1953	2021	-0.189	0.632	0
prcptot	1953	2021	-1.1	0.234	638.4

Warmbad Towoomba

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	1937	2021	0.036	0.738	-
rx5day	1937	2021	0.114	0.451	-
sdii	1937	2021	0.003	0.756	-
r10mm	1937	2021	-0.002	0.948	-
r20mm	1937	2021	0.011	0.483	-
R25mm	1937	2021	0.018	0.132	-
cdd	1937	2021	-0.147	0.455	-
cwd	1937	2021	0.001	0.872	-
r95p	1937	2021	-0.211	0.673	-
r99p	1937	2021	0.421	0.16	-
prcptot	1937	2021	0.187	0.794	-

Rainfall District 87

Buffeldoorns ARS

Indices	**Start Year**	**End Year**	**Slope**	**P Value**	**2021 value**
rx1day	1934	2021	0.027	0.846	-
rx5day	1934	2021	0.324	0.23	-
sdii	1934	2021	-0.024	0.24	-
r10mm	1934	2021	-0.007	0.822	-
r20mm	1934	2021	0.006	0.783	-
R25mm	1934	2021	0.005	0.79	-
cdd	1934	2021	0.332	0.237	-
cwd	1934	2021	0.016	0.173	-
r95p	1934	2021	0.232	0.688	-
r99p	1934	2021	0.157	0.658	-
prcptot	1934	2021	0.192	0.849	-

Rooidam

Indices	**Start Year**	**End Year**	**Slope**	**P Value**	**2021 value**
rx1day	1981	2021	0.229	0.488	-
rx5day	1981	2021	1.443	0.065	-
sdii	1981	2021	0.034	0.349	-
r10mm	1981	2021	-0.098	0.163	-
r20mm	1981	2021	0.018	0.676	-
R25mm	1981	2021	-0.002	0.968	-
cdd	1981	2021	1.254	0.027	-
cwd	1981	2021	-0.015	0.503	-
r95p	1981	2021	0.663	0.616	-
r99p	1981	2021	0.969	0.21	-
prcptot	1981	2021	-1.552	0.496	-

Rainfall District 93

Swartklip Nooitgedacht ARS

Indices	Start Year	End Year	Slope	P Value	2021 value
rx1day	rx1day	1979	2021	0.317	-
rx5day	rx5day	1979	2021	0.477	-
sdii	sdii	1979	2021	0.734	-
r10mm	r10mm	1979	2021	0.589	-
r20mm	r20mm	1979	2021	0.791	-
R25mm	R25mm	1979	2021	0.193	-
cdd	cdd	1979	2021	0.433	-
cwd	cwd	1979	2021	0.634	-
r95p	r95p	1979	2021	0.575	-
r99p	1979	2021	1.007	1.147	-
prcptot	1979	2021	0.84	2.858	-

APPENDIX C: DETAILED ACCOUNT OF STAKEHOLDER ENGAGEMENTS

FIRST STAKEHOLDER WORKSHOP:

Workshop Programme

CSIR South African Weather Service Matlala & Associates WATER RESEARCH COMMISSION

SCENARIO BUILDING FOR FUTURE WATER RESOURCE MANAGEMENT IN LIMPOPO WORKSHOP

Venue: Hybrid: Virtual/CSIR International Convention Centre (CICC)
Date: 30 June 2023
Time: 09h00 – 16h00

Programme Director: Dr Shingirirai Mutanga Research Group Leader – Climate Services – Holistic Climate Change-Council for Scientific and Industrial Research (CSIR).

Opening Plenary

09:00-09:15 Introductions

09:15-09:20: Welcome Remarks: Dr Brian Mantlana - Impact Area Manager- Holistic Climate Change - Smart Place-CSIR.

09:20-09:35: Opening Remarks: Water Research Commission's Strategic Vision for Water Resource Management in South Africa Dr Brilliant Petja – Research Manager (WRC)

09:35- 10:00: Project Overview: Scenario building for future water resource management in Limpopo Province: **Dr Remi Akanbi**– Consortium Lead- University of Limpopo **- Senior Lecturer- UL**

10:00:10:20: Guest Speaker: Department of Water and Sanitation perspective on water resource planning: **Mr Patrick Mlilo** - Director Planning-DWS.

10:20:10:35: DWS Provincial Rep Mr Netili Fortress - Scientist Manager (Pri.Sci.Nat.)

TEA BREAK – 10:35-11:05

Second Session: Progress

11:05-11:35: Historical rainfall and Temperature Analysis-Climate Projections: **Dr Andries Kruger**- South African Weather Services.

11:35-11:55: Scenario Building - Hydrological Modelling. - Trevor Lumsden- Senior Researcher-CSIR

11: 55-13:00: Q & A - Mr Sepadi Motau - Scientist Manager (Pri.Sci.Nat.)

13:00-14:00- LUNCH

Third Session: Facilitator- Dr Shingirirai Nangombe Senior Researcher – Climate Modelling – Holistic Climate Change - Council for Scientific and Industrial Research (CSIR).

14:00-14:15: Purpose and outcome of stakeholder survey: Dr J M Letsoalo. - **Senior Lecturer- UL**

14:15 -14:30: Water variability & developmental implications in Limpopo- Dr Chris Moseki (M&A Associates)

Fourth Session: Facilitator- Ms Tlakale Mogebisa-Candidate Researcher- Climate Modelling-Holistic Climate Change - Smart Place-CSIR.

14:30-14:45: Presentation **- Bayanda Sonamzi-**PhD Candidate -University of Pretoria

14:45-15:00- Presentation **- Grace Mohlala -** MSc Candidate- University of Limpopo.

15:00-15:15: Presentation **-Katlego Mothapo -** MSc Candidate-University of Limpopo.

15:15-15:40: Q and A

Closing Session

15:40-15:50: Reflections of Day and Way Forward: **Dr Shingirirai Mutanga - CSIR**

15:50 - 16:00: Vote of Thanks: **Dr Njabulo Siyakatshana** - Research Group Leader – Climate Modelling- Holistic Climate Change - Smart Place-CSIR.

Workshop Notes

The first workshop on 'Scenario building for future water resource management in Limpopo' was held on the 30th of June 2023 through a hybrid session (physically at the CSIR International Convention Centre and online on Teams). It was chaired by Dr. Shingi Mutanga, a Research Group Leader for the Climate Services Research Group at CSIR. He started by introducing the project team members, including Dr. Remi Akanbi, Dr. Andries Kruger, Dr. Chris Moseki, and Mr. Trevor Lumsden. The chair highlighted that the goal of the workshop was to deepen the understanding and appreciation of the scientific and knowledge generation within the project, with the aim of learning from experts and gaining insights from the Department of Water and Sanitation. He then invited Prof. Sylvester Mpandeli (an Executive Manager at Water Research Commission) to speak on behalf of Dr. Brilliant Petja (Research Manager at WRC).

Prof. Mpandeli highlighted the importance of learning from others and refining research to achieve the ultimate goal. He highlighted the need for future water resource management in Limpopo, a strategic project funded by WRC. Prof. Mpandeli emphasized the need to generate knowledge that can assist policy and community of practice in addressing science-policy interfaces. He also emphasized the responsibility to build a strong heart of young scientists and postgraduate students, exchange ideas, and empower communities. He emphasized the need to move away from theory to practice and drive activities in an integrated way, ensuring agriculture runs independently. He emphasized the need for a multidisciplinary approach to address physical and social economic challenges, such as water, poverty, and inequality. The chair, then thanked Prof. Mpandeli for his insights into how the project should move forward, and not just be a scientific engagement. He then gave the floor to Dr. Remi Akanbi (the Project Lead).

Dr. Akanbi discussed the project in detail, that it began in 2021 and is hosted by the University of Limpopo, partnering with departments including Water and Sanitation (DWS), South African Weather Services (SAWS), and the Council for Scientific and Industrial Research (CSIR), to ensure that the project outputs are relevant and impactful. She stressed that the project's success will be measured by its impact on the province and the capacity it generates. The project focuses on climate change's impact on hydrological processes, particularly in the Limpopo Province. She highlighted that the project will be implemented in all five district municipalities within the province and aims to be a precursor for other research and capacity-building activities in the province. In addition, she also mentioned the students who are currently being supported financially through the project. The project's deliverables include addressing challenges in water and sanitation in collaboration with CSIR, SAWS, and using expertise from M&A associates. She mentioned that the project's success depends on collaboration between the project team, end users, and the funding institution (the WRC).

The project aims to address the increasing water demand in the Limpopo Province due to population growth, urban expansion, and climate change impacting irrigation. She highlighted that the Capricorn District Municipality is the most water-using area, and other sectors like mining and immigration also put pressure on water resources. Therefore, the project aims to address the deficiency in planning processes and integrate climate perspectives in planning phases. The assessment is to be conducted across all five district municipalities, with the specific extent determined by Dr. Andries Kruger and Mr. Trevor Lumsden. The strategic objectives included understanding the status quo of water resources, addressing planning deficiencies, and implementing adaptive measures to mitigate climate change impacts. The project will focus on work packages II and III, which will be further developed and implemented within the department's processes, and Dr. Kruger and the team are responsible for producing the findings.

The Department of Water and Sanitation in South Africa is working on strategic water resource planning to ensure water security. Mr. Patrick Mlilo, responsible for this process, discussed the trajectory of water demand across settlements, demand patterns, the impact on future augmentation schemes, and strategies for demand nodes and catchments in the Limpopo Province. He emphasized the importance of understanding the Limpopo River Basin and strategies for demand nodes and catchments in the region to strengthen the water sector's resilience. The complexity of the policy is increasing as water demands increase, with the expected population growth of around 75 million by 2050. Mr. Mlilo discussed the drivers of water demand, such as natural population growth, migration, and reclassification of urban areas; and the challenges faced by the country, such as inequality, poverty, and unemployment. He also discussed the need for reconciliation strategies and broadening the water resource mix.

He highlighted that the national water and sanitation master plan identifies 12 specific objectives, including reducing demand redistribution of water, addressing water quality and ecological infrastructure, and enhancing human capacity. The plan includes 23 actions, including implementing research, development, and innovation policies, establishing new platforms for synergy, innovations, marketing, and strengthening partnerships. The South African government is conducting research to refine its water management system, focusing on catchments that are mostly imbalanced or in deficit. Interventions include water conservation, water demand management, and groundwater issues.

The discussions proceeded on the floor and online, revolving around water conservation, management, and the potential transfer of water from Zimbabwe to the Musina Makhado area. The area is experiencing water shortages, and the proposed metallurgical complex requires approximately 125 to 150 million litres of water. The feasibility of building additional dams, such as Dentally Dam, could supply water to South Africa. The reallocation of water was highlighted as a critical issue. The implementation of projects such as the Water Augmentation Scheme, Olifants River Development Scheme, Letaba Water Supply System, and Sand River area was also discussed.

The future excess of mine water use, particularly in the Olifants Catchment, was discussed, with required areas of research including strengthening governance, examining institutions and human capacity, and implementing financial strategies to manage water effectively. The importance of information, particularly on transboundary aquifers, was also discussed, along with the need for integrated asset management and the strengthening of management of instruments harmonized across core-based states.

The discussion concluded with a call for a more comprehensive approach to resource planning in South Africa, considering the challenges faced by the country and the need for a more balanced approach to resource management. The groundwater situation in Limpopo was discussed, with an estimated 80 per cent usage from 2012 to the present day. The discussion highlighted the importance of considering groundwater use in scenarios, and the need for further monitoring and reserve determination.

The discussion further revolved around the importance of understanding the groundwater dimension in building future scenarios, and the need for transdisciplinary work in water and ecosystem functions. The researchers discussed the quantification of water volumes through various interventions, to address water conservation issues.

As the discussion proceeded, Netili Khangweleni acknowledged the efforts taken to minimize the impact of climate change and vandalism on water resources. The discussion also touched on the potential for more extensive work, particularly in capacity building through students, and the development of professionals within the sector, including hydrologists. Social facilitators, who can provide contact details for students, especially regarding the issue of water, were also mentioned.

Dr. Kruger from SAWS also gave a presentation, discussing historical climate trends and rainfall as deliverables for work packages II and III. The work packages examined rainfall patterns in the Limpopo Province, focusing on its dryness and increased drought probability over the last 100 years. The results showed that districts such as the Capricorn have experienced gradual drying over the last century. Dr. Kruger emphasized the importance of considering long-term climate trends and analysis periods, such as from 1921 to 2022, which shows significant droughts in the province. The study also highlighted the need for more rainfall and water resources management in the region. When looking at the projected changes in mean annual precipitation from 1976 to 2005, using climate models like RCP 4.5, results showed mostly decreases in annual precipitation, except in the southwest parts during shorter prediction periods and other emissions scenarios. The presentation discussed the impact of climate change, population growth, urbanization, industrial development, and increased agricultural activities on water resources in South Africa, indicating a decrease in precipitation leading to negative impacts on water resources, agriculture, and ecosystems.

Following a series of presentations and discussions, the workshop concluded with the three presentations from the students (Bayanda Sonamzi, a PhD Candidate at University of Pretoria, Grace Mohlala and Katlego Mothapo, MSc Candidates at the University of Limpopo) who are funded by the project. This session of the students was chaired by Miss Tlakale Mogebisi. In closing, Dr. Mutanga gave the reflections of the day and a way forward. Lastly, Dr. Njabulo Siyakhatshana (RGL for Climate Modeling Group, at CSIR) gave the vote of thanks. The meeting then concluded with a round of applause for the contributions and insights provided by the presenters.

SECOND STAKEHOLDER WORKSHOP:

Workshop Programme

South African Weather Service

CLIMATE CHANGE AND WATER RESOURCE MANAGEMENT: LIMPOPO PROVINCE

SEMINAR

Programme Director: Dr Shingirirai Mutanga - Research Group Leader – Climate Services- Holistic Climate Change - Smart Place-CSIR.

Venue: Virtual- Teams
Date: 30 October 2023
Time: 14h00 – 15h30

Preamble

Limpopo Province has been experiencing an increasing demand for water due to population growth and changes in socio-economic conditions (with changes in consumption patterns) and increased mining and industrial activity. The Water Research Commission (WRC) awarded a research grant to a consortium of partners namely (University of Limpopo, South African Weather Services (SAWS) and Council for Scientific and Industrial Research (CSIR) and Matlou Associates to research on the climate change impacts and how climate change perspectives can be incorporated into water resource management in the province. This seminar is intended to share insights and exchange ideas on a component of the project which provides preliminary findings of coupling climate projections data with hydrological modelling, building scenarios for the province's future water resource management.

Agenda

1. **Introductions**
2. **Welcome:** Dr Brian Mantlana
3. **Presentation:** Coupling Climate Projections with Hydrological Modelling for Future Water Resource Management in Limpopo: **Trevor Lumsden** - Senior Researcher- Climate Services- Council for Scientific and Industrial Research.
4. **Respondent:** Dr Chris Moseki - Geohydrologist & Climate Change Research (R&A Associates).
5. Discussion: All
6. **Vote of Thanks and Way Forward:** Dr Remi Akanbi- Consortium Lead - Senior Lecturer- University of Limpopo.

Workshop Notes

Introduction and Context Setting

Dr. Shingi Mutanga introduced himself and Dr. Brian Mantlana (Leading the Holistic Climate Change, CSIR), who provided the context for the project by discussing global trends in climate change, including inadequate climate mitigation ambition and finance, as well as the need to bridge the gap between available climate finance and adaptation needs. He also highlighted the need for capacity building in South Africa.

Introduction to the Project and Preliminary Findings

The meeting began with Dr. Mantlana highlighting the importance of responding to climate change. Dr. Mutanga introduced the project and team members, including Mr. Trevor Lumsden, who presented the preliminary findings on the coupling of climate projections with hydrological modelling for future water resources in Limpopo Province. The study area covers the Limpopo Province with its five district municipalities and extends to include source catchment areas that are outside of Limpopo.

Projections for Changes in Stream Flow

Mr. Lumsden described the ACRU hydrological model, which uses climate projections to simulate future catchment streamflows. The study looked at five different climate models, two emission scenarios, and two different time periods to determine changes in streamflow. The study also included projections for changes in mean annual rainfall, incremental runoff, and accumulated streamflows. The results were presented in the form of maps and plots for larger rivers.

Climate Model Ensemble Results

He discussed the Climate Model Ensemble Results, which compare the SSP245 and SSP585 scenarios. The median maps showed little change, while the 10th percentile maps showed reductions of 10 to 15 per cent and the 90th percentile maps showed increases of 10 to 15 per cent. Mr Lumsden noted that the differences between the emissions scenarios were relatively small because the time period being looked at is around mid-century.

Analysis of Simulated Streamflow and Runoff

He further discussed the uncertainty in climate change models and presented data on simulated streamflow and runoff in different rivers and catchments. The data showed a range of uncertainty in the models, with some, predicting reductions while others predicting increases in flow. The responses are more muted in drainage Region B compared to Region A, which has a drier climate and more variability.

Defining Scenarios and Current Planning in Limpopo

The challenges of defining scenarios for planning for climate change in Limpopo due to the non-linearity of the hydrological system and the uncertainty in climate models were also highlighted by Mr. Lumsden. He presented four scenarios and emphasized the need to consider the whole range of uncertainty, and incorporate all scenarios in planning. He also discussed the current planning strategies in Limpopo, which include interventions on both the supply and demand side.

Discussion on Water Resource Management and Climate Change Modelling

He also presented on climate change modelling and the impact of climate extremes on water resources. Dr. Chris Moseki responded, emphasizing the importance of applying modelling in real-world situations, and managing uncertainty. They discussed the use of natural vegetation cover in modelling and the challenges of choosing which climate models to give more weighting to.

Water Management Areas and Key Dams

Dr. Mutanga gave the floor to Mr. Phasha and Mr. Nditwani to speak, and one of them asked about the criteria for selecting key dams and the demarcation of water management areas. Mr. Phasha clarified the changes in Luvuvhu-Letaba and requested an explanation of the water management areas, which have been divided into different systems.

Hydrological Modelling

Participants asked further questions and provided feedback on various aspects, including the choice of model, the need for reality checks and clear routes for incorporating the information into planning models, and the potential for linking the modelling with land use and climate projections.

Incorporating Climate Change into Modelling

Mr. Tendani Nditwani from the Department of Water and Sanitation explained that their department has faced similar challenges with modelling and has had to compare results from different models. He clarified that their models generate flows for looking into the future and expressed appreciation for the work being done on climate change modelling. Dr. Mutanga added that efforts are underway in the water industry to standardise climate change assessments for the water sector.

Discussion on Scenarios and Modalities for Improving Current Models

The team discussed the importance of sharing scenarios and methods to improve current models. Mr. Lumsden shared that he has only looked at one future period, and Dr. Akanbi asked for more attention on the low scenario. The team agreed to run with the current options, and plans to have more engagement in the future to refine and build better scenarios for the future.

Action Items:

- Trevor Lumsden will share the scenarios with the Department of Water and Sanitation (DWS) for further feedback and potential integration into planning models (after further engagement to unpack them).
- DWS will consider the scenarios and provide input on their applicability and potential modifications.
- DWS will participate in an upcoming workshop in Polokwane (set for 6 Nov 2023) to further engage with the analysis and discuss its implications for water sector planning.

Key Issues:

- How can the findings from the hydrological modelling be integrated into existing planning models and/or processes?
- What are the projected changes in mean annual rainfall and runoff in Limpopo Province?
- What are the implications of these projections for water availability and management?
- How do different climate models and scenarios affect the projections?

THIRD STAKEHOLDER WORKSHOP

Workshop Programme

SCENARIO BUILDING FOR FUTURE WATER RESOURCE MANAGEMENT IN LIMPOPO FEEDBACK WORKSHOP

Venue: The Ranch Hotel and Resort, Polokwane
Date: 6 November 2023
Time: 09h00 – 16h00

Programme Director: Dr Shingirirai Mutanga- Research Group Leader – Climate Services- Holistic Climate Change - Smart Place-CSIR.

09:00-09:30 Arrivals and Registration

Opening Plenary

09:30-09:45: Welcome Remarks: HOD-University of Limpopo Prof **Mphahlele-Makgwane**

09:45-10:00: Opening Remarks: Madam Lucy Kobe (Chief Director)

10:00-10:15: Project Overview: Scenario building for future water resource management in Limpopo Province: **Dr Remi Akanbi**– Consortium Lead- University of Limpopo.

10:15: 10:30 DWS Provincial Outlook to current assessment - Ms Martha Komape

TEA BREAK – 10:30-10:45

Second Session: Project Outputs and Progress

10:45-11:15: Rainfall Analysis – Historical and Projections: Dr Andries Kruger- South African Weather Service".

11:15-11:45: Scenario Building - Hydrological Modelling - Trevor Lumsden- Senior Researcher-CSIR

11:45-12:15: Water variability & developmental implications in Limpopo - Dr Chris Moseki (M&A Associates).

12:15-13:00 Discussion – Q & A Session

13:00-14:00 - LUNCH

14:00 – 15:00 Third Session: Science Communication - Stakeholder Engagement

15:00-15:30: DWS Response to findings: Mr Nethili

15:30-16:00: Tea

Closing Session

15:55 - 16:00: Vote of Thanks and Way Forward: **Dr Shingirirai Mutanga** - Research Group Leader – Climate Services- Holistic Climate Change - Smart Place-CSIR.

Workshop Notes

Opening Addresses

The workshop commenced with addresses by the Head of Department at the University of Limpopo, Prof. Mphahlele-Makgwane, and Ms. Lucy Kobe, Chief Director of the Department of Water and Sanitation in the Limpopo Province. Prof. Mphahlele-Makgwane spoke of the commitment of the University to support research and capacity building in the water sector in partnership with the Water Research Commission and other partners. Ms. Kobe emphasized the importance of incorporating climate change considerations into water resources planning and the need to collaborate with the research team to help facilitate this process.

Overview of Project and Workshop Purpose

Dr. Akanbi then gave an overview of the project, explaining that the work had been divided into work packages with each work package being led by a different organisation in the project team. She explained that presentations would be given on the results of key work packages including the historical and projected rainfall analysis (led by South African Weather Services), the hydrological modelling and scenario building (led by CSIR), and the exploration of developmental implications for Limpopo (led by M&A Associates). Dr. Akanbi stressed the value of the project team receiving feedback on the work from participants and invited all to contribute.

Project Presentations

Dr. Kruger presented the research into historical and projected rainfall trends. Key findings of the work included that drought has become more prevalent in the last 50 years and is becoming more severe. At the same time, wet extremes have also increased with more very wet and extremely wet days being recorded. These trends are likely to continue into the future, with climate projections suggesting more extreme rainfall and increases in drought severity and duration.

Mr. Lumsden presented results from the hydrological modelling and scenario building. These results assessed the impact of climate change on incremental runoff and streamflow by coupling hydrological modelling with climate projections for a range of climate models and emissions scenarios. Differences in hydrological responses between the emissions scenarios were found to be small for the period considered (2036-2065), while a wider range in responses was found for different climate models. This reflects the uncertainty that exists in modelling future rainfall patterns and associated hydrological responses. Based on earlier results in the project, there is greater certainty regarding future changes in extremes (both wet and dry).

Dr. Moseki presented findings of the exploration of the development implications of the climate change impact assessment. Included in this was a review of existing water demands and water resources supply systems, as well as an outline of current and future planned development projects in the province. He expressed concern about the projected increases in droughts, and that water availability had not been considered in a meaningful way in some of the proposed development projects (related to mining and other industries). Dr. Moseki stressed the importance of capping future irrigation demands to ensure that future water demands can be met for all users.

A presentation was then made by an MSc student working on the project (Grace Mohlala). The topic of the presentation related to a case study on land use change in the Letaba Catchment, and the impacts that this has on water quality in a changing climate.

Questions and Answers

Several comments were made by participants in the Q&A session following the project presentations:

- A suggestion was made that research assumptions be stated upfront (rather than during the course of a presentation) as it makes it easier to evaluate the work being presented.
- The importance of groundwater in various parts of the province was highlighted given that the modelling only accounted for surface water resources. The team responded that groundwater modelling was beyond the scope of the project, but that its importance is appreciated and that it would be included in recommendations for future research.
- The Olifants Catchment is highly stressed and the demand for water continues to grow. The water sector needs to continue highlighting this deficit to users. Municipalities need to be included in this discussion as their Integrated Development Plans often do not appreciate the impact of water scarcity in the region.
- The student presentation on land use change and water quality was well received, with the role of the project in contributing to capacity building being recognised. The issue of water quality is also critical in Limpopo.

DWS Presentation on the Provincial Outlook

Mr. Nethili gave a presentation on the provincial outlook for water resources management. The presentation discussed a variety of augmentation projects that are in progress, or planned, to meet future water demands. He concluded that a major challenge to implementing future projects is a lack of funding.

In the discussion that followed the presentation, it was mentioned that the Minister of Water and Sanitation has emphasized that the Department should focus mainly on planning augmentation projects that are within their control (i.e. within South Africa), as projects in neighbouring countries rely heavily on the cooperation of those countries to be successful.

In a further discussion point, it was argued that economics should also be factored into future impact assessments and scenario building, given the challenge that financing augmentation projects presents.

DWS Response to Project Findings

In the final session of the workshop, a representative of the DWS participants provided an overall response to the project findings and the day's discussions. This response included the following points:

- The plans for special economic zones in the Olifants WMA and Musina area are very concerning given that these locations are already water stressed.
- The lack of focus on groundwater and water quality in the project is noted. While water quality was touched on in the student presentation, both issues should be carried forward into the project recommendations for more detailed study in future research given their critical importance.
- It is recognized that wastewater treatment plants are failing and are polluting the country's water resources. This issue needs to be addressed as a top priority, even before climate change.
- Clarity was requested on some of the messaging regarding the projections. This concerned the changes in the extremes versus the means. The team clarified that both wet and dry extremes are projected to increase. At the same time, the impact on overall (mean) conditions is relatively uncertain due to a wide range in changes projected by different climate models.

- The issue of where to incorporate climate projections in the planning process needs to be clarified or investigated.

Closure

Dr. Mutanga (programme director) then offered a vote of thanks to all concerned and closed the workshop.