Spatio-temporal analysis of extreme rainfall events in Limpopo Province

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Declaration

I, Muzila Fulufhelo Marvellous, affirm that the dissertation I am submitting for the Master of Environmental Sciences (Geography) degree at the University of Venda has not been presented for a degree at this or any other institution before, and that it is entirely my own original work in both design and implementation, with all referenced materials appropriately acknowledged.

Signature……f.muzila……

Date .....23/03/2025….

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Dedication

This dissertation is dedicated to my parents and siblings, who always believed in me and encouraged me to do my best in education.

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Acknowledgements

I am thankful to God for being my guide and giving me the strength, ability, and health I needed to finish this research project. He was my pillar of strength and daily source of inspiration. I would also like to acknowledge my supervisors, Dr E Kori and Mr MS Muthige, for their tremendous motivation, wisdom, support, and encouragement during this study and project preparation.

I would also like to give special thanks to my family, especially my parents, Mr. BE and Mrs. TS Muzila, and my siblings, Vhugala and Karabo, for their understanding, patience, and endless support during this demanding period. Their love and encouragement have kept me motivated and focused.

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Abstract

This research on the spatiotemporal analysis of extreme rainfall events in Limpopo Province is critical for understanding the changing rainfall patterns, intensity, and frequency, which have significant implications for water resources, agriculture, infrastructure, and disaster management. However, there is a lack of comprehensive and localized spatiotemporal analysis of extreme rainfall occurrences, particularly in Limpopo Province. The main aim of this study was to analyse spatial and temporal patterns of extreme rainfall in Limpopo province by identifying historical trends, frequency, intensity, and spatial distribution using statistical and geospatial techniques. This was undertaken using historical rainfall data obtained from the South African Weather Service (SAWS). The analysis involved using Geographic Information System (GIS) to examine trends in the frequency and intensity of extreme rainfall, analyse their spatial distribution, and analyse trends in extreme rainfall events using the Student's t-test, to determine the significance and Sen's slope to assess the magnitude of those trends. Extreme precipitation indices developed by the World Meteorological Organization Expert Team on Climate Change Detection and Indices were used. The findings showed that the majority of Limpopo province saw an increase in the intensity of daily rainfall, aligning with global trends overall. A reduction in precipitation during the rainy period was observed in most regions of the east and northeast, while the eastern and southern sections near the slope received seasonal drought. Mara, Oudestad, and Tshivhasie tea Venda showed a strong upward trend in Consecutive Wet Days (CWD), R20mm, and R95p and a decline in Consecutive Dry Days (CDD) from the period of 1993-2023, showing that as the mean rainfall increases, so do extreme rainfall occurrences. In addition, the mean annual rainfall significantly influenced extreme precipitation indices in Limpopo Province. By assessing long-term trends and spatial variations, this study will assist decision-makers who emphasize climate resilience and sustainable development to properly allocate resources and establish areas that need attention in terms of managing impacts associated with droughts and floods, as well as enhancing local interpretation of rainfall and resource allocation to promote sustainability in the province.

Keywords: Extreme rainfall; GIS; Rainfall trends; Sen 'slope; Student t test

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List of abbreviations and acronyms

CDD - Consecutive Dry Days

COLs - Cut off lows

CRS – Coordinate reference system

CSV – Comma separated values

CWD - Consecutive wet days

DJF- December-January-February

ENSO - El Nino Southern Oscillation

ETCCDI – Expert Team on Climate Change Detection and Indices

GIS - Geographic information system

ITCZ-- Intertropical convergence zone

JJA - June-July-August

MAM - March-April-May

MCC - Mesoscale Convective Complex

IOD - Indian ocean dipole

IDW- Inverse distance weighting

SAM - Southern Annular Mode

SAWS - South African weather service

SON - September-October-November

SST- Sea Surface Temperature

TC - Tropical Cyclone

TTTs - Tropical Temperate Troughs

WMO - World Meteorological Organization

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Chapter 1: Introduction

1.1 Background

The primary climatological components used for assessing the status of a geographical area's climate system are rainfall and its specific features (the quantity, duration, severity, and regularity) (Donat *et al*., 2016). Understanding precipitation patterns and extremes is particularly important, as these elements have unavoidable consequences for environmental and socioeconomic development (de Lima *et al*., 2015). The spatial and temporal variability of rainfall, as well as its severe occurrences, are both practical and theoretically relevant. (He and Gautam, 2016).

Understanding historical rainfall trends is also vital for comprehending climate change and its variability. With increasing evidence indicating that climate change and variability significantly impact the environment (Bartzke *et al*., 2018) and agricultural produce (Moeletsi *et al*., 2013), it is crucial to thoroughly examine the distinct ways these alterations occur at different times and locations. This comprehensive insight is essential for formulating targeted strategies to address these changes. The real-world effects of extreme weather phenomena, such as frost, droughts, floods, droughts, or hailstorm, occurring individually or concurrently, can have extensive consequences for agriculture.

Studies conducted by (Rapolaki *et al*., 2019, Crétat *et al*., 2019, Manatsa *et al*., 2017) have identified the El Niño Southern Oscillation (ENSO) as a primary factor driving rainfall fluctuations in southern Africa. This is because it plays a crucial role in determining the occurrence of droughts and floods in this area. Although a strong correlation between the El Niño Southern Oscillation and rainfall patterns in southern Africa has been established, certain aspects still require further clarification (Crétat *et al*., 2019). This is because less than average rainfall is impacted by multiple meteorological systems, including the El Niño Southern Oscillation (Rapolaki *et al*., 2019).

For instance, rainfall variability in Southern Africa is not necessarily caused by El Niño Southern. Furthermore, rainfall fluctuations in Southern Africa are not solely caused by the El Niño Southern Oscillation. The interaction between the ocean and

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atmosphere is also influenced by other weather systems, such as the Southern Annular Mode, during the La Nina or El Nino phases (Manatsa *et al*., 2011).

Rainfall in the south-eastern region of Africa reduces or increases during El Nino (La Nina) episodes, according to a study by Zhao *et al* (2019). This produces dry (wet) circumstances. Synoptic features such as tropical cyclones can also cause rainfall anomalies (Kuleshov *et al*., 2008) and Tropical Temperate Troughs (TTTs) (Erasmus, 2019). Most above-average extreme rainfall events in the Limpopo Basin occur during the La Nina phases (Rapolaki *et al*., 2019). A correlation was observed between La Nina occurrences and below-average dry spells over an inter-annual interval (Reason *et al*., 2005).

(Yin *et al*., 2022) defined extreme rainfall as a higher-than-average level of precipitation experienced at a specific period. Previous studies (Pan *et al*., 2018, Li *et al*., 2023) have defined extreme precipitation in many ways. Numerous indices have been put forward by the Expert Team on Climate Change Detection and Indices (ETCCDI) for the quantitative assessment of changes in extreme precipitation on a global or regional scale (Gao *et al*., 202 2). Several researchers have defined extreme rainfall events using fixed daily precipitation thresholds (Alexander *et al*., 2019, Shaffie *et al*., 2019, Schär *et al*., 2016, Gummadi *et al*., 2018). From a statistical probability viewpoint, extreme rainfall is characterised as daily rainfall that surpasses a specific percentile, such as >90th or meets a specific return duration.

Extreme climate has serious impacts, particularly in locations with a large rural subsistence population and huge parks, such as Kruger National Park (Malherbe *et al*., 2020, Mathivha *et al*., 2017). Droughts in 1982/83, 1997/98, 2002/03, and 2015/16 were significantly linked to El Nino episodes (Ndlovu and Demlie, 2020, Blamey *et al*., 2018). Droughts (2001-2004) and high rainfall in February 2000 (Dyson and Van Heerden, 2001) have severely affected the Limpopo province, resulting in floods in north-eastern South Africa and southern Mozambique.

The populace of the province is expected to increase in the future. This will put further burden on the already restricted supply of water and farming operations (Machete *et al*., 2024). Determining the regional and temporal distribution of extreme precipitation.

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can improve decision-making, monitoring, and management (Kumar and Kumar, 2020). This dissertation focuses on understanding rainfall features and extreme events, including spatial and temporal attributes, to better allocate resources for agriculture and tourism. The spatiotemporal analysis of extreme rainfall occurrences in Limpopo will help policymakers understand event trends. It will also help to improve catastrophe risk reduction and water resource management. The National Disaster Management Framework prioritizes proactive disaster mitigation and flood reduction. Improved water management and climate adaptation are important national priorities (Department of Water and Sanitation, 2020). According to the IPCC (IPCC, 2013), understanding climatic extremes is critical for risk mitigation. An analysis of spatiotemporal patterns, therefore, offers policymakers significant insights. The findings contribute to the development of appropriate flood risk and water resource management methods. Finally, the goal of this research is to help people make better decisions about catastrophe risk reduction and water management.

1.2 Problem Statement

Extreme rainfall events in Limpopo have increased in intensity and frequency, posing considerable challenges to the province's water resource management, agricultural, and infrastructure resilience (Shikwambana *et al*., 2021). Changes in major extreme rainfall indices, such as consecutive dry days (CDD), consecutive wet days (CWD), heavy rainfall days (r20mm), and very wet days (r95p), show changing trends in rainfall, with serious socioeconomic and environmental consequences. Understanding the spatiotemporal changes in these indices is therefore critical for creating successful climate adaptation and disaster risk reduction strategies.

Climate change has caused extreme rainfall variability around the world, with variations in precipitation patterns in Southern Africa contributing to droughts and floods (Engelbrecht *et al*., 2019). Limpopo, a region already prone to climatic variability, has experienced fluctuations in important extreme rainfall indices such as consecutive dry days (CDD), consecutive wet days (CWD), heavy rainfall days (r20mm), and very wet days (r95p). These changes directly affect food security, economic stability, and disaster risk mitigation methods. Without a thorough understanding of the spatial and temporal trends in extreme rainfall, policymakers may struggle to adopt effective climate adaptation plans.

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These changes have serious effects, particularly for water-dependent industries such as agriculture, which employs a significant section of Limpopo's population (FAO, 2021). Increased dry spells and intense rainfall events can cause crop failures, soil degradation, and water scarcity, exacerbating socioeconomic disparities and increasing rural people's vulnerability (IPCC, 2021). Furthermore, excessive rainfall causes flooding, damages infrastructure, displaces communities and disrupts key services, impeding progress toward Sustainable Development Goal 13 (Climate Action).

To address this issue, this study investigates the spatial and temporal distribution of extreme rainfall events and analyse historical trends in extreme rainfall indices using statistical and geospatial techniques, building on previous research methodologies (Kruger & Nxumalo, 2017; Muthige *et al.*, 2018). By assessing long-term trends and spatial variations, this research aims to assist decision-makers such as South Africa's National Development Plan (NDP) and the African Union's Agenda, which emphasize climate resilience and sustainable development, to properly allocate resources and establish areas that need attention in terms of managing impacts associated with droughts and floods, as well as enhancing local interpretation of rainfall and resource allocation, to promote sustainability in the province

1.3 Research Questions

The research seeks to answer the following questions:

- What are the trends in frequency and intensity of extreme rainfall events in Limpopo Province from 1993 to 2023?
- What is the spatial distribution of extreme rainfall events in Limpopo, and how does it vary across different regions?
- What are the correlations between annual mean conditions and annual extreme precipitation indices, as well as the correlations between trends in the annual mean conditions and extreme precipitation indices

1.4 Aim and Objectives

This study sought to investigate the spatio-temporal characteristics of extreme rainfall

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events in Limpopo Province.

The objectives of the study were to:

- examine the trends in the frequency and intensity of extreme rainfall events in Limpopo.
- analyse the spatial distribution of extreme rainfall events in Limpopo Province.
- determine the correlations between annual mean conditions and annual extreme precipitation indices, as well as correlations between trends in the means and in the extremes.

1.5 Hypothesis

Null Hypothesis (H0): There is no significant difference in the mean rainfall extremes across different regions in Limpopo Province.

Alternative Hypothesis (H1): There is a significant difference in the mean rainfall extremes across different regions in Limpopo Province.

For each test, the null hypothesis would be accepted or rejected based on the results of the analysis, and a conclusion would be drawn accordingly. If the p-value is less than the significance level (e.g., 0.05), the null hypothesis would be rejected, and the alternative hypothesis would be accepted, and if the p-value is greater than the significance level, the null hypothesis would be accepted, and it would be concluded that there is no significant trend, relationship, or difference.

1.6 Motivation of the study

Despite the importance of understanding extreme rainfall events in Limpopo, South Africa, there are considerable gaps in existing research on their spatiotemporal analysis. Previous research has focused on analysing rainfall trends and patterns in South Africa (Kruger, 2006; Mackellar *et al*., 2014). However, in-depth research is needed on the spatiotemporal characteristics of extreme rainfall events in Limpopo. The spatial and temporal patterns of extreme rainfall events in Limpopo Province are not well understood, and climate models for the region do not adequately capture them, resulting in Insufficient investigation on sub-daily rainfall extremes and their effects on flash flooding and urban drainage (Alexander *et al*., 2013).

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Previous studies have Investigated rainfall patterns and trends in South Africa (Kruger, 2006; Mackellar *et al*., 2014),have examined the effects of climate change on rainfall patterns in southern Africa (Engelbrecht *et al*., 2013) and Investigated the links between climate models and rainfall variability in South Africa (Reason and Jagadheesha, 2005).The present study sought to examine the trends in the frequency and intensity of extreme rainfall events in Limpopo, analyse the spatial distribution of extreme rainfall events in Limpopo and to determine the correlations between annual mean conditions and annual extreme precipitation indices, as well as correlations between trends in the means and in the extremes.

Data on rainfall patterns in South Africa indicate significant fluctuations from one year to the next, which can lead to weather events related to either drought or flooding (Schulze, 2003). The South African Weather Service has observed that while the overall rainfall in the country is low, only specific regions encounter conditions classified as meteorological drought. The study, therefore, attempted to assess the characteristics of rainfall between 1993 and 2023 in the Limpopo province. The results of this research will help both the South African government agencies and those international to manage extreme rainfall events by utilising analytical methods like Sen's slope and Mann-Kendall's test, to identify trends in extreme rainfall. Furthermore, this study will enhance the existing knowledge regarding RClimDex and the application of Geographic Information Systems to rainfall data, while also providing recommendations for government agencies on long-term variability in extreme rainfall.

1.7 Description of the study area

This study focuses mainly on Limpopo Province (Figure 1.1), which is situated in the northern part of South Africa and shares international borders with Botswana, Zimbabwe, and Mozambique. Limpopo province falls within a tropical climate, which is usually interrupted by short-lived thunderstorms, and very little rainfall is received during the austral winter (Ngwenya, 2019). The mean temperature in summer is about 27˚c, and the total rainfall ranges from 400- 600 mm (Tshiala *et al*., 2011). The primary contributors of rainfall in Limpopo are cloud bands as well as low pressure systems and easterly waves (Van Heerden & Taljaard, 1998).

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Nights are cold during winter (May-August), with brisk mornings and dry sunny days. Limpopo Province is made up of a Lowveld plain that is far less than one thousand metres along the Limpopo River. This province encompasses the 3 major formations of Southern Africa: the raised interior, mountain systems and the low-latitude coastalplain. Mountains are often significant contributors to heavy rainfall due to increased vertical lifts on the lee side. Numerous investigations have shown how the topography of South Africa influences atmospheric circulation, resulting in added impetus for extreme precipitation.

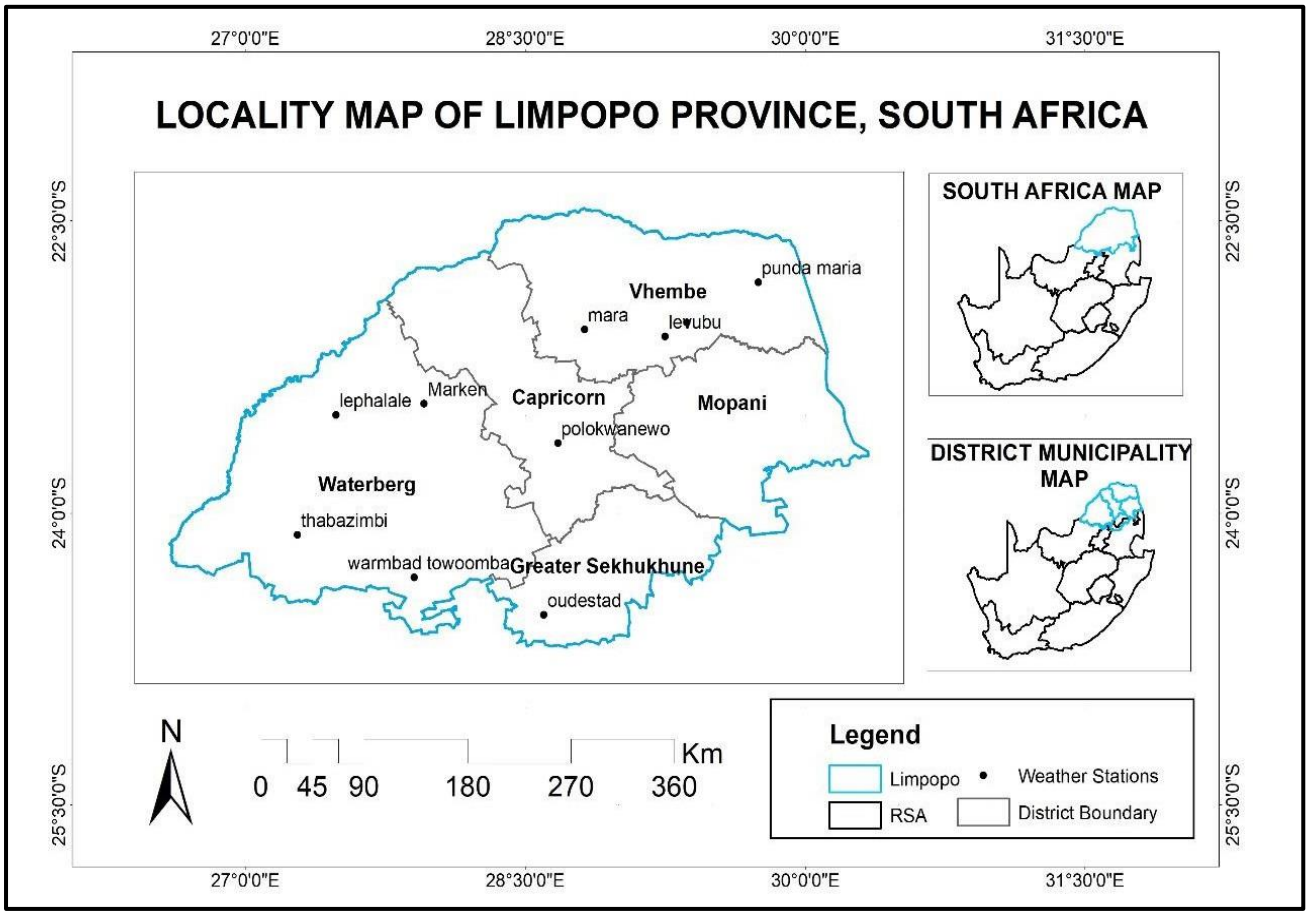


Figure 1.1 Map of the Limpopo Province showing its five District Municipalities and the location of weather stations used in the present study.

1.8 Outline of the dissertation

This dissertation is divided into five chapters that make major contributions to our understanding of the spatiotemporal study of extreme rainfall occurrences in Limpopo Province from 1993 to 2023:

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Chapter 1 provides an introduction, offering background information for research. It also addresses the research's objectives and purposes.

Chapter 2: outlines a review of important literature that informs this study.
Chapter 3: describes the data and procedures utilised in this research. And how these are employed to meet the study's aim.

Chapter 4: presents a discussion of rainfall characteristics, while wet and dry extremes trends present the results and discussions of this study.

Chapter 5: provides a summary of the study's findings, emphasising major outcomes and describing the research contributions. Lastly, the chapter offers suggestions for future research aimed at examining extreme rainfall occurrences to enhance the quality of findings and to further safeguard property and preserve lives.

1.9 Chapter Summary

The chapter introduced the study, focusing on aspects such as its introduction, problem statement, aim, and objectives. The key elements of the research are also outlined here. This is aimed at enhancing awareness and backing the study.

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CHAPTER 2: Literature Review

2.1 Introduction

This chapter examines the spatial and temporal features of extreme rainfall events in South Africa and the country's rainfall-producing systems, with a special emphasis on Limpopo Province. Extreme rainfall events have a significant impact on populations, infrastructure, and the environment. The purpose of this literature review is to consolidate existing research on the spatiotemporal analysis of extreme rainfall events in Limpopo Province, focusing on major findings, methodology, and knowledge gaps. By examining the complex relationships between rainfall patterns, climate variability, and geographical factors, this review hopes to inform future research and decision-making in the region, ultimately contributing to a better understanding of rainfall variability and trends.

2.2 Rainfall Characteristics in South Africa

Rainfall patterns in South Africa demonstrate significant changing seasons, primarily occurring during the warmer periods of October to March in most region of the country. The southwestern part of the country experiences rainfall in the winter, while a narrow area along the southern Cape Coast receives precipitation year-round (Philippon *et al*., 2012) The atmospheric conditions over South Africa are predominantly extra-tropical and conditionally unstable during the early summer months, from October to December (Dyson *et al*., 2015). However, from mid-December to February, the airflow transitions to a more tropical and convectively unstable state (Chikoore *et al*., 2021).

South Africa has a coastline that extends over 2,500 kilometres, bordered by the Atlantic Ocean to the west and the Indian Ocean to the south. The country shares its northern borders with Namibia, Botswana, and Zimbabwe, while Mozambique and Swaziland are located to the northeast. South Africa is separated into several significant geographical regions: the highveld, which mainly consists of grasslands; a nearly continuous mountain range escarpment that surrounds the central plateau; and a slim stretch of coastal lowlands. The large central plateau has elevations ranging from 1220m to 1830m above sea level in the west, south, and east, with peaks surpassing 3050m, the highest being in the Drakensberg mountains (Molautsi, 2021).

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2.3 Rainfall Producing Systems in South Africa

2.3.1 Tropical Cyclones

Tropical cyclones develop in the southwestern region of the Indian Ocean between November and April. This area typically sees around nine tropical cyclones each year. When factoring in less powerful tropical storms, the annual average rises to eleven storm systems (Muthige *et al*., 2018; Jury, 1993). Only 5% of tropical cyclones that originate over the Southwest Indian Ocean make landfall in southern Africa (Reason, 2007; Mavume *et al*., 2009; Fitchett and Grab, 2014). They mainly make landfall over the east southern African mainland, particularly in Mozambique, Zimbabwe, and eastern South Africa, and occasionally over Madagascar. They are linked to a large amount of rainfall when they make their landing.

These weather systems originate in the southwest Indian Ocean or the Mozambique Channel and migrate from west to east. Eline, one of the most famous tropical storms in the last ten years, struck Southern Africa in February 2000, causing devastating flooding in several regions in the southeast (Reason and Keibel, 2004). Tropical storm Idai killed many people and caused extensive damage in southeastern African countries in March 2019. Many tropical cyclones that make landfall often travel over the broad southern African river basins and are frequently associated with floods (Dyson and Van Heerden, 2002). Tropical cyclones have a significant impact on the heavy rainfall patterns of southern Africa. Tropical cyclones can bring a lot of precipitation into the region, resulting in protracted and severe rainfall (Malherbe et al., 2013). Reason and Keibel (2004) found that tropical cyclones have a substantial effect in shaping heavy rainfall patterns in southern Africa.

2.3.2. Cut-off Lows

The cut-off lows are generally renowned for their volatile weather patterns and significant rainfall occurrences (Favre *et al*., 2013). They typically form in the mid-latitudes, on the equatorial side of the polar or sub-tropical jet stream, eventually becoming closed cyclones in the middle and upper troposphere. This phenomenon arises when the upper air systems detach from the principal westerly flow of the mid-latitudes (Palmén, 1949). Based on the work of Qi *et al* (2000), cut-off lows (COLs) are low-pressure systems observed at the synoptic scale, distinguished by a significant

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trough at the 500 hPa level and a closed circulation at lower elevations. Cut-off Lows (COLs) are characterized as baroclinic temperate disturbances that manifest in the westerlies as wide troughs, and they are linked to a cold-cored depression (Tyson, 1989).

These weather patterns typically originate in the upper westerlies as a trough and develop into a closed circulation that reaches the surface. Often, they form when a trough in the high atmosphere develops into an enclosed flow that becomes separated from its origin, expanding downward without making contact with the surface. When the cyclone is entirely enclosed in the middle and upper troposphere, it is referred to as a "cold pool," noted for its strong instability, thunderstorms, high winds, and substantial rainfall (Porcù *et al*., 2007). The low-pressure system subsequently weakens as it transitions to a barotropic state, beginning to exhibit less severe precipitation (Muofhe, 2019).

2.3.3. Inter-Tropical Convergence Zone (ITCZ)

A region defined by convective processes where tropical activities occur; it functions as a low-pressure zone where trade winds from either hemisphere meet, resulting in convective uplift, is referred to as the intertropical convergence zone (ITCZ). Within this convergence zone, closed tropical lows and troughs develop (Tyson and Preston-Whyte, 2000). This system is linked with heightened global warming and the downward motion over the subtropical high-pressure belt; it is primarily influenced by the interaction of insolation and Hadley circulation (Chikoore, 2005). The migration and shifting of the Inter tropical convergence zone follow a specific yearly pattern over southern Africa.

During the summertime in the Southern Hemisphere, the troughs shift south of the equator, connecting with the Angola low and causing heavy rainfall throughout the Limpopo Valley interior and eastern parts of South Africa. The positioning of the Inter tropical convergence zone during the summertime is critical for important river systems, such as the Limpopo and Zambezi, as it contributes substantial amounts of rainfall to these areas. During the La Niña phase of El Nino southern oscillation, the Inter tropical convergence zone trough can reach down to the Tropic of Capricorn (Mwafulirwa,

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1999). Southern Africa experiences considerable amounts of rain during summer months, while the troughs are south of the equator.

During a normal rainy season in southern Africa, the ITCZ's impact can move from central Tanzania to southern Zimbabwe and north of South Africa. This area is distinguished by a larger emission of heat absorbed in the atmosphere of Southern Africa. During the colder months in the southern hemisphere, the intertropical convergence zone moves northward from the equator (Kruger, 2006). The seasonal movement of the ITCZ between summertime and wintertime is predominantly influenced by pressure fluctuations south of Africa (Ker *et al*., 1978), as well as a mid-tropospheric anticyclone system formed over Botswana, which pushes the intertropical convergence zone away (Ncube, 2019).

2.3.4 Cold Fronts and Ridging Anticyclones

The Western Cape is the only Mediterranean climate area in South Africa; hence it mostly relies on cold fronts and ridging subtropical anticyclone systems to produce precipitation in the eastern and western parts of the Cape during the wintertime. (Tyson & Preston-Whyte, 2000). Cold fronts, caused by anticyclones, are distinguished by the migration of cold air from the southwest of the Atlantic Ocean to the southeast along South Africa's south coast. These fronts form as weather systems shift, providing rain during the winter season. Behind the front, conditions conducive to convection are created, where convergence at low-altitude airflow with a southerly direction peak (Ncube, 2019). Typically, cold fronts are linked with prominent cloud bands that stretch from the coast into the interior regions.

During June and July, a high-pressure system substantially impacts rainfall patterns across South Africa (MacKellar *et al*., 2014). This system leads to air sinking in much of southern Africa’s inland regions. The systems often remain stationary for extended periods along the southeast coast throughout the winter months. The rotation of the high- pressure system is anticlockwise, which facilitates the movement of warm, moist air (in a hooking motion) from the Indian Ocean toward the coast and the nearby interior regions. The convection of this moisture can cause heavy rainfall in places such as the Eastern Cape and certain areas of Kwa-Zulu Natal (Tyson & Preston-

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Whyte, 2000). (Tyson, 1989) found that ridging highs and cold fronts contribute to around 16-25% of the overall rainfall in the sub-region.

2.3.5 Tropical Temperate Troughs (TTT)

An important form of weather system exists in numerous places of the planet, connecting the tropics and extra tropics (Erasmus, 2019). This kind of weather system is related with tropical-extratropical interactions and is known as tropical plumes (Hart *et al*., 2010; Knippertz, 2007). However, in southern Africa, similar systems are designated as Tropical Temperate Troughs (Hart *et al*., 2010). Tropical Temperate Troughs are a significant driver for the poleward transport of power (heat), moisture, and momentum, and they consist of a region of increased convergence that is usually detected by cloud (Hart *et al*., 2010; Macron *et al*., 2014; Ratna *et al*., 2013, Vigaud *et al*., 2012).

These cloud bands can be identified on satellite data as extended bands of clouds reaching from the tropics south-eastward (north-eastward) to the South Pole (North Pole) (Hart *et al*., 2010; Macron *et al*., 2014, Erasmus, 2019). Tropical temperate troughs often last several days and can be observed by satellite photography as the associated cloud bands migrate eastward. Because of their length, these systems typically produce enormous amounts of rainfall, which can contribute significantly to a season's total rainfall. These systems provide for a significant portion of southern Africa's summer rainfall (Harrison, 1984).

In the summertime rainfall area, TTT occurrences could account for up to 39% of mean annual rainfall (Crimp *et al*., 1998). Despite both the physical and kinetic properties of these systems not being fully understood at the synoptic scale (Hart et al., 2010; Ratna *et al*., 2013; Vigaud *et al*., 2012), a significant amount of research has been conducted to describe these important rain-producing systems. Tropical Temperate Troughs are distinguished by a cloud belt that extends from the tropics to the mid-latitudes (Erasmus, 2019), signifying a region of increased convection.

On both sides of the cloud band, there are zones of suppressed convection (Macron *et al*., 2014), signifying a region of increased convection. On both sides of the cloud band, there are zones of suppressed convection (Ratna *et al*., 2013) which can contribute to focusing on the inflow of moisture in the tropical temperate troughs for example,

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(Lindesay and Jury, 1991).

Ridge-trough-ridge patterns can form over land or in the ocean. Typically, a tropical temperate trough forming over the ocean only exhibits mid- to upper-level clouds through the subtropics. However, when a tropical temperate trough occurs over a landmass, such as southern Africa, deep convection and heavy rainfall can be sustained by continental heat. (Hart *et al*., 2010). A notable example of the effect of TTTs in South Africa is the occurrence of localised flooding events. For instance, in January 2019, a TTT system contributed to heavy rainfall and subsequent flooding in regions along South Africa's eastern coastline, causing extensive damage and displacement of communities (Bopape *et al*., 2021).

2.3.6 Meso-scale rain-producing systems

South African rainfall is influenced by a variety of meteorological systems, including meso-scale rain-producing systems that play a crucial role in regional precipitation patterns. These systems are characterised by their intermediate size, typically ranging from tens to hundreds of kilometres, and their ability to generate significant rainfall over localised areas. Meso-scale rain-producing systems are probably most important for sub-Saharan Africa, the southwestern cape area of South Africa, and southern Africa (Engelbrecht *et al*., 2020). Recently, there has been substantial disagreement about the importance of mesoscale processes to the yearly, and especially seasonal, rainfall (Guo *et al*., 2022).

Yet, at the same time, knowledge about mesoscale systems, apart from the results at rainfall timescales, is at present extremely limited (Cheeks *et al*., 2020). The timescales of mesoscale rain-producing systems range from a few hours to a few days, and their characteristic dimensions range from ~30 km to ~1000 km, with the majority of rain-producing systems having scales of <~500 km (Bliefernicht *et al*., 2022). The systems include sea and bay breezes, katabatic drainage flow systems in valleys and basins, valley wind flow systems, thunderstorms, squall lines, mesoscale convective complexes and mesoscale convective systems, cloud windward lines and cloud streets, and low-pressure systems, both cut-off systems and systems that are part of the wave train in midlatitudes, particularly outside South Africa on the eastern side of

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southern Africa (Rainbands, 2002). Some mesoscale systems are well documented, but many extensive studies need to be conducted.

For example, the mesoscale systems' patterns and physical/dynamical mechanisms need to be identified on various time scales (Héas *et al*., 2007). Mesoscale rain-producing systems contribute significantly to the spatiotemporal distribution of precipitation in South Africa. For example, mesoscale convective complex (MCCs) often brings intense but localized rainfall, leading to variability in rainfall amounts across relatively small distances. This fluctuation presents issues for agricultural and aquatic conservation, as some areas may experience flooding while others remain dry (Kruger & Jury, 2010).

COLs, on the other hand, can bring widespread and prolonged rainfall, which is crucial for replenishing water reservoirs and supporting agricultural activities in regions that rely on winter rainfall. The interaction between these meso-scale systems and larger-scale weather patterns further complicate rainfall prediction in South Africa (Tyson, 2001). Recent examples of MCCs in South Africa include the severe storms that affected parts of Gauteng and KwaZulu-Natal provinces in December 2023. These MCCs brought heavy rainfall, leading to localised flooding and disruptions to urban areas and agricultural activities (South African Weather Service, 2023).

2.3 Global trends in extreme rainfall events

Global warming has driven extreme rainfall events to become more intense and frequent in many parts of the world. Extreme rainfall events are becoming more frequent and intense globally, with notable developments in Asia and Africa (Sun *et al*., 2021). Guerreiro et al. (2022) have found that high rainfall events are becoming more common worldwide, particularly in tropical regions. Similarly, Li *et al*. (2023) discovered that extreme rainfall occurrences have grown worldwide, with significant variation in geographic and temporal patterns. Heavy rainfall events have increased significantly in North America, Europe, and portions of Asia, which has been related to shifts in atmospheric circulation patterns and increasing oceanic evaporation (Sun *et al*., 2021).

Trends in North America show a significant increase in extreme precipitation,

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particularly in the northeastern United States and parts of Canada. This increase has increased flood hazards, with certain places seeing a 71% rise in the highest 1% of precipitation occurrence between 1958 and 2012 (Assessment, 2018). Similarly, European countries have seen an increase in extreme rainfall occurrences, particularly during the winter months, which is attributable to changes in the North Atlantic Oscillation (Zhang *et al*., 2017). The increased frequency of short-duration, high-intensity rainfall has exacerbated urban floods, putting current drainage systems and infrastructure resilience to the test (Blöschl *et al*., 2017).

Extreme precipitation trends in Asia have also been increasing, particularly in South and Southeast Asia, where monsoon patterns have shifted Because of changes in the climate (Goswami *et al*., 2006). India, for example, has seen a change toward more irregular and intense rainfall, resulting in deadly floods in cities such as Mumbai and Chennai (Singh *et al*., 2014). Extreme rainfall events in China have been related to rising sea surface temperatures and atmospheric instability, culminating in severe flooding events like those that occurred in Henan province in 2021 (Zhang *et al*., 2023).

Extreme rainfall in Africa and South America varies, with some parts enjoying increases and others encountering extended droughts. Heavy rainfall occurrences in Sub-Saharan Africa have increased in recent decades, especially in the Sahel and East Africa (Nash, 2010. This variability is linked to changes in the Intertropical convergence zone (ITCZ) and Indian Ocean Dipole (IPCC, 2021). Similarly, portions of South America, including southern Brazil and Argentina, have seen an increase in intense rainfall, resulting in recurring flooding episodes (Barros *et al*., 2015). However, these gains contrast with diminishing trends in other areas, such as the Amazon Basin, where deforestation has impacted local climate conditions (Davidson *et al*., 2012).

Worldwide patterns show a definite increase in extreme rainfall occurrences, with considerable regional variability. A study by Zhang *et al* (2022) has highlighted the need to take into account the spatial and temporal aspects of extreme rainfall events in climate research. This is because a change in the climate is an important cause of these developments, altering precipitation patterns and increasing global flood hazards. While some areas are seeing more heavy and frequent rainfall, others are seeing changes in seasonality and unpredictability. Effective mitigation and adaptation

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measures are therefore essential for minimising the effects of excessive rainfall and ensuring long-term resilience in climate change.

2.4 Trends in extreme rainfall events in South Africa

In recent decades, South Africa's extreme rainfall patterns have shifted significantly, with certain regions experiencing a spike in both the frequency and intensity of heavy precipitation events. According to research undertaken by the University of Pretoria, exceptional daily rainfall probability has increased significantly in some places during the last 50 years (McBride *et al*., 2022). This tendency is most noticeable in the country's eastern regions, where some stations have reported rises of more than 100mm in 1-in-50 and 1-in-100-year return period values. The increase is particularly noticeable in the country's eastern areas. For example, the Letaba district in Limpopo observed a greater than 35% increase in extreme rainfall occurrences, while Hlobane in KwaZulu-Natal saw its 1-in-50 and 1-in-100-year return period values nearly quadruple (McBride *et al*., 2022).

These findings point to an increased likelihood of excessive rainfall in these places, which is most likely impacted by climate change. Kruger and Nxumalo conducted an analysis of rainfall data from 1960 to 2010, revealing significant increases in extreme rainfall occurrences in South Africa's eastern and northeast areas. The researchers linked these developments to shifts in atmospheric circulation patterns and sea surface temperatures, which have altered the frequency and intensity of convective storms in these regions (Kruger and Nxumalo, 2017). In contrast, the central and western portions of the country have seen a decline in severe precipitation over the same period.

This decline has been connected to a decrease in the frequency of frontal systems and a southerly shift in storm tracks, resulting in lower precipitation and drought conditions in these areas (Mason *et al*., 1999). The trends in extreme precipitation occurrences in South Africa show considerable geographical variability, which is driven by climate change, air circulation changes, and rising surface temperatures. Studies have consistently demonstrated that the country's eastern and northeastern regions are experiencing increasingly frequent and powerful extreme rainfall events,

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increasing the danger of floods and infrastructure damage (Kruger and Nxumalo, 2017, Engelbrecht *et al*., 2015). In contrast, extreme rainfall has decreased in the Western and central regions, resulting in prolonged drought and water scarcity issues (Mason *et al*., 1999).

2.6 Atmospheric Circulation Patterns

2.6.1 El Niño-Southern Oscillation

The El Nino-Southern Oscillation (ENSO) is a complex, multidimensional oceanic and atmospheric climate phenomenon (Anderson *et al*., 2017). It is considered one of the most powerful interannual climate events (Fan *et al*., 2017). Research underscores the complexity of ENSO, attributing its causes to intricate interactions between the Pacific's atmosphere and ocean (Wang *et al*., 2022). Understanding the diversity of ENSO events, including their variable intensity, regional patterns, and temporal characteristics, is crucial for predicting and mitigating its effects.

Studies have demonstrated that ENSO's consequences vary globally, with El Niño events often leading to droughts in Australia, Indonesia, and southern Africa, while causing excessive rainfall and flooding in Peru and Ecuador (Wang *et al*., 2022). Conversely, La Niña events tend to have opposite impacts, resulting in above-average rainfall in Australia and droughts in the southern United States (Loriani *et al*., 2023). The phenomenon's substantial influence on global food supply, water availability, and economic stability makes it a pressing concern.

In South Africa, particularly in Limpopo Province, ENSO has a considerable impact on weather patterns. Research has shown a significant link between ENSO and rainfall variability in specific regions, such as the Luvuvhu River basin, where a notable negative association was found between ENSO and the standardised precipitation index (Mazibuko *et al*., 2021). Furthermore, simulations of extreme rainfall events in Limpopo Province using Extreme Value Theory estimated a 50-year return level of 368 mm in the Thabazimbi region, highlighting the need for comprehensive disaster management plans (Sikhwari *et al*., 2022). Despite significant advances in understanding ENSO, predicting its magnitude and impacts remains challenging. While ENSO predictability has improved

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over the past few decades due to advances in climate modeling and data assimilation, further research is necessary to enhance forecasting accuracy and reliability (Wang *et al.*, 2022).

In South Africa, El Nino southern oscillation has a considerable impact on weather patterns, especially in Limpopo Province. Despite its remote location, the Pacific Ocean is thought to influence summer rainfall in South Africa (Landman & Beraki, 2012, Chamberlin *et al.*, 2001). The north-eastern region of the country (Nash & Grab, 2010), including the Limpopo Province (Meque & Abiodun, 2015) and the south coast of South Africa, where summer rainfall is strongly influenced (Engelbrecht et al., 2017) with rain being higher than normal during La Nina events (Weldon & Reason, 2014), and the southwestern Cape (Engelbrecht *et al.*, 2017).

La Niña events have a significant impact on southern Africa's climate, particularly in terms of rainfall patterns. According to recent studies, La Niña is associated with increased rainfall and prolonged wet periods in the region. A study by Hoell *et al.* (2021) found that La Niña events strengthen atmospheric convection over southern Africa, resulting in more prolonged wet periods(Abdi *et al.*, 2016).This can lead to reduced rainfall, increased evaporation, and higher temperatures. Dry conditions in southern Africa that are caused by El Nino events occur as westerly winds result in increasing evaporation (Jury *et al.*, 2002).

El Nino episodes generate dry conditions in southern Africa because westerly winds increase evaporation. El Nino episodes are associated with a high-pressure system over southern Africa, resulting in aberrant mid-tropospheric descent and below-normal rainfall (Hoell & Cheng, 2018). Dry spells are analysed for the main December-January-February time of austral summer, as this is often when ENSO effects the region the most (Reason *et al.*, 2005). This is due to the fact that below-average rainfall is influenced by factors beyond just ENSO, as other weather systems also play a role in rainfall variability (Rapolaki *et al.*, 2019). For instance, the variation in rainfall in Southern Africa is impacted by various weather systems, such as the Southern Annular Mode, during the El Niño or La Niña phases, rather than only ENSO (Ncube, 2019).

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2.6.2 Indian Ocean Dipole

An ocean-atmosphere-linked phenomenon known as the Indian Ocean Dipole (IOD) climatic mode emerges in the tropical Indian Ocean (Saji *et al*., 1999, Webster et al., 1999). Studies have revealed that the IOD has a significant impact on weather patterns, with positive IOD occurrences frequently producing droughts in Australia and Indonesia, as well as excessive rainfall and flooding in eastern Africa (Ashok *et al*., 2019). In contrast, negative IOD occurrences have the reverse effect, resulting in above-average rainfall in Australia and droughts in eastern Africa.

In South Africa, notably in Limpopo Province, the IOD has been connected to rainfall variability, with research revealing a substantial relationship between IOD episodes and droughts or floods. Furthermore, models of heavy rainfall occurrences in Limpopo Province using heavy Value Theory have revealed a 50-year return level of 368 mm in the Thabazimbi region, emphasizing the importance of comprehensive disaster management measures (Sikhwari *et al.*, 2022).

The literature has examined the correlation between the Indian ocean dipole and other climate phenomena, including the El Niño-Southern Oscillation (ENSO). Research has revealed that the Indian ocean dipole and El Niño-Southern Oscillation can interact and influence each other's effects on climatic variability (Wang *et al*., 2022). Furthermore, researchers have investigated the effects of climate change on the Indian ocean dipole and its prediction. According to research, climate change may increase the frequency, intensity, and length of Indian ocean dipole episodes, potentially affecting regional climatic variability and predictability (Loriani *et al.*, 2023). During positive IOD events, warmer sea surface temperatures in the western Indian Ocean are associated with increased rainfall in areas such as the eastern coastal regions of KwaZulu-Natal. Conversely, negative IOD events cause below-average rainfall, leading to droughts in parts of the country. The negative IOD event, like La Nina, intensifies intense tropical cyclone (TC) behaviours. The warm phase Indian ocean dipole event reduces precipitation over the eastern Indian Ocean, resulting in a severe water shortage (Ashok *et al*., 2019).

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2.6.3 Southern Annular Mode

The Southern Annular Mode (SAM), also known as the Antarctic Oscillation (AAO), represents a pattern of variability in atmospheric circulation, characterised by opposing pressure anomalies in Antarctica and along the coast from 40-50ºS (Reason et al., 2005). It is also known as a tropospheric circulation variability in the southern hemisphere's mid-and high latitudes is mostly influenced by this mode (Mahlalela, 2018). According to (Mahlalela, 2018) it significantly impacts rainfall and temperature distribution from the subtropics to the South Pole. (Mahlalela *et al*., 2020) and (Reason *et al*., 2005) found a link between negative (positive) SAM and wet/dry conditions in western South Africa (Malherbe *et al*., 2016) found a strong correlation between SAM and precipitation in south-eastern Africa, including Limpopo. According to (Ibebuchi, 2021), the negative phase of SAM is influenced by the positive phase of ENSO, which is responsible for increasing the world average sea surface temperature (SST).

Recent research has also looked into the effects of climate change on SAM and its prediction. According to research, climate change may increase the frequency, severity, and length of SAM occurrences, thus affecting regional climatic variability and predictability (Rohli et al., 2022). Furthermore, research has shown that observational data and models are critical for understanding SAM's dynamics and consequences. Studies have employed a variety of observational datasets and modeling methodologies to study SAM's role in shaping regional climate variability (Marshall *et al.*, 2022).

2.7 Chapter Summary

In Chapter 2, a synthesis of previous and earlier works on the local, regional, and global climatology to support this study has been presented together with approaches relevant to the current study. The significance and demand for information on the time of seasonal rainfall in Limpopo Province were stressed. It also explains how severe rainfall is related with other events, such as floods and droughts, and their detrimental repercussions. The primary rain-bearing systems that influence rainfall over southern Africa and other local features that affect the spatial and temporal distribution of rainfall were described.

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Chapter 3: Methodology

3.1 Introduction

The objective of this chapter is to outline the sets of data, tools, and methodologies that are utilised to study spatial-temporal analysis of rainfall events in Limpopo Province from 1993-2022. Daily rainfall data from was derived from the South African Weather Service (SAWS). Esri Arc GIS, Quantum GIS, and RClimDex were utilised to examine rainfall data in the present study.

3.2 Data Used

3.2.1 Rainfall

The rainfall data for this study was collected from the South African Weather Service. This study selected 10 Weather Stations. The selection criteria were based on the spatial distribution of the stations across Limpopo, data length, quality, and completeness, and stations that at least have 90% data available from 1993-2023 over Limpopo Province, South Africa. The observations were made hourly and followed by the World Meteorological Organization (WMO) standard procedures. The stations are located at different latitudes and elevations of altitude above mean sea level (MSL) as shown on Table 3.1

Table 3.1 SAWS weather stations used in the study

Station name	Elevation (m)	Latitude	Longitude	Station number	Available data
Lephalale	839	-23.68	27.71	06743418	1993-2023
Levubu	706	-23.0798	30.2800	07234850	1993-2023
Mara	894	-23.1500	29.5700	07234850	1993-2023
Marken	996	-23.59	28.39	0675666	1993-2023
Oudestad	953	-25.1810	29.3390	0552517	1993-2023
Polokwane wo	1226	-23.86	29.45	0677802	1993-2023
Punda Maria	457	-22.69	30.02	0768011	1993-2023
Thabazimbi	977	-24.58	27.41	0587725	1993-2023
Tshivhasie Tea Venda	976	-22.96	30.35	0766628	1993-2023
Warmbad Towoomba	1143	-24.8990	28.3230	05895941	1993-2023

3.2.2 Identification of Extreme Rainfall Events

The present study attempts to employ a proper ratio of weather stations and the

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duration of recorded data to reach conclusions about overall variations in yearly and periodic precipitation, as well as extreme instances of precipitation. Extreme rainfall occurrences were examined using indices produced by the World Meteorological Organization (WMO) Expert Team on Climate Change Detection and Indices (ETCCDI), which are used worldwide to identify changes in extreme weather events (Donat *et al*., 2013). RClimDex is a software program developed under the WMO ETCCDI that permits the estimation of twenty-seven fundamental indices of temperature and rainfall extremes for the identification of climate changes (Zhang & Yang, 2004).

Table 3.1 lists the four precipitation indices used in the present investigation based on the ETCCDI definitions. The results of the indices are presented on an annual and monthly time scale. In addition to the seasonal indices' values of yearly total precipitation in wet days, total rainfall from daily values greater than (≥ 1 mm), and r20mm, the total number of days with rainfall greater than 20 mm (≥ 20mm), were used to investigate seasonal tendencies in total rainfall and high rainfall events. The base period from which the percentiles for the relevant indices were calculated was identified as 1993- 2023, that can be regarded as the present common norm for comparable trend studies.

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Table 3.2 List of WMO ETCCDI Indices used in this study

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
r20mm	Annual count of days when precipitation ≥ 20mm	Days
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

3.3 Data validity

Validating daily rainfall data from the South African Weather Service (SAWS) involved several steps to ensure the accuracy, completeness, and consistency of the data. Daily rainfall data was obtained from SAWS for the period 1983-2025, and it was ensured that the data was in a CSV format. The data was then cleaned to check for missing values and outliers, and any errors in data recording or transmission were identified and corrected. Duplicate or redundant data was also removed to ensure data consistency.

Next, the data was subjected to quality control checks to verify that it was within reasonable limits, such as using indices produced by the World Meteorological

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Organization (WMO) Expert Team on Climate Change Detection and Indices (ETCCDI), which are used worldwide to identify changes in extreme weather events. Any suspicious or anomalous data points were identified and flagged for further investigation.

3.4 Analysis Methods

3.4.1 Anomalies and Annual Cycle

Historical rainfall data was sourced from the South African Weather Service stations. Rainfall data was then organised into a time series format, with each data point representing a specific time (daily). The rainfall average was calculated for each month over the study period, to identify the annual cycle of rainfall in Limpopo Province. The yearly cycle of the calculated average is visualised using graphs to observe any seasonal patterns or trends. Anomalies provide an important description in climate research

3.4.2 Trend Analysis

Trend analysis can be defined as using an empirical approach to quantify and explain system changes over time (Chandler & Scott, 2011). Polynomial and linear patterns were identified using regression. This aided in analysing rainfall data across a large region, in order to find potential trends and assess their importance. The trend's statistical significance was assessed using the t-test.

Onoz and Bayazit (2003) demonstrated that when the probability distribution is normal, the parametric t-test shows a slightly higher power when compared to the non-parametric Mann-Kendall test. It was also shown that this relative power diminishes as skewness increases, although for distributions with moderate skewness, the t-test's power is almost on par with that of the Mann-Kendall test. This implies that in practical situations, the two tests can be utilized interchangeably, leading to similar results in most cases. The statistical significance of the correlation coefficients was evaluated using the student's t-test, which is a two-tailed test based on the student t-distribution.

In the present study, the long-term trend was determined annually for each station and also during four distinct seasons: summer: December, January, and February (DJF), autumn: March, April, and May (MAM), winter :June, July, and August (JJA),

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and spring :September, October, and November (SON) using monthly rainfall data obtained from SAWS rainfall stations scattered around the study area. The trend was also determined annually for each station. The division was done to enhance the quality of results.

3.3.3 Correlation Analysis

Correlation analysis assesses the relationship between two factors. It shows how and to what extent parameters are related to each other. The correlation coefficient simply measures the degree of linear relationship between two variables. This method does not differentiate between effect and cause; therefore, it must be utilised carefully, to prevent producing false results (Mwafulirwa, 1999). A zero-value interaction between parameters does not always mean that there is no link.

Correlations among precipitation indices and mean annual rainfall were examined as an extra tool for thoroughly inspecting the data was examined for average conditions for all indices listed in Table 3.1, which were created site-by-site at all 10 weather stations. The correlations were calculated using the linear Pearson correlation coefficient, and their significance in statistical analysis was set at 5%. This type of analysis helps to find station data with unexpected behaviour (e.g. Moberg *et al*. 2006). The correlation coefficients' statistical significance was determined using the student t-test (a two-tailed test of the student t distribution).

The t -test was calculated using the following formula:

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}}$$

where:

- r= correlation coefficient
- n = number of data points

3.4.4 Composite Analysis

Composite analysis is frequently used in climatology research to identify common traits (Chikoore, 2005). This method, also known as a superposed period assessment, provides more accurate patterns than those indicated by individual cases (Mbokodo,

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2017). Historical rainfall data from the weather station was collected from 1993 - 2023 to conduct a composite analysis for this study. Data was converted into a consistent format and units. Extreme rainfall events were defined according to the climate indices, as shown in Table 3.1. Rainfall exceeding the 90th percentile of all recorded events was defined as an extreme rainfall event. A geographic information system (GIS) was used to map the spatial distribution of extreme events across different areas in the study area. Data was interpreted using time series plots and line graphs to show temporal trends and patterns

3.4.5 Spatial interpolation

Rainfall maps were produced using Quantum GIS's Inverse Distance Weighted (IDW) interpolation method, which systematically ensures spatial estimation reliability and accuracy. The method begins with the collection of point-based rainfall data from ten South African weather services (SAWS) meteorological stations in Limpopo. The dataset was then pre-processed to look for missing values and ensure the functionality of the coordinate reference system (CRS). After the data was prepared, it was loaded into QGIS as a comma-separated values (CSV) file including rainfall values and their geographic coordinates.

The inverse distance weighted (IDW) interpolation was performed using the Interpolation tool in the Processing Toolbox. The rainfall field was selected as the interpolation attribute, and parameters such as power value and search radius were configured to regulate the weighting influence of nearby points. Higher power values provide more weight to closer points, limiting the influence of distant observations, while an adequate search radius guarantees that enough points contribute to the interpolation process. The IDW interpolation process generates a raster layer representing the geographic distribution of average yearly precipitation, which is then refined through reclassification and a colour gradient for better visualisation.

3.5 Software Description

3.5.1 Geographic Information System

Geographic Information Systems (GIS) have emerged as a vital tool in environmental and climatic research, offering extensive spatial data processing, visualisation, and modelling capabilities. In the framework of the present study, GIS software was used

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to process, analyse, and interpret rainfall data collected from the South African Weather Service (SAWS). For the current research, the primary GIS software platforms used were Esri Arc GIS 10.7.1 and Quantum GIS. These software tools were chosen based on their ability to handle huge datasets, support multiple geographical formats (such as raster and vector), and perform spatial interpolation, trend analysis, and mapping.

Extreme rainfall data from various weather stations were used to generate continuous rainfall surfaces. In addition, the Raster Interpolation plugin was used to create raster surfaces from point data. GIS is used to detect extreme rainfall events, by comparing rainfall readings to pre-established thresholds (such as the 95th percentile, r20mm, CDD, and CWD of rainfall). Events that surpassed these thresholds were flagged, and the spatial patterns of extreme events over time were investigated. ArcGIS is used to create themed maps that depict rainfall intensity, event frequency, and locations that are particularly vulnerable to extreme rainfall events. Layer Symbology enabled the differentiation of rainfall episodes based on severity (light, moderate, or heavy) and the identification of locations affected by excessive rainfall, as shown in Table 3.2.

3.5.2 RClimDex

RClimDex is a software tool created with guidance from the WMO ETCCDI. It allows for the computation of 27 essential indicators related to extreme temperature and precipitation, aimed at recognizing shifts in climate. (Zhang & Yang, 2004). It was created by the Climate Research Division of Environment and Climate Change Canada in partnership with the University of Victoria. The software is intended to operate with daily climatic data, such as rainfall and temperature, and may be used to construct a variety of climate extremes indices, including those for precipitation and temperature. RClimDex offers a user-friendly interface for calculating and evaluating climate extremes indices, making it accessible to researchers and practitioners without substantial programming skills. The software also includes a number of tools for quality control and homogenisation of climate data, which is critical for ensuring the accuracy and reliability of climate extremes indices.

Daily precipitation data from South African weather services was collected between 1993 and 2023 and converted into a text file format with columns for date (year, month,

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and date), precipitation amount, and lowest and maximum temperatures. The source (RClimDex) was selected within the R consol prompt and console prompt. This will load RClimDex into R environment. Once the source code has been properly set up, the RClimDex home page will open. The RClimDex software was then selected and used to do quality control by substituting missing and inappropriate values with currently coded as -99.9. The data was then loaded, and indices calculation settings were configured, including the base period for threshold computation, station latitude, a specific daily precipitation threshold (in mm) to calculate the number of days when daily precipitation levels surpass this threshold., and extreme rainfall indices (r20mm, CWD, CDD, and r95p).

After the selected indices were computed, the resulting climatic indices were saved in a specific subdirectory as comma-separated values (CSV) files. Annual time series plots were created to visualise trends in linear least squares and locally weighted linear regression. Corresponding statistical trend analyses were displayed on the plots, which were saved in JPEG format in a separate subdirectory.

3.6 Ethical issues

The research process involved obtaining the necessary permissions and approvals from the South African Weather Service to access and utilize rainfall data. Researchers also ensured that the data was handled and stored securely, maintaining confidentiality and anonymity where applicable. The study adhered to Category 1 ethics guidelines, which pose minimal risk to humans, animals, or the environment, and prioritized respect for persons, beneficence, non-maleficence, and justice.

3.7 Research limitation

One of the potential limitations of the study was the availability and quality of historical rainfall data. The analysis' precision and reliability were determined through the density and dispersion of rainfall stations, as well as the duration and completeness of the data record. In several locations, notably rural or distant areas, the number of rainfall stations was restricted, affecting the analysis's accuracy. Additionally, data gaps or inconsistencies in the record influenced the dependability of the results. Furthermore, the use of satellite-based rainfall estimates, or reanalysis data, increased uncertainty,

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especially in areas with complex terrain or mixed land cover. These restrictions had an impact on the analytical robustness and capacity to appropriately capture extreme rainfall events.

Another limitation was reliance on two specialised software packages; namely, ArcGIS and RClimDex. ArcGIS had limitations when it came to managing huge datasets or performing complex spatial analysis, especially in places with complex topography. RClimDex, while specifically developed for climate index calculation, had limits in terms of the range of indices that could be calculated and the software's versatility. Furthermore, the necessity for using these software packages hindered the reproducibility and accessibility of the research.

To deal with those limitations, data quality control and validation procedures, to identify and address issues with data accuracy, completeness, and consistency, were implemented. Multiple data sources were used to validate and improve the accuracy of the analysis and carefully select and validate the software packages used, to minimise potential biases. Additionally, expertise and training in using software packages and procedures were used to reduce errors and improve the accuracy of the outcomes. Lastly transparency and documentation, thoroughly explaining the study's limitations and potential biases, as well as the methodologies and software employed.

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3.8 Research Matrix

Objectives	Data source	Methods	Expected outcome
Examine the trend in the intensity and frequency of extreme rainfall events in Limpopo.	Historical weather data from the South African Weather Services	Conduct Annual cycle and anomalies; trend analysis as well as composite analysis	Reports and graphical representations showing trends in frequency and intensity of rainfall patterns
To analyse the spatial distribution of extreme rainfall events in Limpopo.	Meteorological data from the South African Weather Services stations to understand geographical distribution	Use GIS to map spatial distribution of extreme rainfall events within the study area, perform tr;nd analysis and composite analysis to identify the hotspots.	Detailed maps highlighting areas most prone to extreme rainfall
To determine the correlations between annual mean conditions and annual extreme precipitation indices, as well as correlations between trends in the means and extremes	Historical rainfall data, model outputs and observational data from 1993-2023	Conduct trend and correlation analysis. calculate Sen's slope and perform student t test	Graphical representations showing correlation in trends of annual mean rainfall and extreme rainfall indices

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3.7 Chapter Summary

This chapter provides sufficient detail about the dataset and the methods utilised in the research. The chapter provides a detailed overview of rainfall data from the South African Weather Services and the meteorological stations used. Trend and anomalies analysis methods were used, including Sen's slope and p-value, to determine the magnitude of extreme rainfall trend. RClimDex and Geographic Information System (GIS) were used to construct maps and line graphs depicting the properties of the major variable of rainfall.

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Chapter 4: Results and Discussion

4.1 Introduction

This study sought to examine the spatial and temporal patterns of extreme rainfall in Limpopo province, with an emphasis on historical trends, frequency, intensity, and spatial distribution. The study also looked at relationships between annual mean conditions and annual extreme precipitation indices and correlations between trends in the means and extremes. Statistical and geospatial techniques, such as the Geographic Information System (GIS) and RClimDex, were used to investigate trends in extreme rainfall events and calculate indices of extreme precipitation established by the Expert Team on Climate Change Detection of the World Meteorological Organization. This chapter presents the trend analysis results, as well as the frequency, intensity, spatial and temporal analyses of extreme rainfall occurrences in Limpopo Province. The findings also include a correlation between annual mean conditions and annual extreme precipitation indices, as well as correlations between trends in the means and extremes. The results are then discussed, along with the study's conclusion and recommendations for future research, to increase understanding of high rainfall occurrences.

4.2 Mean spatial patterns of rainfall over Limpopo Province

The mean spatial patterns of rainfall in Limpopo Province vary significantly due to the region's diverse topography, climatic effects, and geographical location. Limpopo Province has a summer-rainfall climate, with most precipitation falling between November and March (Figure 4.1), while the winter months, May to September (Figure 4.1), are primarily dry. Altitude, proximity to moisture sources, and prevailing wind patterns all have an impact on rainfall's spatial distribution. Figure 4.1 shows that the months of December, January, and February (DJF) account for between sixty and seventy percent of Limpopo's annual rainfall.

The mean monthly totals for the time frame frequently range from 200-300 mm in wet areas, Levubu and Tshivhase tea Venda, to 100-150 mm in dry sections, Thabazimbi and Lephalale. The March-April-May (MAM) season sees falling rainfall, accounting for 15-25% of the annual total. The Drakensberg escarpment promotes orographic

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precipitation; hence, higher rainfall levels are often recorded in the province's eastern and southeastern regions. In contrast, the western and northern regions, which are lower in height, receive less rainfall, contributing to their arid and semi-arid climates. Figure 4.1 shows that monthly averages range between 50-100 mm in wetter zones (Vhembe District) and 20-50 mm in drier sections (Waterberg District).

Synoptic-scale weather phenomena, such as the tropical cyclone, regional convection and intertropical convergence zone (ITCZ) all have an impact on rainfall distribution in Limpopo Province (Reason, 2017). Due to orographic uplift, the eastern areas of the province, particularly near the Soutpansberg Mountains, receive higher annual rainfall. The majority of the rainfall occurs during the southern summer months, which range from 200 to 1,569.58 mm, as shown by Figure 4.2.

Figure 4.2 shows that areas such as Lephalale received an average of 270.4 mm per year, while Marken received approximately 400.1 mm. Polokwane received 483.4 mm, while Mara and Bela-Bela received between 500 and 700mm. Wet regions such as Levubu averaged 801.4 mm, aided by orographic rainfall, while Tshivhasie Tea Venda had the most, at 1,569.58 mm (Figure 4.2). These results concur with (Maluleke et al., 2023). This spatial discrepancy in precipitation has a direct impact on water availability, vegetation cover, and agricultural output, making some places more drought-prone than others.

Climate variability, including the El Niño-Southern Oscillation (ENSO), affects interannual and decadal rainfall patterns. During the El Niño years, Limpopo Province experiences below-average rainfall, resulting in extended droughts and water stress. La Niña circumstances produce less precipitation than normal, which can cause floods, especially in low-lying locations near river catchments. These climatic changes contribute to the province's overall regional heterogeneity of rainfall, which has an impact on both natural ecosystems and human livelihood.

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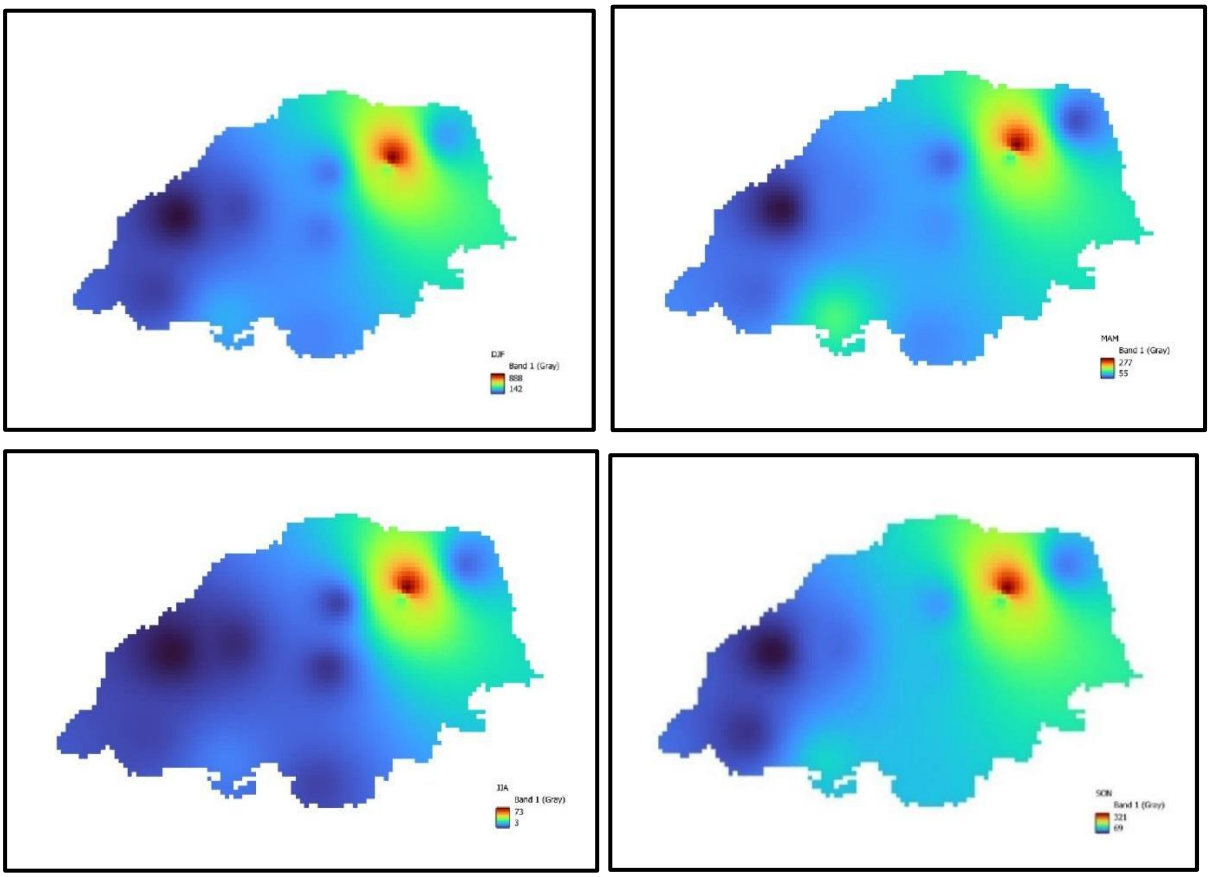


Figure 4.1 Seasonal spatial rainfall patterns during DJF, MAM, JJA and SON for the period of 1993- 2023

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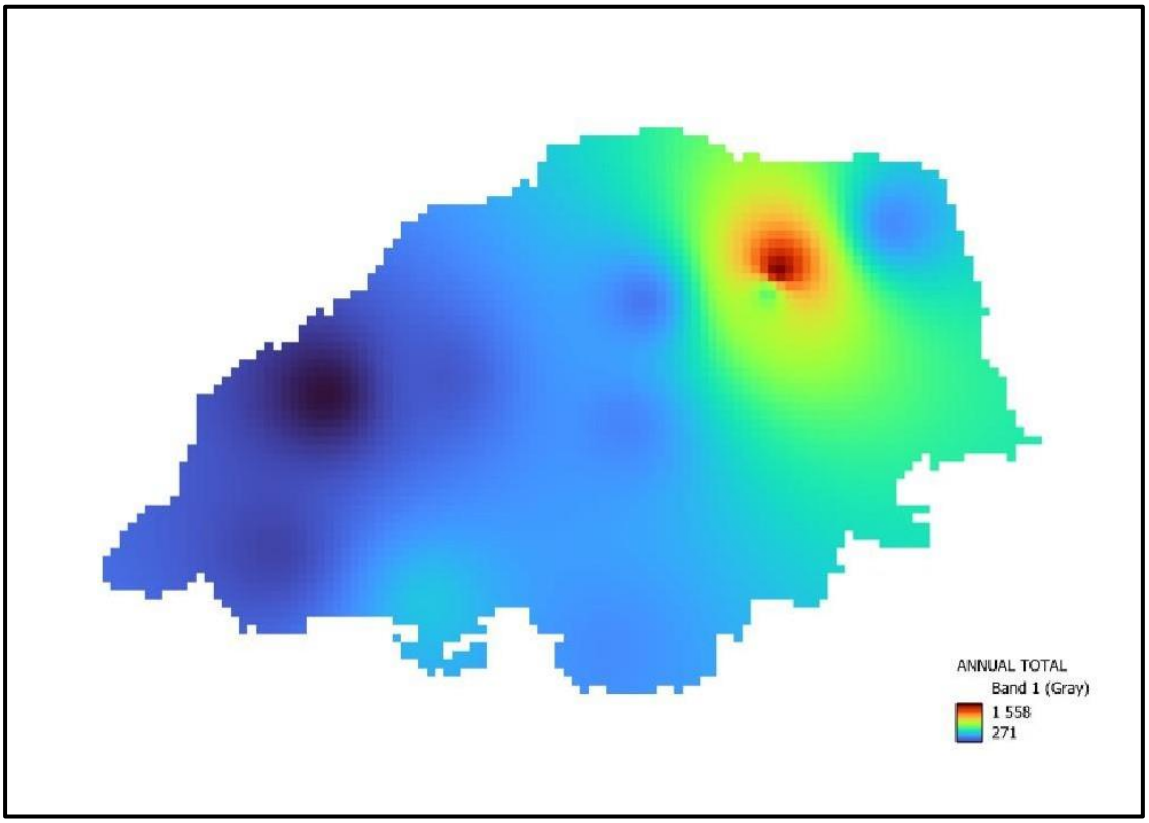


Figure 4.2 Annual total average rainfall over Limpopo Province from 1993-2023

4.3 Annual cycle of rainfall over Limpopo

Limpopo Province exhibits a distinct annual rainfall cycle characterised by pronounced wet and dry seasons (Weldon and Reason, 2014, Mahlalela *et al*., 2019). Limpopo's rainfall primarily occurs during the austral summer season (DJF); specifically, from November to February. The area receives most of its annual rainfall during this wet season. For instance, Levubu experiences a notable peak of 166.8 mm of rainfall in February and a decline to 10.7 mm of rainfall during the dry season (Figure 4.3a). During the winter months (June to August), the entire province receives little to no rainfall (Figures 4.3a and 4.3b).

This dry period is attributed to the subtropical high-pressure systems, which are displaced north due to the seasonal migration of the ITCZ (Musyoki *et al*., 2016; Rapolaki *et al*., 2019; Roffe *et al*., 2021). Lephalale recorded the lowest rainfall of 0.7 mm in July (Figure 4.1b). Despite varying locations, all stations exhibited similar rainfall patterns, with peaks in December and a decrease in June (Figure 4.3a and Figure

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4.3b).The timing of wet and dry periods provides a classification of rainfall seasonality in the Limpopo province (Roffe *et al*., 2019). The months of March and November exhibit the beginning and end of a rainy season, hence the reduced rainfall during these transition months.

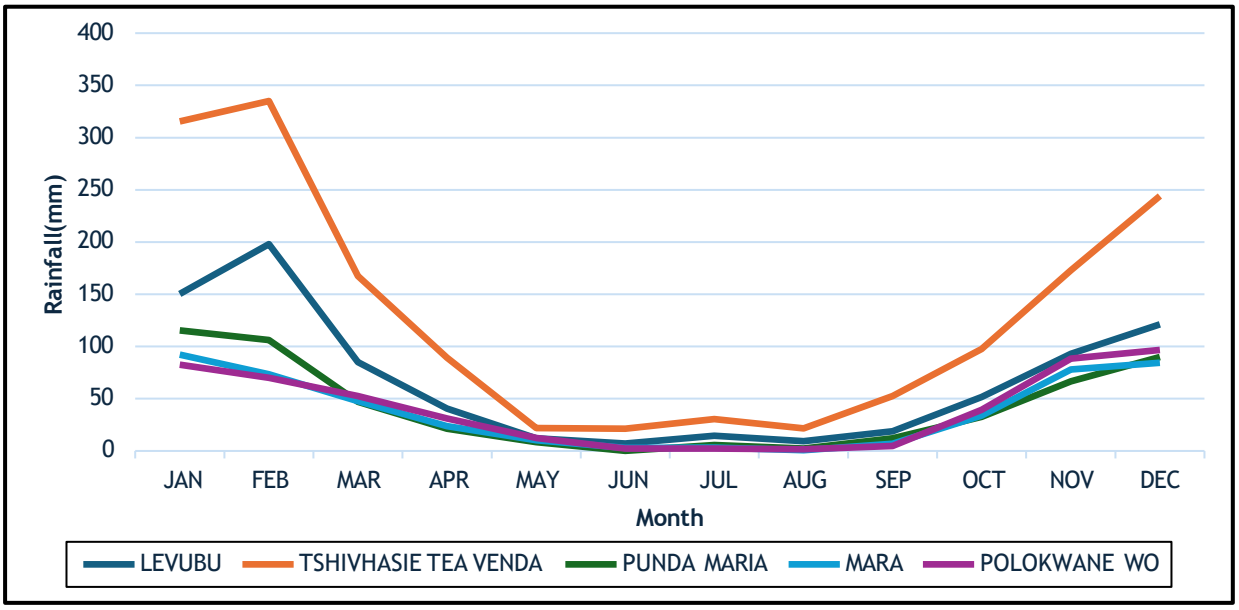


Figure 4.3a Annual rainfall cycle over Limpopo (1993-2023)

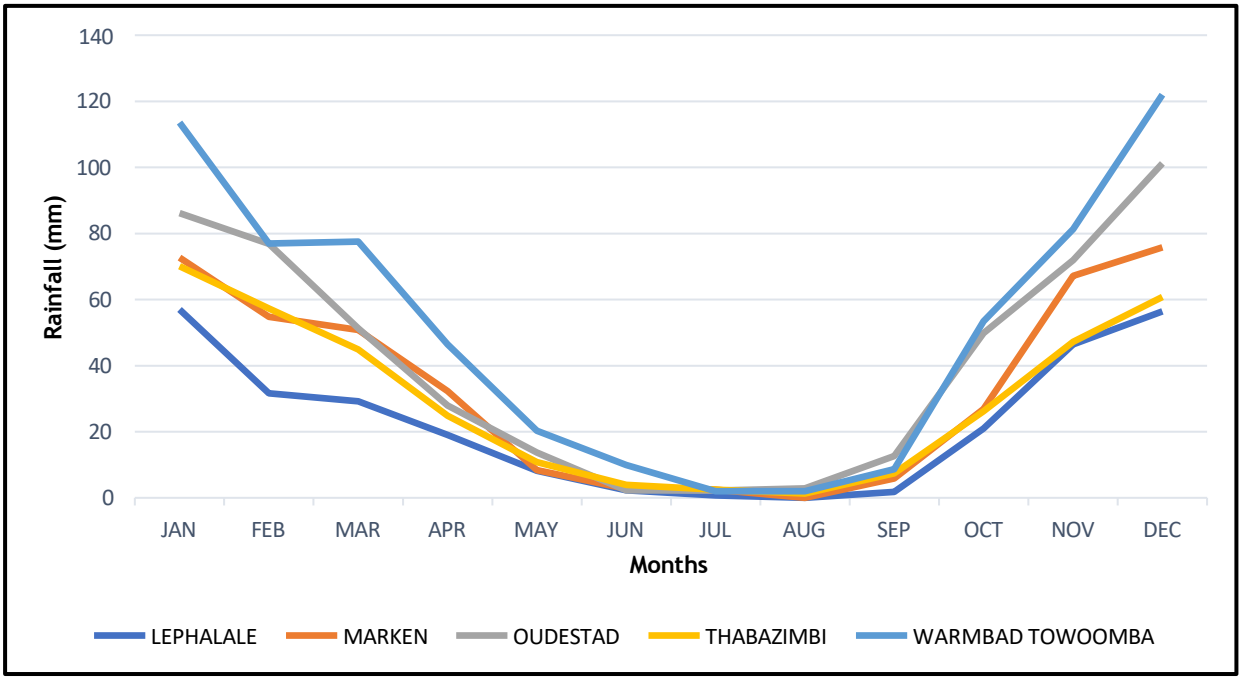


Figure 4.3b Annual rainfall cycle over Limpopo Province

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4.4 Interannual rainfall variability and rainfall trends in Limpopo Province

Limpopo Province receives relatively low rainfall, compared to other South African provinces, except for the Northern Cape Province (Shikwambana et al., 2021). The distribution of rainfall over multiple years in Limpopo Province is quite gradual, with a notable increase in the frequency of extreme weather events. Rainfall variation across Limpopo is significant, as the area experiences events of varying intensities, typically occurs during the austral summer months (December to February), with a peak recorded at 3680.6 mm in the year 2000 and 854.3 mm in 2021. The lowest amount of rainfall observed was 208.8 mm during the 2015/16 period (Figure 4.4a).

Rainfall patterns in Warmbad Towoomba, Mara, and Levubu exhibited an impactful peak in 2000, culminating in floods due to an active tropical cyclone season over the Southwest Indian Ocean (Figures 4.4a-4.4b). Similarly, Oudestad (Figure 4.4b) experienced a distinct peak in rainfall in 1996. In fact, extreme rainfall events, triggered by tropical cyclones, have recurrently affected southern Africa during late summer seasons, specifically in 1983/84, 1999/00, 1996/97, 2007/08, 2011/12, 2016/2017 and 2020/2021(Chikoore *et al*., 2021). The events underscore the importance of monitoring tropical cyclone activity and its impact on regional rainfall patterns.

Limpopo Province shows considerable yearly variation in rainfall, with significant fluctuations in precipitation patterns (Figure 4.4a-4.4b). During those years, the province experienced below-average rainfall, such as in 2015 when Oudestad received just 208.8 mm. Droughts have also occurred during some years, including 1982/83, 1991/92, 1994/95, and 2009/10. Other drought years include 1997/98, 2002/03, 2015/16, and 2018/19, as shown in the figures below. However, other years have experienced above-average rainfall, notably in 2000, due to the La Nina event. The year 2000 marked a peak in precipitation for the region, with notable rainfall totals recorded. Oudestad received 822.2 mm, while Warmbad Towoomba recorded 914.3 mm (Figure 4.4b). Levubu received the highest annual rainfall at 3680.6 mm, as shown in Figure 4.4a.

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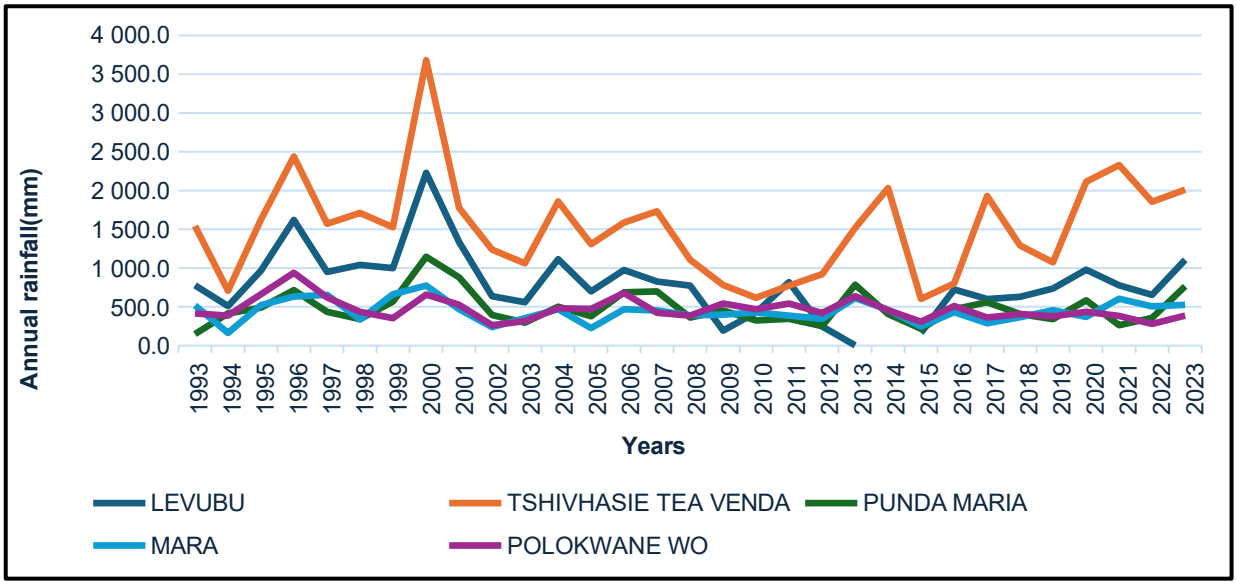


Figure 4.4a Inter-annual rainfall variability over Limpopo Province

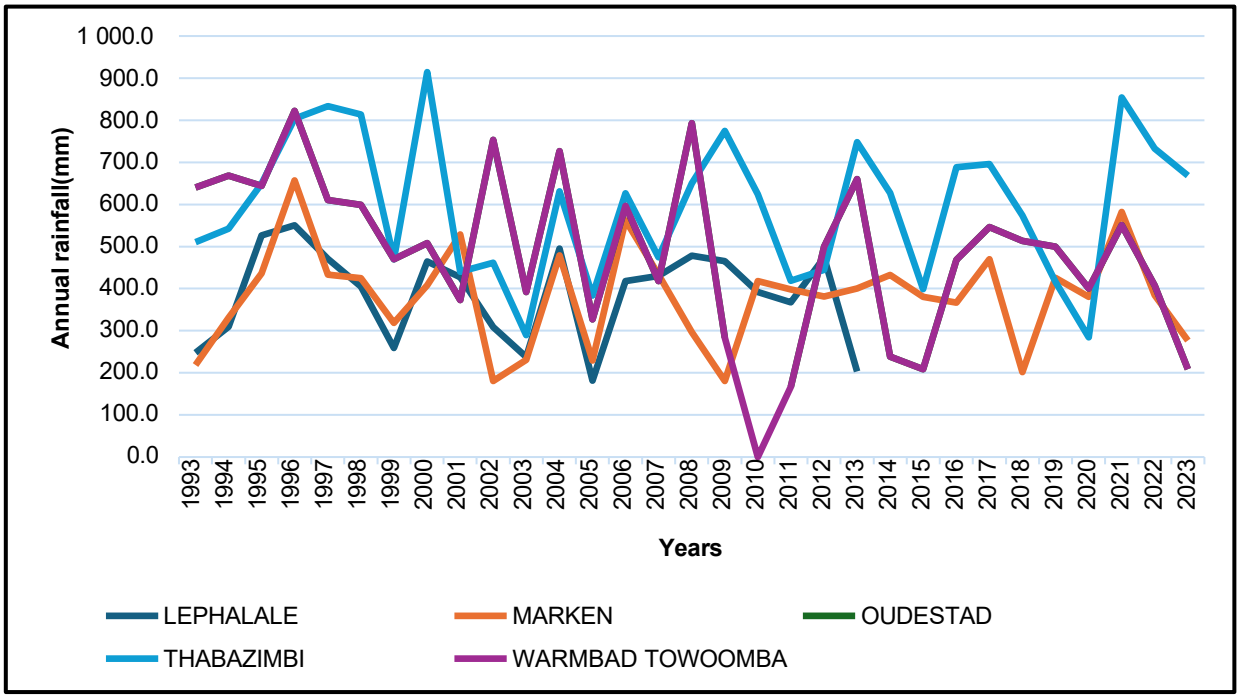


Figure 4.4b Inter-annual rainfall variability over Limpopo Province

4.5 Mean frequency of wet extremes over Limpopo Province

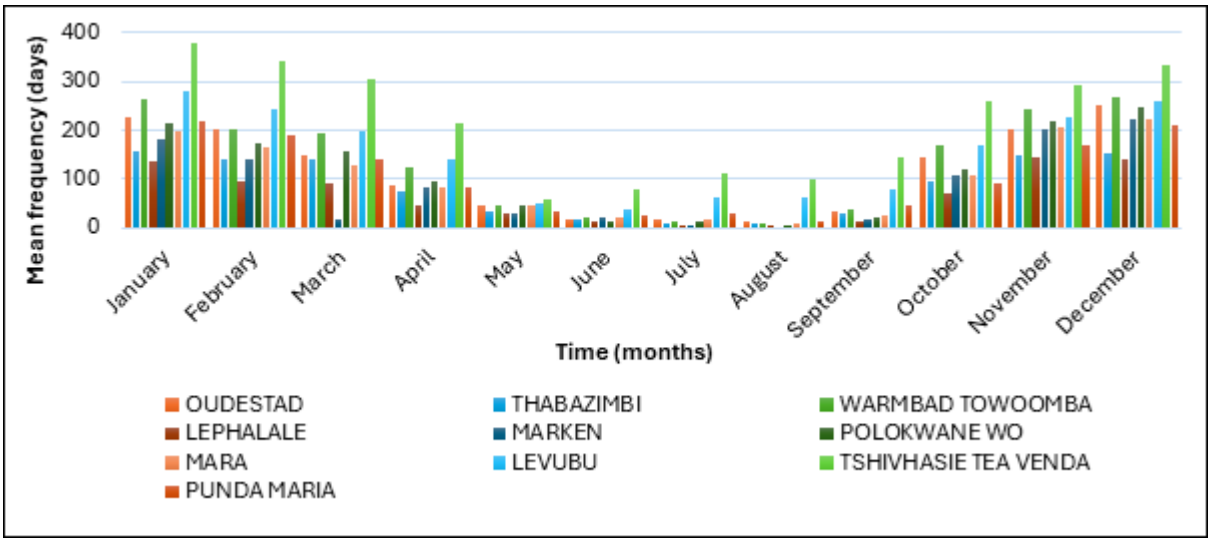
A definite seasonal pattern appears, with the maximum frequency of wet extremes happening throughout the summer months, particularly from November to March. Figure 4.5 depicts the monthly average frequency of wet extreme events in Limpopo Province from 1993 until 2023. Tshivhasie Tea Venda, Levubu, and Warmbad

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Toowoomba have notably higher wet frequency values, ranging from 250-377 days, most likely due to their proximity to moisture-laden air masses and orographic factors that increase rainfall intensity. Almost all stations experience low to moderate wet days ranging from 1 to 7 days throughout the winter season (June, July, and August).

Limpopo's vulnerability to wet extremes varies regionally. The province's northern portions, notably the Vhembe and Mopani districts, are more vulnerable to these extremes since they are close to tropical regions influenced by moisture from the Indian Ocean and periodic low-pressure systems. The frequency of extreme wet events in these places has also increased substantially (Figure 4.5), with serious floods occurring in some years, notably in river basins, such as Limpopo and its tributaries. In contrast, the western regions of Limpopo, which include parts of the Capricorn and Sekhukhune districts, have seen fewer frequent wet extremes, but these areas still endure seasonal rainfall changes that can result in localised flooding.

The increased frequency of wet extremes has serious consequences for Limpopo's agriculture, water resources, and infrastructure. Many of the province's livelihoods rely on farming. Therefore, extreme rain can cause substantial crop damage, particularly in rain-fed areas. Flooding disasters have also interrupted road networks, resulting in economic losses and limited access to markets and services. Furthermore, changes in the frequency of wet extremes test the region's water management systems, necessitating improved flood forecasting, infrastructure resilience, and agricultural adaptation techniques.



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Figure 4.5 Mean frequency of consecutive wet days from 1993-2023 extreme trends

4.6 Mean frequency of dry extremes trends over Limpopo Province

Figure 4.6 depicts the trend distribution of dry period frequency in the Limpopo Province from 1983 to 2023 during seasonal periods. The unequal distribution and changing frequency of dry spells over the extended summer periods are notable aspects of the area. Dry spells showed a northward intensification and migration and intensify patterns in the north of Vhembe and Capricon. (Botai *et al*., 2020) found that Limpopo province experiences frequent dry spells. However, there is a notable insignificant trend of dry spells in Limpopo.

This suggests that their frequency did not vary, or that the changes were minor and insignificant. However, these results are still considered important in the current study. This is because these tendencies may be significant over time. The maximum dry-spell occurrence with an average of 930 days is observed over the Mara station in the June- August (JJA) period. During the December-January (DJF) period (Figure 4.6), the province experienced decreasing trends.

The dry season, typically ranging from May to September, has considerably higher mean frequencies across all stations, with peak occurrences reported around August and September. This trend fits with the region's climatological pattern, where winter and early spring are marked by low rainfall, leading to long dry conditions. Notably, areas such as Mara, Marken, and Tshivhasie Tea Venda (Figure 4.6) have consistently higher dry frequency numbers than others, indicating regional diversity in drought sensitivity. Conversely, the wetter months, which run from November to March, have lower mean frequencies of severe dry occurrences.

The decrease in dry days coincides with the summer rainfall season, which is affected by the South African monsoon system. During these months, greater precipitation decreases the likelihood of severe dry spells, as demonstrated by a general decrease in mean frequency values across all stations (Figure 4.6). However, other locations, such as Thabazimbi and Punda Maria, continue to endure moderate levels of dryness, which could be attributed to specific meteorological conditions. The study found that dry spells occur most frequently in the north of Vhembe (Levubu, Mara and Tshivhasie tea Venda) and Capricorn district (Polokwane Wo).

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These findings correlate with Usman and Reason's (2004) observation that these regions fall inside the drought corridor, known for low rainfall and dry spells. Despite being close to large moisture sources in the Indian Ocean, this area is nonetheless prone to multi-year droughts (Thoithi *et al.*, 2021). This is indicated by the high frequency of dry spells. According to (Cook *et al.*, 2004), dry spells in South Africa are caused by a decrease in moisture from the tropical/subtropical Southwest Indian Ocean (SWIO).

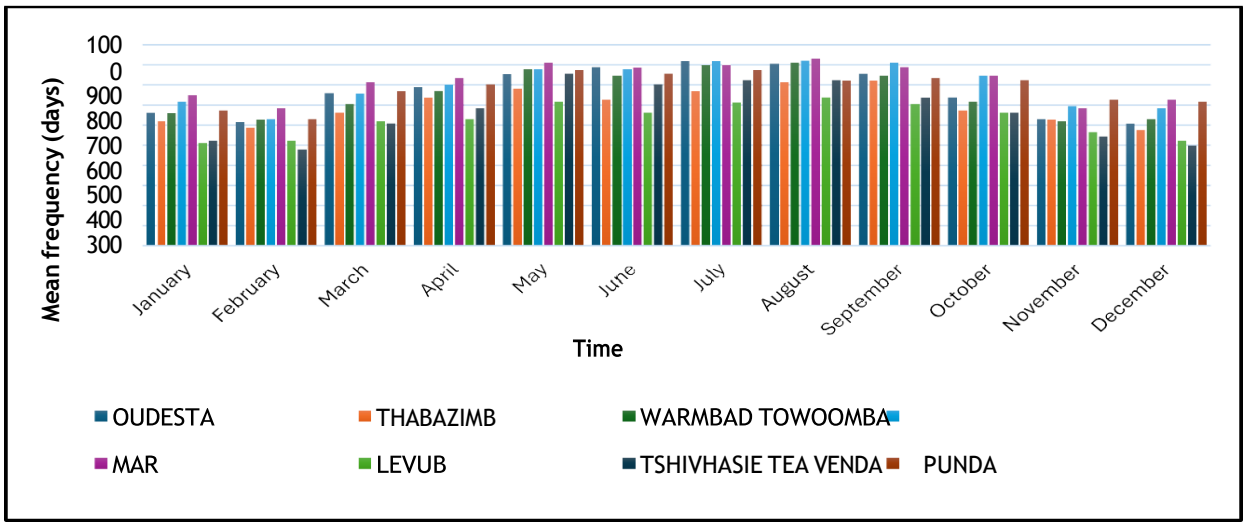


Figure 4.6 Trends in mean frequency of consecutive dry days from 1993-2023

4.7 Frequency and intensity of Extreme rainfall

4.7.1 Consecutive wet days (CWD)

The analysis of rainfall trends based on the CWD (Consecutive Wet Days) indices across the graphs revealed notable variations in rainfall frequency over time, influenced by global climatic phenomena and regional weather events. The CWD index, which measures the number of consecutive days with rainfall above 1 mm, indicates sustained wet periods and provides insights into changes in rainfall persistence. These trends are shaped by various climatic factors, including the influence of tropical cyclones, El Nino, and La Nina events, contributing to the observed variability in rainfall patterns. From 1983 to 2023, the CWD indices across the stations show fluctuations (Figure 4.7), with periods of increased or decreased wet days reflecting the impacts of specific climatic drivers.

Tropical cyclones have substantially increased the frequency of consecutive wet days

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(Zhang *et al*., 2018). These systems, characterised by their ability to transport substantial amounts of moisture, result in extended rainfall periods over affected regions. For example, Cyclone Eline in 2000 brought heavy and sustained rainfall across southern Africa, leading to a notable increase in CWD values in locations such as Levubu and Punda Maria (Figure 4.7a-b). CWD values exceeded 10–15 days during this period, marking one of the wettest periods.

Similarly, Cyclone Dineo in 2017 caused a surge in rainfall in areas such as Tshivhasie Tea Venda, with CWD indices reflecting consecutive rainfall events lasting over 10 days (Figure 4.7a-b). El Nino events, in contrast, are associated with a notable reduction in the frequency of consecutive wet days. El Nino is characterised by the warming of the central and eastern Pacific Ocean, which alters atmospheric circulation patterns and suppresses convection over southern Africa. This suppression of rainfall leads to shorter wet periods and lower CWD indices.

For instance, during the 1997-1998 El Niño, one of the strongest on record, CWD values dropped to below 15 days in Lephalale. Similarly, the 2015-2016 El Niño event, known for its severe drought conditions, caused a sharp decline in CWD indices across all regions, with many locations experiencing low values. These reductions highlight the impact of El Niño on disrupting rainfall continuity and contributing to prolonged dry spells. La Niña events, on the other hand, enhance rainfall persistence due to increased convection and moisture transport into the region.

Our analysis supports earlier studies on the link between La Niña episodes and higher rainfall in southern Africa. (Hoell *et al.*, 2021) and Hoell *et al*. (2021) found that La Niña occurrences intensify atmospheric convection over southern Africa, leading to longer wet spells. Our analysis found that the 1999-2000 La Niña event, which coincided with Cyclone Eline, resulted in a significant rise in Consecutive Wet Days (CWD) values, with some places having more than 15 consecutive wet days. Similarly, the 2010-2011 La Niña episode increased CWD indices in locations like Polokwane Wo and Marken, with values exceeding 12 days. More recently, the 2020-2021 La Niña event resulted in elevated CWD values in areas such as Tshivhasie Tea, Venda and Mara, where consecutive wet days

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exceeded 10 days, reflecting the enhanced moisture transport and sustained precipitation typical of La Niña conditions.

In analysing the overall trends, it becomes clear that the interplay between tropical cyclones and La Niña events synergistically increases the CWD indices. For example, during the 1999-2000 La Niña, the combination of enhanced convection and the impact of Cyclone Eline resulted in a significant extension of wet periods across multiple regions. Similarly, the 2020-2021 La Niña, though moderate, amplified rainfall persistence in areas prone to tropical cyclone influence. On the other hand, the contrasting effects of El Niño events are evident in the sharp reductions in CWD values during years such as 1997-1998 and 2015-2016, underscoring the disruption of rainfall continuity during these periods. Increased consecutive wet days can improve river flows and groundwater recharge, boosting freshwater availability for ecosystems (Seneviratne et al., 2021).

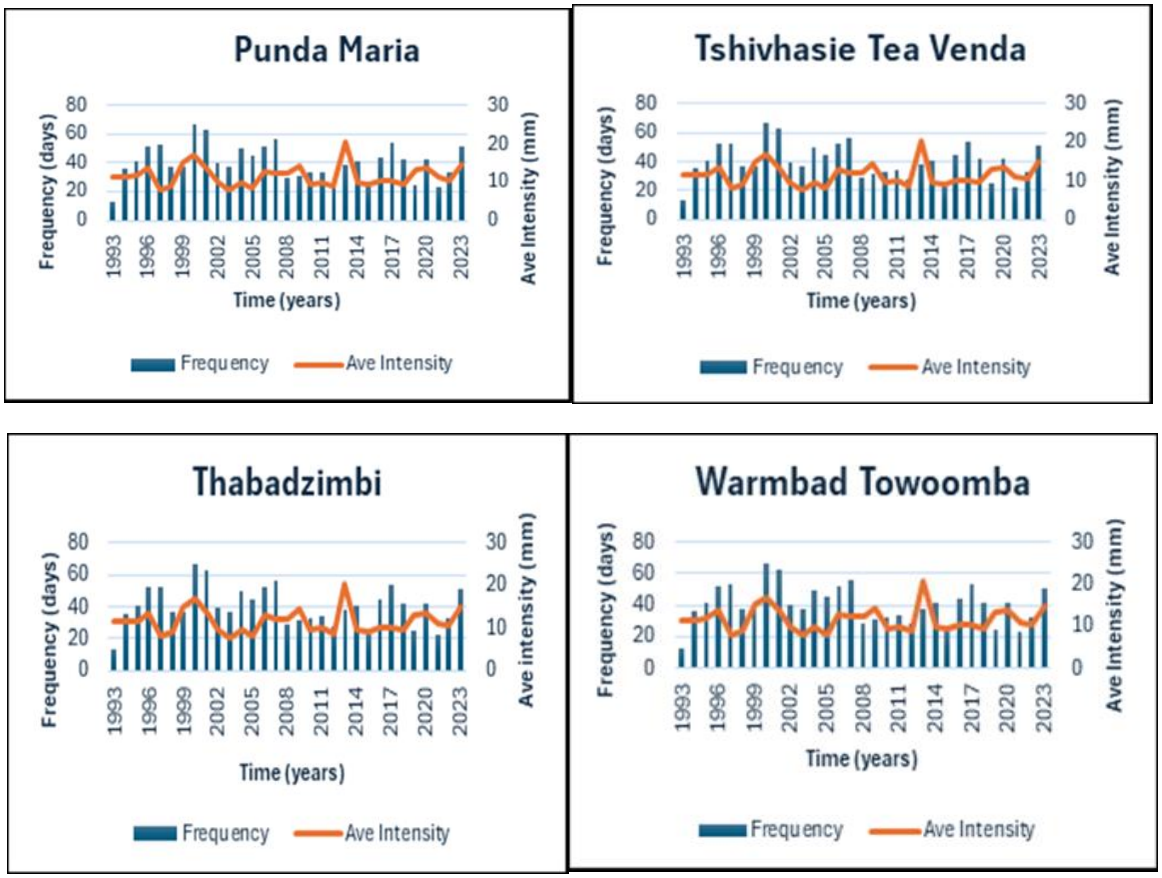


Figure 4. 7 a Frequency and intensity of Consecutive wet days over the Saws stations in Limpopo from 1993-2023.

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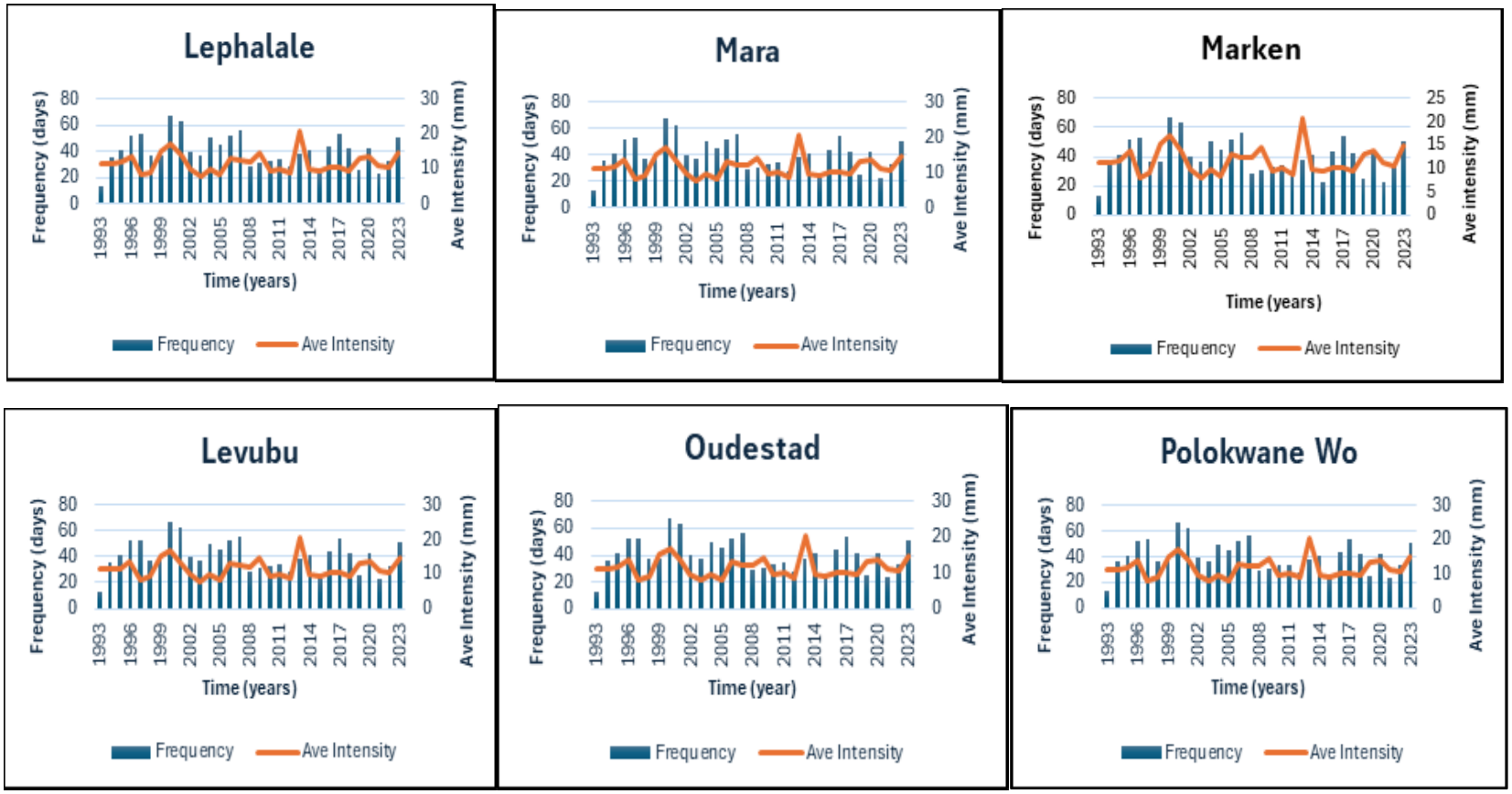


Figure 4.7 b Frequency and intensity of Consecutive wet days over the Saws stations in Limpopo from 1993-2023

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4.7.2 Number of very heavy precipitation days (r20mm index)

The r20mm index is crucial for tracking extreme precipitation events and climate trend shifts. An increase in days with rainfall exceeding 20mm often signals changes in climatic conditions, especially linked to climate change. Analysis of r20mm events in Limpopo shows significant inter-annual variability, reflecting fluctuating rainfall patterns (Figure 4.8). The r20mm indices reveal notable variability in heavy rainfall events over the years. Certain years stand out due to substantial increases or decreases in heavy rainfall driven by major climatic phenomena and extreme weather events. For example, during tropical cyclones such as Eline in 2000 and Dineo in 2017, the r20mm index demonstrates pronounced spikes. These spikes are attributed to the substantial moisture these systems bring, which results in prolonged and intense rainfall episodes. In 2000, Cyclone Eline impacted southern Africa, causing heavy rainfall in locations such as Levubu and Punda Maria, where the r20mm index reached values exceeding 10–15 days. These findings are consistent with Malherbe *et al*. (2013) and Reason and Keibel (2004), who noted that tropical cyclones can bring significant moisture to the region, resulting in prolonged and intense rainfall events.

Similarly, Cyclone Dineo in 2017 contributed to heavy rainfall events in regions like Tshivhasie Tea Venda, with the r20mm index showing values exceeding 12 days. Conversely, during El Nino years, the r20mm index reveals a notable reduction in the frequency of heavy rainfall events. El Nino conditions, characterised by warming in the central and eastern Pacific Ocean, disrupt regional rainfall patterns by suppressing convection and weakening monsoon activity over southern Africa. For instance, in 1997-1998, one of the strongest El Nino events on record, the r20mm index values dropped to below 5 days in many locations, such as Thabazimbi and Warmbad Toowoomba. Similarly, during the 2015-2016 El Nino event, drought conditions prevailed, with the r20mm index remaining below 4 days across most regions. Strong El Nino phases typically lead to drier conditions, reducing heavy rainfall days in the region (Mastrorillo *et al*., 2016).

In contrast, La Nina events, which involve cooling in the central and eastern Pacific Ocean, enhance rainfall over southern Africa. The r20mm indices during strong La Nina

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years, such as 1999-2000 and 2010-2011, demonstrate marked increases in the frequency of heavy rainfall events. The 1999-2000 La Nina, coupled with the impact of Cyclone Eline, led to r20mm values exceeding 10 days in regions like Mara and Levubu. Similarly, the 2010-2011 La Nina event contributed to an increase in heavy rainfall, with values reaching 8–12 days in areas such as Polokwane Wo and Marken (Figure 4.8).

These increases were driven by the enhanced convection and moisture transport associated with La Nina conditions, which strengthened the monsoon systems over southern Africa. In some regions, the interplay between tropical cyclones and La Nina events further amplified the r20mm indices. For example, during the 2020-2021 La Nina, areas such as Tshivhasie Tea Venda and Punda Maria experienced r20mm values exceeding 10 days. This increase in heavy rainfall frequency was due to the combined effect of La Nina-driven moisture transport and localised weather systems that intensified rainfall.

Overall, the r20mm indices highlight the sensitivity of heavy rainfall events to climatic oscillations and extreme weather systems. Years marked by El Nino, such as 1997-1998 and 2015-2016, show significant reductions in the frequency of heavy rainfall, with r20mm values dropping below 5 days in most regions. In contrast, La Nia years like 1999-2000 and 2010-2011, as well as years influenced by tropical cyclones such as 2000 and 2017, show substantial increases in heavy rainfall, with r20mm values reaching 10–15 days (Figure 4.8) in several locations. These patterns emphasize the critical role of large-scale climatic drivers in modulating the intensity and frequency of extreme rainfall events in southern Africa.

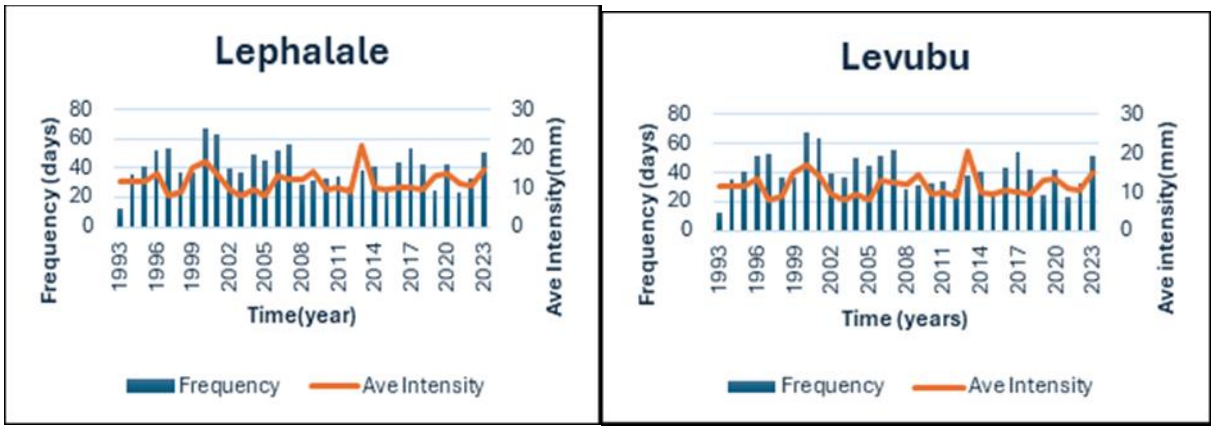


Figure 4. 8 a Number of very heavy precipitation days

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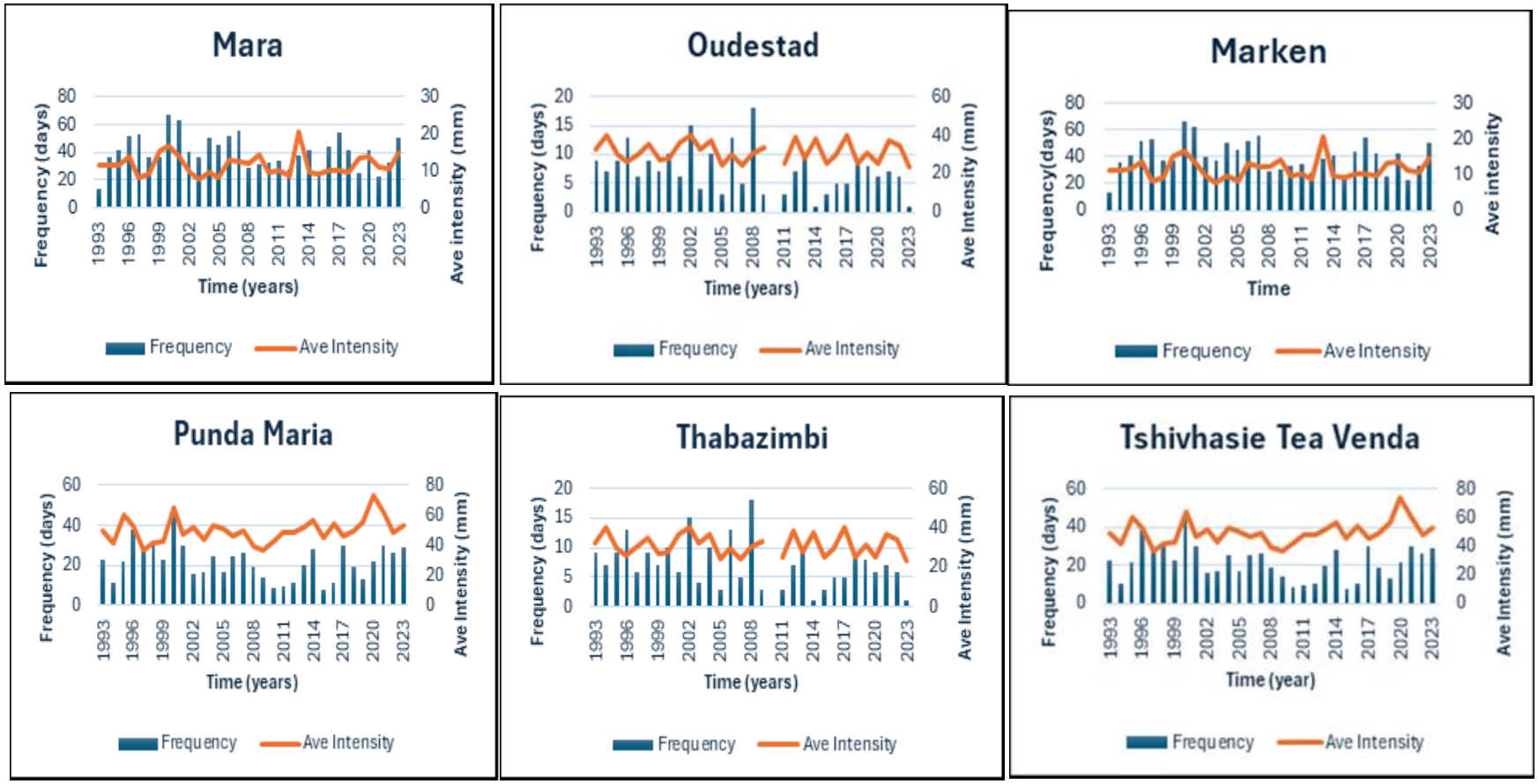


Figure 4.8 b Number of very heavy precipitation days

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4.7.3 Consecutive dry days (CDD)

The trends in rainfall recorded using severe event indices CDD (Consecutive Dry Days) provide a clear picture of dry period variability across time. The Consecutive dry days index, which counts the longest period of consecutive days with less than 1 millimeter of rainfall, is an important predictor of drought potential and rainfall distribution patterns. The consecutive dry days indices at all stations indicate short-term and long-term changes influenced by tropical cyclones, La Niña and El Niño occurrences. From 1983 to 2023, El Niño occurrences had a significant impact on extending dry spells in southern Africa, as evidenced by increased consecutive dry days indices.

This reduction in rainfall contributes to an extension of dry times. During the 1997- 1998 El Niño, which was one of the greatest on record, most stations had high consecutive dry day indices. Figure 4.9 showed that stations such as Thabazimbi and Warmbad Toowoomba experienced dry spells of more than 100 consecutive days. Similarly, the 2015-2016 El Nino episode generated substantial drought conditions, with consecutive dry days exceeding 120 days in stations like Lephalale and Marken (Figure 4.9). In contrast, La Niña causes more rainfall in southern Africa, breaking dry spells and decreasing consecutive dry days.

During the 1999-2000 La Niña, stations such as Punda Maria and Levubu witnessed shorter dry spells, with consecutive dry days indices falling below 60 days. This reduction in dry periods corresponded with the impact of Cyclone Eline, which produced strong and consistent rainfall, notably reducing the duration of dry spells. Similarly, in the years 2010-2011 La Nina event led to a decrease in consecutive dry days, with stations like Mara and Tshivhasie Tea Venda experiencing dry spells of less 70 days (Figure 4.9a-b). The moderate La Niña event in 2020-2021 led to shorter dry periods in locations such as Polokwane Wo, and Oudestad. Consecutive dry days values remained much lower than long-term averages.

Tropical cyclones, while most associated with greater rainfall, also play an important role in interrupting dry spells and altering CDD indices. Cyclones produce intense and widespread rainfall, breaking long dry spells and resetting CDD values to lower levels. For example, Cyclone Eline in 2000 enhanced rainfall frequency and intensity while greatly reducing dry spells in affected areas. During this time, CDD values fell dramatically in

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areas like Levubu and Punda Maria, with dry spells lasting less than 50 days. In 2017, Cyclone Dineo disturbed dry periods in places such as Tshivhasie Tea Venda, leading to a decrease in CDD indices. The CDD indices emphasise the sensitivity of southern Africa to climate variability, with La Niña events influencing the region's dry and wet cycles.

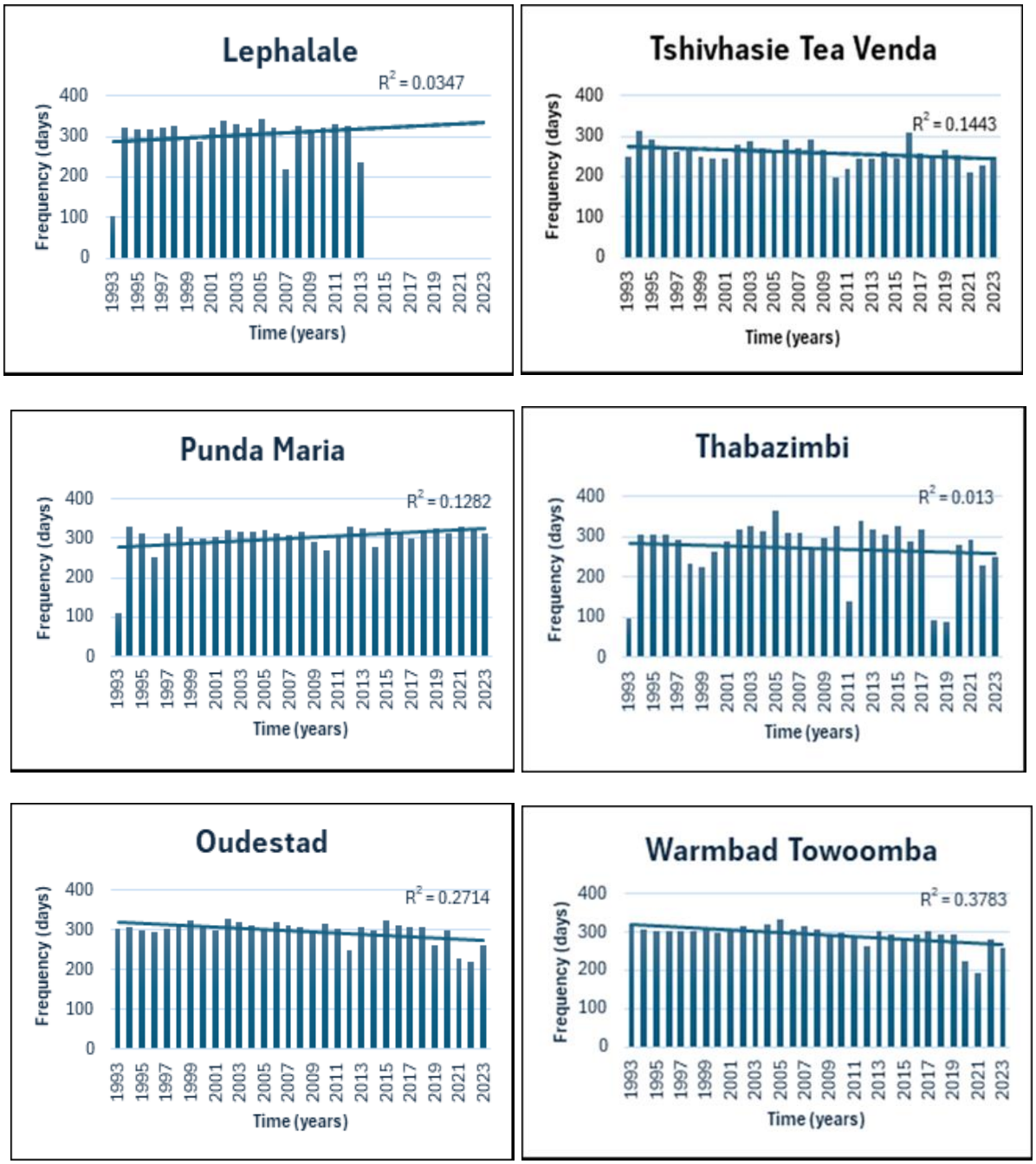


Figure 4. 9 a Frequency of occurrence of Consecutive Dry Days over Limpopo province.

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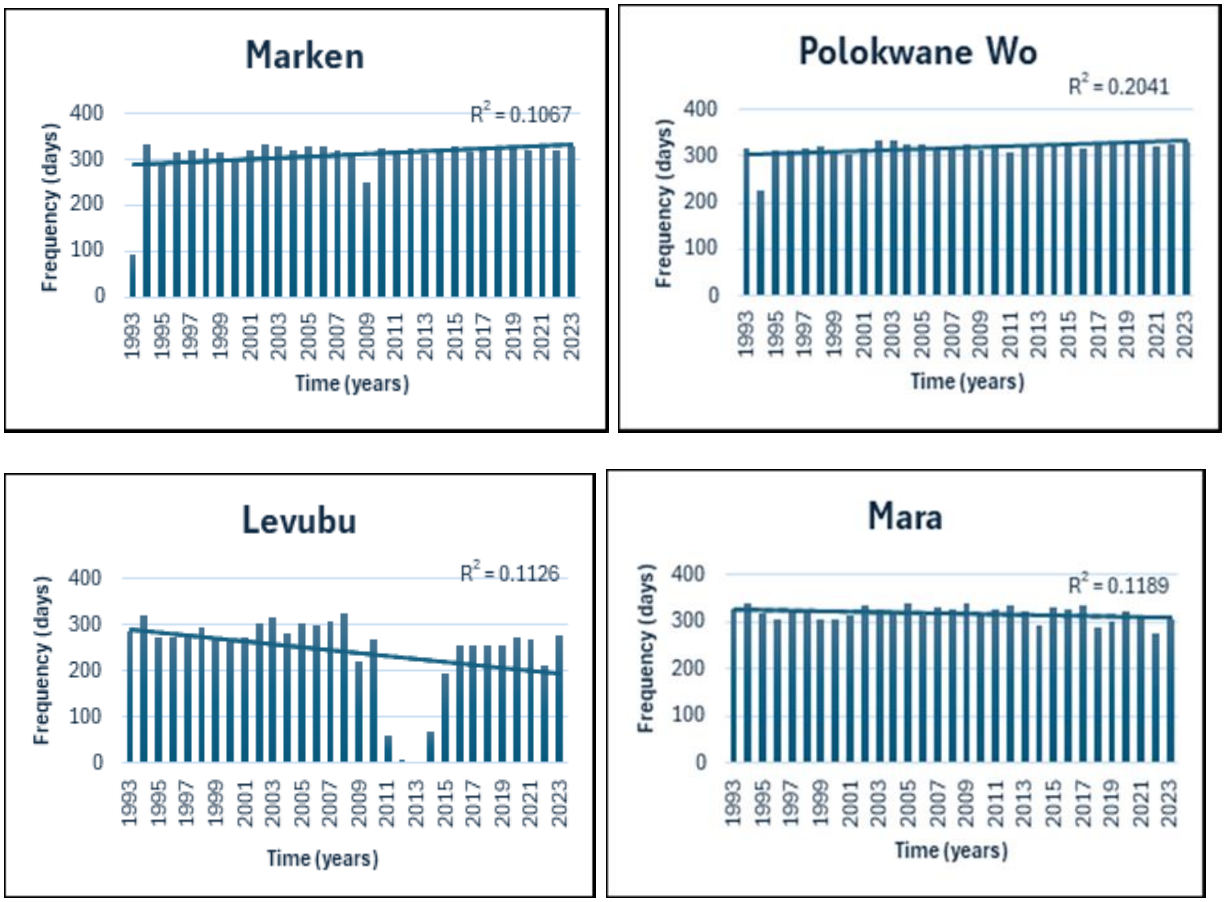


Figure 4.9 b Frequency of occurrence of Consecutive Dry Days over Limpopo province.

4.8 Spatial distribution of extreme rainfall events in Limpopo Province

4.8.1 Number of very heavy precipitation days (r20mm index)

Limpopo Province's diverse terrain and climate zones influence the spatial distribution of extreme rainfall events. According to previous studies, the eastern portions of Limpopo, particularly the Vhembe District, have a greater incidence of heavy rainfall events due to their proximity to the Indian Ocean and subtropical climate (Tyson & Preston-Whyte, 2000; Kruger, 2006). The increasing humidity and moisture availability from the Indian Ocean increase the frequency and intensity of rainfall events in these areas, especially during the summer months. This is consistent with our data, which reveal that the eastern parts of Limpopo, particularly Levubu, Mara, Punda Maria, and Tshivhasie Tea Venda, experience a higher frequency of r20mm extreme rainfall events (Figure 4.10).

Furthermore, the orographic effects of the Soutpansberg Mountains in the north and

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the escarpment in the east can increase rainfall, resulting in more frequent r20mm events in these areas. The middle and western sections of Limpopo, including parts of the Capricorn (Polokwane Wo) and Sekhukhune districts (Oudestad) as shown in figure 4.10, have fewer r20mm extreme rainfall events since they are in the province's more arid and semi-arid zones. The climate in these locations is characterised by decreased moisture availability and less heavy rainfall, with more erratic and seasonal precipitation patterns. However, during the summer months, particularly when impacted by La Nina conditions or tropical disturbances, the frequency of extreme rainfall events can increase in these regions, but they are still less frequent than in the eastern districts.

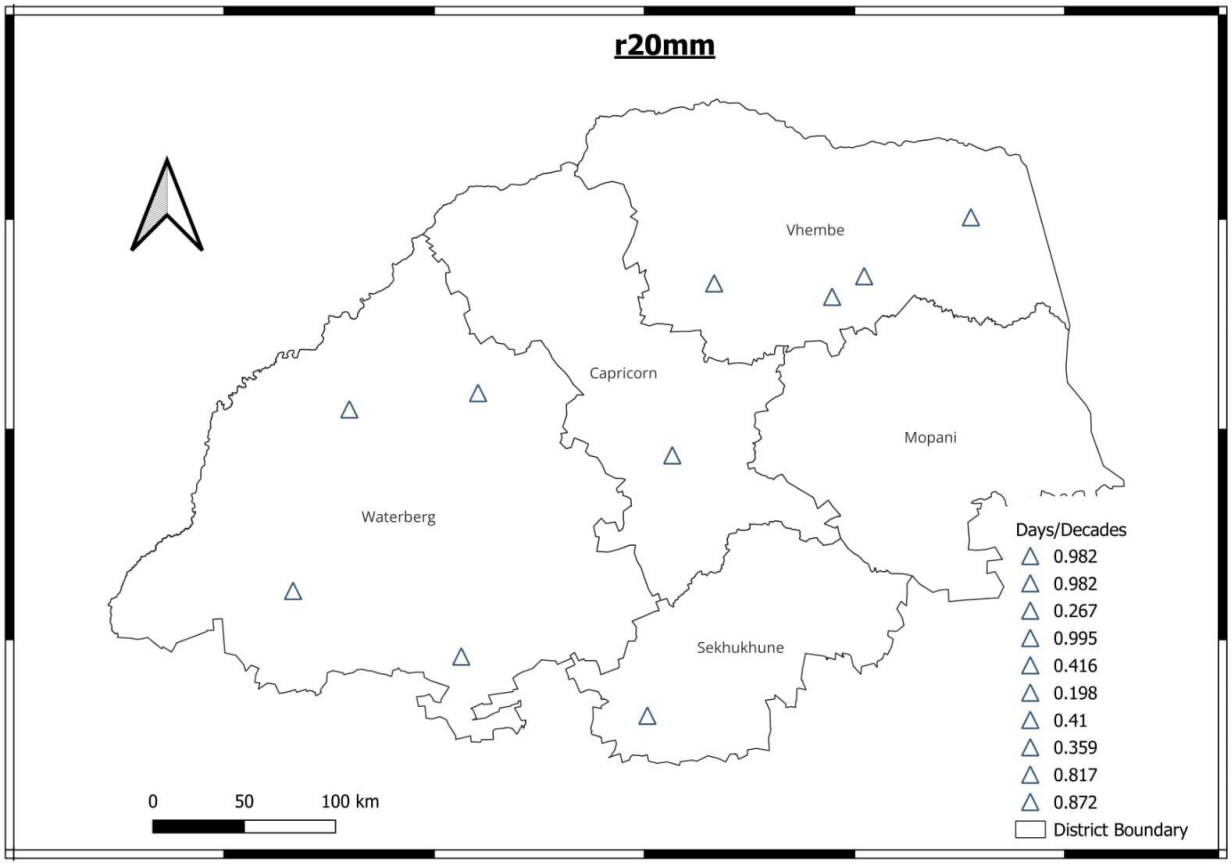


Figure 4.10 Trends in r20mm, precipitation ≥ 20 mm for the period 1993–2023. Statistical significance at the 5% level is represented by a shaded symbol.

4.8.2 The annual precipitation from daily precipitation (r95th)

The regional distribution of the r95p percentile index in Limpopo Province (Figure 4.11)

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reveals variations in extreme rainfall patterns among regions. The northern and northwestern (Lephalale, Levubu and Tshivhasie Tea Venda) regions of the province display a rising tendency in extreme rainfall, implying that these areas see increasingly frequent heavy rainfall events. Conversely, Mara, Marken, Oudestad, Thabazimbi and Warmbad Towoomba stations show a combination of moderate upward trends and a slight downward trend in Polokwane Wo, showing a specific difference and spatial distribution in extreme precipitation patterns. The result is consistent with earlier research, which has shown that extreme rainfall events are growing more often and intense in specific parts of South Africa a according to Sikhwari *et al*. (2022).

Although most years will have a total of zero, r95p can indicate more extreme daily rainfall circumstances, particularly beyond the initial time frame, and if they occurred sooner or later in the time under analysis. Although not statistically significant, nearly all stations in the region have experienced a rise in intense precipitation, as demonstrated by r95p (Fig 4.11).

This distribution suggests that specific areas of Limpopo Province are becoming increasingly vulnerable to heavy rainfall events, which may have implications for flood risk, soil erosion, and water management. With greater growing trends, the northern regions may experience more frequent severe storms and flooding, damaging agriculture, infrastructure, and livelihoods. Meanwhile, locations with less pronounced trends may not see dramatic changes, but they may still be affected by overall shifts in rainfall variability. The rise in yearly rainfall in the northern, northwestern, south and central sections of the country can be attributed to an increase in intense rainfall events.

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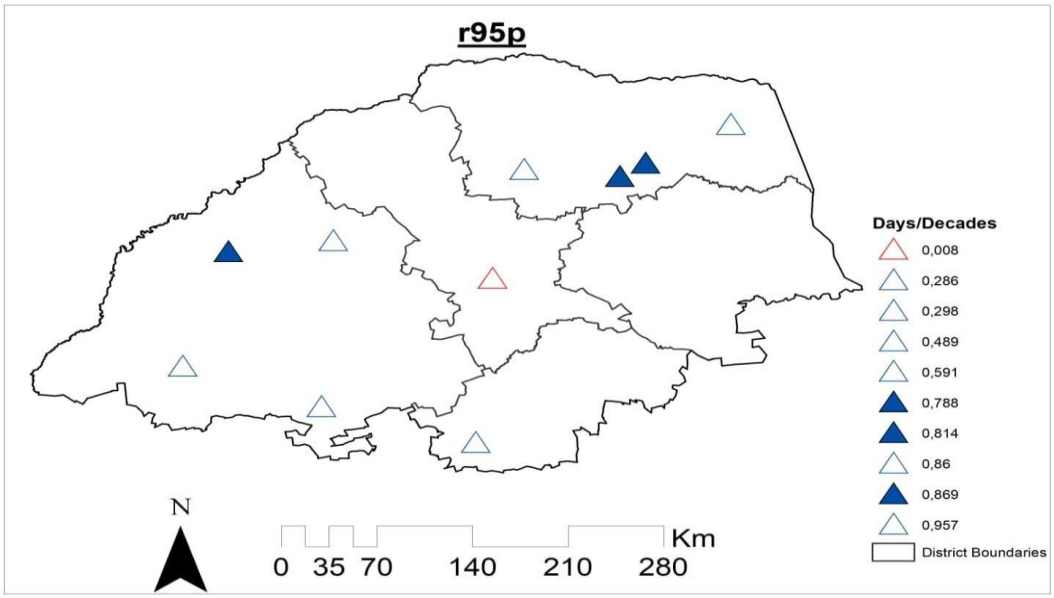


Figure 4.11 Trends in r95p, precipitation > 95th percentile, for the period 1993-2023. Statistical significance at the 5% level is represented by shaded symbol

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4.8.3 Consecutive Wet Days (CWD)

The map (Figure 4.12) depicts the regional distribution of CWD (Consecutive Wet Days) in Limpopo Province, indicating trends in the frequency of extended wet periods throughout the province. The varied sizes triangles represent changes in the magnitude of change in consecutive wet days patterns, as measured in days per decade. Figure 5.3 demonstrates a drop in CWD in most of the stations reporting statistically significant declines of more than 0.2 days per decade except Oudestad and Tshivhasie Tea Venda. The Continuous rainy Days (CWD) index shows the highest number of continuous rainy days per year.

The south-Western Cape experiences the longest yearly wet spell in winter, while the rest of the country often experiences it in summer. Several rain-bearing systems, including the semi-stationary subtropical easterly wave, tropical depressions, Angolan Low-pressure system, Northwest cloud bands, and Cut Off Lows, contribute to heavy rainfall during austral summer months. Overall, the spatial pattern indicates a general growing tendency of consecutive wet days across the province, with some places experiencing greater increases than others, although not statistically significant. The observed increase in consecutive wet days across the province is consistent with prior research on climate variability in Southern Africa. For example, Engelbrecht *et al.* (2019) discovered that climate change is anticipated to cause changes in rainfall patterns, including increases in extreme rainfall events.

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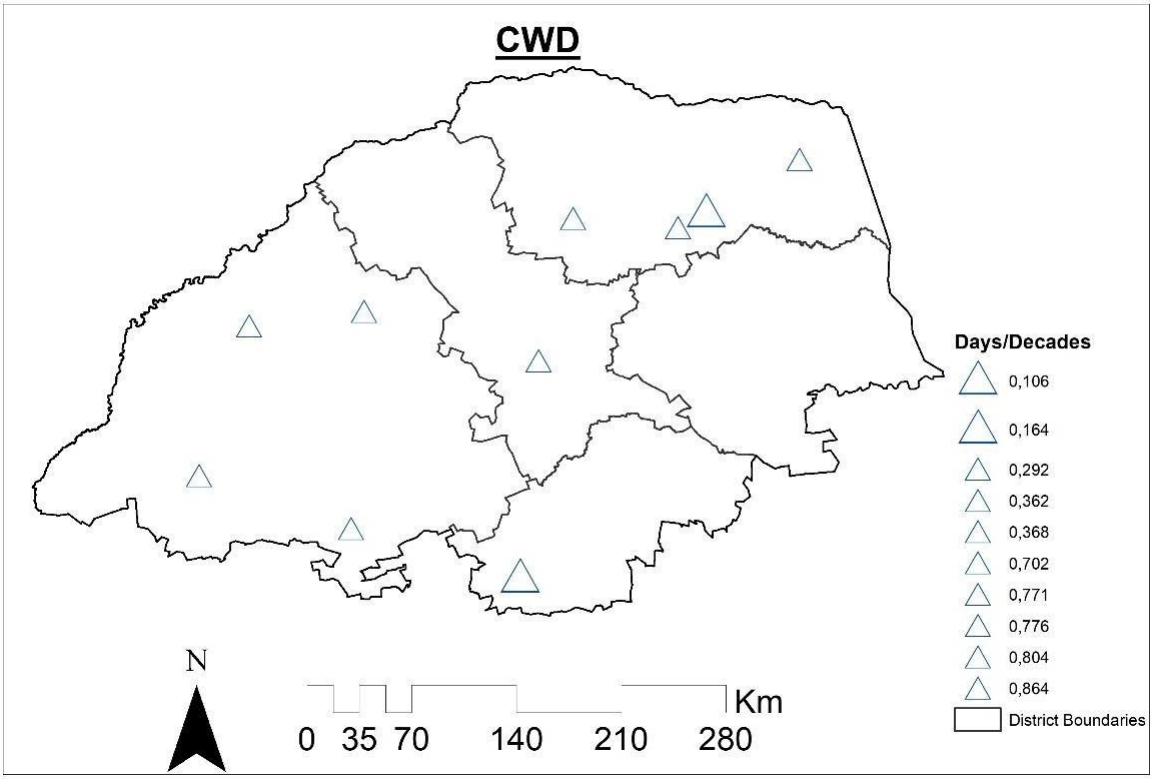


Figure 4.12 Trends in CWD for the period 1993-2023. Statistical significance at the 5% level is represented by a shaded symbol

4.8.4 Consecutive Dry Days (CDD)

The spatial distribution of rainfall trends in Limpopo, as shown in Figure 4.13 demonstrates significant regional variations in consecutive dry days (CDD), which serves as a signal of shifting rainfall patterns. Areas with high consecutive dry days values, mainly in the region's north (Punda Maria) and southwest (Lephalale, Thabazimbi and Warmbad Towoomba), indicate a rise in consecutive dry periods, implying a decrease in rainfall frequency and the possibility of drought aggravation. The result is consistent with past research, which showed that southern Africa is experiencing changes in rainfall patterns, including increases in dry spells (Kruger, 2006). In contrast, lower consecutive dry days values are recorded in the central and eastern regions, where shorter dry spells suggest rather steady rainfall patterns. Consecutive dry days variations emphasize shifts in precipitation distribution, which could be driven by larger climatic changes, topographical features, or land use changes that affect moisture retention and rainfall dynamics. The presence of

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statistically significant stations Lephalale, Punda Maria, and Warmbad Towoomba, represented by shaded triangles, supports the observed rainfall trends. The shading indicates a 5% statistical significance threshold, implying that the observed changes in rainfall patterns are not attributable to random variability but rather reflect a systematic climatic trend. The concentration of important areas in regions with higher consecutive dry days (CDD) values indicates that drying trends are more dramatic and constant throughout time. This means that these places are seeing a statistically verifiable drop in rainfall, confirming concerns about rising aridity and the possibility of more regular drought occurrences.

The spatial distribution of these statistically significant locations follows a pattern in which the most significant drying trends are concentrated in Limpopo's northwest and southwest, with less significant changes reported in the middle and eastern regions. This unequal distribution implies that some locations are more prone to climatic changes, perhaps due to height differences, prevailing wind patterns, or environmental circumstances. The inclusion of both significant and non-significant locations suggests that rainfall patterns are not uniform across the province, emphasizing the importance of specialised climate adaptation efforts tailored to specific regions experiencing significant change.

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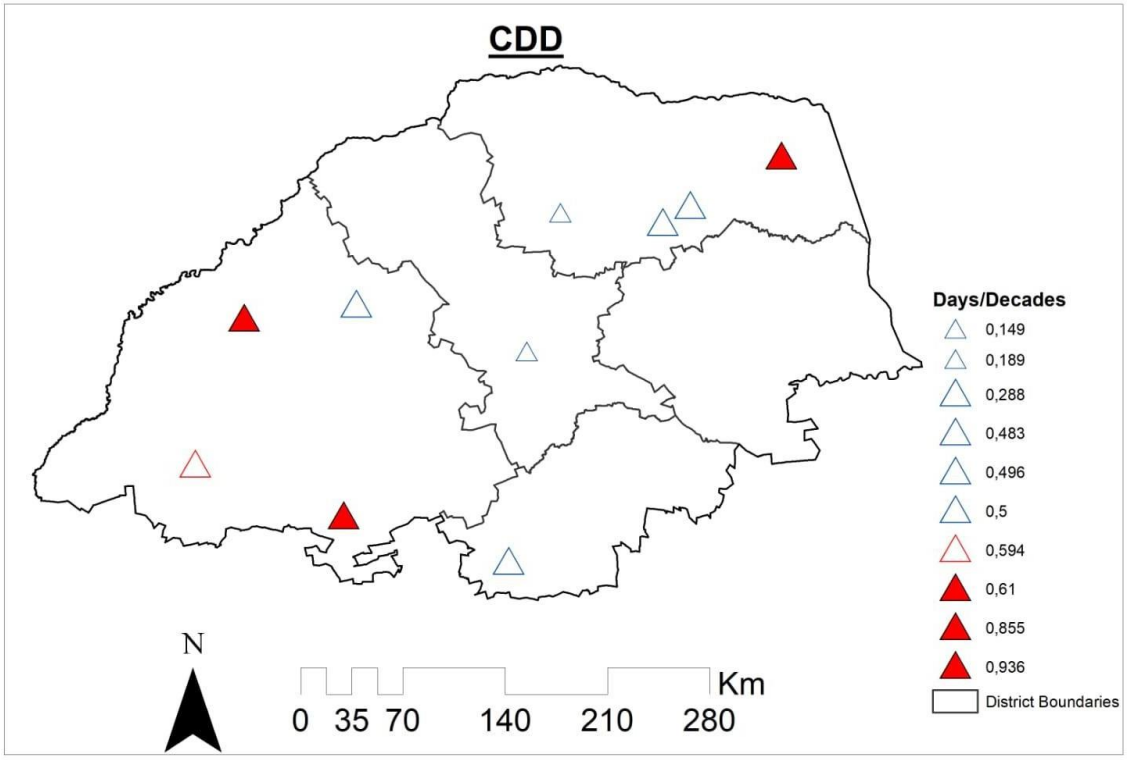


Figure 4.13 Trends in CDD for the period 1993– 2022. Statistical significance at the 5% level is represented by a shaded symbol.

4.9 Trends and correlations

4.9.1 Correlation between mean and extreme precipitation indices

This analysis also investigated the relationship between average annual rainfall and extreme precipitation indicators in Lephalale. The findings indicated that years with greater mean annual rainfall have more days with at least 20mm of rainfall (r20mm), shorter dry spells (CDD), and more extreme rainfall events (r95P). The correlation coefficients (r-values) revealed high positive correlations between r20mm and r95P, a negative connection for CDD, and a weak positive association for CWD. The statistical significance of these correlations was confirmed by the student's t-test, which revealed that r20mm, CDD, and r95P all exhibit significant associations with mean rainfall whereas the correlation between CWD and mean monthly rainfall was not statistically significant, implying that it could be attributable to chance. These indices showed a

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significant increase in trend for r20mm and r95P, a decrease trend for CDD, and a weaker, less obvious trend for CWD.

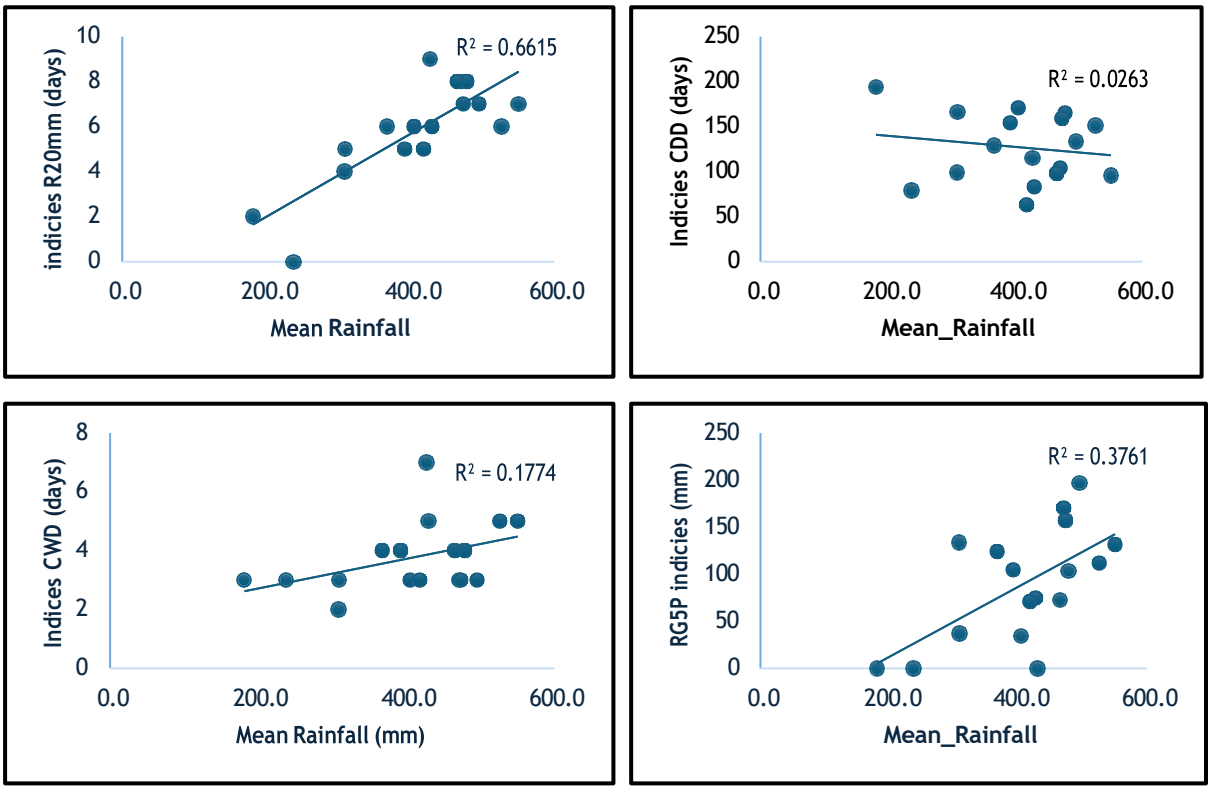


Figure 4.14 Correlation between mean rainfall and extreme indices in Lephalale

The Levubu results found strong positive relationships between mean annual rainfall and r20mm, CWD, and r95P, implying that years with greater mean annual rainfall have more days with at least 20mm of rainfall, longer consecutive wet periods, and more extreme rainfall (Figure 4.15). In contrast, CDD revealed a minor negative correlation, indicating a slight decrease in consecutive dry days as mean rainfall increased. The statistical significance of these correlations was confirmed by the student's t-test, which revealed that r20mm, CWD, and r95P all exhibit significant associations with mean rainfall. In contrast, the correlation between CDD and mean rainfall was not statistically significant. These indices also showed significant increasing trends for r20mm and r95P, a moderate upward trend for CWD, and a minor decreasing trend for CDD, although weak.

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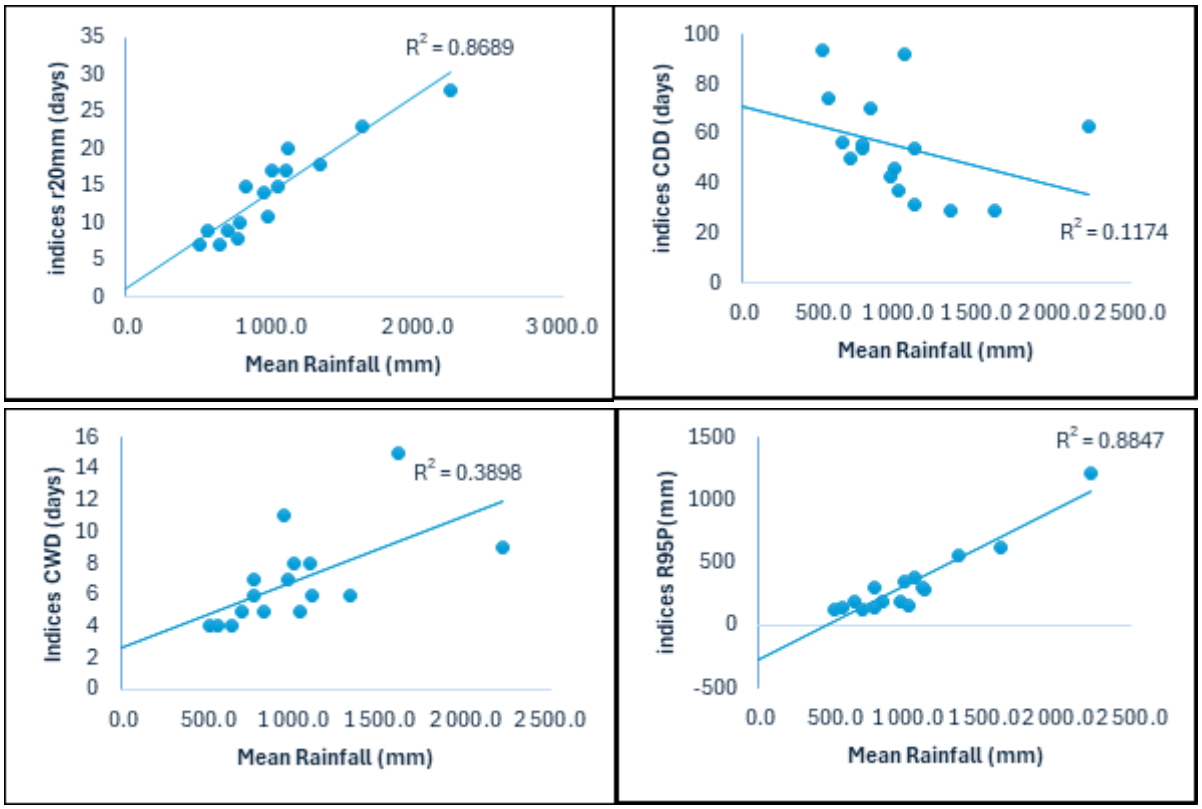


Figure 4.15 Correlation between mean rainfall and extreme indices in Levubu

The results in the Figure 4.16 showed a strong upward trend in r20mm and r95p, showing that as mean rainfall increases, so do extreme rainfall occurrences. Furthermore, CWD showed a positive trend, indicating that wet periods increase with greater rainfall whereas, CDD exhibited a modest decrease trend, which was weak and not statistically significant. Correlations between average yearly rainfall and extreme precipitation indices were also investigated. The findings also revealed significant positive correlations between r20mm, CWD, and r95p, indicating that years with greater mean annual rainfall have more days with at least 20mm of rainfall, longer consecutive wet periods, and more severe rainfall events. These associations were discovered to be statistically significant, showing strong and relevant links between the mean rainfall and these extreme precipitation indices.

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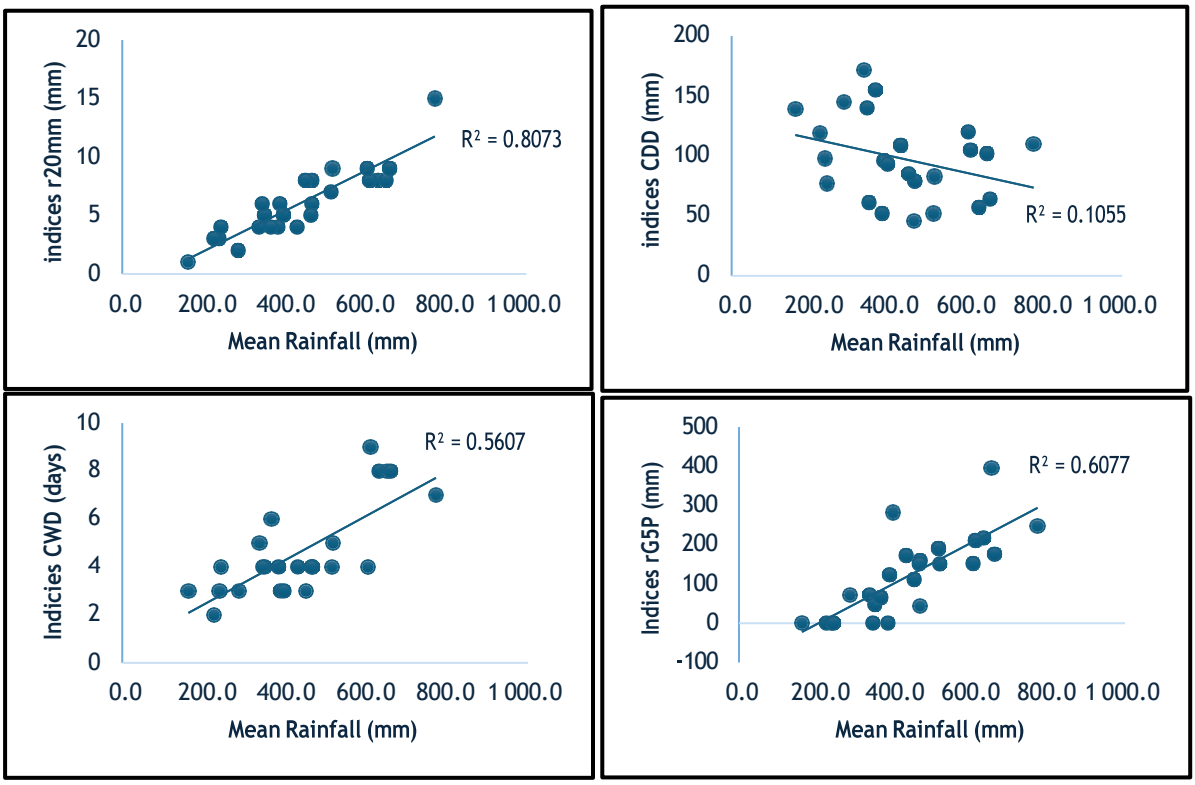


Figure 4.16 Correlation between mean rainfall and extreme precipitation indices in Mara

The scatter plots below (Figure 4.17) show the relationship between the yearly mean rainfall and extreme indices in Marken. The data showed strong positive trends in r20mm and r95p, showing that extreme rainfall days increase as average rainfall increases. In contrast, consecutive wet days increased slightly but not significantly while consecutive dry days showed a uniform trend, showing no obvious correlation with mean rainfall. Correlations between average yearly rainfall and extreme precipitation indices were also analysed.

The results revealed a significant positive correlation for r20mm, showing that years with a higher mean annual rainfall have more days with rainfall more than 20mm. Furthermore, r95p exhibited a moderate positive correlation, showing that extreme rainfall occurrences are likely to increase with the mean annual rainfall. Consecutive dry days exhibited an extremely weak link, while consecutive wet days showed a weak positive correlation, indicating that increased annual rainfall has an insignificant effect on the length of consecutive dry days.

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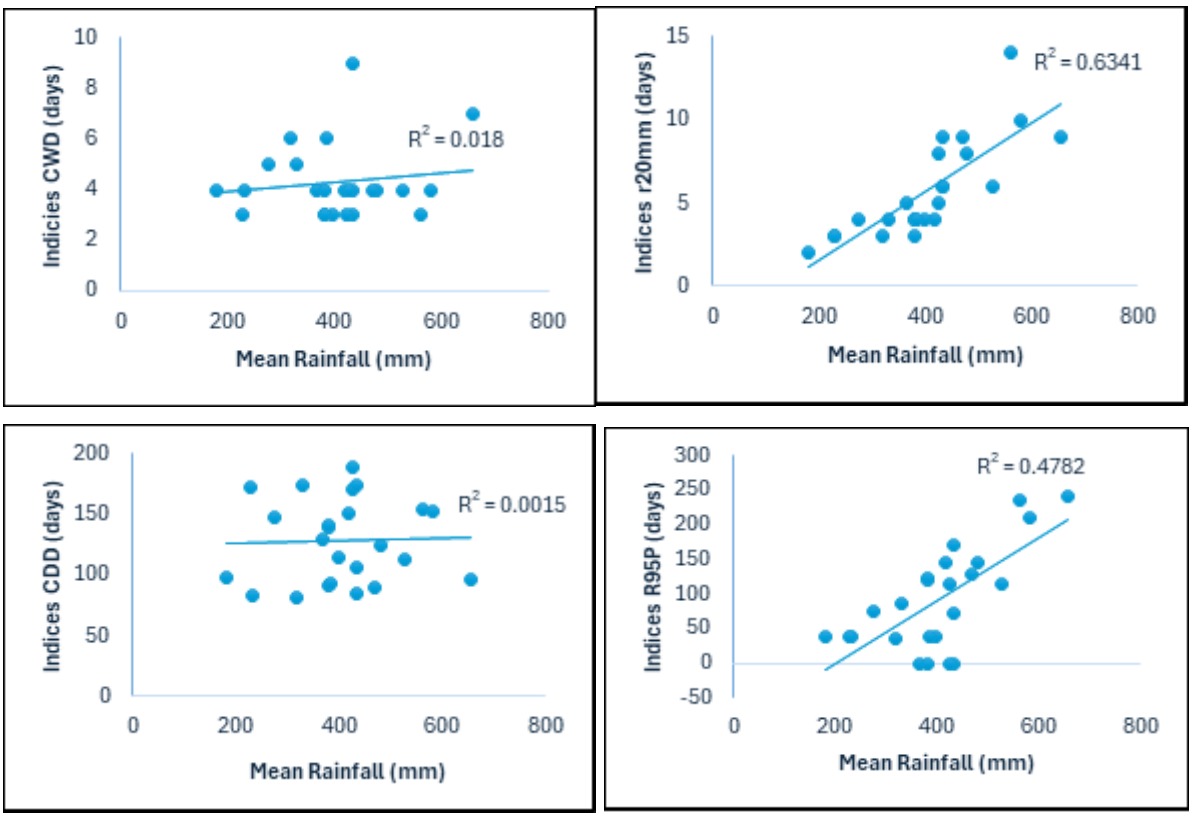


Figure 4.17 Correlation between mean rainfall and extreme precipitation indices in Marken

The correlation between the mean annual rainfall and extreme precipitation indices in Oudestad displayed a significant positive trend in r20mm and r95p (Figure 4.18), showing that extreme rainfall days increase as the mean rainfall increases. Consecutive wet days increased slightly, but not statistically significantly, while the consecutive dry days showed a flat or random trend, indicating that the is no correlation with mean rainfall. Correlations between mean annual precipitations and extreme precipitation indices were also examined. The findings revealed significant positive correlations for r20mm and moderate positive correlations for r95p (Figure 4.18), showing that years with greater mean annual rainfall have more days with rainfall exceeding 20mm and more severe rainfall events. These associations were found to be statistically significant, showing the significant correlations between mean rainfall and extreme precipitation indices, while the consecutive dry and wet days had a weak or non-significant correlation with mean rainfall.

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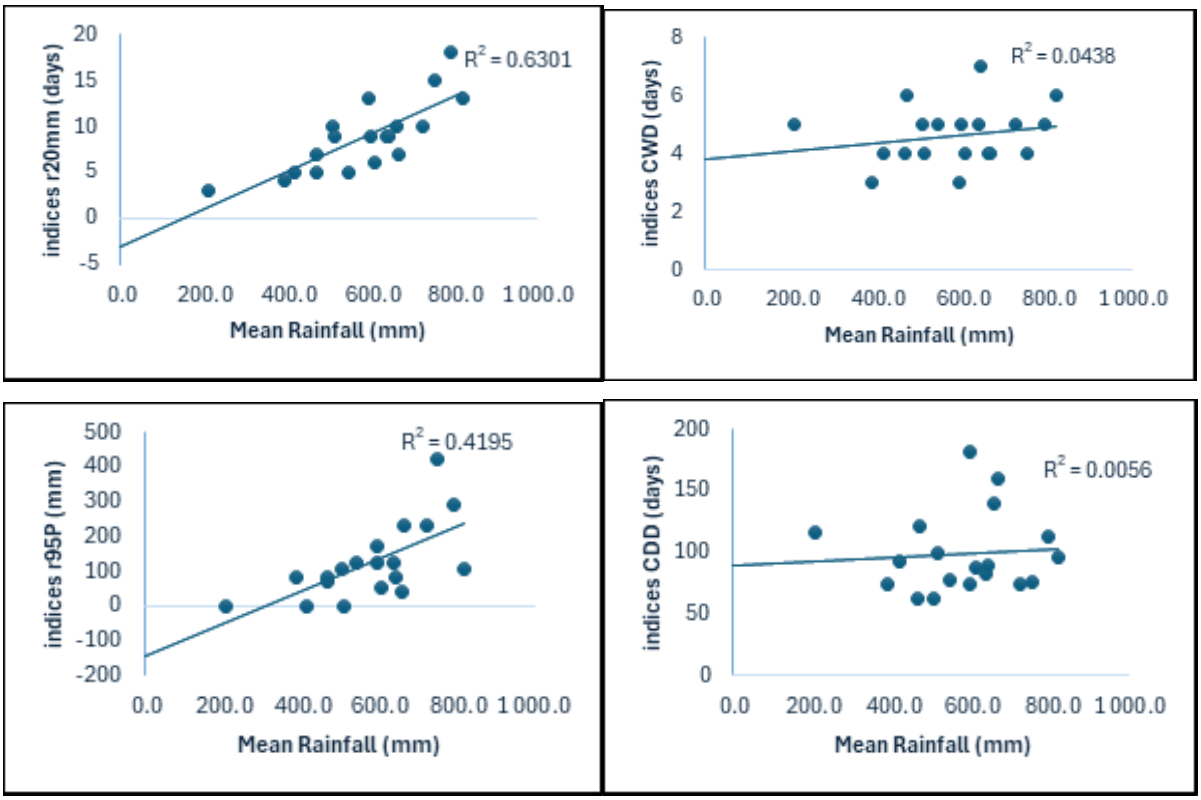


Figure 4.18 Correlation between mean rainfall and extreme precipitation indices in Oudestad

This study investigated the association between average annual rainfall and extreme precipitation indicators in Polokwane WO. The findings in showed a strong positive relationship between r20mm and r95p (Figure 4.19), implying that years with greater mean annual rainfall have more days with rainfall exceeding 20mm and more severe rainfall events. Furthermore, consecutive wet days exhibited a moderate positive connection, implying lengthier wet spells in wetter years. Conversely, the number of consecutive dry days exhibited a mild negative connection, indicating that dry days decreased slightly as mean rainfall increased.

The trends in these indices were also investigated, and the results revealed substantial positive trends for r20mm and r95p, showing that extreme rainfall days increase as mean rainfall increases (Figure 4.19). Consecutive wet days showed a mild growing trend, whilst consecutive dry days showed a flat trend, demonstrating no clear association with average rainfall. Overall, the findings indicate that mean annual

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rainfall is positively correlated with r20 mm, r95p, and consecutive wet days, but less so with consecutive dry days.

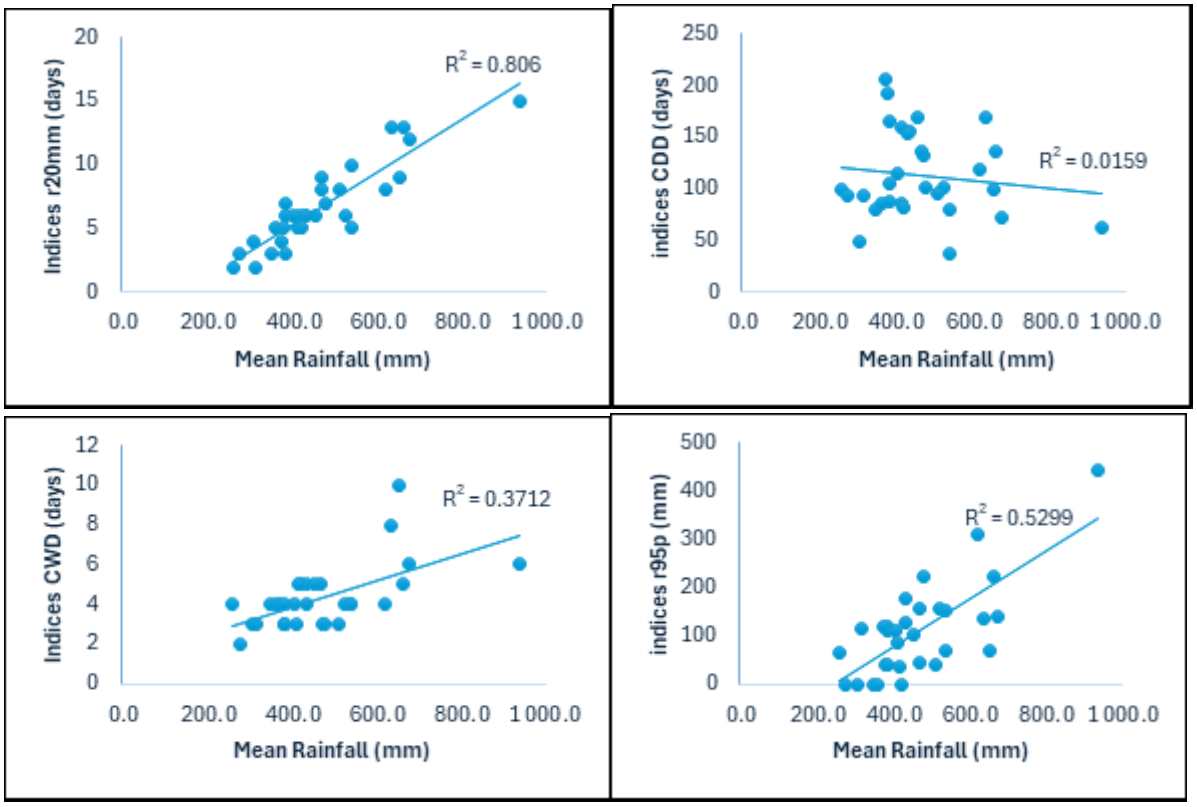


Figure 4.19 Correlation between mean rainfall and extreme precipitation indices in Polokwane Wo

In Punda Maria, the findings revealed a significant positive correlation between mean annual rainfall and r20mm, implying that years with higher mean annual rainfall have significantly more days with rainfall exceeding 20mm. Furthermore, consecutive wet days exhibited a moderate positive correlation, indicating that longer consecutive wet days are more likely to occur during the years with higher average rainfall. However, consecutive dry days showed a very weak positive correlation with mean rainfall (Figure 4.20). The statistical significance correlation of these was validated, with r20mm, CWD, and r95p all having statistically significant correlates with mean rainfall. Only CDD was shown to be statistically insignificant, implying that its correlation with mean rainfall is weak. These indices also showed strong positive trends for r20mm and r95P, implying that extreme rainfall days increase as mean rainfall increases. CWD showed a slightly

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increasing trend, whereas CDD showed a flat trend, demonstrating no apparent correlation with average rainfall.

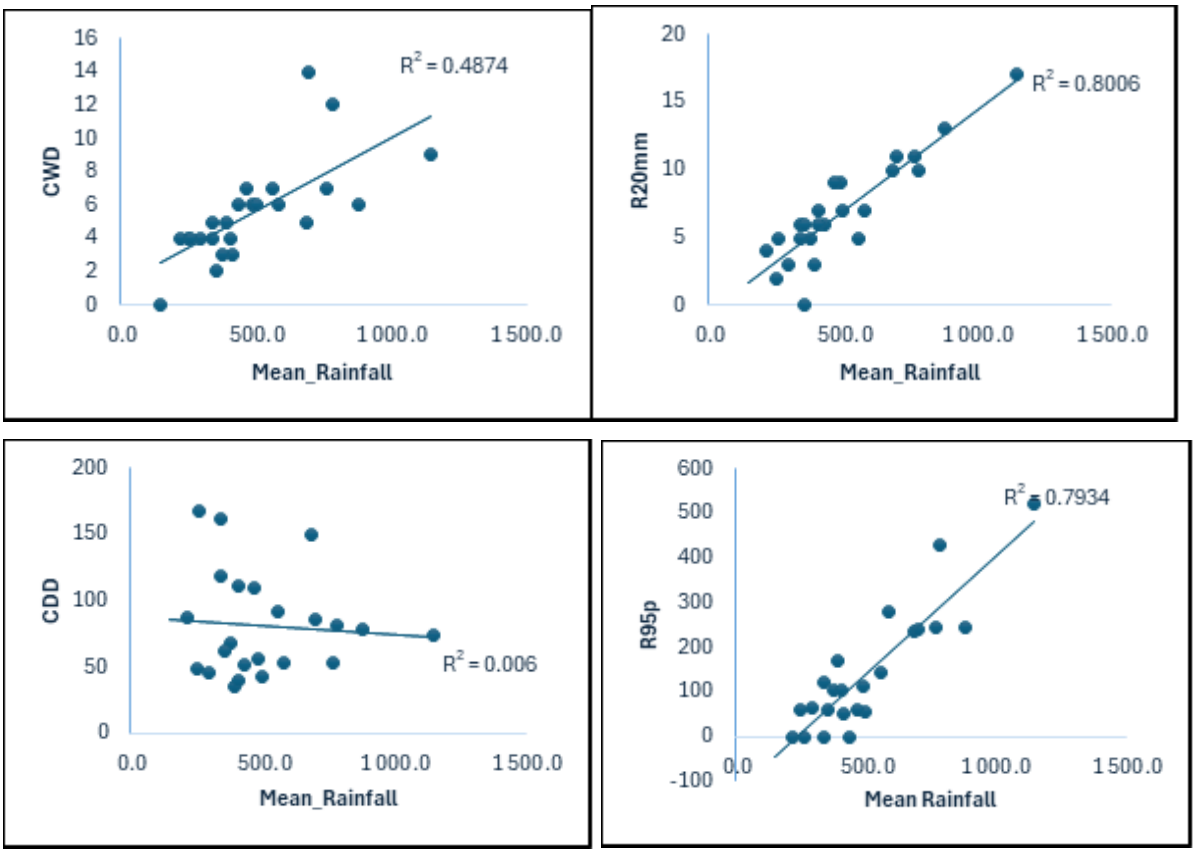


Figure 4.20 Correlation between mean rainfall and extreme precipitation indices in Punda Maria

Figure 4.21 results showed a strong positive association between mean annual rainfall and r20mm, CWD, and r95p. r20mm showed a very strong positive connection, showing that years with greater mean annual rainfall have significantly more days with rainfall above 20mm. Similarly, CWD and r95p showed strong positive relationships, implying that consecutive wet days and r95p increase with average annual rainfall. The statistical significance of this correlation was confirmed, with r20mm, CWD, and r95p all exhibiting an increase in correlation with mean annual rainfall. CDD was found to have an insignificant minor positive association that was not statistically significant, indicating a weak or chance relationship with the mean rainfall.

These indices also showed significant positive trends for r20mm and r95p, demonstrating that extreme rainfall days increase with mean annual rainfall. CWD also

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showed a moderately increasing trend, but CDD showed a weak trend, showing no significant correlation with mean rainfall.

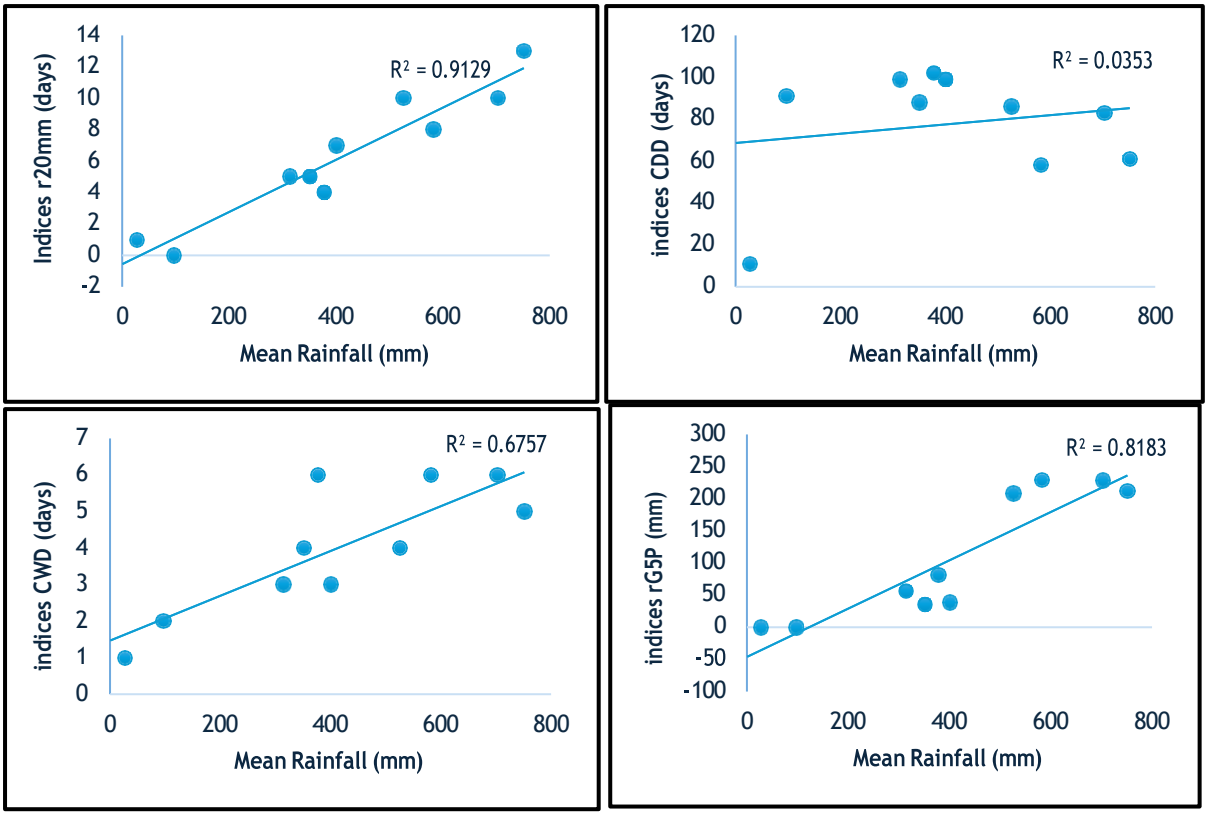


Figure 4.21 Correlation between mean rainfall and extreme precipitation indices in Thabazimbi

Figure 4.22 depicts the correlation between average yearly rainfall and extreme precipitation indices in Tshivhasie Tea Venda. The results show a strong positive association between mean annual rainfall and r20mm, CWD, and r95p. r20mm and r95P revealed a strong correlation, showing that years with greater mean annual rainfall have significantly more days with rainfall exceeding 20mm. CWD showed a moderate to significant positive correlation, implying that longer consecutive wet days occur during the years with higher average rainfall.

The statistical significance of these relationships was determined using the student's t-test procedure, which revealed that all correlations are statistically significant. This provides compelling evidence that annual rainfall affects severe precipitation indices in Tshivhasie Tea, Venda. The trends in these indices also revealed that CDD has a moderate negative correlation, implying that long dry spells reduce as yearly rainfall

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increases. Consequently, the findings indicate that average annual rainfall has a considerable influence on extreme precipitation indices in this region. Furthermore, r20mm and r95p show a sharp rising trend, indicating more frequent extreme rainfall during the wetter years, while CWD displays a modest positive trend, indicating that the wetter years have longer wet spells and CDD displays a negative trend, indicating that the wetter years have fewer consecutive dry days.

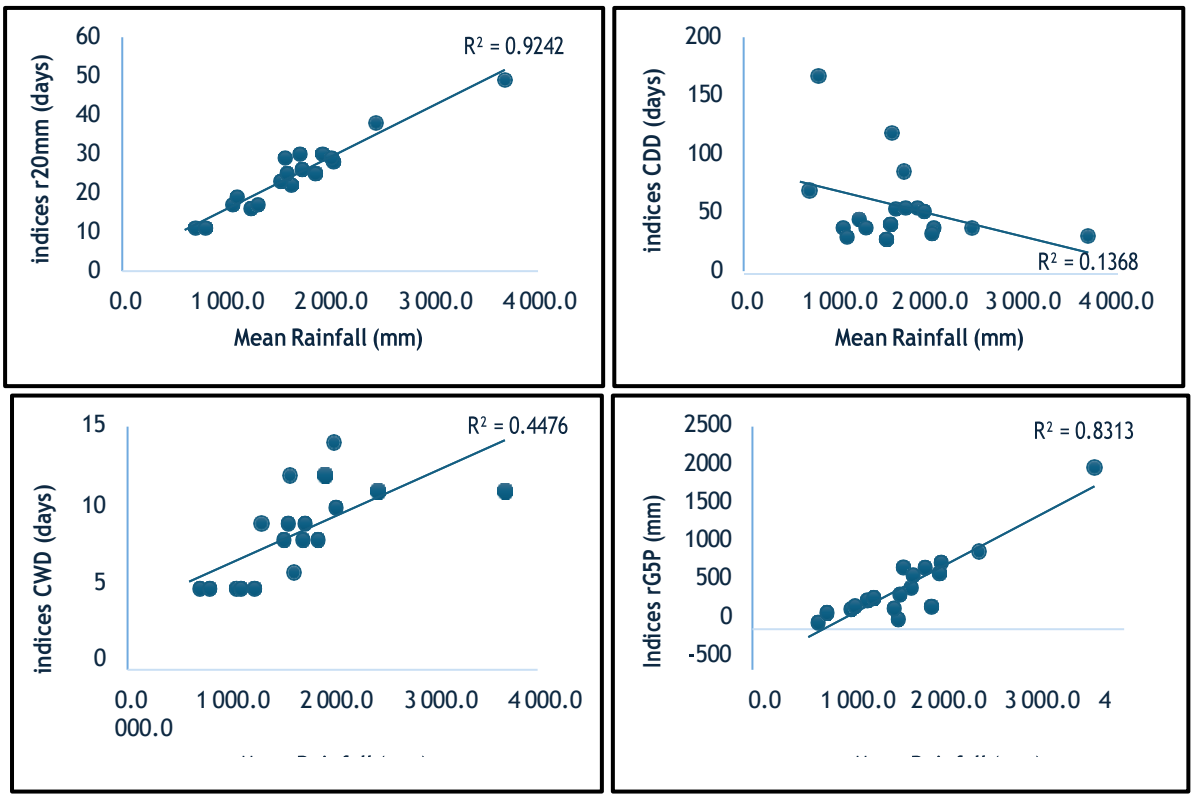


Figure 4.22 Correlations between the mean rainfall and extreme precipitation indices in Tshivhasie Tea Venda

In Warmbad Towoomba, the results showed a notable positive correlation between mean annual rainfall and r20mm, CWD, and r95p (Figure 4.23). In addition, r20mm and r95P exhibited strong positive correlation, showing that higher mean rainfall years include more days with rainfall exceeding 20mm and more r95p occurrences. CWD showed a moderate positive connection, indicating that wetter years result in a moderate increase in the frequency of consecutive wet days. The statistical significance of these connections was validated, with r20mm, CWD, and r95p all

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exhibiting significant correlations. However, CDD did not demonstrate a statistically significant correlation, implying that the number of consecutive dry days does not change considerably with mean annual rainfall in this station. The patterns in these indices also revealed that r20mm and r95P are on a steep rising trend (Figure 4.23), indicating more frequent extreme rainfall occurrences as mean annual rainfall increases. CWD has a moderate positive trend, but CDD has a little negative trend, indicating a decrease in consecutive dry days as rainfall increases.

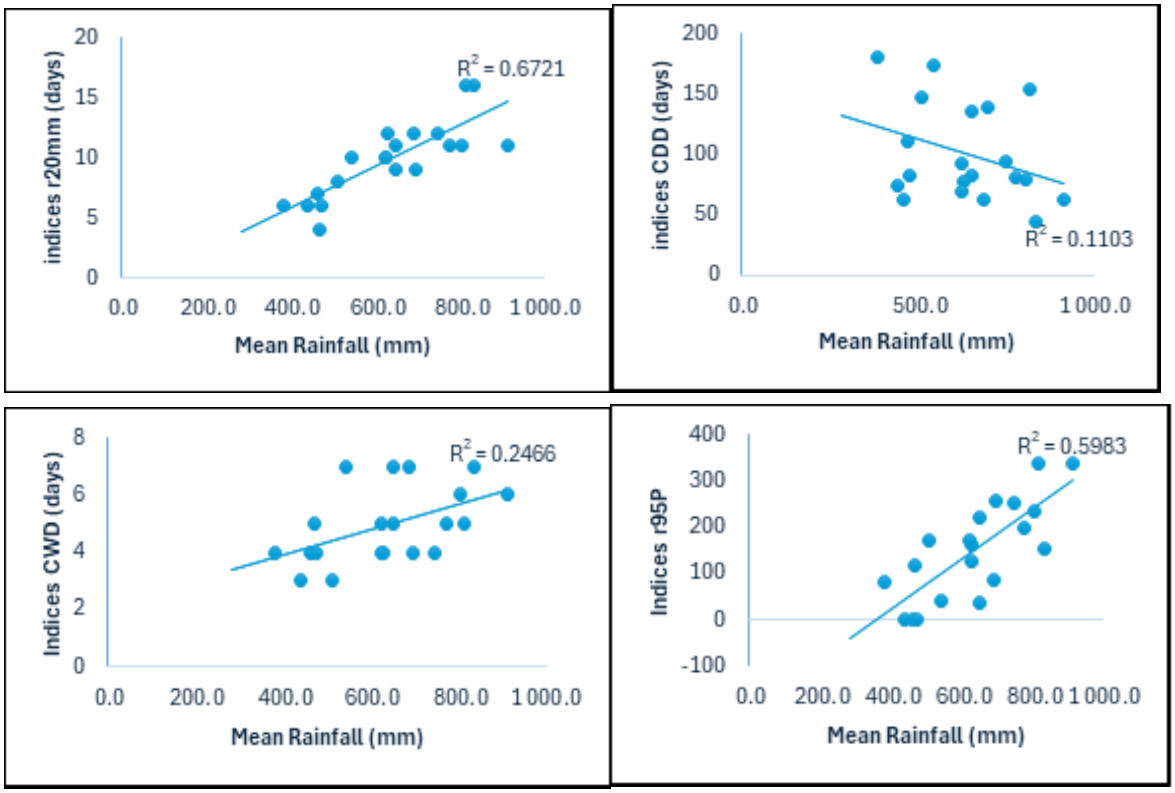


Figure 4.23 Correlation between mean rainfall and extreme precipitation indices in Warmbad Towoomba

4.9.2 Correlations between trends in mean annual rainfall and extreme rainfall

Figure 4.24 and Table 4 showed the correlation between trends in mean annual rainfall and several extreme rainfall indices, such as r20mm, CDD, CWD, and r95P. Analyses were conducted for the complete 30-year duration (1993-2023) and for three consecutive sub-periods of roughly equal length: 1993–2002, 2003-2012, and 2013-2023. Alongside the precipitation trends determined for each individual station, trends were also calculated for the entire region using the indices (Section 3.2), derived by averaging the data from all stations. The findings revealed a weak to moderate positive

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correlation between mean annual rainfall and r20mm, indicating that as the mean annual rainfall increases, the number of heavy rainfall days increases, too.

The correlation between the two variables is not statistically significant; this is because the r value is below 0.5, and the R^2 value indicates that only a small percentage of the variation in r20mm may be explained by changes in mean annual rainfall. In contrast, the correlation between mean annual rainfall and r95P was moderate and statistically significant, showing that increases in mean annual rainfall correspond to increases in severe rainfall events.

The correlation between the mean annual rainfall and CDD was weak and negative, indicating that as mean annual rainfall increases, the number of consecutive dry days decreases. However, this correlation is not statistically significant, and other climatic conditions could have a higher influence on CDD trends. Finally, the relationship between mean annual rainfall and CWD was weak and not statistically significant, showing that changes in mean annual rainfall are unlikely to predict changes in consecutive wet days. Overall, the findings indicate that the trend in mean rainfall is a more accurate indicator of extreme rainfall events than consecutive wet or dry days.

Table 4.1 Correlations in trends between mean annual rainfall and extreme precipitation indices across Limpopo

Index	**r20mm**	**CDD**	**CWD**	**r95p**
S	4.1	-4.86	1.61	1.52
R	0.35	-0.27	0.18	**0.49**
R^2	0.11	0.07	0.03	0.24

Slopes of the line of best fit (s) and correlations (r) that are statistically significant at the 5 % level are in bold; the coefficients of determination (R^2) are also given.

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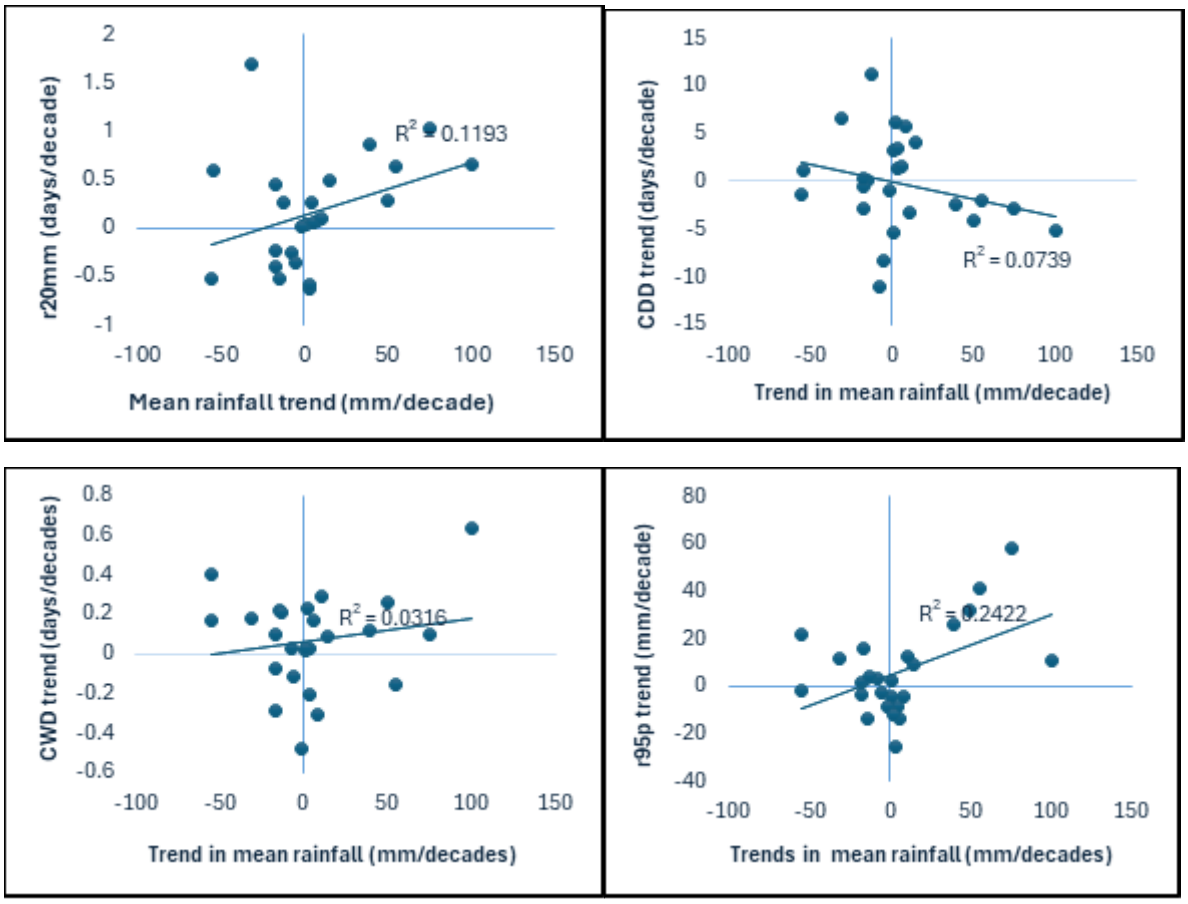


Figure 4.24 Correlation Between Trends in Mean Annual Rainfall and extreme precipitation indices from 1993-2023

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Chapter 5 Conclusion and Recommendations

5.4.1 Summary and Conclusion

The main objective of this study was to analyse spatial and temporal patterns of extreme rainfall in Limpopo province. The first objective sought to understand the trend in frequency and intensity of extreme rainfall. The second objective was to investigate the spatial distribution of extreme rainfall, while the third objective was to investigate the correlation between mean annual rainfall and extreme precipitation indices, as well as their trends.

The first objective examined the trend, frequency and intensity of extreme rainfall events in Limpopo Province. The frequency and intensity of extreme rainfall events in Limpopo Province vary significantly due to global meteorological events. An increase in the frequency of consecutive wet days were observed mainly during the period when South Africa was experiencing La Nina events and tropical, with areas such as Levubu, Polokwane Wo, Marken, Mara, Punda Maria, and Tshivhasie Tea Venda seeing over 10-15 consecutive wet days. The R20mm index analyses rainfall intensity and indicates significant changes in extreme precipitation. Heavy rainfall occurrences increased during some years, influenced by the tropical cyclones and La Nina.

Similarly, the frequency and intensity of consecutive dry days increased in years during which South Africa experienced El Nino episodes, with stations such as Thabazimbi, Warmbad Toowoomba, Lephalale, and Marken having dry spells of over 100 and 120 days, respectively. Conversely, during the years when the country experienced LA Nina and tropical cyclones, it resulted in shorter dry spells, with stations such as Punda Maria, Levubu, Mara, Tshivhasie Tea Venda, Polokwane Wo, and Oudestad having less than 60, 70, and 50 days, respectively. El Nino years resulted in decreased extreme rainfall events.

Objective 2 analysed the spatial distribution of extreme rainfall events in Limpopo., the spatial distribution of extreme rainfall events in Limpopo varied significantly across the province, with regions such as Vhembe, which includes Levubu, Mara, Punda Maria, and Tshivhasie Tea Venda, experiencing a higher incidence of r20mm events due to their subtropical climate and proximity to the Indian Ocean. The central and western

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sections, which include parts of Capricorn (Polokwane Wo) and Sekhukhune districts (Oudestad), experienced less R20mm events due to their arid and semi-arid climates. The spatial distribution of extreme rainfall patterns in Limpopo Province, as revealed by the r95p percentile index, differs by region, with the northern and northwestern regions, including Lephalale, Levubu, and Tshivhasie Tea Venda, showing an increasing trend in extreme rainfall, implying more frequent heavy rainfall events. In comparison, stations such as Mara, Marken, Oudestad, Thabazimbi, and Warmbad Towoomba exhibited a moderate increase trend, while Polokwane Wo had slightly negative trend.

The results showed that the spatial distribution of Consecutive Wet Days (CWD) in Limpopo reveals a mixed trend, with most stations, with the exception of Oudestad and Tshivhasie Tea Venda, experiencing statistically significant decreases of more than 0.2 days per decade, indicating a decrease in extended wet periods, while the overall spatial pattern suggests an increasing tendency of consecutive wet days across the province. Lastly, the spatial distribution of rainfall trends in Limpopo Province revealed significant regional variations in consecutive dry days (CDD), with areas such as Punda Maria, Lephalale, Thabazimbi, and Warmbad Towoomba in the north and southwest experiencing increased consecutive dry periods, implying decreased rainfall frequency and increased drought risk, while the central and eastern regions exhibited shorter dry spells and relatively stable rainfall patterns.

Objective 3 determined the correlations between annual mean conditions and annual extreme precipitation indices, as well as the correlations between trends in the means and in the extremes. The analysis of extreme rainfall indices from ten different weather stations in Limpopo Province showed a statistically significant positive correlation between mean annual rainfall and extreme precipitation for indicators such as R20mm, CWD, and R95P. The findings further indicated that the years with higher annual mean rainfall have more days with rainfall exceeding 20mm longer consecutive wet days, and more r95p. However, when the mean rainfall, the number of consecutive dry days decreases. The trends in these indicators also show that extreme rainfall events are becoming more and more intense in the wetter years, while consecutive dry days are declining. Overall, the data indicate that the mean annual rainfall has a significant influence on extreme precipitation indices in Limpopo Province, emphasizing the

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significance of including rainfall variability in climate change mitigation and adaptation efforts. An analysis of the correlation between mean annual rainfall and extreme rainfall occurrences shows a moderate to high positive correlation, particularly with R95p. This shows that the higher mean annual rainfall has a positive correlation with more severe rainfall events. On the other hand, the correlations between mean annual rainfall and R20mm, CDD, and CWD are weak and less statistically significant. Furthermore, the overall pattern suggests that the mean annual rainfall is a better predictor of extreme rainfall occurrences than consecutive wet or dry days. This emphasises the significance of factoring in mean annual rainfall trends for predicting and controlling extreme rainfall occurrences. In conclusion, the findings showed that much of Limpopo Province has seen an increase in the intensity of daily precipitation, aligning with global trends overall.

Observations of reduced rainfall during the wet periods were recorded in numerous areas across the east and northeast, while the southern and eastern regions along the escarpment faced shorter annual dry spells. Mara, Oudestad and Tshivhasie tea Venda showed a strong upward trend in Consecutive Wet Days (CWD), r20mm and r95p, as well as a decrease in Consecutive Dry Days (CDD) for the period 1993-2023, showing that as the mean rainfall increases, extreme rainfall occurrences increase, too. Finally, the mean annual rainfall has a significant influence on extreme precipitation indices in Limpopo Province.

5.4.2 Recommendations

The present study aimed at examining spatio-temporal analyses of extreme rainfall events in Limpopo Province. The findings underscore the need for improved techniques to adjust to changing rainfall features in the agricultural and water sectors, affecting both districts and individual farmers. These findings contribute to understanding decision making in the agriculture industry in response to changing climate conditions.

- The study found significant increases or decreases in extreme rainfall events. However, the root r causes of these dramatic shifts have not been fully addressed.

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- Climate attribution studies are vital for understanding the causes of seasonal rainfall fluctuations.
- Understanding the impact of climate change on these variances is crucial for establishing effective mitigation and adaptation strategies.
- Policymakers need to understand how climate change affects seasonal rainfall, to make informed decisions.
- Future research should focus on specific locations within Limpopo Province, as variability in rainfall patterns across the province may obscure greater trends.
- Finally, identifying local hotspots of excessive rainfall could aid in developing region- specific responses and strategies.

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