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School of Geography Archaeology and Environmental Sciences

MSc Environmental Science Research Report

Exploring extreme rainfall events in KwaZulu-Natal over the period 1989-2019

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Declaration

I, Thabisile Phiwengomusa Zibusisozonke Ntleko (Student No 2392382) declare that this research report submitted for MSc in Environmental Science at the University of Witwatersrand has not been previously submitted for a degree at this or any other University, in part or in full. All the sources of information have been fully acknowledged in the references.



Signed: Date:25/05/2023

Abstract

Changes in weather and climate extremes have been observed across the globe. These include an increase in the frequency, magnitude, and severity of extreme events, have been attributed mainly to climate change due to increased anthropogenic activity since pre-industrial times. Although these weather and extreme events have increased and intensified globally on average, some spatial and temporal variations of trends are evident at regional scales. This study was conducted to explore the incidence and trends of extreme rainfall events over KwaZulu-Natal for the period 1989-2019. Rainfall data was sourced from the South African Weather Service for 11 stations distributed across the province. Extreme climate events (ECEs) were identified by calculating subsets of the World Meteorological Organisation (WMO) Expert Team on Climate Change Detection Indices (ETCCDI) and WMO Expert on Sector-Specific Climate Indices (ET-SCI) for each of the 30 years of interest. Thereafter, trends in these extreme climate events were calculated using linear regression. The results reveal marked spatial and temporal differences in both the occurrence of the ECEs and their trends. The incidence of ECEs depict a seasonal pattern, where majority of events occur during the summer rainfall months. However, over the coastal regions ECE's occur throughout the year and exhibit more frequent and intense events compared to overland regions. The trend analysis detected a majority of decreasing trends in the frequency, intensity and duration of extreme rainfall events for the period of study, with only 10 of the 77 calculated trends being statistically significant. The spatial distribution of trends was heterogeneous for most parts of the province apart for the KwaZulu-Natal Midlands, which consistently observed decreasing trends for all calculated indices.

Keywords: Extreme Rainfall Events, Extreme Rainfall Trends, Climate Change, KwaZulu-Natal

In memory of my father

Siyamazi Ukumakwakhe Elijah Ntleko

1950 – 2021

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List of Acronyms and Scientific Terms

AMO- Atlantic Multidecadal Oscillation

CMIP- Coupled Model Intercomparison Project Phase

COL- Cut-Off Low

CORDEX- Coordinated Regional Climate Downscaling Experiment

CWD- Continuous Wet Days

EA- East Atlantic Pattern

EAWRUS- East Atlantic/Western Russia Pattern

ENSO- El Niño Southern Oscillation

ETCCDI- Expert Team on Climate Change Detection Indices

ET-SCI- Expert Team on Sector Specific Climate Indices

GCM- Global Climate Model

GDP- Gross Domestic Product

GWL- Global Warming Level

IOD- Indian Ocean Dipole

IPCC- Intergovernmental Panel on Climate Change

LP- Low Pressure

MEI- Multivariate ENSO Index

MCC- Mesoscale Convective Complex

MCS- Mesoscale Convective Systems

NOA- North Atlantic Oscillation

NPGO- North Pacific Gyre Oscillation

PDO- Pacific Decadal Oscillation

PNA- Pacific North American

RCP- Representative Concentration Pathways

R20- Number of very heavy rainfall days

R50- Number of extreme rainfall days

R95p- Total precipitation from heavy rainfall days

R99p- Total precipitation from very heavy rainfall days

Rx1day- Annual maximum one-day rainfall

Rx5day- Annual maximum five-day rainfall

SADC- Southern African Development Community

SAM- Southern Annular Mode

SAWS- South African Weather Service

SCAND- Scandinavian Pattern

SIOD- Sub-tropical Indian Ocean Dipole

SRES- Special Report on Emission Scenarios

SSP- Shared Socio-economic Pathways

TC- Tropical Cyclone

TTT- Tropical Temperate Trough

WMO- World Meteorological Organisation

Chapter 1: INTRODUCTION

1.1 Background

One of the most pertinent characteristics of a changing climate is the global and regional change in precipitation (Donat *et al.*, 2016). The average global temperature has increased close to 1°C since pre-industrial times, predominantly attributed to anthropogenic forcings, and projections indicate a further 1.5°C to 2°C increase will be reached by 2100 (Pendergrass *et al*., 2015; IPCC, 2019, 2021). According to Fischer and Knutti (2015), 75% of the observed moderate hot extremes since pre-industrial times have been credited to anthropogenic warming, and the projected warming by the end of the 21st century will see increases in intensity and frequency of extreme weather and climate events (Seneviratne *et al.*, 2012). Observed changes in extreme precipitation have exhibited different spatial and temporal patterns, with opposing trends (Donat *et al.*, 2013, 2016).

Increases in the frequency and intensity of heavy rainfall have been observed over most land areas across the globe since the 1950s (IPCC, 2021). Broadly, wetting trends have been observed at higher latitudes, and drying trends over the subtropics and tropics excluding regions in the monsoon trough (Trenberth, 2011). In regions where wetting and drying trends have been observed, opposing trends of extreme rainfall incidents have been detected, with the largest fraction of changes depicting increasing trends (Donat *et al.*, 2016). Anthropogenic forcing has been attributed to 18% of the observed increases in rainfall extremes since pre-industrial times (Fischer and Knutti, 2015). This smaller percentage, as compared to the 75% for temperature, indicates that other factors may be at play in influencing changes in extreme rainfall events. Increasing drought frequencies is a key threat under climate change,

particularly in South Africa, which has been identified as one of the drought hot spots (Seneviratne *et al.*, 2012).

South Africa experiences oscillations in wet and dry spells, mainly driven by the large-scale variability modes form the adjacent Indian and Atlantic Oceans (Dieppois *et al.*, 2016). Droughts and localized to widespread floods are common in South Africa, and the latter is mainly contributed to by regional and localised synoptic scale systems (Botes, 2014). Examples of such events include the 2015/2016 dry hydrological year, which resulted in drought conditions across the Southern African Development Community (SADC) region and saw disaster declarations in seven of the nine South African Provinces (Blamey *et al.*, 2018). The 1984 floods over north-eastern KwaZulu-Natal were a major event caused by Tropical Cyclone Domonia, where rainfall amounts reached 800mm in places (SAWS, 1991). The semi-aridity and rainfall variability of South Africa makes it vulnerable to the effects of climate change and added onto that vulnerability is its low adaptive capacity (Engelbrecht *et al.*, 2015).

Extreme weather and climate incidences result in significant societal and environmental impacts (Lennard and Hegerl, 2015; Tabari, 2020). Therefore, knowing the changing nature and ultimate impacts of extreme rainfall is important to help facilitate proper adaptation and disaster mitigation planning (Westra *et al.*, 2014)

1.2 Study Rationale

Understanding the past changes and frequencies in extreme climate and weather occurrences is beneficial for the reliable prediction of future events (Damberg and AghaKouchak, 2014). With future projections indicating further warming and drying in South Africa and an increase in the frequency of extreme events, there may be shifts in climate extremes impacting on the environment, society and the economy (Few,

2003; Williams *et al.,* 2007; Engelbrecht *et al.*, 2015; Pinto *et al.*, 2016). Extreme weather and climate events have been observed to have spatial and temporal variances in South Africa, therefore, changes in these events may display similar variations (Zarch *et al.,* 2015; Botai *et al.,* 2018). This necessitates the investigation of extreme events at regional or localised scales, which can aid in isolating vulnerable areas persistently prone to extreme events. This information can be used for adaptation planning, and for policy development (Lennard and Hegerl*,* 2015). These studies are particularly important in regions such as KwaZulu-Natal, which are characterised by cyclic periods of dry and wet years and is prone to annual regional flooding and intra-annual drought periods (Dube and Jury, 2000; Botes, 2014; Blamey *et al.*, 2018).

1.3 Study Aims and Objectives

The study aims to investigate the incidence and changes in rainfall extremes over KwaZulu-Natal, and whether these depict any spatial or temporal patterns.

Based on the above aim, the following objectives will guide the study:

i. To evaluate the quality of rainfall data over KwaZulu-Natal for the period 1989-2019
ii. Identify incidence of extreme rainfall events by calculating subsets of the World Meteorological Organisation (WMO) Expert Team on Climate Change Detection Indices (ETCCDI) and Expert Team on Sector-specific Climate Indices (ET-SCI).
iii. Calculate trends in the incidence of extreme rainfall events through regression analysis.

1.4 Overview of the Study

The main aim of the study is to investigate extreme rainfall trends over KwaZulu-Natal for the period 1989-2019, and to investigate any spatial or temporal patterns in extreme events. Chapter 2 presents a literature review, examining global and regional trends in extreme rainfall events, global and regional projections of extreme rainfall events related to climate change, the climate drivers linked to rainfall variability and extreme rainfall in South Africa, and the synoptic scale systems linked to extreme rainfall events in South Africa. Chapter 3 details the study site, including the climate and geography of the study area, and the synoptic scale systems linked to rainfall in KwaZulu-Natal. Chapter 4 details the methodology used for data quality control and trend analysis calculating subsets of the ETCCDI and ET-SCI. Chapter 5 presents the analyses of the incidence of extreme rainfall, including the mean annual incidence and seasonality of events, and the trends and spatial distribution of the trends. Chapter 6 discuss the results and their link to literature, and Chapter 7 concludes the study through a synthesis and an examination of the achievement of aims and objectives.

Chapter 2: LITERATURE REVIEW

2.1 Introduction

One of the main characteristics of a changing climate is the global and regional changes in precipitation, which exhibit differing spatial and temporal variations across the globe (Donat *et al.*, 2016). This literature review chapter explores literature relating to extreme rainfall events on a global scale and for South Africa. The first section defines extreme events in the context of this research. This is followed by an extensive review of observed extreme rainfall trends globally and in South Africa, with a focus on studies that used subsets of the WMO ETCCDI/ET-SCI indices to analyse trends. This is followed by a review of future predictions of extreme rainfall trends, and the various influencing factors related to climate change. The second section considers the climate drivers that influence rainfall variability and subsequently extreme rainfall events, looking at global and local climate drivers and how these interact to influence extreme rainfall. The third part of the literature review links extreme rainfall events to synoptic-scale weather systems, with focus on those events that can be attributed to widespread rainfall and flooding events.

2.2 Defining Extreme Events

The Intergovernmental Panel on Climate Change (IPCC) defines an 'extreme weather event' as "an event that is rare at a particular place and time of the year" and an 'extreme climate event' as "a pattern of extreme weather that persists for some time such as a season" (Seneviratne *et al*., 2021:1522). Extreme weather and climate events can be further defined as "the occurrence of a value of a weather or climate variable above (below) a threshold value near the upper (lower) ends of the range of observed values of a variable" (Seneviratne *et al*., 2012:116). Statistical thresholds for extreme events are generally specified as a range from the 90th to 99th percentile at

the upper end, and the 5th to 10th percentile at lower ends (McPhillips *et al.*, 2018). Extreme events can also be defined as hydrological extremes, such as droughts and flooding, which contribute to physical, socio-economic and ecological vulnerabilities (Meehl *et al.*, 2000; Trenberth, 2011). Floods can be associated with intense and extreme rainfall, over a long or short period, resulting in widespread and devastating impacts such as Tropical Cyclone Domonia (1984), or the April 2019 and 2022 floods in KwaZulu-Natal (Trenberth, 2011; Lennard and Hegerl, 2015; Zarch, Sivakumar and Sharma, 2015; Bopape *et al.*, 2021; Tramblay *et al.*, 2021; Thoithi, Blamey and Reason, 2022). However, they can also be caused by moderate rainfall resulting in localised damage and pluvial floods that affect natural and artificial drainage systems (Seneviratne *et al.*, 2021; Tramblay *et al.*, 2021). Droughts are associated with an extended period of rainfall shortage, over a particular timescale, which are often but not always linked to extreme temperatures (Rouault and Richard, 2005; Trenberth, 2011; Lennard and Hegerl, 2015; Zarch, Sivakumar and Sharma, 2015). Droughts are defined based on four different classes: agricultural, meteorological, hydrological, and socio-economic droughts, and they all exhibit different temporal scales (Ujeneza and Abiodun, 2015; Seneviratne *et al.*, 2021)**.** The temporal scale for agricultural droughts is three to six months when rainfall shortages result in crop damage, while the hydrological drought is 12 months to two years, where its effect on surface and/or groundwater water supply is observed (Rouault and Richard, 2003).

The analysis of extremes considers two types of descriptions. The first is extreme indices that constitute moderate extreme events with an annual temporal scale or shorter, while the second is an application of the extreme value theory and investigates the behaviour of extremes at a multi-year to multi-decadal temporal scales (Kharin *et al.*, 2013). The former allows for clearer identification of changes in characteristics of

extreme events as events occur more frequently (Kharin *et al.*, 2013). As will be seen throughout the literature review, most studies have analysed extreme events trends by investigating these 'moderate extreme events' by way of analysing subsets of the extreme rainfall indices as recommended by the WMO ETCCDI (WMO, 2009).

2.3 Observations of Extreme Rainfall Trends: Globally and South Africa

Investigations of daily rainfall extremes have been conducted at global scales where findings indicated diverse changes in the spatial and temporal scales of extreme rainfall trends (Easterling *et al.*, 2000; Groisman *et al.*, 2005; Alexander *et al.*, 2006; Trenberth, 2011; Seneviratne *et al.*, 2012, 2021; Donat *et al.*, 2013, 2016, 2019; Westra *et al.*, 2013; Asadieh and Krakauer, 2015). Opposing trends have been identified in the same regions, however, the percentage of increasing trends has been larger compared to decreasing trends, and more so in extreme rainfall intensities as indicated by the upper percentile and day maximum rainfall extremes or associated indices (Easterling *et al.*, 2000; Groisman *et al.*, 2005; Asadieh and Krakauer, 2015; Donat *et al.*, 2016; Kumar *et al.*, 2021). The annual one-day maximum (Rx1day) observed trends for the period 1900 to 2009 were updated on a global scale and found that the spatial distribution of increases or decreases in trends had no clear pattern, apart from southern Africa, where decreases in intensity were observed over the eastern parts (Westra *et al.*, 2013). Of the stations used in the study, two thirds showed increasing trends while a third showed a decreasing trend, with less than 10% of these stations showing significant trends (Westra *et al*., 2013). Globally, the annual one-day maximum daily rainfall has increased by 5.73mm.day on average and increased by 10%/K of global warming since the beginning of the 20th century (Asadieh and Krakauer, 2015). Min *et al.,* (2011) compared observed and simulated Rx1day and five-day consecutive (Rx5day) rainfall trends. Simulations were enforced with

“historical anthropogenic and natural (solar and volcanic) forcings” (Min *et al.,* 2011:378). Both observations and simulations indicated increases in trends for both rainfall extremes, with larger trends in the Rx1day (Min *et al.,* 2011). Donat *et al.,* (2019) investigated the intensification of observed Rx1day rainfall events over humid and arid regions for the period 1951-2010. Humid regions were identified as the midlatitudes and tropics, which included “south-east Asia, India, eastern South America, south-east US, Europe and small regions in northern tropical and eastern coastal Australia, eastern tropical Africa and south-east Africa”, and arid regions as the subtropics and continental interior, which included “central and north-east Asia, central Australia, north-west North America, northern and south-western Africa” (Donat *et al.*, 2016:508, 2019). Results showed increasing trends in all regions, with more significant trends in arid regions (Donat *et al.*, 2016; 2019).

Studies at regional scales in North America (Bell and Sloan, 2006; Armal *et al.*, India (Sen Roy and Balling Jr, 2004; Basher *et al.*, 2018; Kumar *et al.*, 2021), Australia (Haylock and Nicholls, 2000), Asia (Limsakul and Singhruck, 2016; Wang *et al.*, 2016; Wei *et al.*, 2017), South America (Marengo *et al.*, 2010), Europe (Tank and Können, 2003; Casanueva *et al.*, 2014), Africa (New *et al.*, 2006; Ojara *et al.*, 2021), have also corroborated global findings. A study in Thailand found irregular spatial trends Rx1day and Rx5day values, but a greater tendency towards increasing trends (Limsakul and Sinhruck 2016). Negative trends were exhibited for heavy rainfall frequency, i.e., frequency of events exceeding 20mm, (R20mm) and a general drying trend, i.e., reduction in continuous wet day (CWD). Trends in extreme rainfall in the Beijing-Tianjin Sand Source Region, China over the period 1960-2014, exhibited a general decreasing trend in the frequency, duration, and intensity of rainfall extremes, with intensity indices depicted by Rx1day and Rx5day detecting statistically significant

trends (Wei *et al*., (2017). Over Canada, increasing trends in extreme rainfall intensity and frequency (Rx1day, Rx5day, R95p, R99p, R10mm and R20mm) dominated over decreasing trends, and were mainly confined over the northern and southern parts of Canada (Yang *et al.*, 2019). A study in Europe examined the changes in the contribution of very extreme precipitation (R95pTOT) and continuous wet/dry days (CWD/CDD) compared to mean precipitation (Casanueva *et al.*, 2014). The R95pTOT had more statistically significant trends compared to mean precipitation, and the increasing trends were evident in all seasons, with significant spatial patterns over the northern and central Europe (Casanueva *et al.*, 2014). Spatial and temporal patterns were also observed for mean precipitation and CWD in the different parts of the continent, and the trends of these indices were synonymous, that is, mean precipitation and CWD increased or decreased in the same area (Casanueva *et al.*, 2014). Opposing trends of these indices were found in winter compared to summer (Casanueva *et al.*, 2014). Similarly, a study in the western Himalayas, which investigated spatial and temporal variations in day maximum indices corroborated these general findings, where two-to-five-day maximum rainfall extremes had seen an increasing trend for the period 1981 to 2014, with spatial distributions depending on seasonality (Kumar *et al.*, 2021). Higher intensities of day maximum extremes were observed in lower altitude stations during the monsoon seasons and higher altitude stations during the winter seasons (Kumar *et al.*, 2021). An investigation of trends of extreme rainfall events in East Africa detected increasing trends in extreme rainfall intensities (upper percentile and day maximum extremes), with most increases being observed over the coastal regions as well as the Lake Victoria Vicinity (Ojara *et al.*, 2021).

The general findings of rainfall extremes observations in South Africa have been a drying trend with insignificant change in average precipitation (Easterling *et al.*, 2000; Groisman *et al.*, 2005; Trenberth, 2011; Donat *et al.*, 2013). However, statistically significant increases in annual mean precipitation were observed over the southern interior (Kruger and Nxumalo, 2017). The highest frequency of extreme rainfall events, defined as rainfall above 20mm (R20mm), have been observed over the "eastern coastal belt and eastern escarpment, the Cape south coast and the south-western Cape" (Engelbrecht *et al.*, 2013:177). Increasing trends in very heavy and extreme rainfall intensity and frequency were observed over the central and south-eastern parts of the country (Mason *et al.*, 1999; Kruger, 2006; New *et al.*, 2006; Roy and Rouault, 2013; Kruger and Nxumalo, 2017). The magnitude of the 10-year maximum rainfall events over the period 1931-1990 had large increases along the east coast (Mason *et al.*, 1999). Extreme trends over southern and west Africa detected a few significant increasing trends in magnitude of average rainfall and Rx1day rainfall and non-significant increasing trends in very wet day intensities (R95p), extreme wet day intensities (R99p) and Rx5day intensities (New *et al.*, 2006). Heavy rainfall frequencies (R20mm) detected non-significant decreasing trends (New *et al.*, 2006). Positive trends in rainfall intensity and frequency predominantly occurred during the summer season, which correlates to the rainfall season of the eastern and central South Africa, with predominantly negative trends in winter (Kruger, 2006; Roy and Rouault, 2013; Dieppois *et al.*, 2016). The trends in the frequency and intensity of hourly R95p extreme had strong positive trends over the southeastern and western coasts of South Africa (Roy and Rouault, 2013). This seasonal variation was also depicted by Engelbrecht *et al.*, (2013), where increasing trends in extreme rainfall events were detected over the eastern parts of South Africa and the North West Province during

austral spring and summer and increases over the south-west during austral autumn and summer. Dry spells increased over the region, with the western, central and southern parts of the country depicting significant trends (Kruger, 2006; Kruger and Nxumalo, 2017). Drought indices indicated that South Africa generally experiences moderate droughts with cyclical oscillations at interannual and interdecadal time scales across the country (Dube and Jury, 2000; Rouault and Richard, 2003; Zarch *et al.*, 2015).

2.4 Future Changes of Extreme Rainfall Trends: Globally and South Africa

Observations have demonstrated increases in rainfall extremes, and climate models predict a further increase in the 21st century (Pendergrass *et al.*, 2015). The projected variations in intensity of rainfall extremes are largely accredited to the expected increased moistening of the atmosphere due to the increased water holding capabilities associated with warmer air (Westra *et al.*, 2014; Pendergrass *et al.*, 2015; Donat *et al.*, 2019).The atmosphere's water holding volume is linked to the Clausius Clapeyron equation, where saturation increases by 6-7% per degree Celsius of warming (Ban *et al.*, 2015; Martel *et al.*, 2021). Global Climate Models (GCMs) project increases in average rainfall by 2-3% per degree Celsius, but this varies geographical and with regards to rainfall duration and intensity (Martel *et al.*, 2021). GCMs project a future where extreme rainfall events surpass the Clausius Clapeyron rate, however, the scaling depends on the frequency and duration of rainfall extremes, i.e., events with longer return periods or shorter durations may have greater increases in a warming climate (Martel *et al.*, 2021).

Future predictions of extreme rainfall depict similar variations to those that have been observed in trend analyses, however, some variances are based on the GCM

uncertainties, the emission scenarios modelled, and internal variability (Trenberth, 2011; Sillmann *et al.*, 2013; Engelbrecht *et al.*, 2015; Thompson *et al.*, 2015). The IPCC 6th Assessment Report considers two sets of emission scenarios based on the Coupled Model Intercomparison Project Phase 5 and 6 (CMIP5 and CMIP6; Lee *et al*., 2021). The CIMP5 emission scenarios, called the Representative Concentration Pathways (RCPs) consider a "wide range of possibilities in socio and economic development" based on certain radiative forcings (Kharin *et al.*, 2013:348). The estimated radiative forcing values by 2100 are 2.6W/m^2 for RCP2.6, 4.6W/m^2 for RCP4.5 and 8.5W/m^2 for RCP8.5. The RCP8.5 forcing exceeds Special Report on Emission Scenarios (SRES) A2, RCP4.5 is similar to SRES B, SRES A1B falls between RCP8.5 and RCP4.5 (Kharin *et al.*, 2013). RCP8.5 is generally accepted as the most likely future emission scenario, which considers no changes in anthropogenic forcings, however, some scientists dispute the likelihood of this scenario as it depicts an unrealistic increase in the use of fossil fuels (Martel *et al.*, 2021). The CMIP6 emission scenarios, called the Shared Socio-economic Pathways (SSPs) focus on five emission scenarios, SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 depicting radiative forcing by 2100 (Lee *et al.*, 2021). Most studies projecting changes in future climate extremes are based on emission scenarios, however, Pendegrass *et al.* (2015) found that projections for future extremes were attributed more to the degree of warming rather than the composition of the anthropogenic forcing. Nevertheless, there have been no significant variations in terms of trend directions across the different emission scenarios (Pendergrass *et al.*, 2015; Kharin *et al.*, 2018). It is noted, however, that the respective highest scenarios, RCP8.5 and SSP5-8.5, generally depict the largest changes or increases in future projection (Kharin *et al.*, 2013; Almazroui *et al.*, 2020). No discernible change in precipitation is projected between

the different SSP scenarios, however, projections indicate regional and seasonal contrasts (Lee *et al.*, 2021). Global Warming Level (GWL) based studies consider projections of future extremes at 1.5, 2, 3 and 4 degrees Celsius global warming relative to pre-industrial conditions (Seneviratne *et al.*, 2021).

Generally, areas that have observed wetting and drying trends in the past century are projected to experience increases in those trends (Groisman *et al.*, 2005). According to Orlowsky and Seneviratne (2013), rainfall intensities (95th, 99th, above 99th percentiles, and Rx1day amounts), will not change, however, the frequency of these events will increase, and be more spatially homogeneous. This finding contrasts with Westra *et al.,* (2014), who's finding not only depicts increases in frequency and intensity of events, but also found that increases would be larger for sub-daily extremes than daily extremes. Longer return period extreme events will also see an increase in intensity and frequency (Kharin *et al.*, 2013). Simulations of the Rx1day at different emission scenarios detected increases over most of the globe, with higher increases over the "equatorial Pacific, Africa, Arabian Peninsula and India", but lower in the "subtropical eastern ocean basin and Mediterranean" (Pendergrass *et al.*, 2015:8771). An investigation into the relationship of future changes in 1-in-30-year extreme rainfall and flood intensities with water availability for the period 2077-2099 under the RCP8.5 emission scenario exhibited an increase in intensity for all climatic zones but there was significant uncertainty in "Latin America, Africa, Middle East and Australia" (Tabiri, 2020:3). Projections indicated increases in extreme events with global warming at 6.3%/K for humid regions, 5.8%/K for semi-humid regions, 5.6%/K for semi-arid and 5.4%/K for arid regions at the Clausius Clapeyron rate (Tabiri, 2020). It is noted that the Clausius Clapeyron rates in these findings do not exceed the 7% Clausius Clapeyron rate, which Martel *et al.,* (2021) suggested could be exceeded

with longer return period events. In humid to semi-humid regions, changes in extreme rainfall events are caused by thermodynamic effects, whereas in most arid regions, dynamic effects offset the thermodynamic effects (Tabari, 2020). Flooding intensity is also projected to increase across the globe but more so in humid regions (Tabiri, 2020). Projected changes in the higher percentiles of daily and hourly rainfall extremes over the Alpine region under the RCP8.5 emissions scenario revealed slight increases in both frequency and intensity of daily and hourly extremes (Ban *et al.*, 2015). Kharin *et al.,* (2018) investigated the risk factor of climate extremes at 1.5°C and 2.0°C warming and found a 17% and 19% increase in rainfall extremes respectively and a higher risk of increases for longer return period events. In an earlier study, Fischer and Knutti (2015) found that the probability of increase for extreme rainfall events exceeding the 99.99^{th} percentile at 2°C warming could range between a factor of 1.5-3, dependant on the region, and an extreme event which occurred every 30 years in pre-industrial conditions was likely to occur every 10-20 years. Martel *et al.,* (2020) investigated the projected changes in 100-year sub daily, Rx1day, and Rx5day rainfall extremes for the period 2080-2099 using the 1980-1999 reference period. Results showed increases in the frequency of rainfall extremes in most places but decreases in some places in the tropics and subtropical regions (Martel *et al.*, 2020). The 100-year return period was 4-5 times more frequent in the future (Martel *et al.*, 2020). Future projections of changes in the Rx1day rainfall extreme that were investigated by Donat *et al.,* (2019) found increases for both humid and arid regions, with larger increases for humid regions and larger increases for the RCP8.5 emission scenario. These findings are comparable to those of Tabiri (2020). Most arid regions showed increases in extreme rainfall events, with regional decreases for north and south-west Africa (Donat *et al*., 2019).

Projections for future precipitation changes for South Africa exhibit mixed patterns, however, a general drying with regards to mean total is expected (Pinto *et al.*, 2016; Almazroui *et al.*, 2020). This is evident across the different GCMs simulations, i.e., CMIP5, CMIP6 and Coordinated Regional Climate Downscaling Experiment (CORDEX) simulations, and for the different emission scenarios, both RCPs and SSPs (Pinto *et al.*, 2016; Almazroui *et al.*, 2020). Changes in mean rainfall amounts are not projected to be significant (Fauchereau *et al.,* 2003). However, Lumsden *et al., (*2009) contradicted this finding and found projections of significant increases in annual mean precipitation over the east and decreasing over the west coast and adjacent interior. Projections also exhibited that there may be variations in seasonal mean precipitation in the future, which may affect seasonal rainfall onset and duration (Shongwe *et al.*, 2009; Pinto *et al.*, 2016). There is a general tendency towards increased drying, which will manifest as lesser wet days (or increases in days with no rainfall) but a more significant signal is depicted over the south-west (Lumsden, Schulze and Hewitson, 2009; Abiodun *et al.*, 2017; Maúre *et al.*, 2018). When considering extreme rainfall events, increases in very heavy to extreme rainfall frequency, maximum daily extremes and decadal wet events can be expected over the eastern parts (Groisman *et al.*, 2005; Lumsden *et al.*, 2009; Shongwe *et al.*, 2009; Engelbrecht *et al.*, 2013; Pinto *et al.*, 2016; Pohl *et al.*, 2017). Seasonal variations in future projections have also been detected where extreme rainfall events will increase for austral spring and summer (Engelbrecht *et al.*, 2013). Extreme rainfall events were projected to increase in a NW-SE pattern during austral spring, linked to a projected increase in cloud bands associated with tropical temperate troughs (Englebrecht *et al.*, 2013). Future projections of closed low pressure systems and associated extreme rainfall exhibit decreases of both in the future over southern Africa, except for low pressures and

associated extreme rainfall over Mozambique, the Mozambique channel, and the north-eastern South Africa (Englebrecht *et al.*, 2013). This corroborates findings in the IPCC report where global occurrences of tropical cyclones will remain unaffected or become less with global warming (Seneviratne *et al.*, 2021). However, the intensity of rainfall associated with these systems are projected to increase (Seneviratne *et al.*, 2021). Drought frequency is projected to be more significant over the western parts of the country (Shongwe *et al.*, 2009; Engelbrecht *et al.*, 2015).

2.5 Flooding in South Africa

Flooding is a common phenomenon in South Africa (Dyson and Van Heerden, 2002). Flooding occurs when the normal boundaries of the accumulation of water overflow due to heavy precipitation or the exceedance of drainage systems discharge capacity (Douben, 2006). Flooding in smaller catchment areas is often caused by single day extreme rainfall events during thunderstorms, but larger floods are caused by the influence of moisture advection from the surrounding oceans (i.e., Atlantic, and Indian ocean) over approximately 3-5 days (Tramblay *et al.*, 2021) Flooding has been correlated more to soil moisture than to extreme events (Tramblay *et al.*, 2021). The Rx1day, Rx5day and soil moisture was correlated to flooding events across Africa, and results indicated correlation coefficients of 0.47, 0.53 and 0.57 respectively, however, over the eastern South Africa, flooding events were mainly attributed to RX5day extreme rainfall events (Tramblay *et al.*, 2021). Although flooding will likely increase in a warming climate, observed flooding trends have not been changing consistently (Tramblay *et al.*, 2020). In west Africa, a study based on flooding trends in 11 catchments of Sahelina and Sudanian zones, found increasing trends for flooding

intensity and frequency for the Sahelian catchments but decreased for one Sudanian catchment (Nka *et al.*, 2015). Similarities were also found between flood trends and trends in the intensity of heavy rainfall and Rx5day (Nka *et al*., 2015). Over the Western Cape in South Africa, the frequency of floods has increased during the past four decades from two flood events per year to more than four flood events per year between the period of 1900-2018 (Dube *et al.*, 2022).

Some of the largest floods in eastern South Africa are attributed to tropical depressions, tropical storms and tropical cyclones making landfall over Mozambique, and subsequently affecting the north-eastern parts of the country as well as northern and coastal KwaZulu-Natal (Botes, 2014; Tramblay *et al.*, 2021). Examples are Tropical Storms Domonia and Imboa in 1984 (Botes, 2014; Mpungose *et al.*, 2022). Widespread flooding has also been associated with Cut-Off Lows (COLs) such as the widespread flooding over the coastal areas of KwaZulu-Natalin April 2019 and April 2022 (Bopape *et al.*, 2021; Thoithi *et al.*, 2022). Although, the April 2022 floods were predominantly caused by a COL at a large scale, a Mesoscale Convective System (MCS) which developed off the east coast and its interaction with a meso-low contributed to the heavy rains and flooding along the KwaZulu-Natal coast (Thoithi *et al*., 2022).

2.6 The Effect of Climate Drivers on Extreme Rainfall

Large modes of climate drivers influence rainfall variability at interannual to interdecadal scales. El Niño Southern Oscillation (ENSO) is the most influential climate driver on rainfall globally (Sun *et al.*, 2015). The ENSO is an interannual ocean and atmospheric coupled phenomena that has range of two to six- year patterns

between warm (El Niño) and cool (La Niña) phases (Goly and Teegavarapu, 2014). It forms through the warming of the tropical Pacific Ocean to the west of South America, and influences rainfall characteristics and extremes (Goly and Teegavarapu, 2014; Wei *et al.*, 2017). However, it has a vast global influence which is typically in conjunction with other local climate drivers, and this varies for different regions (Sun *et al.,* 2015). In southern Africa, rainfall is influenced by three modes of SST variability: ENSO, Subtropical Indian Ocean Dipole (SIOD) and the Southern Annular Mode (SAM; Hoell *et al*., 2017; Reason and Rouault, 2005), with the ENSO considered to be the most dominant. El Niño (La Niña) generally leads to anomalously dry (wet) conditions over southeastern Africa during austral spring and summer (Reason and Mulenga, 1999; Hoell *et al.*, 2017). Drought conditions are generally linked to a mature El Niño phase (Mason and Tyson, 2000; Baudoin *et al.*, 2017). However, there are instances where it is linked to a La Niña phase, as was seen with the 1992/1993 drought (Reason and Rouault, 2005; Blamey *et al.*, 2018). The SIOD positive phase is characterized by warm (cool) SST anomalies in the southwest (southeast) Indian Ocean, and a negative phase by cool (warm) SST anomalies (Suzuki *et al.*, 2004; Hoell *et al.*, 2017). Reason and Mulenga (1999) found that rainfall increases over southeastern Africa in a positive SIOD phase, and relationships between the rainfall and the SIOD are more defined in austral summer. The SAM mainly affects the southwestern South Africa (Reason and Rouault, 2005). Wet (dry) winters are linked to a negative (positive) phase of the SAM (Reason and Rouault, 2005). ENSO has a strong correlation to the variability of mean precipitation at both seasonal and annual scales; however, some correlation has also been identified with extreme precipitation (King *et al.*, 2014; Wei *et al.*, 2017; Yang *et al.*, 2019). Numerous studies have found variations in the effects of climate drivers on extreme rainfall in the same region, be it

spatially or temporally, and that other climate drivers generally modulate ENSO or even have more of an influence on extreme rainfall compared to ENSO (Casanueva *et al.*, 2014; Goly and Teegavarapu, 2014; King *et al.*, 2014; Jiang *et al.*, 2016; Wei *et al.*, 2017; Xiao, Zhang and Singh, 2017; Yang *et al*., 2019). There have also been results indicating a combination of phases between ENSO and other climate modes having an influence on extreme rainfall (e.g., Limsakul and Singhruck, 2016; Rapolaki *et al*., 2019). Over the Limpopo River Basin in southern Africa, the top 20 and 200 daily extreme rainfall events were linked to the La Niña phase in combination with a positive SIOD phase (Rapolaki *et al.*, 2019). Weak yet statistically significant correlations between ENSO and Pacific Decadal Oscillation (PDO) with extreme rainfall indices were detected in Thailand, where extreme rainfall events were more abundant in a La Niña and PDO cool phase scenario (Limsakul and Singhruck, 2016). In China, extreme rainfall responded to different phases of the ENSO, Indian Ocean Dipole (IOD), North Atlantic Oscillation (NOA) and PDO, and depicting opposing trends and spatial variations (Xiao *et al.*, 2017). In Australia, there was a distinct seasonal and spatial influence of ENSO on extreme rainfall, that is, ENSO influenced extreme rainfall during the warm season and particularly over the eastern parts (King *et al.*, 2014). In the Beijing-Tianjin Sand Source Region, China, extreme precipitation intensities (RX1day and RX5day) were mainly positively correlated to the East Asian Summer Monsoon (EASM) compared to ENSO, however, when correlated to ENSO, extreme precipitation was higher during El Niño (Wei *et al.*, 2017). In Canada, the R95p and R99p indices were analysed, including their relationship to various climate drivers that influence rainfall (Yang *et al.*, 2019). Different parts of the country were influenced differently by the climate drivers, that is, western Canada was strongly related to the positive phases of Multivariate ENSO Index (MEI; an index representing

ENSO), PDO, PNA and North Pacific Gyre Oscillation (NPGO), central Canada was teleconnected with NOA and NPGO and eastern Canada by MEI, PNA and NPGO (Yang *et al.,* 2019). In Florida (USA), spatial and seasonal variations were depicted when the relationship between extreme rainfall and the Atlantic Multidecadal Oscillation (AMO) was investigated (Goly and Teegavarapu, 2014). Results showed that extreme rainfall (RX1day, RX5day and CDD) positively correlated to the warm phase of the AMO across the state but only in certain areas for frequency based extreme rainfall indices (Goly and Teegavarapu, 2014). Extreme rainfall was more dominant towards March to April during the AMO cool phase and towards the end of the season (June to August) for the warm phase (Goly and Teegavarapu, 2014). Investigating the ENSO influence on extreme rainfall, it was found that El Niño and La Niña contributed to an increase and decrease in extreme and total precipitation respectively (Goly and Teegavarapu, 2014). A combination of AMO-ENSO phases was also investigated with varying results of spatial and temporal patterns. In the western USA, a dipolar spatial pattern was exhibited when ENSO was correlated to extreme precipitation, wherein, there was a positive (negative) correlation over the northern (southern) regions (Jiang *et al.*, 2016). A wavelet analysis during the winter season indicated a two-to-20-year band of extreme rainfall indices, indicating that extreme rainfall variability may be governed by other ocean oscillations apart from ENSO, which exhibits 2–8-year cycles (Jiang *et al.*, 2016). Over Europe numerous climate drivers were observed to have influenced extreme rainfall variability and these varied seasonally (Casanueva *et al.*, 2014). The North Atlantic Oscillation (NOA), East Atlantic Pattern (EA), East Atlantic/Western Russia Pattern (EAWRUS) and Scandinavian Pattern (SCAND) being the most dominant. In summer and winter, the NOA was more correlated to mean and extreme rainfall but with opposing signs. In

spring and autumn, the SCAND, the EAWRUS and the EA influenced the changes of extreme rainfall, with a greater influence in autumn (Casanueva *et al.*, 2014).

2.7 Linking Extreme Rainfall to Synoptic-Scale Systems

South Africa is a semi-arid region with spatial and seasonal variations in rainfall (Blamey and Reason, 2013; Botai *et al.*, 2018). These spatial and temporal distributions of rainfall are influenced by different factors: topography, the subtropical location of the region, and the atmospheric-oceanic interactions with the surrounding oceans, particularly the Agulhas Current along the east coast of the subcontinent (Blamey and Reason, 2013). The east and interior of South Africa is dominated by summer rainfall (November to March), apart from the south-western parts, that receive most of their rainfall in winter (June to August), and the south coast which experiences rainfall all year round (Roffe *et al.*, 2021)

South Africa is influenced by rain-bearing systems from the tropical easterlies as well as westerly mid-latitude disturbances, which include: the Tropical Temperate Trough (TTT), Tropical Lows, the cold front and upper trough and the COL (Tyson and Preston-Whyte, 2000). The summer rainfall region of South Africa is also influenced by the ridging high over the east coast and an easterly low pressure over the northern interior, which results in wet conditions (Cook *et al.*, 2004). Most extreme rainfall events that lead to widespread flooding are produced by a synoptic scale circulation that is dominated by a combination of these systems (Reason and Mulenga, 1999; Tyson and Preston-Whyte, 2000; Singleton and Reason, 2007).

2.7.1 Tropical Temperate Troughs

The TTT is the dominant rain-producing system for most of southern Africa, which forms a band of convection in a NW-SE orientation across the subcontinent (Williams *et al.*, 2007; Hart *et al*., 2010). This system is a connection between a semi-permanent tropical low pressure usually situated over southern Africa and a westerly mid-latitude system passing south of Africa (Reason and Mulenga, 1999; Tyson and Preston-Whyte, 2000). The easterly flow over subtropical southern Africa and westerly flow from the tropics results in a convergence and uplift zone which leads to widespread rains across southern Africa (Reason and Mulenga, 1999; Tyson and Preston-Whyte, 2000).

TTTs are the most dominant over the summer rainfall region, with a frequency of 3-4 of these cloud band systems occurring between November and March per month (Hart *et al.,* 2013). They contribute an overall 30% to the total rainfall during the summer season, with peak monthly contributions in November and January (Hart *et al.,* 2013). Over KwaZulu-Natal, TTTs contribute to 40% of total summer rainfall. Rainy days (R10mm), heavy rain days (R20mm) and very heavy rain days (R50mm) were linked to TTTs, where 60% of rain days and heavy rain days events were linked to TTTs during November and January (40% in December), and approximately 50% of very heavy rain days were linked to TTTs throughout summer (Hart *et al.,* 2013). Over the Limpopo River Basin, Rapolaki *et al.,* (2019) found that of the top 20 extreme rainfall events that had been observed in the region for the period 1981-2016 45% of these were produced by TTTs, 45% by tropical lows 10% by Mesoscale Convective Systems (MCS). For the top 200 events 48% were produced by TTTs, 28% by tropical lows and 14% by MCS (Rapolaki *et al.*, 2019).

2.7.2 Cut-off Lows

A COL is a closed cold-cored low-pressure system that detaches from the upper westerlies and extends to the surface (Tyson and Preston-Whyte, 2000). They are associated with “deep moist convection, which can lead to significant amounts of rain over a short period, leading to flash-flooding” (Singleton and Reason, 2007:295). Where COLs are intense (although less frequent over South Africa) daily rainfall amounts can even accumulate to three times the monthly average (Favre *et al.,* 2012; Molekwa *et al.,* 2014). They occur in any season but are more common between late summer until autumn, where they produce heavy and widespread rainfall over the country (Singleton and Reason, 2007; Favre *et al*., 2013). An estimated eleven COLs occur in the subcontinent (Singleton and Reason, 2007). There are fewer COLs in spring compared to autumn, but precipitation is more widespread and intense (Favre *et al.*, 2012; 2013).

COLs contribute to a large portion of extreme rainfall days along the east and south coasts of the country, as well as the transition zone between summer and winter rainfall regions (Favre *et al.*, 2013). A study by Favre *et al*., (2012) of COLs between the period 1979-2010, showed that south and east coasts had the most contribution of COL induced rainfall to annual amount of rainfall, as well as a higher frequency of rain days (8-15 days) and extreme rain days (approximately 1-2 days) credited to COLs. COLs associated with blocking can result in two or three days of continuous heavy rainfall leading to severe flooding (Favre *et al.,* 2013). Molekwa *et al*., (2014) found that the frequency of COL was more dominant in winter and less in summer over the Eastern Cape, with heavy rain day events (R20mm) being more frequent in winter. The largest contributions of COLs to extreme rainfall were in ‘all-year rainfall’ are of the Eastern Cape. Most out-of-season rainfall across the country is attributed to

these systems, i.e., winter rainfall in summer regions is largely attributed to COLs, and vice versa for summer rainfall in winter regions (Favre *et al.,* 2013). COLs have been linked to some well-known heavy rainfall and widespread flooding over KwaZulu-Natal over the years. These are briefly unpacked in Chapter 3.

2.7.3 Mesoscale Convective Complexes

Although not as large-scale, Mesoscale Convective Complexes (MCCs) have also been known to notably contribute to summer rainfall in South Africa, particularly to intense rainfall (Blamey and Reason, 2013; Rapolaki *et al.*, 2019). The spatial distribution of MCCs is mainly confined to the eastern parts of southern Africa, and these systems can produce maximum rainfall more than 130mm and can contribute between 8-16% of the total summer rainfall (Blamey and Reason, 2012). The largest amount of rain recorded in the April 2022 floods over the south coast of KwaZulu-Natal were attributed in part to a Mesoscale Convective System (MSC) which tracked down from Maputo and connected to a meso-low off the KwaZulu-Natal coast (Thoithi *et al.*, 2022).

2.8 Conclusion

As outlined in the literature review, numerous studies on the trends of extreme rainfall events have been conducted in South Africa and globally. Various methods have been adopted, with the most common being the calculation of moderate extremes from the WMO ETCCDI. Results from various studies have indicated varying spatial and temporal changes in extreme rainfall trends, which is expected due to the highly spatial and temporal variability of rainfall.

In the South African context, a few studies have explored trends in extreme precipitation by analysing subsets of the ETCCDI indices (Mason *et al*., 1999; Kruger,

2006; New *et al*., 2006; MacKellar *et al*., 2014; Kruger and Nxumalo, 2017). These studies considered South Africa as a whole or sections of the SADC region. A common restriction that has been identified in literature regarding studies on historical trends is the lack of sufficient station coverage over an area, to give a clear depiction of a region's climate (MacKellar *et al*., 2014, Kruger and Nxumalo, 2017). According to Kruger (2006) this restriction can result in incoherent representation of spatial trends. Due to the high variability of rainfall across spatial and temporal scales, trends can often be difficult to detect and are sensitive to location and observation period (MacKellar *et al*., 2014). Literature also recommends the updating and re-assessment of trends on a regular basis as new observational datasets become available (Mackellar *et al*., 2014; Kruger and Nxumalo, 2017).

Over KwaZulu-Natal, trend analysis has only been assessed on microclimates of specific regions (Nel, 2009; Strydom and Savage, 2018, Strydom *et al*., 2020; Ndlovu *et al*., 2021; Mpungose *et al*., 2022), while the incidence of extreme rainfall events has been assessed using historical meteorological and hydrological data, i.e., flooding data, of specific extreme events (Botes, 2014).

This study is therefore important as it will be the first application of the ETCCDI indices to explore the incidence and trends of extreme rainfall across KwaZulu-Natal. Although having a shorter observational period than the previous updated study by Kruger and Nxumalo (2017), which assessed trends for a period of 1921-2015, and considered South Africa has a whole, this study will include recent additional data up to 2019 and consider 11 stations in KwaZulu-Natal, where only six stations represented KwaZulu-Natal in the study by Kruger and Nxumalo.

Chapter 3: Study Area

The study region is KwaZulu-Natal, which is a Province located over the eastern parts of South Africa. This study area was chosen due to the April 2019 floods which caused widespread flooding. These floods triggered an interest in exploring the incidence of extreme rainfall over the province.

3.1 Geography and topography

KwaZulu-Natal is one of the nine provinces of South Africa, located over the sub-tropical north-eastern part of South Africa (Fig. 1), with the geographical coverage spanning 27-31°S and 28-32°E and a surface area of 94,000 km^2 (Turpie *et al.,* 2020). It is bounded by neighbouring provinces and countries: Eastern Cape to the south, Lesotho and the Free State to the west, Mpumalanga to the north-west and Eswatini to the north. The topography extends from the coast, ranging from sea level to 200m.asl to the Drakensberg Mountain Range 3500m.asl, with an elevated plateau of 1000-2000m.asl between the coast and the Drakensberg Mountain Range (Blamey and Reason, 2009; Botes, 2014). The east coast of KwaZulu-Natal is flanked by the Indian Ocean and the warm Agulhas Current.

The population of KwaZulu-Natal is the second largest in the country and it is the second largest contributor to the national Gross Domestic Product (GDP), contributing 15.8% share of the national GDP in 2011 (Turpie *et al.,* 2020). The economic hub of KwaZulu-Natal is concentrated in the metropolitan areas of Durban, Pietermaritzburg,

and Richards Bay, with manufacturing and tertiary industries being the main contributing sectors of the economy (Turpie *et al*., 2020).

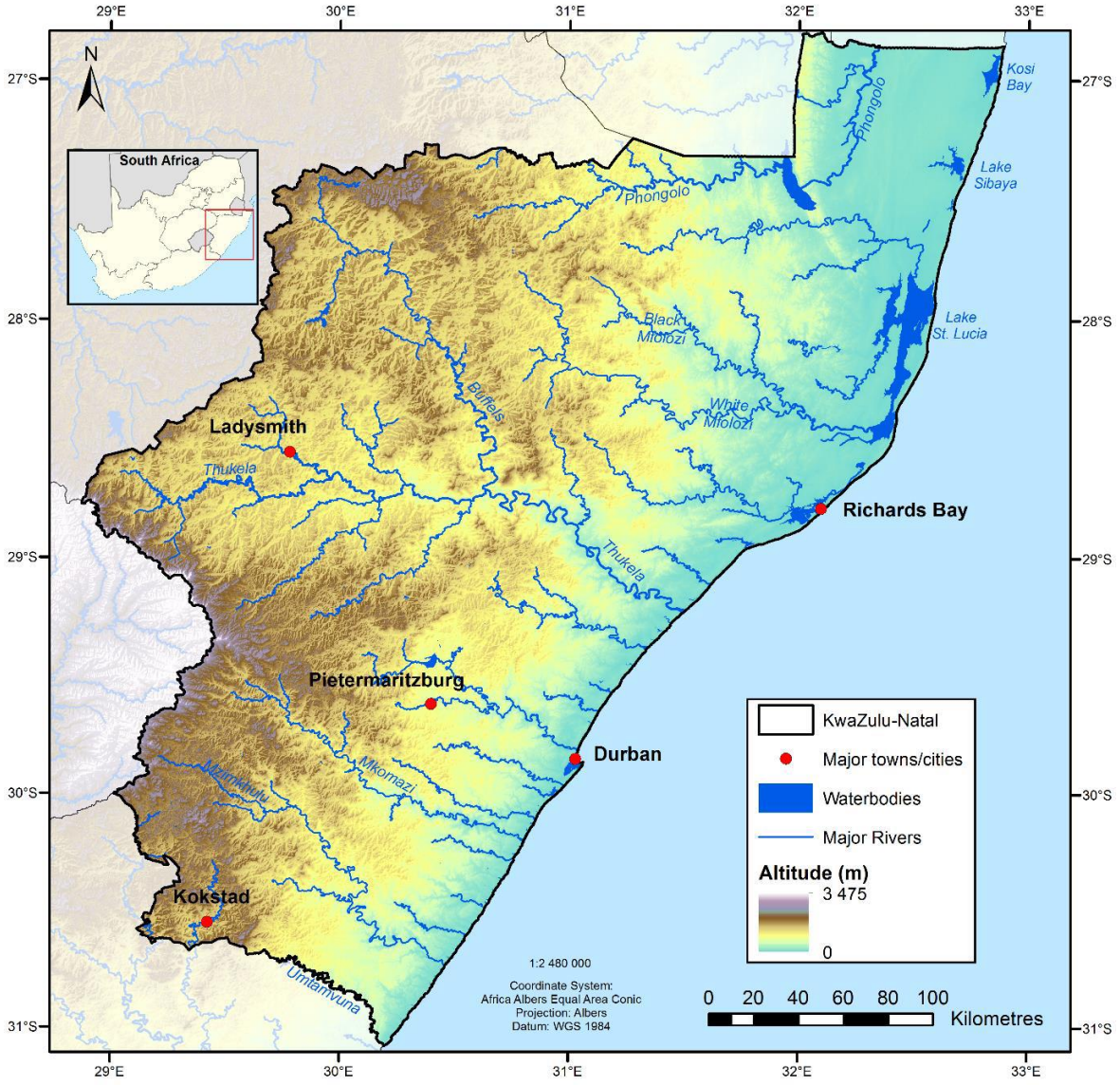


Figure 1: Topographical Map of KwaZulu-Natal (Turpie et al., 2020)

3.2 Climate of KwaZulu-Natal

The climate of KwaZulu-Natal falls under the 'temperate' climate region based on the Köppen-Geiger classification (Englebrecht and Englebrecht, 2016). It is dominated by three climatic zones two of which have dry winters and hot and warm summers respectively (Cwa and Cwb) and one (Cfb) with a warm summer and no dry season

(Englebrecht and Englebrecht, 2016). The climate of South Africa, and subsequently KwaZulu-Natal, is influenced by the location of the subtropical high-pressure belt (Camp, 1999; Tyson and Preston-Whyte, 2000). The high-pressure belt is situated overland in winter, resulting in subsidence and dry conditions (Tyson and Preston-Whyte, 2000). It results in a blocking effect for cold fronts to affect most areas of the country (Dedekind *et al.,* 2016). In summer, the high-pressure belt weakens and moves south, and a low-pressure trough dominates the interior (Tyson and Preston-Whyte, 2000; Roy and Rouault, 2013). The south-easterly position of the Indian Ocean anticyclone (the Mascarene High) in summer aids in the advection of moisture to the east, which converges with tropical moisture brought by the interior low or orographic influences, and results in long periods of rainfall in summer (Camp, 1999).

3.2.1 Temperature

KwaZulu-Natal is classified as a temperate climatic region based on the Köppen Geiger classification, however, the variations in temperature across the province splits the region into subtropical and temperate regions (Camp, 1999). The coastal and lowland areas of KwaZulu-Natal have a subtropical climate, where the average temperatures of the coldest month range between 13-18°C while midlands and highland regions have a temperate climate, where the average temperature of the coldest months is below 13°C (Camp, 1999). The spatial orientation of the average temperature follows the topography (Fig. 2), where highest temperatures occur along the low-lying or coastal areas and gradually decrease towards the Drakensberg escarpment (Kruger, 2007). Inland temperatures are more extreme than coastal temperatures as the latter are moderated by the ocean and the high specific heat

capacity of water, resulting in temperate diurnal to seasonal temperatures (Ndlovu *et al*., 2021).

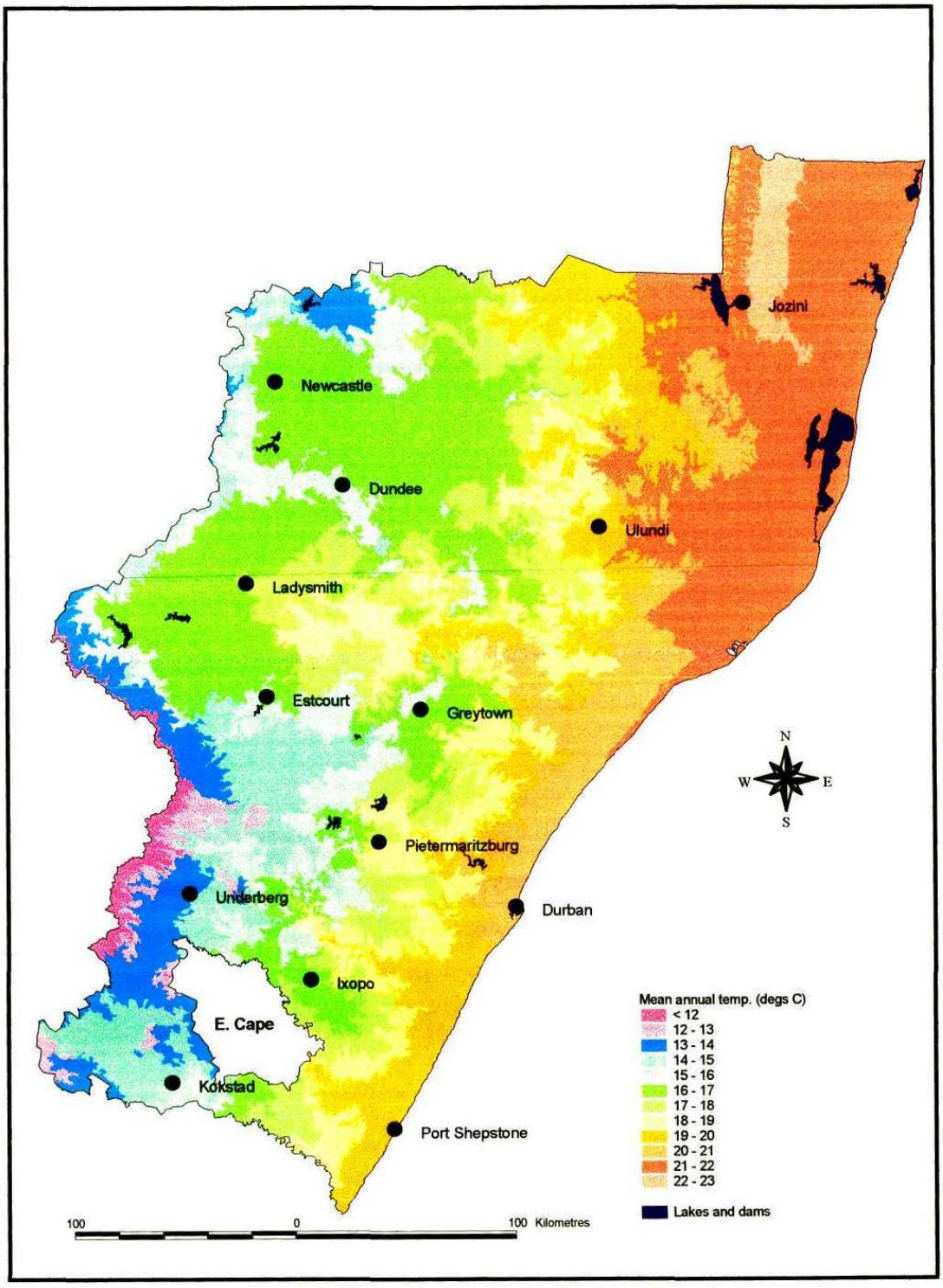


Figure 2: Mean annual temperature of KwaZulu-Natal (Camp, 1999)

3.2.2 Rainfall and extreme rainfall events

3.2.2.1 Average rainfall and distribution

KwaZulu-Natal receives average annual rainfall between 650-1400 mm (Fig. 3), which predominantly occurs over the summer period (Nel, 2009; Ndlovu *et al.,* 2021). It is dominated by three of the 24 climatic regions of South Africa (regions 6, 7 and 12), and these regions have variable rainfall at annual, seasonal, and monthly temporal scales (Ndlovu *et al.*, 2021). Region 6 stretches from the east coast to the Drakensberg, is characterised as wet and humid and receives up to 1400mm average rainfall (Ndlovu *et al.*, 2021). Region 7 is situated in the northern parts of KwaZulu-Natal, is characterised as hot with an annual average rainfall of 900mm (Ndlovu *et al.,* 2021). Region 12 is in the southern parts of KwaZulu-Natal, with an average rainfall ranging between 650-1000mm (Ndlovu *et al.,* 2021). The seasonality of rainfall in KwaZulu-Natal depicts higher rainfall during summer (December, January, February) with average rainfall above 300mm across the entire Province, which starts to decrease during autumn (March, April, May), ranging from 150mm to above 300mm along the coastal regions and adjacent interior (Kruger, 2007). During winter (June, July, August), average rainfall across the province is less than 100mm, except for the coastal regions where rainfall can average between 100-200mm (Kruger, 2007). In spring, average rainfall increases again ranging from 150mm to above 300mm (Kruger, 2007).

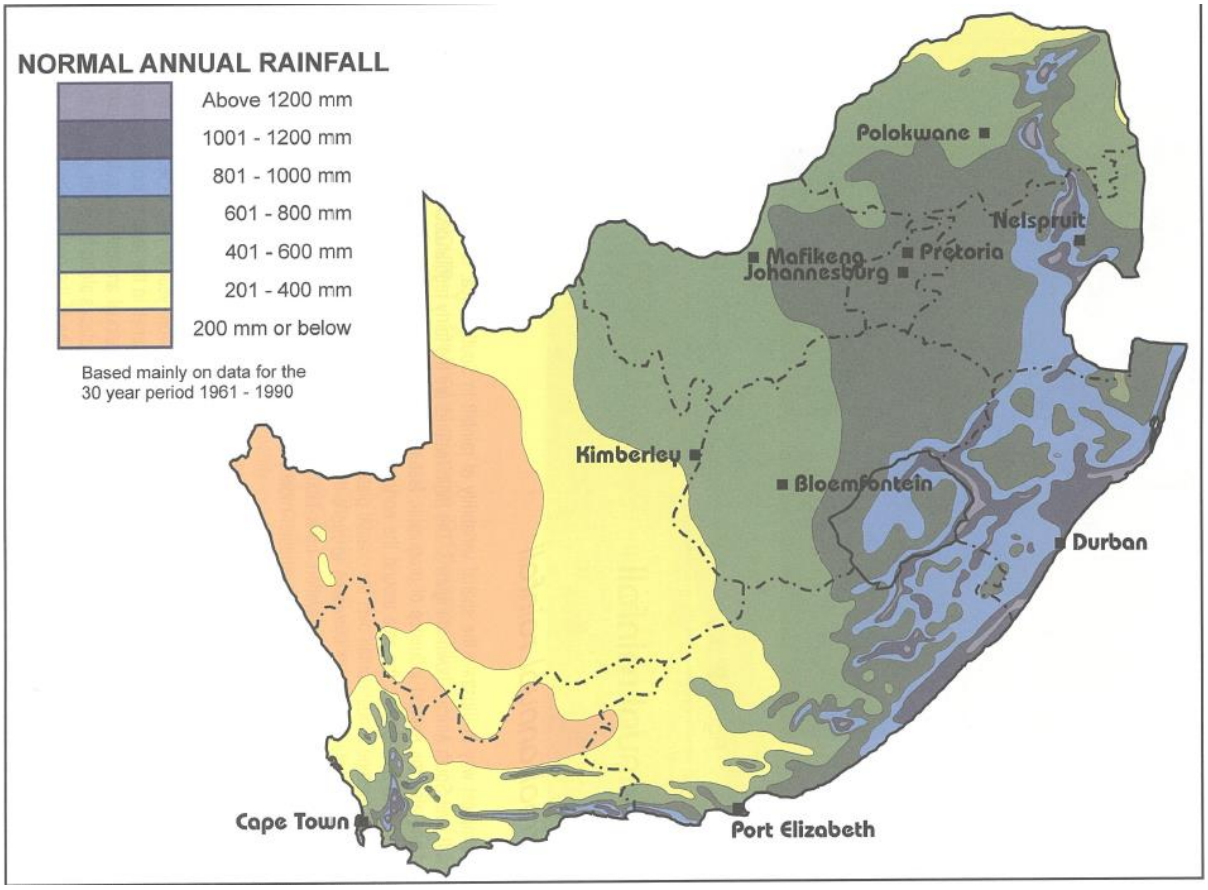


Figure 3: Average annual rainfall for South Africa (Kruger, 2007)

3.2.2.2 Extreme rainfall and flooding

KwaZulu-Natal experiences interannual rainfall variations and is also prone to cyclical periods of droughts and annual regional flooding (Dube and Jury, 2000; Botes, 2014). It is one of the provinces with the most frequent occurrence of floods, ranging between small to medium flood events at localised scales to extreme and widespread flood events (Botes, 2014). Storm and extreme rainfall events over KwaZulu-Natal have an average duration of three to four days, with the highest occurrence from January to May (Botes, 2014). The coastal zones and adjacent interior of KwaZulu-Natal are most prone to extreme rainfall events and flooding, particularly the southern coastal belt (Botes, 2014; Mpungose *et al.*, 2022). The predominant rain type in KwaZulu-Natal is convective in nature, and KwaZulu-Natal is considered a hotspot for severe convection throughout the summer period due to its proximity to and influence from the Agulhas

Current (Tyson and Preston-Whyte, 2000; Blamey *et al*., 2017). Noteworthy heavy rain and widespread flooding events are listed in Table 1.

Table 1: Extreme rainfall and widespread flooding events in KwaZulu-Natal

Flooding event and system	**Multiple day accumulation (days)**	**Stations**	**Fatalities/cost of damage**
TS Domonia Jan/Feb1984	1018 mm (5) 955 mm (5) 925 mm (5) 702 mm (5) 347 mm (5) 402 mm (5) 539 mm (5)	Tokazi Cwaka Agri Boshoek Cape St. Lucia Hluhluwe Dam Nongoma Louwsburg	R100 million in damage, more than 200 fatalities, tens of thousands affected
September 1987 COL	914 mm (4) 881 mm (4) 874 mm (4) 757 mm (4) 742 mm (4)	Langepan Kwambonambi Cwaka Agri Paddock Marah	400 deaths/displacement of tens of thousands of people
April 2019 COL	440 mm (2) 326 mm (2) 304 mm (2) 297 mm (2) 255 mm (2)	Margate Durban Paddock Port Edward Scottburgh	71 deaths, displacement of 1400 people, R650 million in damage
April 2022 COL	575 mm (8) 530 mm (8) 490 mm (8) 326 mm (8) 295 mm (8) 158 mm (8)	Margate Pennington Port Edward King Shaka IA Richards Bay Pietermaritzburg	440 fatalities, 40 000 displaced people, R17 billion in estimated damages

Tropical Cyclone Domonia, 1984

In early February of 1984, Tropical Cyclone Domonia made landfall over the Mozambican coastline, and made its trajectory over the subcontinent affecting the northern parts of KwaZulu-Natal (Kovacs *et al.*, 1985). Three weeks later, Tropical Cyclone Imboa affected the Zululand coast, with heavy rains occurring along the coast between Cape St. Lucia and Durban (Kovacs *et al.*, 1985). The five-day rainfall accumulation from Tropical Cyclone Domonia recorded rainfall figures of more than 700 mm in Cape St. Lucia and over 500 mm in Louwsburg (Kovacs *et al.,* 1985).

Flooding event September 1987

In September 1987, a COL system resulted in widespread flooding over KwaZulu-Natal, with rainfall records reaching 800 mm over a period of five days (Thoithi *et al.*, 2022). This flooding event resulted in over 500 deaths and the dispersion of tens of thousands of people (Thoithi *et al.*, 2022).

Heavy rain and flooding event 22-23 April 2019

A COL produced large amounts of rainfall and flooding over southern KwaZulu-Natal and northern parts of the Eastern Cape on 22-23 April 2019 (Bopape *et al.*, 2021). The extent of the devastation resulted in the declaration of a provincial disaster (Bopape *et al.*, 2021). The impacts of the heavy rain and flooding resulted in 71 fatalities, displacement of 1400 people and estimated damages of R650 million (Bopape *et al.*, 2021; Letsatsi and Kruger, 2022).

Heavy rain and flooding event 10-12 April 2022

A COL affected the KwaZulu-Natal coast on 10-12 April 2022, resulting in heavy rain and devastating floods (Thoithi *et al.*, 2022). The heaviest rainfall was measured over the south coast, with some stations recording rainfall exceeding 300 mm. Flooding associated with this event caused over 400 deaths, displacement of 40 000 people and missing people (Thoithi *et al.*, 2022).

3.3.3 Humidity

KwaZulu-Natal is one of the most humid Provinces in South Africa (Schulze, 1997). The spatial distribution of relative humidity follows the topography much like the

temperature, where more humid areas are depicted along the coastal areas and adjacent interior, becoming less humid in the west over the escarpment (Schulze, 1997). Relative humidity is above 60% over the province, with the coastal and adjacent interior exhibiting relative humidity above 70% for the majority of the year (Schulze, 1997). Seasonal variations in relative humidity can also be detected, with relative humidity decreasing during the autumn into winter and increasing from spring into summer (depicted in images in Appendix B, Schulze, 1997). The summer months are the most humid and wet months for the province, which correlates with KwaZulu-Natal being a summer rainfall region (Schulze, 1997; Roffe *et al.*, 2021).

3.3 Rainfall-bearing systems

KwaZulu-Natal is influenced by the TTT, Tropical/Subtropical Lows, Tropical Cyclones/depressions, the cold front and upper trough and the COL (Diab *et al.,* 1991; Tyson and Preston-Whyte, 2000; Botes, 2014). Tropical Cyclones and Tropical Depressions affect KwaZulu-Natal infrequently compared to other atmospheric circulation systems, and their influence is mainly over the eastern/north-eastern parts of KwaZulu-Natal (Harrison, 1984; Mpungose *et al.*, 2022). These systems produce summer rainfall (November to February); however, cold fronts bring rain in winter through to early summer, with COLs occurring over the winter to spring months (April to November), but predominant from March to May and September to November (Camp, 1999; Tyson and Preston-Whyte, 2000; Botes, 2014). TTTs contribute 40% of the total summer rainfall over KwaZulu-Natal, with 60% of heavy rainfall and extreme rainfall days being linked to these systems (Hart *et al.*, 2013).

Chapter 4: METHODOLOGY

4.1 Introduction

The analysis of extreme trends requires a long and continuous time series with a daily temporal resolution to “obtain reasonable estimates of intensity and accuracy of rare events” and “to consider the sub-monthly nature of extremes” (WMO, 2009: 9). Selecting candidate stations considers data completeness and series length (WMO, 2009). The WMO stipulates a minimum of 30 years of data when conducting a climate related study, with data gaps not exceeding four years (Kundzewicz and Robson, 2000). Ninety percent data completeness has generally been accepted in some trend analysis studies (Moeletsi and Walker, 2012; Kruger and Nxumalo, 2017). This section details the data preparation, quality control methods used and data verification process that was undertaken. The second part of this section details the methodology for the trend analysis, which calculated a subset of the WMO ETCCDI and ET-SCI indices.

4.2 Data and Quality Control

Daily rainfall data was sourced from the South African Weather Service (SAWS). The SAWS reports 24-hour accumulated rainfall, which is measured at 08h00 SAST (Dyson, 2009). In this study, rainfall stations with records spanning a 30-year period were considered, where 90% of the dataset (i.e., less than 10% of missing values) was complete. This data efficiency percentage is considered as sufficient, however, should not include accumulated totals (Moeletsi and Walker, 2012; Kruger and Nxumalo, 2017). During the quality control process, it was established that most of the

stations had data completeness percentages ranging between 97-99.5% (Table 2), which makes the data suitable for the study.

Table 2: Table showing 30-year rainfall stations used in the study and coinciding data completeness.

Station Name	Latitude (°S)	Longitude (°E)	Elevation (m)	Percentage of data completeness	Period of missing data	Station Name	Latitude	Longitude	Elevation (m)	Percentage of data completeness	Period of missing data
Cedara	29.54	30.27	1017	99.79%	2001- 1 day 2003- 2 days 2004- 6 days 2006- 3 days 2007- 4 days 2008- 3 days 2010- 1 day 2013- 1 day 2014- 3 days	Mount Edgecombe	29.71	31.05	94	99.86%	1989- 5 days 1991- 2 days 1992- 92 days 1993- 183 days 1994- 180 days 1995- 9 days 1999- 10 days 2003- 4 days 2004- 3 days 2007- 15 days 2008- 2 days 2009- 9 days 2012- 3 days 2014- 4 days 2018- 5 days
Durban South	30.01	30.93	14	96.15%	2003- 1 day 2004- 1 day 2009- 2 days 2010- 3 days 2011- 4 days 2012- 16 days 2013- 8 days 2014- 1 day 2017- 3 days 2018- 213 days 2019- 184 days	Newcastle	27.73	29.92	1241	96.63%	1989- 31 days 1990- 3 days 1991- 5 days 1992- 2 days 1994- 11 days 1995- 28 days 1996- 43 days 1997- 19 days 1998- 11 days 1999- 59 days 2000- 41 days 2001- 16 days 2004- 3 days 2005- 12 days 2006- 11 days 2007- 2 days 2009- 10 days 2010- 5 days 2011- 3 days 2012- 5 days 2013- 6 days 2014- 12 days 2015- 8 days 2017- 29 days 2018- 7 days

Emerald	29.94	29.96	1154	98.69%	2001- 1 day 2002- 30 days 2003- 2 days 2006- 29 days 2010- 27 days 2011- 13 days 2012- 20 days 2013- 9 days 2014- 4 days 2016- 3 days 2017- 1 day 2018- 7 days 2019- 2 days	Paddock	30.75	30.26	506	96.76%	1992- 61 days 1993- 68 days 1994- 8 days 1995- 24 days 1997- 4 days 1999- 21 days 2000- 30 days 2001- 15 days 2002- 61 days 2003- 6 days 2004- 31 days 2005- 1 day 2006- 10 days 2007- 9 days 2008- 1 day 2009- 6 days 2010- 2 days 2011- 1 day 2017- 5 days 2018- 3 days
Estcourt	29.01	29.86	1159	98.60%	1995- 2 days 2001- 1 day 2003- 4 days 2004- 2 days 2006- 1 day 2007- 8 days 2010- 1 day 2012- 82 days 2013- 51 days 2014- 5 days 2018- 1 day 2019- 1 day	Pietermaritzburg darville	29.60	30.43	613	98.80%	1992- 31 days 1993- 30 days 2001- 1 day 2003- 2 days 2004- 2 days 2007- 7 days 2010- 68 days 2011- 17 days 2012- 26 days 2013- 3 days 2015- 11 days 2017- 1 day 2018-6 days
Makatini	27.39	32.18	63	98.96%	1990- 30 days 1994- 29 days 1997- 2 days 2001- 2 days 2003- 2 days 2004- 2 days 2005- 2 days 2006- 3 days 2008- 10 days 2009- 13 days 2010- 1 day 2013- 4 days	Shaleburn	29.79	29.35	1614	99.50%	1989- 32 days 1996 - 1 day 1999- 1 day 2001- 1 day 2002- 2 days 2003- 5 days 2004- 10 days 2005- 26 days 2006- 3 days 2007- 13 days 2010- 1 day 2016- 2 days

					2014- 5 days 2015- 8 days 2017- 1 day 2018- 1 day 2019- 3 days						
Maphumulo Prison				91.72%	1989- 151 days 1990- 62 days 1997- 7 days 2001- 2 days 2002- 275 days 2003- 120 days 2005- 31 days 2008- 29 days 2010- 30 days 2011- 67 days 2014- 8 days 2015- 14 days 2016- 13 days 2017- 10 days 2018- 119 days 2019- 8 days						

4.2.1Quality control

The main purpose of the quality control process is to point out errors caused by human error through manual keying, identifying outliers as well as identifying accumulated values over multiple days following a period of no data records (*WMO,* 2009). The ClimPactv2 software, which was used for data analysis, also has a quality control aspect which identifies missing days as well as outliers. The missing days text file was used to identify days not accounted for in the dataset. These days were subsequently added with a value of -99.90, to indicate that day as having missing data. The outliers were identified through the production of a box-and-whisker plot as well as a spreadsheet that identifies outliers. Outliers are flagged when precipitation values fall outside the range of p25-5IQR for the lower bound and p75 +5IQR for the upper bound (Alexander and Herold, 2016). These outliers were compared to SAWS raw data to identify whether any outliers were due to rainfall accumulation over several days. The raw data from SAWS has certain alphabetical letters which give more detail on the reported data. The letters “A” and “B” indicate that any rainfall that may have occurred is included in the total accumulation at the end of the period, while “C” next to a rainfall value indicates rainfall accumulated over several days. During the analysis of the raw data, rainfall values with a “C” next to them were identified and omitted from the analysis. Most of these values were not statistically identified as an outlier, apart for one day in the Maphumulo Prison weather station, where a value of 156mm was identified as an outlier. This reiterates the importance of visual checking of raw data to supplement statistical quality control tests (WMO, 2009). Outliers were also compared to a few sources, including the SAWS climate summaries, CAULEM (a history of notable weather events in South Africa:1500-1990) and newspaper articles archives from the SAWS. SAWS climate summaries highlighted significant systems

that occurred every month as well as the one-day maximum for each station in the SAWS network. These one-day maxima values were compared to the outliers identified by the ClimPactv2 software, and if these values coincided with a supposed outlier, that value was accepted as part of the analysis. Newspaper articles also aided in identifying some noteworthy rainfall days. If an article indicated key words such as ‘heavy rain’, ‘flooding’, ‘storm’ or ‘good rains’ in the KwaZulu-Natal Province, and the dates coincided with the dates of the outliers, these values were accepted into the analysis. Outliers were also analysed by comparing stations in the dataset that are within a 50km radius of each other to determine if significant rainfall may have been recorded on the same day. For example, if Cedara, Pietermaritzburg and Maphumulo Prison were compared and highlighted outliers on the same, that value was accepted as part of the analysis. For other stations where there were no stations within a 50km radius to compare to, a method adapted from Dyson (2009) was applied, where rainfall values were accepted if other stations in the province were reporting significant rainfall on the same days.

Major outliers can be seen in the annual box plots (Appendix A), created from the ClimPactv2 software (Table 2). Major outliers were selected based on the method adopted by Dyson (2009), where these were considered as rainfall events exceeding the 99th percentile for each station. These outliers were compared to verification references detailed above, i.e., newspaper articles, CAELUM, climate summaries, and in comparing whether other stations in the province or within 50km radius of said station also recorded high rainfall values.

The event dates for most of the major outliers spans the summer rainfall period between October to March (Roffe *et al.*, 2021), with a few events occurring in late autumn, winter and early spring. This seasonality in heavy rainfall events correlates to the findings of Dyson and Van Heerden (2002) that over 60% of heavy rainfall and flooding events occurred during the summer rainfall season.

Table 3: Table highlighting major outliers (rainfall values above the 99th percentile

Station name	99th Percentile value	Outlier value	Date of event	Event or contributing synoptic system
Cedara	48.6	71.1	1989-01-06	
		57.4	1989-11-29	Natal floods 28-30 November 1989
		67.0	1991-01-23	
		64.6	1991-11-10	Heavy rains 9–15 November 1991
		69.2	1991-11-13	Heavy rains 9–15 November 1991
		59.3	1993-03-03	
		56.6	1994-02-15	
		62.9	1995-12-25	Heavy rains 20-29 December 1995
		63.2	1996-05-17	
		68.3	1996-07-08	Intense cold front 3-8 July 1996
		48.8	1999-01-11	
		176.8	1999-11-15	
		49.5	1999-12-11	
		97.8	1999-12-27	
		83.6	2001-04-11	
		60.0	2001-09-12	
		55.4	2001-12-10	
		58.5	2002-07-19	
		49.4	2003-02-04	
		53.4	2007-11-21	
		58.2	2008-11-13	
		70.0	2012-08-07	
		69.2	2012-09-06	
		48.8	2017-02-13	
		54.2	2018-02-21	Flooding event 20-21 February 2018
Durban	81.1	106	1989-04-15	Natal floods 14-15 April 1989
		94	1989-11-29	Natal floods 28-30 November 1989
		163.5	1991-03-24	Cut-off Low system
		82.6	1995-04-09	Heavy rains & flooding 8-10 April 1995
		265	1996-01-12	Pressure surge, flooding
		101	1996-01-26	Heavy rains 16-27 January 1996
		82.1	1996-02-14	Heavy rain 12-14 February 1996
		105.6	1996-07-07	Intense cold front 3-8 July 1996
		119.3	1996-07-08	Intense cold front 3-8 July 1996
		107.1	1997-04-01	
		178	1998-04-14	Cold front, flooding
		127	1999-02-04	
		82.7	2002-01-24	
		82.5	2002-07-20	
		89.5	2003-04-13	

		112.6 95.6 97.2 166.8 94.2 89.3 141 126.2 99.6 101.2 101.6 108.2	2004-01-23 2006-11-13 2007-11-01 2008-03-11 2008-06-18 2009-11-19 2012-03-04 2016-05-07 2016-07-25 2016-07-26 2017-05-14 2017-10-10	 KZN south coast floods 17-18 June 2008 Flooding 23-26 July 2016 Flooding 14-15 May 2017 Cut-Off Low Flooding 09-11 October 2017 Cut-Off Low
Emerald	47.5	61.7 111 62.8 60.7 50.8 60.0 50.5 58.5 142.5 97.0 77.5 55.5 59.5 194 76 62.7 63.0 72.0 51.4 56.0 80.0 77.8 62.4 71.4 65.4	1989-01-06 1989-11-29 1991-02-06 1993-03-03 1993-10-21 1995-03-12 1995-12-16 1995-12-25 1996-07-08 1999-02-02 1999-12-20 2001-01-01 2001-01-28 2002-01-31 2004-12-06 2005-01-02 2006-10-13 2007-03-04 2008-03-11 2009-12-09 2012-08-07 2012-12-15 2013-01-06 2017-02-12 2017-11-14	 Natal floods 28-30 November 1989 Flooding 16-19 December 1995 Heavy rains 20-29 December 1995 Intense cold front 3-8 July 1996
Estcourt	51.4	77.6 64.0 114 51.5 68.0 55.0 74.0	1992-12-20 1995-12-24 1996-01-25 1997-03-20 1999-02-03 1999-03-21 2001-09-12	Heavy rains Drakensberg Heavy rains 20-29 December 1995 Heavy rains 16-27 January 1996

		81.0 95.0 65.0 53.8 68.0 75.2 86.6 112.2	2002-01-23 2004-02-13 2004-11-08 2005-11-13 2007-12-11 2008-01-14 2018-01-26 2018-02-21	Flooding event 20-21 February 2018
Makatini	62.2	67.6 82.0 71.5 65.8 76.5 128 78.0 80.0 127.5 100 63.7 82 139.8	1991-05-12 1991-05-13 1993-03-01 1997-04-03 1997-11-11 1998-01-07 2000-02-11 2000-11-18 2001-04-10 2004-01-23 2006-10-17 2014-03-08 2018-02-16	Heavy rain & flooding 11-13 May 1991 Low pressure over interior 6-10 Jan 1998
Maphumulo Prison	87.3	121.5 97.8 119.6 89.7 91.0 110 100 90.0 100 100 100 120 111.2 111.9 186.6 104.2 120	1990-10-19 1991-01-29 1991-02-17 1993-10-06 1994-07-23 1994-08-03 1994-08-19 1995-04-08 1996-02-10 1997-11-30 1998-02-15 2005-11-03 2007-11-01 2009-01-21 2017-01-27 2017-05-13 2017-05-14	 Heavy rains & flooding 8-10 April 1995 15-21 Feb 1998, effects of deep Low Pressure and TC Beltane
Mount Edgecombe	76.3	104.2 138.4 108 93 84.3 79.8	1989-02-06 1989-11-29 1991-02-15 1991-02-24 1991-03-12 1994-12-24	 Natal floods 28-30 November 1989 Blocking High during TC Cynthia

		175.2	1995-03-23	Trough north-east of the country
		81.6	1995-04-09	Heavy rains & flooding 8-10 April 1995
		156	1996-01-12	Pressure surge, flooding
		96	1996-01-26	Heavy rains 16-27 January 1996
		97.8	1996-07-07	Intense cold front 3-8 July 1996
		79.4	1996-07-08	Intense cold front 3-8 July 1996
		88.0	1999-10-25	
		218	1999-10-26	Flooding
		183.6	2000-02-13	
		93.2	2001-05-01	
		129.6	2001-12-22	
		82.2	2007-11-01	
		107.4	2012-03-11	
		142.4	2016-07-25	Flooding 23-26 July 2016
		96.4	2017-05-14	Flooding 14-15 May 2017 Cut-Off Low
		161.8	2019-04-22	Cut-Off Low heavy rains and flooding
		77.4	2019-11-10	Storms and flooding 10-12 November 2019
Newcastle	83.6	141	1989-12-31	
		101.3	1993-02-07	
		163.1	1995-01-18	
		146.5	1996-01-15	
		112	1996-02-18	
		170.3	1999-01-10	
		222.2	2000-01-07	
		110	2001-09-12	
		86.2	2012-09-06	2 days after TC Dineo remnant low
		109.4	2017-02-19	
		241	2017-12-30	
		115.5	2019-11-10	Storms and flooding 10-12 November 2019
Paddock	95.8	139.9	1989-02-16	
		149.4	1989-04-15	KZN coastal flood 14-15 April 1989
		117.3	1989-11-29	Natal floods 28-30 November 1989
		117	1990-03-24	KZN heavy rains
		109.5	1991-11-14	
		144.2	1993-09-22	
		167.4	1996-07-08	Intense cold front 3-8 July 1996
		110	1996-11-17	
		177	1997-06-12	Hailstorm, low pressure 10-13 June 1997
		204	1999-02-04	
		194.6	2000-01-16	
		131.4	2001-11-15	
		127.2	2001-11-16	
		129.4	2002-07-20	

		108.4	2004-07-27	
		153.8	2006-09-26	
		380	2008-06-17	KZN south coast floods 17-18 June 2008
		96.6	2008-06-18	KZN south coast floods 17-18 June 2008
		114.6	2008-11-12	
		135	2009-11-18	
		110.6	2011-07-10	
		147.4	2012-08-11	
		120.2	2012-12-10	
		97.4	2013-10-26	
		111.2	2013-10-27	
		101.8	2013-12-10	
		266.6	2016-07-24	Flooding 23-26 July 2016
		146.2	2017-10-09	Flooding 09-11 October 2017 Cut-Off Low
		234.6	2019-04-22	COL heavy rains and flooding
Pietermaritzburg darville	50.1	91.5	1989-11-29	Natal floods 28-30 November 1989
		56.3	1991-01-27	
		58.5	1991-02-15	
		64.5	1995-11-21	
		69.0	1999-02-02	
		58.3	2000-12-20	
		63.5	2001-09-12	
		63.0	2002-07-19	
		67.5	2003-03-18	
		115.5	2007-03-04	
		69.0	2008-01-14	
		85.0	2008-02-12	
		80.0	2009-10-24	
		74.0	2010-01-26	
		65.8	2011-12-01	
		64.8	2012-09-06	
		50.6	2013-01-06	
		62.8	2016-03-16	
		60.0	2017-02-13	
		51.2	2017-05-04	
Shaleburn	53.5	82.3	1989-02-13	
		56.5	1989-11-05	
		58.0	1990-12-12	
		75.0	1993-04-04	
		57.0	1994-12-09	
		67.0	1995-01-14	Hailstorm & flash flooding
		58.0	1995-12-22	Heavy rains 20-29 December 1995
		74.0	1996-01-26	Heavy rains 16-27 January 1996
		68.5	1996-03-03	
		91.0	1996-07-08	Intense cold front 3-8 July 1996

		64.0 65.0 62.5 73.0 62.5 68.5 57.0 57.6	1999-11-28 2000-03-17 2001-12-29 2003-02-08 2003-03-19 2004-01-27 2004-03-29 2018-03-21	

4.3 Extreme Rainfall Incidence and Trend Analysis Procedure

This study adopts methods from various studies where non-parametric approaches for climate trends were adopted (Alexander *et al.*, 2006; Moeletsi and Walker, 2012; Donat *et al.*, 2013, 2019; Roy and Rouault, 2013; Kruger and Nxumalo, 2017; Rapolaki *et al.*, 2019; Yang *et al*., 2019). The trend analysis of daily extremes was analysed by calculating seven of the core 27 indices of temperature and rainfall of the WMO ETCCDI (Table 4), of which two of the indices for part of the 34 core indices from the WMO ET-SCI. The ClimPact2 software was used to calculate indices. This software is based on the RClimDEX software developed for WMO ETCCDI indices calculations (Alexander and Herold, 2016). The ClimPACT2 is written in R, which is a language used for statistical analysis and graphics (Alexander and Herold, 2016).The ClimPact2 software calculates core indices developed by the WMO ET-SCI and subsets of the core WMO ETCCDI indices (Alexander and Herold, 2016).

These indices consider ‘moderate extremes’ that occur several times a year and are recommended to achieve uniformity in the detection of climate and weather extremes across different countries (Zhang *et al.*, 2011; Alexander and Herold, 2016; Bohlinger and Sorteberg, 2018). These indices however do not represent ‘rare events’ effectively, therefore, extreme value theory approach is recommended for extremes at the tail ends of rainfall distribution (Seneviratne *et al.*, 2012). The value of climate indices derived from daily data can identify pertinent information on climate extremes which is otherwise smoothed out when climate data is analysed at monthly timescales (Alexander and Herold, 2016).

Table 4: List of WMO ETCCDI and WMO ET-SCI rainfall indices used in the study.

Index ID	Definition	Description	Unit	Index
R20	Number of very heavy rainfall days	Annual count of days >= 20 mm	[days]	ETCCDI/ET-SCI
R50	Number of extreme rainfall days	Annual count of days >= 50 mm	[days]	ETCCDI
Rx1d	Maximum 1-day rainfall	Annual maximum 1-day rainfall	[mm]	ETCCDI/ET-SCI
Rx5d	Maximum 5-day rainfall	Annual maximum 5-day rainfall	[mm]	ETCCDI/ET-SCI
CWD	Continuous Wet Days	Maximum annual number of consecutive wet days (when rainfall >= 1 mm)	[days]	ETCCDI
R95p	Total precipitation from heavy rainfall days	Annual sum of daily rainfall >= 95th percentile	[mm]	ETCCDI
R99p	Total precipitation from very heavy rainfall days	Annual sum of daily rainfall >= 99th percentile	[mm]	ETCCDI

The ClimPACT2 output files contained various .csv files and plotted graphs. The graph plots for the trends of the 7 indices are attached in Appendix D. The various .csv files contained the trends for the different indices for individual stations, and the annual and monthly incidence of the seven indices. The annual and monthly .csv files for the different indices were used to calculate the average and temporal occurrences of extreme events over the 30-year period, 1989-2019. When investigating the temporal scale of annual maximum one-day events (Rx1d), extreme events were considered, which were defined as rainfall values above the 99th percentile of the individual stations (adopted from Dyson, 2009). The top 20 events were considered when investigating the temporal scale of annual 5-day maximum events (adopted from (Rapolaki *et al.*, 2019). The trend .csv file was used to analyse the trends of individual indices across KwaZulu-Natal and this information was used to display the spatial distribution of trends using the ArcGIS mapping software.

Chapter 5: RESULTS

5.1 Introduction

This results section will describe the incidence and mean incidence of extreme rainfall events. Secondly, it will describe the temporal frequency of extreme rainfall events based on four of the seven calculated indices. Lastly, it will describe trends of extreme rainfall events over KwaZulu-Natal.

5.2 Extreme Rainfall Incidence

5.2.1 Mean annual total of extreme events.

For extreme rainfall intensity indices, the mean annual totals are 75.61mm for the maximum one-day extreme rainfall events (Rx1day), 119.32mm for maximum 5-day extreme rainfall events (Rx5day), 214.97 mm for very wet day events (R95p), and 72.84 mm for extreme wet day events (R99p; Table 5). For extreme rainfall frequency indices, the mean annual total for heavy rainfall events (R20mm) is 11.21 days and 1.76 days for extreme rainfall events (R50mm). The considerable difference between the mean annual total R20mm and R50mm indicates that extreme rainfall events are rarer compared to heavy rainfall events (Hart *et al.*, 2013). The mean annual total for continuous wet day index (CWD) is 5.96 days. The coastal stations, i.e., Durban South, Mount Edgecombe, and Paddock, together with Shaleburn, which is located close to the Drakensburg Mountains consistently have higher mean annual totals for most of the indices, except for CWD, where more frequent continuous wet days are observed in Cedara, Emerald and Shaleburn. This reiterates the concept of topography and maritime influences producing spatial heterogeneity in the quantity of rainfall (Hart *et al.*, 2013; Ojara *et al.*, 2021). The coastal stations also depict mean annual averages

that are consistently higher than the total mean average for all the stations combined, except for Durban and Mount Edgecombe for CWD. This indicates that incidence of extreme rainfall is more frequent and more intense along the coastal regions, which is consistent with the literature (Engelbrecht *et al.*, 2013; Botes, 2014; Mpungose *et al.*, 2022).

Table 5: Mean annual total for extreme rainfall indices over KwaZulu-Natal for the period 1989-2019

Station	**Ave RX1day (mm)**	**Ave RX5day (mm)**	**Ave R95p (mm)**	**Ave R99p (mm)**	**Ave R20mm (days)**	**Ave R50mm (days)**	**Ave CWD (days)**
Cedara	58,47	93,59	196,12	66,06	9,93	0,83	6,50
Durban South	100,18	142,46	297,67	110,35	13,3	2,89	5,33
Emerald	60,12	94,18	189,60	62,36	9,64	0,88	6,60
Estcourt	59,4	97,15	168,07	54,32	10,21	0,93	6,11
Makathini	66,61	102,98	156,41	48,49	8,8	1,16	4,68
Maphumulo Prison	78,36	133,21	219,21	65,95	11,88	2,29	5,35
Mount Edgecombe	85,09	127,23	248,53	77,5	12,09	2,45	5.00
Newcastle	73,24	120,36	154,33	27,92	10,91	2,18	5,36
Paddock	135,26	211,04	371,04	165,15	12,67	3,61	6,23
Pietermaritzburg	57,49	84,76	128,36	55,61	10,21	0,87	6,17
Shaleburn	57,5	105,58	235,3	67,52	13,67	1,23	8,19
Total average	**75,61**	**119,32**	**214,97**	**72,84**	**11,21**	**1,76**	**5,96**

5.2.2 Incidence of extreme rainfall events

The ETCCDI/ET-SCI analysis considers ‘moderate extremes’ which can occur several times a year (Data, 2009; Bohlinger and Sorteberg, 2018). They also describe the frequency, magnitude, and persistence of extreme events (WMO, 2009). Rx1day, which are above the ‘extreme event’ threshold (99th percentile, Dyson, 2009), have occurred regularly on an annual scale across KwaZulu-Natal over the 30-year period (Table 6). These events are confirmed by analysing the ETCCDI/ET-SCI RX1day output indices at both annual and monthly timescales. Moreover, some of these events have a significant enough impact to gain media coverage and can be attributed to large-scale systems such as the April 2019 flooding events which were caused by a

COL. However, most of these events are not captured by the media, indicating that these are likely heavy rain and flooding events occurring at a much smaller or localised scale and attributed to mesoscale systems.

The newly adopted SAWS early warning system caters for dissemination of heavy rain and flooding alerts at a localised to a wider scale (SAWS, 2022b). The Impact-Based Forecasting and Warning System (IBFWS) was adopted by SAWS in 2020, which focuses on “what the weather will do” as opposed to “what the weather will be” (WMO, 2021; ESCAP, 2021). This approach in disseminating or communicating weather and warnings is a means of communicating risks and impacts of extreme weather events and combines hazard and vulnerability information to identify risks and facilitate decision making (WMO, 2021). The methodology for creating warnings includes generating a forecast, identifying thresholds for significant weather events (e.g., flooding) and thresholds for significant impacts, the latter being a collaborative approach with end users (ESCAP, 2021). The SAWS uses a qualitative approach to identify hazard impacts, rather than a model-based approach, which involves impact selection and communication by emergency managers (ESCAP, 2021). The process starts by generating a weather forecast, followed by determining the impact levels based on impact tables (Appendix C), then contacting disaster managers prior to issuing impact-based warnings (ESCAP, 2021). The weather alerts are issued based on a risk-based matrix that considers a combination of the likelihood and severity of an impact (Jenkins *et al.*, 2022). Minimal to minor impacts consider localised impacts from a weather event, while significant to severe impacts consider widespread effects from said weather events (SAWS, 2022b).

An impact-based warning was issued for the heavy rainfall and flooding event which occurred in KwaZulu-Natal in April 2022 (SAWS, 2022a). On the 12th of April 2022, a media release was issued by the SAWS with an orange level 5 warning for heavy rain for the coastal and adjacent areas of KwaZulu-Natal, which meant there was a medium likelihood for significant impacts associated with the rain (SAWS, 2022a). Subsequently, this warning escalated to orange level 9, indicating a medium likelihood of severe impacts due to the large amounts of rain that had been recorded (SAWS, 2022a). This flooding event was captured by the media as one of the deadliest flooding events in the KwaZulu-Natal coast (Naidoo, 2022). Since the period for this study pre-dates the launching of the IBFWS in South Africa, no evidence of issued alerts is available for the scope of this study, which describes how the SAWS IBFWS caters for localised to widespread extreme rainfall and flooding events, and how frequently these events are alerted for.

Table 6:Incidence of extreme rainfall event and confirming ETCCDI/ET-SCI indices.

Station name	Extreme rainfall event	Date of event	Event or contributing synoptic system	Confirmation from ETCCDI/ET-SCI index (yes/no)	Indices (Annual vs Monthly)
Cedara	71.1	1989-01-06		Yes	RX1day (ANN)
	57.4	1989-11-29	Natal floods 28-30 November 1989	Yes	RX1day (MON)
	67.0	1991-01-23		Yes	RX1day (MON)
	64.6	1991-11-10	Heavy rains 9-15 November 1991	Yes	R50mm
	69.2	1991-11-13	Heavy rains 9-15 November 1991	Yes	RX1day (ANN)
	59.3	1993-03-03		Yes	RX1day (ANN)
	56.6	1994-02-15		Yes	RX1day (ANN)
	62.9	1995-12-25	Heavy rains 20-29 December 1995	Yes	RX1day (ANN)
	63.2	1996-05-17		Yes	RX1day (MON)
	68.3	1996-07-08	Intense cold front 3-8 July 1996	Yes	RX1day (ANN)
	48.8	1999-01-11		Yes	R20mm
	55.4	1999-01-31		Yes	RX1day (MON)
	176.8	1999-11-15		Yes	RX1day (ANN)
	49.5	1999-12-11		Yes	R20mm
	97.8	1999-12-27		Yes	RX1day (MON)
	83.6	2001-04-11		Yes	RX1day (ANN)
	60.0	2001-09-12		Yes	RX1day (MON)
	55.4	2001-12-10		Yes	RX1day (MON)
	58.5	2002-07-19		Yes	RX1day (ANN)
	49.4	2003-02-04		Yes	RX1day (ANN)
	53.4	2007-11-21		Yes	RX1day (ANN)
	58.2	2008-11-13		Yes	RX1day (ANN)
	70.4	2012-08-07		Yes	RX1day (ANN)
	69.2	2012-09-06		Yes	RX1day (MON)
	48.8	2017-02-13		Yes	RX1day (ANN)
	54.2	2018-02-21	Flooding event 20-21 February 2018	Yes	RX1day (ANN)
Durban South	106	1989-04-15	Natal floods 14-15 April 1989	Yes	RX1day (ANN)
	94	1989-11-29	Natal floods 28-30 November 1989	Yes	RX1day (MON)
	163.5	1991-03-24	Cut-Off Low system	Yes	RX1day (ANN)
	82.6	1995-04-09	Heavy rains and flooding 8-10 April 1995	Yes	RX1day (ANN)
	265	1996-01-12	Pressure surge, flooding	Yes	RX1day (ANN)
	101	1996-01-26	Heavy rains 16-27 January 1996	No	N/A
	82.1	1996-02-14	Heavy rains 12-14 February 1996	Yes	RX1day (MON)
	105.6	1996-07-07	Intense cold front 3-8 July 1996	No	N/A
	119.3	1996-07-08	Intense cold front 3-8 July 1996	Yes	RX1day (MON)
	107.7	1997-04-01		Yes	RX1day (ANN)
	178	1998-04-14	Cold front, flooding	Yes	RX1day (ANN)
	127.5	1999-02-04		Yes	RX1day (MON)
	82.7	2002-01-24		Yes	RX1day (ANN)

	82.5	2002-07-20		Yes	RX1day (MON)
	89.5	2003-04-13		Yes	RX1day (ANN)
	112.6	2004-01-23		Yes	RX1day (ANN)
	95.6	2006-11-13		Yes	RX1day (ANN)
	97.2	2007-11-01		Yes	RX1day (ANN)
	166.8	2008-03-11		Yes	RX1day (ANN)
	94.2	2008-06-18	KwaZulu-Natal south coast floods 17-18 June	Yes	RX1day (MON)
	89.3	2009-11-19	2008	Yes	RX1day (ANN)
	141	2012-03-04		Yes	RX1day (MON)
	126.2	2016-05-07		Yes	RX1day (ANN)
	99.6	2016-07-25		No	N/A
	101.2	2016-07-26	Flooding 23-26 July 2016	Yes	RX1day (MON)
	101.6	2017-05-14	Flooding 14-15 May 2017 Cut-Off Low	Yes	RX1day (MON)
	108.2	2017-10-10	Flooding 09-11 October 2017 Cut-Off Low	Yes	RX1day (ANN)
Emerald	61.7	1989-01-06		Yes	RX1day (MON)
	111	1989-11-29	Natal floods 28-30 November 1989	Yes	RX1day (ANN)
	62.8	1991-02-06		Yes	RX1day (ANN)
	60.7	1993-03-03		Yes	RX1day (ANN)
	50.8	1993-10-21		Yes	RX1day (MON)
	60.0	1995-03-12		Yes	RX1day (ANN)
	50.5	1995-12-16	Flooding 16-19 December 1995	Yes	R50mm
	58.5	1995-12-25	Heavy rains 20-29 December 1995	Yes	RX1day (MON)
	142.5	1996-07-08	Intense cold front 3-8 July 1996	Yes	RX1day (ANN)
	97.0	1999-02-02		Yes	RX1day (ANN)
	77.5	1999-12-20		Yes	RX1day (MON)
	55.5	2001-01-01		Yes	R50mm
	59.5	2001-01-28		Yes	RX1day (ANN)
	194	2002-01-31		Yes	RX1day (MON)
	76	2004-12-06		Yes	RX1day (ANN)
	62.7	2005-01-02		Yes	RX1day (ANN)
	63.0	2006-10-13		Yes	RX1day (MON)
	72.0	2007-03-04		Yes	RX1day (ANN)
	51.4	2008-03-11		Yes	RX1day (ANN)
	56.0	2009-12-09		Yes	RX1day (ANN)
	80.0	2012-08-07		Yes	RX1day (ANN)
	77.8	2012-12-15		Yes	RX1day (MON)
	62.4	2013-01-06		Yes	RX1day (MON)
	71.4	2017-02-12		Yes	RX1day (ANN)
	65.4	2017-11-14		Yes	RX1day (MON)
Estcourt	77.6	1992-12-20	Heavy rains Drakensberg	Yes	RX1day (ANN)
	64.0	1995-12-24	Heavy rains 20-29 December 1995	Yes	RX1day (ANN)
	114	1996-01-25	Heavy rains 16-27 January 1996	Yes	RX1day (ANN)
	51.5	1997-03-20		Yes	RX1day (MON)

	68.0	1999-02-03		Yes	RX1 day (ANN)
	55.0	1999-03-21		Yes	RX1day (MON)
	74.0	2001-09-12		Yes	RX1day (ANN)
	81.0	2002-01-23		Yes	RX1day (ANN)
	95.0	2004-02-13		Yes	RX1day (ANN)
	65.0	2004-11-08		Yes	RX1day (MON)
	53.8	2005-11-13		Yes	RX1day (ANN)
	68.0	2007-12-11		Yes	RX1day (MON)
	75.2	2008-01-14		Yes	RX1day (MON)
	86.6	2018-01-26		Yes	RX1day (MON)
	112.2	2018-02-21	Flooding event 20-21 February 2018	Yes	RX1day (ANN)
Makatini	67.6	1991-05-12	Heavy rain & flooding 11-13 May 1991	Yes	R50mm
	82.0	1991-05-13		Yes	RX1day (ANN)
	71.5	1993-03-01		Yes	RX1day (ANN)
	65.8	1997-04-03		Yes	RX1day (MON)
	76.5	1997-11-11		Yes	RX1day (ANN)
	128	1998-01-07	Interior low-pressure 06-10 January 1998	Yes	RX1day (ANN)
	78.0	2000-02-11		Yes	RX1day (MON)
	80.0	2000-11-18		Yes	RX1day (ANN)
	127.5	2001-04-10		Yes	RX1day (ANN)
	100	2004-01-23		Yes	RX1day (ANN)
	63.7	2006-10-17		Yes	RX1day (ANN)
	82	2014-03-08		Yes	RX1day (MON)
	139.8	2018-02-16		Yes	RX1day (ANN)
Maphumulo Prison	121.5	1990-10-19		Yes	RX1day (MON)
	97.8	1991-01-29		Yes	RX1day (MON)
	119.6	1991-02-17		Yes	RX1day (ANN)
	89.7	1993-10-06		Yes	RX1day (MON)
	91.0	1994-07-23		Yes	RX1day (MON)
	110	1994-08-03		Yes	RX1day (ANN)
	100	1994-08-19		No	N/A
	90.0	1995-04-08	Heavy rains & flooding 08-10 April 1995	Yes	RX1day (ANN)
	100	1996-02-10		Yes	RX1day (ANN)
	100	1997-11-30		Yes	RX1day (MON)
	100	1998-02-15	15-21 February 1998, deep LP & TC Beltane	Yes	RX1day (ANN)
	120	2005-11-03		Yes	RX1day (MON)
	111.2	2007-11-01		Yes	RX1day (ANN)
	111.9	2009-01-21		Yes	RX1day (ANN)
	186.6	2017-01-27		Yes	RX1day (MON)
	104.2	2017-05-13		No	N/A
	120	2017-05-14		Yes	RX1day (MON)
Mount Edgecombe	104.2	1989-02-06		Yes	RX1day (MON)
	138.4	1989-11-29	Natal floods 28-30 November 1989	Yes	RX1day (MON)
	108	1991-02-15		Yes	RX1day (ANN)

	93	1991-02-24	Blocking High during TC Cynthia	Yes	RX1day (MON)
	84.3	1991-03-12		Yes	RX1 day (MON)
	79.8	1994-12-24		Yes	RX1day (MON)
	175.2	1995-03-23	Trough north-east of the country	Yes	RX1day (MON)
	81.6	1995-04-09	Heavy rains & flooding 08-10 April 1995	Yes	RX1day (MON)
	156	1996-01-12	Pressure surge, flooding	Yes	RX1day (ANN)
	96	1996-01-26	Heavy rains 16-27 January 1996	Yes	R50mm
	97.8	1996-07-07	Intense cold front 3-8 July 1996	Yes	RX1day (MON)
	79.4	1996-07-08	Intense cold front 3-8 July 1996	Yes	R50mm
	88.0	1999-10-25		Yes	R50mm
	218	1999-10-26	Flooding	Yes	RX1day (MON)
	183.6	2000-02-13		Yes	RX1day (ANN)
	93.2	2001-01-01		Yes	RX1day (MON)
	129.6	2001-12-22		Yes	RX1day (ANN)
	82.2	2007-11-01		Yes	RX1day (MON)
	107.4	2012-03-11		Yes	RX1day (ANN)
	142.4	2016-07-25	Flooding 23-26 July 2016	Yes	RX1day (ANN)
	96.4	2017-05-14	Flooding 14-15 May 2017 Cut-Off Low	Yes	RX1day (MON)
	161.8	2019-04-22	Cut-Off Low heavy rains & flooding	Yes	RX1day (ANN)
	77.4	2019-11-10	Storms & flooding 10-12 November 2019	Yes	RX1day (MON)
Newcastle	141	1989-12-31		Yes	RX1day (MON)
	101.3	1993-02-07		Yes	RX1day (ANN)
	163.1	1995-01-18		Yes	RX1day (MON)
	146.5	1996-01-15		Yes	RX1day (MON)
	112	1996-02-18		Yes	RX1day (MON)
	170.3	1999-01-10		No	N/A
	222.2	2000-01-07		No	N/A
	110	2001-09-12		Yes	RX1day (MON)
	86.2	2012-09-06		Yes	RX1day (MON)
	109.4	2017-02-19	2 days after TC Dineo remnant low	Yes	RX1day (MON)
	241	2017-12-30		No	N/A
	115.5	2019-11-10	Storms & flooding 10-12 November 2019	Yes	RX1day (ANN)
Paddock	139.9	1989-02-16		Yes	RX1day (MON)
	149.4	1989-04-15	KZN coastal floods 14-15 April 1989	Yes	RX1day (ANN)
	117.3	1989-11-29	Natal floods 28-30 November 1989	Yes	RX1day (MON)
	117	1990-03-24	KZN heavy rains	Yes	RX1day (ANN)
	109.5	1991-11-14		Yes	RX1day (ANN)
	144.2	1993-09-22		Yes	RX1day (MON)
	167.4	1996-07-08	Intense cold front 3-8 July 1996	Yes	RX1day (ANN)
	110	1996-11-17		Yes	RX1day (MON)
	177	1997-06-12	Hailstorm, low pressure 10-13 June 1997	Yes	RX1day (ANN)
	204	1999-02-04		Yes	RX1day (MON)
	194.6	2000-01-16		No	N/A
	131.4	2001-11-15		No	N/A
	127.2	2001-11-16		No	N/A

	129.4	2002-07-20		Yes	RX1day (MON)
	108.4	2004-07-27		Yes	RX1day (MON)
	153.8	2006-09-26		Yes	RX1day (MON)
	380	2008-06-17	KZN south coast floods 17-18 June 2008	Yes	RX1day (ANN)
	96.6	2008-06-18	KZN south coast floods 17-18 June 2008	Yes	R50mm
	114.6	2008-11-12		Yes	RX1day (MON)
	135	2009-11-18		Yes	RX1day (ANN)
	110.6	2011-07-10		Yes	RX1day (ANN)
	147.4	2012-08-11		Yes	RX1day (ANN)
	120.2	2012-12-10		Yes	RX1day (MON)
	97.4	2013-10-26		Yes	R50mm
	111.2	2013-10-27		Yes	RX1day (ANN)
	101.8	2013-12-10		Yes	RX1day (MON)
	266.6	2016-07-24	Flooding 23-26 July 2016	Yes	RX1day (ANN)
	146.2	2017-10-09	Flooding 09-11 October 2017 Cut-Off Low	Yes	RX1day (ANN)
	234.6	2019-04-22	Cut-Off Low heavy rains & flooding	Yes	RX1day (ANN)
Pietermaritzburg darville	91.5	1989-11-29	Natal floods 28-30 November 1989	Yes	RX1day (ANN)
	56.3	1991-01-27		Yes	RX1day (MON)
	58.5	1991-02-15		Yes	RX1day (ANN)
	64.5	1995-11-21		Yes	RX1day (ANN)
	69.0	1999-02-02		Yes	RX1day (ANN)
	58.3	2000-12-20		Yes	RX1day (ANN)
	63.5	2001-09-12		Yes	RX1day (ANN)
	63.0	2002-07-19		Yes	RX1day (ANN)
	67.5	2003-03-18		Yes	RX1day (ANN)
	115.5	2007-03-04		No	N/A
	69.0	2008-01-14		Yes	RX1day (MON)
	85.0	2008-02-12		Yes	RX1day (MON)
	80.0	2009-10-24		Yes	RX1day (ANN)
	74.0	2010-01-26		Yes	RX1day (MON)
	65.8	2011-12-01		Yes	RX1day (MON)
	64.8	2012-09-06		Yes	RX1day (MON)
	50.6	2013-01-06		Yes	RX1day (ANN)
	62.8	2016-03-16		Yes	RX1day (ANN)
	60.0	2017-02-13		Yes	RX1day (ANN)
	51.2	2017-05-04		Yes	RX1day (MON)
Shaleburn	82.3	1989-02-13		Yes	RX1day (MON)
	56.5	1989-11-05		Yes	RX1day (MON)
	58.0	1990-12-12		Yes	RX1day (ANN)
	75.0	1993-04-04		Yes	RX1day (ANN)
	57.0	1994-12-09		Yes	RX1day (MON)
	67.0	1995-01-14	Hailstorm & flash flooding	Yes	RX1day (ANN)
	58.0	1995-12-22	Heavy rains 20-29 December 1995	Yes	RX1day (MON)
	74.0	1996-01-26	Heavy rains 16-27 January 1996	Yes	RX1day (MON)
	68.5	1996-03-03		Yes	RX1day (MON)

	91.0 64.0 65.0 62.5 73.0 62.5 68.5 57.0 57.6	1996-07-08 1999-11-28 2000-03-17 2001-12-29 2003-02-08 2003-03-19 2004-01-27 2004-03-29 2018-03-21	Intense cold front 3-8 July 1996	Yes Yes Yes Yes Yes Yes Yes Yes Yes	RX1day (ANN) RX1day (MON) RX1day (ANN) RX1day (ANN) RX1day (ANN) RX1day (MON) RX1day (MON) RX1day (MON) RX1day (MON)

5.3 Temporal Distribution of Extreme Rainfall Events

5.3.1 Extreme rainfall intensity

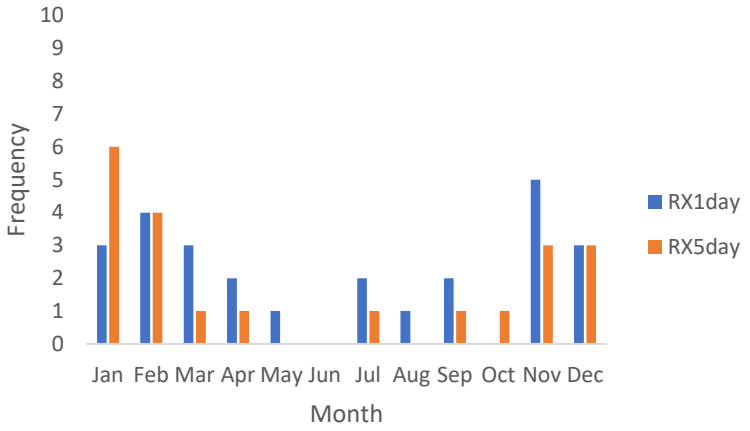
For the analysis of the temporal pattern of extreme rainfall intensities, thresholds were defined to analyse events that would have potentially resulted in flood events. For Rx1day frequency, events above the 99th percentile were chosen (Dyson, 2009), where extreme rainfall events were considered as those above the 99th percentile. For Rx5day events, the top 20 events were chosen (Rapolaki *et al.*, 2019).

Analysing the Rx1day monthly distribution, these events increase during the summer rainfall season, between October and February and decrease during the autumn and winter season, May to August. Peak frequencies are detected during early or late summer for various stations (Fig. 4), with some peak occurrences being detected in winter for some coastal stations. For Cedara, peak Rx1day events occur during November and February, while in Emerald peak events occur in December, January, and March. Over Estcourt peak occurrences for Rx1day events are during December and January, with a peak in February for Makathini. Peak events for Maphumulo Prison occur during November, January, and February, while over Mount Edgecombe they occur during November, February and March. Peak events for Newcastle, Pietermaritzburg and Shaleburn occur during January and February. For Durban and Paddock, the frequency of Rx1day events span throughout the year, with notable peaks in April and November for Durban and July and November for Paddock. Results for the frequency of the top 20 RX5day events show similar patterns to RX1day frequency, indicate increasing frequency over the summer rainfall season from October to March, and less frequent events during autumn and winter. For Cedara, peak Rx5day events occur during January and February, while in Emerald peak events occur in December, January, and February. Over Estcourt peak occurrences

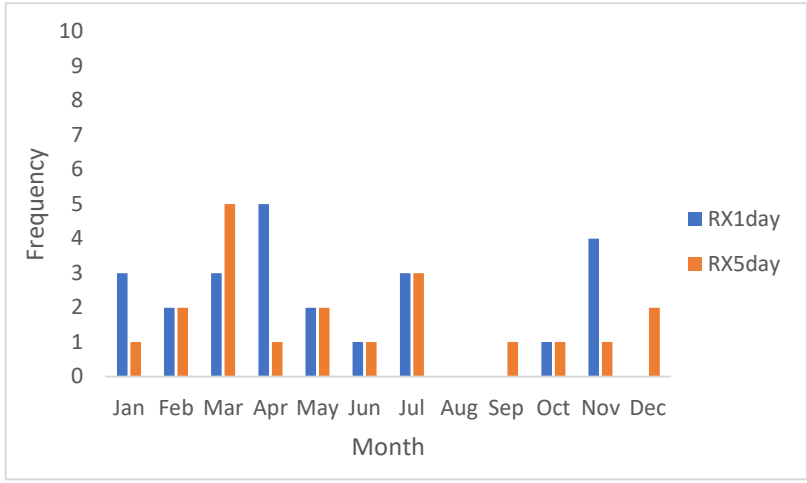
for RX5day events are during December and January, with peak events in January and February for Makathini. Peak events for Maphumulo Prison occur during November and February, with a high frequency in winter (July) that is comparable to the summer month events. Over Mount Edgecombe, peak events occur during December and February, with a notable peak in July. Peak events for Newcastle and Shaleburn occur during January and February, but over December and February over Pietermarizburg. For the coastal stations, Durban and Paddock, similar patterns are detected as Rx1day, where Rx5day events occur throughout the year, but peak occurrences in March and July for Durban but July and October over Paddock.

In summary, the frequency and intensity of extreme rainfall incidents occur predominantly during the summer rainfall season, with peaks occurring in early or late summer. For coastal stations, Durban South and Paddock, extreme rainfall intensity events occur throughout the year, with some notable peaks in at least one of the winter months.

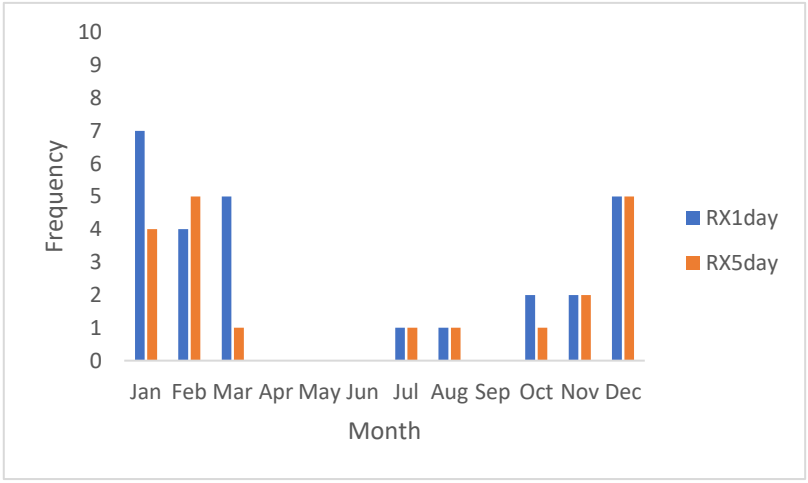
a) Cedara



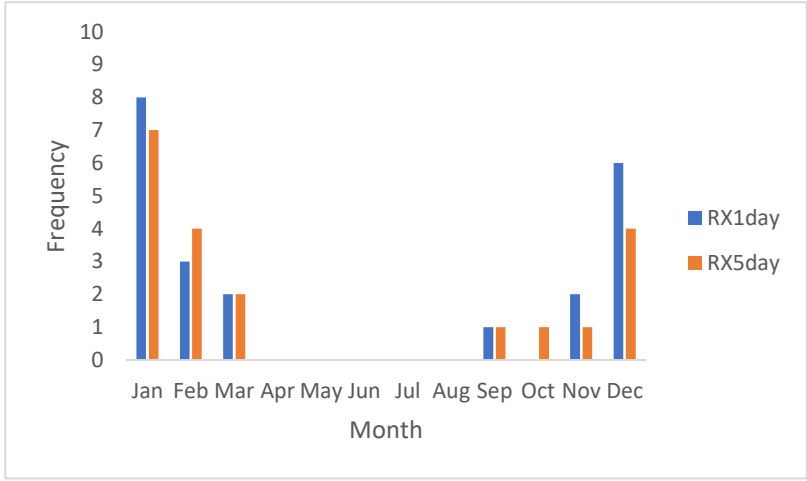
b) Durban South



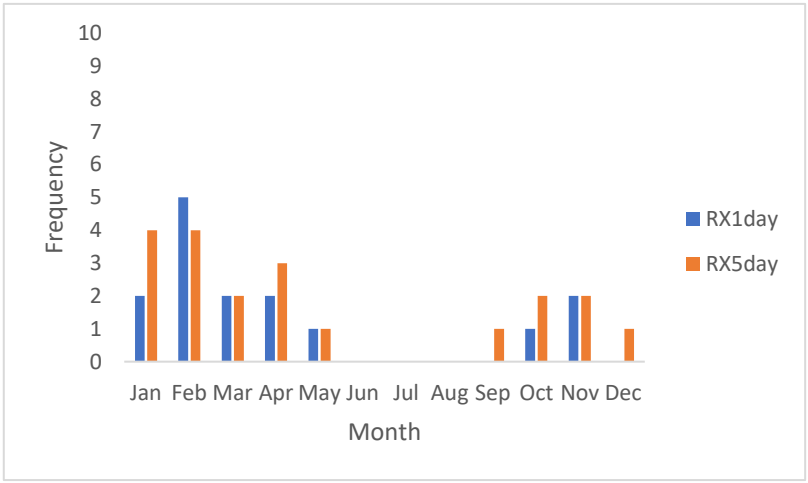
c) Emerald



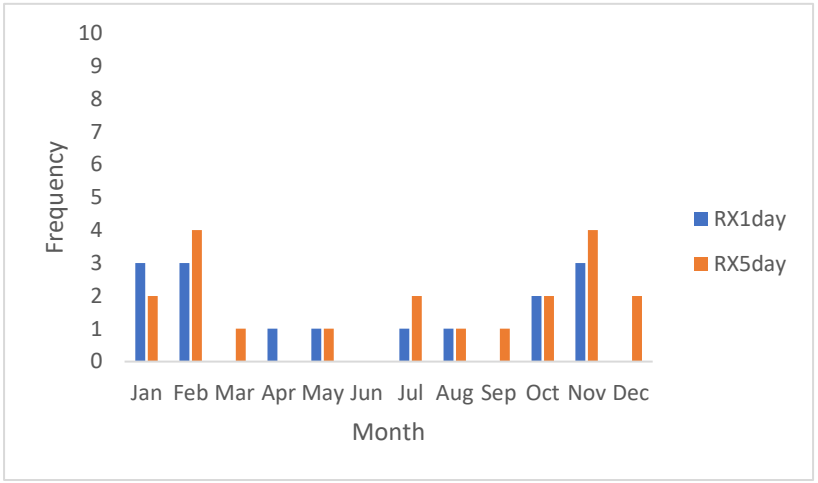
d) Estcourt



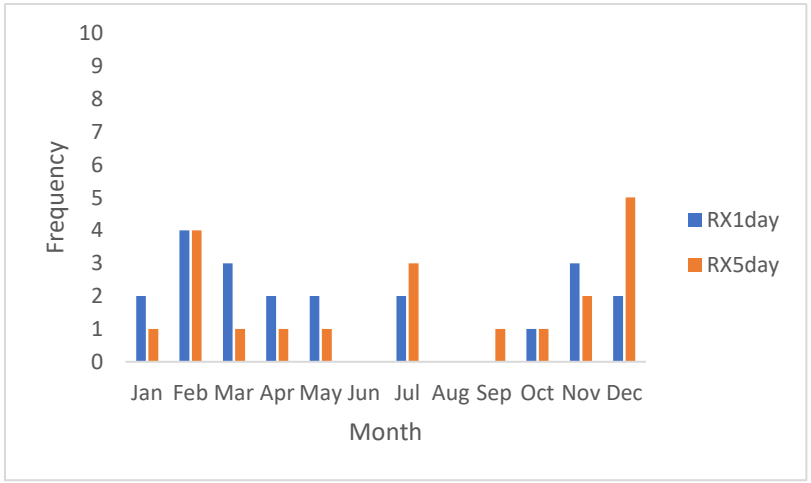
e) Makathini



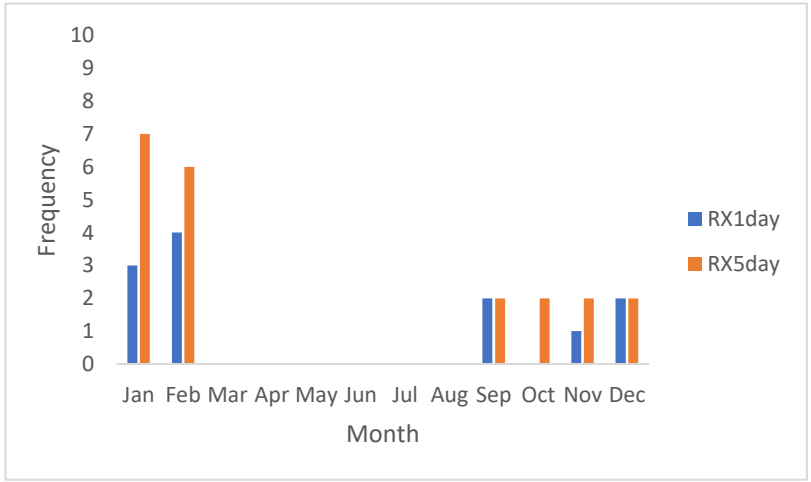
f) Maphumulo Prison



g) Mount Edgecombe



h) Newcastle



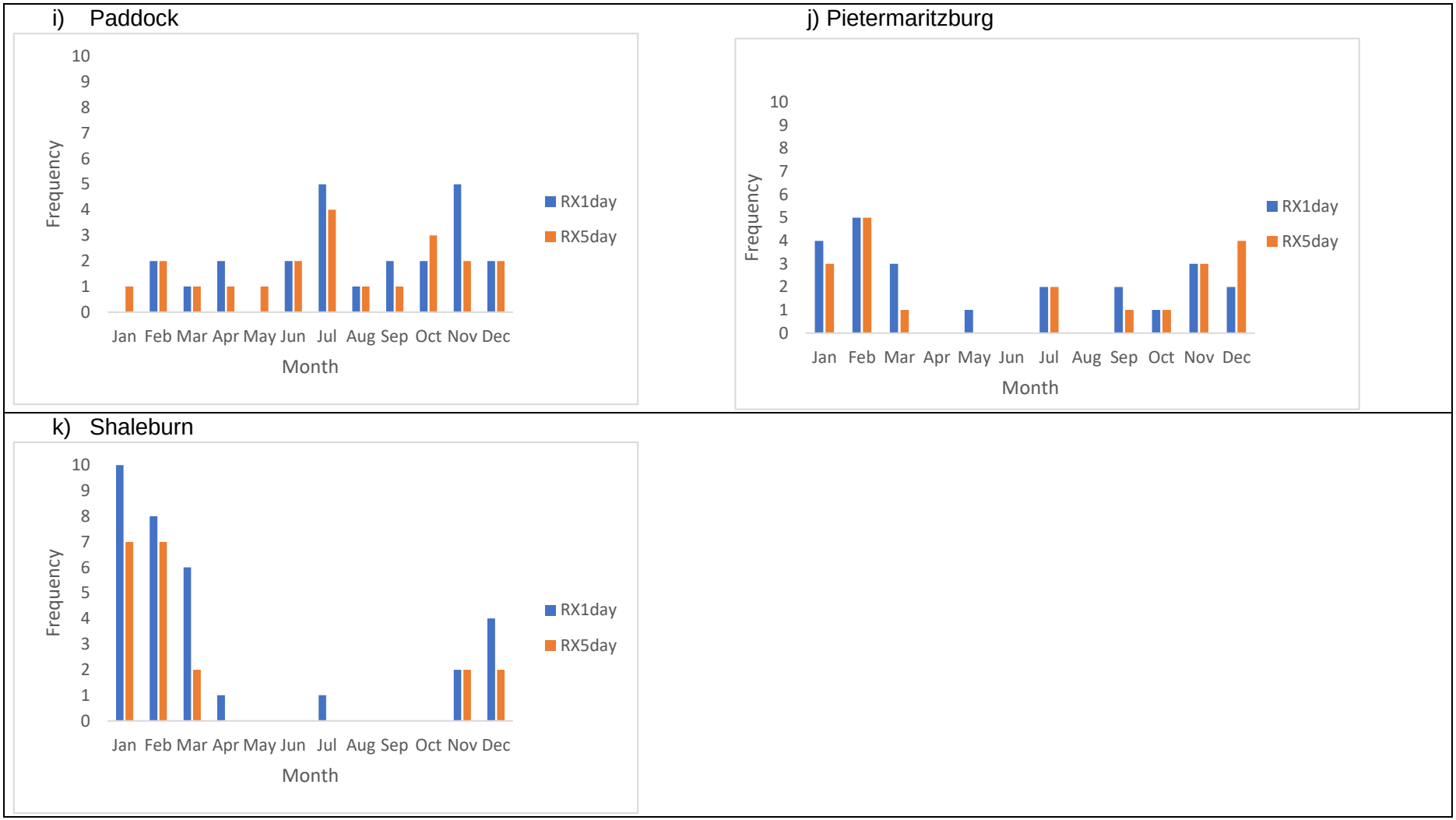


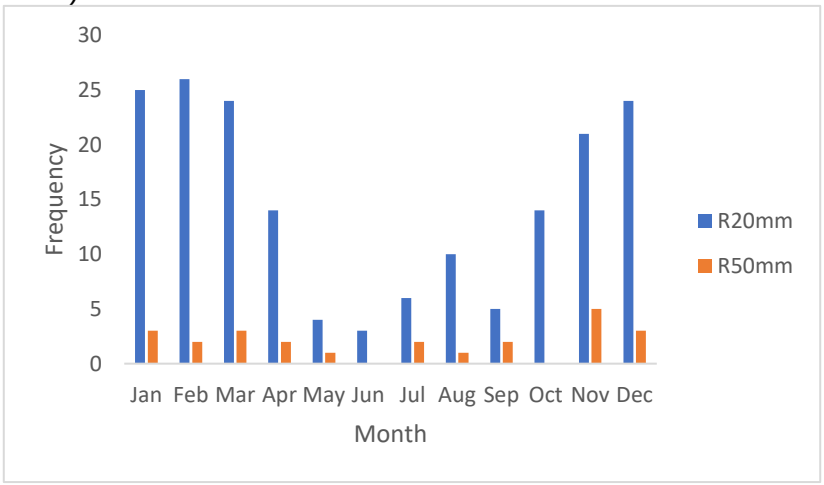
Figure 4: Graphs showing monthly distribution of the frequency of Rx1day and Rx5day events.

5.3.2 Extreme rainfall frequency

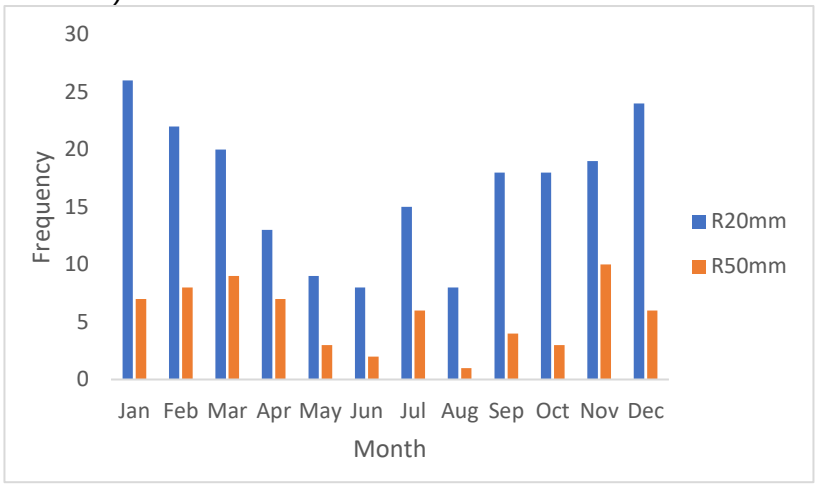
Analysing the monthly distribution of heavy (R20mm) and extreme (R50mm) rainfall frequency indices (Fig. 5), it is evident that both events span throughout the year, however, R20mm events are more frequent than R50mm events. The frequency of R20mm and R50mm events increase during the summer rainfall season, October to March, with minima occurring during the winter season, June to August. Peak R20mm events for Cedara and Emerald occur during December to March. For Estcourt and Mount Edgecombe, peak R20mm events occur during December to February, with peak events at Makathini occurring November, December, and February. Maphumulo Prison detects peak R20mm events from November to February, with Newcastle during November, December, and February. Peak R20mm events occur during December, January and March over Pietermaritzburg, and December to March over Shaleburn. For the coastal stations, Durban and Paddock, the frequency of winter R20mm events is comparable to the frequency of events at the start of the summer rainfall season, however, there are still clear peaks during the summer season, from December to February for Durban and November, December, and February for Paddock. Peak R50mm events for Cedara occur in November, but in December and January for Emerald and Estcourt. For Makathini and Mount Edgecombe, R50mm events peak in December to February and in November and February for Maphumulo Prison. Peak R50mm events for Pietermaritzburg and Shaleburn occur in January and February. For coastal stations, Durban, and Paddock, peak R50mm events are also detected in summer and during transition seasons. For Durban, peak R50mm events occur during March, April, and November, while for Paddock during April October and December.

In summary, heavy and extreme rainfall days occur throughout the years, with higher frequencies during the summer rainfall season and peaking at various times of the austral summer months. Extreme rainfall (R50mm) days are rarer compared to heavy rainfall days (Hart *et al.*, 2013). For coastal stations, heavy and extreme rainfall days had as high a frequency in winter as during the summer rainfall seasons, and peaks were also detected during transition seasons.

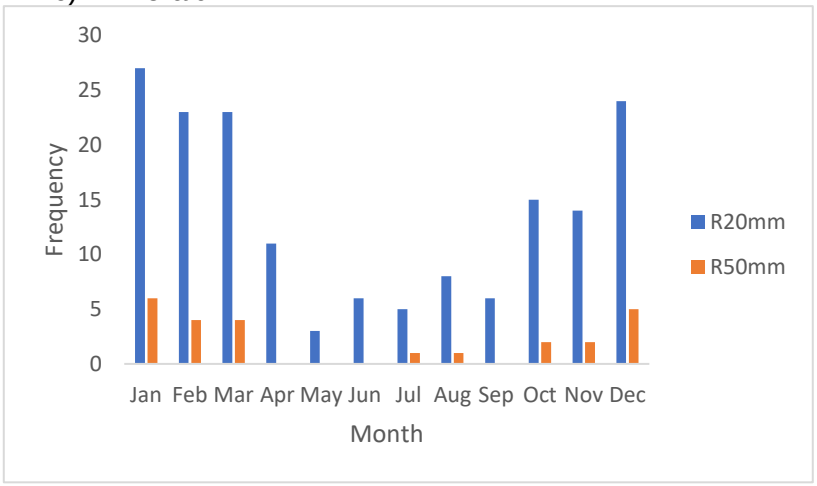
a) Cedara



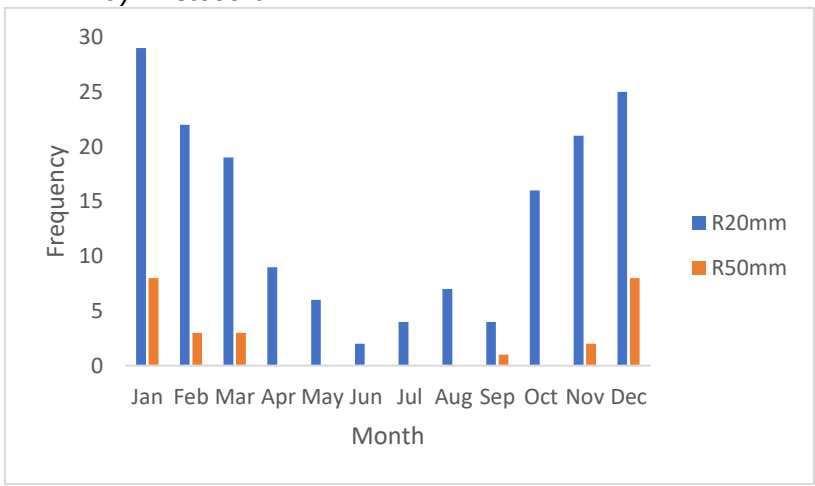
b) Durban South



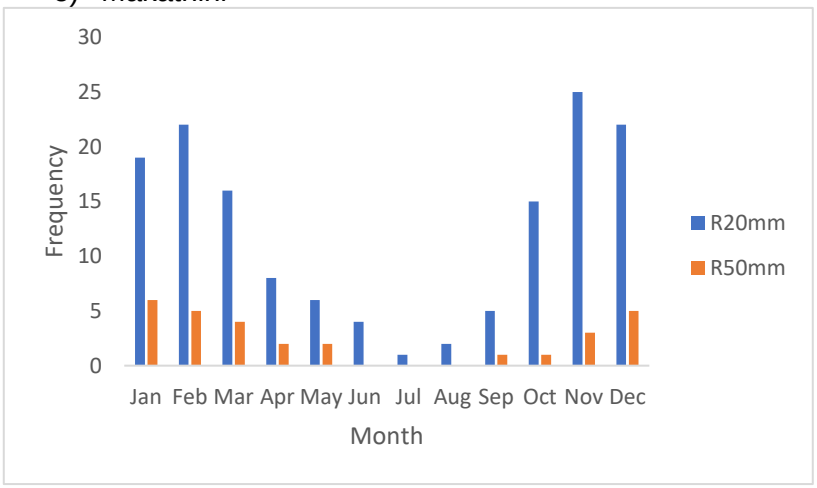
c) Emerald



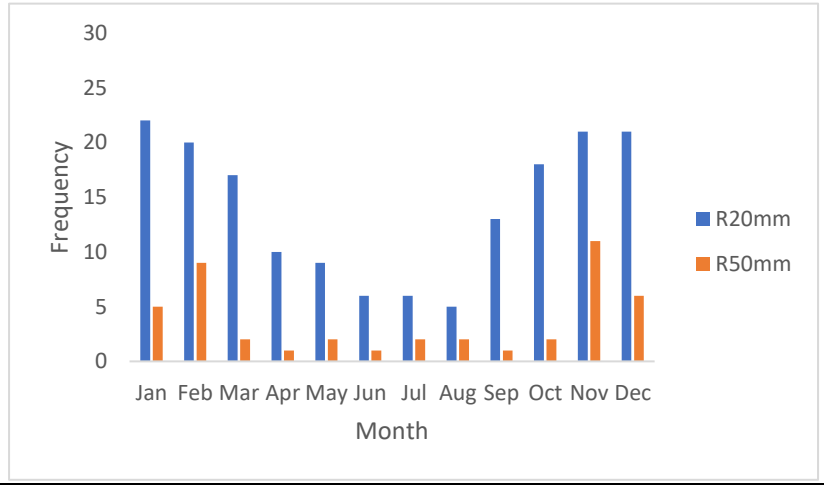
d) Estcourt



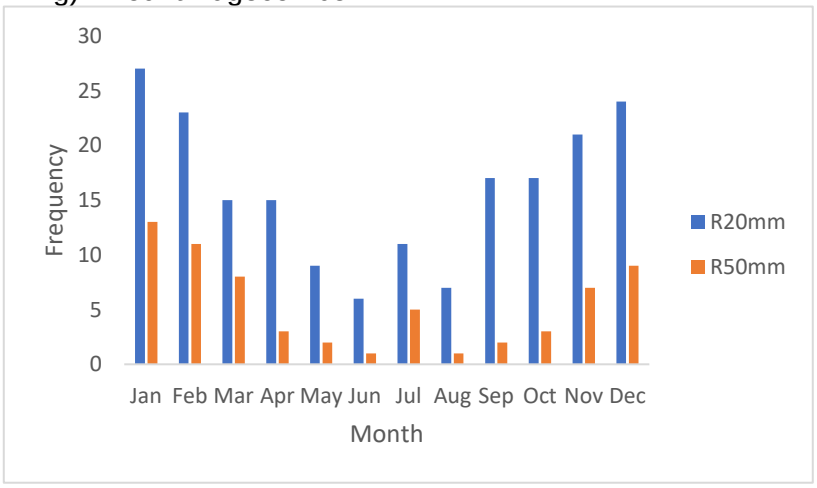
e) Makathini



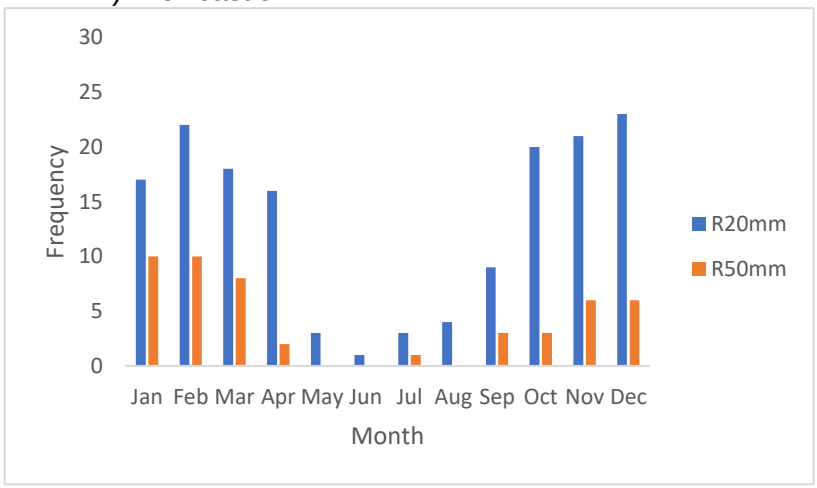
f) Maphumulo Prison



g) Mount Edgecombe



h) Newcastle



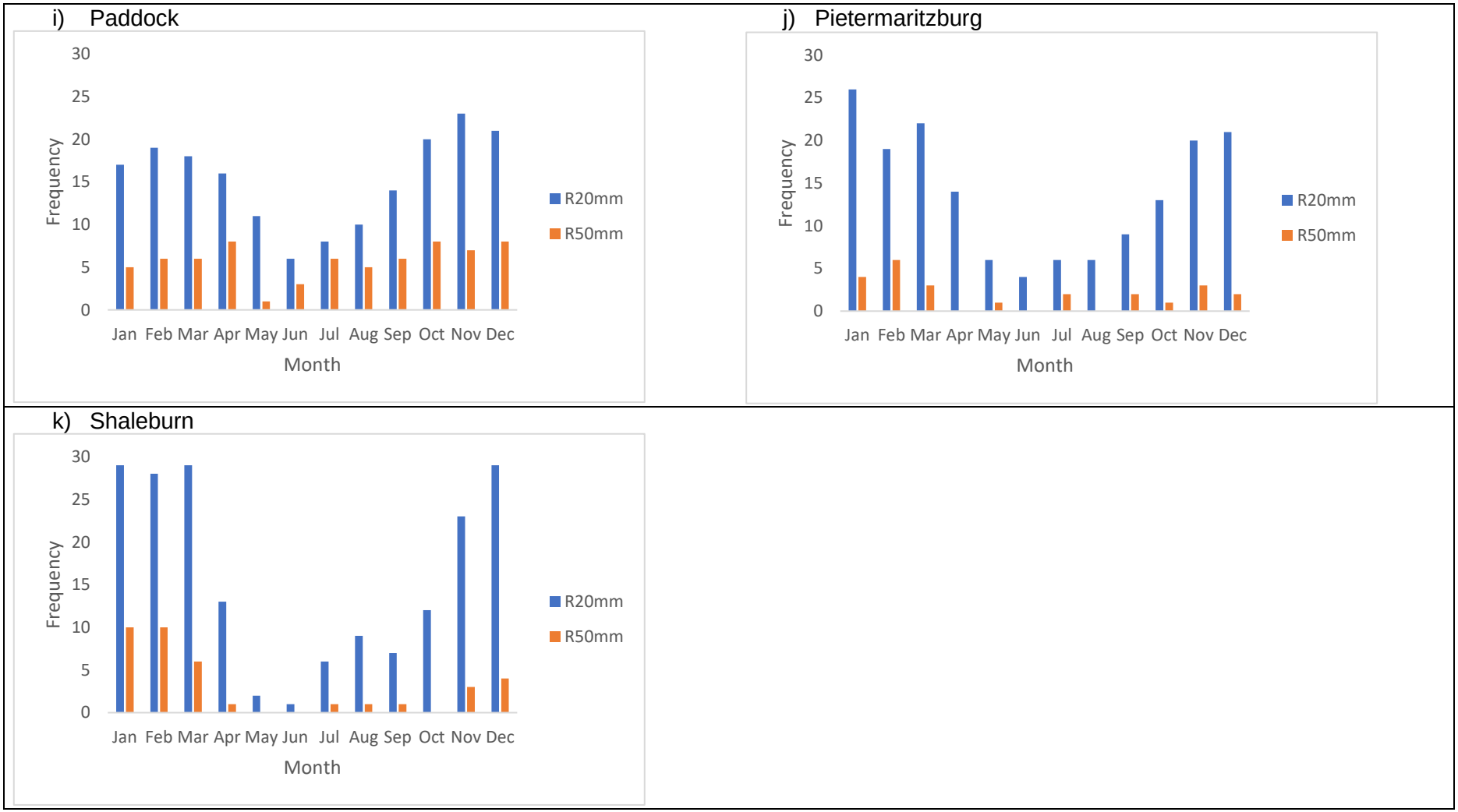


Figure 5: Graphs showing monthly distribution of the frequency of R20 mm and R50 mm events.

5.4 Analysis of Extreme Rainfall Trends

For the 30-year period of 1989-2019, of the 77 trends that were tested only 10 were detected as statistically significant, spanning six of the 11 stations (Table 7; Appendix C). All 10 detected decreasing trends. Cedara detected three indices which had low rates of statistically significant decreasing trends, namely Rx5day (-1.5 mm/year, p=0.027), R20mm (-0.17 day/year, p=0.002) and R50mm (-0.04, p=0.051). Emerald detected a low statistically significant decreasing trend of -0.08, p=0.021 for CWD. Makathini detected two indices which had decreasing statistically significant trends, R95p (-4.12 mm/year, p=0.052) and R20mm (-0.18, p=0.048). One index detected a statistically significant decreasing trend for Maphumulo Prison, namely the extreme wet day index, R99p (-5.14 mm/year, p=0.052). Pietermaritzburg detected two indices with statistically significant decreasing trends, namely RX5day (-1.22 mm/year, p=0.038) and R95p (-4.75 mm/year, p=0.029). Shaleburn detected one index with a decreasing statistically significant trend, R99p at -2.75 mm/year, with p= 0.049). It was noted across all the stations that there were no statistically significant trends for Rx1day.

5.4.1 Extreme rainfall intensity indices

Analysing the results for one day maximum (Rx1day) extreme rainfall events, decreasing trends are observed for 8 of the 11 stations, indicating a decreasing intensity, with increasing trends for the remaining three. The rate of change for Rx1day across all stations was low, ranging between -0.4 to -0.9 for decreasing trends, and 0.1 to 0.3 for increasing trends. None of the 11 stations exhibited trends that were statistically significant based on the p-values (Table 7). Similar trends were observed for five-day annual maximum (Rx5day) extreme rainfall events, with 10 of the 11

stations detecting decreasing trends and one station detecting an increasing trend. Of the 11 stations, only two, namely, Cedara and Pietermaritzburg exhibited statistically significant trends for Rx5day events, with larger rate of change, -1.52 mm/year for Cedara and -1.22 mm/year for Pietermaritzburg. For the remaining stations, rates of change were lower, ranging between -0.9 to -0.08 for decreasing trends, and 0.1 to 0.2 for increasing trends. The R95p and R99p, both exhibited decreasing trends for eight and nine out of eleven stations respectively, with two and one station calculating increasing trends respectively. For R95p indices, two stations, Makathini and Pietermaritzburg had statistically significant (negative) trends, with rates of change of -4.12 mm/year and -4.75 mm/year while Maphumulo Prison and Shaleburn detected statistically significant (negative) trends for R99p, with rates of change of -5.14 mm/year and -2.75 mm/year. For R95p, rates of change ranged from -8 to -2 for decreasing trends, and 0.7 to 5 for increasing trends. Rates of change for R99p ranged from -5 to -0.2 for decreasing trends, with one increasing trend at 0.26 mm/year. The direction of trends for extreme rainfall intensity indices (Rx1day, Rx5day, R95p and R99p) was unanimous for seven of the 11 stations, all exhibiting decreasing trends, with one station, Estcourt, detecting increasing trends across all extreme rainfall intensity indices.

5.4.2 Extreme rainfall frequency

Analysing the results for heavy rainfall and extreme rainfall frequency indices, R20mm and R50mm respectively, nine and seven of the 11 stations detected decreasing trends, with only Cedara with a statistically significant (decreasing) trend for both indices. Positive insignificant trends were exhibited for the remaining two and four stations. The direction of the trends was unanimously negative for 7 of the 11 stations

for both R20mm and R50mm, with two stations, Maphumulo Prison and Newcastle detecting unanimously positive trends across the two extreme rainfall frequency indices, and two stations, Durban South detecting opposing trends. The rates of change for R20mm were low, ranging from -0.18 to -0.04 for decreasing trends, and 0 to 0.2 for increasing trends. rates of change for R50mm were lower, ranging between -0.0009 to -0.02 for decreasing trends and 0.02 to 0.1 for increasing trends.

5.4.3 Rainfall duration

Analysing the results for the continuous wet day index, CWD, 6 of the 11 stations detected negative trends, with only Emerald with a statistically significant [decreasing] trend of -0.08 mm/year, and the remaining five stations detecting increasing insignificant trends. Rates of change were low for CWD, ranging between -0.08 to -0.02 for decreasing trends and 0.002 to 0.07 for increasing trends.

In summary, decreasing trends were dominant for all the stations across all the calculated rainfall indices. Only negative trends were statistically significant, with RX1day not detecting any statistically significant changes. Most indices had low rates of change, apart for R95p and R99p, which detected larger rates of change for majority of the stations.

Table 7: Table showing trend analysis statistics for 11 stations in KwaZulu-Natal for the period 1989 to 2019. Bold values indicate significant trends at 5% significance level.

Station	RX1day (mm)		RX5day (mm)		R95p (mm)		R99p (mm)		R20mm (days)		R50mm (days)		CWD (days)	
	Trend	P-value	Trend	P-value	Trend	P-value	Trend	P-value	Trend	P-value	Trend	P-value	Trend	P-value
Cedara	-0.56	0.367	**-1.52**	**0.027**	-5.12	0.064	-2.58	0.162	**-0.17**	**0.002**	**-0.04**	**0.051**	-0.04	0.269
Durban South	-0.88	0.448	0.18	0.897	-2.19	0.625	-0.23	0.947	-0.08	0.468	0.02	0.718	-0.02	0.568
Emerald	-0.79	0.150	-0.85	0.319	-1.82	0.464	-1.38	0.332	-0.08	0.269	-0.02	0.314	**-0.08**	**0.021**
Estcourt	0.13	0.770	0.25	0.662	0.71	0.659	0.26	0.862	-0.07	0.305	0.01	0.543	-0.05	0.262
Makathini	-0.46	0.508	-0.67	0.522	**-4.12**	**0.052**	-2.01	0.151	**-0.18**	**0.048**	-0.03	0.135	0.002	0.935
Maphumulo Prison	-0.93	0.297	-0.11	0.948	-2.08	0.633	**-5.14**	**0.052**	0.23	0.133	0.03	0.600	0.07	0.416
Mount Edgecombe	-0.36	0.748	-0.08	0.955	-2.17	0.624	-2.90	0.352	-0.13	0.260	-0.03	0.554	0.04	0.238
Newcastle	0.35	0.675	-0.29	0.819	5.66	0.224	-0.74	0.667	0.21	0.076	0.10	0.107	-0.04	0.556
Paddock	0.38	0.861	-0.08	0.976	-8.48	0.120	-2.18	0.603	-0.13	0.226	-0.10	0.082	0.03	0.313
Pietermaritzburg	-0.51	0.157	**-1.22**	**0.038**	**-4.75**	**0.029**	-0.75	0.491	-0.14	0.094	-0.009	0.602	-0.05	0.291
Shaleburn	-0.45	0.066	-0.91	0.068	-2.57	0.224	**-2.75**	**0.049**	-0.04	0.626	-0.04	0.066	0.01	0.683

5.5 Spatial Patterns of Trends of Extreme Indices

5.5.1 Extreme rainfall intensity indices

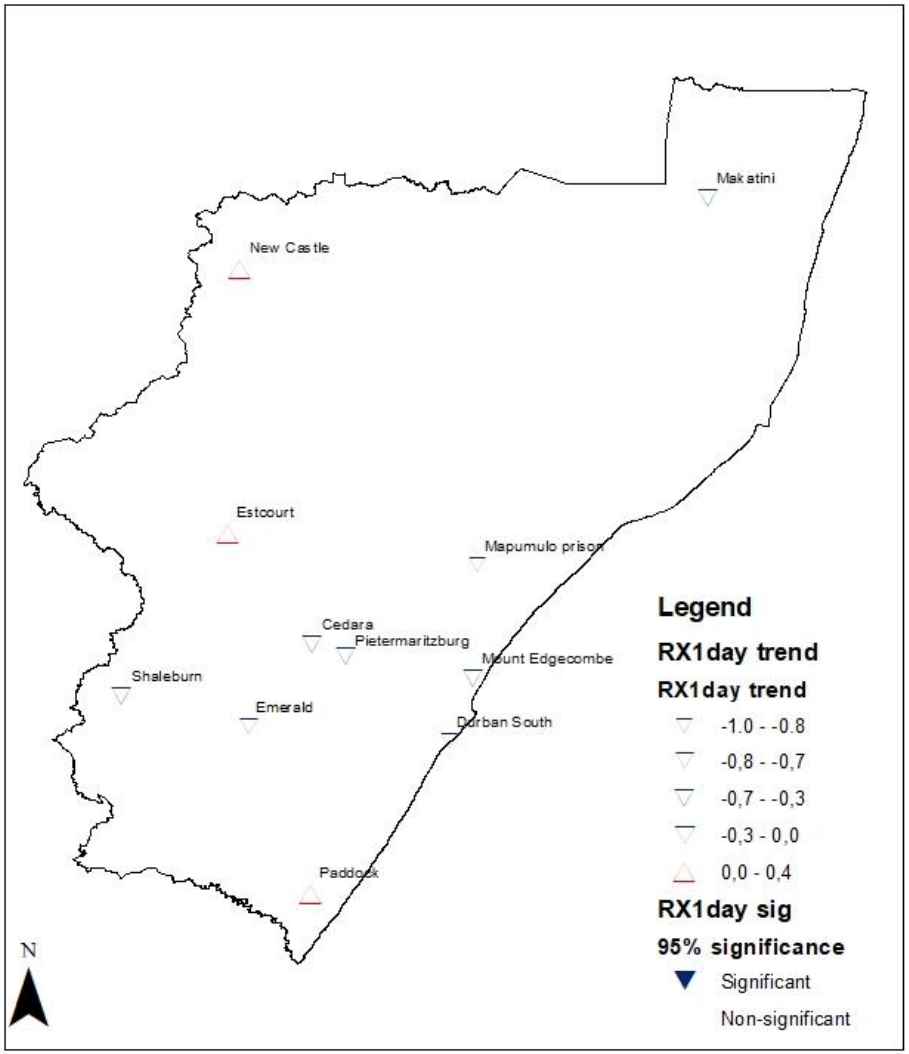
Paucity of data in the northern parts of KwaZulu-Natal Province may distort the spatial representation of trends. Spatial patterns of extreme rainfall intensity are heterogeneous throughout the province for the different indices, which results in no clear spatial patterns for some indices in some parts of the province. The spatial representation of Rx1day trends (Fig.6a) indicates decreasing trends in the east and southern parts of the province, but an increasing trend in the west and north-west. No statistically significant trends are depicted. Rx5day trends (Fig.6b) indicating increasing trends along the coastal regions and adjacent interior, and the extreme western parts. Decreasing trends are observed on the central and southern parts of the province, with statistically significant decreasing trends only for stations over the Midlands, i.e., Cedara and Pietermaritzburg. Spatial patterns for R95p (Fig. 6c) indicate decreasing trends over the eastern and southern areas of the province but increasing in the west and north-west, with one statistically significant decreasing trend for Pietermaritzburg. The R99p indices (Fig.6d) indicates more heterogenous spatial patterns, but similar to R95p in the west and extreme north-west, with increasing trends and north-east and extreme south-east, with decreasing trends. Shaleburn is the only station depicting a significant decreasing trend.

5.5.2 Extreme rainfall frequency and duration indices

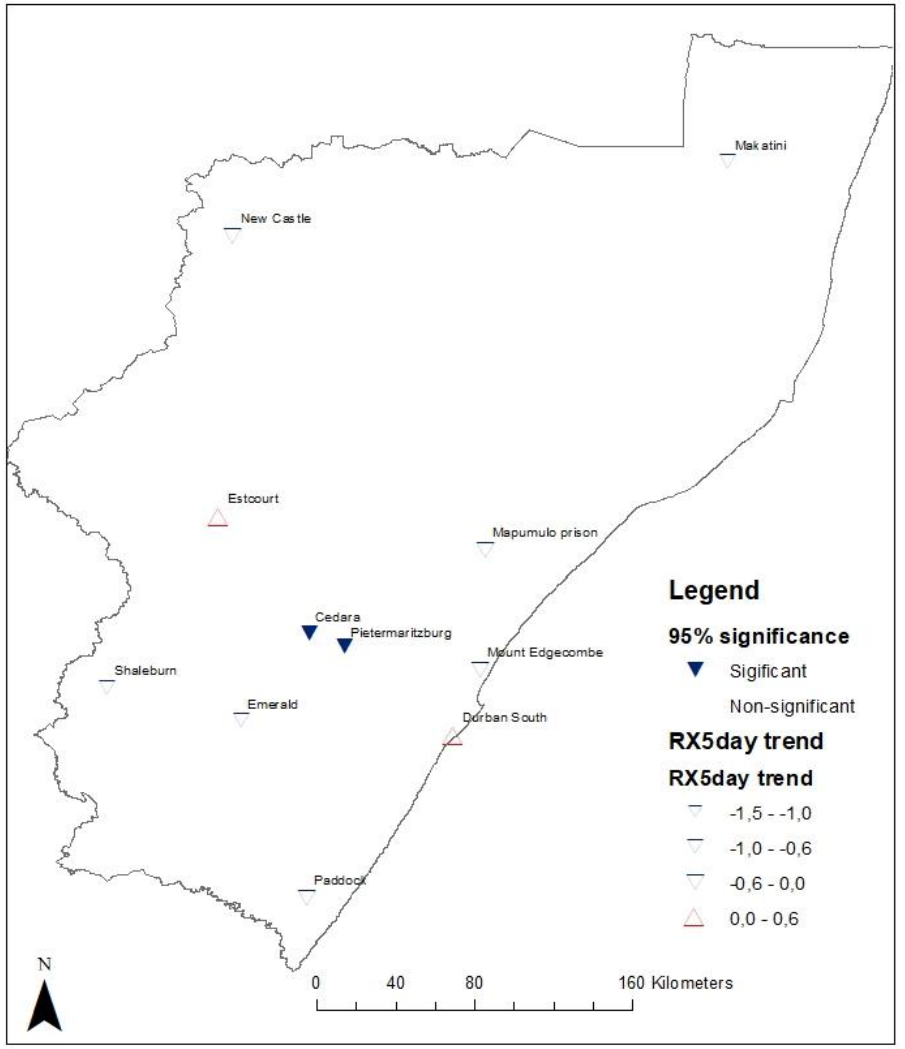
The spatial patterns for the R20 mm index (Fig. 6e) indicates decreasing trends over the south-east, south-west and extreme north-eastern parts of the province, where Makathini and Cedara depict statistically significant decreasing trends. Non-significant increasing trends are detected in the extreme east and north-west. The R50mm index

(Fig. 6f) is similar to R20mm, with decreasing trends over the southern and extreme north-eastern parts of the province, with and statistically insignificant increase in the north-west. Statistically significant trend was depicted over Cedara. The rainfall duration index (CWD) indicates opposing trends for the province (Fig.6g), resulting in no clear spatial pattern across the region, however, Emerald depicts a statistically decreasing trend.

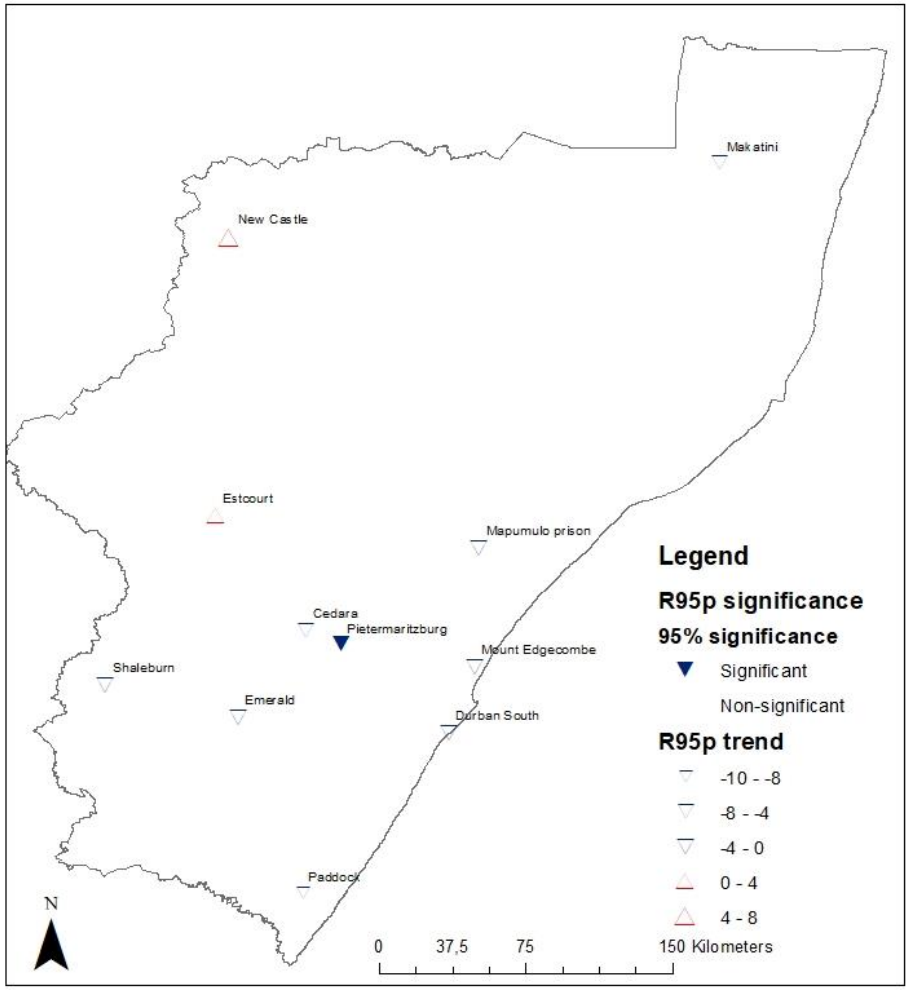
a) Rx1day



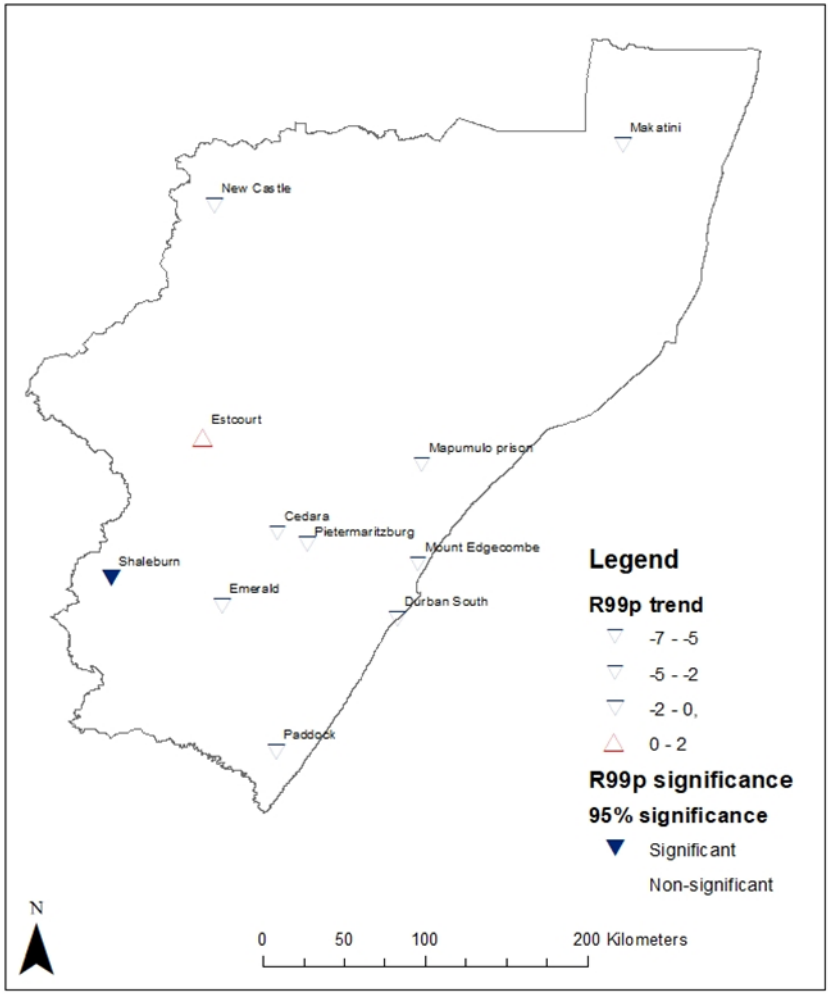
b) Rx5day



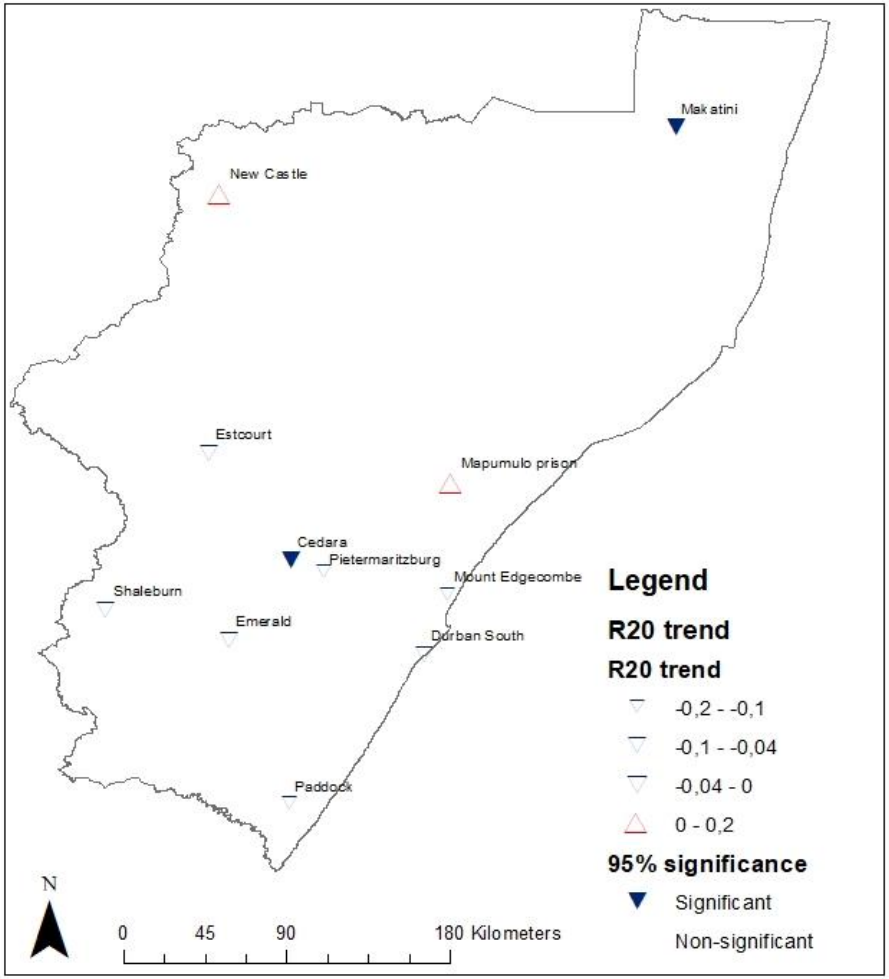
c) R95p


Makatini
New Castle
Estcourt
Mapumulo prison
Cedara
Pietermaritzburg
Mount Edgecombe
Shaleburn
Emerald
Durban South
Paddock
Legend
R95p significance
95% significance
Significant
Non-significant
R95p trend
-10 - -8
-8 - -4
-4 - 0
0 - 4
4 - 8
N
0
37,5
75
150 Kilometers

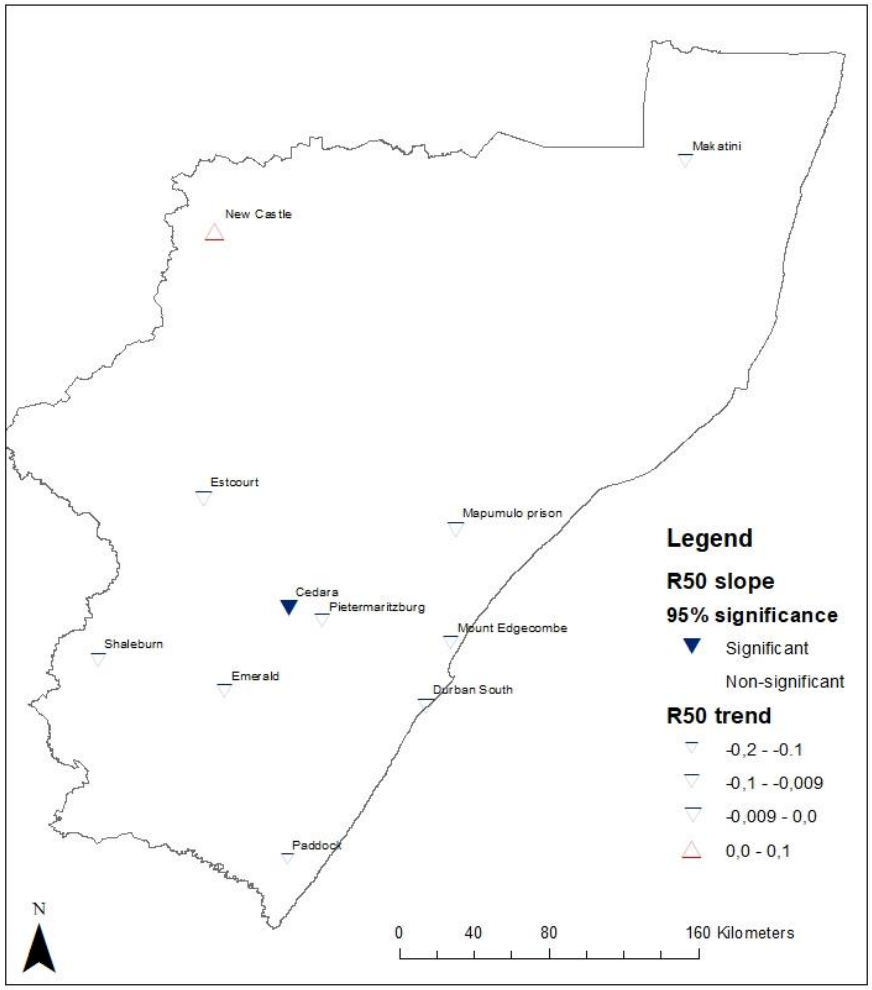
d) R99p


Makatini
New Castle
Estcourt
Mapumulo prison
Cedara
Pietermaritzburg
Mount Edgecombe
Shaleburn
Emerald
Durban South
Paddock
Legend
R99p trend
-7 - -5
-5 - -2
-2 - 0,
0 - 2
R99p significance
95% significance
Significant
Non-significant
N
0
50
100
200 Kilometers

e) R20mm



f) R50mm



g) CWD

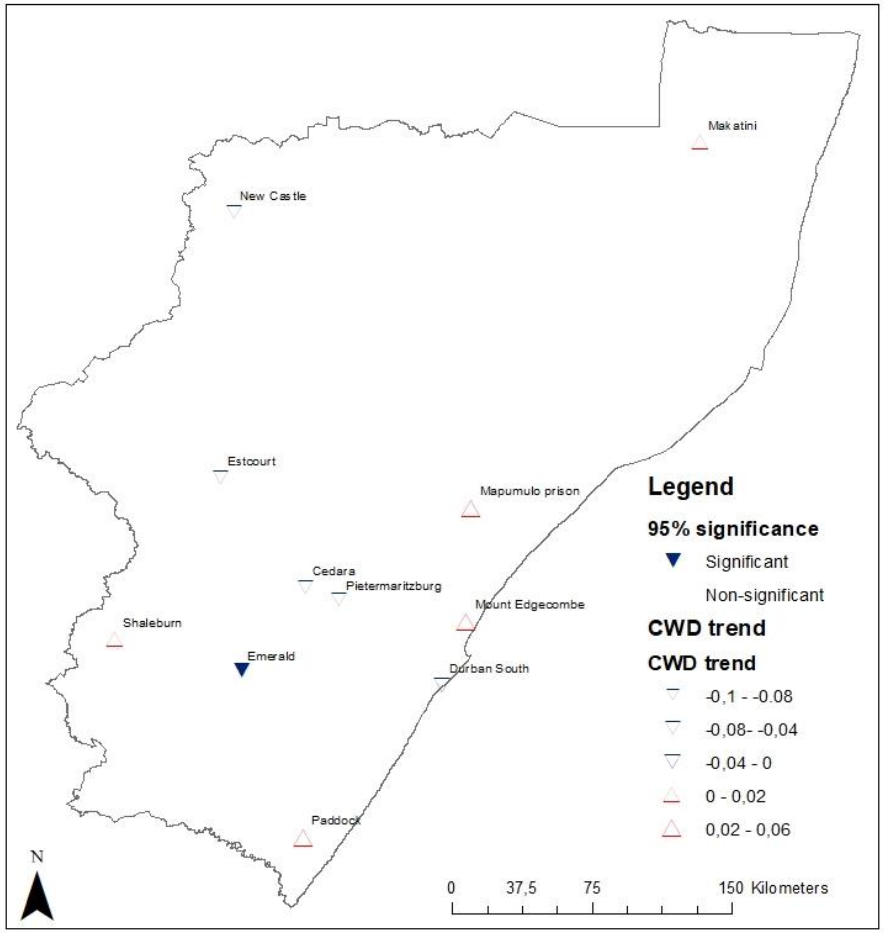


Figure 6: Maps showing spatial distribution of trends for: a) Rx1day, b) Rx5day, c) R95p, d) R99p, e) R20 mm, f) R50 mm and g) CWD.

Chapter 6: DISCUSSION

The primary focus of the study was to explore extreme rainfall incidence over KwaZulu-Natal and to explore extreme rainfall trends for the period 1989- 2019. The results of this study indicate that there are temporal patterns with regards to the occurrence of extreme rainfall events. The results of the trend analysis generally detect decreasing trends in extreme rainfall events, with very few trends being statistically significant.

6.1 Defining Extreme Events

Extreme weather events are described as rare events in a certain place and time of year while extreme climate events are the persistence of patterns of extreme weather events over a long period (Seneviratne *et al.*, 2021). Extreme weather and climate events are typically defined based on their occurrence above or below a defined threshold of a climate variable (Seneviratne *et al.*, 2012). The analysis of extreme events constitutes of either calculating extreme indices of 'moderate extremes', which occur on an annual basis, or extreme value theory which considers extreme events at multi-year and mutli-decadal scales (Kharin *et al.*, 2013). The WMO ETCCDI and ET-SCI cater for the analysis of moderate extremes based on 27 and 34 core daily temperature and precipitation indices respectively (Alexander and Herold, 2016). The value of these indices for trend analysis is to better achieve uniformity in detecting climate and weather extremes across the globe, and they are able to identify important information on climate extremes which is smoothed out when trends are analysed at larger timescales (Zhang *et al.*, 2011; Alexander and Herold, 2016; Bohlinger and Sorteberg, 2018).

In this study, subsets of the WMO ETCCDI/ET-SCI indices were calculated, with special focus on indices that calculate trends for extreme rainfall intensity, extreme rainfall frequency and rainfall duration. In chapter 5, Table 6, majority of daily rainfall amounts, whose magnitude is above the 99th percentile value, were confirmed by calculating subsets of the ETCCDI/ET-SCI indices. These were mainly confirmed by the Rx1day or the R50 mm. This highlights the value of the ETCCDI/ET-SCI indices in detecting daily extreme events, those associated with known events with media coverage and attributable to large-scale systems, and those which are likely more isolated and localised and attributable to small scale or mesoscale systems.

Floods and droughts are also defined as extreme events (Meehl *et al.*, 2000; Trenberth, 2011). Flood events can be linked to extreme and intense rainfall with widespread and devastating impacts but can also be associated with moderate rainfall resulting in localised damage which affects natural and artificial drainage systems (WMO, 2009; Trenberth, 2011; Lennard and Hegerl, 2015; Zarch *et al.*, 2015; Seneviratne *et al.*, 2021; Tramblay *et al.*, 2021). The incidence of extreme rainfall events (Table 6) indicates that KwaZulu-Natal is prone to heavy rainfall and flooding events, which can occur multiple times at intra- and inter-annual scales. This further reiterated findings that KwaZulu-Natal has the highest recorded flood events in South Africa (Botes, 2014; Mpungose *et al.*, 2022). The incidence of extreme rainfall events in Table 6 have also been linked to large-scale and mesoscale rain-bearing systems, ranging from tropical easterlies to midlatitude westerlies, such as cold fronts and COLs and localised thunderstorms, as confirmed by multiple sources (SAWB, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998; SAWS 1991). Known extreme rainfall and flooding events during winter and the transition months were attributed to cold fronts and COLs, which corroborated findings that out-of-season rainfall, and particularly

over the east coast of South Africa, was mainly associated with COLs (Favre *et al.*, 2013). Over the summer months, it is not clear from Table 6 which synoptic-scales systems are attributed to extreme rainfall and flooding events, however, literature highlights that KwaZulu-Natal is a summer rainfall region, and a large percentage (60%) of summer rainfall totals and summer extreme rainfall events (50%) are caused by TTTs (Hart *et al.*, 2013). Proving this was however beyond the scope of this study. The newly launched SAWS IBFWS early warning system caters for dissemination of extreme rainfall and flooding events at localised to widespread scales by adopting a risk-based matrix which considers the likelihood and severity of impacts of hydrological events (SAWS, 2020, Jenkins *et al.,* 2022). This system was used to disseminate alerts for the April 2022 floods over KwaZulu-Natal (SAWS, 2022a). The alerts were able to highlight the severity of the floods and subsequent devastating impacts for the most vulnerable areas. This early warning system is a useful tool for highlighting the different temporal and spatial scales that extreme rainfall and flooding events occur in in KwaZulu-Natal. However, the study period pre-dates the launch of this early warning system, therefore, unable to link any of the extreme rainfall incidences in Table 6 to any alerts.

6.2 Mean Incidence and Temporal Variations of Extreme Rainfall Events

6.2.1 Mean annual totals of extreme rainfall events.

The results for the average annual totals for the seven calculated indices indicated that the range in the average continuous wet days (CWD) over KwaZulu-Natal for the period 1989-2019 is between 4-6 days, with the mean annual total average being 5.96 days. Shaleburn, located over the south-western parts of the province, and close to the Drakensberg mountains, was the only station depicting average continuous wet days higher than the range and the mean total average at 8.19 days. Results also

show that the coastal stations, i.e., Durban South, Mount Edgecombe and Paddock consistently had higher mean annual averages for rainfall extremes, which were also higher than the average for all the stations. This confirms findings that the coastal regions of KwaZulu-Natal are more prone to extreme events and flooding (Engelbrecht, Engelbrecht and Dyson, 2013; Botes, 2014; Mpungose *et al.*, 2022). Paucity of station data representing the north coast of KwaZulu-Natal in this study was unable to confirm findings of Botes (2014) and Mpungose *et al.,* (2022) that the southern coastal belt of KwaZulu-Natal is more prone to flooding and extreme events. However, a study on the change in climate variables in KwaZulu-Natal, found that Cape St Lucia, in the north coast, had a high frequency and intensity of heavy and extreme rainfall events compared to inland stations (Ndlovu *et al.*, 2021). This, however, still confirms that the extreme rainfall events are more frequent and intense along the coastal strip. Apart for the average annual one-day maximum (Rx1day) and average frequency of extremely heavy rainfall events (R50mm), Shaleburn detected high averages of extreme event intensity and frequency compared to other inland stations. This confirms findings that the eastern escarpment, along with the eastern coastal strip have more frequent and intense extreme rainfall events (Engelbrecht *et al., 2013)*.

Results also indicate that the incidence of extremely heavy rainfall events (R50 mm) are rarer compared to very heavy rainfall events (R20 mm) based on the average frequency (Table 5) for the individual stations and the total average. This is also confirmed in literature (Hart *et al.*, 2013).

6.2.2 Temporal occurrence of extreme events

The temporal scale of extreme events detected in extreme rainfall intensity indices (Rx1day and Rx5day) and extreme rainfall frequency indices (R20mm and R50mm) depict seasonal and monthly variations. Extreme events predominantly occur during the summer rainfall season with a decrease in frequency over the winter months. Notable peaks are detected either early or late summer for individual stations. These findings agree with a study on the climate variability of KwaZulu-Natal, which found seasonal and monthly variations in rainfall and extreme rainfall events, particularly defined over the inland areas of KwaZulu-Natal (Ndlovu *et al.*, 2021). The coastal regions show well-distributed rainfall throughout the year, and this translates to the occurrence of extreme rainfall events as well, as was observed in this current study (Ndlovu *et al.*, 2021). The coastal stations, Durban South and Paddock, highlight that coastal regions have extreme rainfall event occurrences distributed throughout the year. This is due to the influence of midlatitude westerly systems, cold fronts and cut-off lows, which predominantly occur during transition and winter months (Camp, 1999; Tyson and Preston-Whyte, 2000; Botes, 2014).

6.3 Trend Analysis and Future Trends

6.3.1 Trend analysis versus observations

Studies on extreme rainfall trends on a global scale found opposing trends for rainfall extremes, with increasing trends being more predominant, particularly for upper percentile and day maximum extremes (Easterling *et al.*, 2000, Groisman *et al.,* 2005; Asadieh and Krakauer, 2015; Donat *et al.*, 2016; Kumar *et al.*, 2021). The results of this study found similar and contrasting results, where extreme rainfall indices depicted opposing trends across the region, but trends were predominantly decreasing. The results of global studies indicating predominant increases in trends are usually

averaged across the globe and may therefore not be a true reflection of regional findings. This highlights the importance of conducting trend studies at regional scales as there may be vast differences between global and regional results (Strydom and Savage, 2018). Most of the indices in this study did not detect statistically significant trends across the region, which was consistent with other studies on trends in daily rainfall extremes over South Africa (New *et al.*, 2006; Westra *et al.*, 2013, Kruger and Nxumalo, 2017). However, trends that were statistically significant, which were 10 out of 77 calculated trends, were those depicting decreasing trends. More noticeable trends were detected at individual stations, consistent with MacKellar *et al.,* (2014). This study found that six of the 11 stations detected statistically significant trends but there was no spatial homogeneity detected. This agrees with global and regional studies which found no spatial uniformity in daily extreme rainfall trends (Westra *et al.*, 2013; Asadieh and Krakauer, 2015; Kruger and Nxumalo, 2017). The daily extreme rainfall trends which were statistically significant were spread across the region and detected in different indices. It is noted however, that of the seven calculated daily extreme rainfall indices, there were no statistically significant trends detected for the Rx1day. However, it did detect a majority of decreasing trends. These findings are in agreement with global and regional studies which detected decreasing trends for the annual maximum one-day extreme rainfall over the eastern parts of South Africa and in particular KwaZulu-Natal (Kruger, 2006; Westra *et al.*, 2013; Donat *et al.*, 2016, 2019; Kruger and Nxumalo, 2017). It is noted however, that Kruger and Nxumalo (2017) detected non-significant increasing trends of the annual one-day maximum extreme rainfall intensity. The remaining indices detected two statistically significant trends each, that is, Rx5day, R95p, R99p, R20mm, except for R50mm and CWD, which had one each. Considering trends at individual stations, Cedara calculated the

most statistically significant trends, with three out of seven indices detecting statistically significant decreasing trends, which were for one extreme rainfall intensity index (RX5day) and the two extreme rainfall frequency indices (R20mm and R50mm). Pietermartizburg and Makathini, each detected two out of seven indices that depicted statistically significant decreasing trends. These stations both detected statistically significant trends with large rates of change for very wet days index (R95p) and the other indices being Rx5day for Pietermartizburg but R20mm for Makathini. Shaleburn and Maphumulo Prison both detected statistically significant decreasing trends for the extreme wet days index (R99p) while Emerald being the only station detecting a statistically significant trend for the rainfall duration index (CWD). The spatial distribution of trends was distorted over the northern parts of the province due to limited station data in the study. The spatial maps indicated that stations over the midlands consistently detected decreasing trends for all calculated indices, and most statistically significant trends were confined in that region. The extreme north-eastern parts also detected consistently decreasing trends for extreme rainfall intensity and frequency indices, except for the rainfall duration index (CWD). No other statistically significant patterns were observed. It is noted however, that spatial patterns in extreme rainfall trend analysis have been observed at seasonal scales based on literature (Engelbrecht *et al., 2013;* Roy and Rouault*,* 2013; Kruger and Nxumalo, 2017*)*.

The general findings for the trend analysis in this study was that the intensity and frequency of daily extreme rainfall events has decreased in KwaZulu-Natal over the period of 1989 to 2019. The contrasting results to similar studies in South Africa (Kruger, 2006; Kruger and Nxumalo, 2017) could be due to the short study period in this study which according to Kruger (2006) can result in the identification of apparent

trends as real trends when a shorter time period is used. This was depicted in a study of the microclimate of the KwaZulu-Natal midlands, where an increase of 20mm per decade was observed over Cedara during the period 1953-2015, but a decrease of 30mm per decade during the period of 1992-2015 (Strydom and Savage, 2018). It is recommended that a study period of close to a century be used to filter out the effects of the decadal-scale cyclical pattern of South African precipitation (Kruger, 2006). Secondly, apart for the midlands and extreme-north-eastern parts of the province, there were no notable spatial distribution patterns detected as opposing trends were detected for most of the region.

6.3.2 Future trends

According to the IPCC 6th Assessment Report (AR6), heavy precipitation will become more frequent and intense with expected global warming, more so for rarer events (Seneviratne *et al.*, 2021). The projected increases in the intensity of extreme rainfall will result in the increase in intensity and frequency of pluvial floods, i.e., surface water and flash floods (Seneviratne *et al.*, 2021). Over South Africa, extreme rainfall is projected to increase by 2100 for global warming projections of 2°C and under emission scenario RCP8.5 (Pinto *et al.*, 2016; Seneviratne *et al.*, 2021). However, the magnitude of heavy rainfall is projected to decrease over western South Africa due to a projected decrease in the frequency cold fronts and closed mid-latitude cyclones (Seneviratne *et al.*, 2021).

Regional future projections of rainfall and extreme rainfall for southern Africa indicate wetting trend for the east with increasing frequency of heavy rainfall (R20mm), especially for the extreme east (Lumsden *et al.*, 2009; Engelbrecht *et al.*, 2013). This is in agreement with the IPCC AR6 (Seneviratne *et al.*, 2021). The frequency of closed

lows and subsequent associated rainfall intensity is projected to decrease for southern Africa, except for tropical lows and tropical cyclones (Engelbrecht *et al.*, 2013; Seneviratne *et al.*, 2021). Engelbrecht *et al.,* (2013) simulated closed lows in the southern domain well but overestimated tropical lows, which suggests that projections may be on par for areas affected by closed lows but there may be discrepancies for tropical lows. Therefore, projections for KwaZulu-Natal may be on par except for the extreme east and northern parts which are also affected by tropical cyclones. Some discrepancies have also been detected in various studies between observations and GCM simulated observations, which are likely to cause uncertainties in future projections. A study comparing observed and model trends for South African rainfall for period 1960-2010 found that the GCM simulations from the CMIP5 underperformed in capturing rainfall trends (MacKellar *et al.*, 2014). Potential causes of these model discrepancies were explored by MacKellar *et al.,* (2014). Similar discrepancies were found in the study of the global trends of annual one-day maximum, also using an ensemble of CIMP5 GCM, where climate models underestimated the rate of change for trends (Asadieh and Krakauer, 2015). A study on future changes in the intensity of persistent extremes (RxEvent) and annual one-day maximum found that the GCM models comprising of 30 ensembles in the CMIP5 showed differences in the magnitude and trend sign for these events in a warming climate (Du *et al.*, 2019). This suggests that future projections may over- or under-estimate rainfall and extreme rainfall trends or indicate opposing signs if they have been found to have discrepancies in simulating observations.

6.4 Study Limitations

The study was conducted for the period 1989-2019 however a few limitations arose. Study limitations arose due to removing one station from the analysis due to the period

of missing data, quality control limitations relating to data verification, and limitations on the indices calculated in the study. These limitations are elaborated on below.

6.4.1 Data Limitations

The SAWS rainfall data used had periods of missing data due to weather stations being closed for certain periods and subsequently reopened again. This has resulted in missing data ranging from a period of a few days to months (Table 2). One station, Mandini had missing data for a full year (1992) and was subsequently omitted from the analysis and is therefore not presented in Table 2. Methods to fill in missing data were considered in the literature such as the Inverse Distance Weighting, which used a minimum of two up to five neighbouring stations or stations within a 50km radius to estimate values at a specific station or replacing data with a 5-day running mean (Moeletsi and Walker, 2012; van Der Walt and Fitchett, 2021). These approaches to fill in missing data were not implemented as 90% data completeness was already achieved even with missing data, and the surrounding stations that could have been used to fill the missing data did not span the same climatological period as the stations used in the analysis.

There were also instances where weather stations were moved to other locations due to various reasons, such as vandalism, however, these relocations posed no significant changes to the observed variables (Lannert, 2022, GIS specialist, SAWS). Some instances did occur where data was identified as outliers (Table 3), however, there was no way to compare or verify these values, therefore there may be some errors in the analysis. Kruger and Nxumalo (2017) note that proper quality control of rainfall data is difficult to conduct over South Africa due to the complexities of the

nature of rainfall, which can be attributed to topography and other rainfall-producing mechanism. Based on these factors it is possible that the results may not be a true reflection of the trend analysis.

The study used individual station data as opposed to gridded data due to the small sample size of station data which had continuous historical rainfall data that spanned the study period. The benefits of using gridded data are noted, some of which are the reduction of natural variability of data, reducing the effects of outliers and catering for uneven distribution of station data (Alexander *et al.*, 2006; Data, 2009a). However, using gridded data can also result in the overrepresentation of regions with higher station density and the loss of useful information at station level (Alexander *et al.*, 2006; WMO, 2009). Despite the limitations of this data there is enough quality data to analyse extreme rainfall trends over KwaZulu-Natal.

6.4.2 Selected indices

The study only calculated and analysed a subset of the ETCCDI/ET-SCI indices that consider wetting trends, particularly focusing on very heavy to extreme intensity and frequency of rainfall events. Dry trends and analysis or trends on droughts that have occurred in KwaZulu-Natal were not explored. However, these have been analysed for South Africa and for KwaZulu-Natal in various studies (Mason and Tyson, 2000; Rouault and Richard, 2003; Kruger, 2006; Ujeneza and Abiodun, 2015; Malherbe *et al.*, 2016; Baudoin *et al.*, 2017; Kruger and Nxumalo, 2017; Ndlovu *et al.*, 2021), using indices such as the Standardized Precipitation Index and the Standardized Precipitation and Evaporation Index.

Chapter 7: CONCLUSION

7.1 Introduction

The study provided insights into the incidence of extreme rainfall events over KwaZulu-Natal and the observed trends for the period 1989-2019. The adopted methodology of calculating subsets of the WMO ETCCDI/ET-SCI proved that KwaZulu-Natal is prone to moderate extreme rainfall events with temporal and spatial variations. The areas within the region which depicted more frequent and intense extreme rainfall events were in line with literature.

Discrepancies were detected in the observed trends in this study compared to global and regional studies, where increases in extreme rainfall trends were observed globally and regionally but decreases were detected in this study. This highlighted the importance of undertaking regional or microclimate investigations of weather and climate extremes, as global and regional investigations may distort results by averaging over a large area.

7.2 Achievement of Aims and Objectives

The primary aim of the study was to investigate the incidence and changes in rainfall extremes over KwaZulu-Natal for the period 1989 to 2019, and whether these depict any spatial or temporal patterns.

The objectives included:

i. To evaluate the quality of rainfall data over KwaZulu-Natal for the period 1989-2019

This objective was achieved in Chapter 4 of the study, subsection 4.2. The outliers that were identified from the quality control process in the ClimPactv2 software were verified against SAWS raw data and compared to SAWS climate summaries and CAULEM (SAWB, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998; SAWS 1991). The data completeness for all stations was sufficient for the data to be used in the study.

ii. Identify incidence of extreme rainfall events by calculating subsets of the World Meteorological Organisation (WMO) Expert Team on Climate Change Detection Indices (ETCCDI) and Expert Team on Sector-specific Climate Indices (ET-SCI).

This objective was achieved in Chapter 5 subsections 5.2 and 5.3. The objective explored the temporal variation of the incidence of the annual one-day maximum, annual five-day maximum, very heavy and extremely heavy rainfall days. The mean annual average indices for the individual stations highlighted that the coastal regions of KwaZulu-Natal depicted higher frequency and intensity of extreme rainfall events, and they were predominantly higher than the provincial or regional average. The incidence of extreme rainfall events was predominantly during the summer rainfall season for the entire province, but all year round for coastal regions.

iii. Calculate trends in the incidence of extreme rainfall events through regression analysis.

This objective was achieved in Chapter 5 subsections 5.4 and 5.5. The objective explored trends of the annual one-day maximum, annual five-day maximum, very heavy and extremely heavy rainfall days, very wet days and extremely wet days, and continuous wet day indices. The trend analysis detected predominantly decreasing

trends over KwaZulu-Natal for the period 1989-2019, with only 10 out of 77 calculated trends being statistically significant. The spatial distribution of trends highlighted the KwaZulu-Natal midlands as the region with consistently decreasing trends for all calculated indices.

7.3 Avenues for Future Research

The study explored the incidence of extreme rainfall events over KwaZulu-Natal and the trends of these extreme events by calculating subsets of the WMO ETCCDI/ESCI indices and their trends. Future studies can explore the incidence and trends of extreme rainfall events for the other eight provinces in South Africa individually. This microclimate study highlighted that KwaZulu-Natal had exhibited predominantly decreasing trends, although in the literature some studies had found increasing trends in extreme rainfall events over the eastern parts of South Africa (Kruger and Nxumalo, 2017). Undertaking these microclimate studies for the individual provinces could be beneficial for providing a localised view of extreme rainfall trends. In addition, the remaining extreme rainfall related indices that form part of the 27 and the 34 core indices of the WMO ETCCDI and ET-SCI respectively should be considered in the future studies, including the integration of the Standard Precipitation Index (SPI) to explore the incidence and trends of droughts. The results of this study found that there were temporal variations to the incidence of extreme events, where majority of extreme rainfall events occurred during the summer rainfall season. Therefore, future studies could broaden this investigation into exploring whether there are any extreme rainfall trends at seasonal scales.

The study used individual meteorological station data which identified many extreme rainfall events as outliers. Subsequently, paucity in station data in the northern parts

of KwaZulu-Natal did not provide an accurate representation of trends in the northern parts. Therefore, using gridded data in future studies would address the scarcity and smooth out outliers.

Due to the scope of this study, the study was not able to do the analysis of linking synoptic scale weather systems to extreme rainfall events. However, this aspect could be undertaken in future studies.

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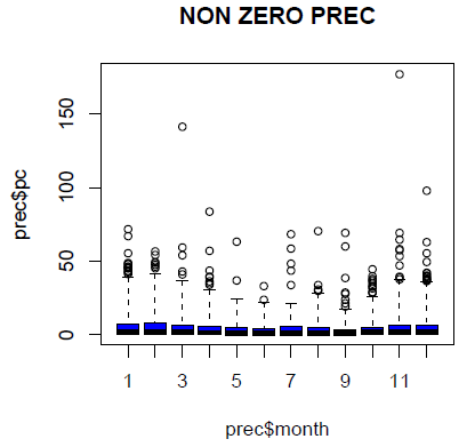
APPENDIX A: OUTLIERS FROM QUALITY CONTROL

Cedara



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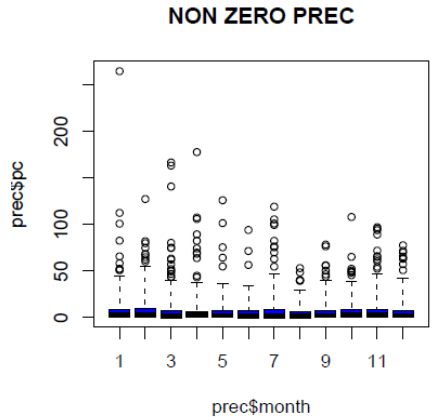

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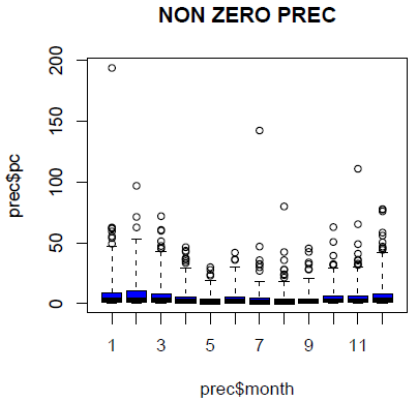

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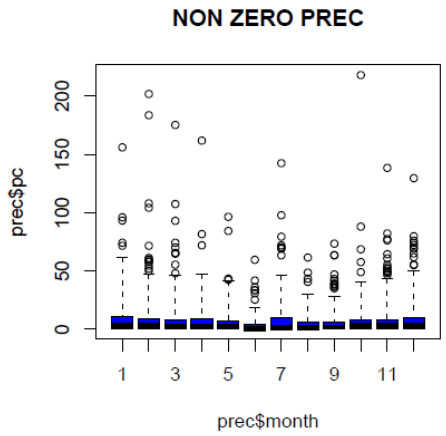
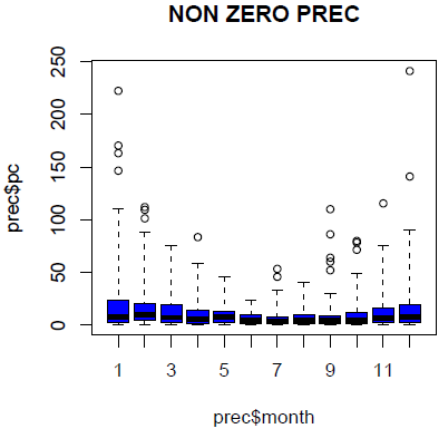
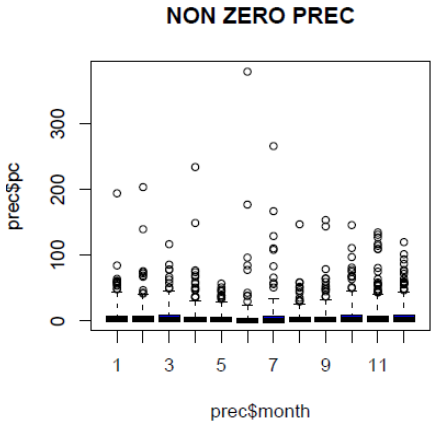


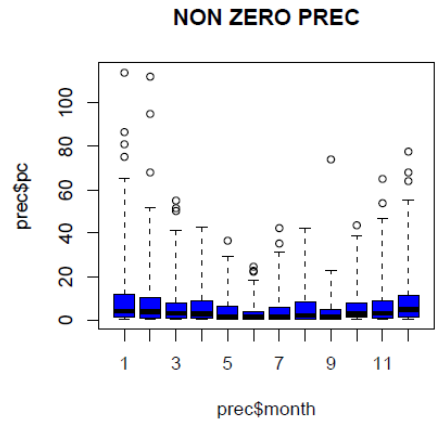
Makathini



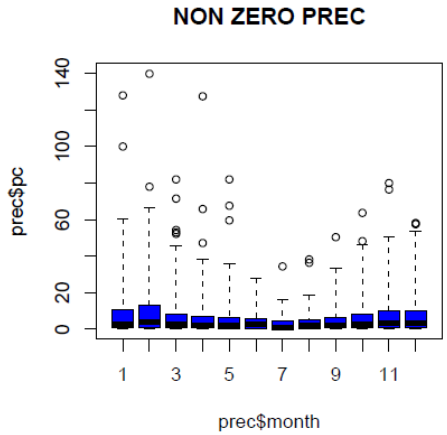
Maphumulo Prison



Mount Edgecombe



Newcastle



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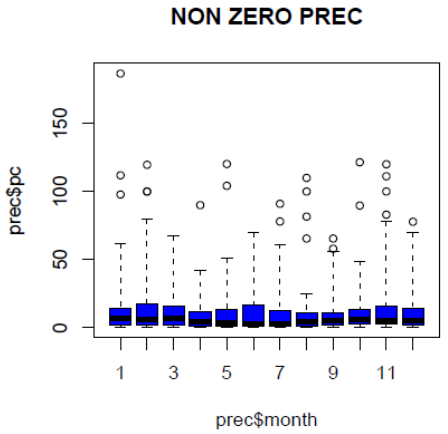
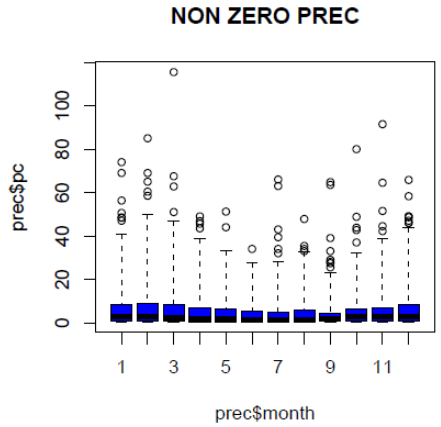


Pietermaritzburg



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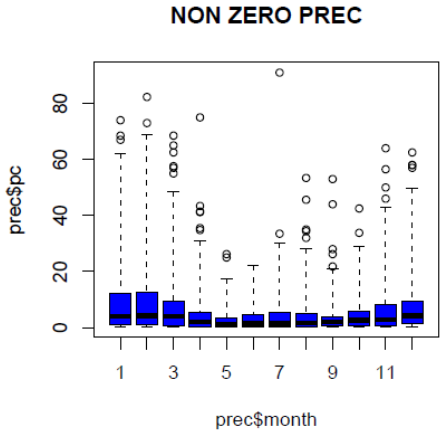
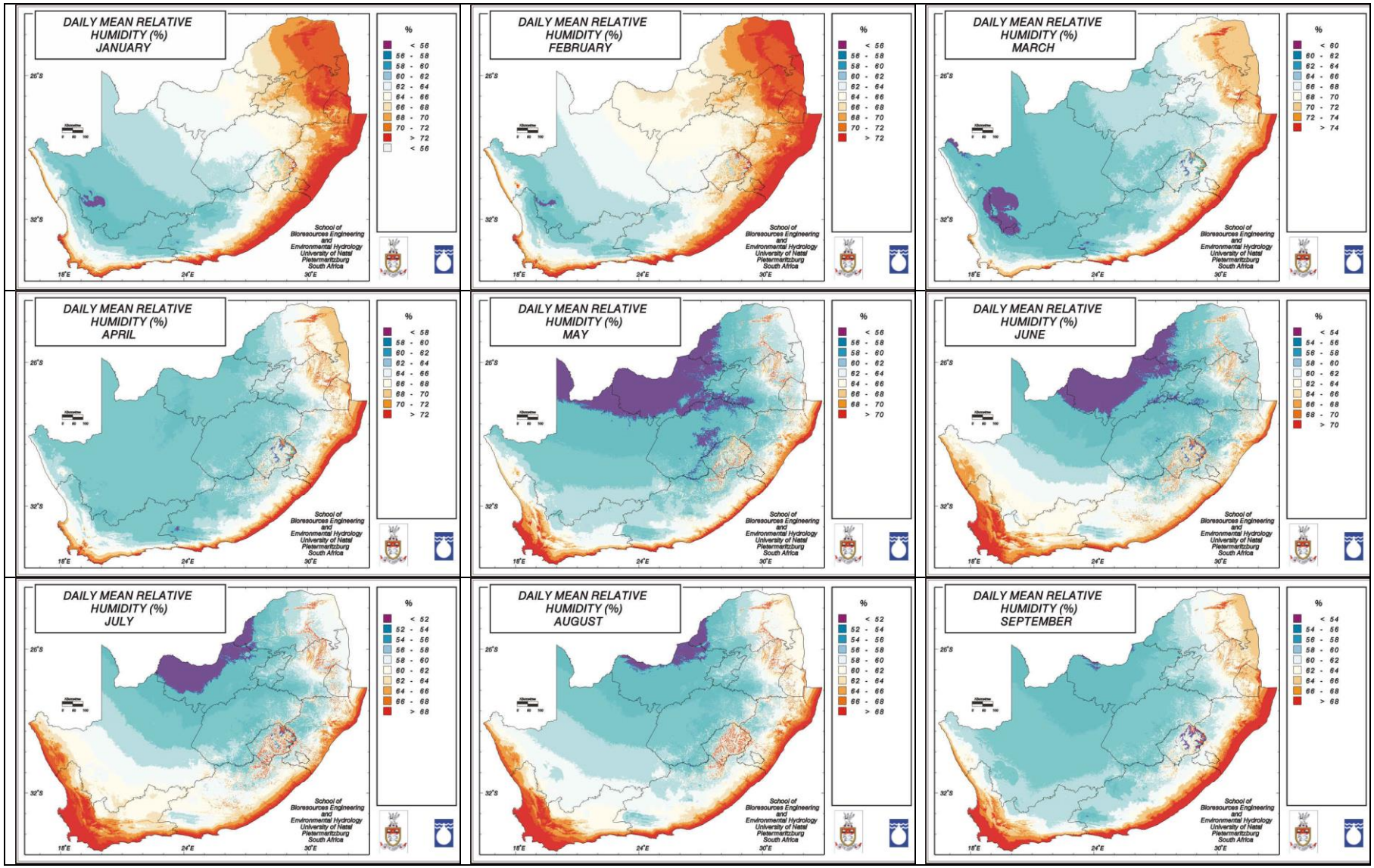
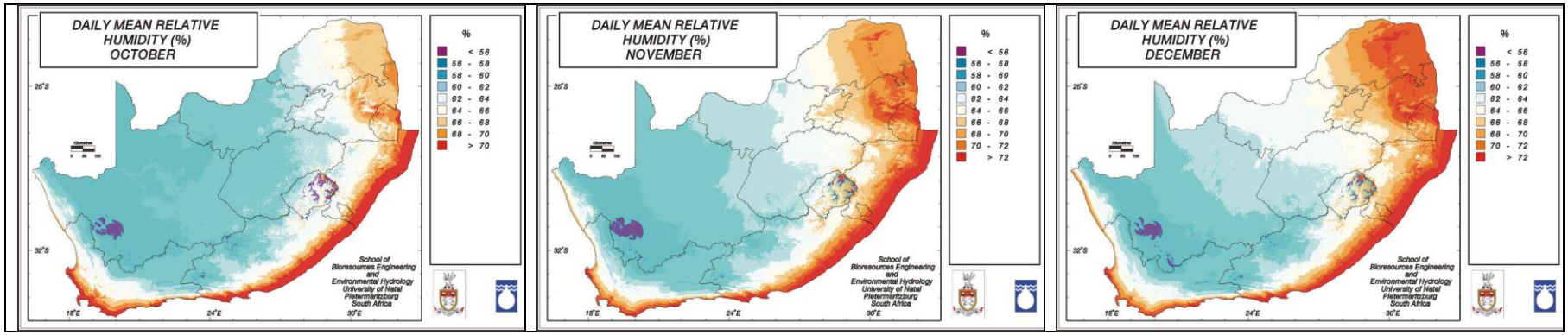


APPENDIX B: RELATIVE HUMIDITY OVER SOUTH AFRICA

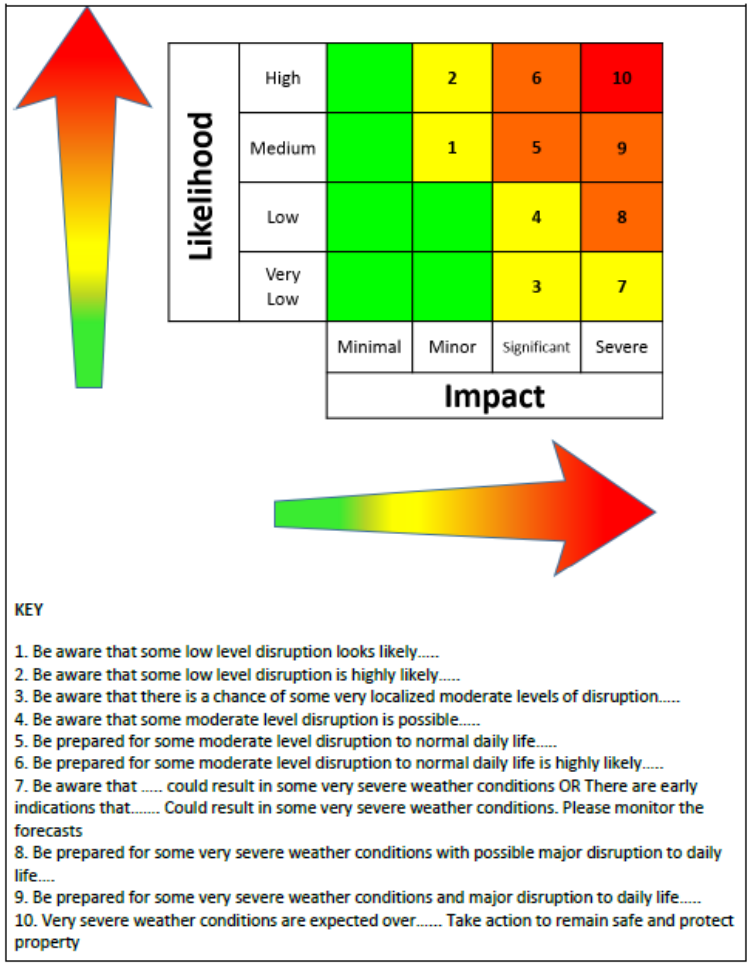




(Schulze, 1997)

APPENDIX C: IBFWS RISK MATRIX AND IMPACT TABLE FOR RAIN

(SAWS, 2022a)



KEY

1. Be aware that some low level disruption looks likely.....
2. Be aware that some low level disruption is highly likely.....
3. Be aware that there is a chance of some very localized moderate levels of disruption.....
4. Be aware that some moderate level disruption is possible.....
5. Be prepared for some moderate level disruption to normal daily life.....
6. Be prepared for some moderate level disruption to normal daily life is highly likely.....
7. Be aware that ..... could result in some very severe weather conditions OR There are early indications that..... Could result in some very severe weather conditions. Please monitor the forecasts
8. Be prepared for some very severe weather conditions with possible major disruption to daily life....
9. Be prepared for some very severe weather conditions and major disruption to daily life.....
10. Very severe weather conditions are expected over..... Take action to remain safe and protect property

Addendum 2: Impact Tables

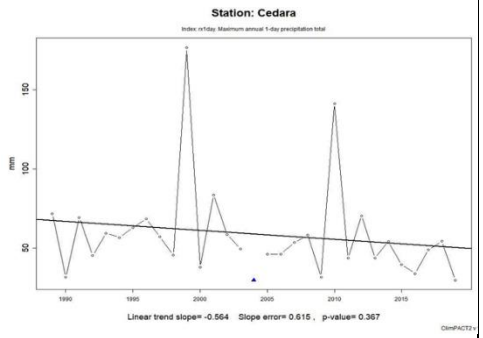
Rainfall

Minimal	Minor	Significant	Severe
Business as usual	Localised Business as usual	Localised Short term strain on emergency personnel	Widespread Prolonged strain on emergency personnel
• Some pooling of water on roads or in formal/informal settlements • Day to day activities not disturbed • Wet roads and reduced visibility • Minimal traffic congestion • Isolated mudslides and rockfalls	• Localised flooding of susceptible formal/informal settlements or roads, low-lying areas and bridges • Major roads affected but can be used, increased travel times • Difficult driving conditions on dirt roads • Minor motor vehicle accidents due to slippery roads and/ reduced visibility • Closure of roads crossing low water bridges • Localised and short term disruption to essential services (water, electricity, hospitals, schools etc) • Localised mudslides, rockfalls and soil erosion • Localised disruption due to sinkholes/potholes/blocked drainage systems • Isolated cases of breakages of farm dam walls • Localised damage to mud-based/make-shift houses/structures • Localised disruption of access to drinking water and damage to crops	• Flooding of roads and settlements *(formal and informal)* • Danger to life (fast flowing streams / deep water) • Displacement of affected communities • Some communities temporarily not accessible/cut-off • Damage to property, infrastructure, loss of livelihood and livestock • Major disruption of traffic flow due to major roads being flooded or closed • Possible damage to roads and bridges • Disruption to essential services (water, electricity, comms, schools, etc) • Mudslides rockfalls and soil erosion • Disruption due to sinkholes/potholes/ blocked drainage systems • Isolated incidents of communicable diseases • Isolated cases of breakages of informal/farm dam walls • Damage to mud-based/make-shift houses/structures • Disruption of access to	• Widespread flooding of roads and settlements • Danger to life (fast flowing streams / deep water) • Large communities not accessible/cut-off for a prolonged period • Widespread displacement of affected communities • Widespread damage to property, buildings and loss of livelihoods and livestock • Widespread transport routes and travel services severely affected • Major roads and bridges damaged or washed away • Widespread, prolonged disruption to essential services (water, electricity, comms, schools, etc) • Widespread mudslides, rockfalls and soil erosion • Long term disruption due to sinkholes/potholes/ blocked drainage systems • Widespread incidents of communicable diseases • Breakage of dam walls • Widespread damage to mud-based/make-shift houses/structures • Widespread disruption of access to drinking water and damage to crops

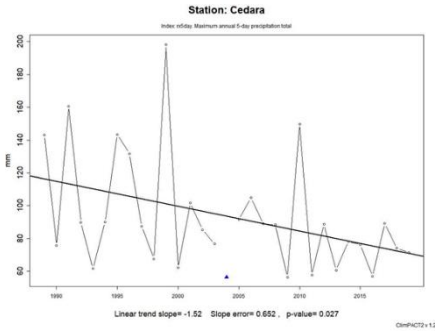
APPENDIX D: LINEAR REGRESSION GRAPHS FOR TRENDS

Cedara

Rx1day



Rx5day



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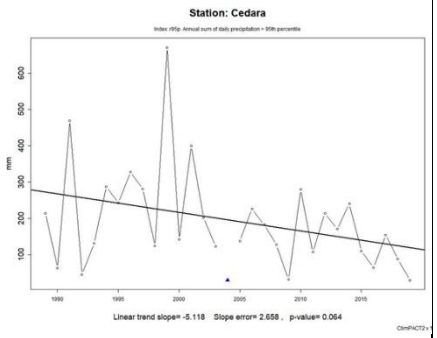

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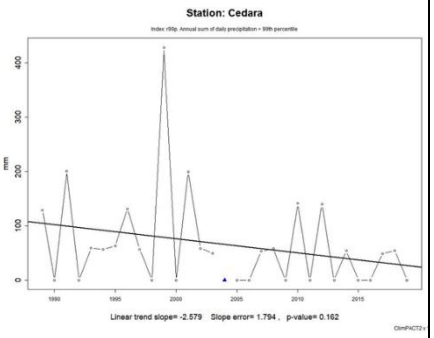

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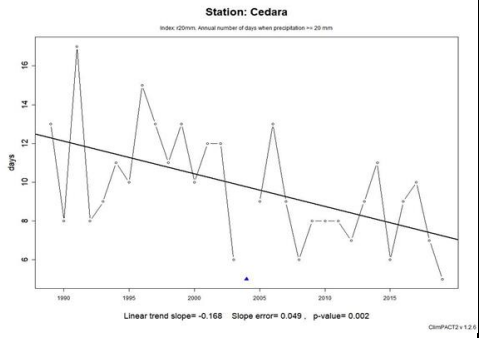

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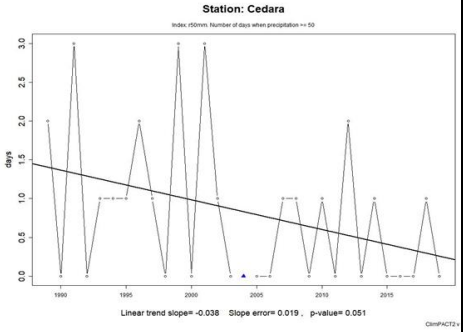

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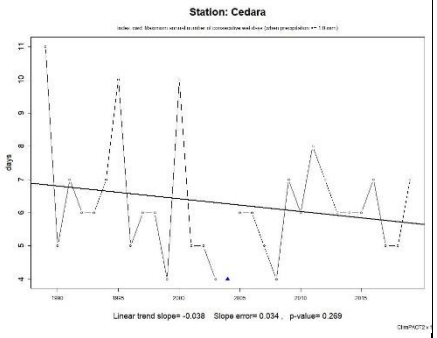

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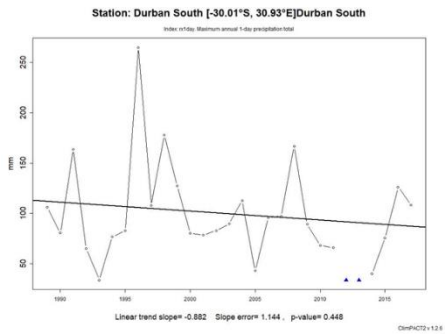	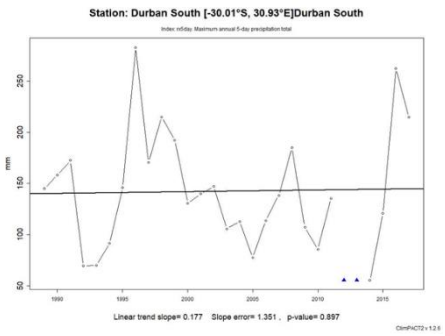	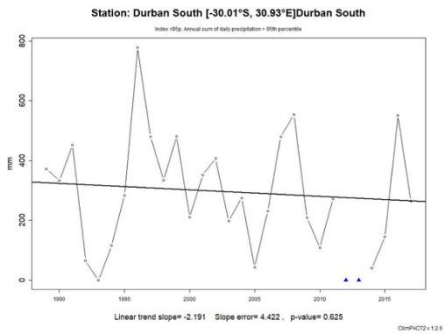	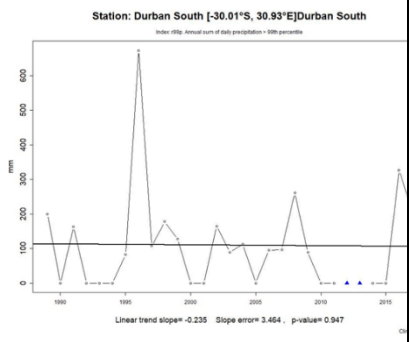
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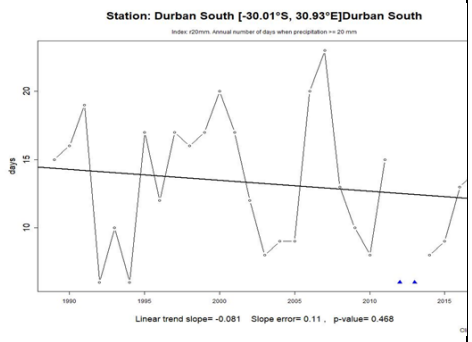	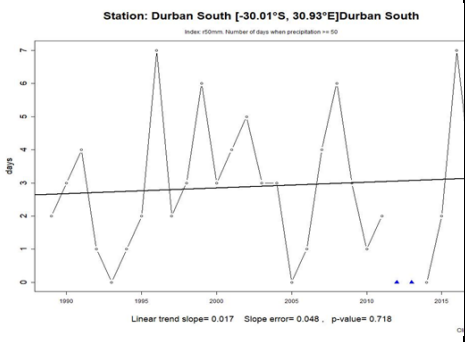	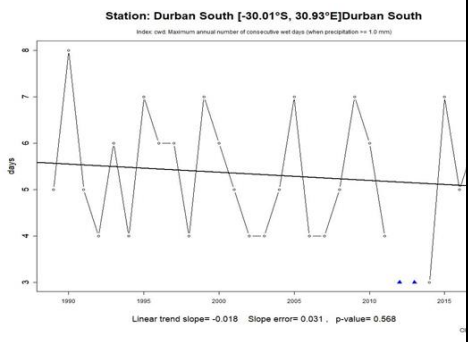	

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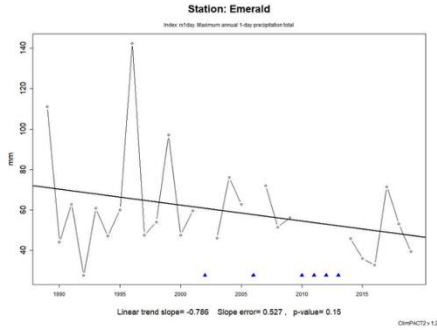	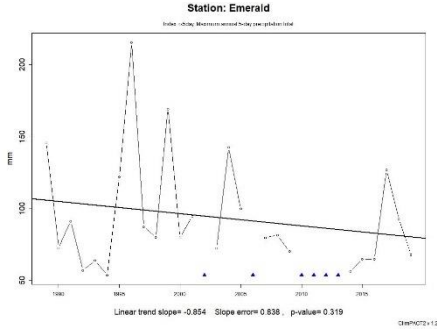	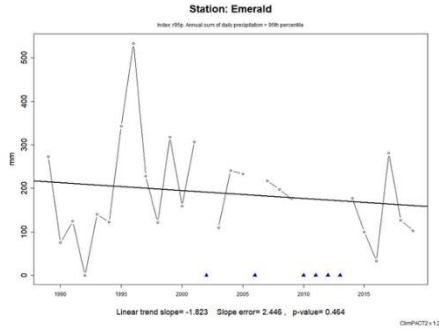	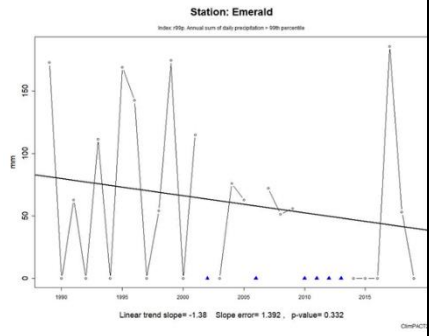
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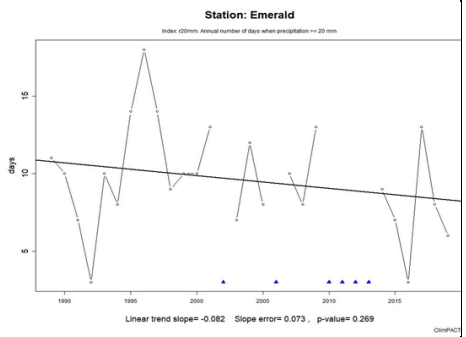
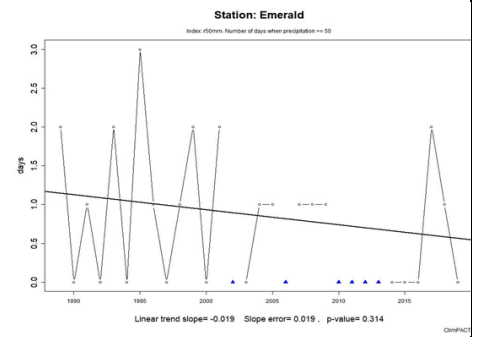
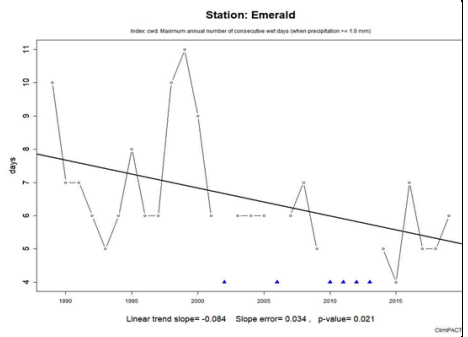
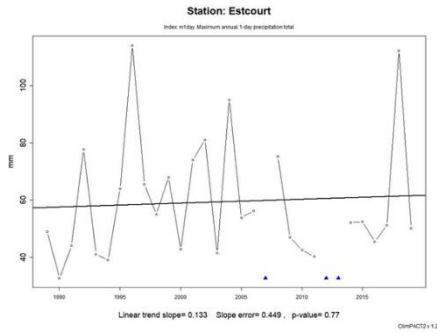
	 m		

Estcourt

Rx1day



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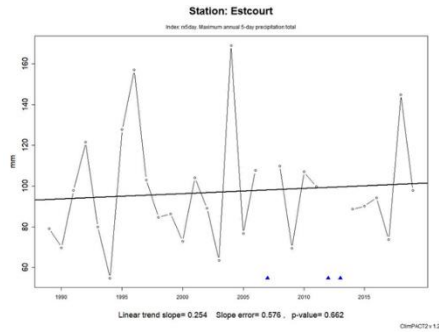

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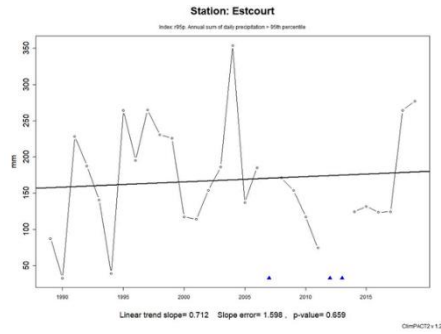

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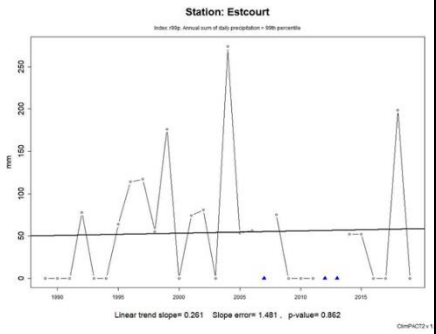

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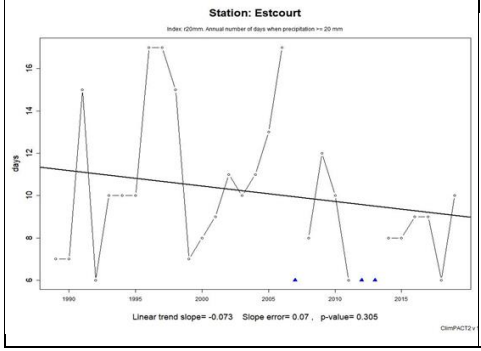

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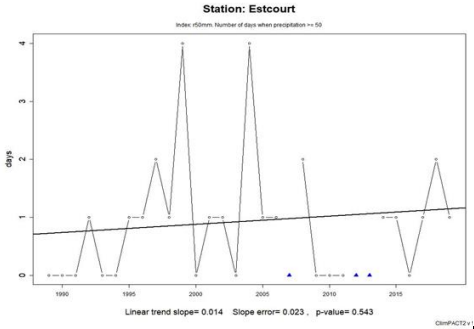

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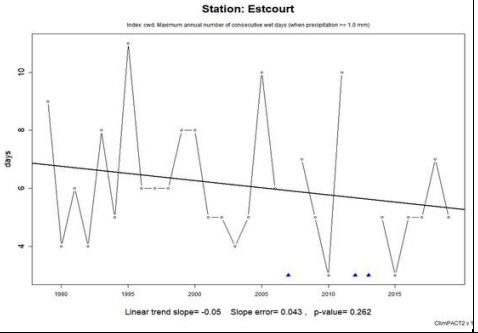
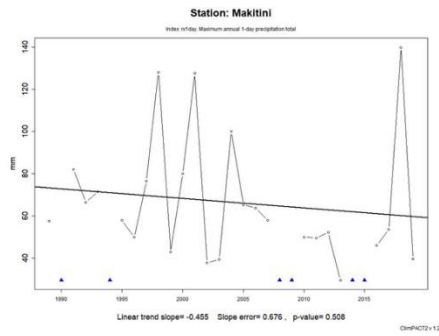
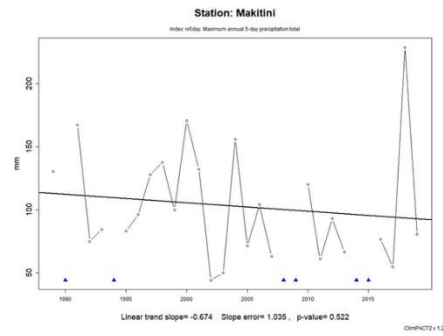
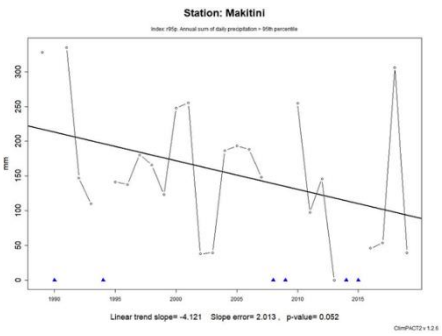
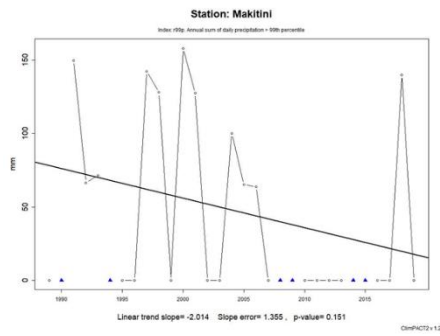


Makathini			
Rx1day	Rx5day	R95p	R99p
			
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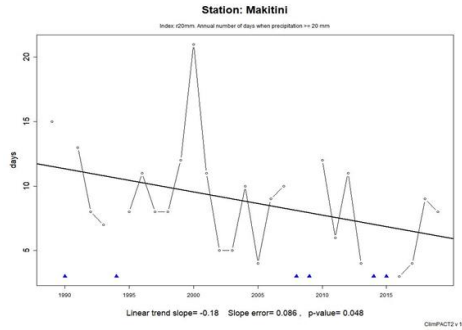	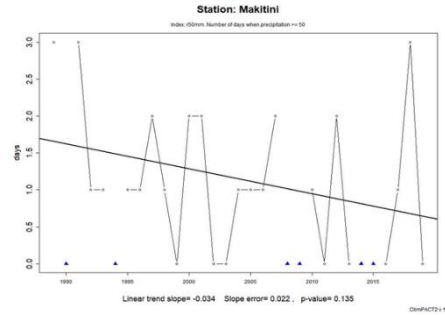	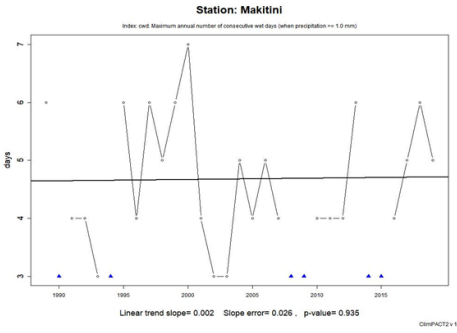	

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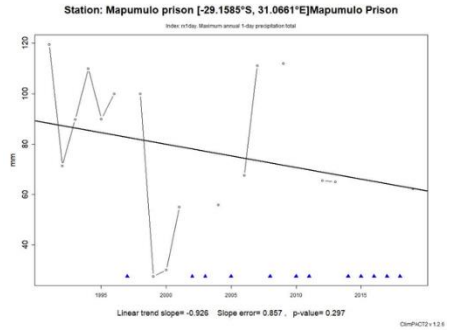	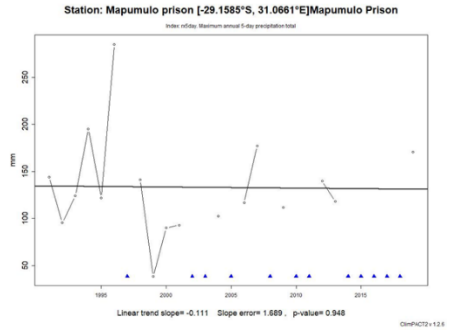	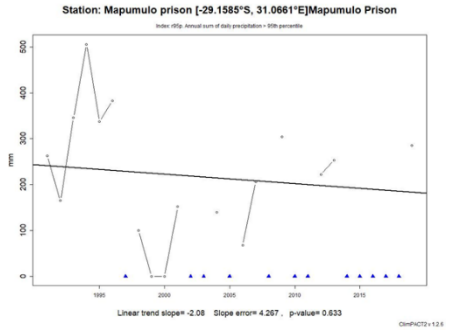	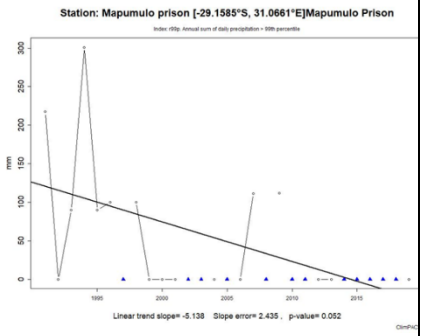
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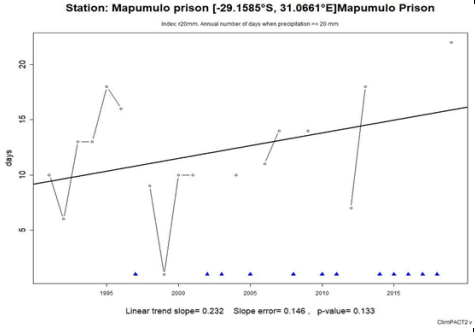
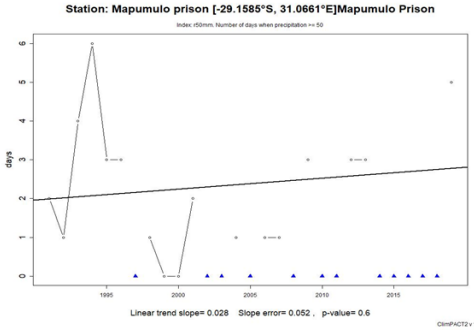
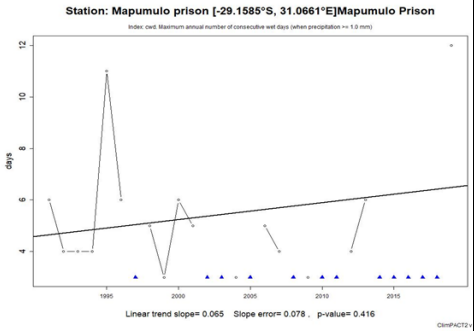
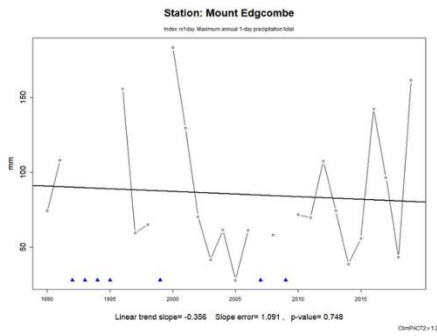
			

Mount Edgecombe

Rx1day



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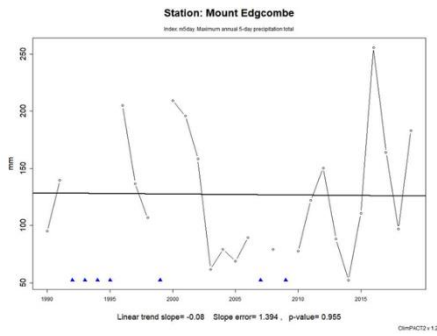

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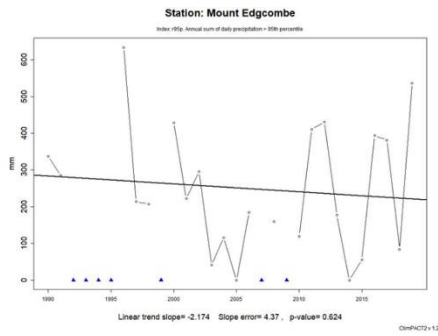

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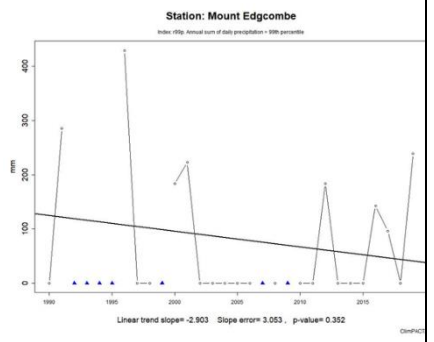

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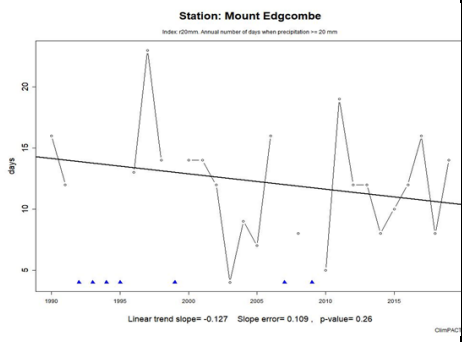

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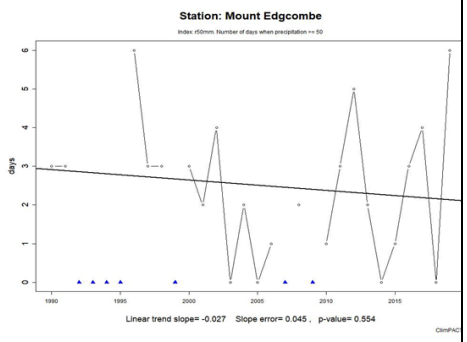

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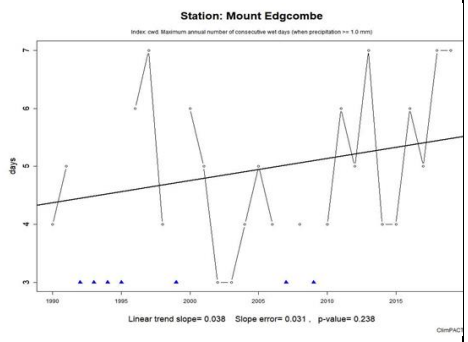
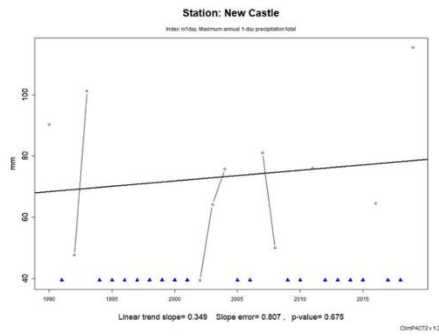
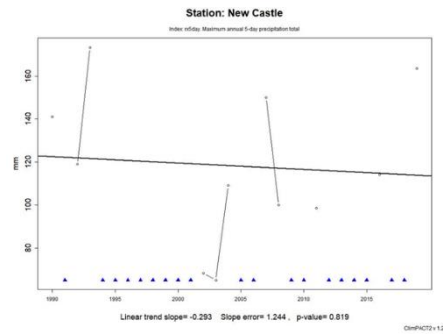


Newcastle

Rx1day



Rx5day



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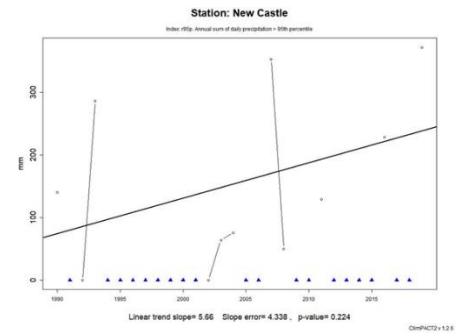

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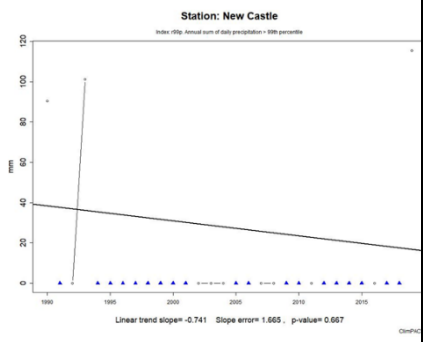
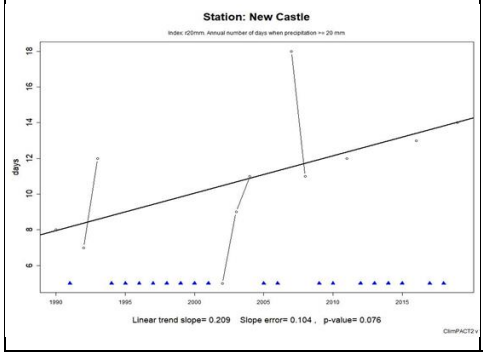


R20mm



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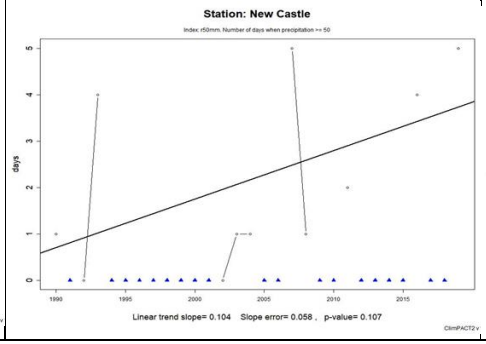
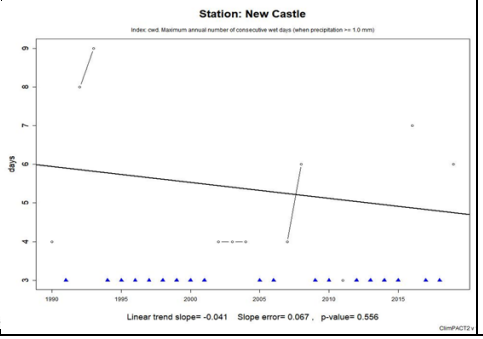
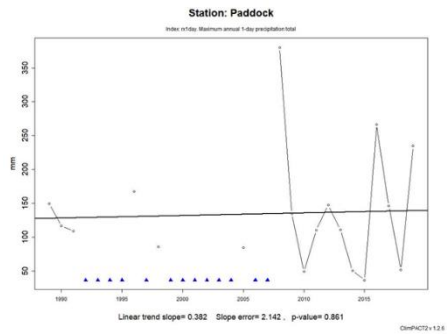
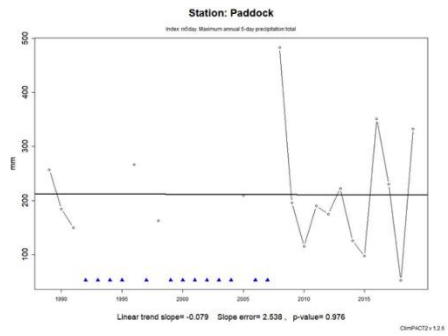
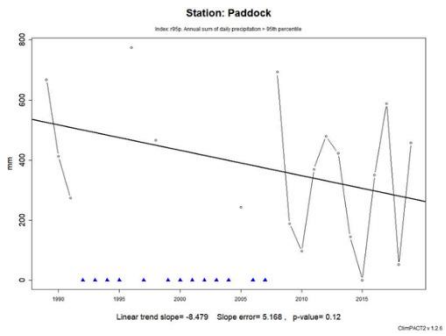
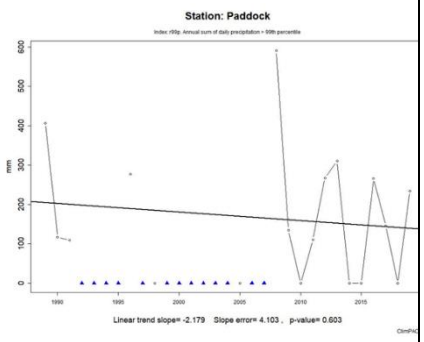
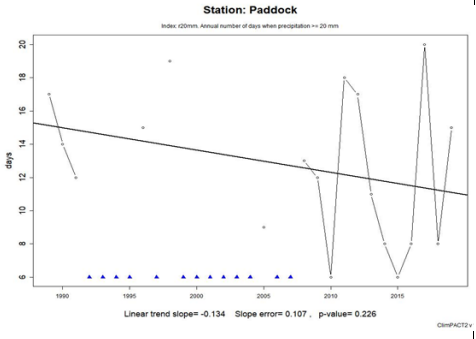
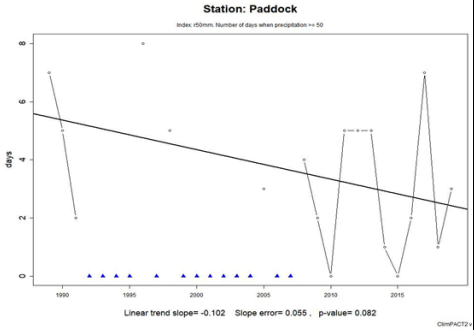
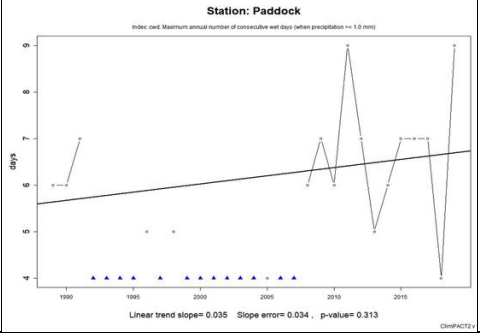


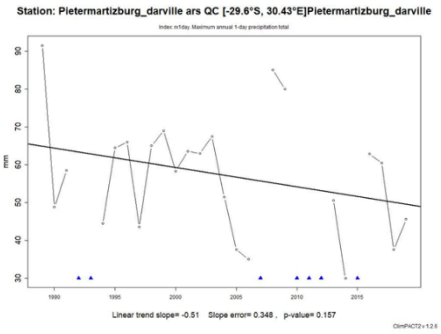
CWD



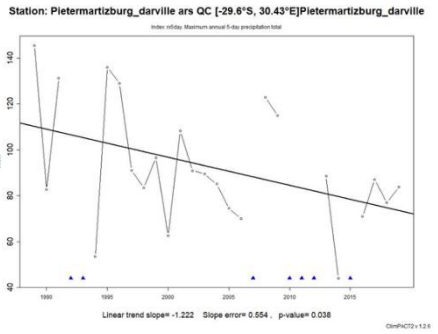
Paddock			
Rx1day	Rx5day	R95p	R99p
			
R20mm	R50mm	CWD	
			

Pietermaritzburg

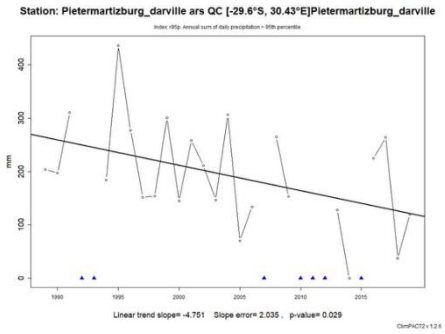
Rx1day



Rx5day



R95p



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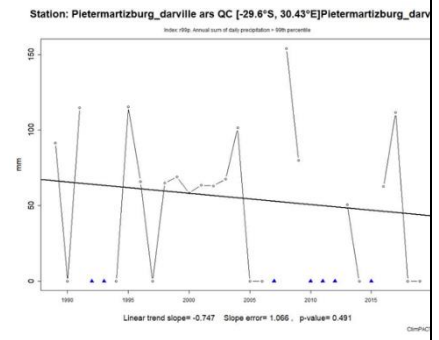
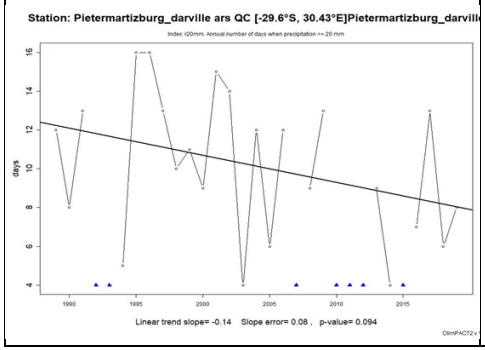
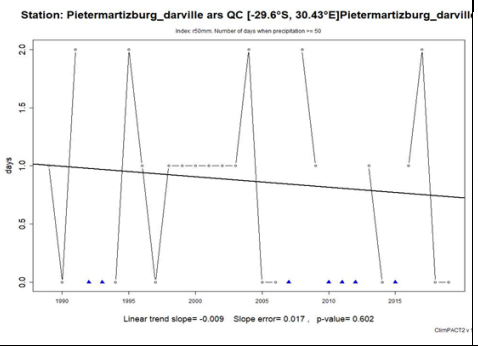


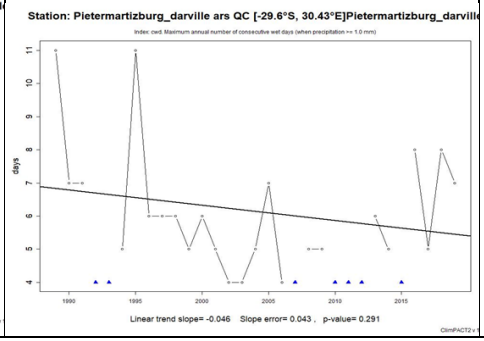
R20mm

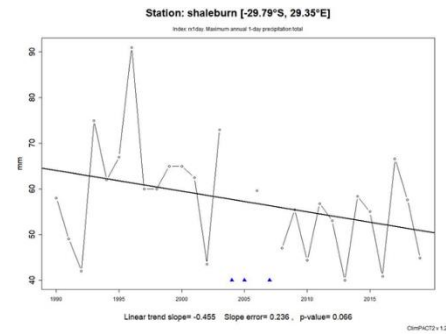
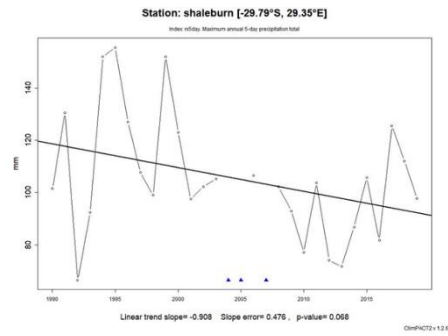
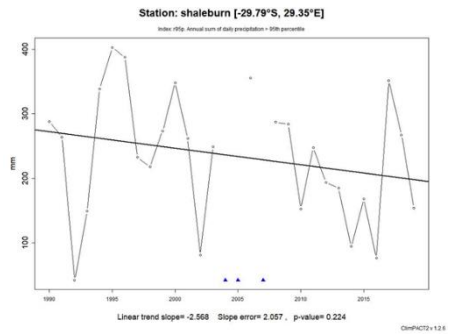
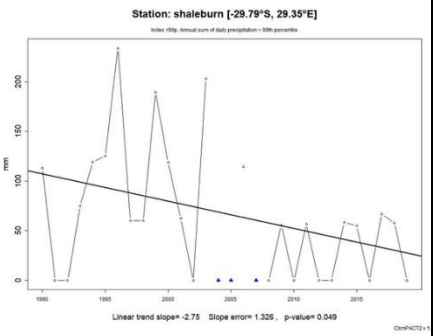


R50mm



CWD



Shaleburn			
Rx1day	Rx5day	R95p	R99p
			
R20mm	R50mm	CWD	
