ASSESSMENT OF SEASONAL AND ANNUAL RAINFALL TRENDS AND VARIABILITY IN SOUTH AFRICA

by

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Abstract

Weather variability, especially rainfall, receives significant global attention. The variability of rainfall distribution in time and space differs. Therefore, examining the trends and patterns of rainfall over South Africa, a water-scarce country, is important. A significant amount of research has been done both in South Africa and globally to find possible relationships between rainfall variability, seasonality, trends, and or climate change. This research was aimed at building on existing research of rainfall patterns in South Africa. The focus was on the use of non-parametric statistical analyses for trend analysis of recorded daily rainfall data (1900-2019), using 46 stations adequately distributed across South Africa. Absolute homogeneity tests were done and homogenous data characterised at monthly, seasonal and annual time steps. South Africa was divided into three rainfall regions: Summer, Winter and 'All year' rainfall regions. These regions were further categorised into eight climatic zones, based on SAWS climatic zones: North-Eastern Interior, KwaZulu-Natal, Western Interior, Central Interior, Southern Interior, North-Western Cape, South Western Cape and South Coast. Trend analysis was performed, and results indicated significant differences between daily, monthly, seasonal to annual time steps.

The daily rainfall reflects insignificant trends. Monthly rainfall recorded statistically significant increasing trends in November, December, and January in the 'All year' and Summer rainfall regions and March, May, June and September recorded statistically significant decreasing trends in all three rainfall regions.

The seasonal and annual trend analysis were performed for a long-term period of 120 years and three short-term periods of 40 years each. The short-term trends shift periodically within the three periods, resulting in only a few rainfall stations recording statistically significant long-term trends. The Summer rainfall region experienced alternating trends shifting across the three short-term periods towards an early or a late wet season with little change in mean annual rainfall. The Winter rainfall region had its main rainfall season becoming shorter, but wetter over the three short-term periods of analysis, while the 'All year' rainfall region experienced alternating shifts of dry and wet cycles with a slightly decreasing mean annual rainfall.

In general, the seasonal rainfall trends of South Africa illustrated shorter, but more pronounced trends, progressively for the three short-term analysis periods. Only a marginal increase in annual rainfall was observed using the long-term analysis, while variability increased over the years, using the short-term analysis.

The observed trends using non-parametric analysis do not have significant deviations from previous research outputs. However, the observed changes in rainfall were relatively low with a

long-term increasing trend in annual rainfall of between 0.6 and1.0 mm during the analysis period of 120 years.

This research, therefore, recommends that the use of projected rainfall (climate change) data in South Africa, should be well guided by considerations based on the observed rainfall data trends. Design and management decisions based on long-term rainfall projections due to climate change should be considered carefully, taking the design life of the infrastructure into consideration.

Opsomming

Die wisselvallige weersomstandighede, veral reënval, geniet wêreldwyd beduidende aandag. Die wisselvalligheid van die verspreiding van reënval in tyd en ruimte verskil. Daarom is dit belangrik om die tendense en patrone van reënval oor Suid-Afrika, 'n waterskaars land, te ondersoek. 'n Aansienlike hoeveelheid navorsing is in Suid-Afrika en wêreldwyd gedoen om die moontlike verband tussen die wisselvalligheid van reënval, seisoenaliteit, tendense en of klimaatsverandering te vind. Hierdie navorsing het daarop gefokus om voort te bou op bestaande navorsing oor reënvalpatrone in Suid-Afrika. Die fokus was op die gebruik van nie-parametriese statistiese ontledings van historiese daaglikse reënvaldata (1900-2019) van 46 stasies, goed versprei oor Suid Afrika, om tendense te ondersoek. Absolute homogeniteitstoetse is gedoen en homogene data is gekarakteriseer vir maandelikse, seisoenale en jaarlikse tyd-stappe. Suid-Afrika is verdeel in drie reënvalstreke naamlik somer-, winter- en 'hele-jaar' reënvalstreke. Hierdie streke is volgens SAWB verder in agt klimaatsones ingedeel: Noord-Oostelike binneland, KwaZulu-Natal, Westelike-binneland, Sentrale binneland, Suidelike binneland, Noordwes-Kaap, Suidwes-Kaap en die Suidkus. Tendens ontledings is uitgevoer, en die resultate het beduidende verskille tussen daaglikse, maandelikse, seisoenale en jaarlikse tyd-stappe getoon.

Die daaglikse reënval het nie enige beduidende tendense getoon nie. Maandelikse reënval het in November, Desember en Januarie in die somer- en 'heel-jaar'-reënvalstreke beduidende toenemende tendense en in Maart, Mei, Junie en September, beduidende dalende tendense in al drie reënvalstreke getoon.

Die seisoenale en jaarlikse tendens ontledings is uitgevoer vir 'n langtermynperiode van 120 jaar en vir drie korttermynperiodes van 40 jaar elk. Die korttermyn tendense wissel oor die drie periodes, wat daartoe aanleiding gee dat slegs enkele reënvalstasies noemenswaardige langtermyn tendense getoon het. Die somerreënvalstreek het wisselende tendense getoon wat gedurende die drie korttermynperiodes gewissel het tussen 'n vroeër of 'n later nat seisoen met min verandering in die gemiddelde jaarlikse reënval. Die hoof reënvalseisoen van die winterreënvalstreek het korter en natter geword oor die drie korttermyn-ontledingsperiodes, terwyl die 'hele jaar' reënvalstreek wisselende verskuiwings tussen droë en nat siklusse ervaar het met 'n effense dalende gemiddelde jaarlikse reënval.

In die algemeen het die seisoenale reënval tendense van Suid Afrika 'n toenemende korter, maar duideliker tendense, vir die drie korttermyn-ontledingsperiodes geïllustreer. Slegs 'n geringe toename in jaarlikse reënval is waargeneem met behulp van die langtermyn-ontleding, terwyl korttermyn-ontledings ʼn toename in wisselvalligheid oor die jare toon.

Die waargenome tendense met behulp van nie-parametriese ontledings het nie beduidende afwykings van vorige navorsingsresultate getoon nie. Die waargenome veranderinge in reënval is egter relatief min, met ʼn langtermyn toenemende tendens van jaarlikse reënval wat wissel tussen 0.6 en 1.0 mm oor die ontledingsperiode van 120 jaar.

Hierdie navorsing beveel dus aan dat die gebruik van reënval data soos voorspel deur klimaatsveranderinge, versigtig oorweeg moet word met inagneming van die waargenome reënval tendense. Ontwerp en bestuursbesluite gebaseer op vooruitskattings van langtermyn reënval as gevolg van klimaatsveranderinge, moet versigtig binne die konteks van die ontwerp-leeftyd van die infrastruktuur oorweeg word.

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List of Abbreviations and Acronyms

C_k	Coefficient of Kurtosis
C_s	Coefficient of Skewness
C_v	Coefficient of Variation
DEA	Department of Environmental Affairs
ENSO	El Niño Southern Oscillations
GCM	Global Climate Models
H_a	Alternative Hypothesis
H_o	Null Hypothesis
IDW	Inverse Distance Weighting
IPCC	Intergovernmental Panel on Climate Change
KZN	KwaZulu-Natal
MK	Mann-Kendall
mm	Millimeters
mm/year	millimeters per year
NR	Normal Ratio
R_m	Mean Rainfall
R_{max}	Maximum Rainfall
R_{min}	Minimum Rainfall
S	Mann-Kendall statistic
SAWS	South African Weather Service
SNHT	Standard Normal Homogeneity Test
SST	Sea Surface Temperatures
τ	Kendall's Rank Correlation Coefficient
WMA	Water Management Area
WMO	World Meteorological Organization
Z	Standard Normal Variate

1 Introduction

1.1 Background

South Africa is a semi-arid country (Schulze, 1979). It has a variable topography with climate varying from wet and sub-humid along the eastern coast to semi-desert and desert in the dry northwestern region (Dinar *et al.,* 2012). The mean annual rainfall for South Africa is approximately 450 mm/year (Botai *et al.,* 2018). The country is water-stressed with high spatiotemporal rainfall variability. Easterling *et al.* (2000), Kruger (2006), Donat *et al.* (2013), Kruger & Nxumalo (2017) and Jury (2018) highlighted the effects of climate change on South Africa and suggest that it should be expected to be hotter and drier in future. This will directly impact on the hydrological cycle, hence affecting agriculture and other important production sectors in the industry relying heavily on freshwater and thus affecting the country's economy. Therefore, there is the need to understand rainfall patterns and trends to enable adequate planning and avert or manage effects that will impact on the country's economy.

Rainfall is a key factor in the hydrologic cycle and any change in the pattern directly impacts on the water resources of a given area (Chabalala *et al.*, 2019). The changing rainfall patterns is of great concern to researchers and policymakers in the water fraternity (Gajbhiye *et al.*, 2016). Observed rainfall time series data for a given area is fundamental for hydrologic analysis. The long-term meteorological data provides essential statistics on rainfall variability, trends, and cycles in trying to answer the question of climate change (Che Ros *et al.*, 2016). This research uses daily observed rainfall data for the period 1900-2019 to establish trends and variability of rainfall in South Africa.

Recent studies indicate that a relatively long (>100 years) dataset is instrumental to establish long-term trends, rainfall cyclic patterns, and return periods of hydrological events (Ndebele *et al., 2*020). Some of the studies done in South Africa on rainfall trends include those of Mason *et al.* (1999), Easterling *et al.* (2000), New *et al.* (2000), Rouault *et al.* (2003), Misra (2003), Groisman *et al.* (2005), Kruger (2006), New *et al.* (2006), Van Wageningen and Du Plessis (2007), MacKellar *et al*. (2014), Du Plessis and Schloms (2017) and Kruger and Nxumalo (2017). From these studies, deductions can be made that over the past 100 years there has been an increase in extremes and interannual variability of rainfall over specific areas of South Africa. Research on rainfall trends for South Africa has been done extensively by the above-mentioned researchers. However, most of the researchers used either the Global Climate Models (GCMs) or parametric methods while highlighting the need for using a statistical (non-parametric) approach in determining trends. Although the GCMs come in handy and give a clear picture of existing scenarios at times, emphasis must be put on understanding behavioral patterns of important climatical variables used by these models to ensure a better understanding and interpretation of model results. Therefore, this research seeks to build on existing research of rainfall trends in South Africa through investigations into the claims of change in rainfall patterns by GCMs using a statistical (non-parametric) approach. The Mann-Kendall test and Sen's slope estimator are used to test for trends and rate of change, respectively. The Modified Mann-Kendall is used to check for effects of autocorrelation on the magnitude of trends.

1.2 Problem Statement

South Africa is a water-scarce country and therefore understanding of the rainfall trends and patterns which affect the hydrological cycle is important. The food production industry (agriculture) is a great contributor to the country's economy. Rainfed agriculture such as wheat production heavily relies on rainfall patterns. A slight delay in the start of the rainfall season may have several impacts such as failed germination, short season or rains during harvest season, which could result in low yield. This may lead to a shortage of produce in the market and an increase in prices while the purchasing power of citizens does not necessarily change. The effects of such changes in rainfall pattern may impact negatively on the industrial and production sectors and ultimately the country's economy.

A proper understanding of rainfall trends and variability is important for planning purposes as a country. This research, therefore, focuses on building on existing work of rainfall trends in South Africa by investigating the claims of change in rainfall patterns using a statistical (non-parametric) approach. Questions of concern include: Can rainfall trends be observed in South Africa? What are these trends? Are they significant? What is the rate of change? Do the results compare with previous research outputs?

1.3 Research Aim and Objectives

The main aim of this research was to investigate the possible trends based on the claims of seasonal and annual rainfall variability in South Africa as suggested by GCMs and parametric methods from previous studies. The following specific objectives lead to the achievement of the main aim.

1. To obtain observed historical daily rainfall data, perform quality analysis and patch stations with missing records.
2. To identify and remove inhomogeneities in time series rainfall data that result in non-climatic induced rainfall trends by performing absolute homogeneity tests; Standard Normal Homogeneity Test (SNHT), Von Neumann, Pettitt and Buishand Range.
3. To classify homogeneous rainfall data stations into existing rainfall regions and climatic zones.
4. To determine monthly, seasonal, and annual rainfall variability of the obtained rainfall time series.
5. To determine daily, monthly, seasonal, and annual rainfall trends using the Mann-Kendall test and modified Mann-Kendall test.
6. To determine the rate of change in daily, monthly, seasonal, and annual rainfall and its significance level using Sen's slope estimator.
7. To determine long-term (120 years) trends and short-term (40 years) trends and the rate of change in annual and seasonal rainfall.
8. To critically evaluate and discuss the results obtained for rainfall trends and variability in South Africa.

1.4 Research Scope and Constraints

1.4.1 Scope

This research covers South Africa. It starts by dividing the country into six regions defined by Water Management Areas (WMAs), as illustrated in Figure 1.1. Each WMA consists of areas with similar climatic and hydrological characteristics. The selection of these WMAs was based on the fact that most of the effects of rainfall trends and variability to the South African economy and other important production sectors such as agriculture can be primarily conciliated through the impacts of the water sector (DEA, 2013). The WMA regions are;

1. The Limpopo, Olifants and Inkomati WMAs in the Northern Interior.
2. The Pongola–Umzimkulu WMA in KwaZulu-Natal.

3. The Vaal WMA in the Central Interior.
4. The Orange WMA in the North west.
5. The Mzimvubu-Tsitsikama WMA in the South east.
6. The Greede-Gouritz and Berg Olifants WMAs in the South west.

However, in the selection of these WMAs, it was noted that the definition of a zone/region has a hydro-climatic context and the selected WMA regions would not agree with homogenous climatic zones and their trends. Contrasting trends for stations within similar regions weakening observed trends would be expected. Stations would also not represent spatial heterogeneity of the regions selected (MacKellar *et al.,* 2014). Therefore, to solve this challenge, this research maintained the WMAs as hydrological regions while adopting rainfall regions and climatic zones as defined by SAWS (Figure 4.6) based on which the discussions of trends analysis results were done.

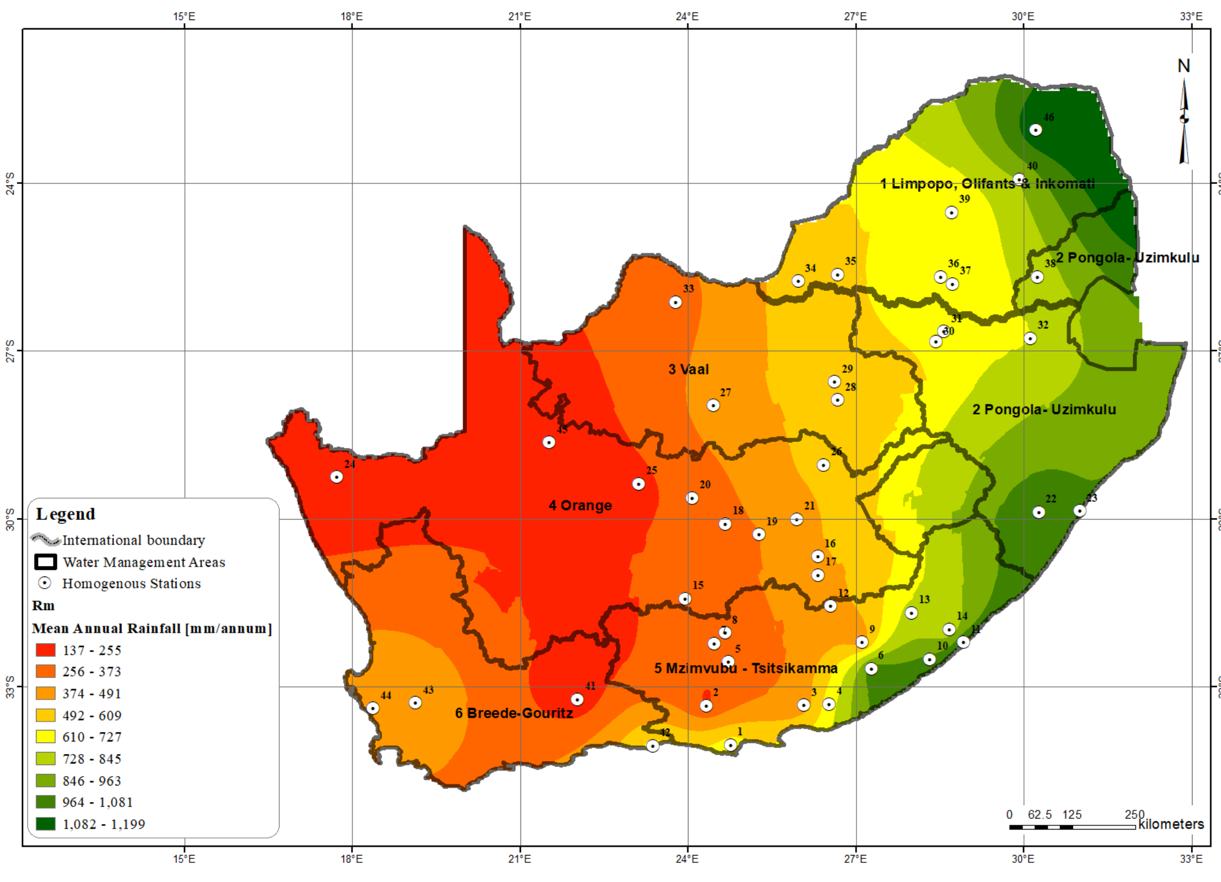


Figure 1.1: Water Management Areas, (DEA, 2013).

1.4.2 Constraints

The main constraint to this research was getting an adequately spread century-long daily time series rainfall data. Data was obtained from the South Africa Weather Service (SAWS). For quality data and hence trustworthy research output, there was a need to identify stations that were operational during the research period of interest and had at least 90% of daily values available.

Performing proper quality control of rainfall data was constrained due to the regionally different rainfall producing mechanisms and complex topographies. However, nearby stations were used to check cases of long periods recording zero amount of rainfall and in cases of high disparities, such values were flagged and omitted.

Furthermore, the delineation of WMAs (hydrological regions) to be used for this research did not consider homogeneity of rainfall distribution across the region. This is largely in areas of complex topography such as the Western Cape. This does not give a true reflection of spatial heterogeneity of the region and hence rainfall distribution. However, as a mitigation measure, the WMAs were maintained as hydrological regions while further classifying South Africa into rainfall regions and SAWS climatic zones, based on which the analysis and discussion of rainfall trends were done. The possible effects of rainfall trends to the different WMAs at the respective climatic zones are thereafter highlighted in summary.

1.5 Research Methodology

To establish the annual, seasonal, and monthly trends and variability of rainfall over the past century in South Africa, the following procedure was used:

1. Comprehensive literature review of:
    i. Climate change considering rainfall trends and variability.
    ii. Previous studies on global rainfall trends and variability.
    iii. Previous studies on South Africa's rainfall trends and variability at a regional and local level.
    iv. Identification of data quality techniques and their applicability to daily rainfall analysis.
    v. Homogeneity of rainfall time series data and homogeneity testing techniques.
    vi. Rainfall trends and trends analysis techniques.

vii. Literature Summary and conclusion.

2. Discussion of methodology.
   i. Rainfall time series data.
   ii. Quality analysis of the rainfall time series data.
   iii. Homogeneity test.
   iv. Statistical analysis of rainfall time series data.
   v. Trend analysis of the rainfall time series data.
3. Critical evaluation and discussion of results providing possible contextual commentary of the results while relating to previously done research.
4. Drawing of conclusions and recommendations for future work.

1.6 Document Outline

The structure of this thesis is as outlined. Chapter 1 gives an introduction highlighting the importance of trend analysis highlighting the aim of the research. Chapter 2 provides a review of global and regional rainfall trends and analysis methods, justifying the methods discussed in Chapter 3. Data analysis is performed in Chapter 4 and the results thereof are discussed in Chapter 5. In Chapter 6 conclusions and recommendations based on the finding of the results are given.

2 Literature Review

This chapter presents detailed concepts required to analyse rainfall trends and variability in South Africa using rainfall time series data. It entails a discussion on climate change, global and regional rainfall trends.

2.1 Climate Change

Climate change is a dominant challenge facing human beings especially for the twenty-first century. The changes in climatic components are attributed to increased greenhouse gas emissions into the atmosphere (IPCC, 2013). Hydrological changes resulting from climate change can be evaluated through change in rainfall patterns. Changes in rainfall patterns have been detected globally by several researchers such as by Mphale *et al.* (2014), Stojković *et al.* (2014), Syafrina *et al.* (2015) and Onyutha *et al.* (2016). The Intergovernmental Panel on Climate Change (IPCC) observes a decrease in surface water resulting from increased rainfall variability (Lakhraj-Govender and Grab, 2019). This concurs with Brekke *et al.* (2009) observation of magnitude and frequency of rainfall being significantly affected because of climate change.

Climate fluctuation in Africa is controlled by the complex continental topography and marine influences (Jury, 2018). Rainfall trends in Africa have large temporal and spatial variability. The Sahel region in North Africa records a multi-decadal variability of rainfall with Central Africa experiencing a slight decrease in rainfall. Furthermore, in South Africa, weak long-term trends with increasing variability in annual rainfall have been observed over the years (Richard *et al.,* 2001, Tudhope *et al.,* 2001, Malhi and Wright, 2004 and Tadross *et al.,* 2005). These intra-decadal oscillations are a result of interactions between the Pacific El Niño Southern Oscillations (ENSO) with the Indian and Atlantic Oceans climates (Nicholson *et al.,* 2000 and Richard *et al.,* 2001).

Rainfall in South Africa has high variations annually due to zonal air circulations and solar radiation changes. During Summer, warm moist air from the Agulhas current and the Indian Ocean is drawn by easterly winds. During Winter, dry air is drawn from the Benguela current and the Atlantic Ocean by the westerly winds. The net effect is annual variability in climate resulting in an alternating change in length of Summer and Winter seasons (Jury, 2018). Climate observations using GCMs have been used by numerous researchers in the analysis and projection of rainfall changes. This research goes on to build on existing research on rainfall trends to investigate claims of shifts and trends using a statistical (non-parametric) approach.

2.2 Rainfall Trends

2.2.1 Global Rainfall Trends

Trend detection remains to be an active area of interest in hydrology (Karpouzos *et al.,* 2010), to investigate the effects of rainfall and other climatic variables on human activities such as farming. Due to anthropogenic influences and natural variability in the weather of a specific region, the assumption of stationarity of time series data, suggesting time-invariant characteristics, has become invalid (Jain and Lall, 2000). Therefore, trend analysis of rainfall time series is important in the planning of regional and global water resource management and most important, planning for rainfed and irrigated agriculture. This will avert cases of food shortage and economic contractions because of possible shifts in rainfall patterns.

Trenberth (2015) observes a global increase in the recurrence of extreme rainfall events suggesting a study of change in precipitation patterns over time to give an insight towards understanding the effect it has on human activities. Globally considerable attention has been given towards the understanding of rainfall trends by improving and extending various sets of data and more sophisticated analysis (Kumar *et al.,* 2010). In Canada, Adamowski and Bougadis (2003), investigated the yearly maximum rainfall time series for the Ontario province. An increasing trend in the 5 to 10 min rainfall duration in six out of eight regions was observed. Burn and Taleghani (2013) analysed trends of the annual maximum time series of Canada by applying the Mann-Kendall test. Less decreasing than increasing trends were observed in line with the findings of Adamowski and Bougadis (2003).

In Malaysia, Suhaila *et al.* (2008) analysed trends in daily rainfall between 1975 and 2004. A trend of decrease in frequency and total rainfall was observed. It was also reported that during the southwest monsoon, intensity of rainfall increased. In 2015, Amirabadizadeh *et al.* (2015) used the Mann-Kendall trend to investigate rainfall trends in the Langat River Basin in Malaysia. The result was a fluctuating trend in annual and seasonal rainfall. The rate of increasing annual precipitation was much higher compared to the increase in seasonal precipitation. Che Ros *et al.* (2016) investigated long-term trends of Kelantan River Basin rainfall in Malaysia.

Using a 30-year sampling period, a fluctuating trend was observed with an increasing trend for the period 1957-1987 and decreasing trend during the period 1981-2011.

Several studies also addressed precipitation changes through the identification of precipitation indices. Modarres *et al.* (2007) analysed monthly and annual rainfall amounts and events in Iran. They observed fluctuating trends for monthly rainfall. Significant trends were recorded during the Spring and Winter seasons. Kousari and Zarch (2011) analysed trends of maximum and minimum temperature and rainfall for Iran and observed a decreasing trend in rainfall. However, the observed trends for arid regions of Iran were insignificant.

In Italy, Brunetti *et al.* (2000) investigated the amount and number of rainfall events. Spring and Autumn were observed to have decreasing trends. Crisci *et al.* (2002) investigated trends in extreme events for 81 rainfall stations at Tuscany in Italy. Extreme events were observed to be increasing. Liuzzo *et al.* (2016) analysed trends for extreme rainfall events for different time durations in Sicily, Italy, between 1950 and 2018. The increasing extreme events resulted in more frequent floods.

In Ethiopia, Mengistu *et al.* (2014) investigated the variability and distribution of rainfall in the Nile Basin. Insignificant increasing trends were observed at annual and seasonal timesteps. Onyutha *et al.* (2016) investigated rainfall trends for the same drainage basin in Ethiopia. Annual rainfall was observed to increase between 1940 and 1990. Tadese *et al.* (2019) characterized rainfall for the Awash River Basin of Ethiopia and observed annual rainfall to be declining. There was a correlation between rainfall stations data and streamflow data for the catchment and hence the decreasing trends in the annual rains were highlighted by a decrease in the streamflow, especially at lower parts of the catchment.

The general observation of global rainfall trends is consensus towards increasing rainfall variability. Globally there is an increase in the recurrence of extreme events. However, focusing on specific areas, there is either a trend of fluctuating increase or decrease in the frequency and amount of rainfall received, hence the variability. This motivates the need for trend analysis, in understanding the effects thereof, for planning and mitigation measures.

Table 1: Summary of global rainfall trends

Researcher	Findings
Trenberth (2015)	Observed a global increase in the recurrence of extreme rainfall events during the past two decades.
Adamowski and bougadis (2003)	Observed an increasing trend in the 5-10 mins duration rainfall at Ontario, Canada during 1905-1998.
Burn and Taleghani (2013)	Observed an increasing trend in the annual maximum series of Canada over the past two decades.
Suhaila *et al.* (2008)	Observed a decrease in the frequency and amount of daily rainfall in Malaysia during 1975-2004.
Amirabadizadeh *et al.* (2015)	Observed a fluctuating trend in annual and seasonal rainfall for the Langat River Basin, Malaysia during 1974-2004.
Che Ros *et al.* (2016)	Observed a fluctuating rainfall trend; increasing trend during 1957-1987 and decreasing trend during 1981-2011, for the Kelantan River Basin, Malaysia.
Modarres *et al.* (2007)	Observed a fluctuating trend in the monthly rainfall of Iran for the past 30 years.
Kousari and Zarch (2011)	Observed an increasing trend in the minimum and maximum rainfall series of Iran during 1955-2000.
Brunetti *et al.* (2000)	Observed a decreasing trend in the amount and number of rainfall events for Spring and Autumn seasons of Italy during the past century.
Crisci *et al.* (2002)	Observed an increasing trend in extreme rainfall events at Tuscany, Italy during 1970-1994.
Liuzzo *et al.* (2016)	Observed an increasing trend for extreme rainfall events in Sicily, Italy during 1950-2018 resulting in frequent floods.
Mengistu *et al*. (2014)	Observed insignificant increasing trends for annual and seasonal rainfall at the Nile River Basin, Ethiopia during 1981-2010.
Onyutha *et al*. (2016)	Observed increasing rainfall trends at the Nile River Basin, Ethiopia during 1940-1990.
Tedese *et al*. (2016)	Observed decreasing annual rainfall trends at the Awash River Basin, Ethiopia during 1954-2016.

2.2.2 Rainfall Trends in South Africa

Rainfall trends and variability is of interest to agriculture, ecology, water resources management and academia amongst other sectors of the economy (MacKellar *et al.,* 2014). As a result, several researchers have focused their studies on investigating rainfall trends from observed records and derived indices for South Africa. The greatest constraint to such studies has been the inadequacy of observed long-term time series data to satisfactorily characterize the rainfall regions. South Africa has a good network of weather observation stations in comparison to other African countries (Easterling *et al.*, 2000 and New *et al.,* 2000). However, Pitman (2011) provides a concerning picture of the declining number of rainfall monitoring stations coupled with poor documentation. During the period 1970-2004, functional rainfall observation stations were reported to decrease by 50%. This is equivalent to the number of stations that were available in 1920. However, the available rainfall stations for South Africa still provide for adequate data to investigate rainfall trends over the past century. It is always challenging to identify long term changes given a large spatiotemporal variability of rainfall. This makes trend analysis sensitive to specific locations and their respective period of observation. Therefore, investigation of rainfall trends with the availability of new observed data, and using different techniques, is necessary to allow for a proper representation of rainfall trends over time.

To properly analyse rainfall trends, it is necessary to understand that the rainfall of South Africa is mostly influenced by the La Niña and El Niño Southern Oscillations. The El Niño Southern Oscillation phase (ENSO) causes a decrease in rains with a rise in temperatures while La Niña causes the opposite (MacKellar *et al.,* 2014). ENSO is usually associated with extreme weather conditions resulting from the interaction of the atmosphere and the ocean, causing a cyclic variation on sea surface temperatures (SST). This interaction is what determines the wetness or dryness within a given cycle (Lester, 2019).

Several studies have already been conducted involving historical rainfall data for South Africa. Such studies include but are not limited to the following; Mason *et al.* (1999), Easterling *et al.* (2000), New *et al.* (2000), Misra (2003), Rouault *et al.* (2003), Groisman *et al.* (2005), Kruger (2006), New *et al.* (2006), Van Wageningen and Du Plessis (2007), Du Plessis and Burger (2015), Du Plessis and Schloms (2017) and Kruger and Nxumalo (2017). According to Easterling *et al.* (2000), who researched rainfall trends for South Africa amongst other parts of the globe, the South-western and KwaZulu-Natal regions were observed to record significant increases in extreme rainfall events during the periods 1926-1997 and 1901-1997 respectively. Groisman *et al.* (2005), concurs with the observation by showing an increasing frequency for extreme rainfall events along the eastern coast of South Africa between 1906-1997. Mason *et al.* (1999) demonstrate increasing rainfall intensity during the period 1961-1990 in comparison to 1931-1960.

Rouault *et al.* (2003) also observed insignificant rainfall trends for December to April as observed by Richard *et al.* (2001) for 1901-1998. Nonetheless, a greater interannual rainfall variability was observed for the period after 1960. New *et al.* (2006) analysed extreme rainfall events for South Africa from 1961-2000 and observed a significant increasing trend. Kruger (2006) also observed increased extreme rainfall events in the Eastern Cape and Free State from 1910-2004. New *et al.* (2000) analysed annual rainfall using an artificial dataset for the period 1901-1995 and observed no significant trends in annual rainfall.

Groisman *et al.* (2005) analysed annual and Summer rainfall from 1906-1997 for eastern South Africa observing no significant trend. However, there was a significant increase in the frequency of heavy rainfall events. Nel (2009), illustrated a shift in seasons for rainfall stations in the Drakensberg region from 1955-2000. The mean annual precipitation did not show any trends. Summer rains increased with decreasing Winter and Autumn rainfall hence shorter and more pronounced seasonal cycles. Thomas *et al.* (2007), concur with the findings of Nel (2009) for the northwest of KZN by observing an increasing early and decreasing late seasonal rainfall for the period 1950-2000. Seasonal shifts with a tendency of late seasonal onset and decreasing rainfall events were observed for the Limpopo region.

Tadross *et al.* (2005), observed a trend of late onset of rains for Limpopo during the period 1979-1997. The trend was noted to be a likely periodical variability as opposed to a long-term trend. Kruger (2006) observed increasing dry spells in Eastern Cape and Free State with decreasing length of wet spells in north eastern South Africa from 1910-2004. Kruger and Nxumalo (2017) observe a trend of increasing rainfall in western South Africa, stretching to the Southern Interior while the north-east region had a decreasing trend in rainfall. The South-Western Cape was observed not to experience an increasing trend which concurs with MacKellar *et al.* (2014) who acknowledged a decreasing rainfall trend at the Southern Coast. Kruger and Nxumalo (2017) agree with the findings of Van Wageningen and Du Plessis (2007) and Donat *et al.* (2013) by observing an increasing trend in rainfall intensity, frequency, and quantity over the region. In contrast, Du Plessis and Burger (2015) observe no evidence of trends or change in intensities for rainfall of short duration for South Africa. Du Plessis and Schloms (2017) investigated seasonal shifts in rainfall patterns for the Western Cape in South Africa using parametric methods. Variation in rainfall patterns and cyclicity of dry and wet periods within the seasons were observed. However, it is of importance to note that their findings were based on limited data. From literature, no consistent significant trend in annual rainfall was observed, instead, there seems to be consensus over a tendency of an increase in extremes and interannual variability over specific areas of South Africa, (Rouault *et al.*, 2003, Groisman *et al.*, 2005, Midgley *et al.*, 2005, Kruger, 2006, New *et al.*, 2006, Schulze *et al.*, 2011 and Du Plessis and Schloms, 2017). Kruger and Nxumalo (2017) include the most significant period using historical rainfall data for trend analysis in South Africa for the period 1921-2015 but using the climate change detecting software RclimDex. There is however a need to investigate rainfall trends using a statistical non-parametric approach which is yet to be utilized for South Africa.

Table 2: Summary of research findings on rainfall trends for South Africa.

Researcher	Findings
Mason *et al.* (1999)	Observed increased extreme rainfall events from 1961-1990 compared to 1931-1960 across South Africa.
Easterling *et al.* (2000)	Observed rainfall events to be increasing in the eastern and south western parts of South Africa over the past century.
New *et al.* (2000)	Annual rainfall was observed to have no significant trends from 1979-1997.
Rouault *et al.* (2003)	Observed a greater interannual rainfall variability for the period 1960-1998 for the entire of South Africa.
Groisman *et al.* (2005)	Observed increased extreme rainfall events with no change in Summer and annual totals for the period 1906-1997 in Eastern South Africa.
Tadross *et al.* (2005)	Observed a significant trend of late onset for the period 1979-1997 in the Limpopo region.
New *et al.* (2006)	Observed an increasing trend of extreme rainfall events across South Africa from 1961-2000.

Researcher	Findings
Kruger (2006)	Observed an increase in extreme rainfall indices and dry spell duration over parts of Eastern Cape and Southern Free State for the period 1910-2004. Further, the length of wet spells decreased in the Eastern Cape for the same period.
Thomas *et al.* (2007)	Observed an increasing trend for early seasonal rainfall and a decreasing trend for late seasonal rainfall from 1950-2000 for North-West KZN. A tendency of late onset with increasing dry spells for the same period in the Limpopo region was also observed.
Van Wageningen and Du Plessis (2007)	Observed a tendency of less but more intense rainfall in the Western Cape.
Nel (2009)	Observed a trend of shifting seasonality at stations within KZN from 1955-2000. Summer rainfall increased accompanied a decreasing Winter and Autumn rains.
MacKellar *et al*. (2014)	Observed a decreasing trend in the amount of rainfall received along the Southern Cape Coast for the period 1960-2010.
Du Plessis and Burger (2015)	Observed there is no evidence of trends or change in intensities of short duration rainfall in the Western Cape.
Du Plessis and Schloms (2017)	Using a parametric approach, observed variation in rainfall patterns and cyclicity of dry and wet periods within the seasons for the past century in the Western Cape.
Kruger and Nxumalo (2017)	Observed a significant trend of increasing rainfall in western South Africa stretching to the Southern Interior while in the northeastern there was a decreasing trend.

2.3 Quality Control and Estimation of Missing Rainfall Data

2.3.1 Quality Control

Prior to performing hydrological analysis using rainfall data, it is essential to inspect the data and conduct a cleaning exercise where necessary (Ndebele *et al.,* 2020). Quality control procedures are often used to detect errors that could have been made during recording, storage and manipulation of data (Aguilar *et al.*, 2003). Quality control is recommended as part of climate monitoring principles to consistently assess the homogeneity and quality of climatic data (WMO, 2002).

Quality control procedures are critical where long temporal datasets are put into use as they may contain observer, instrumentation or relocation errors (Aguilar *et al.*, 2003). Furthermore, where rainfall data is involved, quality control is more difficult compared to other climatic parameters such as temperature. This is because daily precipitation amounts have a relatively poor spatial correlation (Kruger, 2006). This challenge can further be complicated by rainfall data from arid areas or regions receiving conventional rainfall with sparse data as is the case for some of the regions in South Africa.

To evaluate the validity of observed rainfall time series data, several methods are often used such as; tolerance, gross error, internal and spatiotemporal consistency checks (Aguilar *et al.*, 2003). Gross error checking identifies salient mistakes like negative or anomalous values. Outliers are checked by tolerance test. The spatial and temporal coherency test determines if observations made at a time are consistent with neighboring stations for homogenous areas. To have confidence in results, quality control should always be considered.

Because of long periods involved and sparse weather stations, it is rare to find stations that can be used for spatial and temporal coherence tests. From literature, most studies have accepted data by trusting quality control measures of their respective weather services organization (Kruger, 2006). However, upon obtaining stations with adequate length of observed data, statistical indices are derived for comparison of different stations. Stations having consistently different results from the rest with no explanation are usually flagged and omitted. Before this test is done, stations having more than 10% missing rainfall data in their time series are disregarded. Some of the recent studies on rainfall trend analysis that have used the above methods of quality control include; Kruger (2006), Ahmad and Deni (2013), Che Ros *et al.* (2016), Onyutha *et al.* (2016), Kruger and Nxumalo (2017), Elhagrsy *et al.* (2018) and Chabalala *et al.* (2019).

2.3.2 Estimation of Missing Rainfall

A complete time series of rainfall data without missing values is highly valuable and in demand for hydrological analyses (Suhaila *et al.,* 2008). However, it is almost impossible to have rainfall data without missing values because of diverse reasons. Gaps could be because of the relocation of gauge station, break down or failure of an instrument for a given period, errors in techniques used or human negligence (Burhanuddin *et al.,* 2015). Rainfall is dynamic in nature, characterized by high temporal and spatial variability. This may also affect the quality of rainfall data with uncertainties posed by outliers (Krauße and Cullmann, 2012). These factors result in poor quality rainfall data having a bad implication on analysis and may subsequently lead to biased results. Therefore, the estimation of missing rainfall values is an important exercise and the use of appropriate techniques in filling the gap is significant for any hydrological study (Suhaila *et al.,* 2008).

Several methods exist for estimating missing rainfall data such as the Thiessen polygon, Arithmetic Mean, Regression, Normal Ratio (NR), Isohyetal, and Inverse Distance Weighting (IDW) methods. However, the NR and IDW methods remain to be the most used estimation techniques for missing rainfall data for hydrological analysis. From literature, the following researchers find these two methods useful in their work; Tabios and Salas (1985), Hubbard (1994), Eischeid *et al.* (1995), Lennon and Turner (1995), Tang *et al.* (1996), Xia *et al.* (1999), Teegavarapu and Chandramouli (2005), Gyamfi et al. (2016) and Chabalala *et al.* (2019). For IDW and NR methods the closest and most highly correlated among adjoining to the target stations, are guiding principles.

2.3.2.1 Inverse Distance Weighting (IDW) Method

The Inverse Distance Weighting (IDW) is a simple method to apply. It assumes that rainfall values for target station are influenced by the adjacent stations and least by stations further from the target station (Suhaila *et al.,* 2008). However, Tung and Asce (1984), Ashraf *et al.* (1997) and Nalder and Wein (1998) show that more comprehensive techniques such as kriging and regression produce more reliable results than IDW. Furthermore, the need of improving the IDW method to make it simpler, less time consuming during its application and providing more reliable results are highlighted. Hence, several modifications have been proposed on the IDW methods by researchers such as Shepard (1968), Hodgson (1989) and Teegavarapu and Chandramouli (2005) suggesting that IDW highly depends on the presence of a positive autocorrelation. Teegavarapu and Chandramouli (2005) after conducting several studies concluded that substituting the weighting factor of inverse distance with a correlation coefficient was superior to the traditional IDW. Patra (2008) notes that the IDW method has a limitation of estimating missing rainfall data between the highest and lowest values of the index stations. However, he goes on to acknowledge the method is widely accepted globally for scientific analysis.

The following relation may be used to describe the IDW method.

$$P_x = \frac{\sum_{i=1}^{n} P_i \times W_i}{\sum_{i=1}^{n} W_i} \qquad \text{Equation 1}$$

Where;

P_x – Rainfall data for missing station x,

$P_i \ldots P_n$ - Rainfall data of index stations,

$W_i = 1/D^2$,

$D^2 = (\Delta X^2 + \Delta Y^2)$ Distance calculated using X and Y coordinates with missing rainfall station having coordinates (0,0).

2.3.2.2 Normal Ratio (NR) Method

The NR interpolation method was first proposed by Paulhus and Kohler (1952) and is hinged on the ratio of target and adjacent stations data. This technique is quite simpler in the computation of missing rainfall data. To optimize the NR method, Young (1992) suggested the adoption of a correlation coefficient of daily time series data between adjacent and target stations. This is founded on adjacent stations having a high correlation to the target station data because these stations tend to be from one homogenous rainfall zone. Due to the simplicity of this method and less controversy, this research selects the NR method assuming gauges to be having an adequate distribution in the study area with little variation of recorded rainfall data from the mean.

The NR method is applied when the annual rainfall of index station vary by ≥ 10% of missing station (Patra, 2008). The rainfall of the surrounding index stations is weighted by the ratio of normal annual rainfall by using the relation given in Equation 2.

$$P_x = \frac{N_x}{n}\left(\frac{P_1}{N_1} + \frac{P_2}{N_2} + \cdots + \frac{P_n}{N_n}\right) \quad \text{Equation 2}$$

Where;

P_x – Rainfall data for missing station x,

P_1, P_2, …, P_n – Rainfall data of index stations,

N_1, N_2, …, N_n – Normal annual rainfall of index stations,

P_n and N_x – Corresponding values for missing station x,

n – Number of stations surrounding the target station.

2.3.2.3 Regression Method

This method establishes a multiple linear regression of the form:

$$P_x = a_0 + a_1P_1 + a_2P_2 + a_3P_3 + \cdots + a_nP_n \quad \text{Equation 3}$$

The coefficients a_0, a_1, …, a_n are calculated by the least square method. Equation 3 can then be applied in computing the P_x (missing data) for a given station. The Regression method is comparatively accurate compared to other methods requiring good mathematical knowledge and digital computational skills for proper application. Where large amounts of missing data are being estimated, a random error component $\varepsilon_1 \times S_{xy}$ may be introduced. Where ε_1 is a random number with zero mean and unit standard deviation, selected from mathematical tables. S_{xy} is the standard error of estimate, defined by Equation 4.

$$S_{xy} = \sqrt{\sum_{i=1}^{n} \frac{1}{n}(Y_i - Y_{ei})^2} \quad \text{Equation 4}$$

Where Y_{ei} is the estimated value of Y_i for a given X_i and n is the number of data. To maintain the standard deviation of the estimated value of P_x close to the standard deviation of observed rainfall, the term $\varepsilon_t \times S_{xy}$ is added. This method is not popular among researchers because of the complex nature of the computations involved (Patra, 2008).

2.3.2.4 Thiessen Method

The Thiessen method assumes that any point in the catchment has similar to equal amount of rainfall to the adjacent gauge station. Therefore, it applies rainfall records of the nearest gauge station to half the distance towards the target station. Weights for individual gauge stations within a study area, (forming a Thiessen polygon network), are determined by the area represented. The polygons are formed by the perpendicular bisectors of lines joining neighboring gauges. The relationship defining the Thiessen method is given by Equation 5.

$$P_x = \frac{1}{A}\sum_{j=1}^{j} A_j P_j \ldots\ldots \text{Equation 5}$$

Where;

P_x – Estimated missing rainfall value for station x,

P_j – Available rainfall station data,

A – Total area of the catchment,

A_j – Individual Thiessen polygon area.

The Thiessen polygon method is considered to be better than the NR method. However, this method is considered to be very inflexible. In the case of a new station being introduced, the Thiessen polygon network must be reconstructed again. Furthermore, this method does not cater for orographic influences of rainfall on the catchment. Because of these reasons, the method is not favored (Chow *et al.,* 2013). Figure 2.1 illustrates a typical Thiessen polygon network in a catchment.

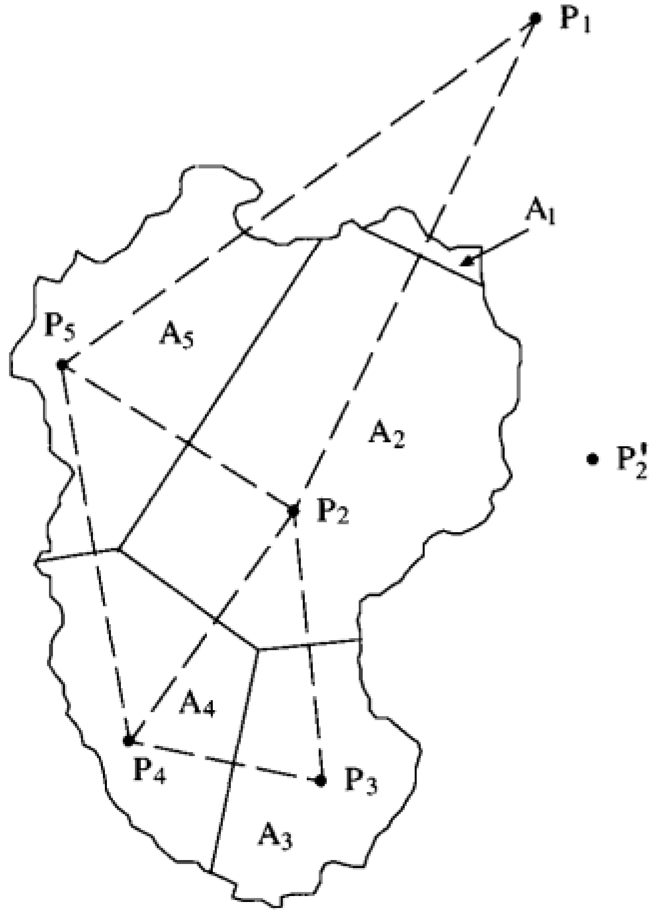


Figure 2.1: Thiessen polygon network in a catchment (Chow *et al.,* 2013).

2.3.2.5 Isohyetal Method

The Isohyetal method constructs isohyets and uses them to interpolate the observed rainfall data values to obtain the missing values. Computer programs such as ArcGIS are usually used to do automated contouring. Once the Isohyetal map is constructed, the area represented by the station with missing data is measured and multiplied by mean rainfall of the two neighboring isohyets to compute missing rainfall value. The Isohyetal method is flexible and comparatively better than the Thiessen polygon method. With knowledge of storm patterns and topography of the region, the construction of isohyets can be done to the suitability of the catchment. However, for areas experiencing complex storms, a dense network of gauges will be required to properly construct an Isohyetal map. However, due to the complex nature of this method, it is rarely used by researchers (Chow *et al.,* 2013). Figure 2.2 illustrates a typical Isohyetal map for a study area.

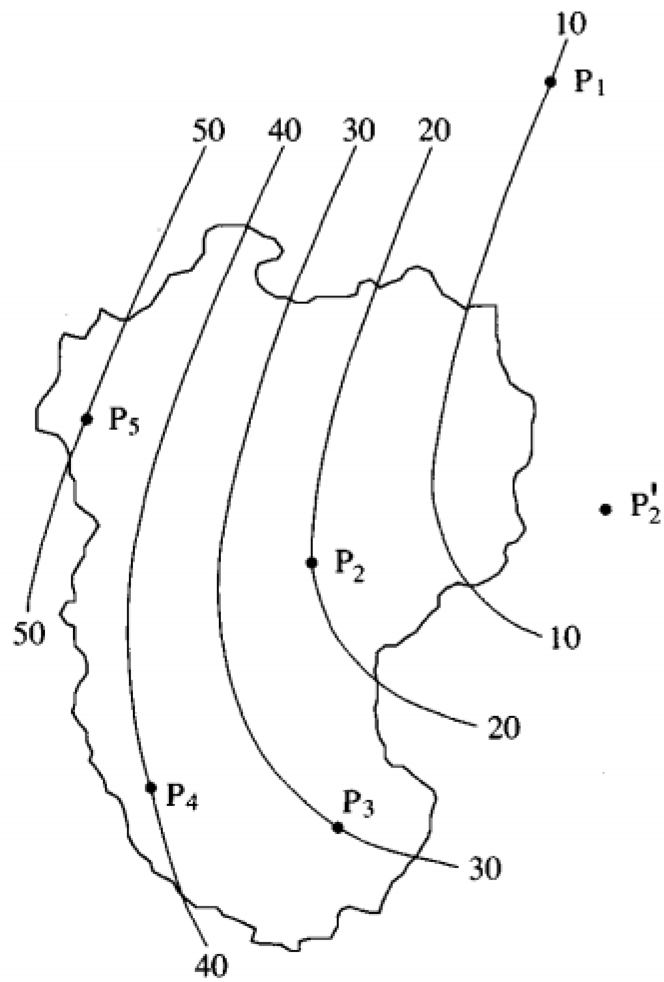


Figure 2.2: An Isohyetal map for a study area (Chow *et al.,* 2013).

From literature, the Normal Ratio (NR) method remains to be the most favored among researchers because of its flexibility and ease of applicability. Patra (2008) notes that on a flat terrain all the discussed methods can be suitably applied. However, in hilly regions, the NR method is best suited for more effective and better results. This research adopts the NR method to the suitability of complex nature of South African terrain as has been applied in several other studies such as Ashraf *et al.* (1997), Modarres *et al.* (2007), Kundu *et al.* (2014), Shree and Kumar (2018), Chabalala *et al.* (2019) and Tadese *et al.* (2019).

2.4 Homogeneity Analysis

In statistical hydrology, a given set of data is considered homogenous if all observations arise from the same population and have the same distribution (Chebana and Ouarda, 2010). Homogeneity analysis is the verification process to ensure that data collected does not represent a mix of several samples from different populations. From the above definition, it is evident that the chronological order of data is not important for a sample to be homogenous. Instead, it is assumed that a given distribution will always have similar characteristics over time and only vary in location and scale (Puri and Sen, 1971).

Long-term rainfall data is often inhomogeneous because of variety of non-climatic factors causing artificial trends (Luhunga, 2014, Mestre *et al.*, 2013 and Peterson *et al.*, 1998). Heino (1994), Tuomenvirta (2002) and Li-juan and Zhong-wei (2012) observe that abrupt changes in the environment, variation in methods of data handling procedures, change in schedule and routine operation procedures, or instrumental disclosure and errors can result in unreliable shifts indicating inhomogeneity. Old data is often associated with inhomogeneities compared to recently observed datasets. This is justified by the fact that in the past many countries had rainfall observation systems that were not well equipped and distributed (Che Ros *et al.*, 2016). Data processing procedures were also not standardized compared to today, leading to more errors. It is therefore imperative to remove such inhomogeneities from historical time series rainfall data for a more reliable hydrological analysis. There are several methods to identify and correct inhomogeneities.

Peterson *et al.* (1998) suggested visual analysis to be the simplest approach of identifying inhomogeneities preferably when being done by experienced meteorologists. However, it is worth noting of this method to has been proved laborious and time-consuming. The impracticability of this approach comes into play when dealing with a huge amount of time series data. To improve on this method, digital processing, and statistical tools are applied to extract potentially problematic sequences in the data. Thereafter, the data can be plotted and with the expertise of experienced meteorologists, the appropriateness of results evaluated.

2.4.1 Relative Homogeneity tests

Several statistical techniques have been developed over time to test for homogeneity. These tests can be broadly classified to be either relative or absolute tests. Relative tests are applied to adjacent stations regarded to be homogenous. On the other hand, absolute methods are used where the time series are not correlated (Wijngaard *et al.,* 2003 and Sahin and Cigizoglu, 2010). Relative methods are considered to detect inhomogeneities due to climate variations easily compared to absolute methods (Peterson *et al.*, 1998). However, for many countries, relative testing has been found unsuitable as rainfall stations are often randomly distributed within different localities, each representing unique geographical positions and climatic environments. This makes it difficult to identify homogeneous reference stations (Suhaila *et al.,* 2008). Also, Buishand (1982) notes that the relative method doesn't show how real changes can be distinguished from random fluctuations. These reasons amongst others have resulted in researchers preferring absolute homogeneity test methods over the relative test methods as highlighted through several studies such as; Hirsch (1982), Alexandersson and Moberg (1997), Peterson *et al.* (1998), Wijngaard *et al.* (2003), Suhaila *et al.* (2008), Che Ros *et al.* (2016) and Gyamfi *et al*. (2016).

2.4.2 Absolute Homogeneity tests

The absolute homogeneity test is composed of the Buishand range, Standard Normal Homogeneity test (SNHT), Pettitt and Von Neumann ratio tests. While the Von Neumann ratio test allows for the identification of breaks in a time series, the Buishand range, Pettitt, and SNHT identifies the years containing breaks (Wijngaard *et al.,* 2003). The SNHT identifies break points at the start and terminal of a time series while the Buishand range and Pettitt tests identify break points at the center of a time series (Yusof and Kane, 2012, Cristina and Amílcar, 2009 and Hawkins, 2008).

2.4.2.1 The Buishand Range test

Buishand range test makes an assumption of the test variables to be independent, having a normal distribution (null hypothesis). The alternative hypothesis is that the time series has a shift. The test statistic defined by Equation 6, gives a partial adjusted sum to the 1^{st} year S^*_k and k until n years (Buishand, 1982). This is be defined by Equation 6.

$$S_k^* = \sum_{i=1}^{k}(Y_i - \bar{Y}) \text{ .... Equation 6}$$

Where;

K = 1,2…n,

$S^*_0 = 0$.

For every test, Y_i is the i^{th} element of time series and $\bar{Y}$ the average of the time series. If the time series is homogenous, S^*_k will fluctuate close to zero as a result of the absence of a regular deviation of the Y_i values to the mean.

Using the Buishand range test, the significance of a given break is tested by a rescaled range R, the range between max and min values of S^*_k. The relationship can be represented by Equation 7.

$$R = \max_{0<k<n} S_k^* - \min_{0<k<n} S_k^* \text{ .... Equation 7}$$

2.4.2.2 Standard Normal Homogeneity Test (SNHT)

The SNHT is a likelihood ratio method that detects for breaks at the start and end of a time series. It has a null hypothesis which makes an assumption of the test variables to be independent and normally distributed. The alternative hypothesis assumes of the test variables to be having breaks. The test statistic (T_k) makes a comparison of the average of the first k years for the time series data to that of the last (n-k) years (Alexandersson and Moberg, 1997).

$$T(k) = k\bar{z}_1^{-2} + (n-k)\bar{z}_2^{-2} \text{ .... Equation 8}$$

Where;

$$\bar{z}_1 = \frac{1}{k}\sum_{i=1}^{n}\frac{(Y_i-\bar{Y})}{s} \text{ .... Equation 9}$$

$$\bar{z}_2 = \frac{1}{n-k}\sum_{i=k+1}^{n}\frac{(Y_i-\bar{Y})}{s} \text{ .... Equation 10}$$

$$S = \frac{1}{n}\sum_{i=1}^{n}(Y_i - \bar{Y})^2 \text{ .... Equation 11}$$

and K = 1,2…n.

$\dot{Z}_1$ and $\dot{Z}_2$ are the arithmetic means before and after change point, while S is the standard deviation. In the event of a break occurring at a given year say K, $T(k)$ will reach an optimum close to the year $k = k_i$ and this indicator is given by Equation 12.

$$T_0 = \max_{1 \leq k \leq n} T(k) \qquad \text{Equation 12}$$

2.4.2.3 Pettitt test

The Pettitt test is a rank method with a null hypothesis having an assumption of variables to be independent and having a normal distribution. The alternative hypothesis assumes of the presence of a jump in the time series data. The ranks $r_1 \ldots r_n$ of the $Y_i \ldots Y_n$ are used to compute test statistics (Pettitt, 1979). The test statistic X_k is given by Equation 13.

$$X_k = 2\sum_{i=1}^{K} r_i - k(n+1) \qquad \text{Equation 13}$$

Where; K= 1,2…n.

In the event a break occurs during the year K, then the statistic is optimal or minimal close to the year $K = K_i$.

2.4.2.4 Von Neumann ratio test

The Von Neumann ratio method has a null hypothesis which assumes the test data to be independent and having an identical distribution. The alternative hypothesis assumes of data series not to be having a random distribution. The Von Neumann ratio (N) is given by Equation 14.

$$N = \frac{\sum_{i=1}^{n-1}(Y_i - Y_{i+1})^2}{\sum_{i=1}^{n}(Y_i - \bar{Y})^2} \qquad \text{Equation 14}$$

When a given time-series has several rapid variations, the value of N will increase above two (Bingham and Nelson, 1981).

To evaluate the significance of meteorological data on the basis of homogeneity results of the above four tests, Schönwiese and Rapp (1997) and Wijngaard *et al.* (2003) developed a categorization system at 5% significance level, comprising of three classes:

1. **Class 1**: The data series is deemed to be **"Useful".** Out of the four tests conducted, it satisfies a requirement that only one or none of the null hypothesis being rejected, an indication of time series data being homogenous. Time series belonging to this category are suitable for trend analysis.

2. **Class 2**: Time series in this category is considered **"doubtful"**. It satisfies the requirement of rejecting the null hypothesis for 2/4 tests. Although there is a presence of inhomogeneity, with caution, the time series in this class can be used for trend analysis.

3. **Class 3**: Time series under this category is considered **"suspect"**. It satisfies the requirement of rejecting three or all the four null hypotheses for the tests. A clear presence of inhomogeneity is detected rendering the time series data falling in this class as unfit for trend analysis and must be discarded.

2.5 Rainfall Trend Analysis

A trend is a steady decrease or increase in the characteristics of a time series, as illustrated by Figure 2.3. Trend analysis is the determination of whether a probability distribution from which a time series arises has changed with time. A trend generally describes the rate of change through change of central values of a distribution such as the mean. Trend analysis is often done in trying to comprehend the past and use it to predict the future (Berger, 2010). Several methods are currently being used to perform trend analysis. However, they can be simply classified into two: parametric and non-parametric methods.

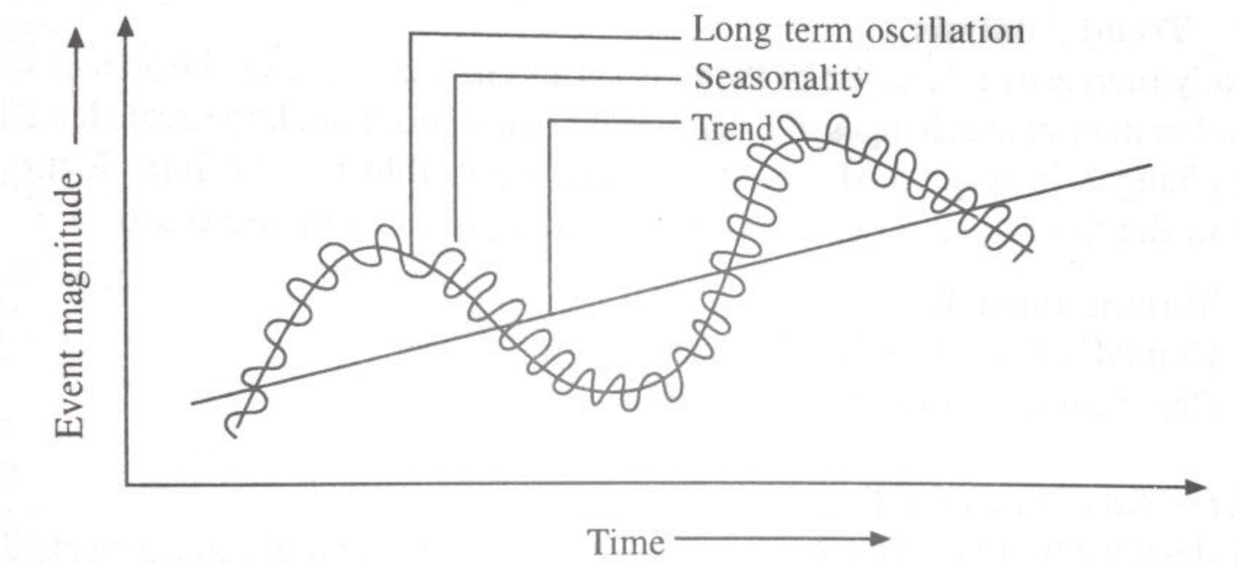


Figure 2.3: Illustration of a trend in a time series (Patra, 2008).

Parametric methods are often concerned with regression analysis and are applicable where a linear relationship exists between variables concerned. Parametric methods are mostly graphic and require an expert for proper application. The requirement of linearity and expertise to apply this method makes non-parametric methods preferable. Non-parametric methods are applied where the variable distribution is unknown or is not a requirement. This makes the application of non-parametric methods flexible and works best with computations involving large amounts of data (Berger, 2010).

2.5.1 Parametric Methods

There are various methods of parametric analysis that can be used whenever the variable distribution is known. However, there are four commonly used methods.

2.5.1.1 Semi Average Method

The semi-average method divides a given time series data into two halves. When the number of years are odd, the series is divided into two halves by omitting the middle year. The arithmetic mean is then obtained for each of the two parts to give two values. These values are then plotted against the middle year of each part and the values joined to form a trend line. This trend line can then be elongated upwards/downwards to obtain values in between or for future prediction. This method will always give the same trendline irrespective of the person doing it, hence simple, which is an advantage compared to other methods (Berger, 2010).

In summary, the procedure for semi average method is as follows:

i. Time series data is split into two halves. In the event of data having an odd number, the two halves are obtained by omitting the middle year.
ii. The average of each half is calculated, hence getting two values.
iii. The points are plotted at the mid-point (year) for each half.
iv. A straight line is then used to join the two points.
v. An extension to either side can then be made on the straight line.
vi. This line is the trend line by the method of semi averages.

2.5.1.2 Moving Average method

The moving average method of trend analysis removes random fluctuations in a given time series data. The moving average for a given period (t) is composed of arithmetic means of x terms from the first to the last. The 1st average is the mean of first (t) terms; the second average is the mean of the second term to (t+1) until the final one. In the event it is odd, then the moving average is placed against the mid-value of the time interval it covers. When (t) is even, then the moving average is between the two middle periods hence not corresponding to any period. The moving average will then have to be selected for a period. In this case, the two-yearly moving averages that correspond to a period selected is taken. The resultant moving averages become the trend values.

In summary, the moving average method starts by smoothening the irregularities of time series, then it subtracts the smoothened ordinates from corresponding sample events. The moving average method procedure is as follows:

i. Arrange the rainfall data to create a time series.

ii. A moving average of three or five is often used to smoothen time series. The equations for a moving average of three are.

$$x'_2 = \frac{(a_1x_1 + a_2x_2 + a_3x_3)}{3}$$ ……………………….………………..…….. Equation 15

$$x'_3 = \frac{(a_1x_2 + a_2x_3 + a_3x_4)}{3}$$ …………………………………….……………. Equation 16

$$x'_{n-1} = \frac{(a_1x_{n-2} + a_2x_{n-1} + a_3x_n)}{3}$$ …………………………….………….Equation 17

In this process, the first and last data of the series are lost and the coefficients a_1, a_2, and a_3 are determined by fitting a polynomial to the series. In this case, data can be arranged in three columns as (x_1 x_2 x_3), (x_2 x_3 x_4), (x_3 x_4 x_5), and so on. By the least square method, coefficients a_1, a_2, and a_3 can also be calculated.

iii. Using the fitted equation, the smoothened values are written. For m = 3, (n-2) values of the x'_I, are obtained. The moving average value will range from x_2 to $x_{n-1.}$

When applying the moving average method to a time series, an oscillatory movement is often introduced into the random component. The oscillations already present with a period less than or equal to m is often dampened out. This effect is called the 'Yule effect'. When applying this method, care must be taken in discussing the oscillatory property of time series being used while at the same time ascertaining the trends (Patra, 2008).

2.5.1.3 Analytical method (Least Squares)

The least-squares method is an analytical technique that is most popular and widely used in fitting mathematical functions to a given set of data. The method has proved to yield excellent results when the correct mathematical functions are applied. To decide on the type of mathematical function to use, an examination of plotting data is sufficient. For graphical representation, arithmetic scales, semi-log, or log scales are often used. The curve types used to describe data are often; straight line, exponential curve, or the second degree of a parabola.

The procedure of the least square method involves trying to fit a curve passing through scattering points of a scatter diagram. The total of squares of departures of observed points from the fitted points should always be minimum. In Figure 2.4, the error between observed and estimated points obtained after fitting the line is illustrated as (Y_o – Y_e). For a given number of sets of (X_i, Y_i) observations, the line $Y= a+bx$, is selected in such a way that $\sum (Y_o - Y_e)^2$ is always minimum. In that case, the curve should always pass close to all the points in the diagram. The procedure to obtain the best value of *a* and *b* from the equation *Y= a+bx* is in such a way that the error function S_e is given by Equation 18 is minimum.

$$S_e = \sum_{i=1}^{N} (y_{0i} - y_{ei})^2 \quad \text{Equation 18}$$

Where;

N – Number of sets of data,

Y_{0i} (= Y_i) – observed data,

Y_{ei} – Computed/ fitted curve points corresponding to X_i.

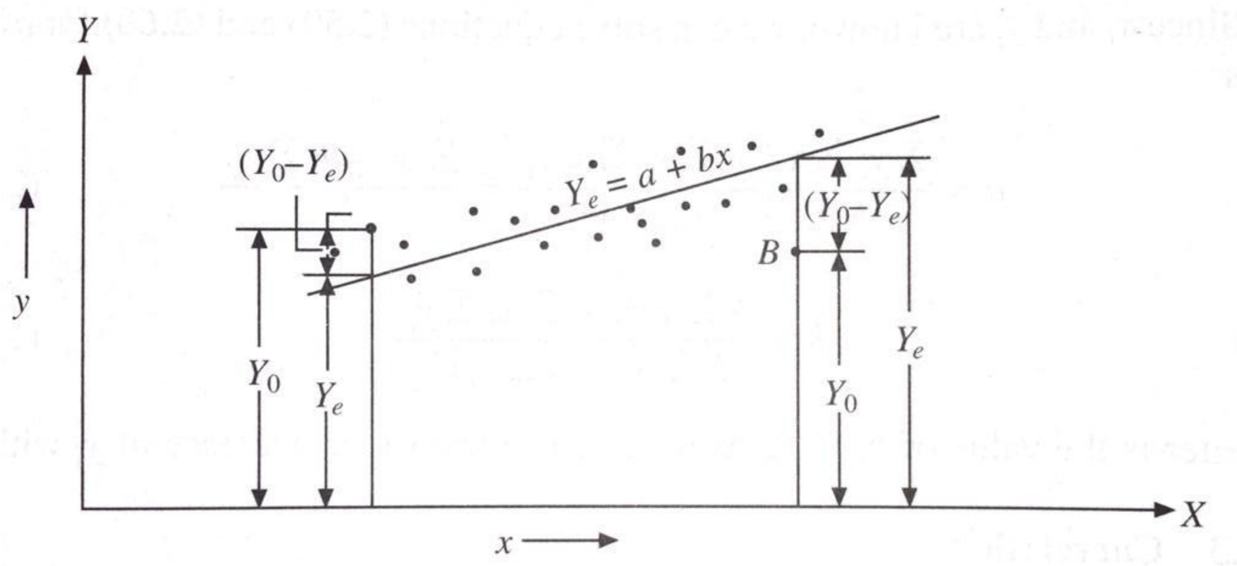


Figure 2.4: Scatter diagram between two variables X and Y (Patra, 2008).

To get a trend using the least square method, the regression constants *a* and *b* from the observed *N* values of Y_i and X_i must be evaluated. First, from the linear equation *Y = a + bx*, the parameter *a* is the intercept whereas *b* is the regression gradient of the curve. Therefore, to evaluate regression constant, Y_{ei} is substituted as $a + bx_i$ in Equation 18 and the resulting equation becomes;

$$S_e = \sum_{i=1}^{N} (y_i - a - bx_i)^2 \quad \text{Equation 19}$$

Since the value of S_e should always be minimum, Equation 19 is differentiated with respect to *a* and equated to zero. The result is Equation 20.

$$\sum y_i - Na - b\sum x_i = 0 \quad \text{............ Equation 20}$$

Again Equation 19 is differentiated with respect to *b* and equated to zero to obtain Equation 21;

$$\sum xy_i - a\sum x_i - b\sum x^2{}_i = 0 \quad \text{............ Equation 21}$$

Solving Equations 20 and 21 using the known x_i and y_i, values of *a* and *b* are obtained as;

$$a = \frac{\sum y_i \sum x_i^2 - \sum x_i \sum x_i y_i}{N\sum x_i^2 - (\sum x_i)^2} = \frac{\sum y_i - b\sum x_i}{N} \quad \text{............ Equation 22}$$

And,

$$b = \frac{N\sum x_i y_i - \sum x_i \sum y_i}{N\sum e_i^2 - (x_i)^2} \quad \text{............ Equation 23}$$

The value of *b* gives the rate of increase or decrease of y_i with respect to x_i. The greater the value, the faster the rate, and positive or negative is an indication of increase or decrease. Hence, trend analysis using the least-squares approach (Patra, 2001).

2.5.1.4 Graphical Method

The graphical method involves plotting of *x* and *y* coordinates to scale on a rectangular system and all points marked on it. The resulting plot is a scatter diagram as illustrated in Figure 2.4. A curve is then traced by eye approximation such that it passes nearly through the mean of the spread of all points. This makes the method quick and practical. For a given value of *x*, the corresponding value of *y* can be read from the graph. The limitation of this procedure is that it is subject to large errors and the results yielded are not accurate. This is especially true if the best fit curve passing through the mean is not drawn properly. However, this method has the advantage of being simple, not involving complex mathematical techniques, and can be used to describe different kinds of trends (Patra, 2008 and Berger, 2010).

2.5.2 Non-Parametric Methods

The use of non-parametric methods in trend analysis of hydrological variables is important as it provides information on possible future changes to these variables (Jhajharia *et al.*, 2014). The most used non-parametric methods in hydrology are Mann-Kendall and Sen's slope estimator. Scheff (2016) highlights non-parametric methods to be advantageous over parametric methods because of its ability to work with data of great variance with test results not being affected by extreme deviations. The methods are also easily applicable to skewed, nominal, interval, ordinal, or ratio data. Because of these advantages, several researchers have applied non-parametric tests for trends analysis of hydrological variables, such as; Gyamfi *et al*. (2016) and Ndebele *et al.* (2020) in South Africa, Anttila and Ruoho-airola (2002), Patle and Libang (2014), Che Ros *et al.* (2016) Kocsis and Anda (2018), Shree and Kumar (2018) and Kocsis *et al.* (2020)in other parts of the world.

2.5.2.1 Mann-Kendall Test

The Mann-Kendall test is often applied in detecting increasing/decreasing trends in hydrologic data series (Maintainer and Pohlert, 2018). The test has been applied for hydrological analysis because of its simplicity, robustness, and ability to cope with missing values (Gavrilov *et al.*, 2016). The test is applicable to time series not having a normal distribution (Helsel and Hirsh, 2002 and Birsan *et al.*, 2005). For autocorrelated data, Hamed *et al.* (1998) came up with a modified Mann-Kendal test. The robustness of the Mann-Kendal test in detecting monotonic trends in hydrological series was investigated by Yue *et al.* (2002) and found to be adequate.

The Mann-Kendall test is founded on the works of Mann (1945) and Kendall (1975). The test relates to Kendall's rank correlation coefficient. The method is described in detail by Hipel and McLeod (1994).

When testing for the presence of a decreasing/increasing trend, the null hypothesis (H_o) is that the data is from a sample with independent variables that have an identical distribution. The alternative hypothesis (H_a) is that the data follows a given trend. This alternative hypothesis is two-sided, appropriate for either decreasing or increasing trend. However, if the trend direction is already specified then a one-tailed test is used.

The Mann-Kendall test statistic (*S*) is defined by the relation in Equation 24 as;

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign(x_j - x_k)\ ,\ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 24}$$

Where; X_j *and* X_k are sequential data series in time series for the years *j* >*k*, and

$$Sign(x) = \begin{cases} +1, x > 0 \\ 0, x = 0 \\ -1, x < 0 \end{cases} \ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 25}$$

S has been proved to have a normal distribution (Kendall, 1975). The mean and the variance are defined as;

$$E[S] = 0$$

$$Var[S] = \{n(n-1)(2n+5) - \sum_{j=1}^{p} tj(tj-1)(2tj+5)\}/18 \ldots\ldots\ldots \text{Equation 26}$$

Where;

p - number of tied groups in the data set,

t_j – number of data in the j^{th} tied group,

n- number of data in the time series.

When *S* is positive, it is an indication of an increasing trend while when *S* is negative, it is an indication of a decreasing trend with time. When the number of data in a given series is more than 10, the standard normal variate *Z* can also be used in hypothesis testing. *Z* is given as;

$$Z = \begin{cases} \frac{S-1}{[Var\ (S)]^{1/2}}, if\ S > 0 \\ 0,\ if\ S = 0 \\ \frac{S+1}{[Var(S)]^{1/2}},\ if\ S < 0 \end{cases} \ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 27}$$

And since *S* is related to Kendall's rank correlation coefficient (Ʈ) and the test for Ʈ is similar to testing *S*.

$$\tau = \frac{S}{D} \ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 28}$$

Where; D is the number of possible pairs of observations from a total of n observations.

$$D = \binom{n}{2} \text{......Equation 29}$$

For this research, hypothesis testing is done at a significance level of α =10% (Kendall, 1975) and is used in a two-tailed test, whereby the null hypothesis is that there is no trend in the time series. The alternative hypothesis is that there is a significant increasing/decreasing trend in the time series. The selected level of significance defines the probability of rejecting the null hypothesis when in fact it is true. Therefore at a 10% significance level for a sample data of 100, it is expected that 10 data points would be rejected.

2.5.2.2 Modified Mann-Kendall Test

The presence of autocorrelation in a given time series increases the probability of observing false trends. (Hamed *et al.,* 1998). The effect of autocorrelation was usually disregarded until Hamed *et al.* (1998) came up with a modified non-parametric test. To avert uncertainties caused by serially dependent data, this research applies the modified Mann-Kendall test.

Autocorrelation is also caused by seasonal cycles in time series. Gilbert (1987) suggested the use of a trend analysis method that can remove seasonality effects. Hirsch (1982) and Hirsch and Slack (1984) came up with the seasonal Mann-Kendall test, a form of modified Mann-Kendall test which divides the data into seasons and uses statistics for each season to perform the test. This eliminates the effects of seasonality within seasons.

In the modified Mann-Kendall test, a series with *x* observations for *K* seasons over *L* years is as expressed by the matrix in Equation 30 (Rahman *et al.,* 2017).

$$\begin{matrix} x_{11} & x_{21} & \dots & x_{K1} \\ x_{12} & x_{22} & \vdots & x_{K2} \\ \dots & \dots & & \dots \\ x_{1L} & x_{2L} & \dots & X_{KL} \end{matrix} \text{...... Equation 30}$$

Let x_{il} be the datum of the i^{th} season of the l^{th} year. Each season for the entire time series is used to calculate the Mann Kendall statistic S. S_i is calculated for I^{th} season as follows;

$$S_i = \sum_{k=1}^{n_i-1} \sum_{l=k+1}^{n_i} sgn(x_{il} - x_{ik}), \qquad \text{Equation 31}$$

Where *l* is greater than *k* and n_i is the number of data for the i^{th} season and sgn (x_{il} -x_{ik}) is given by;

$$sgn(x_{il} - x_{ik}) = \begin{cases} 1 \; if \; x_{il} - x_{ik} > 0 \\ 0 \; if \; x_{il} - x_{ik} = 0 \\ -1 \; if \; x_{il} - x_{ik} < 0 \end{cases} \qquad \text{Equation 32}$$

The method of calculating VAR(S_i) is defined by Gilbert (1987) whereby, the statistic *S*' of the seasonal Mann-Kendall is calculated as given by equation 33 and VAR(S') by Equation 34;

$$S' = \sum_{i=1}^{K} S_{i,} \qquad \text{Equation 33}$$

$$Var(S') = \sum_{i=1}^{K} Var(S_i) \qquad \text{Equation 34}$$

The *Z*-test statistic is calculated and tested using the hypothesis test given in Equation 35;

$$Z = \begin{cases} \frac{S'-1}{[Var(S')]^{1/2}} \; if \; S' > 0 \\ 0 \; if \; S' = 0. \\ \frac{S'+1}{[Var(S)]^{1/2}} \; if \; S' < 0 \end{cases} \qquad \text{Equation 35}$$

2.5.2.3 Sen's Slope estimator

Sen (1968) slope estimator is a method which calculates change per time unit. It is often applied after identifying trends using a non-parametric method. It applies a linear model to approximate slope while holding the variance of residuals constant (Santos, 2015). First, the *N*' slope estimates are computed as;

$$Q = \frac{x'_i - x_i}{i' - i} \qquad \text{Equation 36}$$

Where x'_i and x_i are the series values during the period *i*' and *i*, respectively, and where *i*'>*i*. *N*' is the number of data pairs for which *i*'>*i*. In the event of a single datum for specific periods, *N*' is given as;

$$N' = \frac{n(n-1)}{2} , \quad \text{Equation 37}$$

Where *n* is the number of periods (Gilbert, 1987). The *N*' values of *Q* are arranged from the smallest to the largest and the median value gives the slope of the trend. Sens slope is advantageous as the impact of outliers are limited (Shadmani *et al*., 2012). It is also robust with few statistical limitations (Lavagnini *et al.*, 2011).

Numerous researchers have found the application of Sen's slope estimator in their work to be useful. Amongst them are; Abghari *et al.* (2013), Guo and Xia (2014), Amirataee *et al.* (2016), Che Ros *et al.* (2016), Liuzzo *et al.* (2016), Zamani *et al.* (2017), Kocsis *et al.* (2017), Kocsis and Anda (2018), Shree and Kumar (2018), Lakhraj-Govender and Grab (2019) and Ndebele *et al.* (2020).

2.5.2.4 Seasonal Slope estimator

The seasonal slope estimator is derived from the Sen's slope estimator (Gilbert, 1987). The single N_i slope is first calculated for the i^{th} season using Equation 38.

$$Q_i = \frac{x_{il} - x_{ik}}{1-k}, \quad \text{Equation 38}$$

Where *l*>*k* and x_{il} is the datum of the i^{th} season for k^{th} year. This calculation is done for each of *K* season. And *N1*' + *N2*' +… + *NK*' = *N*' estimates of slope ranked, and the median obtained (Gilbert, 1987). This research applies the seasonal slope estimator to find the rate of change per unit time for autocorrelated time series data.

2.6 Literature Review Summary

From literature review, a global shift in rainfall trends and patterns have been observed. Researchers have attributed the shift to climate change while using GCMs & parametric methods in their analysis and projection of climatic variables. This research investigates the shift in rainfall trends using a non-parametric approach while evaluating and discussing it in relation to previous research output.

The climate of Africa is governed by continental and marine interactions. In Southern Africa, the climate is influenced by interactions between the Pacific El Niño Southern Oscillations (ENSO) with the Atlantic and the Indian Ocean climates. Hence, Climate change as a result of increased greenhouse gasses in the atmosphere has been indicated to cause changes in rainfall patterns.

Due to increased climatic variability, rainfall trend analysis has become important for the planning, design and implementation of sustainable water resources management. This has attracted interest of academia, water resources management, agriculture and ecology resulting in extensive research in rainfall trends and variability of South Africa.

Easterling *et al.* (2000) observed a trend of increased rainfall in the Eastern and South-Western South Africa between 1901-1997. Groisman *et al.* (2005), concurs by noting a significant increase in the recurrence of extreme rainfall events in Eastern South Africa between 1906-1997. Mason *et al.* (1999) observed increased high rainfall intensity in 1961 to 1990 in comparison to 1931 to1960. Kruger (2006) observed an increase in extreme rainfall indices in the Eastern Cape and Southern Free State from 1910-2004. New *et al.* (2006) observed an increase in extreme rainfall for different regions of South Africa during 1961-2000. Nel (2009) observed a shift in seasons in the KZN during 1955-2000 and is complemented by Thomas *et al.* (2007) who observed an increase in the early seasonal rainfall and a decrease in the late-season rainfall at the North-West KZN for the same period. Dry spell duration is observed to increase at the Eastern Cape and Free State while wet spell duration increases at the North-Eastern and Eastern South Africa from 1910-2004 (Kruger, 2006).

Kruger and Nxumalo (2017), observed an increasing trend in western South Africa, stretching to the Southern Interior, with the North-Eastern Interior region experiencing a decreasing trend. Donat *et al.* (2013) in concurrence observe an increase in rainfall intensity and frequency over the same region. The South Western Cape was also observed not to have increasing trends, in concurrence with MacKellar *et al.* (2014). Du Plessis and Schloms (2017) observed shifts in rainfall patterns and the cyclicity of dry and wet periods within seasons for Western Cape using parametric methods. From the literature, significant trends over long periods are not evident.

Instead, a significant increase in extremes and interannual variability of rainfall over specific areas of South Africa are highlighted. Kruger and Nxumalo (2017) incorporate a significant period (1921-2015) for trend analysis in South Africa but using a climate change detecting software RClimDex while highlighting the need to use non-parametric methods, hence the gap for this research.

The statistical methods applicable to rainfall trend analysis discussed in this chapter inform the selection and application of methods used in this research. The applied methods as utilized are discussed in detail in chapter three.

3 Methodology

This chapter explains the methodology used in arriving at rainfall trends and variability. It discusses the source of data, preparation of data and methods applied to analyse trends in the time series data. The general outline used in methodology is summarized in Figure 3.1.

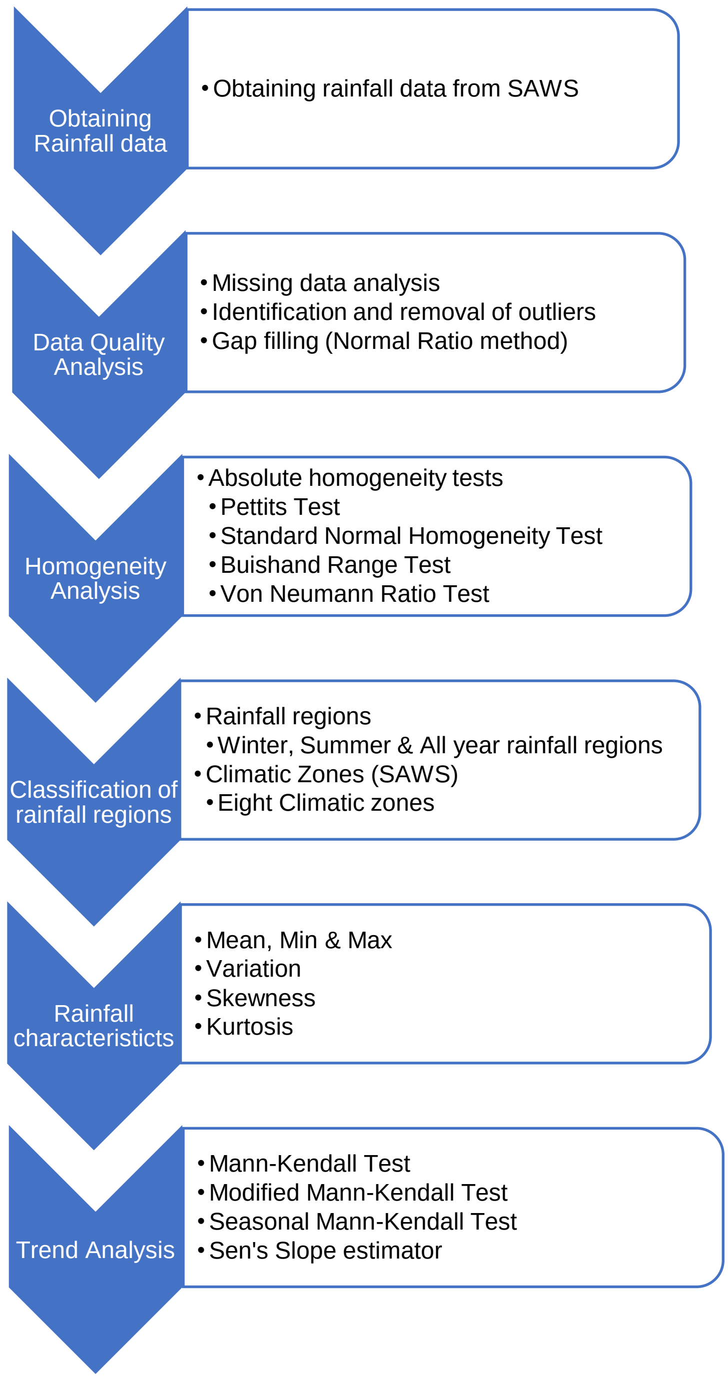


Figure 3.1: General outline of methodology.

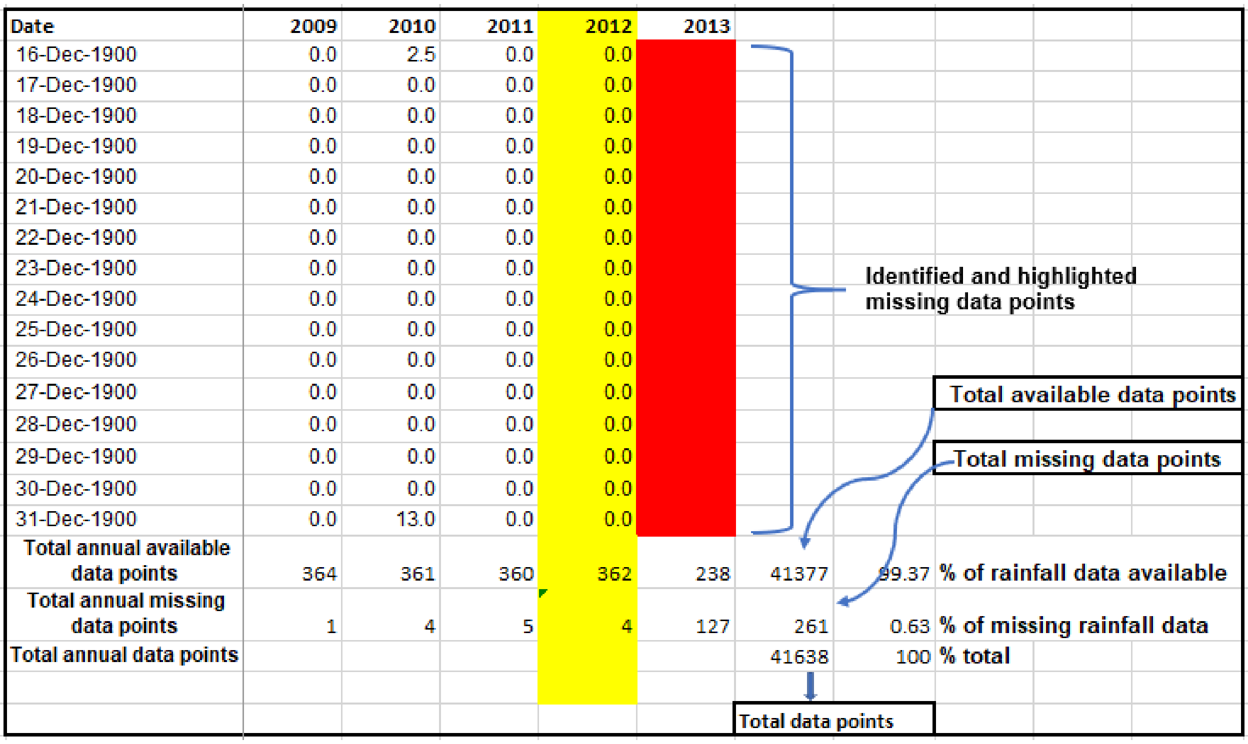
3.1 Data Collection

In South Africa, climatological variables are measured and hosted by the South African Weather Service (SAWS). Rainfall stations having at least 100 years of daily rainfall data were identified from SAWS stations register. This period of study was chosen to obtain the longest period possible while still retaining adequate weather observation stations with rainfall records spanning the whole period, to obtain good spatial coverage of results over South Africa. The stations identified were then plotted in the study area to check on the distribution and were found to be a good representative distribution for South Africa. Thereafter, daily rainfall data for all the 70 identified meteorological stations were acquired from the agency and subjected to quality analysis for acceptability for use in this research.

3.2 Quality Control

Having obtained rainfall data from SAWS, it was necessary to inspect the quality of the data and perform quality control measures where necessary. This was done to detect and correct errors that could have been made during observation, recording, formatting, and transmission processes. An assumption was therefore made that rainfall data obtained had dominant errors in observation, change in time, instrumentation, and station relocation. Since daily rainfall was used, it was noted that quality control could be difficult because of poor spatial correlation and in some cases sparsity of data. This is because quality control methods applied rely on a significant correlation between rainfall stations which is not easily achieved with the diverse topography in some regions of South Africa with sparsely distributed rainfall stations.

However, to curb these challenges, the data obtained was prepared into a continuous time-series format. This enabled the identification and highlighting of gaps in the time series data as illustrated in Figure 3.2. Thereafter, gross error checking was performed to identify and remove negative values. A tolerance test was also performed through visual inspection of plotted time series for the identification and removal of outliers, such as extremely large amounts of rainfall e.g., 1000 mm of daily rainfall. The omitted values were assumed to be missing values. A station-by-station analysis of the percentage of missing rainfall values was then conducted at a daily time step as illustrated by Figure 3.2. In an attempt to reduce uncertainty posed by limited time-series data, stations with more than 10% of missing values (Du Plessis and Burger, 2015, Gyamfi *et al.,* 2016 and Tadese *et al.*, 2019), were flagged and the remaining considered acceptable for use in this research. This resulted in a selection of 62 out of 70 meteorological stations with data spanning 1900-2019 for most of them. These stations were then subjected to the Normal Ratio method for estimation of missing rainfall values.

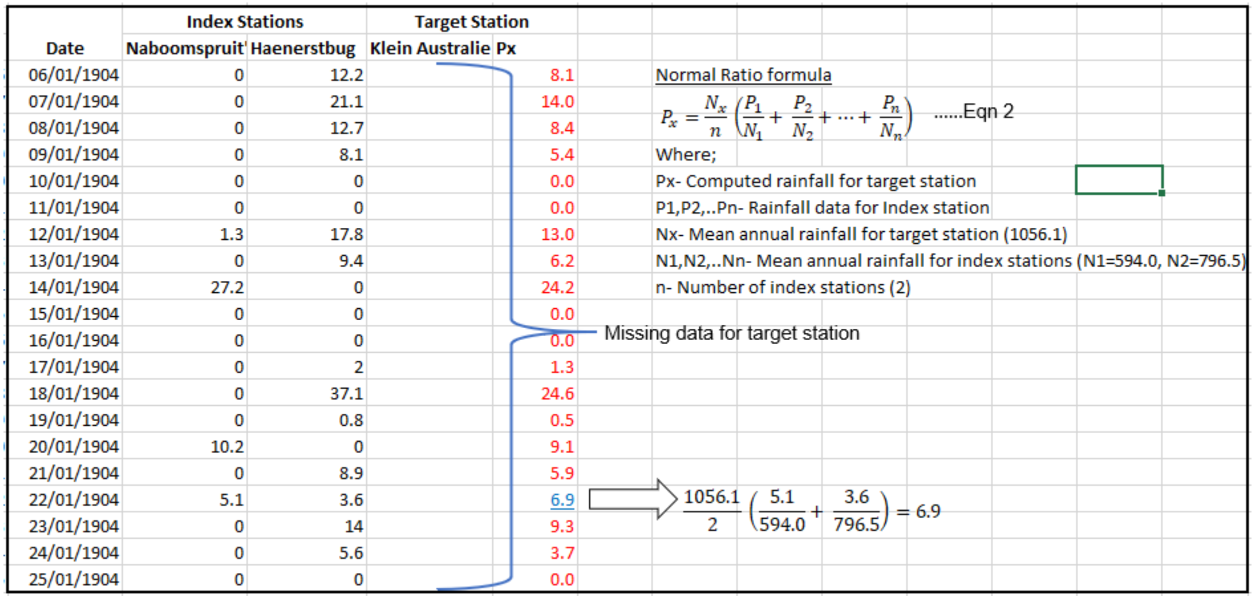


Date	2009	2010	2011	2012	2013			
16-Dec-1900	0.0	2.5	0.0	0.0				
17-Dec-1900	0.0	0.0	0.0	0.0				
18-Dec-1900	0.0	0.0	0.0	0.0				
19-Dec-1900	0.0	0.0	0.0	0.0				
20-Dec-1900	0.0	0.0	0.0	0.0				
21-Dec-1900	0.0	0.0	0.0	0.0				
22-Dec-1900	0.0	0.0	0.0	0.0				
23-Dec-1900	0.0	0.0	0.0	0.0				
24-Dec-1900	0.0	0.0	0.0	0.0				
25-Dec-1900	0.0	0.0	0.0	0.0				
26-Dec-1900	0.0	0.0	0.0	0.0				
27-Dec-1900	0.0	0.0	0.0	0.0				
28-Dec-1900	0.0	0.0	0.0	0.0				
29-Dec-1900	0.0	0.0	0.0	0.0				
30-Dec-1900	0.0	0.0	0.0	0.0				
31-Dec-1900	0.0	13.0	0.0	0.0				
Total annual available data points	364	361	360	362	238	41377	99.37	% of rainfall data available
Total annual missing data points	1	4	5	4	127	261	0.63	% of missing rainfall data
Total annual data points						41638	100	% total

Figure 3.2: Identification of missing data points and computation of the percentage of missing rainfall data.

Normal Ratio (NR) Method

The NR method is based on the principle that data recorded at nearby stations are highly correlated with data of target stations because these stations tend to be from a homogenous rainfall zone. It is applied when the mean annual precipitation of the index station differs by ≥10% to that of the target station (Patra, 2008). To the suitability of these conditions, it was ensured that index and target stations met the above conditions before the method was applied. For example, identifying Klein Australie station to be the target station with index stations as Haenerstberg and NaboomSpruit stations with a mean annual rainfall of 1056.1 mm, 796.5 mm, and 594.0 mm, respectively. The first condition of a 10% difference in mean annual rainfall of target station and index stations was checked and found to be within limits. Equation 2 was then applied to calculate the missing values for the target station as illustrated in Figure 3.3. The same procedure was then applied to fill the gaps of missing rainfall data for all the stations.



	Index Stations		Target Station	
Date	Naboomspruit	Haenerstbug	Klein Australie	Px
06/01/1904	0	12.2		8.1
07/01/1904	0	21.1		14.0
08/01/1904	0	12.7		8.4
09/01/1904	0	8.1		5.4
10/01/1904	0	0		0.0
11/01/1904	0	0		0.0
12/01/1904	1.3	17.8		13.0
13/01/1904	0	9.4		6.2
14/01/1904	27.2	0		24.2
15/01/1904	0	0		0.0
16/01/1904	0	0		0.0
17/01/1904	0	2		1.3
18/01/1904	0	37.1		24.6
19/01/1904	0	0.8		0.5
20/01/1904	10.2	0		9.1
21/01/1904	0	8.9		5.9
22/01/1904	5.1	3.6		6.9
23/01/1904	0	14		9.3
24/01/1904	0	5.6		3.7
25/01/1904	0	0		0.0

Figure 3.3: The Normal Ratio method.

After filling the gaps for all the stations, each station was then subjected to the absolute homogeneity tests.

3.3 Homogeneity Test

The homogeneity test is an important part of this research as it ensures that the different rainfall stations' data used for trend analysis come from their respective population and have a similar distribution. The absolute homogeneity method was employed consisting of four tests; the Pettitt test (Pettitt, 1979), the Standard Normal Homogeneity Test (SNHT) (Alexandersson, 1986), the Buishand Range test (Buishand, 1982), and Von Neumann's ratio test (Von Neumann, 1941).

These four homogeneity tests under the null hypothesis suppose the test variable (daily rainfall) to be independent and having an identical distribution. While under the alternative hypothesis, the Pettit, SNHT, and Buishand Range tests assume of a stepwise shift in the mean (a break point) to be present. The Von Neumann ratio test has alternative hypothesis assuming the time series not to be randomly distributed. Therefore, it does not provide information on the year the break is likely to have occurred.

Although the first three tests have several similarities, they are different. The SNHT identifies break points near the start and termination of a time series relatively easily, while Pettitt and Buishand range tests identify breaks at the middle of a time series (Hawkins, 2008). The Buishand range test and SNHT assume variable values to be having a normal distribution, while the Pettitt test doesn't. Instead, it makes no requirement of variable distribution and applies itself to the ranks of elements of the time series rather than the values. This ranking by Pettitt is also an implication of it being slightly sensitive to outliers in comparison to the three other tests. The Von Neumann ratio test is complementary to the rest of the tests owing to its sensitivity to departures of homogeneity not defined by strict stepwise shifts (Buishand, 1982).

Section 2.4.2 illustrates the mathematical formulation of the four tests applied for homogeneity analysis. To illustrate how the homogeneity tests have been applied in this research, a ten-year annual rainfall data series for Roodbloem station in Table 3 is used. The data were subjected to the four homogeneity tests Pettitt, SNHT, Buishand, and Von Neumann ratio tests simultaneously. These four tests have a null hypothesis (H_0) that data is homogenous and an alternative hypothesis (H_a) that there is a year with a change in data. The results of the tests were then subjected to a two-tailed test at a 5% significance level.

Table 3: Annual rainfall data for Roodbloem station (1900-1910).

Year	Annual Rainfall (mm)
1900	358.0
1901	354.1
1902	263.8
1903	135.2
1904	244.8
1905	278.1
1906	418.5
1907	261.7
1908	156.1
1909	300.6
1910	281.1

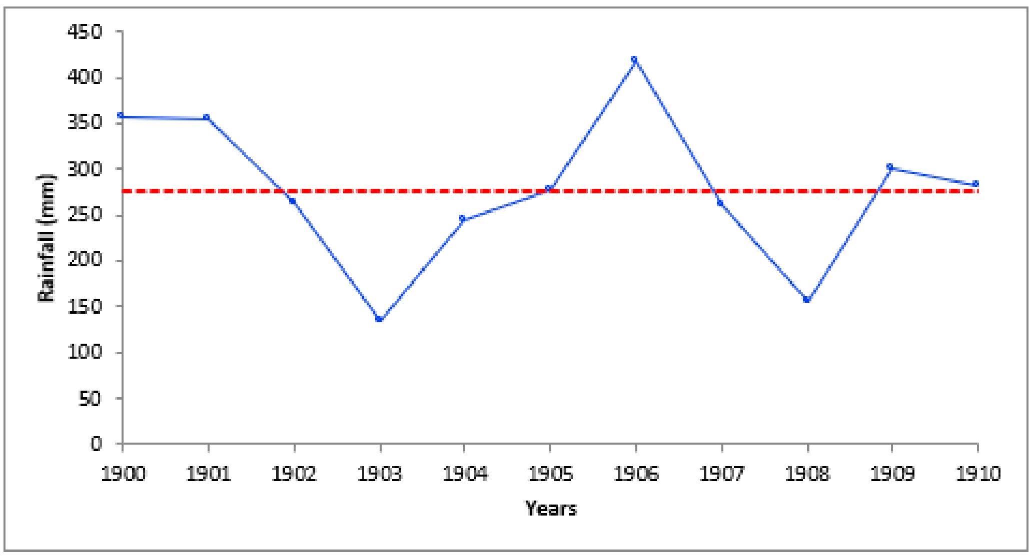
The four absolute homogeneity tests were done using XLSTAT software and results compiled as illustrated in Table 4.

Table 4: Homogeneity results for Roodbloem station (1900-1910).

Summary:

	Pettitt	SNHT test	Buishand	Von Neumann
P values	0.992	0.736	0.658	0.279

Test interpretation:
H_0: Data are homogeneous
H_a: There is a date at which there is a change in the data
As the computed p-value is greater than the significance level alpha=0.05, one cannot reject the null hypothesis H_0.



Results of the four tests show that the annual rainfall data for Roodbloem station is homogenous. The graph on the bottom of Table 4 shows that in all the four tests, the mean did not deviate significantly from 277.4 mm (shown by the dotted red line). The second step of homogeneity analysis was the evaluation and classification of the results for the four tests. A classification system with three main classes (Wijngaard *et al.,* 2003) was adopted. The criterion categorizes the daily time series into the following classes.

Class 1: 'Useful'- one or zero tests reject the null hypothesis.
Class 2: 'Doubtful'- two tests reject the null hypothesis.
Class 3: 'Suspect'- three of the four tests reject the null hypothesis.

In this case, none of the tests rejected the null hypothesis and therefore the rainfall data was considered useful (class 1). The same procedure is applied to all the stations' rainfall data and only those found to be homogenous (Class 1 and in exceptional cases, Class 2) used for trend analysis. Homogenous rainfall stations were then classified into rainfall and climatic regions.

3.4 Classification of Rainfall Regions

This research started with the division of South Africa into six regions defined by Water Management Areas (WMAs) as illustrated in Figure 1.1. The selection of these WMAs was based on the fact that the effects of rainfall variability to the South African economy and other important production sectors can be primarily conciliated through the water sector. However, it was noted that the WMAs did not necessarily agree with homogenous climatic zones and trends. Therefore, this necessitated the adoption of rainfall regions and climatic zones as defined by SAWS while retaining the WMAs as hydrological regions. The rainfall regions were categorized based on rainfall characteristics then further classified into climatic zones.

The rainfall regions were defined based on the main rainfall season for the respective homogenous rainfall stations. South Africa experiences four seasons; Winter (June-July-August), Spring (September-October-November), Summer (December-January-February), and Autumn (March-April-May). Based on these four seasons, rainfall stations could be grouped into three rainfall regions: Winter, Summer and ‘All year’ rainfall regions. The classification of rainfall stations into these three regions was based on analysis of the distribution of annual rainfall at a monthly timestep, still to be discussed. Climatic zones were then further derived from the established rainfall regions.

Having classified the rainfall stations according to the seasons and bearing in mind the complexity of rainfall in South Africa, it was imperative to further classify stations in these rainfall regions based on the distribution of rainfall within its main rainfall season. This led to eight climatic zones as established by SAWS. These climatic zones are; South Western Cape and North-Western Cape in the Winter rainfall region. The Southern Interior, Western Interior, Central Interior, North-Eastern Interior and KwaZulu-Natal in the Summer rainfall region. The South Coast in the ‘All-year’ rainfall region. These climatic zones, still to be discussed, are coupled with the rainfall regions in discussing rainfall trends taking place in the different WMAs (hydrological regions) in South Africa. Whereas the WMAs are only mentioned in the discussion of results summary due to rainfall trends not being in line with the WMAs (hydrological) boundaries, the maps illustrating trends highlight the distributions of rainfall trends across the different WMAs.

3.5 Rainfall Characteristics

The rainfall characteristics determined are: mean, minimum and maximum rainfall, coefficient of variation, coefficient of skewness and kurtosis coefficient. Owing to the simplistic nature of methods for calculating these rainfall characteristics, only the basic definition of each characteristic with respective formulae without examples are discussed herein. These rainfall characteristics are determined directly using excel functions.

The characterization of rainfall time series data considers long-term (120 years) and short-term (40 year) periods, at monthly, seasonal, and annual time steps. The 40-year periods were arrived at following the World Meteorological Organization (WMO) adoption of a classical period of 30 years in climate definition. These periods cater for short-term (climate) characteristics likely to have been experienced in the 21 or 28-years rainfall cycles (Alexender, 2005). However, in this research, not all stations had their data from the year 1900 and ending in 2019. Hence to cater for the staggered start and end, while maintaining the climate definition period, 40-year periods, (1900-1939, 1940-1979, 1980-2019) were selected and defined as short-term periods. Trend analysis also considers the long-term and short-term periods.

3.5.1 Mean

Mean is the average of all the records about which a given distribution is equally weighted. The mean represents a location in a distribution in which all negative and positive departures balance. The sum of all departures from the mean of a given distribution is always zero. There are various types of mean such as harmonic mean, geometric mean, arithmetic mean, and weighted mean. This research applies arithmetic mean as shown in Equation 39.

$$X_{av} = \left(\frac{1}{N}\right) \sum_{i=1}^{N} X_i \quad \text{Equation 39}$$

Where;

X_{av} – Arithmetic mean,

X_i – Rainfall values,

N – Number of rainfall records.

The minimum (R_{min}) and maximum (R_{max}) values are also determined to put into perspective the range of data for a given rainfall distribution.

3.5.2 Coefficient of Variation (C_v)

Coefficient of variation (C_v) is a dimensionless measure of variability represented as the ratio of standard deviation to the mean as shown in Equation 40.

$$C_v = \frac{\sigma}{X_{av}} \qquad \text{Equation 40}$$

Where;

C_v – Coefficient of variation,

σ – Standard deviation,

X_{av} – Arithmetic mean.

Standard deviation is calculated using the expression in Equation 41.

$$\sigma_n = \sqrt{\frac{1}{N}(X_i - X_{av})^2} \qquad \text{Equation 41}$$

Where;

σ_n – Standard deviation,

N – Number of rainfall records,

X_{av} – Arithmetic mean,

X_i – Rainfall values.

3.5.3 Coefficient of Skewness (C_s)

Coefficient of skewness is the third moment about the mean representing symmetry of distribution of data about the mean. If the peak of the data is distributed to the right, it is said to be negatively skewed while if distributed to the left, then is positively skewed. Coefficient of skewness is expressed as illustrated in Equation 42.

$$C_S = \frac{U_3}{\sigma^3} \qquad \text{Equation 42}$$

Where;

C_s – Coefficient of Skewness,

U_3 – Third moment about the mean,

σ^3 – Standard deviation cubed,

and,

$$U_3 = \frac{1}{N}\sum(X_i - X_{av})^3 \text{ ....Equation 43}$$

Where;

U_3 – Third moment about the mean,

N – Number of rainfall records,

X_{av} – Arithmetic mean,

X_i – Rainfall values.

3.5.4 Kurtosis coefficient (C_k)

Kurtosis coefficient is the ratio of fourth power about the mean to the square of variance. It gives a representation of the groupings of data at a central place. It is can also be termed as the measure of 'peakedness' with a value that tends to become zero as it represents the fourth power of deviation from mean. Coefficient of skewness is illustrated by Equation 44.

$$C_k = \frac{U_4}{\sigma^4} \text{ ....Equation 44}$$

Where;

C_k – Kurtosis coefficient,

U_4 – Fourth moment about the mean,

σ^4 – Standard deviation to power four,

and,

$$U_4 = \frac{1}{N}\sum(X_i - X_{av})^4 \text{ ....Equation 45}$$

Where;

U_4 – Fourth moment about the mean,

N – Number of rainfall records,

X_{av} – Arithmetic mean,

X_i – Rainfall values.

3.6 Trend Analysis

Trend analysis was carried out in this research to establish whether there has been a change in the rainfall time series of South Africa over time. There are several methods of performing trend analysis but because of the advantages of non-parametric over parametric methods such as not requiring the time series to follow a specific distribution and its' ability to deal with autocorrelation, the non-parametric approach is favored in this research. The tests used are the Mann-Kendall test for trend and Sen's slope estimator for the rate of change with time.

3.6.1 Mann-Kendall Test

The use of the Mann-Kendall (MK) test is extensive in the hydrological and climatological analysis of time series because of its simplicity and robustness. Mann-Kendall test has been used in this research to determine monotonic trends over time in daily, monthly, seasonal, and annual rainfall. The method applied follows closely details and descriptions of Gilbert (1987) and Hipel and McLeod (1994).

To illustrate the Mann-Kendall test, annual rainfall data (1900-1910) for Roodbloem station in Table 3 was used. The null hypothesis (H_0) of the Mann-Kendall trend test performed is that the time series comes from a sample with variables (rainfall values) having an identical distribution. The alternative hypothesis (H_a) is that the time series follows either an increasing/decreasing trend. For the time series, the MK test calculates the statistic *S* illustrated by Equation 24. The variance of *S* (var[S]) is calculated using Equation 26. Using the variance and Mann-Kendall statistic calculated, the standard normal variate (*Z*) to be used for hypothesis testing is calculated using Equation 27.

To calculate the above parameters, a table of row and column heading consisting of the data elements in the time series is constructed. The values in the table forming a triangle consists of values that make up of Mann-Kendall statistic given by Equation 25. This is illustrated in Figure 3.4.

	358	354.1	263.8	135.2	244.3	278.1	418.5	261.7	156.1	300.6	281.1
358											
354.1	-1										
263.8	-1	-1									
135.2	-1	-1	-1								
244.3	-1	-1	-1	1							
278.1	-1	-1	1	1	1						
418.5	1	1	1	1	1	1					
261.7	-1	-1	-1	1	1	-1	-1				
156.1	-1	-1	-1	1	-1	-1	-1	-1			
300.6	-1	-1	1	1	1	1	-1	1	1		
281.1	-1	-1	1	1	1	1	-1	1	1	-1	

$$Sign(x) = \begin{cases} +1, x > 0 \\ 0, x = 0 \\ -1, x < 0 \end{cases}$$ .... Equation 25

Figure 3.4: The Mann-Kendall trend test.

To get the Mann-Kendall statistic S as given by Equation 24, the values in the table, obtained from Equation 25, in Figure 3.4 are summed up. For this test, S = -5, as illustrated in Figure 3.5, indicating the possibility of a decreasing trend, consistent with the line chart of the time series data fitted with a trend line having a downward slope shown in Figure 3.6.

Summary	
n	11
Significance level	0.05
Var[S]	7.484567901
MK-stat(S)	-5
s.e.	2.735793834
z-stat	-1.462098478
p-value	0.143714226
trend	NO

$$Var[S] = \{n(n-1)(2n+5) - \sum_{j=1}^{p} tj(tj-1)(2tj+5)\}/18$$ .... Equation 26

$$Z = \begin{cases} \frac{S-1}{[Var\,(S)]^{1/2}}, if\ S > 0 \\ 0,\ if\ S = 0 \\ \frac{S+1}{[Var(S)]^{1/2}},\ if\ S < 0 \end{cases}$$ ...... Equation 27

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign(x_j - x_k)$$, ... Equation 24

Figure 3.5: Mann-Kendall test results.

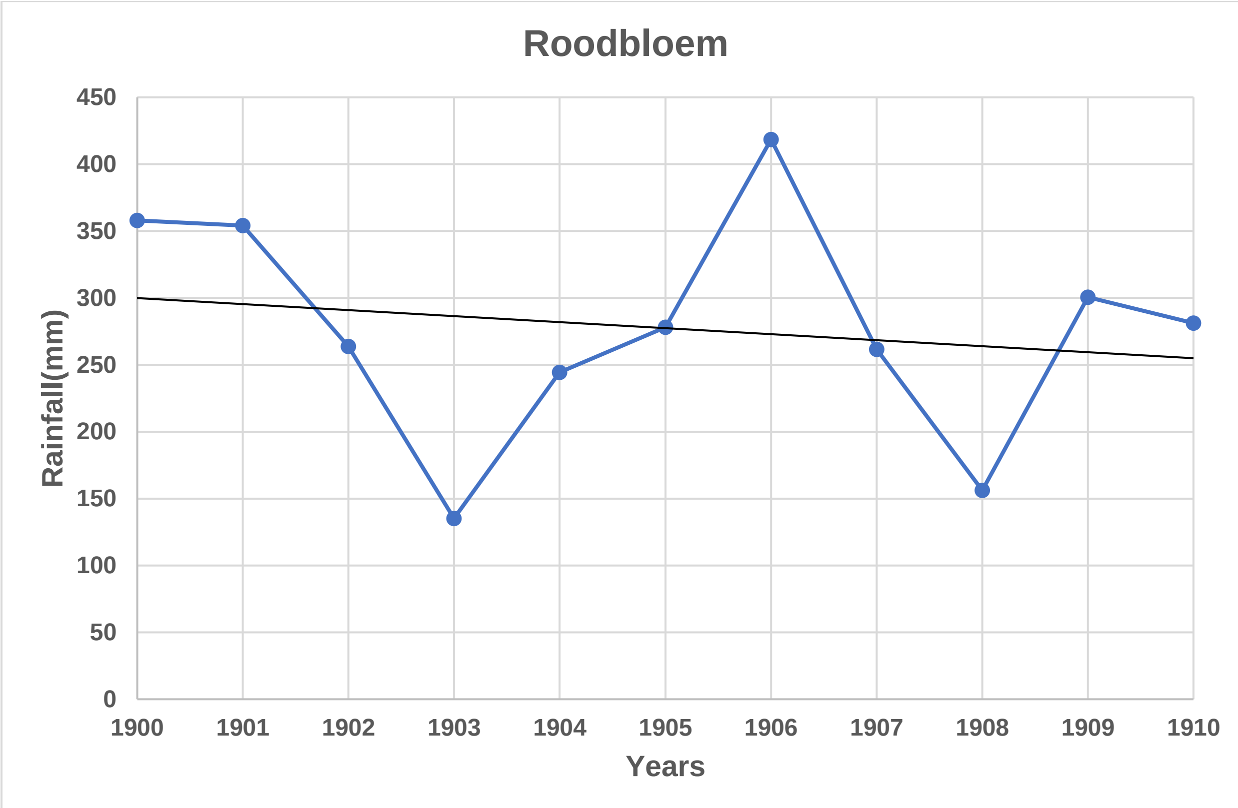


Figure 3.6: Line graph for Roodbloem showing a decreasing trend.

Upon calculating the Mann-Kendall statistic S, the next step was the calculation of standard normal variate (Z) given by Equation 27. However, to get the value of Z, the square root of the variance of MK statistic Var[S] is required. Therefore, using Equation 26, Var[S] was calculated, and square root obtained indicated as S_e, also termed as the standard error. Having obtained Var[S] and S_e, the value of Z was calculated. This value is important for hypothesis testing at the selected level of significance. To obtain the percentage significance (P) of the results obtained from Z, statistical tables are used. However, for this research, the value of P was obtained directly using statistical functions in excel. For the Roodbloem annual time series, the values for Mann-Kendall statistic (S), variance (Var[S]), standard normal variate (Z), and the significance level of trend obtained (P) is illustrated in Figure 3.5.

Having obtained P, hypothesis testing using two-tailed test at a significance level of 10% was done. The two-tailed tests allow us to cater for either a decreasing or increasing trend. For this test, P = 14.37% and S = -5. The negative value of S is an indication of a decreasing trend. However, since hypothesis testing was done at a 10% significance level while the obtained P

value was greater than 0.1, the conclusion was; there is no statistically significant trend for Roodbloem annual rainfall. This is illustrated in Figure 3.5 which shows the results for annual trend analysis using the Mann-Kendall test. Running the same test in excel, the results were confirmed to be similar as illustrated in Figure 3.7.

Mann-Kendall trend test / Two-tailed test (Rainfall):

Kendall's tau	-0.091
S	-5.000
Var(S)	165.000
p-value (Two-tailed)	0.143
alpha	0.05

An approximation has been used to compute the p-value.

Test interpretation:

H0: There is no trend in the series

Ha: There is a trend in the series

As the computed p-value is greater than the significance level alpha=0.05, one cannot reject the null hypothesis H0.

Sen's slope:

Series\Test	Kendall's tau	p-value	Sen's slope
Rainfall	-0.091	0.143	-6.378

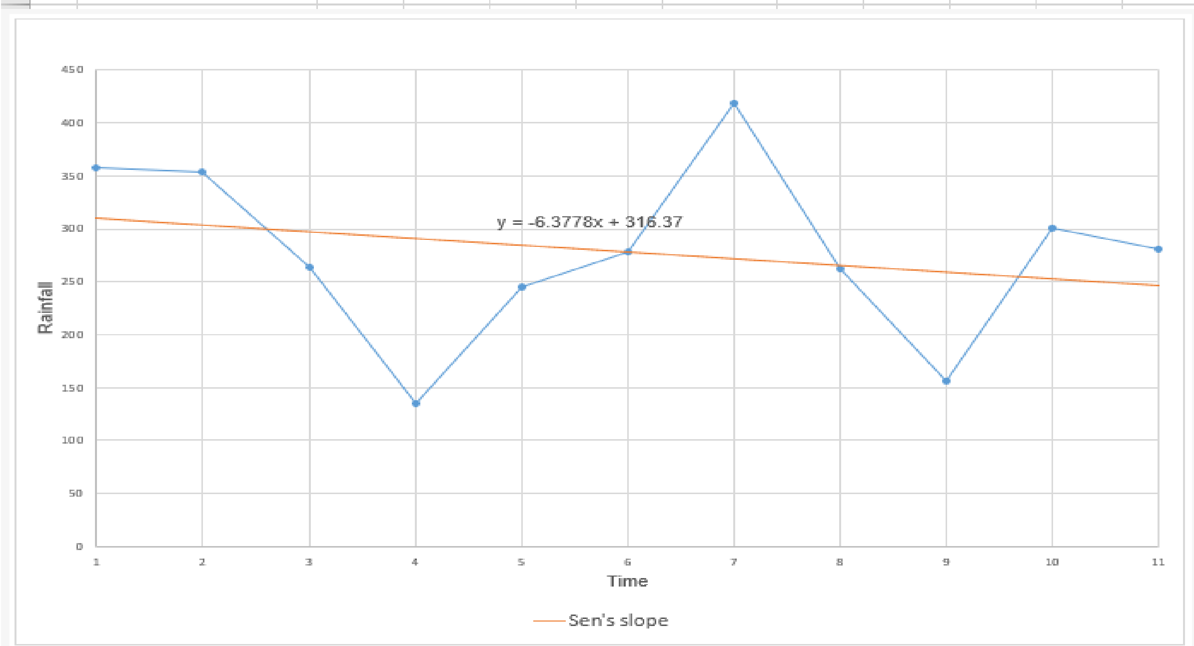


Figure 3.7: Results of the Mann-Kendall and Sen's Slope test in excel.

The same procedure has then been used to carry out the Mann-Kendall trend test for all the stations at a daily, monthly, seasonal, and annual timestep using XLSAT in excel. Modified and Mann-Kendall is done to cater for autocorrelation and seasonality.

3.6.2 Modified Mann-Kendall Test

To overcome uncertainties in trend identification that could be caused by the existence of a significant autocorrelation, the modified Mann-Kendall method as proposed by Hamed *et al.* (1998) was applied. This modified Mann-Kendall test was performed to improve on the standard Mann-Kendall test by detecting for the presence of serial correlation within the ranks of the time series upon elimination of the suspected trend. The identified trend is therefore ensured not to be due to autocorrelation. For example, in case of a serial correlation, the Mann-Kendall test may falsely detect a significant trend. This is corrected by the modified Mann-Kendall test. However, autocorrelation in rainfall data is not pronounced like in runoff data (Hamed *et al.,* 1998). In this research modified Mann-Kendall was performed after the standard Mann-Kendall for daily, monthly, annual, and seasonal trends to identify and eliminate effects of autocorrelation if any. The procedure of application used is like that of standard Mann-Kendall only that it eliminates ties in the ranks of the data. The hypothesis used and its level of significance for the test are maintained to be the same as that for the standard Mann-Kendall test.

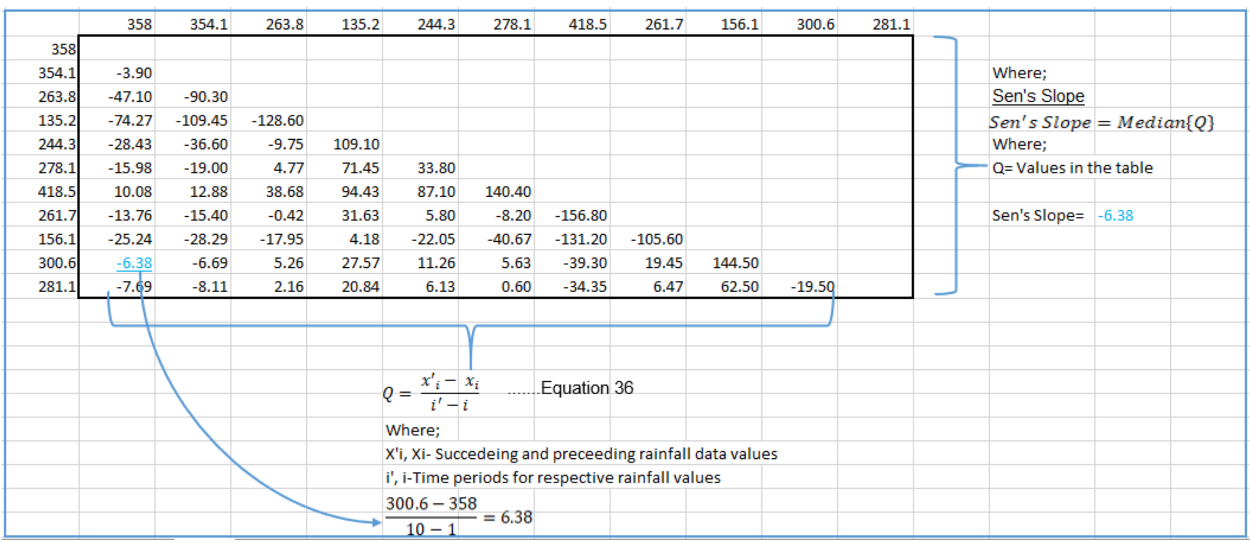
3.6.3 Seasonal Mann-Kendall Test

The seasonal Mann-Kendall test, a form of modified Mann-Kendall test was carried out to find the effects of seasonality on the trend of the time series. It was performed with and without taking care of serial dependence while assessing the changes in daily, monthly, and seasonal trends. The test is performed to find whether there is a trend from season to season or from year to year. Despite the standard Mann-Kendall test being powerful, the results can be misleading in case of the presence of seasonality. The seasonal Mann-Kendall test has often been less powerful; however, this research used it to enable it to give a more rigorous statement regarding the significance of trends realized. The procedure of application of seasonal Mann-Kendall is the same as for the standard Mann-Kendall test. The hypothesis and level of significance for hypothesis testing remain the same as that of the Standard Mann-Kendall test.

3.6.4 Sen's Slope estimator

Sen's slope estimator, a non-parametric method was applied to calculate the rate of change. It calculates change per unit time using a linear model that estimates the rate of the trend while keeping the variance of residuals minimal (Santos, 2015). Upon detecting significant trends, the next step was to find the rate of change. Using Roodbloem annual rainfall data, from Table 3, the steps for the implementation of the Sen's slope are explained.

Using the rainfall data, a table with rows and columns consisting of the elements of the time series was created as illustrated in Figure 3.8. Equation 36 was then used to calculate ranks (*Q*) which form the elements contained in the table. The Sen's slope was then calculated by finding the median of the rank values in the table. For this case, Sens' Slope was -6.38 mm/year. However, it is important to note that the trend for this set of data was insignificant and therefore the Sen's slope obtained is also insignificant. For this research, the same procedure has been applied to calculate Sen's slope but using XLSTAT in excel. Where Modified or Seasonal Mann-Kendall has been applied, the same procedure was used to arrive at Modified and Seasonal Sen's slope.



	358	354.1	263.8	135.2	244.3	278.1	418.5	261.7	156.1	300.6	281.1
358											
354.1	-3.90										
263.8	-47.10	-90.30									
135.2	-74.27	-109.45	-128.60								
244.3	-28.43	-36.60	-9.75	109.10							
278.1	-15.98	-19.00	4.77	71.45	33.80						
418.5	10.08	12.88	38.68	94.43	87.10	140.40					
261.7	-13.76	-15.40	-0.42	31.63	5.80	-8.20	-156.80				
156.1	-25.24	-28.29	-17.95	4.18	-22.05	-40.67	-131.20	-105.60			
300.6	-6.38	-6.69	5.26	27.57	11.26	5.63	-39.30	19.45	144.50		
281.1	-7.69	-8.11	2.16	20.84	6.13	0.60	-34.35	6.47	62.50	-19.50	

Figure 3.8: Sen's Slope test.

The results for the Mann-Kendall test and Sen's slope using XLSTAT software in excel were confirmed to be similar to that calculated from the basic principles using equations. This could be seen by comparing the excel results in Figure 3.7 and that of formulas in Figure 3.5 and Figure 3.8. The added advantage of using XLSTAT in excel is that it combines both Mann-Kendall and Sen's slope tests while producing summarized results which include graphs as shown in Figure 3.7.

4 Data Analysis

4.1 Introduction

This section contains the output obtained from applying the methodology as described in Chapter three. This involves obtaining data from SAWS and performing data quality analysis, homogeneity analysis and classification of rainfall data stations into regions. Rainfall characteristics are also discussed in brief. The tables and figures of data and results used in this section are presented in Part II (Appendix), as a separate document.

4.2 Data Quality Analysis

Rainfall stations having at least 100 years of daily rainfall data were identified from the South Africa Weather Services (SAWS) register, resulting in 72 stations. The stations were plotted and found to be of satisfactory distribution across South Africa. However, because of some stations having stopped operations within the period of interest, hence inconsistent data records, daily rainfall data for 70 out of the 72 stations requested were obtained (Table A1 in Appendix A). The distribution of the stations across South Africa is illustrated in Figure 4.1.

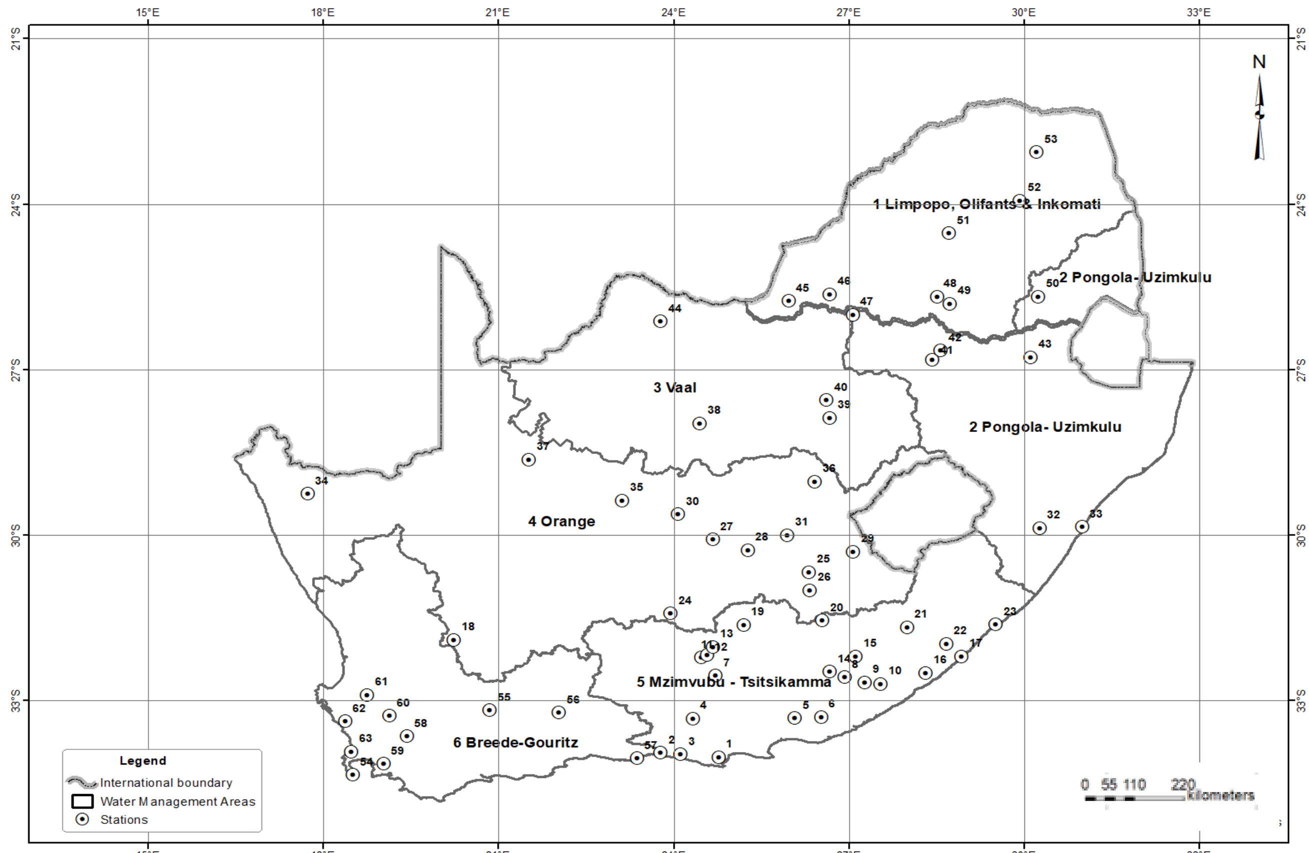


Figure 4.1: Distribution of rainfall data stations obtained from SAWS.

The data for the 70 stations obtained from SAWS were then subjected to quality analysis where data considered to be erroneous were omitted. An analysis of missing data was performed and stations meeting the threshold of having 90% of data selected for trend analysis (Du Plessis and Schloms, 2017 and Kruger and Nxumalo, 2017). A total of 62 out of 70 stations were found to have met the threshold (Table A2 in Appendix A).

The selected stations (with ≤ 10% missing values) were then subjected to the Normal Ratio (NR) method for gap filling. Nearby stations with significant correlation were identified and used as target stations in gap filling. The process was repeated until all gaps were filled.

4.3 Homogeneity Analysis Results

Homogeneity analysis was carried out to ensure that rainfall data for each station comes from the same population with a similar distribution. Artificial trends causing inhomogeneity were removed, improving the credibility, and increasing the confidence of trend analysis results to be obtained. Absolute homogeneity tests (Pettitt, SNHT, Buishand Range, and Von Neumann ratio) were applied to test the variability of the time series rainfall data.

The absolute homogeneity tests were applied to the annual rainfall time series data for the 62 stations, and results for each of the four tests assessed at a 5% significance level, and those found to be homogeneous highlighted in bold in Table B1 in Appendix B. The homogeneous stations were further categorized to be either ‘useful’, ‘doubtful’ or ‘suspect’ (Wijngaard *et al.,* 2003), as illustrated in Table 5.

Table 5: Section of summary of homogeneity results and classification as in Table B1.

No	Station Name	Pettit Test	SNHT	Buishand Range	Von Neumann	Classification
1	Humansdorp	**0.165**	**0.559**	**0.258**	**0.455**	Useful
2	Lottering-Bos	0.037	0.014	0.009	0.028	Suspect
3	Witelsbos-Bos	0.048	0.027	0.008	**0.393**	Suspect
4	Steytlerville-Mag	**0.735**	**0.310**	**0.109**	**0.097**	Useful
5	Alicedale-Mun	**0.319**	**0.010**	**0.089**	**0.230**	Useful
6	Grahamstown-Tnk	**0.978**	0.025	**0.482**	**0.083**	Useful
7	Klipfontein	**0.526**	**0.320**	**0.115**	**0.206**	Useful
8	Hogsback-Bos	0.026	0.017	0.040	0.035	Suspect
9	Amatola State Forest	**0.349**	**0.083**	**0.809**	**0.334**	Useful
10	Kei Road-Pol	0.043	**0.067**	0.019	0.010	Suspect

Humansdorp was one of the stations classified as ‘useful’ (class 1), after all four homogeneity test results indicated the station data to be homogenous as illustrated in Table 5 and Table 6. The results for the four tests (Pettitt, Buishand Range, SNHT, and Von Neumann ratio) were all significant at a 5% significance level, hence class 1 homogeneity. Figure 4.2 illustrates the distribution of annual rainfall about the mean for Humansdorp station.

Table 6: Homogeneity results for Humansdorp station.

Results Summary for Humansdorp:

	Pettitt	SNHT test	Buishand	Von Neumann
Rainfall	**0.165**	**0.559**	**0.258**	**0.455**

Test interpretation:

H_0: Data are homogeneous

H_a: There is a date at which there is a change in the data

As the computed p-value is greater than the significance level alpha=0.05, one cannot reject the null hypothesis H0.

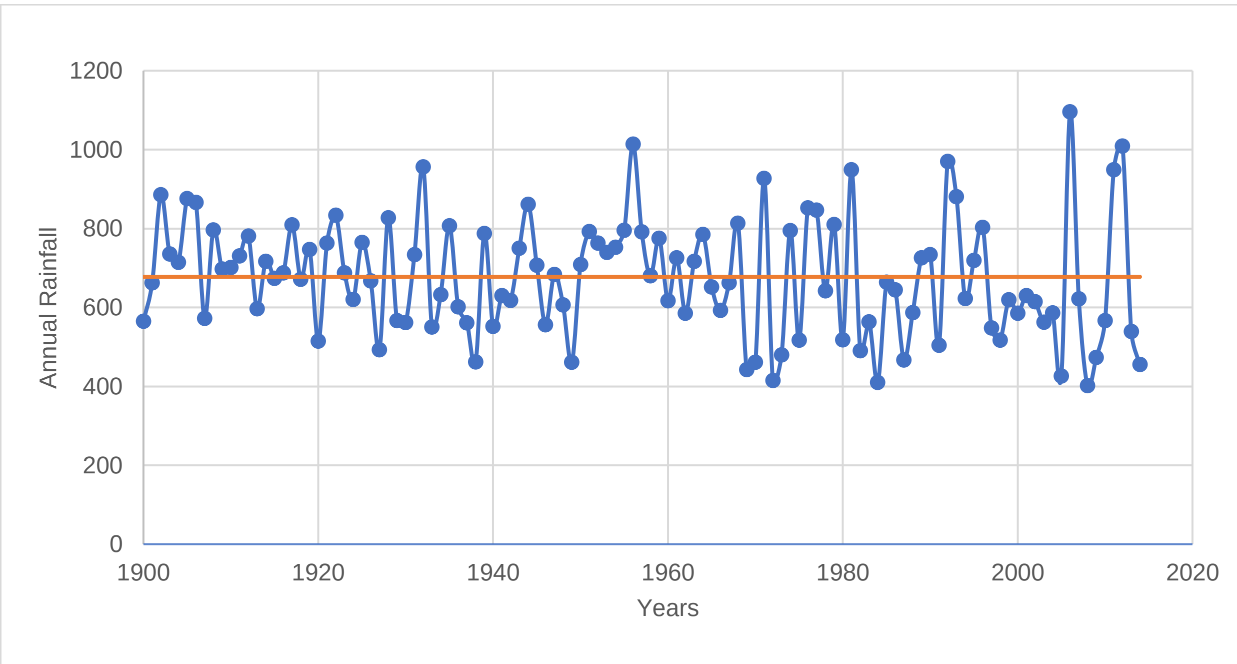


Figure 4.2: Distribution of annual rainfall for Humansdorp station.

Hopetown-TNK station was classified as ‘doubtful’ (class 2), after Pettitt and SNHT indicated the station data to be homogeneous, while the Buishand Range and Von Neumann Ratio indicated the station data to be inhomogeneous as illustrated in Table 7. To illustrate the presence of inhomogeneity, the annual rainfall was plotted as illustrated in Figure 4.3. In 1952 there was a significant change in mean from 256 mm (red line) to 329 mm (green line) hence the inhomogeneity. As discussed in chapter two, the Buishand range test is powerful in detecting breaks at the middle of the time series, and this property was highlighted by the homogeneity results for this station.

Table 7: Results of homogeneity analysis for Hopetown-TNK station.

Homogeneity Results Summary for Hopetown- TNK:

	Pettitt	SNHT test	Buishand	von Neumann
Rainfall	**0.074**	**0.098**	0.022	0.022

Test interpretation: Buishand and Von Neumann
H0: Data are homogeneous
Ha: There is a date at which there is a change in the data
As the computed p-value is lower than the significance level alpha=0.05, one should reject the null hypothesis H0, and accept the alternative hypothesis Ha.

Test interpretation: Pettit and SNHT
H0: Data are homogeneous
Ha: There is a date at which there is a change in the data
As the computed p-value is greater than the significance level alpha=0.05, one cannot reject the null hypothesis H0.

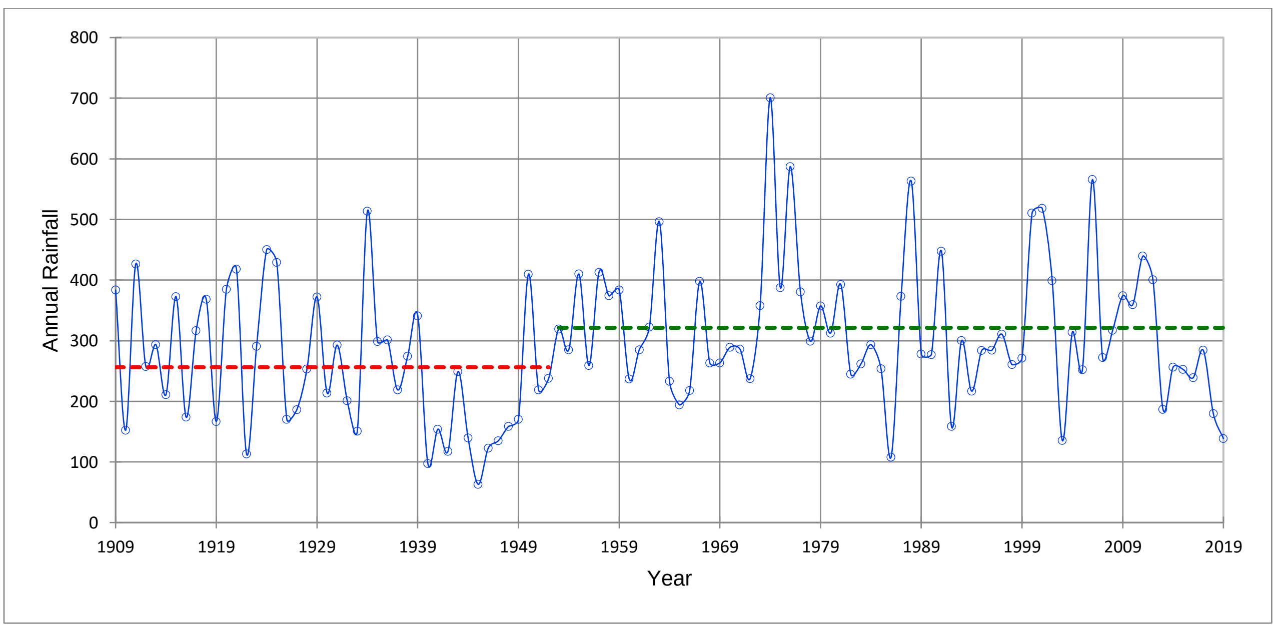


Figure 4.3: Distribution of annual rainfall for Hopetown-TNK station.

Lottering-Bos station was considered as 'suspect' after the results for all four homogeneity tests were inhomogeneous as illustrated in Table 8. The Pettit, SNHT and Buishand homogeneity results all indicated a break in the time series during the year 1936. This was further illustrated in Figure 4.4 where the mean annual rainfall changes from 1181 mm (red line) to 1029 mm (green line). All the stations falling in the 'suspect' category were considered unsuitable for further trend analysis.

Table 8: Results of Homogeneity analysis for Lottering-Bos station.

Homogeneity Results Summary for Lottering-Bos:

	Pettitt	SNHT test	Buishand	Von Neumann
Rainfall	0.037	0.014	0.009	0.028

Test interpretation:

H_0: Data are homogeneous

H_a: There is a date at which there is a change in the data

As the computed p-value is lower than the significance level alpha=0.05, one should reject the null hypothesis H_0, and accept the alternative hypothesis H_a.

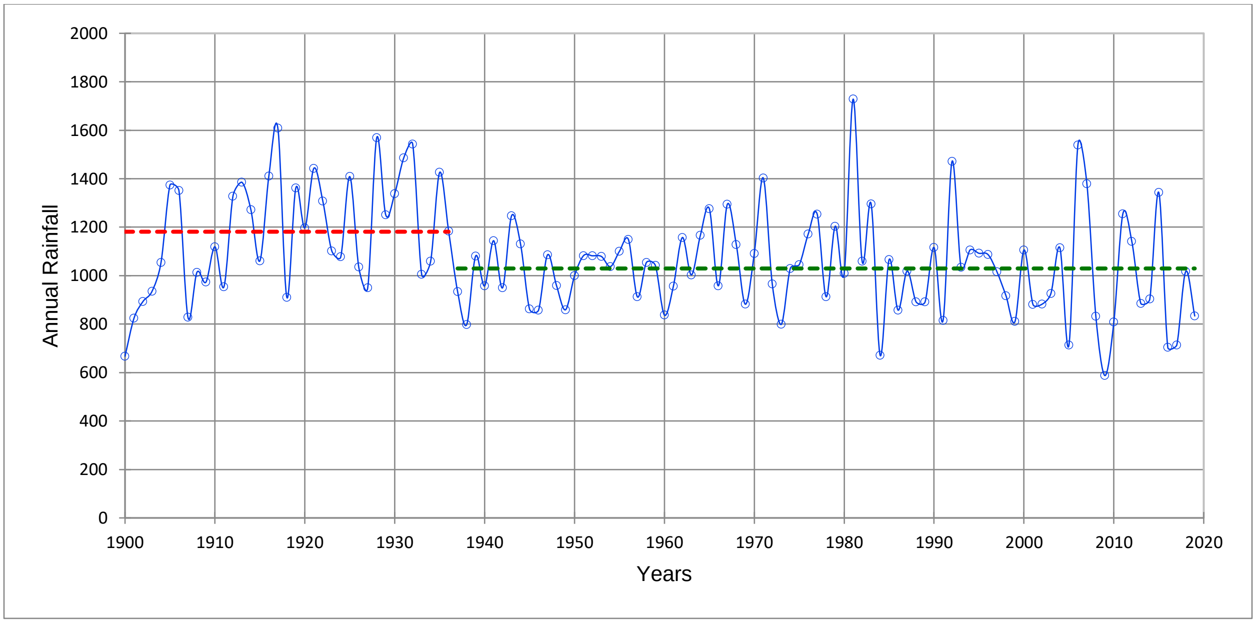


Figure 4.4: Distribution of annual Rainfall for Lottering-Bos station.

Upon classification of homogeneity results, 41 stations were categorized as ‘useful’, 5 stations ‘doubtful’, and 16 as ‘suspect’. From Wijngaard *et al.* (2003) classification, ‘useful’ and ‘doubtful’ data are considered suitable for trend and variability analysis. However, when performing trend analysis with rainfall data classified as doubtful ‘caution’ was exercised. Hence a total of 46 stations were considered homogenous and fit for trend analysis as summarized in Table 9 with their spatial distribution illustrated in Figure 4.5.

Table 9: Homogenous rainfall data stations.

No	Station Name	Pettit	SNHT	Buishand	Von	Classification	Rainfall regime
1	Humansdorp	0.165	0.559	0.258	0.455	Useful	All Year
2	Steytlerville-Mag	0.735	0.310	0.109	0.097	Useful	All Year
3	Alicedale-Mun	0.319	0.010	0.089	0.230	Useful	All Year
4	Grahamstown-Tnk	0.978	0.025	0.482	0.083	Useful	All Year
5	Klipfontein	0.526	0.320	0.115	0.206	Useful	Summer
6	Amatola State Forest	0.349	0.083	0.809	0.334	Useful	Summer
7	Winterhoek	0.531	0.070	0.374	0.181	Useful	Summer
8	Bloemhof	0.474	0.281	0.087	0.105	Useful	Summer
9	Exwell Park	0.606	0.861	0.502	0.664	Useful	Summer
10	Kentani - Bos	0.460	0.001	0.163	0.001	Doubtful	All Year
11	Cwebe Nature Reserve	0.533	0.042	0.262	0.013	Doubtful	Summer
12	Sterkstroom	0.962	0.139	0.658	0.359	Useful	Summer

No	Station Name	Pettit	SNHT	Buishand	Von	Classification	Rainfall regime
13	Engcobo Prison	0.702	0.135	0.727	0.238	Useful	Summer
14	Xhora Prison	0.901	0.365	0.472	0.168	Useful	Summer
15	Richmond C/K-Tnk	0.800	0.096	0.709	0.560	Useful	Summer
16	Ellesmere	0.338	0.229	0.120	0.985	Useful	Summer
17	Burgersdorp-Pol	0.156	0.001	0.071	0.085	Doubtful	Summer
18	Petrusville-Pol	0.424	0.347	0.269	0.787	Useful	Summer
19	Philippolis-Pol	0.398	0.016	0.276	0.294	Useful	Summer
20	Hopetown-Tnk	0.074	0.098	0.022	0.022	Doubtful	Summer
21	Lillydale	0.368	0.204	0.062	0.387	Useful	Summer
22	Richmond S.A. P	0.293	0.001	0.471	0.000	Doubtful	Summer
23	Durban Botanical Gardens	0.152	0.152	0.253	0.063	Useful	Summer
24	Steinkopf	0.170	0.080	0.912	0.070	Useful	Winter
25	Nuwejaarskraal	0.003	0.058	0.010	0.151	Doubtful	Summer
26	Maselspoort Dam	0.851	0.451	0.273	0.260	Useful	Summer
27	Boetsap-Pol	0.996	0.260	0.748	0.078	Useful	Summer
28	Odendaalsrus	0.646	0.041	0.332	0.172	Useful	Summer
29	Bothaville-Mun	0.219	0.334	0.231	0.325	Useful	Summer
30	Beerlaagte	0.619	0.785	0.447	0.525	Useful	Summer
31	Balfour	0.606	0.260	0.627	0.250	Useful	Summer
32	De Emigratie	0.524	0.322	0.634	0.441	Useful	Summer
33	Morokweng	0.404	0.114	0.311	0.040	Useful	Summer
34	Ottoshoop-Pol	0.455	0.151	0.239	0.026	Useful	Summer
35	Swartruggens-Pol	0.047	0.133	0.043	0.052	Doubtful	Summer
36	Premier Mine-Cullinan	0.179	0.295	0.151	0.496	Useful	Summer
37	Bronkhorstspruit-Mun	0.149	0.777	0.829	0.720	Useful	Summer
38	Machadodorp	0.661	0.589	0.775	0.036	Useful	Summer
39	Naboomspruit-Pol	0.463	0.099	0.565	0.131	Useful	Summer
40	Haenertsburg	0.365	0.330	0.165	0.218	Useful	Summer
41	Prince Albert-Tnk	0.573	0.508	0.250	0.182	Useful	All Year
42	Plettenbergbaai-Pol	0.219	0.273	0.085	0.174	Useful	All Year
43	Tulbagh	0.406	0.287	0.200	0.009	Useful	Winter
44	Darling-The Towers	0.162	0.227	0.108	0.007	Useful	Winter
45	Thornlea	0.938	0.500	0.433	0.031	Useful	Summer
46	Klein Australie	0.057	0.371	0.136	0.040	Useful	Summer

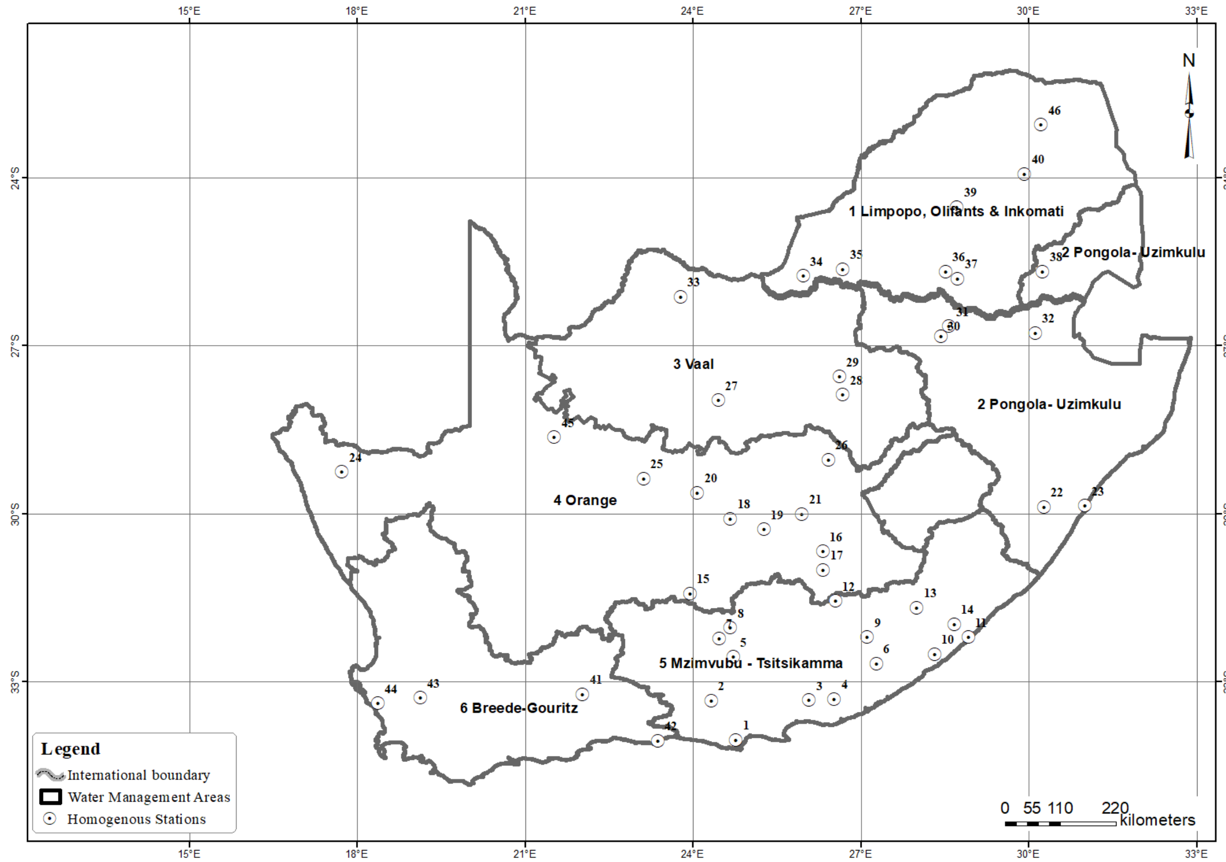


Figure 4.5: Distribution of homogenous stations in South Africa.

4.4 Rainfall Regions

The climate of South Africa is characterized by four seasons i.e., Spring, Summer, Autumn and Winter. The Western Cape region experiences Winter rainfall as a result of the effects of the cold Benguela and northward displacement of high-pressure systems; while the warm moist Indian ocean currents produce an 'All-year' rainfall along the South Coast and inland plateau which mainly experiences wet summer with thundershowers (Du Plessis & Schloms, 2017). Based on the above rainfall distribution, the rainfall stations were categorized into their respective Summer, Winter and 'All year' rainfall regions as indicated in Table 9. These regions were then further subdivided into 8 climatic zones based on SAWS classification of South Africa climate as summarized in Table B 2 in Appendix B and illustrated in Figure 4.6.

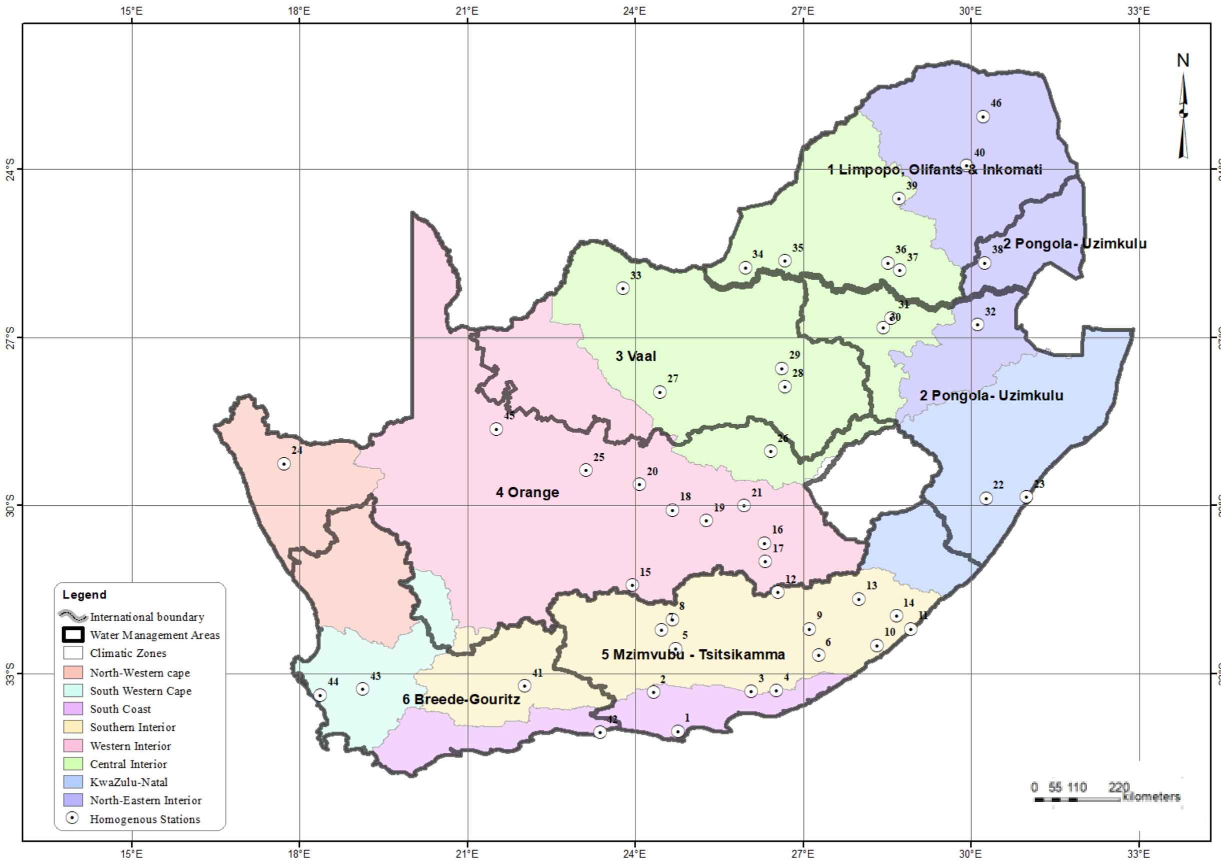


Figure 4.6: Climatic zones of South Africa (SAWS, 1972).

The classification of climatic zones was such that; the North-Western Cape and South Western Cape have a Winter maximum rainfall in June of 30 mm and 70 mm, respectively. The South Coast experiences an ‘All year’ rainfall of 30-40 mm. The Southern Interior, Western Interior, Central Interior, KwaZulu-Natal, and the North-Eastern Interior regions all experience a Summer maximum rainfall. The Southern and Western Interior regions experience a March maximum rainfall of about 60 mm. The KwaZulu-Natal, Central Interior and North-Eastern Interior regions experience a January maximum rainfall of about 80-130 mm.

4.5 Rainfall Characteristics

The rainfall characteristics: mean, coefficient of skewness, coefficient of kurtosis, coefficient of variation, minimum and maximum rainfall were determined. The analysis of these parameters was done for the long term (120 years) and the short term (40-year) periods. Further, the analysis was done at annual, monthly, and seasonal timesteps. These characteristics gave an insight on the expected trends.

The mean rainfall for the different timesteps (Monthly (Table C2 in Appendix C), annual (Table 12), and seasonal (Table C3 in Appendix C)) was determined for the past century as illustrated in Table 10 for the respective seasons. The maximum and minimum annual rainfall were also determined (Table 12) to find the range and change in amount of rainfall received at different stations over the years in the different regions of South Africa.

Table 10: Extract of Table C3 in Appendix C showing the mean seasonal rainfall.

No	Station Name	Lat (Deg)	Long (Deg)	Elevation (m)	Summer	Autumn	Winter	Spring
1	Humansdorp	-34.03	24.77	152	139	171	172	196
2	Steytlerville-Mag	-33.33	24.33	419	76	76	31	61
3	Alicedale-Mun	-33.32	26.08	276	115	122	70	126
4	Grahamstown-Tnk	-33.3	26.53	539	197	112	176	192
5	Klipfontein	-32.55	24.72	673	88	78	31	65
6	Amatola State Forest	-32.67	27.28	884	364	239	123	304
7	Winterhoek	-32.22	24.47	876	119	104	54	95
8	Bloemhof	-32.03	24.67	1,091	117	98	39	70
9	Exwell Park	-32.2	27.12	914	188	115	28	102
10	Kentani-Bos	-32.5	28.32	488	342	239	101	307

Variation analysis was performed to illustrate the measure of dispersion of annual rainfall about its mean for the different regions of South Africa and summarized in Table 12. Table 11 shows an extract of annual variation results C_V%. Variation ranging from 20%-30% was considered high, 30%-40% very high and >40% extremely high (Gomes, 1985).

Table 11: Extract of Table 12 showing characteristics of annual rainfall.

No	Station Name	period	Years	R_{min}	R_{max}	R_m	C_v (%)	C_s	C_k
1	Humansdorp	1900-2014	115	402	1096	678	21.69	0.33	-0.25
2	Steytlerville-Mag	1900-2019	120	90	561	244	37.40	0.91	1.15
3	Alicedale-Mun	1900-2008	109	89	840	433	30.05	0.36	0.08
4	Grahamstown-Tnk	1900-2019	120	268	1188	677	26.24	0.40	0.18
5	Klipfontein	1900-2019	120	87	593	262	34.51	0.76	0.66
6	Amatola State Forest	1900-2019	120	552	1791	1030	22.66	0.50	0.52
7	Winterhoek	1900-2019	120	153	655	372	31.61	0.35	-0.51
8	Bloemhof	1900-2019	120	127	661	324	31.90	0.67	0.65
9	Exwell Park	1900-2019	120	206	798	433	25.52	0.38	0.45
10	Kentani-Bos	1900-2019	120	440	1855	990	24.71	0.46	1.05

Skewness analysis was done to illustrate the symmetry of distribution about the mean. Table 11 shows an extract of the skewness results (C_S). The coefficient of skewness values greater than zero indicate the respective station data to be positively skewed with a long right tail, while coefficient of skewness less than zero indicates the data to be negatively skewed with a long-left tail.

Kurtosis analysis was performed to illustrate the groupings of rainfall data around a central place. Kurtosis describes the peak of rainfall data to be either leptokurtic with a $C_K \geq 3$, platykurtic, ≤ 3 or a normal curve, 3. A normal curve is bell shaped, while leptokurtic has a sharp peak and platykurtic has an almost flat peak. Kurtosis analysis was instructive in the selection of non-parametric methods for trend analysis in this research as it can be seen in an extract of the results illustrated in Table11 that none of the stations had a normal distribution. Trend analysis was performed after characterization of rainfall. The results of rainfall characteristics and trends are discussed in the next chapter.

5 Results and Discussion

This section contains the results and discussions obtained from applying data analysis in Chapter 4. These include rainfall characteristics, trend and sub-trend (long-term and short-term) analysis results and discussions for the respective time periods. In conclusion, a summary of trend analysis results is done. The outline of the presentation of results in this chapter is as presented in Figure 5.1. The tables and figures of results are presented in Part II (Appendix), as a separate document.

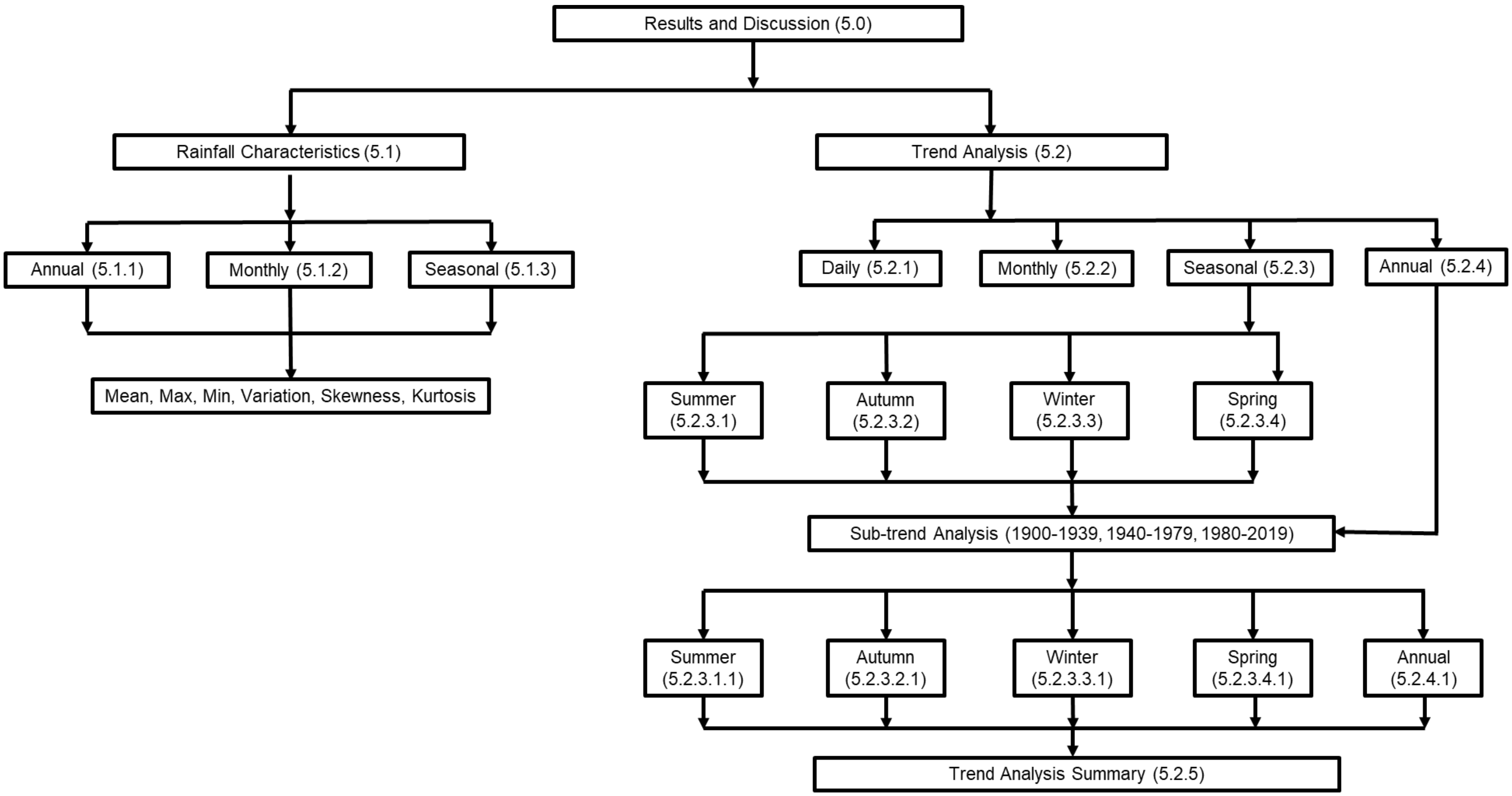


Figure 5.1: General outline of the presentation and discussion of results.

5.1 Rainfall Characteristics

5.1.1 Annual Rainfall Characteristics

The annual South African rainfall was observed to vary significantly from west to east as illustrated in Figure 5.2. The central part of the country experienced an average of 450 mm/year while the Eastern region of the country was slightly wetter, experiencing an average of at least 600 mm/year. The Western part of the country was dry having an average of less than 250 mm/year. The Drakensberg Mountain region was observed to have an average rainfall ranging from 750-1350 mm. The average annual rainfall for South Africa was calculated to be approximately 560 mm with 43.5% of stations having a mean greater than that of the country.

The maximum annual rainfall (R_{max}) during the study period was 3248 mm in the North-Eastern Interior region during the year 2000. The minimum annual rainfall (R_{min}) recorded was 19 mm in 1922 in the Western Interior zone. The distribution of the long-term maximum and minimum annual rainfall is illustrated in Figure 5.3. The maximum annual rainfall ranged from 310 mm to 3247 mm while the minimum annual rainfall ranged from 19 mm to 588 mm. From Figure 5.3, the South Coast was wet while the Western Interior was extremely dry.

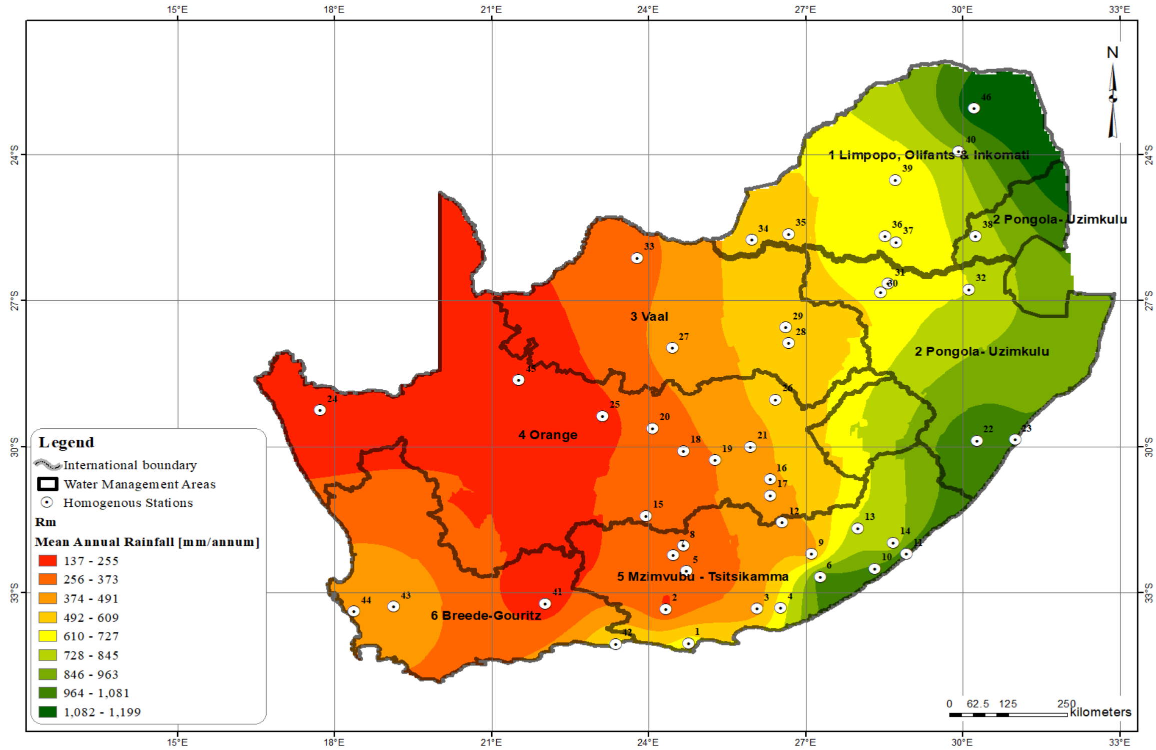


Figure 5.2: Long term mean annual rainfall (1900-2019).

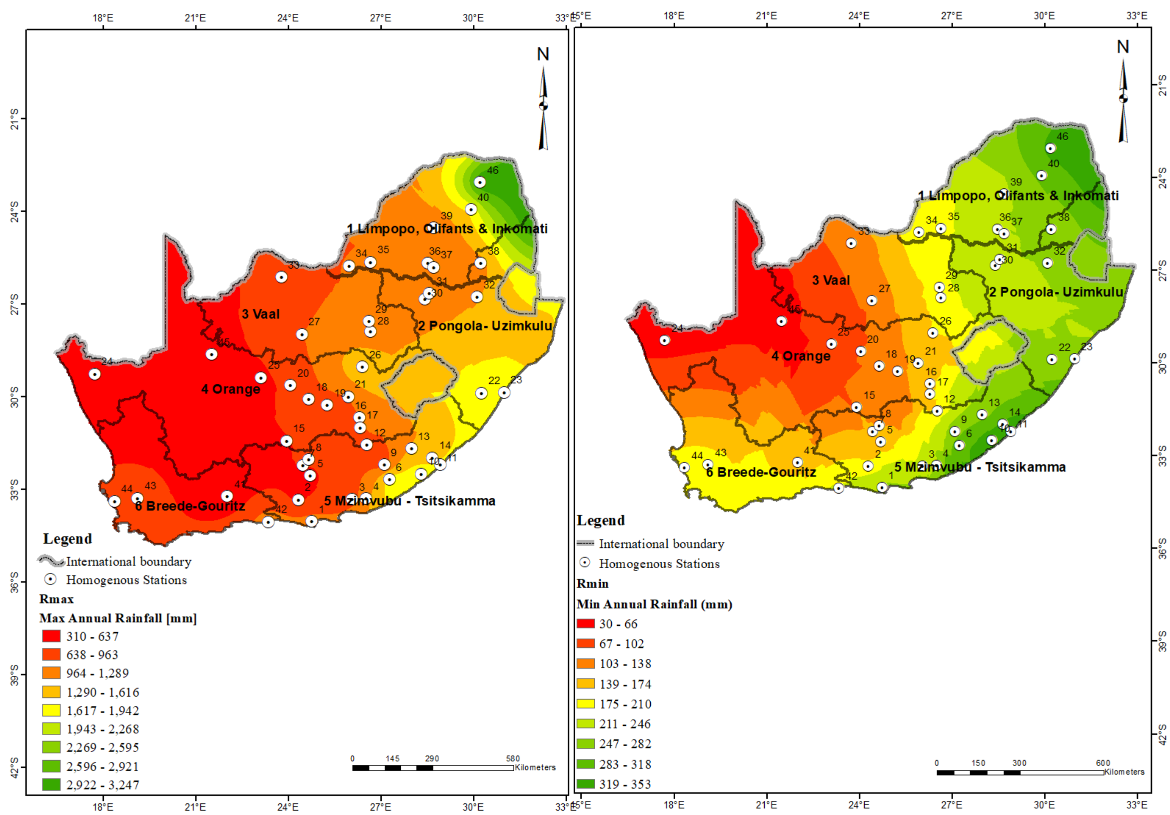


Figure 5.3: Maximum and Minimum annual rainfall distribution (1900-2019).

The analysis of coefficient of variation was undertaken to quantify and validate the spatial variability of annual rainfall. It shows the measure of the dispersion of rainfall data about its mean. The variation ranged from a maximum of 50.3% to a minimum of 21.7%, decreasing from south to north with the highest in the dry Western Interior region of South Africa, as was also observed by Nel (2009). The average long-term variation for the entire country was calculated to be 31.0%. A total of 23 homogeneous stations (50%) had a high variation (20% ≤ C_V ≤ 30%), while 20 stations (43.5%) had very high variation (30% ≤ C_V ≤ 40%), and 3 stations (6.5%) had extremely high variations (C_V ≥ 40%). The three stations with extremely high variation are in the dry Western Interior region experiencing low rainfall. The scarcity and low frequency of rainfall in the region and especially the western part of South Africa could be the reason behind extremely high variability. Generally, South Africa is a semi-arid country, and this explains why almost 50% of homogenous stations have a high variability of annual rainfall. The distribution of variation of annual rainfall across South Africa is illustrated in Figure 5.4.

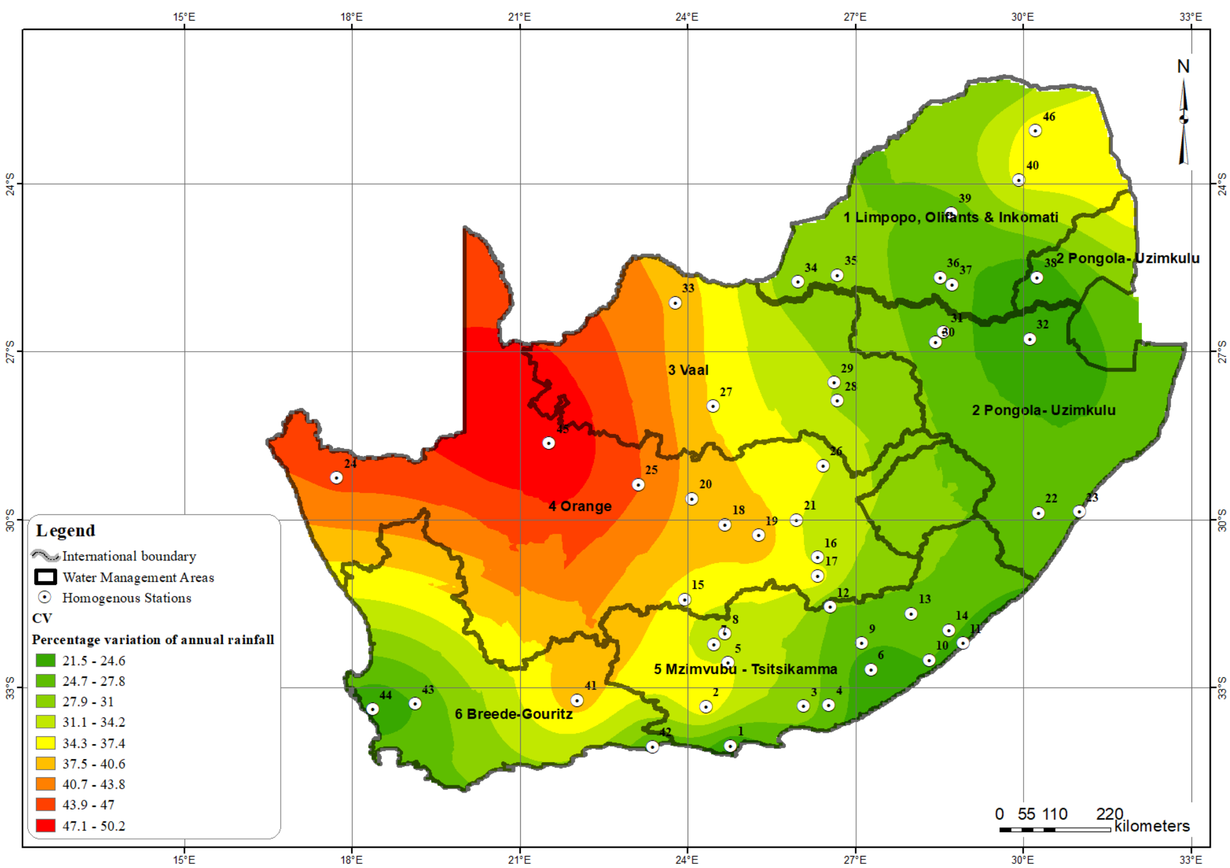


Figure 5.4: Distribution of percentage variation of annual rainfall (1900-2019).

Skewness is the third moment towards the mean, representing symmetry of the distribution of data about the mean. Analysis of skewness for annual rainfall indicated the coefficient of skewness was in the range of -0.66 to 2.47. The mean annual skewness for the entire country was 0.53. Three stations (0.1%) had a distribution of annual rainfall data to be negatively skewed, with a long-left tail while the rest (99.9%) had a positively skewed distribution with a long right tail. Generally, the skewness values were low for the entire country.

Kurtosis is a parameter that considers the fourth moment of data about the mean. It represents the congestions or groupings of data at a central place. It can also be defined as the measure of 'peakedness'. Kurtosis analysis indicated that 44 of the stations (95.7%) had a platykurtic distribution, with data distribution having an almost flat peak. Two of the stations (4.3%) had a leptokurtic distribution with data distribution having a sharp peak.

Kurtosis and skewness results played a significant role in the decision to use non-parametric over parametric methods for trend analysis, as the comparative advantage of the non-parametric approach not requiring the normality of data distribution. The 95.7% of stations with platykurtic distribution, and 99.9% of the stations having positively skewed data justify the use of a non-parametric approach for trend analysis. Table 12 gives a summary of the annual rainfall characteristics discussed. The abbreviations R_{min}, R_{max}, R_m, C_v, C_s, and C_k represent minimum, maximum, mean, coefficient of variation, coefficient of skewness, and coefficient of kurtosis respectively, for annual rainfall.

Table 12: Summary of annual rainfall characteristics for South Africa (1900-2019).

No	Station Name	period	Years	R_{min}	R_{max}	R_m	C_v (%)	C_s	C_k
1	Humansdorp	1900-2014	115	402	1096	678	21.69	0.33	-0.25
2	Steytlerville-Mag	1900-2019	120	90	561	244	37.40	0.91	1.15
3	Alicedale-Mun	1900-2008	109	89	840	433	30.05	0.36	0.08
4	Grahamstown-Tnk	1900-2019	120	268	1188	677	26.24	0.40	0.18
5	Klipfontein	1900-2019	120	87	593	262	34.51	0.76	0.66
6	Amatola State Forest	1900-2019	120	552	1791	1030	22.66	0.50	0.52
7	Winterhoek	1900-2019	120	153	655	372	31.61	0.35	-0.51
8	Bloemhof	1900-2019	120	127	661	324	31.90	0.67	0.65
9	Exwell Park	1900-2019	120	206	798	433	25.52	0.38	0.45
10	Kentani-Bos	1900-2019	120	440	1855	990	24.71	0.46	1.05
11	Cwebe Nature Reserve	1900-2019	120	589	1723	1094	21.85	0.36	-0.10

12	Sterkstroom	1900-2019	120	195	917	467	27.93	0.65	0.84
No	**Station Name**	**period**	**Years**	**R_{min}**	**R_{max}**	**R_m**	**C_V (%)**	**C_s**	**C_k**
13	Engcobo Prison	1900-2019	120	96	1325	781	26.43	0.08	0.67
14	Xhora Prison	1900-2019	120	258	1425	727	26.80	0.70	1.39
15	Richmond C/K-Tnk	1900-2019	120	114	620	320	36.28	0.57	0.04
16	Ellesmere	1900-2013	114	189	963	477	32.67	0.80	0.66
17	Burgersdorp-Pol	1900-2019	120	92	939	433	36.45	0.63	0.74
18	Petrusville-Pol	1900-2019	120	142	887	348	38.28	1.07	1.73
19	Philippolis-Pol	1905-2017	113	90	828	372	39.69	0.56	0.31
20	Hopetown-Tnk	1909-2019	111	63	701	295	39.38	0.65	0.70
21	Lillydale	1906-2010	104	140	966	424	34.47	1.05	2.02
22	Richmond S. A. P	1916-2016	101	218	1860	1088	25.70	0.43	1.30
23	Durban Botanical Gardens	1900-2019	120	218	1667	968	27.25	-0.66	1.89
24	Steinkopf	1900-2019	120	7	313	139	44.87	0.29	-0.40
25	Nuwejaarskraal	1901-2019	119	61	591	228	44.05	0.85	0.93
26	Maselspoort Dam	1905-2019	115	255	1684	550	34.45	2.47	11.23
27	Boetsap-Pol	1900-2019	120	87	955	433	37.00	0.54	-0.06
28	Odendaalsrus	1906-2019	114	146	920	497	30.52	0.14	-0.04
29	Bothaville-Mun	1905-2019	115	200	1100	563	31.12	0.59	0.36
30	Beerlaagte	1904-2012	109	256	1097	629	26.60	0.62	0.47
31	Balfour	1904-2010	107	301	1155	689	26.29	0.47	-0.21
32	De Emigratie	1907-2012	105	335	1268	724	21.97	0.64	1.22
33	Morokweng	1911-2010	100	93	701	317	39.92	0.65	0.36
34	Ottoshoop-Pol	1904-2012	109	232	997	551	28.63	0.46	-0.13
35	Swartruggens-Pol	1906-2019	113	191	1010	591	29.75	0.25	-0.34
36	Premier Mine-Cullinan	1904-2008	105	269	1168	693	25.63	0.22	-0.19
37	Bronkhorstspruit-Mun	1907-2010	113	256	1106	661	25.71	0.26	-0.06
38	Machadodorp	1904-2019	116	72	1165	779	21.96	-0.59	1.76
39	Naboomspruit-Pol	1904-2019	116	149	1026	610	26.36	-0.04	0.36
40	Haenertsburg	1904-2019	116	277	1722	851	35.24	0.61	0.25
41	Prince Albert-Tnk	1900-2019	120	43	353	171	39.48	0.53	0.04
42	Plettenbergbaai-Pol	1900-2011	112	358	1188	655	24.78	0.63	0.47
43	Tulbagh	1900-2019	120	265	817	491	24.83	0.33	-0.50
44	Darling-The Towers	1900-2013	114	309	746	486	22.15	0.37	-0.59
45	Thornlea	1900-2019	120	19	568	192	50.26	0.94	1.75
46	Klein Australie	1904-2019	116	487	3248	1188	36.06	1.11	3.66

The results of annual rainfall characteristics (Table C1 in Appendix C) for the periods 1900-1939, 1940-1979 and 1980-2019 gave an insight into the need for further sub-trend analysis. Analysing the distribution of the mean annual rainfall during the three respective periods for each station, the following deductions were made. A third of the stations had their mean annual rainfall steadily increasing over the three periods. A fifth of the stations had their mean annual rainfall consistently dropping. Half of the stations had either an increasing then decreasing or decreasing then increasing (fluctuating) mean annual rainfall during the three periods as summarized in Table 13 and illustrated in Figure 5.5.

Table 13: Summary of mean annual rainfall during the three short-term periods.

Mean annual rainfall over the three respective periods	Number of stations	Percentage (%)
Increasing steadily	16	34.8%
Fluctuating	23	50.0%
Decreasing steadily	7	15.2%
Total	46	100%

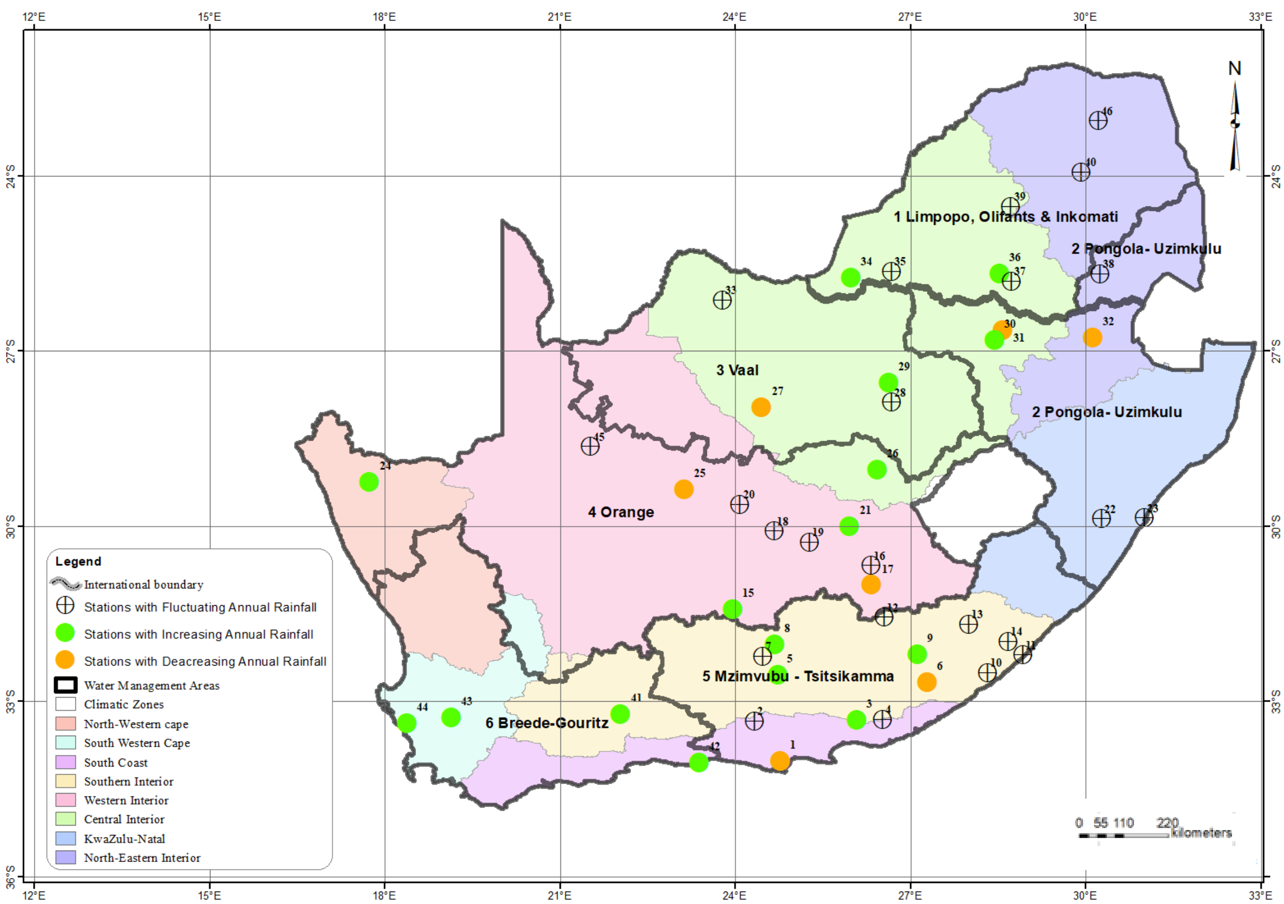


Figure 5.5: Distribution of rainfall stations characterized by mean annual rainfall.

The mean annual rainfall of the entire country for the three periods was 559 mm, 556 mm, and 562 mm, respectively. The mean annual rainfall for the period 1940-1979 was below the long-term annual mean of 559 mm. Across the three respective periods, the percentage of stations with a mean annual rainfall greater than the long-term mean (559 mm) gradually increased from 41.3%, 45.7% to 47.8% respectively. The minimum mean annual rainfall recorded over the three periods increased gradually from 131 mm, 141 mm to 147 mm while the maximum mean annual rainfall decreased from 1286 mm, 1150 mm to 1158 mm. These characteristics are indicative of possible interesting sub-trends.

It was further observed that during the period 1940-1979, there was an increase in the amount of annual rainfall received in stations along the South Coast zone of the 'All-year' rainfall region (Figure 5.6). The proportion of regions receiving minimum mean annual rainfall (in red) also gradually decreased during the period 1940-1979 compared to 1900-1939, as illustrated in Figure 5.6. The distribution of mean annual rainfall during the periods 1900-1939 and 1980-2019 periods was almost similar. However, during the period 1980-2019, there was a slight increase in areas receiving high mean annual rainfall (in green) especially along the South Coast and the North-Eastern Interior zones, and a reduction in areas with low annual rainfall along the South Western Cape as projected by Schulze *et al.* (2009). The minimum mean annual rainfall also increased during the second period and was steady through to the third period. The rate of change and its significance during these periods formed the basis of sub-trend analysis still to be discussed. Other characteristics such as the maximum annual rainfall, skewness, and variation did not vary greatly from the long-term annual rainfall characteristics. The annual rainfall characteristics over the periods were summarized (Table C1 in Appendix C) and their distribution illustrated in Figure 5.6.

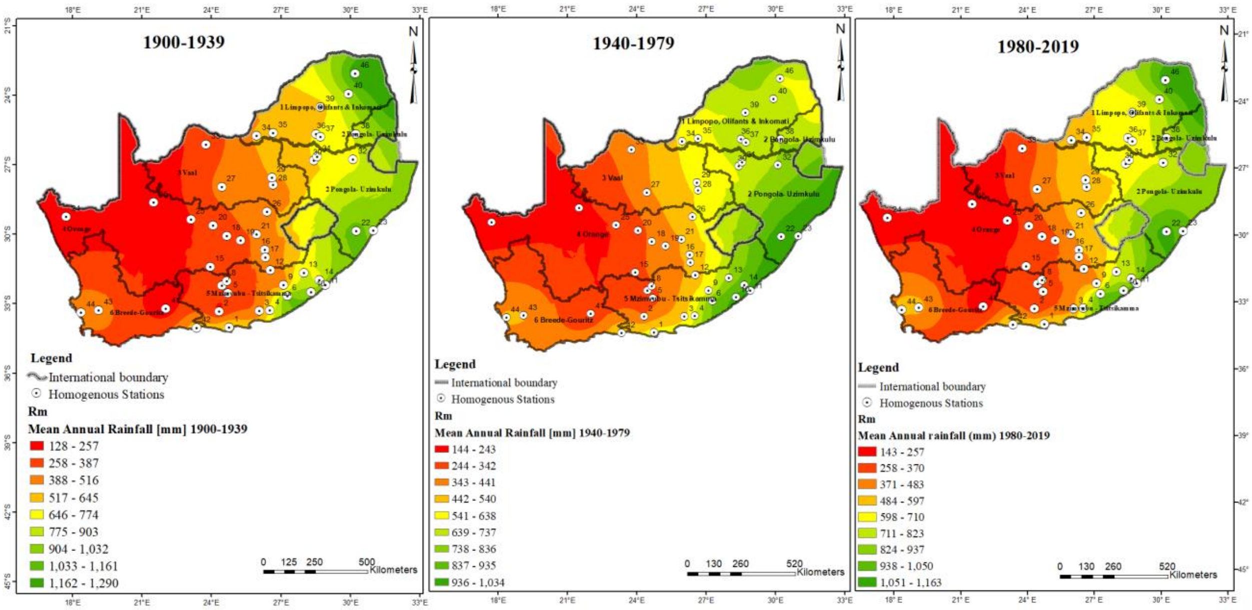


Figure 5.6: Distribution of mean annual rainfall for the three respective short-term periods.

5.1.2 Monthly Rainfall Characteristics

Monthly rainfall in South Africa varies significantly in time and space and influences the different seasons experienced. It exhibits variability with most of the rainfall occurring during November, December, and January, in the Summer rainfall regions. The South Western part of the country (Winter rainfall region) is an exception with most of its rainfall occurring during June, July, and August.

The monthly rainfall (Table C2 in Appendix C) was derived from the daily rainfall. The average monthly characteristics for each station was computed. Table C2 in Appendix C further gives the summary statistics for each month for all the stations. Plotting the distribution of monthly rainfall for all the stations separately, it was observed that the stations had different monthly distributions. The monthly rainfall distribution was categorized into three rainfall regions and summarized in Table 9. The first group had a distribution with peak rainfall during November, December, and January in the KZN, Southern, Central, Western and North-Eastern interior zones of the Summer rainfall region. The second group had a peak rainfall distribution during June, July, and August for stations in the North-Western Cape and South Western of the Winter rainfall region. The third group experienced rainfall throughout the year in the South Coast of the 'All-year' rainfall region. The rainfall statistics for the three regions are summarized in Table 14.

Table 14: Summary statistics for the Summer, Winter and 'All Year' rainfall regions.

Region	Summary Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Summer rainfall region	Mean	89	82	78	44	22	12	12	15	26	51	71	79
	Max	249	221	164	104	53	38	47	49	92	112	138	180
	Min	14	18	25	18	11	4	3	3	3	10	15	12
	CV (%)	54.3	44.2	38.4	37.8	46.7	67.7	83.2	79.0	80.2	58.2	54.1	54.2
Winter rainfall region	Mean	9	9	14	29	50	65	59	55	34	23	16	10
	Max	12	12	18	39	67	86	79	74	48	34	22	14
	Min	4	5	8	12	18	24	22	20	10	7	5	5
	CV (%)	41.7	33.2	32.5	41.5	45.1	44.2	44.2	45.1	50.8	49.9	48.3	37.5
'All Year' rainfall region	Mean	44	43	48	41	41	35	40	49	51	52	49	45
	Max	75	51	56	59	63	52	58	77	78	72	61	71
	Min	23	29	37	24	15	9	10	12	16	21	24	24
	CV (%)	39.5	17.2	14.8	30.7	43.3	49.0	48.3	52.9	43.7	35.0	27.1	34.2

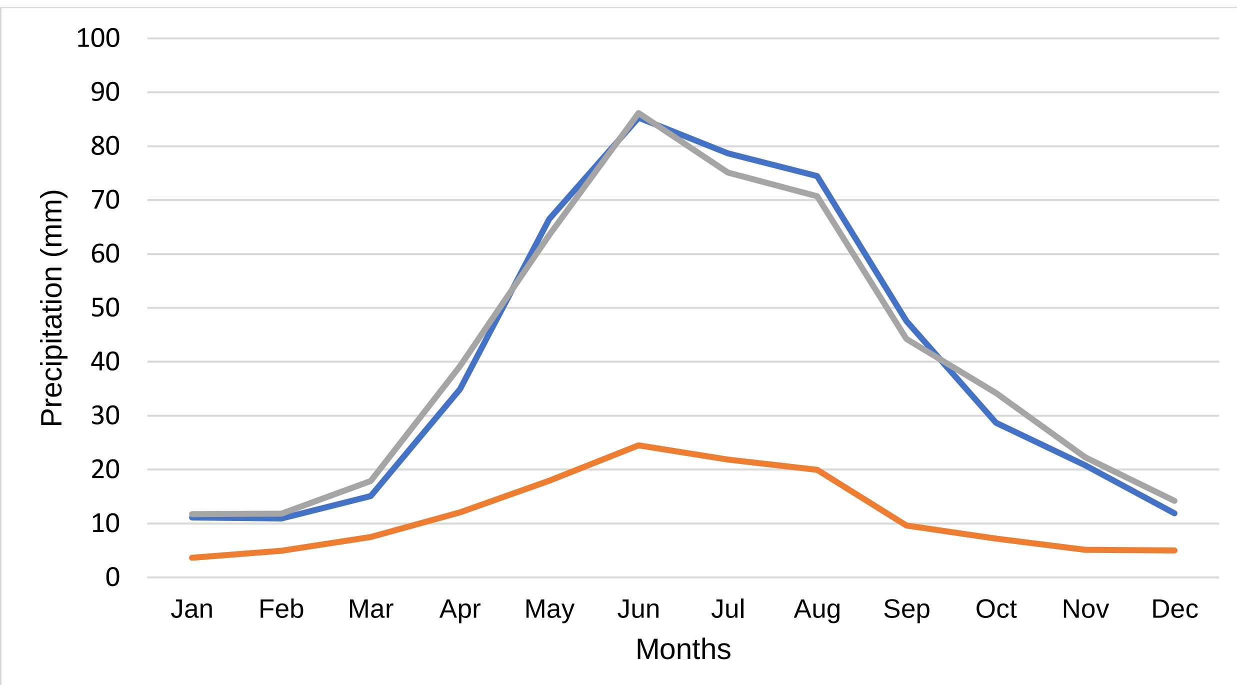


Figure 5.7: Monthly rainfall distribution for stations in the Winter rainfall region.

Stations in the Winter rainfall region (Figure 5.7) received less than 25 mm/month in December, January and February. The onset of rains was in April with May receiving double that of the previous months, with an average of 50 mm/month. Rainfall peaks between June and August with an average ranging from 65 mm in June to 55 mm in August. The rainfall starts to taper off again in September. December marks the beginning of dry season with an average of 10 mm/month, while January and February receive ≤ 15 mm/month. These observed characteristics complement the findings of the characterization of South-Western Cape rainfall by Ndebele *et al.* (2020).

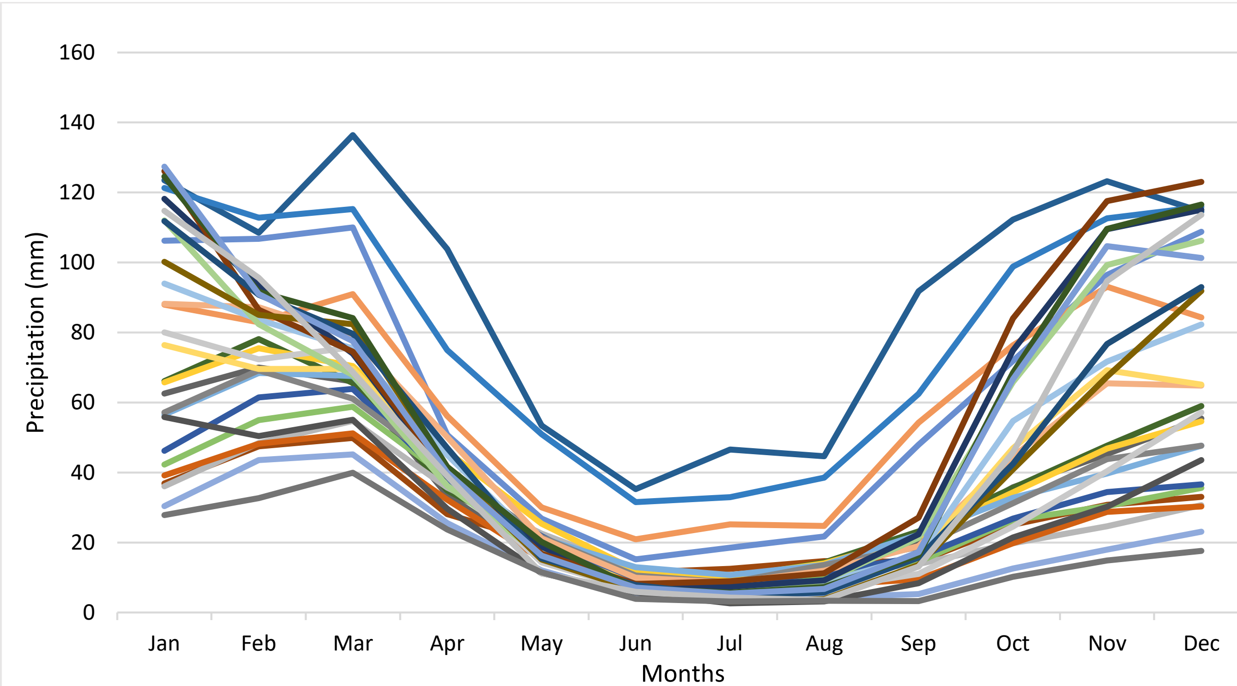


Figure 5.8: Monthly rainfall distribution for stations in the Summer rainfall region.

In the Summer rainfall region (Figure 5.8), the months of June, July and August receive less than 18 mm/month. The onset of rains is in September and by October rainfall doubles to an average of 51 mm/month. Rainfall peaks between December (79 mm) and January (89 mm). Rainfall starts decreasing in February. June is the driest month, with a mean of 12 mm/month contributing to approximately 2.6% of the annual total.

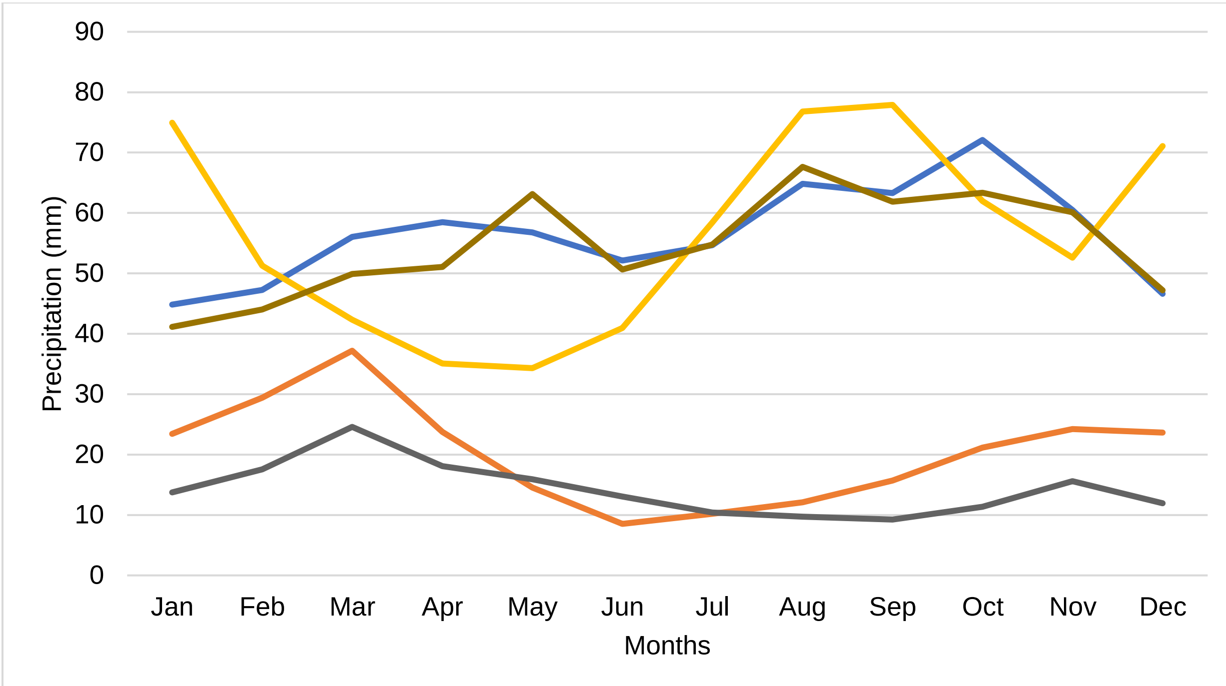


Figure 5.9: Monthly rainfall distribution for stations in the 'All year' rainfall region.

The monthly rainfall for the 'All year' rainfall region stations slightly varied across the year as illustrated in Figure 5.9 and summarized in Table 14. The monthly rainfall variation is highest in the Summer rainfall region followed by Winter rainfall region and least in the 'All Year' rainfall region as can be seen in Table 14.

5.1.3 Seasonal Rainfall Characteristics

South Africa is characterized by four main seasons: Winter (June-July-August), Spring (September-October-November), Summer (December-January-February), and Autumn (March-April-May). Seasonal rainfall exhibits variability according to the different rainfall regions.

The seasonal rainfall (Table C3 in Appendix C) was calculated by using monthly rainfall that form the respective seasons. Having identified the rainfall regions of South Africa, the seasonal rainfall characteristics are discussed for the respective regions i.e., Summer, Winter and 'All-year' rainfall regions. A summary of seasonal rainfall contribution during the period 1900-1939, 1940-1979 and 1980-2019 is given in Table 15.

Table 15: Contribution (%) of seasonal to annual total rainfall for the respective regions.

Summer Rainfall Region					
	Summer (%)	Autumn (%)	Winter (%)	Spring (%)	Total (%)
1900-1939	41.30	24.73	8.16	25.81	100
1940-1979	40.70	26.62	8.13	24.59	100
1980-2019	42.30	22.48	8.35	26.92	100
1900-2019	41.40	24.62	8.21	25.77	100
Winter Rainfall Region					
	Summer (%)	Autumn (%)	Winter (%)	Spring (%)	Total (%)
1900-1939	14.04	24.73	37.30	23.89	100
1940-1979	13.61	26.37	37.40	22.62	100
1980-2019	13.47	25.29	37.80	23.39	100
1900-2019	13.70	25.48	37.53	23.39	100
'All Year' Rainfall Region					
	Summer (%)	Autumn (%)	Winter (%)	Spring (%)	Total (%)
1900-1939	26.03	23.34	20.94	29.68	100
1940-1979	25.60	25.16	22.49	26.75	100
1980-2019	26.13	22.38	22.81	28.68	100
1900-2019	25.92	23.62	22.08	28.38	100

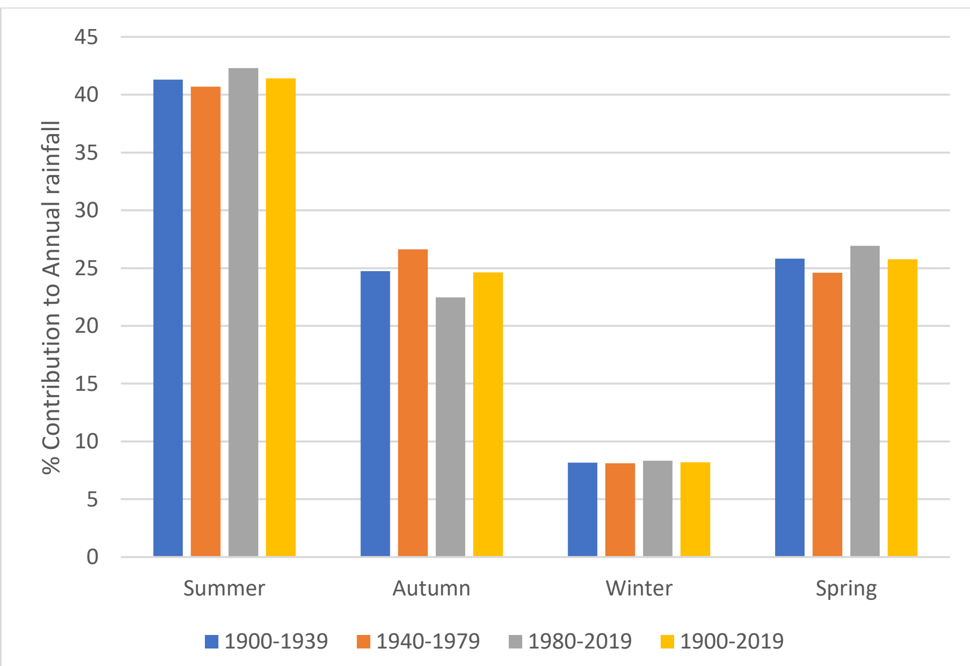


Figure 5.10: Change in contribution of seasonal to annual rainfall (Summer rainfall region).

For the Summer rainfall region, the mean Summer seasonal rainfall was 238 mm/season accounting for 41.4% of the annual total rainfall in the region as illustrated in Figure 5.10. During the periods 1900-1939, 1940-1979 Summer rainfall contributed an average of 41.3%, 40.7% and 42.3% of total annual rainfall (Table 15), respectively. The percentage contribution during the third period was more than that of the two previous periods and higher than the long-term 41.4% Summer contribution to the annual total rainfall. This suggests an increase in the Summer rainfall contributing to the total annual rainfall as was observed by Kruger (2006) and complemented by projections of Schulze *et al.* (2009). Kruger and Nxumalo (2017) also, observed an increased Summer rainfall extending to the Central Interior of South Africa, which forms part of the Summer rainfall region for this research.

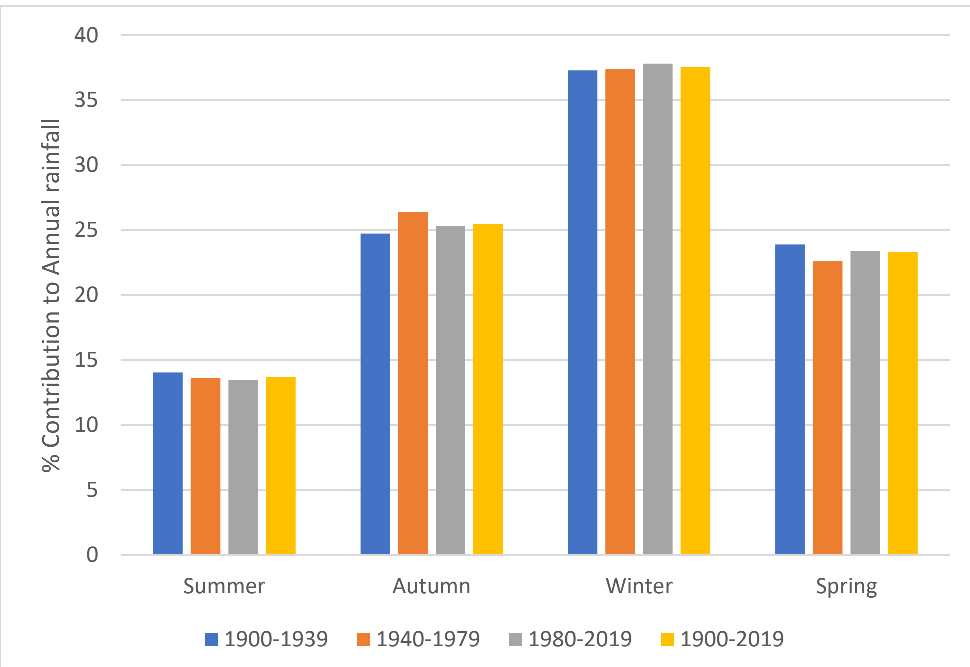


Figure 5.11: Change in contribution of seasonal to annual rainfall (Winter rainfall region).

For the Winter rainfall region stations, in the South and North-Western Cape, a seasonal precipitation 169 mm/season accounting for 37.5% of annual total rainfall was recorded during Winter as illustrated in Figure 5.11. Rainfall ranged from 159 mm to 181 mm with 37.3%, 37.4%, and 37.8% contribution to annual total rainfall (Table 15), during the three periods, respectively. This was an indication of a slight increase in Winter rains over the years. Less but more intense Winter rainfall has been observed over the Western Cape by Van Wageningen and Du Plessis (2007), Nel (2009) and Ndebele *et al*. (2020). The observation of less but more intense Winter rains motivates the need for trend analysis for the Winter rainfall region to check for the presence of significant increasing trends.

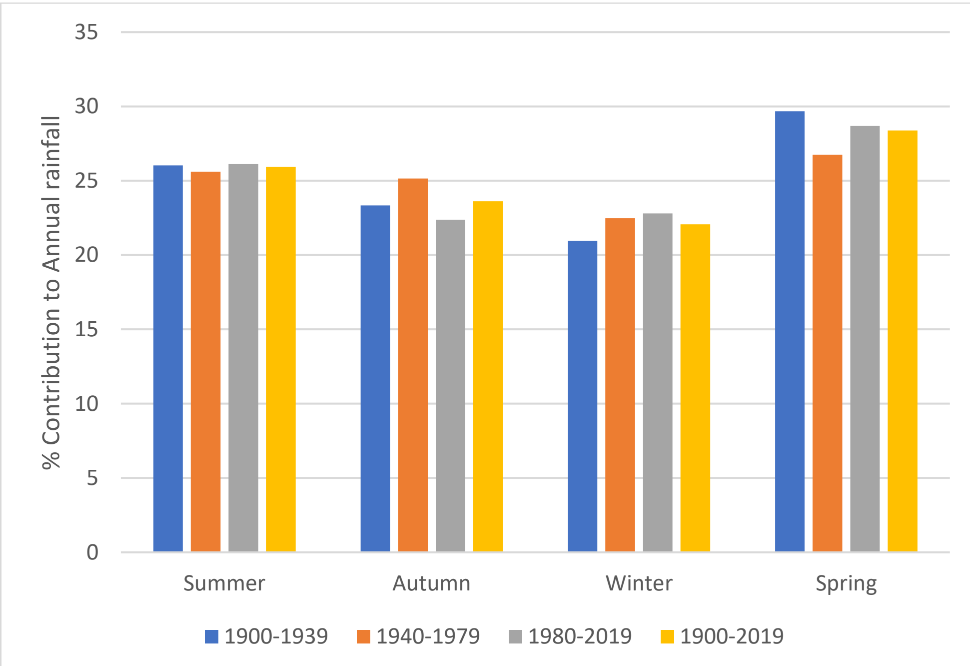


Figure 5.12: Change in contribution of seasonal to annual rainfall ('All year' rainfall region).

For the 'All year' rainfall region (Figure 5.12), the stations recorded low percentage increase during Summer and Winter seasons. Autumn and Spring had fluctuating percentage change of seasonal rainfall as illustrated in Figure 5.12 and summarized in Table 15.

5.2 Trend Analysis

A trend is the steady increase or decrease of a time series characteristic. Trend analysis was performed to check for observed trends in daily, monthly, seasonal, and annual rainfall over South Africa for the period 1900-2019. To identify trends, the Mann-Kendall trend test was performed to rainfall time series for stations identified to be homogenous. Mann-Kendall, a non-parametric trend test does not require normality in the distribution of data. Modified and seasonal Mann-Kendall tests were also applied to take care of the effects of autocorrelation and seasonality in rainfall time series data. Sen's slope estimator was used to establish the rate of change per time unit. Significant trends were spatially illustrated by interpolating the observed trends for all stations across South Africa.

5.2.1 Daily Trend Analysis

The Mann-Kendall test was performed, and Hypothesis testing conducted at 10% significance level using a two-tailed test. The null hypothesis (H_0) was that daily time series comes from a sample with variables (rainfall values) having an independent and identical distribution while the alternative hypothesis (H_a) was that the daily time series has a monotonic trend over time. The results are presented in Table D1 in Appendix D. From the daily trend analysis using the Mann-Kendall test, it was observed that only five stations (highlighted in bold in Table D1) had significant trends at a 10% significant level. However, upon subjecting daily time series for these stations to Sen's slope estimator, the rate of change was found to be insignificant low i.e., below 0.00001 mm/day. To improve on the results by removing the effects of seasonality and autocorrelation, time series for all the stations were subjected to modified Mann-Kendall and seasonal Mann-Kendall tests. The later tests verified that the observed trends using Mann-Kendall test were accurate. Only an additional one station recorded a significant trend. The rate of change remained to be insignificant (Table D1 in Appendix D). Therefore, although a few stations exhibited significant trends, the rate of change at daily time-step was insignificant for all stations.

5.2.2 Monthly Trend Analysis

Monthly rainfall for all stations were subjected to trend analysis and results (Table D2 to Table D13 in Appendix D) of significant trends (highlighted in bold in Table D2–Table D13) plotted graphically (Figure D-1 to Figure D-83 in Appendix D) to illustrate the rate of trend from Sens' slope estimator. The spatial distribution and rate of change are also illustrated geographically (Figure 5.13 to Figure 5.17) except for July and August which had only one station each recording significant trends. The illustrated significant trends for each month are discussed with respect to their respective rainfall regions and climatic zones.

In an overview, the monthly trend analysis shows that increasing trends dominated the months of November, December, January while April, March, May, June, and September recorded significant decreasing trends in the different climatic zones. July and August had only one station each recording significant trends while March recorded the highest number of stations (14) with significant trends per month. The monthly trends to be discussed suggest possible shifts towards an early/late start or end for the different respective rainfall seasons impacting on the length of the season in the different rainfall regions consistent with projections of Hewitson *et al.* (2006).

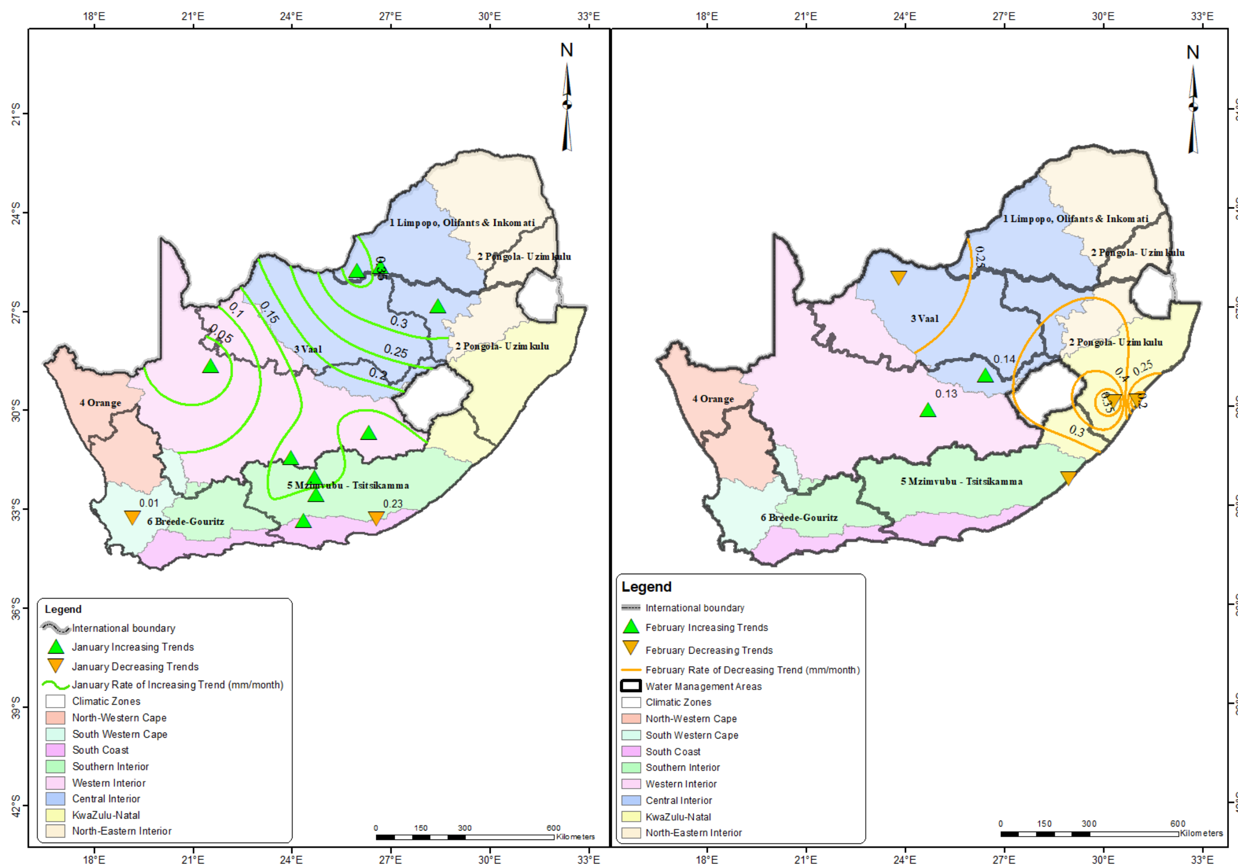


Figure 5.13: Distribution and rate of trends for January and February.

Figure 5.13 illustrates the distribution and rate of trends for January and February. January recorded dominant increasing trends from the Southern Interior (0.15 mm/month), through the Western Interior to the Central Interior zones (0.45 mm/month). Decreasing trend was recorded at the South-Western Cape and the South Coast. In February, KwaZulu-Natal experienced decreasing trends increasing towards the Central Interior suggesting a tendency towards shortening of the Summer season for these climatic zones. Two stations of the Summer rainfall region in the Western and Central interior zones recorded increasing trends. From January to February, there was a shift from a dominant increasing to decreasing trends.

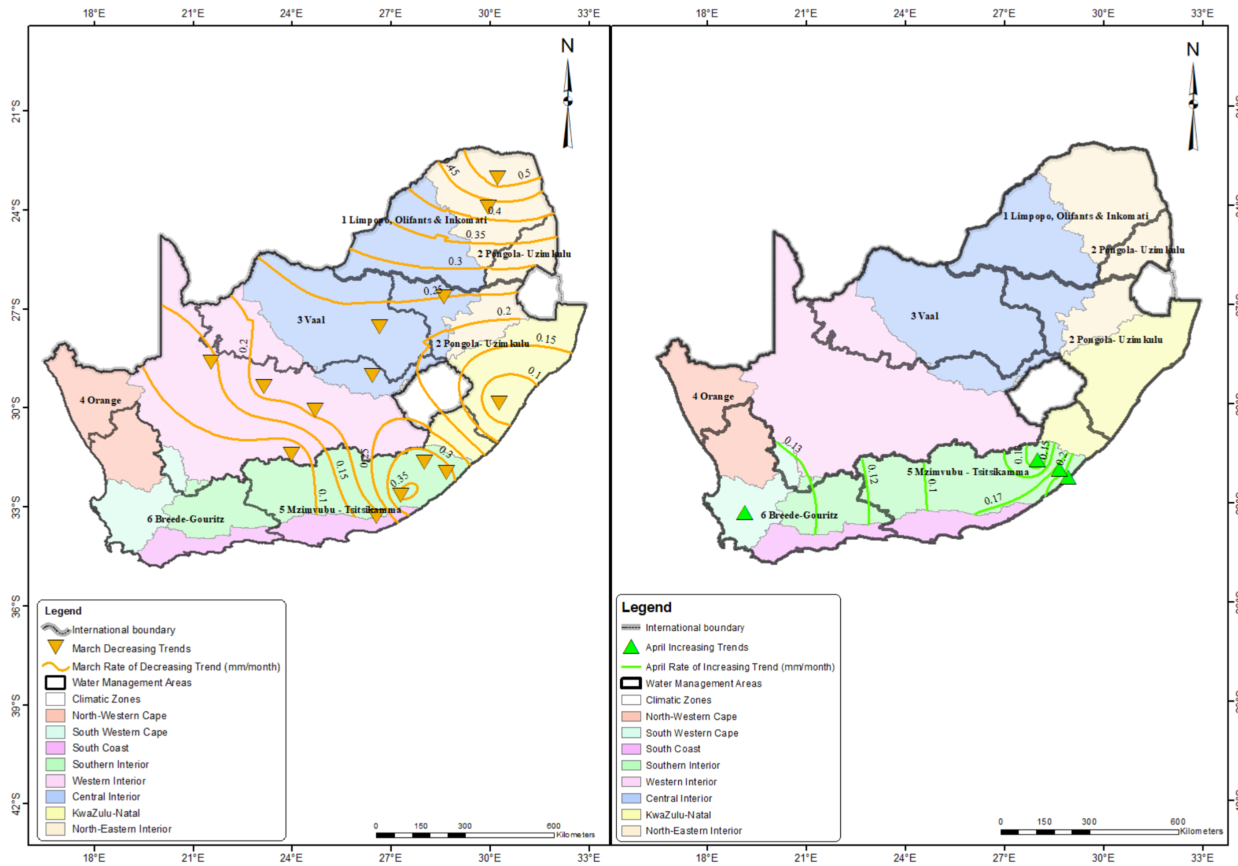


Figure 5.14: Distribution and rate of trends for March and April.

The March and April rainfall trends are illustrated in Figure 5.14. In March, only decreasing trends were recorded. At the South Coast, a decreasing trend of 0.35 mm/month was recorded which decreased to the Southern Interior through the Western Interior, to the Central Interior. The North-Eastern Interior also recorded a significantly high rate of decreasing (0.55 mm/month) trend which decreased towards the Central Interior. The April increasing trends was observed at Southern Interior and the South-Western Cape. The rate of trend ranged between 0.11-0.31 mm/month, increasing from the South-Western Cape to the Southern Interior. Although few stations had significant increasing trends, majority of the stations across South Africa had increasing trends in April. The decreasing trends in March and increasing trends in April are a suggestion of a possible change in the timing of seasons. For the Summer rainfall region, it would suggest late Autumn rains while for the Winter rainfall region, it would be a shift towards early Winter rains.

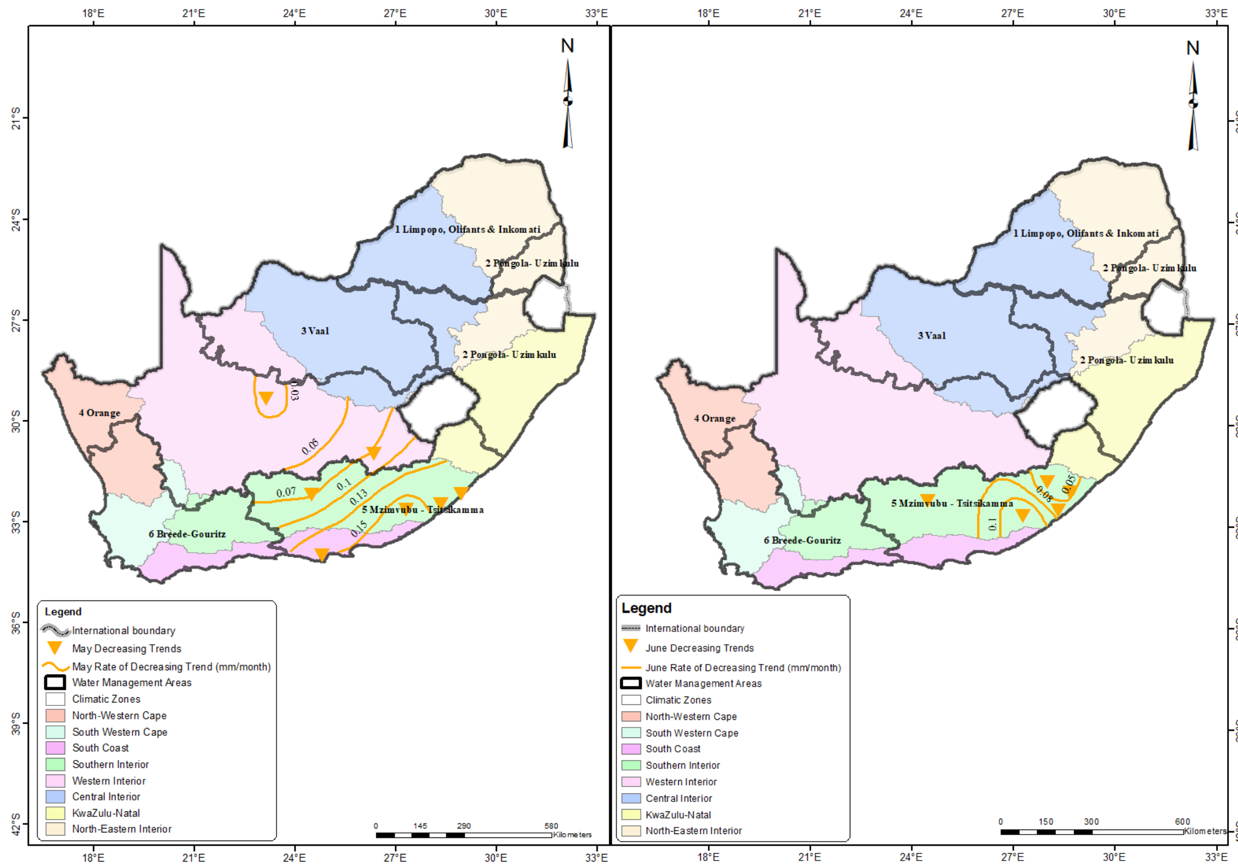


Figure 5.15: Distribution and rate of trends for May and June.

May and June recorded only decreasing trends as illustrated in Figure 5.15. In May, most of the stations recording significant trends were in the South Coast, the Southern Interior, and the Western Interior. The rate of decreasing trend was the highest along the South Coast (0.15 mm/month) then decreased to the Western Interior (0.03 mm/month). The significant decreasing trend in the month of May is a suggestion towards an early ending of Autumn rains in the Southern and Western Interior zones of the Summer rainfall region. Coupled with decreasing trends in March this is an indication of a short Autumn rainy season. In June, trends shift eastwards to be observed only at the Southern Interior. The rate of decreasing trend slightly decreased (0.1 mm/month) compared to May. Although insignificant, stations in the Winter rainfall region at the North and South Western Cape recorded increasing trends in June, the beginning of Winter Season. For both May and June, the significant trends decreased from the coast to the interior.

September and October trends are illustrated in Figure 5.16. September recorded significant decreasing trend for stations in the North-Western Cape, South Coast, Southern, Western and Central Interior zones. The rate of decrease was highest at the South Coast (0.3 mm/month) then decreased to the Southern Interior. The North-Eastern Interior recorded the lowest rate of decreasing trend (0.1 mm/month). October recorded both decreasing and increasing trends. Increasing trends were observed in the KwaZulu-Natal region increasing to the North-Eastern Interior (0.2 mm/month). On the other hand, decreasing trends decreased from the North-Eastern Interior (0.2 mm/month) to the Southern Interior (0.03 mm/month). October was observed to be unique having almost an equal number of stations with opposite trends.

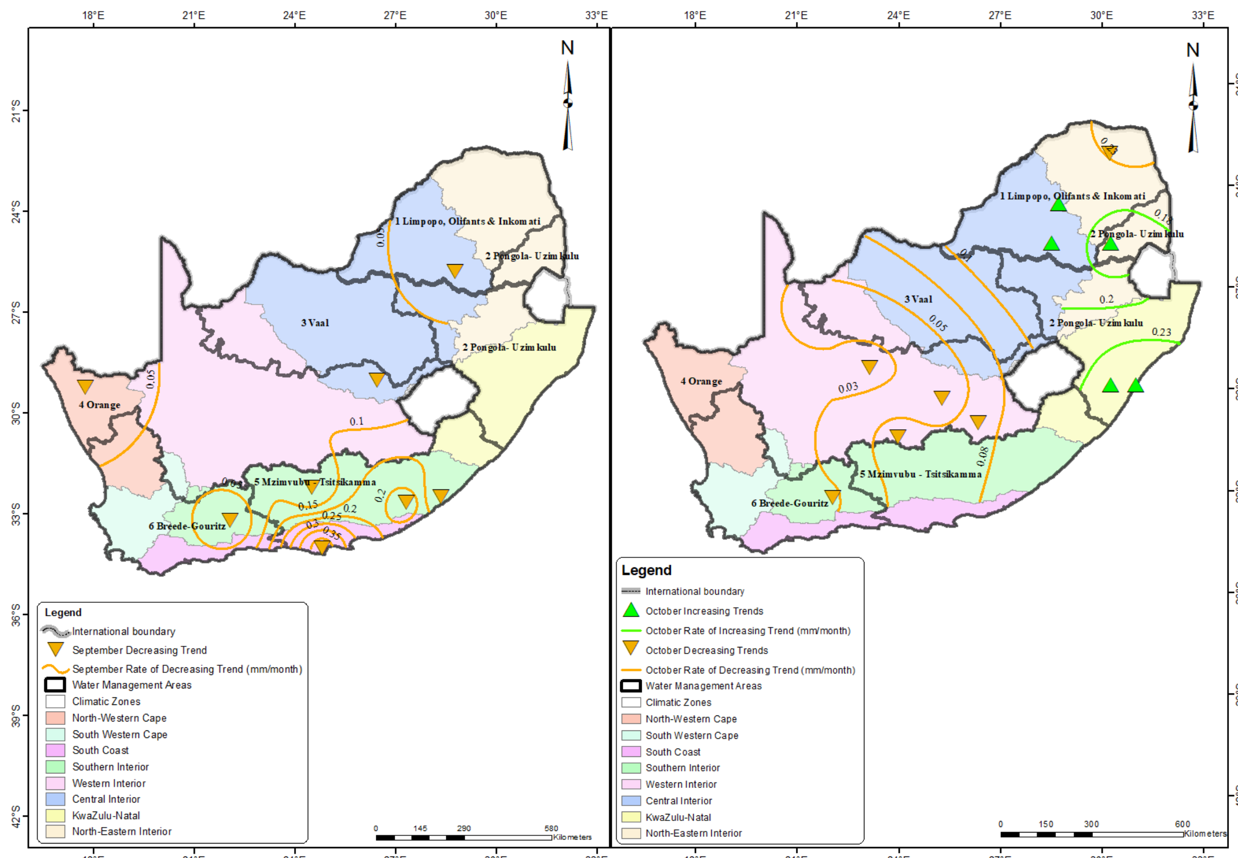


Figure 5.16: Distribution and rate of trend for September and October.

The November and December trends are illustrated in Figure 5.17. November had mostly increasing trends starting along the South Coast to the Southern Interior and increasing to the North-Eastern Interior. However, in between the North-Eastern Interior and the South Coast, at the Western and Central Interior zones, southward decreasing trends were recorded. The two regions acted to bridge the gap between the increasing trends of the South Coast and that of the North-Eastern Interior. In December, a northward increasing trend, starting at the South Western Cape to the Central Interior was recorded. Stations in the Southern Interior had an eastward decreasing trend ranging 0.15 and 0.2 mm/month at the South Coast. A dominant increasing trend in December and decreasing trend for February is an indication of a likely early start and end of the Summer rains.

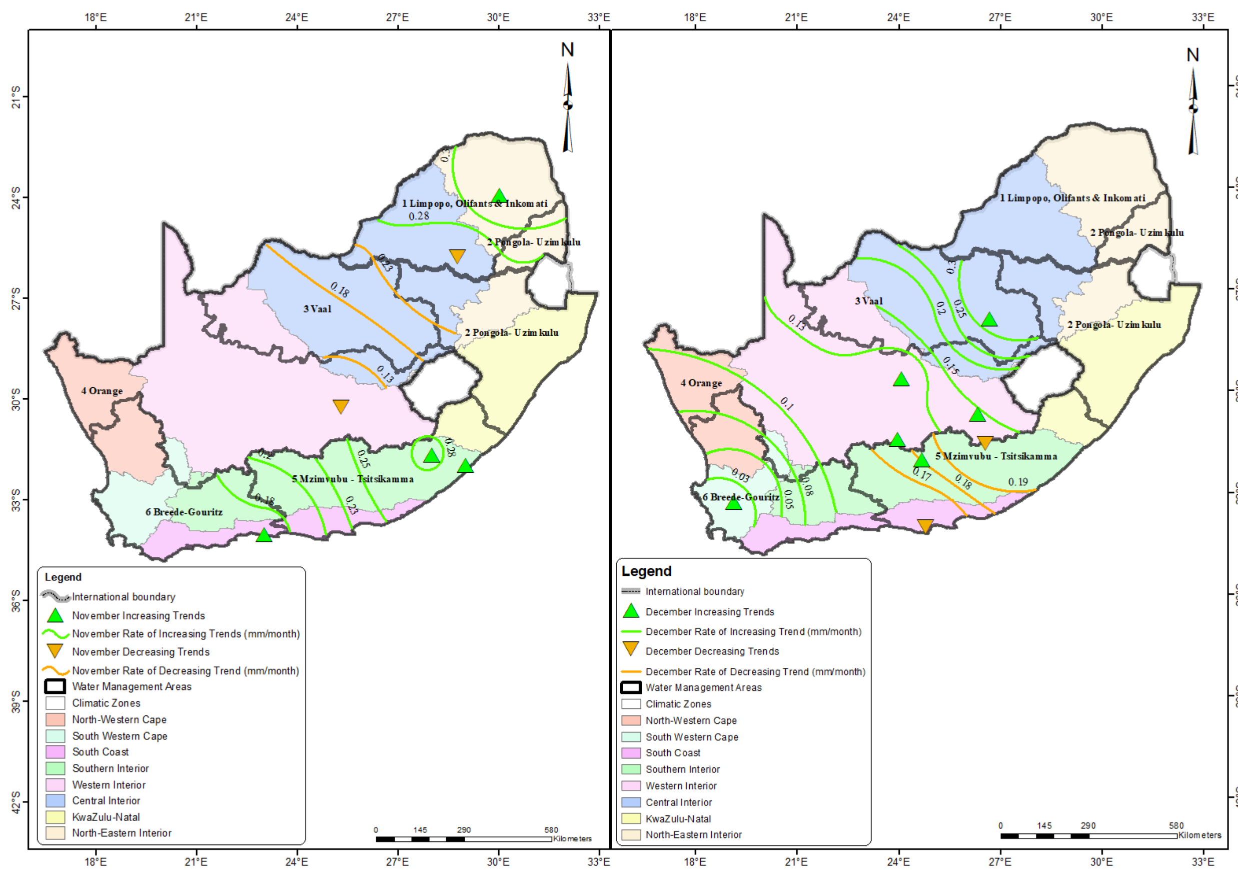


Figure 5.17: Distribution and rate of trend for November and December.

From the results of the monthly trends illustrated above, it was noted that rainfall trends were mostly observed along the South Coast and the Western and the Central Interior towards the North-Eastern Interior. The South-Western Cape region had few stations experiencing significant trends in January (decreasing trends), April and December (increasing trends). The North-Western Cape rarely experienced significant trends apart from September with a decreasing trend of 0.01 mm/month which was low. The South Coast, an 'All year' rainfall region, recorded significant trends in almost all the months except for October. Decreasing trends are dominant in this region apart for January, April, and November. The KwaZulu-Natal zone experienced increasing trends in October and decreasing trends in February. The Central and Western Interior zones tend to act as a connection between the North-Eastern Interior and the South Coast zones bridging either increasing or decreasing trends from both ends. It recorded significant trends in nearly all months except April and June. These monthly trends gave an indication of expected seasonal trends with a likely change in length and timing of the respective seasons.

5.2.3 Seasonal Trend Analysis

Trend analysis was performed for the four established seasons of South Africa: Summer, Autumn, Winter, and Spring. Seasonal trend analysis was done in two phases; long term seasonal trends and seasonal sub-trends. The results of these trends were summarized in tables with significant trends highlighted in bold. The graphs for significant trends were also plotted to illustrate the rate of change. The distribution and rate of trend were plotted for spatial illustration and discussed in consideration of the different rainfall regions and climatic zones of South Africa. The results tables and graphs are attached in Appendix D.

5.2.3.1 Summer Trend Analysis

The results of long-term Summer trend analysis (Table D14 in Appendix D) had both increasing and decreasing trends. Significant trends (For all stations, Figure D-84 to Figure D-96 in Appendix D) were summarised, and the spatial distribution illustrated in Figure 5.18.

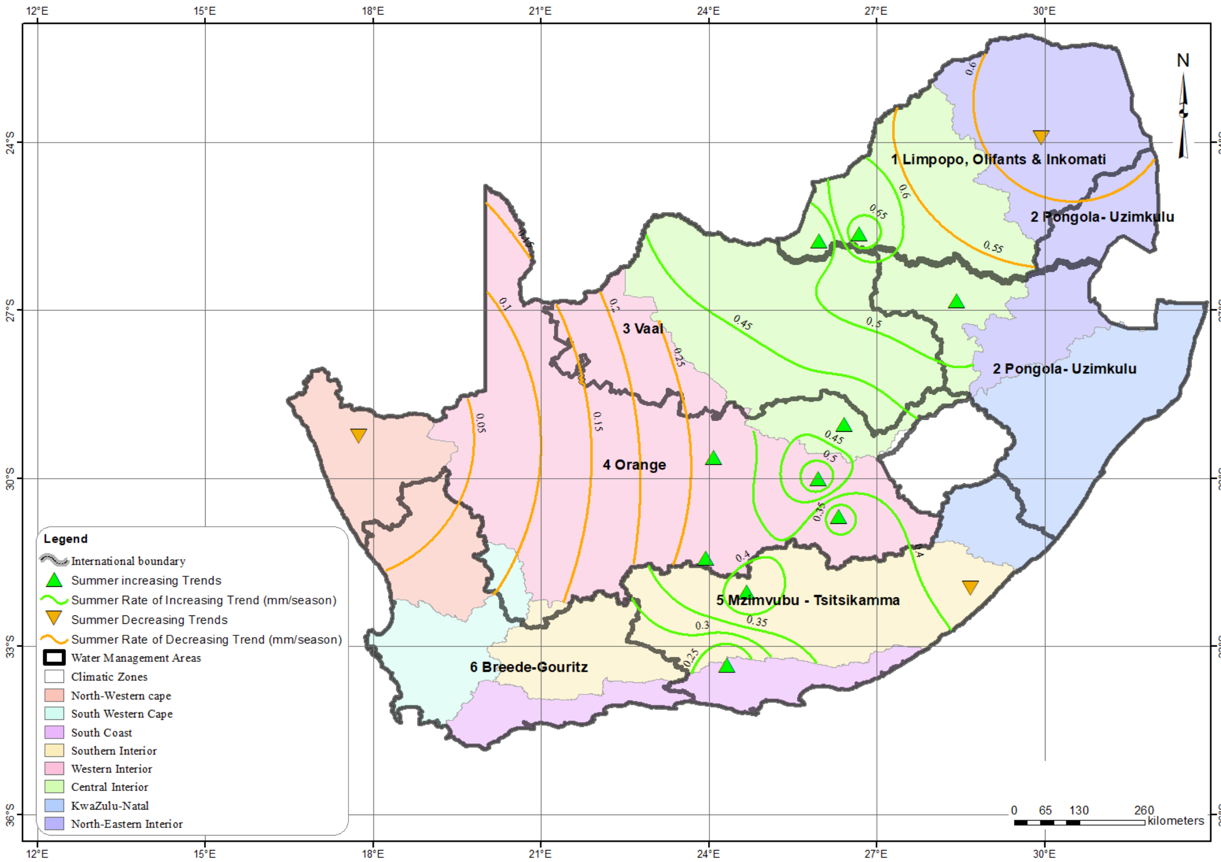


Figure 5.18: Distribution and rate of significant Summer trends (1900-2019).

Trends were recorded in the North-Western Cape, Southern, Western, Central and North-Eastern Interior zones. Increasing trends increased northwards from the Southern Interior, 0.3 mm/season to 0.6 mm/season at the Central Interior. On the other hand, decreasing trends took place southwards, from the North-Eastern Interior at 0.6 mm/season to the North-Western Cape at 0.1 mm/season. The increasing and decreasing trends overlapped at the Central and Western Interior zones motivating the need for sub-trend analysis to evaluate the possibility of short-term changes or shifts in trends. Long term Summer trends were dominated by increasing trends as was projected by DEA (2013) and observed by MacKellar *et al.* (2014) and Kruger and Nxumalo (2017).

5.2.3.1.1 Summer Sub-trend Analysis

Summer trends were further examined by performing sub-trend analysis for the periods 1900-1939, 1940-1979, and 1980-2019. The results are presented in Table D15, D16 & D17 and graphs for significant trends illustrated in Figure D-97 to D-121 in Appendix D for each of the respective periods. The first period had significant trends along the Southern Coast, Southern Interior and Western Interior zones as illustrated in Figure 5.19. The Increasing trends took place at the northern part of the South Coast extending to the Southern Interior and further into the Western Interior. Decreasing trends took place at the central part of the South Coast and the Southern Interior. Increasing trends increased northwards along the north of the South Coast to the Southern and Western Interior zones while decreasing trends decreased from the central South Coast to the adjacent Southern Interior.

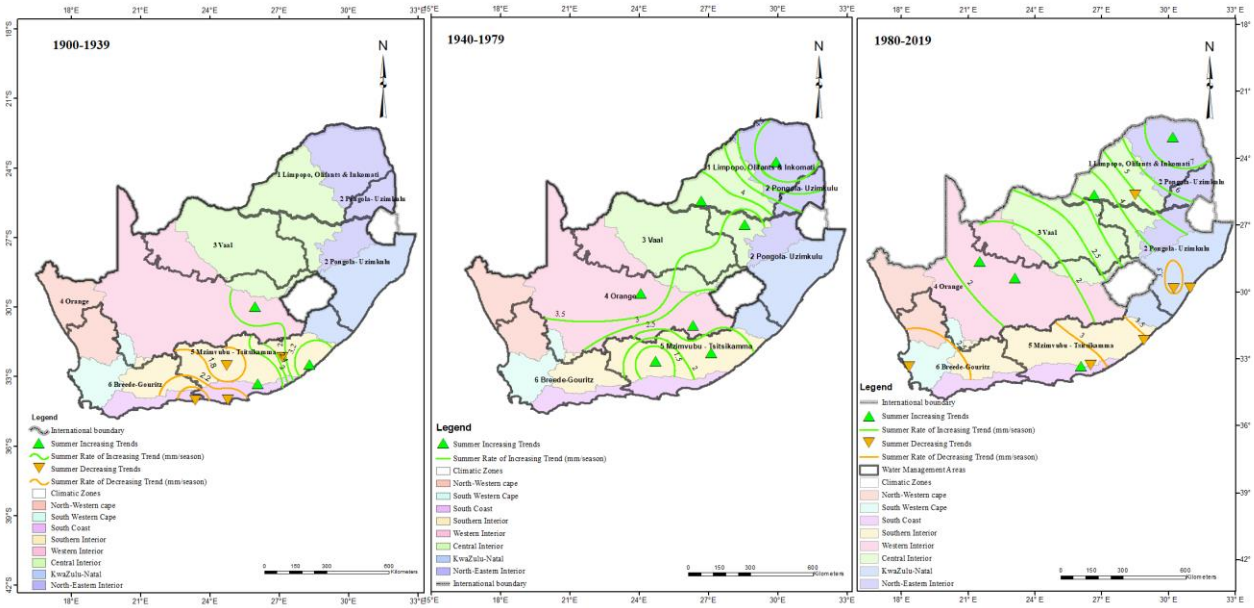


Figure 5.19: Distribution and rate of significant Summer sub-trends.

The trends during the second period (Figure 5.19) suggest a shift of increasing trends towards the Central, Western and North-Eastern Interior zones. A slight increase from 3.2 mm/season in the previous period to over 4.5 mm/season was observed.

During the third period, both decreasing and increasing trends were observed as illustrated in Figure 5.19. The increasing trends were observed at the Western, Central and North-Eastern Interior zones with little to no change in the rate of trend. Decreasing trends were observed at the South Western Cape, South Coast and KZN.

The distribution and rate of long-term Summer trends were likely to have been influenced by the sub-trends of the three periods. The rate of decrease for long term trends was significantly low compared to the first and third periods, respectively. The low rates of decreasing trend for the long-term trend could be due to no significant decreasing trends being recorded during the period 1940-1979. Also, the decreasing trends for the first period were localized compared to the third period. The increasing trends were observed to be consistent at Western, Central and North-Eastern Interior zones, especially for the two latter periods. Similarly, significant long-term increasing trends were observed at the Western and Central Interior zones. The rate of change for increasing trends during the three periods did not vary to the long-term, likely due to the consistency in the rate and distribution of trends.

5.2.3.2 Autumn Trend Analysis

Autumn season contributes approximately 24.7% of annual total rainfall. The results (Table D18 in Appendix D) for long term Autumn trends indicate significant decreasing trends (Figure D-122 to Figure D-128 in Appendix D) for stations in the KZN, Southern, Western, Central and North-Eastern Interior zones. Only one station at the South Coast recorded an increasing trend. The long-term decreasing trends decreased southwards from 0.45 mm/season at the North-Eastern Interior to 0.38 mm/season at the Western Interior, as illustrated in Figure 5.20. The significant long-term decreasing trend for Autumn season which takes place only in the respective climatic zones is an indication of shortening of the rainfall season. Also, most stations with insignificant results had decreasing trends. The general decrease in Autumn rains is in line with observations of Kruger and Nxumalo (2017).

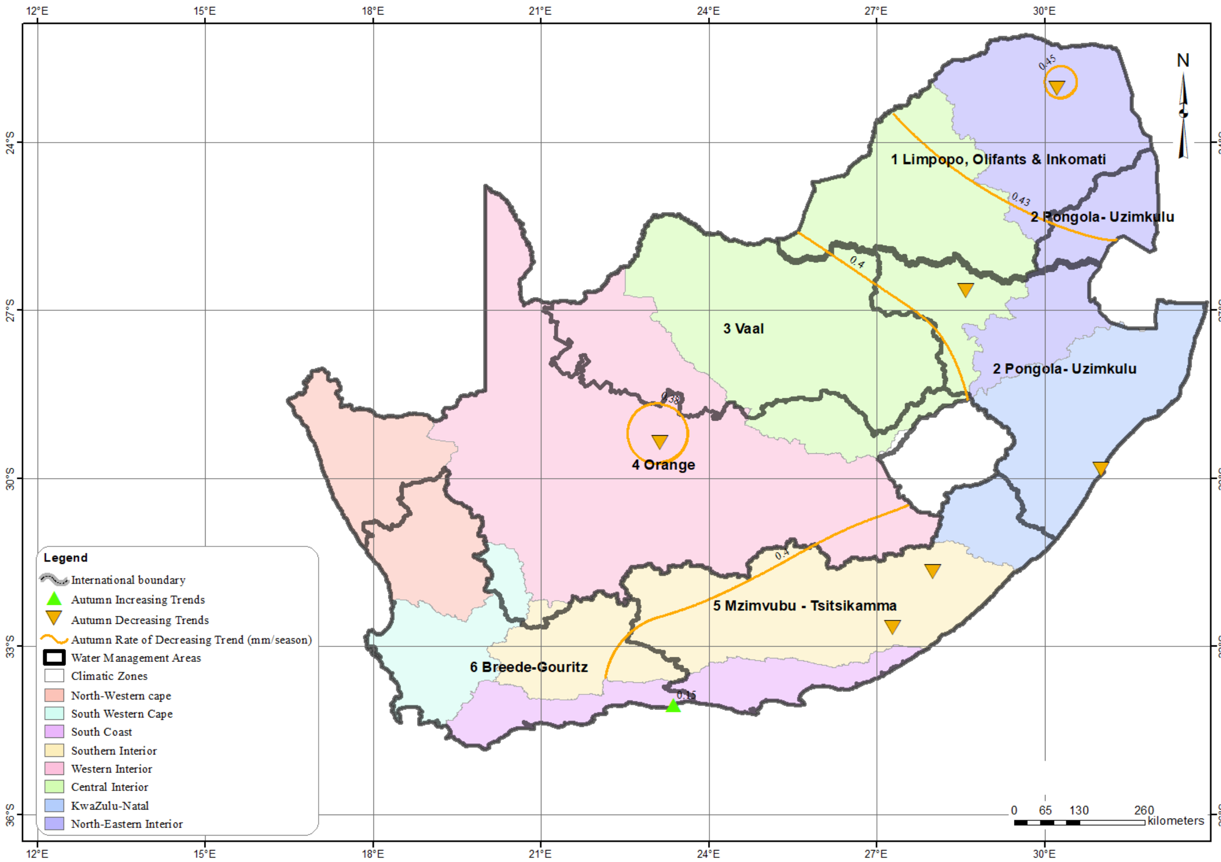


Figure 5.20: Distribution and rate of significant Autumn trends (1900-2019).

5.2.3.2.1 Autumn Sub-trend Analysis

Autumn sub-trend analysis was performed for the three periods to establish short term trends that would have influenced the long-term Autumn decreasing trends. The results for the three respective periods are presented in Table D19, D20 & D21 and graphs for significant trends illustrated in Figure D-129 to D-142 in Appendix D. During the first period both increasing and decreasing trends were observed. Increasing trends were observed in the Central Interior while decreasing trends were observed in the KZN, South and North-Western Cape zones respectively as illustrated in Figure 5.21.

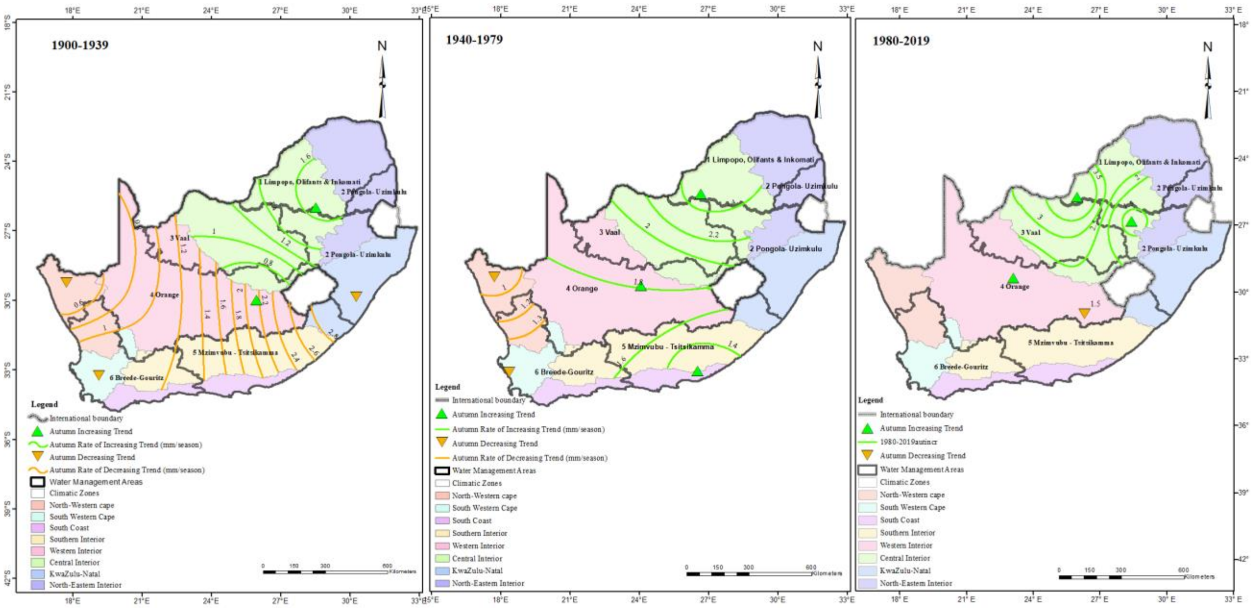


Figure 5.21: Distribution and rate of significant Autumn sub-trends.

During the second period, a shift in trends was noted as illustrated in Figure 5.21. Increasing trends shift to the South Coast through the Western and Southern Interior zones with slight increase in the rate of trend from 1.6 mm/season previously to 2.4 mm/season. The decreasing trends at the South and North-Western Cape are maintained with slight increase in the rate of decreasing trend from 0.6 mm/season to 2.4 mm/season.

During the third period, increasing trends are observed to be dominant taking place at the Central Interior with slight increase in rate of trend to 3.5 mm/season as illustrated in Figure 5.21. Only a single station records decreasing trend at the Western Interior with the rate of change of 1.5 mm/season almost similar to the first period.

The Autumn short-term trends were not observed to have similar patterns to the Autumn long-term trends. Whereas the Central Interior zone consistently recorded significant increasing trends across the three short-term periods, the same was not reflected in the long-term trends. Similarly, the South and North-Western Cape zones record significant decreasing trends during the first two short-term periods, but do not record significant trends in the long-term. The possible influence of Autumn sub-trend on long-term trends remains inconclusive.

5.2.3.3 Winter Trend Analysis.

Winter is the driest season for most parts of South Africa with its rainfall accounting for almost 8.2% of annual total rainfall. However, in the South and North-Western Cape zones, it is the main rainfall season. The results of long term (1900-2019) Winter trend analysis (Table D22 in Appendix D) showed a general increasing trend at the South Western Cape and the Southern Interior zones as illustrated in Figure 5.22. The increasing trend is in line with the observed seasonal characteristics of a general increase in Winter rains. Decreasing trends were observed in the Central and Western Interior zones. Generally, few stations record significant trends (Figure D- 143 to Figure D-147 in Appendix D). The observation of Winter increasing trend, especially in the Western Cape complements findings of Nel (2009), Mackellar *et al.* (2014) and Ndebele *et al.* (2020).

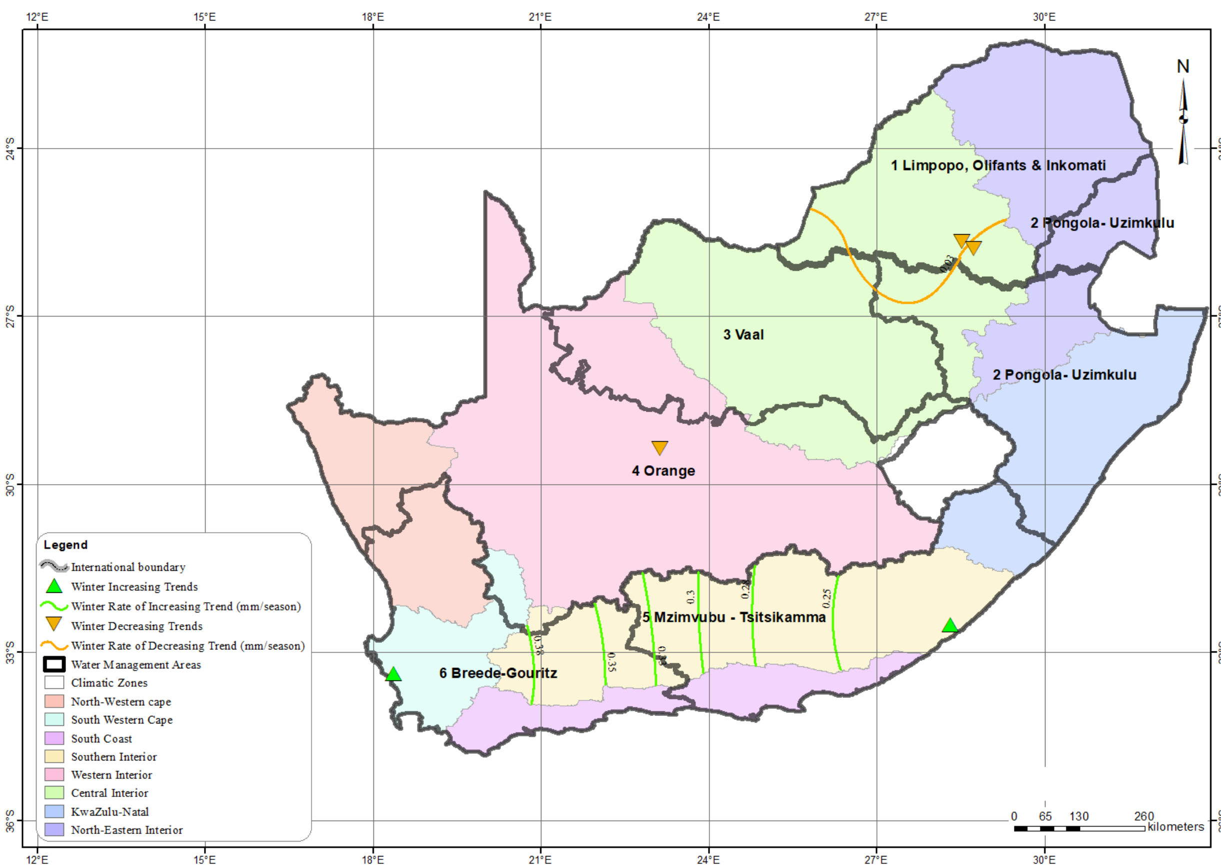


Figure 5.22: Distribution and rate of significant Winter trends (1900-2019).

5.2.3.3.1 Winter Sub-trend Analysis

Trend analysis for Winter was further analysed for the three respective periods to check for sub-trends forcing the long-term trends. The results for the three respective periods were presented in Table D23, D24 & D25 and graphs for the significant trends illustrated in Fig D-148 to D-173 in Appendix D.

During the first period, both decreasing and increasing trends were observed. The decreasing trends took place at the Central Interior zone while the increasing trends were observed at the South Coast, Southern and North-Eastern Interior zones as illustrated in Figure 5.23.

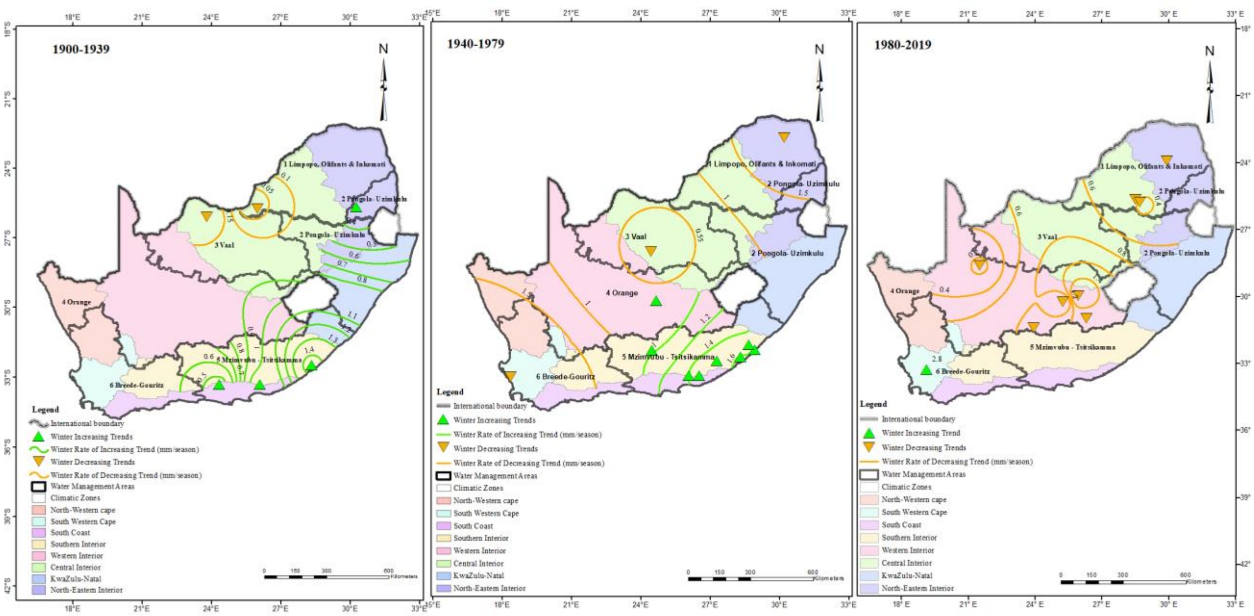


Figure 5.23: Distribution and rate of significant Winter sub-trends.

During the second period, a shift in trend was observed. The increasing trends were localized around the South Coast and Southern Interior zones as illustrated in Figure 5.23. On the other hand, decreasing trends were observed in the South Western Cape, Central and North-Eastern Interior zones. Both the rate of increasing and decreasing trends record slight increases compared to the previous period.

During the third period, decreasing trends were observed to be dominant. Decreasing trends took place in the Western, Central and North-Eastern Interior zones as illustrated in Figure 5.23. Only a single station recorded an increasing trend in the South Western Cape with a slight increase in the rate of trend.

The Winter sub-trends were observed to have possible influence on the observed Winter long term trends. The observed consistent significant increasing trend during the first two short-term periods confirm the long term increasing trend in the Southern Interior zone. Similarly, the Central Interior zone consistently records significant decreasing trends during the three short-term periods confirming the long-term decreasing trend for the same zone.

5.2.3.4 Spring Trend Analysis

Spring season accounts for approximately 23.2% of annual total rainfall. The results (Table D26 in Appendix D) of long-term trends indicate very few stations had significant trends (Figure D-174 to Figure D-176 in Appendix D) with a spatial distribution as illustrated in Figure 5.24. Increasing trends took place in the Central Interior zone increasing northwards to a maximum of 0.5 mm/season. Decreasing trend was observed at the South Coast at a rate of 0.69 mm/season. Observing these trends with the seasonal rainfall characteristics in Table 15, the similarity in the decrease of Spring rainfall in the South Coast zone could be seen. Spring season was observed to have a high number of insignificant decreasing and increasing trends, across the country (Table D26 in Appendix D) complementing observations of Nel (2009).

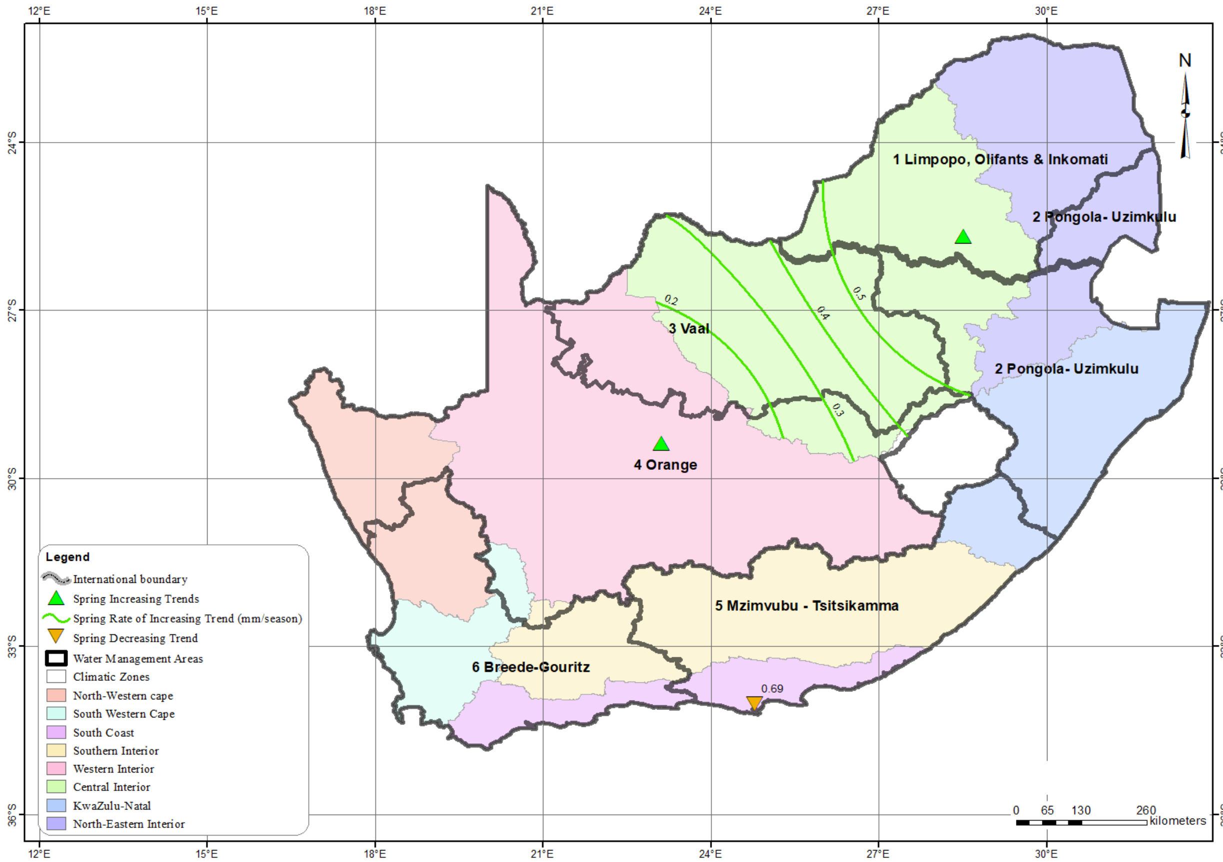


Figure 5.24: Distribution and rate of significant Spring trends (1900-2019).

5.2.3.4.1 Spring Sub-trend Analysis

Spring trends were further analysed for the three periods to check for short-term trends influencing the low number of stations with significant long-term trends. The results for the three respective periods are presented in Table D27, D28 & D29 and the graphs for significant trends illustrated in Figure D-177 to D-216 in Appendix D.

During the first period, significant increasing and decreasing trends were observed. Decreasing trends were observed in the South Western Cape, North-Western Cape, Southern and North-Eastern Interior zones. Increasing trends were observed in the South Coast, Southern and Western Interior zones as illustrated in Figure 5.25.

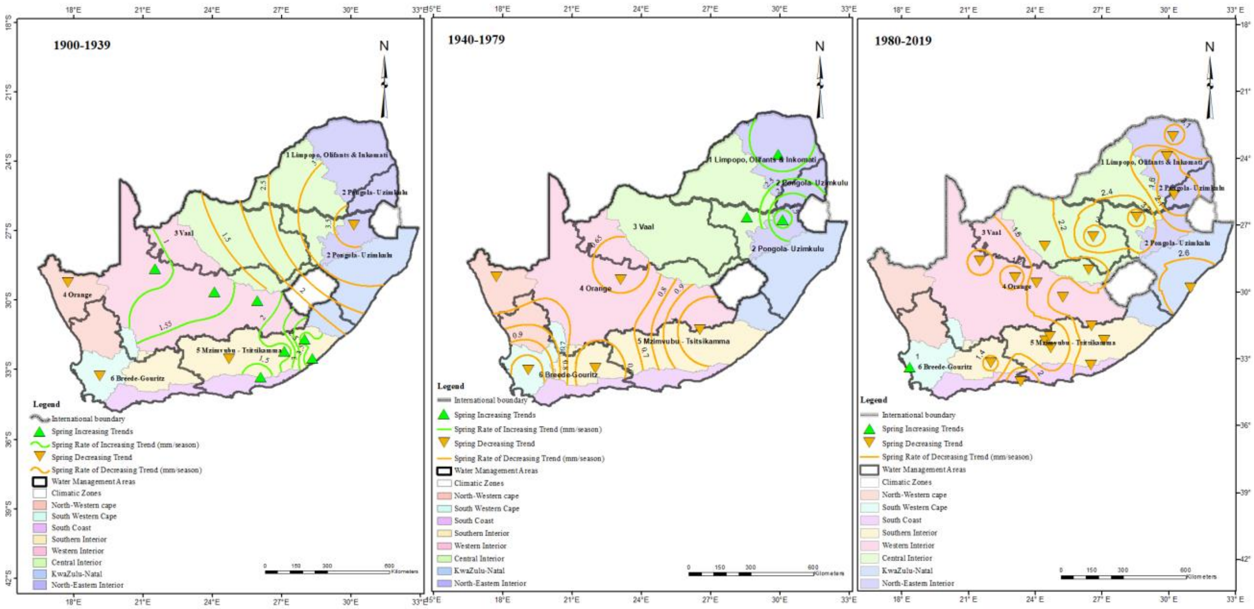


Figure 5.25: Distribution and rate of significant Spring sub-trends.

During the second period, decreasing trends were observed to be dominant, taking place in the South and North-Western Cape and the Southern and Western Interior zones as illustrated in Figure 5.25. The rate of decreasing trend slightly decreased compared to the previous period. Increasing trends were observed in the Central and North-Eastern Interior zones with similar rate of trend to the first period.

During the third period, a shift towards an almost fully decreasing trend was observed as illustrated in Figure 5.25. Only one station in the South-Western Cape recorded an increasing trend. Decreasing trends dominated the South Coast, KZN, Western, Central, and North-Eastern Interior zones. The rate of decreasing trend slightly increased compared to the previous period.

Observing the short-term trends across the three respective periods, a tendency towards dominant decreasing trends was observed. However, this was inconsistent with the observed long-term trends. Only the long-term decreasing trend at the South Coast was confirmed. The relationship between Spring sub-trends and long-term trends remained inconclusive. MacKellar *et al.* (2014) and Kruger and Nxumalo (2017) noted that long term trends for Spring were not evident in line with the observations of this research.

In performing seasonal sub-trend analysis for the periods, 1900-1939, 1940-1979, 1980-2019, it was observed that periodical seasonal trends were more evident than long term trends. Long term trends had few stations with significant trends compared to the short-term periods. Spring had only three stations with significant long-term trends and were sparsely distributed across the country. Summer which is the main rainfall season of South Africa had significant increasing trends across the three periods resulting in a significant increasing long-term trend, a suggestion of increasing rains. Observing the decreasing trend in Spring and Autumn, especially for the period 1980-2019 a likelihood of a shorter wet season could be seen. Autumn had an alternating increasing and decreasing trends within the periods but a long-term decreasing trend. Winter rainfall experienced a gradual slight increasing trend during the first two periods but then decreased significantly during the last period. The observation, especially during the last period of an increasing Summer with decreasing Autumn, Spring and Winter trends suggest a shift in seasonality whereby the wet seasons were becoming shorter while the dry season was becoming drier respectively, hence more pronounced seasonal cycles.

5.2.4 Annual Trends Analysis

Upon establishing monthly and seasonal trends this research goes further to analyse annual rainfall trends. Annual rainfall trend analysis was performed for long term and short-term (40 year) periods. The results were tabulated, and significant trends highlighted in bold. The graphs for significant trends were also plotted and a spatial illustration of rate and distribution done.

The results (Table D30 in Appendix D) for long-term annual trends had both increasing and decreasing trends across the different climatic zones. The Figure 5.26 illustrates the spatial distribution of significant trends (Figure D-217 to Figure D-225 in Appendix D). Generally, there was a slight increase in annual rainfall in line with the observed annual rainfall characteristics. Increasing trends were recorded at the South-Western Cape, South Coast and the Southern, Western and Central Interior zones. Decreasing trends were recorded at the lower parts of the South Coast and the Western Interior zones. The observation of increasing rainfall at the South-Western Cape complements observations of MacKellar *et al.* (2014) and Kruger and Nxumalo (2017).

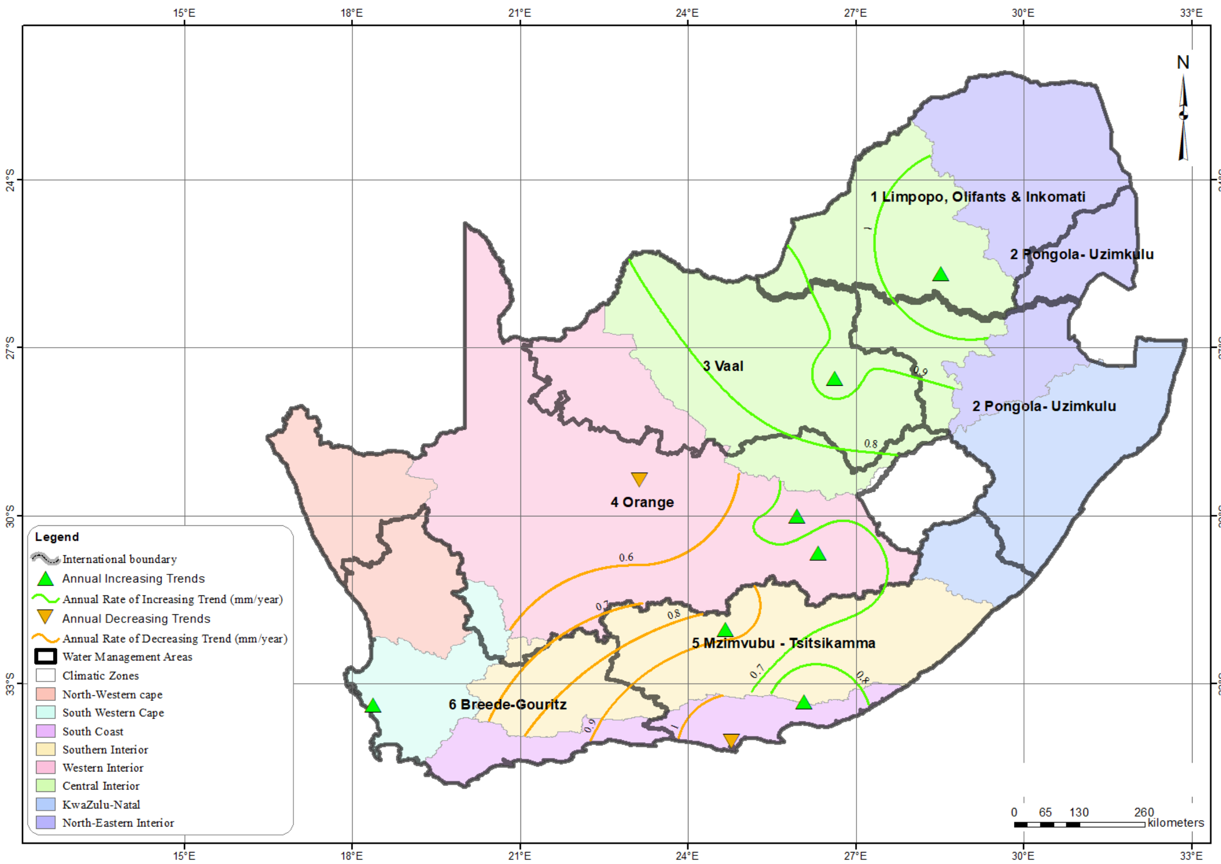


Figure 5.26: Distribution and rate of significant Annual long-term trends (1900-2019).

5.2.4.1 Annual Sub-trend Analysis

Annual trends analysis was further performed for the three defined periods to check for possible changes in sub-trends influencing the long-term trends. The results for the three respective periods are presented in Table D31, D32 & D33 and the graphs for the significant trends illustrated in Figure D-226 to Figure D-257 in Appendix D.

During the first period increasing and decreasing trends were observed as illustrated in Figure 5.27. Decreasing trends were observed at the South and North-Western Cape and KZN zones. Increasing trends were observed in the Western, Central and North-Eastern Interior zones. The South Coast and Southern Interior zones recorded both increasing and decreasing trends.

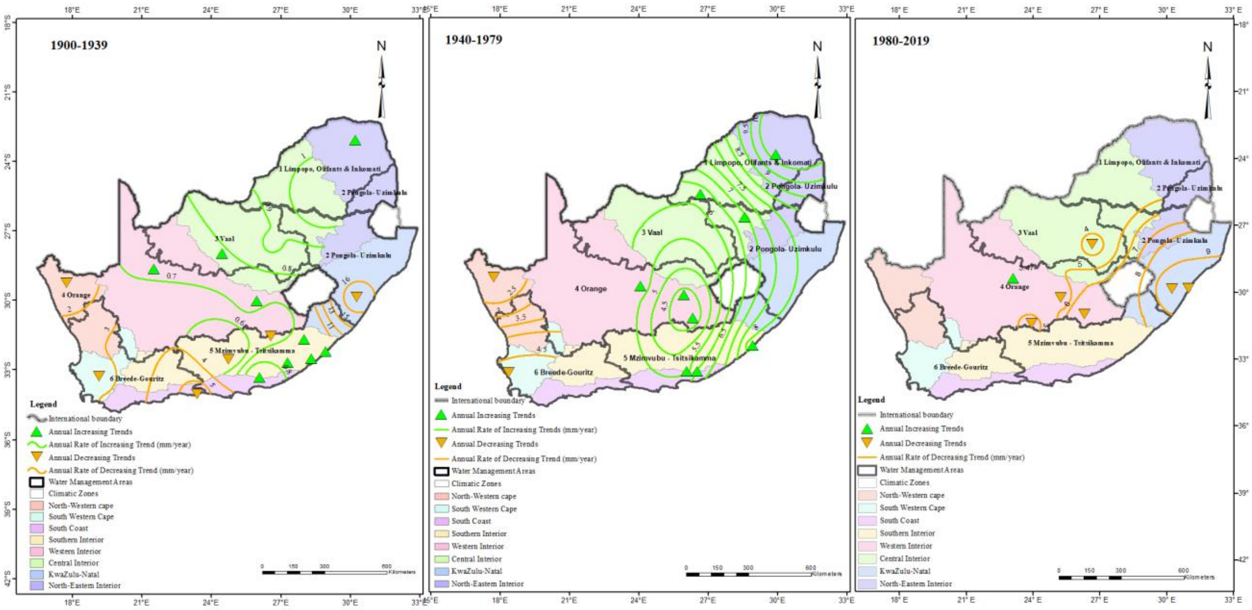


Figure 5.27: Distribution and rate of significant Annual sub-trends.

During the second period, a shift towards a more dominant increasing trend was observed as illustrated in Figure 5.27. Increasing trends were observed at the South Coast, Southern, Western, Central and North-Eastern Interior zones. The decreasing trends were observed at the South and North-Western Cape. The rate of increasing and decreasing trends increased slightly in comparison to the previous period for the respective zones.

During the third period, a dominant decreasing trend with a decrease in the number of stations recording significant trends was observed as illustrated in Figure 5.27. Only one station recorded an increasing trend in the Western Interior zone. Decreasing trends were observed in parts of KZN, Central and Western Interior zones. The rate of decreasing trend increased slightly compared to the previous period. The observation of a dominant decreasing trend in KZN, Western, Central and North-Eastern Interior zones of the Summer rainfall region complements observations by MacKellar *et al.* (2014) and Kruger and Nxumalo (2017) of a decreasing in precipitation during the same period, but then further note of increased intensity.

Generally, it could be observed from sub-trend analysis that the number of stations experiencing significant trends gradually increased during the first and second periods before reducing again in the final period. The trends observed shift periodically, for example, during the period 1900-1939, the region along the South Coast zone experienced both decreasing and increasing trends.

During the second period (1940-1979), the region experienced increasing trends only and in the final period (1980-2019), it recorded no significant trends at all. Observing the long-term trends, the effect of these shifting trends could be seen. First, very few stations record significant long-term trends. Stations with significant trends also have very low rates of change. The South Coast zone recorded decreasing long-term trends while the Southern Interior zone recorded a long-term increasing trend after recording alternating trends within the three respective short-term periods. The South and North-Western Cape zones recorded significant decreasing trends for the first two short-term periods and during the final short-term period recorded no significant trend. The result was a long-term increasing trend, implying the insignificant increasing trends during the final short-term period had an influence on the long-term trends. Generally, the whole country records long-term increasing trends which is low, and some researchers have considered it to be insignificant. The seasonal and annual trends are observed to paint an almost similar picture for the three respective short-term periods and in the long-term. It is therefore worth noting of the presence of short-term trends which shift/change periodically for the different climatic zones. These alternating shifts and changes in trends can be attributed to the cyclicity of rainfall (Alexander, 2005).

5.2.5 Trends Analysis Summary

To effectively summarize rainfall trends taking place across the different climatic zones of South Africa and discuss it in the context of previously observed trends, Table 16 was constructed. It gives an overview of the seasonal and annual long-term and short-term trends taking place across the different climatic zones while giving an opportunity for deducting possible effects of rainfall trends to the respective WMAs (hydrological) regions. Despite the high variability of rainfall across South Africa, several interesting deductions could be made.

Table 16: Summary of rainfall trends for South Africa (1900-2019).

Seasons	Periods	Climatic Zones							
		North-Western Cape	South Western Cape	South Coast	Southern Interior	Western Interior	Central Interior	KwaZulu-Natal	North Eastern Interior
Summer	1900-1939	No trends	No trends	Fluctuating	Fluctuating	Increasing	No trends	No trends	No trends
	1940-1979	No trends	No trends	No trends	Increasing	Increasing	No trends	No trends	Increasing
	1980-2019	Decreasing	Decreasing	Increasing	Decreasing	Increasing	Fluctuating	Decreasing	Increasing
	1900-2019	Decreasing	Decreasing	Increasing	Fluctuating	Fluctuating	Fluctuating	No trends	Decreasing
Autumn	1900-1939	Decreasing	Decreasing	No trends	Decreasing	Fluctuating	No trends	Decreasing	No trends
	1940-1979	Decreasing	Decreasing	Increasing	Increasing	Increasing	Increasing	No trends	No trends
	1980-2019	No trends	No trends	No trends	No trends	Fluctuating	No trends	No trends	No trends
	1900-2019	No trends	No trends	Increasing	Decreasing	Decreasing	Decreasing	Decreasing	Decreasing
Winter	1900-1939	No trends	No trends	Increasing	Increasing	Increasing	Decreasing	Decreasing (dark red)	Increasing
	1940-1979	Decreasing	Decreasing	Increasing	Fluctuating	Fluctuating	Decreasing	No trends	Decreasing
	1980-2019	No trends	Increasing	No trends	No trends	Decreasing	Decreasing	No trends	Decreasing
	1900-2019	No trends	Increasing	No trends	Increasing	Decreasing	Decreasing	No trends	No trends
Spring	1900-1939	Decreasing	Decreasing	Increasing	Fluctuating	Increasing	Decreasing	Decreasing	Decreasing
	1940-1979	Decreasing	Decreasing	No trends	Decreasing	Decreasing	Increasing	No trends	Increasing
	1980-2019	No trends	Increasing	Decreasing	Decreasing	Decreasing	Decreasing	Decreasing	Decreasing
	1900-2019	No trends	No trends	Decreasing	No trends	Increasing	Increasing	No trends	No trends
Annual	1900-1939	Decreasing	Decreasing	Fluctuating	Fluctuating	Increasing	Increasing	Decreasing	Increasing
	1940-1979	Decreasing	Decreasing	Increasing	Increasing	Increasing	Increasing	Increasing	Increasing
	1980-2019	No trends	No trends	No trends	No trends	Fluctuating	Decreasing	Decreasing	Decreasing
	1900-2019	No trends	Increasing	Fluctuating	Fluctuating	Fluctuating	Increasing	No trends	No trends

Legend

- No trends
- Increasing Trends
- Decreasing Trends
- Fluctuating Trends

The South Western and North-Western Cape zones are in the Winter rainfall region, hence receive most rainfall during Winter. The climatic zones mainly cover the Breede and a small part of the Orange WMAs. The North-Western Cape experiences mainly decreasing or no trends at all, across the four seasons. Winter being the main rainfall season and having no significant trends, result in the annual rainfall having no trends. This observation complements the findings of Du Plessis and Burger (2015) who observed no evidence of trends and no change in intensities for the short duration rainfall. On the other hand, the South Western Cape experiences an increasing Winter and Spring rainfall trend during the period 1980-2019, resulting in an increased annual rainfall during the same period and a general long-term increasing trend. This observation of increasing trend is in line with the findings of Kruger and Nxumalo (2017), Van Wageningen and Du Plessis (2007) and Donat *et al*. (2013) who observed an increase in the amount of rainfall for the same region. Further, Ndebele *et al.* (2020), observed an insignificant increasing Winter trend. The observed trends suggest possible increase in the annual rainfall for the Breede WMA at the South Western Cape, with a decrease in annual rainfall at the North-Western Cape region for the same WMA.

The South Coast zone experiences an 'All year' rainfall. This climatic zone covers the Breede and Mzimvibu WMAs. The Summer, Autumn, and Winter seasons are observed to have either increasing or fluctuating sub-trends resulting in Summer and Autumn having long-term increasing trends with Winter having no significant long-term trend. On the contrary Spring records a long-term decreasing trend after recording an increasing short-term trend (1900-1939) and a decreasing short-term trend (1980-2019). For the period 1940-1979, no significant trends were observed. These seasonal trends resulted in fluctuating annual long-term trends. However, the increasing annual rainfall trends dominate the Mzimvubu and Breede WMAs hence getting wetter. These observations are in line with the findings of Du Plessis and Schloms (2017) who observe a shift towards a longer rainfall season at the South Coast.

The Southern Interior zone is a Summer rainfall region, adjacent to the South Coast, and covers the Breede and Mzimvubu WMAs. The effects of the South Coast climate to the Southern Interior could be observed in the similarity of trends across the four seasons (Summer, Autumn, Winter, Spring). Summer is observed to have a fluctuating long-term trend. Increasing trends dominate the Mzimvubu and Breede WMAs, similar to the South Coast. While Kruger (2006) observed a trend of decreasing length of the wet season, Kruger and Nxumalo (2017) observed a trend of increasing rainfall for the same region The findings of this research complement the findings of the latter in observing an increasing seasonal and annual rainfall trend.

The Western Interior zone experiences a general fluctuating trend. Summer is its main rainfall regime and is observed to have a long-term fluctuating trend. The Orange WMA is majorly covered by this climatic zone. The western part of the Orange WMA is arid with few rainfall stations. However, this zone records an increasing trend in Summer and annual rainfall. The

Spring season is observed to have decreasing short-term trends (1940-1979 & 1980-2019). Autumn and Winter rainfall trends fluctuate. The Orange WMA is therefore anticipated to have fluctuating rainfall in contrast to Kruger and Nxumalo (2017) observation of an increasing rainfall trend for the Western parts of South Africa.

The Central Interior zone covers mainly the Vaal and parts of the Limpopo and Pongola WMAs. Summer is its main rainfall regime. The zone is observed to have significant trends in the Summer and Spring seasons, and also at an annual time step. The Winter season records a consistent decreasing trend while the Autumn season records a consistent increasing trend over the three short-term periods. Further, observing the Spring sub-trends, during the period 1980-2019, decreasing trends were recorded. This was a suggestion of a shift towards a late but extended rainfall season likely to impact on the respective WMAs. Tadross *et al.* (2005), complement the findings of this research by observing a late onset for this zone.

The KwaZulu-Natal (KZN) zone at the North-Eastern part of South Africa experiences a Summer rainfall regime and covers the Pongola and Mzimvubu WMAs. The KZN records very few significant trends (Table 16) complementing findings of Groisman *et al.* (2005) who observed no change in the Summer and annual rainfall over the same zone. The Autumn rains decreased, suggesting shortening of the Wet season as observed by Kruger (2006) and Nel (2009). While Thomas *et al.* (2007) observed a tendency of a shift in seasons towards an early seasonal rainfall with decreasing trends for the late seasonal rainfall, this research makes a contrasting observation of decreasing Summer and Spring rains, especially for the period 1980-2019.

The North-Eastern Interior zone is situated at the northern most part of South Africa, at the Limpopo and Pongola WMAs. The zone experiences Summer rainfall. The zone is observed to have a fluctuating seasonal trend resulting in no significant long term annual trends. Summer rainfall is observed to be having a consistent increasing trend over the periods 1940-1979 and 1980-2019. However, the zone experiences a long-term decreasing Summer rainfall suggesting it is getting drier as observed by Thomas *et al.* (2007). The Spring season was observed to have a long-term increasing trend. However, for the period 1980-2019, the Spring rains decreased in line with observations of Thomas *et al.* (2007). While Autumn is observed to have a long-term decreasing trend, further complementing works of Thomas *et al.* (2007), the sub-trends record no significant trends, contrasting observations by Tadross *et al.* 2005) of significant decreasing trends for the period 1979-1997 at the Limpopo WMA. Generally, the Limpopo WMA at the North-Eastern Interior zone is getting drier.

In general, the long-term increase in annual rainfall has been observed to be gradual but insignificantly low. Across the 8 climatic zones, there is a general consistency towards slight to no increase in annual rainfall apart from exceptions such as the North and South Western Cape which consistently recorded decreasing trends in annual rainfall. For these two climatic regions, only the latter records a statistically significant increasing trend during the period 1980-2019. Whereas the South Coast, South Western Interior, Western Interior and Central Interior zones record long-term increasing trends, the KwaZulu-Natal and North-Eastern Interior zones recorded no significant trend as a result of alternating increasing and decreasing trends over the short-term periods (1900-1939, 1940-1979 & 1980-2019). These variations result in an insignificantly low long-term increase, in the annual rainfall of South Africa.

When critically analysing the amount and trends of rainfall, it was observed that for some periods there were increasing trends for a given season with succeeding and preceding seasons recording decreasing trends and the vice versa. From this phenomenon and linking it to the monthly rainfall characteristics and trends a likely shift towards an early or late wet season could be observed across the different short-term periods. For example, during the period 1940-1979, increasing trends were recorded in the climatic zones of the Summer rainfall region while there was a decrease in the amount of Spring rainfall and a significant increase in Autumn rainfall. This suggests a late but extended wet season in these climatic zones of Summer rainfall region during the period 1940-1979. On the other hand, the climatic zones of the Winter and 'All year' rainfall regions had a significant increase in the amount of rainfall received in Autumn and Winter seasons, suggesting an early wet season for these regions. In the period 1980-2019, the trends shift. The climatic zones of the Summer rainfall region record increased Summer and Spring rains with a decrease in Autumn rains, suggesting a shift towards an early but short wet season. However, for the climatic zones of the Winter and 'All year' rainfall regions, the Winter rains increase while Autumn rains decrease hence a shorter but more wet season.

From the above-described phenomenon, it could be suggested that a limited alternating seasonal shift in the climatic zones of the Summer rainfall region with little change in mean annual rainfall was observable. On the other hand, the climatic zones of the Winter rainfall region were shifting towards a shorter but wetter rainfall season. The implication of the described seasonal shifts is a more pronounced seasonal cycle. The climatic zones of the ‘All year’ rainfall region experienced similar alternating shifts in seasonal rainfall. In conclusion, the increase in rainfall over South Africa remains to be relatively low with pronounced seasonal cycle.

6 Conclusions and Recommendations

This chapter gives a conclusion of the research through a discussion, highlighting key results and thereafter provide recommendations.

6.1 Conclusions

This research was based on eight-point objectives in trying to answer whether there are rainfall trends in South Africa, the significance of the trends, the rate of change and how it compares with previous research output. A non-parametric approach was favored after identifying the need for its application to rainfall trend analysis and the benefits thereof. The research starts by dividing the country into six regions defined by Water Management Areas (WMAs). The selection of the WMAs was based on the fact that most of the effects of rainfall trends and variability to the South African economy and other important production sectors such as agriculture can be primarily conciliated through the water sector. These WMAs are; Limpopo, Pongola, Vaal, Orange, Mzimvubu and Greede-Gouritz. However, it was thereafter noted that in selection of these WMAs, their definition based on a hydro-climatic context would not agree with homogenous climatic zones. This led to the identification of three rainfall regions (Winter, Summer, 'All year') defined by the characteristics and distribution of rainfall in South Africa. These three rainfall regions were then classified into eight climatic zones as defined by SAWS. The climatic zones are; North-Western Cape, South Western Cape, South Coast, Southern Interior, Western Interior, Central Interior, KwaZulu-Natal, and North-Eastern Interior. These climatic zones formed the basis of discussion of rainfall trends and in summary a brief overview of possible effects of trends to the respective WMAs are highlighted.

Having defined the study area, the longest available set of daily observed rainfall data was targeted, while trying to have an adequate regional representation of rainfall station distributions across South Africa. A 120-year long rainfall dataset (1900-2019) provided for a robust analysis of rainfall trends capturing both short term (40-year periods) and long term (120 years) trends. Data quality analysis was performed, and anomalous data discarded. Gaps identified were filled using the Normal Ratio (NR) method. Homogeneity analysis was performed using absolute homogeneity tests (Pettit, Buishand, SNHT, Von Neumann), removing inhomogeneous data sets with possible artificial trends. The homogenous data were then characterized into daily, monthly, annual, and seasonal time steps. The mean, max, min, variation, skewness, and kurtosis for the respective time steps were determined for both short-term and long-term periods. Thereafter, trend analysis was performed using the Mann-Kendall test and the rate of change computed using Sen's slope estimator. Trend analysis was done at daily, monthly (12 months), annually, and seasonally (Summer, Autumn, Winter, Spring) for both long-term and short-term periods. The results of trend analysis were then discussed in light of the eight climatic zones and rainfall regions. Because of the climatic zones overlapping across different WMAs, the trends taking place at different WMAs and the possible effects from the trends were discussed under trend analysis summary while comparing with previously observed trends.

The results highlight high variability in rainfall received across South Africa from daily, monthly, seasonal to annual time steps. The country had a coefficient of variation of 31%, with a mean annual rainfall of approximately 560 mm. The maximum and minimum annual rainfall recorded was 3248 mm and 19 mm, respectively. The results for daily trends analysis were insignificant. Monthly trends had November, December and January recording significant increasing trends in the Southern, Western and Central Interior zones of the Summer rainfall region and North-Western Cape of the Winter rainfall region. March, May, June, and September had decreasing trends across the country, while July and August had only a single station each recording significant trends.

The increase in annual rainfall was observed to be gradual, but insignificantly low during the period 1900-2019. The increasing trend was observed particularly at the South Western Cape and Central Interion zones while the South Coast, Southern Interior and Western Interior zones had fluctuating trends. Analyzing the annual trends further, during the period 1900-1939, decreasing trends were recorded at the North-Western Cape, South Western Cape and the Kwa-Zulu Natal zones while increasing trends took place at the South Coast, Southern Interior, Western Interior, Central Interior and North-Eastern Interior zones. During period 1940-1979, annual rainfall trends were almost similar to the first period (1900-1939) while during the final period, 1980-2019, significant decreasing trends were recorded only in the Central Interior, KwaZulu-Natal, and North-Eastern Interior zones. The observed periodical shift in trends, increasing to decreasing and vice versa, across the respective climatic zones confirm the insignificantly low increasing long-term annual trends.

The seasonal rainfall trends were observed to be shifting. During the periods 1900-1939 and 1980-2019, a similarity in the trends of seasonal rainfall was observed. During the period 1940-1979, the climatic zones of the Summer rainfall region had a decrease in the amount of Summer and Spring rains with an increase in Autumn rains suggesting a late but extended Winter. On the other hand, the climatic zones of the Winter and 'All year' rainfall regions had a significant increase in the amount of Winter and Autumn rains suggesting an early wet season. During the period 1980-2019, the climatic zones of the Summer rainfall region record increased Summer and Spring rains with decreased Autumn rains suggesting a shift towards an early but short wet season. The climatic zones of the Winter and 'All year' rainfall regions record showed increasing Winter rains with decreasing Autumn rains hence shorter, but wetter rainy seasons.

The observed annual and seasonal trends have possible effects on the WMAs. The Limpopo WMA in the North-Eastern Interior zone is getting drier with the observed decrease in rainfall especially during the period 1980-2019. The Pongola and the Vaal WMAs are observed to be having a tendency of getting wetter. Significant long-term increasing trends are observed in these two WMAs. However, during the period 1980-2019, a tendency towards late onset of rains is noted and a short-term decreasing trend recorded. The Mzimvubu and Orange WMAs experience a fluctuating trend, recording both increasing and decreasing trends across the three short-term periods. However, despite the fluctuating trends, increasing trends dominate and the WMAs are likely to be getting slightly wetter. The Breede WMA was getting drier until the period 1980-2019 when slight increases in rainfall were recorded in the South Western Cape. However, the North-Western part of the WMA seems to be getting drier.

In conclusion, after analysing and observing the annual and seasonal in long-term (120 years) and short-term (40 years) trends of South Africa, this research finds that the following rainfall trends can be observed.

- The climatic zones of the Summer rainfall region (KZN, Southern, Western, Central and North-Eastern Interior regions) experienced alternating trends shifting across the three short-term periods towards an early or late wet season with little change in mean annual rainfall. In the long-term, an insignificant increase in annual rainfall is observed.
- The climatic zones of the Winter rainfall region (South and North-Western Cape) had its main rainfall season becoming shorter but wetter over the three short-term periods of analysis. In the long-term, a decrease in annual rainfall at the North-western Cape and a slight increase at the South Western Cape are observed.

- The South Coast zone of the ‘All year’ rainfall region experienced alternating shifts of dry and wet cycles during the short periods with slight decreasing mean annual rainfall in the long-term.
- Generally, the seasonal rainfall cycle of South Africa illustrated a shorter but more pronounced trend progressively for the three short-term analysis periods. Only a marginal increase in annual rainfall was observed using the long-term analysis, while variability increased over the years, using the short-term analysis.
- In conclusion, the observed trends, using the non-parametric approach, did not have significant deviations from previously observed trends. However, the observed change in rainfall remained to be relatively low.

6.2 Recommendations

Based on the findings of this research, the following recommendations are made:

- Slight changes in rainfall for South Africa are observed over the past 120 years. Therefore, the use of projected rainfall (climate change) data in South Africa, should be well guided by considerations based on the observed rainfall data trends.
- Design and management decisions based on long-term climate change projections should be considered carefully, taking the design life of the infrastructure into consideration.

For further studies, the presence, nature and distribution of extreme rainfall trends in South Africa should be studied for short term periods of 40 years or less. This would be paramount to the further understanding of the rainfall trends of South Africa.

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Appendices

This section contains tables and figures of data and results provided electronically as part II of this report. It is structured in four parts: Appendix A, B, C & D on data quality analysis, homogeneity analysis, rainfall characteristics and trend analysis, respectively.