Extreme Rainfall Distributions: Analysing change in the Western Cape

JAN DE WAAL BSc(Hons)
16848861

Thesis submitted in fulfilment of the requirements for the degree MSc (in Geography and Environmental Studies) at Stellenbosch University.

SUPERVISOR: Dr JN Kemp

CO-SUPERVISOR: Mr A Chapman

2012

DEPARTMENT OF GEOGRAPHY AND ENVIRONMENTAL STUDIES

DECLARATION

By submitting this research report electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the owner of the copyright thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Signature: --

Date: --

ABSTRACT

Severe floods in the Western Cape have caused significant damage to hydraulic structures, roads and other infrastructure over the past decade. The current design criteria for these structures and flood return level calculations are based on the concept of stationarity, which assumes that natural systems vary within an envelope of variability that does not change with time. In the context of regional climate change and projected changes in rainfall intensity, the basis for these calculations may become unrealistic with the passage of time. Hydraulic structures and other infrastructure may become more vulnerable to damaging floods because of changing hydroclimatic conditions. This project assesses the changes in extreme rainfall values over time across the Western Cape, South Africa.

Using a Generalised Pareto Distribution, this study examines the changes in return levels across the Western Cape region for the periods 1900-1954 and 1955-2010. Of the 137 rainfall stations used in this research, 85 (62%) showed an increase in 50-year return level, 30 (22%) a decrease in 50-year return level and 22 (16%) stations displayed little change in rainfall intensity over time. While there were no clear spatial patterns to the results, they clearly indicate an increase in frequency of intense rainfalls in the latter half of the 20th and early 21st century. The changes in return level are also accompanied by a change in the frequency of high intensity 2-3 day long storms. 115 (84%) of the 137 rainfall stations showed an increase in the frequency of long duration, high intensity storms over the data record. This change generates a shifting risk profile of extreme rainfalls, which, in turn, creates challenges for the design of hydraulic structures and any infrastructure exposed to the resulting damaging floods. It can therefore be argued that it is inappropriate to design structures or manage water resources assuming stationarity of climate and that these principles should be assessed in order to reduce the risk of flood damage owing to increasing storm intensity.

KEY WORDS

Flood Risk, Stationarity, Disaster Risk, Hazard, Extreme Rainfall, Generalized Pareto Distribution, Climate

ACKNOWLEDGEMENTS

I sincerely thank:

- The South African Weather Service
- Richard Kunz of UKZN
- Arthur Chapman
- Dr Jaco Kemp
- USAID

for their assistance and advice to this study.

CONTENTS

TABLES

FIGURES

ACRONYMS AND ABBREVIATIONS

CLT	Central Limit Theorem
DiMP	Disaster Mitigation Programme for Sustainable Livelihoods
DMA	District Municipal Area
DWA	Department of Water Affairs
EVD	Extreme Value Distribution
EVT	Extreme Value Theory
GEV	Generalized Extreme Value
GIS	Geographic Information Systems
GDP	Gross Domestic Product
GPD	Generalized Pareto Distribution
POT	Peaks Over Threshold
SANParks	South African National Parks
SANRAL	South African National Roads Agency Ltd
SDF	Standard Design Flood
SRES	Special Report on Emissions Scenarios

1 INTRODUCTION

The impacts of and projected changes in extreme hydrometeorological events globally have featured prominently and have been widely documented in academic literature over the past few decades (IPCC, 2012). This change in awareness has also been displayed locally and may stem from an apparent increase in extreme flood and drought events across Southern Africa (DiMP, 2010) together with the global concern over future climate change and the implications it has for water and flood management as well as agriculture.

Substantial losses to infrastructure, agricultural land and human life can be attributed to flooding over the past decade, particularly in the Southern Coast of the Western Cape, with intense flood events occurring in Montagu, Heidelberg and other district municipalities over the past decade (DiMP, 2010). Midgley *et al.* (2005) suggest that the Western and Northern Cape provinces of South Africa are most at risk to the impacts of climate change, with a projected decrease in winter rainfall in the Western Cape as well as a possible increase in intensity and irregularity of rainfall events in the province. The DiMP RADAR publication (DiMP, 2010) reports that over ZAR2.5 billion (~$290million) damage can be attributed to eight severe floods, caused by cut-off low weather systems in the Western Cape, between 2003 and 2008. This extensive damage is the responsibility of several national government departments, provincial government departments, district and local municipalities and the private sector (including agriculture) (DiMP, 2010). The social and economic costs of flooding in the Western Cape are therefore shown to be problematical and a severe hindrance to socio-economic development due to flood response measures requiring substantial financial and human resources. Damaging flood risk is therefore a significant problem in the Western Cape.

Flood planning is generally based on calculated flood threshold levels, including a 1:50 year flood line (see for example SANRAL (2007)). However, the definition of flood thresholds is based mostly on concepts of stationary weather data and stationary land-use patterns. Although these may be updated from time to time, planning based on such estimated thresholds could potentially become outdated as rainfall patterns change over time. A failure to accommodate changing thresholds potentially exposes inhabitants of flood-prone lands to a significant change in likelihood and magnitude of hazard exposure.

Milly *et al*. (2008) point out that the assumption of stationarity is dead. These claims are echoed by studies by Stedinger *et al.* (1985); Matalas (1998); and Schilling and Stakhiv (1998) amongst others, which point to the need for water resource engineering practices and research to review the assumptions of stationarity.

1.1 CONCEPTUAL FRAMEWORK

Effective disaster risk mitigation and management requires an understanding of the drivers of vulnerability: exposure, resistance and resilience (Pelling, 2003). Pelling's model is, however; a static model and does not take into account changes to these factors over time. It is important to understand how flood drivers are changing over time – particularly in the context of global climate change and the climatological risk profile of the Western Cape (Midgley *et al.*, 2005, for example). This will better inform flood mitigation strategies and planning – including the need to prevent current and future occupation of flood-prone areas by humans.

The Pressure and Release Model (Wisner *et al.*, 2004) assesses changing or "progressive" vulnerability. The Pressure and Release Model aims to understand and assess the vulnerability of a system or people group in a holistic manner, where current vulnerability stems from root causes (Wisner *et al.*, 2004). These root causes lead to the dynamic pressures which are placed on a system. When such pressures placed on a system are met with exposure to a hazard there is the potential for the occurrence of a disaster event (Wisner *et al.*, 2004).

The over-arching conceptual framework for this thesis accounts for the changes in natural hazards with time. These changes can include the magnitude, frequency and seasonality of the natural hazard, which, in turn, affect the exposure of human populations and infrastructure. One well-understood definition of disaster risk is that it is a product of hazard and vulnerability (Wisner *et al.*, 2004). Pelling (2003) defines vulnerability as a function of exposure, resilience and resistance. The static nature of the model, unlike the Wisner *et al*. (2004) "Pressure and Release" model, limits the model in the assessment of changes vulnerability conditions.

As a result this project will use a conceptual framework that assesses the change in exposure to a hazard (in this case extreme rainfall) over time. It is important to note that the framework used will assess changing risk (as a function of changing exposure) as opposed to changing vulnerability, where risk is defined by the UNISDR (2009) as "The combination of the probability of an event and its negative consequences". Flood risk is therefore driven by exposure to results of extreme rainfall, and consequences of that exposure.

Any increase in frequency and intensity of extreme rainfall events over the historical record will increase the degree of exposure to which a system is subjected. An increase in exposure increases the risk of flooding and the vulnerability of the system to damaging flooding. It is therefore important to assess how extreme rainfall has changed over time (exposure) and thus changed the risk of damaging floods to the Western Cape.

1.2 FORMULATION OF THE RESEARCH PROBLEM

The results of a study by de Waal (2010) suggest a change in the frequency of occurrence and intensity of extreme weather over the last two decades in the southern part of the Western Cape, resulting in marked damage to infrastructure, agriculture and human life. Figure1.1 (below) shows some of the results from de Waal (2010) where the frequency of extreme events (>70mm) at one weather station in the Duiwenhoks river catchment is shown to increase from 33 events between 1950 and 1979 to 54 between 1980 and 2009, as well as an increase in the magnitude of these events.

This pattern of change is apparent at several other stations (0025450_W Dun Donald and 0009783_W Blackdown) in the Duiwenhoks catchment of that study, raising the question of whether there has been a long-term change in the frequency of severe weather in the Southern Cape. Such changes, if they exist statistically and are significant, could pose substantial challenges to planning standards and infrastructural integrity. It is the intention of this thesis to conduct a formal assessment of whether such changes do exist or not.

This thesis investigates if extreme rainfall patterns have changed over time in the Western Cape. It draws from literature the implications of these changes on various socio-economic sectors. The research approach is to utilise the change over time of the statistical extreme value distributions of rainfall.

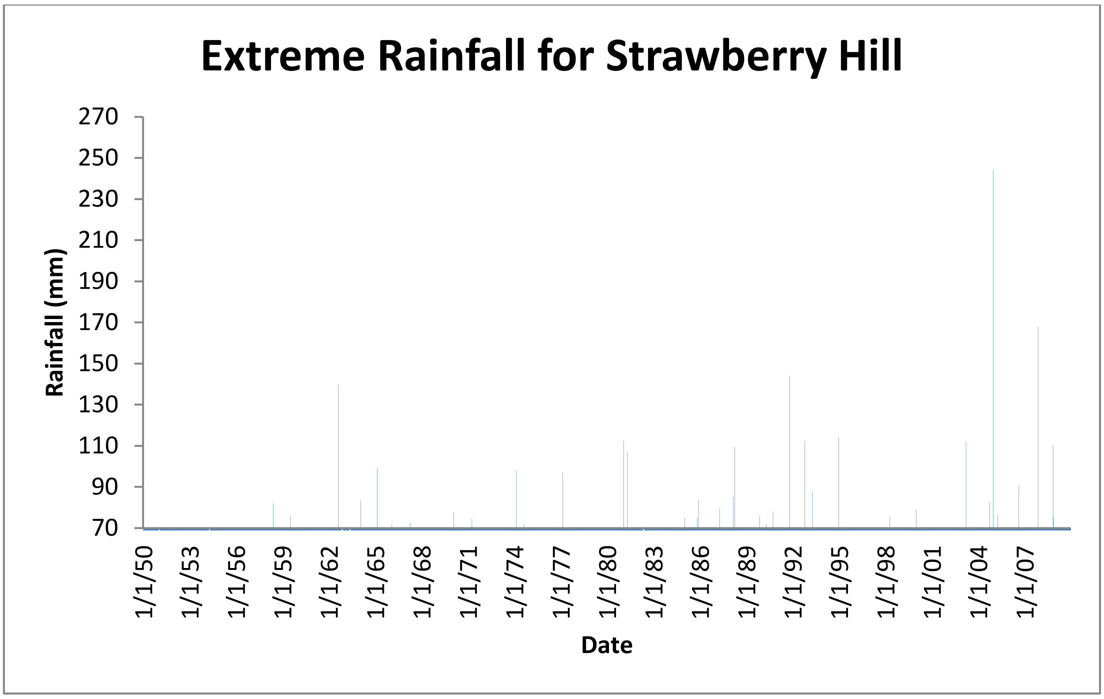

Figure 1.1 Extreme rainfall events between 1950 and 2009 for the Strawberry Hill rainfall station in the Duiwenhoks River Catchment. Note the increase in frequency and magnitude of extreme rainfall events over time.

(Source: de Waal, 2010)

The results and conclusions drawn from the data analysis will then be placed in a "disaster risk" context by assessing how extreme rainfall changes can increase or reduce the risk of a disaster occurrence in the Western Cape.

1.3 RESEARCH AIM AND OBJECTIVES

The aim of this research project is to determine whether the frequency and intensity of extreme rainfalls in the Western Cape have changed through the historical record and to discuss the implications of such change on various socio-economic sectors.

To achieve this aim, the following objectives have been set:

a) Statistically assess how extreme rainfall records have changed through the historical record using software capable of examining extreme value distributions;
b) Determine whether there is a coherent spatial pattern emerging in the changes of extreme rainfall in the different regions in the Western Cape;
c) Discuss how results might influence the future assumptions of stationarity for the Western Cape and what implications this might have on the design of hydraulic structures and design criteria utilised, should changes be detected.

1.4 OVERVIEW OF METHODS

Katz *et al.*, (2005) state that "It is the unusual disturbances that have disproportionate effects on ecosystems". It is, therefore, the rare, but extreme, event with its implied excursion outside an expected range of thresholds that causes the greatest impact. It is not the averages or even variances, which are adequately described within the Central Limit Theorem (CLT), that are useful for describing the statistical nature of these rare events. As described in more detail later, the CLT is not very useful at the edges of a distribution, where it tends to underestimate the severity of an event. What is needed is the use of a separate method – which is the statistics of extremes. The application of this technique to the problem of rainfall in the Southern Cape is the basis of this thesis.

One of the most important tasks in analysing extremes is to choose the basis for calculation of the statistics of extremes (Katz, 2010). There are two fundamental approaches used in extreme value theory: the "Block Maxima" approach and "Peaks over Thresholds" (POT) approach

(Katz, 2010). The block maxima approach relies on the identification of the highest magnitude value for each year and fitting a distribution to the data, while the POT approach fits a distribution to all data points that exceed a defined threshold (Katz, 2010). This project uses a POT approach to calculate changing return levels for 137 rainfall stations across the Western Cape. The reasons for the choice of calculation method are discussed in greater detail in the methods section of the project. The results are then analysed spatially using ArcGIS to determine whether there are any spatial trends to these changes.

2 BACKGROUND TO RESEARCH PROJECT

Milly *et al*. (2002) state that the number of severe floods has shown a large increase through the twentieth century. Furthermore, the risk of severe floods, in excedance of the 100-year flood level, is projected to increase in the future due to increasing rainfall intensities. The Western Cape Province has been impacted by severe storms occurring almost annually over the past decade (DiMP, 2010), which has resulted in substantial damage to agriculture, development, roads and hydraulic structures. This includes the washing away of bridges, breaking of dam walls and other hydraulic structures, damages to culverts, washing away of sewerage works and damage to property (DiMP, 2010). All infrastructure and town planning should take into account the possible flood-lines and return levels of extreme events. However; while national and provincial roads as well as hydraulic structures are designed to accommodate high magnitude floods (SANRAL, 2007) the estimation methods of these flood-lines and return levels are based on the assumption of stationarity. Flood levels are shown to be increasing over time in some places in the world (Milly *et al.*, 2002). The estimation of flood return levels requires long data records (multi-decadal) of high quality data (Milly *et al.*, 2002). Unfortunately, in many areas, the length of the data record is a limiting factor in the assessment of these return levels. In such cases the possibility of climate change in a region is largely ignored and a concept of “stationarity” is assumed (Milly *et al.*, 2008). Stationarity is the theory that natural systems vary within an envelope of variability that does not change with time. This is a foundational concept that is prevalent throughout hydrological engineering practice (Milly *et al.*, 2008). The design of hydraulic structures and flood-lines are therefore based on this concept, assuming that weather events are independent outcomes of a stationary climate (Milly *et al.*, 2008). It is, however, evident that climate is changing at a rapid rate in some places (Bates *et al.*, 2008) and that the concept of stationarity is no longer an appropriate assumption on which to base return level calculations. Extreme value analyses in South Africa have largely been predicated on stationary rainfall processes (e.g. Alexander (1990), Kjeldsen *et al.* (2002) and Smithers & Schulze (2004)). This thesis is therefore a first look at whether stationarity exists in the Western Cape, where flooding has caused substantial damage and financial losses recently.

2.1 STUDY AREA

The study area for the research project is the Western Cape of South Africa (shown in Figure 2.1). The rainfall stations used in this analysis are distributed throughout the province. In total, 137 rainfall stations were used in this study (Figure 2.1). The Western Cape has significant changes in topography from the coastal plain, to the escarpment, to the plateau of the Karoo. These changes in topography influence the volume of rainfall received across different areas in the Western Cape. The region falls in a winter rainfall zone, where mid-latitude cyclones bring rainfall to the Southern Coast.

The Western Cape of South Africa has a Mediterranean climate and therefore receives most of its precipitation in the winter from frontal systems, which are driven by westerly waves between 40°S and 50°S (Tyson & Preston-Whyte, 2000). The rainfall pattern is also influenced by the Cape Fold Mountains, which creates an orographic effect. Certain areas in the Western and Eastern Cape provinces (which includes the zone from Grabouw to Knysna and beyond) are exposed to "cut-off low" weather systems which can cause significant volumes of rainfall to fall in a short period of time (Singleton & Reason, 2006). These storms are not limited to coastal areas and have been known to affect inland areas as well. Cut-off low weather systems can be defined as a mid-latitude cyclone that becomes separated from the main low pressure system and moves off independently (Tyson and Preston-Whyte, 2000). These storms lose momentum when they are no longer part of the westerly wave system and therefore move very slowly. Cut-off low weather systems are largely associated with great atmospheric instability and convection, resulting in intense rainfall, snow on high altitude surfaces and strong winds (DiMP, 2010). As a result, cut-off lows are often one of the main drivers behind severe floods in the Western Cape. The most notable example of the disastrous effect this can have is the tragic loss of 104 lives in the Laingsburg floods in 1981.

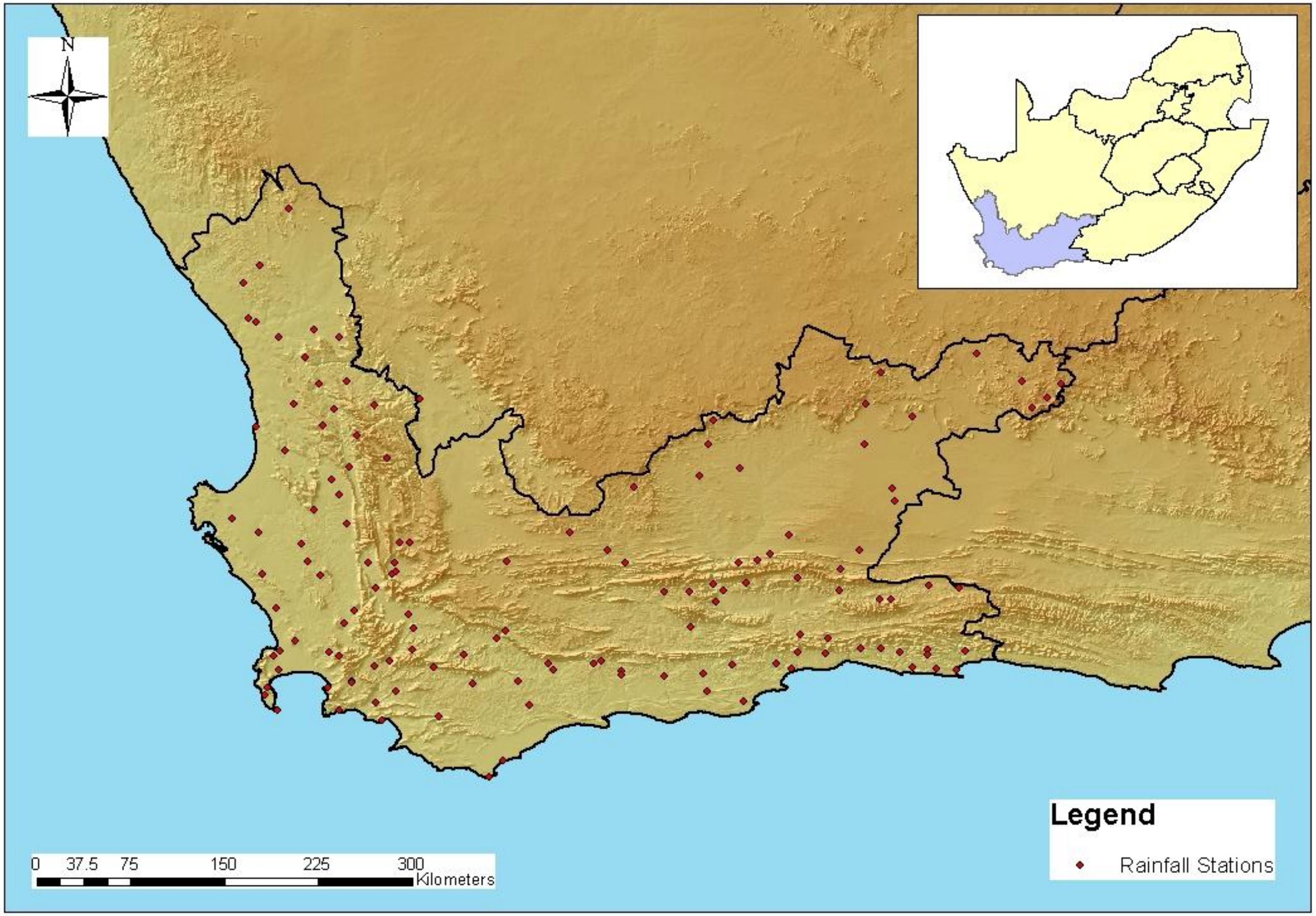

Figure 2.1 The Western Cape Province of South Africa

Figure 2.2 below shows the mean annual rainfall distribution for the Western Cape:

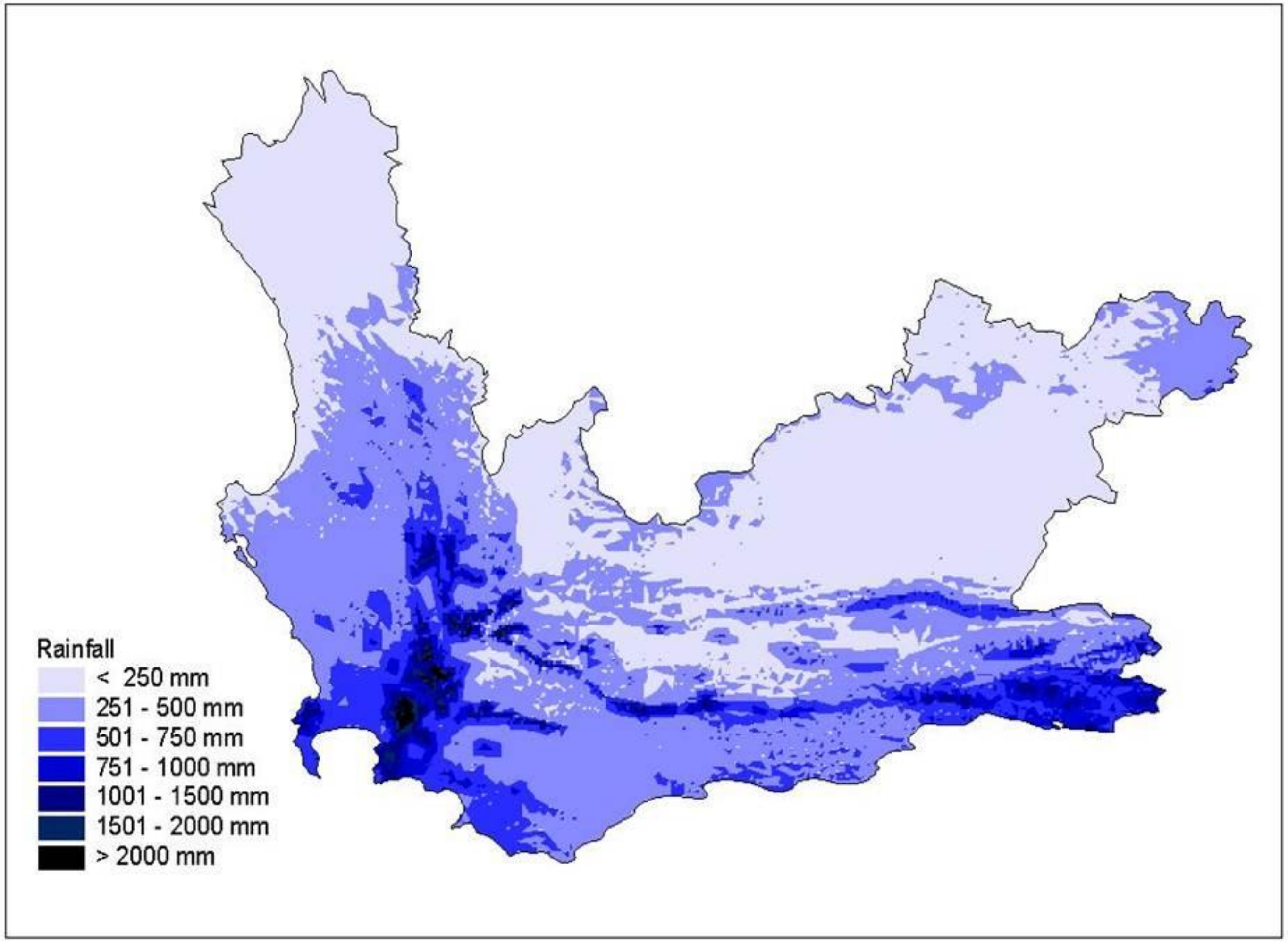

Figure 2.2 Mean annual precipitation for the Western Cape

(Source: Midgley *et al.*, 2005)

Figure 2.2 shows that mean annual precipitation in the region is largely influenced by topography, with increases in mean precipitation noticeably over the escarpment (>2 000mm in some areas) and Cape Fold Mountains, while the interior of the Karoo and West Coast are much drier areas which can receive as little as 50mm.

Stats SA estimates that roughly 10.45% (5 287 863) of the country's total population lives in the Western Cape which is also one of two regions (along with Gauteng) experiencing an increase in migration from other provinces. The highest population density is in the greater Cape Town Metropolitan area. An estimated 206 000 people migrated into the Western Cape between 2006 and 2011. This is offset by an estimated out-migration of approximately 111 000 for the same period. As a result the Western Cape has the second largest (to Gauteng) net migration of all the provinces in South Africa (StatsSA, 2011). This infers a rapidly growing population and redistribution to urban areas such as Cape Town. The Western Cape comprises five district municipalities, namely the: West Coast, Boland, Central Karoo, Eden and Overberg district municipalities as well as the City of Cape Town (DiMP, 2010). PROVIDE (2005) suggests that, in 2000, roughly 62.2% of the province's population was located in metropolitan areas, 27.4% in smaller towns and 10.4% in rural areas. This poses significant risk in urban areas, where larger numbers of people are exposed to extreme events.

In 2003, the Western Cape contributed an estimated 14.5% of the National Gross Domestic Product (GDP) (PROVIDE, 2005). The estimated GDP per capita for 2000 was roughly R21 300 – significantly higher than the national mean of R12 400 (PROVIDE, 2005). In 2000 the average household earned a combined income of R75 000 (PROVIDE, 2005). This, however, does not show the difference in earnings across racial groups and agricultural/non-agricultural households. On average, white, non-agricultural households earned R165 320 per annum, which is substantially higher than the household earnings of agricultural African and coloured households, which earned, on average, R14 700 and R28 100 respectively (PROVIDE, 2005). This marked difference in earnings clearly indicates high levels of inequality in the province, where agricultural households are generally poorer than non-agricultural ones. The low levels of income among the rural poor increase their vulnerability to damaging floods brought about by extreme events due to their lack of resources to cope with and recover from severe floods. Similarly, poor populations have settled on land that is prone to flooding, which has increased their exposure to the hazard.

2.2 RELEVANT LITERATURE

This section will discuss the literature relevant to this study. The literature was divided into several clusters:

- Contextual Literature
- Climate Change
- Flood Management
- Design Flood
- Disaster Risk and Vulnerability Theory
- Theory of Extremes

2.2.1 Contextual Literature

Cut-off low and severe frontal weather systems have been associated with significant floods in the Western Cape over the past decade, with national "states of disaster" being declared after several events (Midgley *et al.*, 2005). Changes in rainfall pattern trends, particularly extreme rainfall, have recently received much attention due to the increasing economic, social, infrastructural and human losses associated with extreme rainfall (Milly *et al.*, 2008). From the period of 2003 to 2008, the Western Cape was hit by eight cut-off low weather systems bringing intense precipitation and causing significant floods (DiMP, 2010). The dates of these floods, as well as the associated financial losses, are presented in Table 2.1.

Table 2.1 Financial losses due to extreme flood events in the Western Cape (2003-2008)

DATE	AREA	FINANCIAL LOSS
March 2003	Montagu	R 238.3 million
December 2004	Eden District Municipality	R 57.9 million
April 2005	Overberg and Karoo districts	R 8.9 million
August 2006	Southern Cape Municipalities	R 479.2 million
June 2007	The West Coast municipalities	R111.3 million
November 2007	The Overberg, Eden and Cape Winelands districts	R 830.9 million
July 2008	The West Coast municipalities	R 57.0 million
November 2008	Cape Winelands and Overberg districts	R 791.2 million

(Source: DiMP, 2010)

The floods listed above have caused approximately R2.5 billion damage to various sectors of the economy, governmental departments and local municipalities (DiMP, 2010). The single biggest storm in terms of damage done for this period was the November 2007 event which caused in excess of R830 million damage to the Eden, Overberg and Cape Winelands districts (DiMP, 2010). National departments and parastatals (state owned enterprises) typically affected by a flood event are the Department of Water Affairs (DWA), South African National Parks (SANParks), South African National Roads Agency (SANRAL), Transnet, and Telkom. Provincial government departments most affected by flooding are Agriculture, Education, Cape Nature, Housing, Provincial Roads, Public Works and Emergency Services (DiMP, 2010). The economic sector affected the most by these eight intense storms in the Western Cape was agriculture, which suffered reported losses of up to R1 billion over the five-year period from 2003 to 2008 – 57% of the total damage cost to provincial departments (DiMP, 2010). Of the national departments affected by these flood events, SANRAL, Transnet and DWA accounted for 38%, 36% and 18% of the total damage costs, where roads and railway lines are damaged as well as repeated damage to flow-gauging stations in rivers and dams. Furthermore, the recurrence of these extreme rainfall events seems to repeatedly affect the same local municipalities and districts, particularly the Eden, Overberg and Central Karoo districts. The constant exposure of the same areas to extreme rainfall increases the vulnerability (by reducing the coping capacity of the region) and impacts of flooding on the region by reducing the recovery time after a severe event (DiMP, 2010). Flooding clearly has a substantial impact on many departments and particularly agriculture in the Western Cape.

2.2.2 Climate Change

Although flood controls are numerous, ranging from vegetation cover and land use to underlying geology and gradient of a catchment, the dominant driver of flood causation is intense rainfall falling for the time of concentration. Midgley *et al.* (2005) project that rainfall totals are likely to decrease in the Western Cape in the future, although the intensity of rainfall events is likely to increase, particularly in mountainous regions. There is a projected southward shift of the westerly wave due to a stronger Hadley circulation and increased humidity in the future (Midgley *et al*., 2005). The westerly wave is the track along which mid-latitude cyclones form and travel. As mid-latitude cyclones are the dominant source of rainfall for the Western Cape, a southward shift would reduce the number of cold fronts passing over the Western Cape and thus reduce the number of rainfall events (Midgley *et al.*, 2005). However, an increase in humidity due to increased energy in the earth’s system would potentially result in greater amounts of rainfall and thus the intensity of events may increase (Trenberth *et al.*, 2003). Analyses of rainfall distribution patterns have, in the past, largely focussed on medians, means and trends (Gilleland & Katz, 2006). The Fauchereau *et al.* (2003) study of South African data sets suggest that the daily rainfall distribution has changed since the 1970s, with a large portion of South Africa indicating a shift towards a higher frequency of extreme events. This suggests that while the intensities of extreme events are projected to increase over time, the frequency of these extreme events occurring has already shown to be increasing through the historical record. Studies performed by Crimp & Mason (1999), Groisman *et al.* (2005), Kruger (2006), Mason & Joubert (1997) and New *et al.* (2006), all suggest the same outcomes; however, these assessments have not applied standard classical extreme value statistics to the problem.

Mukheibir (2008) describes the variable and unpredictable nature of water availability in South Africa as a limiting factor towards development, and thus any changes in the rainfall distribution could have significant impacts on various governmental sectors as well as compounding the vulnerability of the poor. Increased intensity in extreme rainfall events could increase the probability of flood and soil movement (landslides etc.) damage, increase soil erosion and degradation, destroy agricultural produce and storage systems, as well as increase the pressure on flood relief efforts and the insurance sector (van Aalst, 2006).

2.2.3 Flood Management

The potential impact of flooding is further exacerbated by the increase of agricultural land and change in land use within river catchments (Bronstert *et al.*, 2002) and reduced storage capacities of reservoirs due to increased rates of sedimentation. Flood management practices and policies have previously been mostly concerned with post-event recovery rather than implementing flood mitigation, reduction and prevention practices (Viljoen & Booysen, 2006). This has resulted in a reactive rather than proactive method of dealing with flood events. Disaster management efforts are also predominantly uncoordinated with little communication between various stakeholders involved in response measures such as non-governmental organizations and local disaster relief, while there is often little evidence of cooperative flood prevention measures between agriculture, DWA and environmental affairs (Viljoen & Booysen, 2006). The Disaster Management Act (No. 57 of 2002) highlights the need to prevent, reduce and mitigate the impacts of an imposed external stressor such as a disaster event, over a responsive approach to management. In order to reduce flood risk, planning needs to incorporate stakeholders at different levels – local, provincial, national and private sectors (Viljoen & Booysen, 2006). In the wake of such significant extreme flood events caused by cut-off lows and the subsequent large output of capital into post-event recovery systems and practices, it is important to perform studies on the changing dynamics of rainfall, which can provide important information to guide the decision-making and planning process.

2.2.4 Design Flood

The estimations of design flood events are important when it comes to designing infrastructure and engineering structures (Smithers & Schulze, 2004). A Design Flood is defined as the amount (volume) of streamflow that can be expected as a result of the interaction between the meteorological and hydrological conditions of the relevant geographic area (Parker, 2002). However, it is difficult to determine a reasonably accurate estimation of flood frequency and magnitude due to the uncertainty in changes in hydrological processes (Smithers & Schulze, 2004). It is therefore important to determine what the design rainfall for a certain region is. Design rainfall is described as the precipitation intensity and duration associated with a certain return period (Smithers & Schulze, 2004). The estimation of design rainfall aids in the generation of design flood hydrographs, which are used when designing infrastructure and hydraulic structures (such as bridges, culverts, spillways and drainage systems), so as to determine the strength of the structure required and the placement thereof as well as the capability of the structure to pass high level flows without failure. A Depth-Duration-Frequency relationship of rainfall events is therefore formed so as to predict return levels (discussed in Section 3.3). This information is used for estimating possible flood sizes necessary to determine the hazard posed to these structures by high flows (Smithers & Schulze, 2004). These authors have designed a regional approach to predicting design rainfall across South Africa based and scaled on rainfall values estimated from reliable data stations, allowing for the reliable predictions of design rainfall to be made. This program is called the Regional L-moment Algorithm and Scale Invariance and allows for the estimation of design rainfall events from a two-year to a two-hundred-year return period and a precipitation period of between five minutes and seven days (Smithers and Schulze, 2004). These design flood analyses typically do not break up the rainfall record into different time periods in order to assess changes in return periods over time.

Milly *et al.* (2008) suggest that water management and flood management systems are based on the assumption that natural systems are in a state of stationarity. Planners have used this supposition to design management systems on the assumption that the probability density function of a variable (such as maximum rainfall) does not change over time and can be estimated from the historical record. The probability density functions therefore are used to design for a flood event or water supply (Milly *et al.*, 2008). However, these authors warn that under the influence of global climate change the stationarity of variability is no longer a valid assumption due to the changes in means, medians and extremes of precipitation and temperature. Warming increases the amount of evaporation and water in the air, which leads to increased rainfall and increased flood risk (Milly *et al.*, 2008). It is therefore important to assess how climatic patterns, particularly with regard to extreme events and the intensity thereof, are changing with time.

The extent to which a flood may impact humans and development (damage potential) can be influenced by the: high flood level, peak discharge, flow velocity, flood volume and duration of flood event (SANRAL, 2007). Rainfall intensity in small catchments is the main factor leading to flooding, while in larger catchments, rainfall intensity as well as duration and distribution are important factors. It is also established that, generally, there is a strong relationship between peak runoff and rainfall intensity (SANRAL, 2007). Rainfall intensity, duration and distribution are therefore important factors in calculating flood peaks. The SANRAL Drainage Manual (2007) describes the different methods used to calculate these flood peaks. These methods are:

- Statistical
- Rational
- Alternative Rational Method
- Unit Hydrograph
- Standard design flood
- Empirical method.

(SANRAL, 2007)

The Drainage Manual suggests the use of two or more of these methods when calculating flood peaks.

Statistical methods require the use of past flood peak data to calculate the return level for a particular return period. It is therefore appropriate to use this method only when there is sufficient historical flood data for the catchment, or where there are sufficient data from neighbouring catchment areas that are comparable to those of the catchment in question (SANRAL, 2007). The length of data record required for this calculation is preferably greater than half of the desired return interval.

The Rational Method is a deterministic method for calculating peak flow rates in small catchment regions (SANRAL, 2007). The method assumes that river flow rate is a function of rainfall intensity and river catchment area. The method for calculating peak flow assumes that rainfall intensity is constant for the duration of the storm (SANRAL, 2007).

The Alternative Rational Method for determining peak flow is another deterministic method, which has been adapted from the Rational Method. This method requires the calculation of point precipitation from the modified Hershfield equation (SANRAL, 2007). Rainfall intensity is calculated using this equation for short duration storms (<6 hours) and the DWA Technical Report 102 (Adamson, 1981) for rainfall durations of between 1 and 7 days. The modified Hershfield equation calculates the variable: $P_{l,T}$ which is precipitation intensity as a function of storm duration and return period. This calculation incorporates the Return Period for the extreme storm event.

The Unit Hydrograph method (recommended for catchments between $15km^2$ and $5000km^2$ in area) assumes stationarity through time (SANRAL, 2007).

The Standard Design Flood (SDF) method for calculating peak flow was developed with the aim of understanding and taking into account the levels of uncertainty in flood intensity and frequency estimates (SANRAL, 2007). Poor estimates have led to a large number of damaging events to engineered structures and development (SANRAL, 2007). As most of the damaging floods in South Africa occur when the storm in question has a longer duration than the “response time” for the catchment, the SDF method therefore takes into account the effect of catchment saturation on increasing peak flow rates

2.2.5 Disaster Risk and Vulnerability

The potential for negative consequences on human well-being and socio-economic outcomes due to exposure to natural hazards needs to be defined. The risks associated with increasing frequency and intensity of extreme rainfall events are substantial (Mason *et al.*, 1999). Extreme rainfall is linked with potential harm to human lives and infrastructure through the generation of floods.

Risk is a product of likelihood of exposure to a hazard, and the potentially damaging consequences of that exposure (UNISDR, 2009). High risk is therefore influenced by high exposure to an external stressor.

Pelling (2003) defines vulnerability as a result of three interacting factors. These factors are: exposure, resistance and resilience – shown in figure 2.3 below.

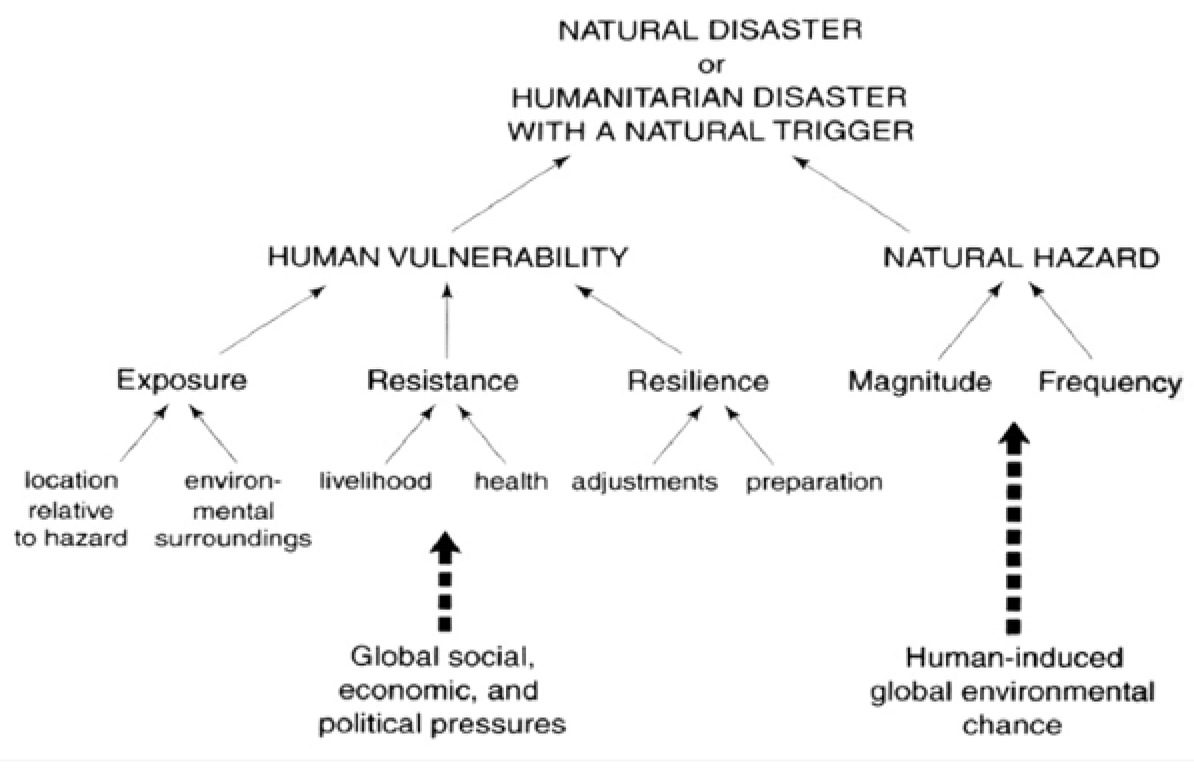

Figure 2.3 Elements of human vulnerability

SOURCE: Pelling (2003)

Exposure is largely driven by location and is defined as the degree to which a person or group of people is exposed to an external stress or hazard (Pelling, 2003). It is exposure to a hazard that is largely responsible for the damage done. The Western Cape has a high exposure to intense rainfall events. Changes in the intensity and frequency of these events will further increase the overall exposure of the region to this natural hazard. In this way, vulnerability and risk are linked, where increased exposure increases the vulnerability of the exposed population, which increases the risk of negative consequences. Resistance is described to be the financial or physical ability of the affected to resist the impact of the stress, while resilience is often associated with resistance and is defined as the ability of the affected to deal with and bounce back from the event (Pelling, 2003). In the Western Cape context, resistance to an external stressor is usually quite low due to the constrained financial resources of the local population – particularly the rural poor. As vulnerability is a function of exposure and risk is the likelihood of exposure, the concepts of risk and vulnerability are linked. Although vulnerability is largely associated with resistance and resilience to an external stressor, it is greatly influenced by the risk of being affected by a hazard.

2.2.6 Theory of Extremes

Extreme Value Theory is useful for extrapolation from limited data into areas where there are few or none. Extreme events are rare phenomena, which often lie outside the range of most measured or observed data. These events have very low probability, but are associated with high impacts and can lead to substantial damage and losses due to their magnitude. In order to plan for the occurrence of such events, it is necessary to model the rare phenomena by extrapolating from existing, recorded data. The theory of extremes allows for this extrapolation by using well- established statistical principles.

Central Limit Theorems (CLTs) are the fundamental building blocks of probability theory in statistics (Eliazar & Klafter, 2010). CLT describes the macroscopic parameters of a data ensemble (or set) where the aggregate probability laws are Gaussian or Levý (Eliazar & Klafter, 2010). These parameters are the mean and standard deviation. Under the CLT, data is distributed along a normal distribution curve, where the spread of the distribution is governed by the standard deviation of the data ensemble. The normal distribution describes the probability density function of the data set accurately within the measures of standard deviation. However, there are very few data points in the extremes (tails) of the normal distribution and these data are not described well by the normal curve. This gives rise to the need for a different set of curves that more accurately predicts the behaviour of these data and Extreme Value Distributions do this where extreme probability laws are either: Fréchet, Weibull, or Gumbel (Eliazar & Klafter, 2010).

Extreme rainfall, floods, heat waves and large fires are examples of extreme events that occur less frequently than the average event and can have severe impacts. It is therefore important to determine the frequency of occurrence of damaging events and their potential magnitudes. As exposure is a function of location (Pelling, 2003) and magnitude of hazard, it is impossible to completely avoid exposure to a hazard in a particular region (such as the Western Cape). A means of estimating frequency and quantum of a hazard is therefore important in order to better anticipate and reduce exposure. In the sphere of disaster risk identification and management, the calculation of extremes is not concerned with mean conditions. It is the estimations of rare but dangerous events that are required in order to protect ourselves more fully from disaster.

Just like the CLT is useful for describing average conditions within the boundaries of the standard deviations, rare events also have a probability distribution, which can be usefully approximated in order to anticipate potentially dangerous conditions with greater accuracy rather than allowing everyday actions to be left to fate (Katz, 2010). Extreme value theory is used to model the likelihood of extreme (high magnitude) and rare (low probability) events (Katz, 2010). As these extreme events are rare, it is necessary by definition to operate with small data sets and to understand that estimates of probabilities then carry imprecision.

Extreme Value Distribution (EVD) theory has evolved and been an extremely useful statistical discipline over the past 60 years, with applications in the fields of environmental sciences, engineering, economics and reliability modelling (Coles, 2001). The statistical analyses of meteorological variables and distributions have often focused on that variable's average over time, particularly when dealing with rainfall (Gilleland & Katz, 2006). However, in the context of a changing climate it is increasingly important to consider and analyse the extremes of variables because changes in the frequency of extremes are how the impacts of climate change are expected to be experienced (IPCC, 2012). Extreme Value theory therefore focuses on the probabilistic nature relating to high or low values of a variable in a data record (Smith, 2003).

According to Gilleland & Katz (2006), there are two main methods to statistically analyse extreme values. One can either fit the relevant data to a model and assess the results by simulating the model; or an extreme value distribution can be fitted to the data. This thesis is concerned with fitting an extreme value distribution (EVD) to the data and is further explained below.

There are two fundamental approaches to fitting an EVD to the data: either through that of Block Maxima or through the peaks over threshold (POT) (Gilleland & Katz, 2006). The Block Maxima approach identifies the largest magnitude event per annum and fits a Generalised Extreme Value (GEV) distribution to the data points (Katz, 2010). The POT approach requires a high threshold for the data series (determining a level that defines an extreme event) and then fits a Generalized Pareto Distribution (GPD) model to the data above that threshold, or other distributions dependent on the tails of the data distribution pattern (Gilleland & Katz, 2006). This GPD distribution determines the probability of any variable being higher than a high value over the given threshold. In performing this analysis it is important to choose an appropriate threshold because if the threshold chosen is too high, too much data is discarded and there will be a high variance associated with the probability estimate (Gilleland & Katz, 2006). If it is chosen too low, then the data does not conform to the asymptotic requirements of the GPD theory in the tail of the data distribution. For further reading on the POT approach, the publications of Coles (2001), Katz *et al*. (2002), Katz *et al*. (2005), Gilleland & Katz (2006) are recommended. Extreme Value theory can also be used to determine the return interval of an extreme event, which is derived from the distribution (Gilleland and Katz, 2006). Return intervals are important for flood planning and infrastructure design, as buildings and flood mitigation measures need to take flood and rainfall intensity levels into account, so as to be designed to withstand the effects of these extreme events.

3 METHODS

3.1 HYPOTHESIS

The core hypothesis of this thesis is that the frequency of extreme rainfall over the Western Cape has increased over the last 100 years and that these changes are detectable in the existing rainfall records. The null hypothesis is that there has been no change and that an analysis will indicate this. The existence of non-stationary rainfall processes would result in changes to the distribution of extreme events, rendering previous estimates of the return periods less useful for planning and disaster mitigation purposes. A key assumption is that the methods used will show a change if they exist.

In order to meet the aims and objectives described previously, this research employs a conceptual framework aimed to assess the progression of flood risk in the Western Cape, due to changes in extreme rainfall, over time. Risk is described as a function of exposure to, resilience and resistance to an imposed external stressor or hazard (Pelling, 2003). This project performs an analysis of how exposure to extreme meteorological events has changed over time. A change in rainfall depth-duration and frequency will influence the exposure of the Western Cape to extreme weather events and thus influence the risk assessments of the region to damaging floods in the future.

The model employed in this project assesses only the changes in exposure to extreme events over time, where exposure is influenced by the frequency and intensity of extreme rainfall events. The framework will not take into account how humans have exposed themselves to powerful storms by inappropriate development and settlement in risk-prone areas. The model can therefore be referred to as a progression model as it determines how exposure has progressed over time, rather than determining the root causes of this exposure change.

3.2 DATA

Rainfall data from the South African Weather Service (SAWS) and the Agricultural Research Council Institute for Soil, Climate and Water (ARC-ISCW) was used in this study. This has been collated and error-checked by the School for Bio resources, Engineering and Environmental Hydrology (BEEH), at the University of KwaZulu-Natal. The Daily Rainfall Utility Extractor (Kunz, 2001) contains a database of numerous rainfall stations in South Africa, comprising SAWS rain gauges as well as data from ARC-ISCW and even some privately monitored rain gauges. The Kunz extractor was used to identify those stations with suitably long (100 years) records of daily rainfall data from a database of South African Weather Services stations. Within the data record of the Kunz extractor, an automated method developed by Lynch (2003) is implemented to interpolate the records of stations where rainfall data was missing. A co-ordinate range was inputted into the program to search for the rainfall stations in the Western Cape and the stations with suitably long records were selected for analysis. The Kunz extractor data set is complete up until the year 2001, when the data set ends. Further data for the selected rainfall stations was obtained directly from SAWS and appended to each of the selected stations.

The SAWS data contained missing values, which were filled in with a value of "0" in order to be processed by the statistical software, "R". As the POT approach uses all the data points above a defined threshold, the input of "0" for missing data does not influence the extreme value distribution of each data set. The complete data sets were stored in MS Excel (.xls) formats and later converted to text (.txt) files in order to be read into "R".

The data were organised into columns of:

a) Station ID
b) Date
c) Precipitation (in mm)
d) Data Quality.

The data record for each station was then divided into two time periods of roughly equal length (1900-1954 and 1955-2010) so as to compare the return level and return intervals for both time periods.

3.3 CALCULATING EXTREMES

As noted earlier, the two fundamental approaches described by Katz (2010) for calculating the statistics of extremes are the Block Maxima and POT approaches. The Block Maxima approach to extreme value analyses has been developed for longer than the POT approach and assumes that the maximum value of a sequential series of data points (say daily rainfall) for a year fits a Generalized Extreme Value distribution (GEV) (Katz, 2010). The GEV distribution has three possible forms shown in Figure 3.1:

- The Gumbel distribution (positively skewed), the
- Frechet distribution (heavy upper tail) and the
- Weibull distribution (a bounded upper tail).

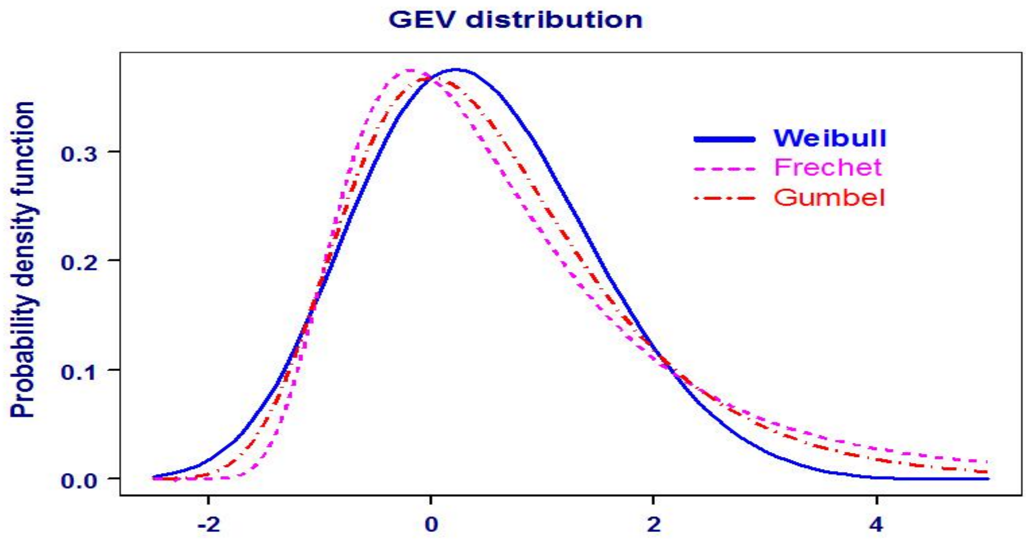

Figure 3.1 Possible forms of a GEV

SOURCE: UCAR (2010)

In the Block Maxima approach, the data points representing the largest magnitude event per period of a cyclic duration are fitted to a Generalized Extreme Value (GEV) distribution. If the data record were 100 years long, the GEV distribution curve would be calculated around 100 data points (each the maximum value for the year they occurred in). This approach, however, has significant limitations when analysing changes in rainfall extremes over time. As Katz (2010) argues, the block maxima approach discounts all extreme rainfall events occurring in a calendar year that are lower than the maximum value for that period. As a result it would be difficult to determine whether there is any significant change in the frequency of severe storm events occurring (which changes the return period for such magnitude storm events). For example, were the period 1900-1930 to have, on average, 4 separate rainfall events all exceeding the threshold defining an extreme event per year, the Block Maxima approach would fit 31 “Block Maxima” points to the distribution curve. If this were to increase to 20 threshold-exceeding extreme events per annum from 1931-1961, the GEV approach would still fit 31 points to the GEV distribution and one would not be able to determine that the probability of a certain magnitude event occurring is increasing (return period decreasing). This renders the GEV or “Block Maxima” approach an inappropriate one as it gives a skewed picture of the temporal nature of the extreme value distribution of the data series.

As a result, the ‘Peaks over Threshold’ (POT) approach was developed more recently and states that all data points exceeding an extreme threshold are fitted to a Generalized Pareto

Distribution (GPD) (UCAR, 2010). The GPD approach to analysing changes in extreme precipitation is a far more valid approach when performing such analyses as it fits all the values exceeding the determined threshold to the GPD. It is thus more useful for determining whether there is a change in return period and return level for the data set because it can accommodate more data. The GPD has three forms shown in Figure 3.2:

- Exponential (thin tail)
- Pareto (heavy tail)
- Beta (bounded). (UCAR, 2010)

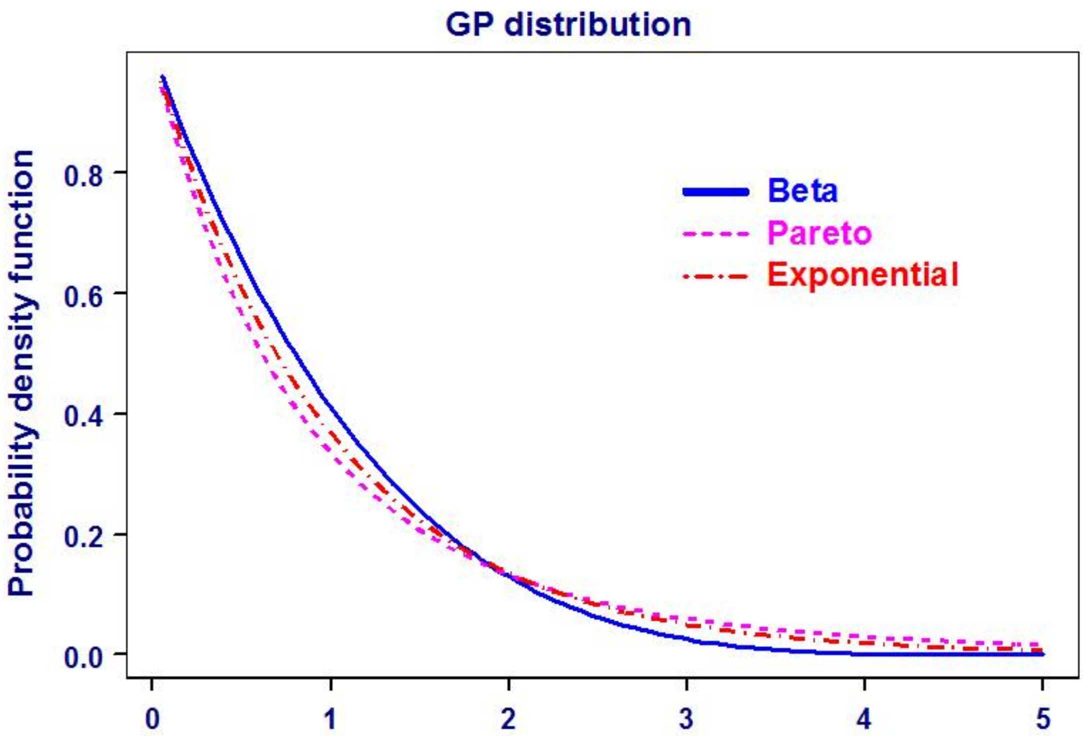

Figure 3.2 Possible forms of a GPD

SOURCE: UCAR (2010)

The GPD assumes a Poisson process, which will be discussed in Section 3.5.

This study uses the POT approach, appropriate for rainfall distribution analyses (Coles, 2001). The GPD is described as a heavy-tailed distribution, which makes it appropriate for rainfall analyses, as extreme precipitation distributions exhibit largely heavy-tailed characteristics (Katz *et al.*, 2002 and Gilleland & Katz, 2006). The POT method was used as a means of extracting extremes by setting a minimum value for what defines an extreme rainfall event, or a high threshold.

Use of the GPD requires the use of a high threshold, using only that data above the threshold value to model the tail of the distribution. The choice of threshold must be such that the excess over the threshold should have a nearly exponential distribution – to fit with the requirements of the GPD theorem. A statistical compromise needs to be achieved between setting the POT threshold high enough – the excess distribution (above the threshold) converges to that of the GPD – and low enough to have a sample of sufficient size so that the location, size and scale parameters can be estimated efficiently (Gilleland & Katz, 2006). Therefore, setting the high threshold is not an explicit process and nor does it imply an exact value - the outcome is subjective. Ismev – an “add-on” software package for R - provides a technique of fitting a range of thresholds, in which the scale and shape parameters gradually change over the fitted range. The user is required to choose a threshold in which the scale and shape parameters have not diverged sufficiently to imply increasing uncertainty in those parameters. While this is a useful process when applied as an intensive examination of an individual record, it is an overly time-consuming method when applied to many stations (as in this study). A more direct approach which could give sufficiently robust results is required.

Karl *et al*. (1995) suggested, in using a GPD approach, calculating a fixed threshold for all stations quantified by the variation of the mean 95^{th} percentile of all stations.

For this project, this process is impractical due to the size of the Western Cape and the high spatial variability in rainfall intensity over the region. This high spatial variability is displayed in the results from calculating the 95^{th} percentile of all rainfalls above 1mm for several rainfall stations across the region. 95^{th} percentile values across the province ranges between 12.7mm and 51mm, with a standard deviation of 6.95. Due to this high variability in rainfall intensity, it would be inappropriate to calculate a fixed threshold for all of the stations as Karl *et al.*, (1995) did. Such a method would not describe the extreme value distributions of all of the rainfall stations accurately. Consequently, the researcher calculated individual 95^{th} percentile thresholds for each rainfall station. The code used for making this calculation in “R” is shown in Appendix A. The results (which will be discussed in Section 4.1) confirm the notion that it would be inappropriate to define a fixed threshold for all of the rainfall stations, as was done by Li *et al*. (2005) in their study of Australian rainfall. The reason it is not ideal in the Western Cape is due to the high spatial variability of mean annual precipitation, a result of the rugged topography, which causes strong orographic effects in rainfall generation, the strong rain shadow effects and the changing spatial density of the stations across the study area. The changes of extreme value distributions over time were determined in order to address whether the assumption of stationarity (Milly *et al*., 2008) can be held, or that a new assumption of non-stationarity must be accommodated in on-going and future Extreme Value Distribution (EVD) assessments.

3.4 STATISTICAL SOFTWARE

While extreme value methods have been implemented in a number of statistical software packages, R statistical computing language was chosen for this analysis. R is an open source version of the commercial S-Plus language. R is a software programme that allows for the manipulation, calculation and graphical representation of data (Venables & Smith, 2012). The programme stores data and has a wide range of operators for data calculations as well as graphical display capabilities for data analysis (Venables & Smith, 2012). R can be used as a statistics system as it allows for the implementation of many user-defined statistical techniques – some of which are built into the software, while others may be used in the form of packages (such as ismev and extRemes), or even be written by the user.

The benefit of using R is to take advantage of the 'ismev' package for analysing extreme value distributions, which is an R port of the S-Plus package written by Coles (2001), as well as the R graphical user interface that accompanies the extRemes package (Stephenson & Gilleland, 2005). Gilleland & Katz (2006) promote the use of open source software packages such as R and the "add-on" "extRemes package" to perform extreme value distribution analyses in climate research. 'Ismev' (Stephenson, 2011) and 'extRemes' (Gilleland & Katz, 2006) were adopted as suitable packages for this analysis.

3.5 DECLUSTERING

In utilising the Generalized Pareto Distribution function for analysing the probability distribution of rainfall events, it is assumed that rainfall extremes fit the "Poisson process" - a stochastic process in which events occur continuously (as opposed to discrete occurrences) and independently of each other (Katz, 2010). The Poisson process has a long history of use in modelling rainfall (e.g. Eagleson, 1981). It is therefore important to determine whether the data points that exceed the threshold value (threshold exceedances) are independent of each other when fitting a GPD (Gilleland & Katz, 2006). In a GPD, only independent extreme values should be included and not multiple extreme values that belong to the same event (in which case they are not truly independent).

In the case of large storm systems such as cut-off lows and mid-latitude cyclones and cold fronts, prevalent in the Western Cape, rainfall can last for up to three days and more per storm. As a result, the rainfall observed for more than one day in the same event may exceed the threshold and thus the individual observations may not be independent. These data points need to be "declustered" in order to remove such related threshold exceedances. The process of declustering groups consecutive extreme rainfall observations that are related to the same event into one extreme event for further statistical processing. This process is done using the extRemes package, which has a specific function "dclust" for that purpose. A run length of 3 days for each storm system was used. This code is displayed in Appendix A. This section of code outputs the number of clustered threshold exceedances to the user interface and declusters the data set, creating a new data set (referred to as "P1" in the code), which is saved as an internal temporary workfile. The new "declustered" data set was then fitted to a GPD using the "extRemes" package in "R". The results of the declustering are shown and discussed in Section 4.2.

3.6 RETURN LEVEL PLOTS AND SPATIAL REPRESENTATIONS

Once the threshold was determined, the threshold exceedances were declustered and fitted to a GPD. The changes in the EVD (or not) were then related to the causal chain of disaster occurrence and its contribution to disaster impact and disaster risk mitigation is discussed later. By breaking up the data record into two equal length time periods (1900-1954 and 1955-2010) it is possible to compare the return level and return intervals for both time periods in order to determine whether there was a change in frequency and magnitude of these extreme events over the historical record.

A Generalised Pareto Distribution (GPD) was then fitted to the declustered data sets using the gpd.fit() function provided by ismev package. Graphs showing return intervals, comparing the time period 1900-1954 and 1955-2010 for each individual rainfall station, are outputs from the gpd.fit function. These results are shown in the results section.

The terms “return interval” and “return level” are used to describe the probability of extreme event occurrence (UCAR, 2010), where:

$$T = \frac{1}{p}$$

Where: T is the return period/interval
P is the probability of exceeding the high threshold.

For example, if the probability of a rainfall event being higher than 120mm is 0.01, then the return period/level for a 120mm event is 100 years.

Return interval can be defined as the frequency of occurrence of an event of certain magnitude, while the return level is the magnitude of an event – usually associated with a probability of occurrence.

The return level plots generated by the gpd.fit() command are not continuous functions and, because rainfall is a random process, no two measures are likely to be similar or fall on convenient ordinal values. As a result, the value of the 50- and 20-year return levels for each graph was approximated by using the approxfun() command in R. This command approximates the magnitude of the return level for any defined return interval – in this case, the 20- and 50-year return interval.

These calculated values were plotted using ArcMAP in order to determine whether there were any spatial patterns evident in the results. The percentage change in return levels from 1900-1954 to 1955-2010 was interpolated across the entire study area using the Inverse Distance Weighted technique available in ArcMAP, while a spatial autocorrelation was run (Moran’s I) in order to determine whether there was any spatial clustering of changing return levels or not. Spatial autocorrelation measures the similarity of features near to each other and determines whether they are clustered, dispersed or random.

4 RESULTS

4.1 CALCULATIONS OF 95th PERCENTILE

The individual 95th percentile for the entire historical record of each rainfall station was calculated and used as the threshold above which daily rainfall is defined as an extreme event. The 95th percentile values range between 12.7mm and 51mm, have an average of 25.53mm and a standard deviation of 6.95. The values for all stations are included in Appendix B. The Western Cape is a large area with large changes in altitude and proximity to mid-latitude cyclones (which are the cause of most of the Western Cape's maximum rainfalls). In order to determine whether the extremity of intense rainfall was influenced by altitude, the 95th percentile for each station was plotted against altitude, shown in Figure 4.1 below:

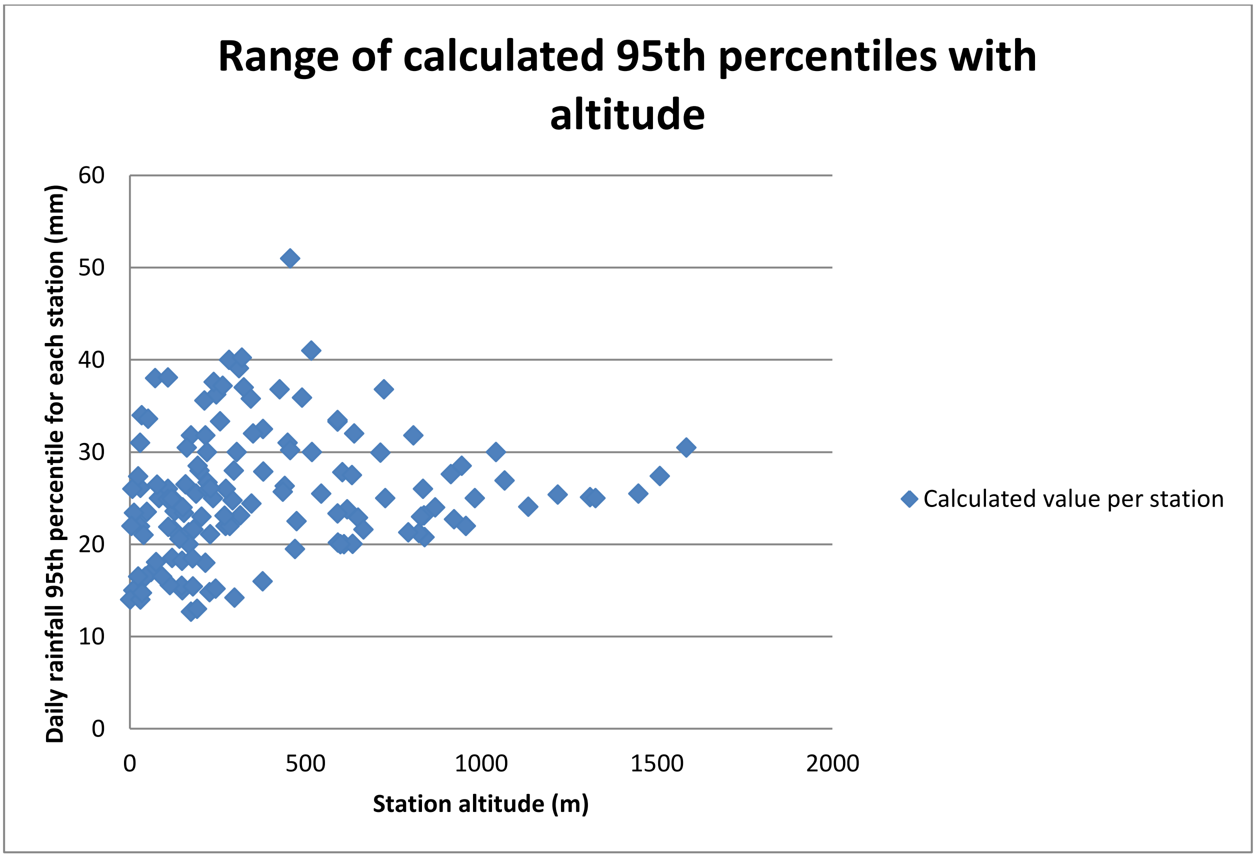

Figure 4.1 Graph comparing changes in altitude with the severity of extreme rainfall (95th percentile)

Figure 4.1 above shows the change of 95th percentile of daily rainfall per station with altitude. From the graph one can determine that the change in rainfall intensity across the Western Cape cannot be attributed only to changes in altitude but to other factors as well. The Western

Cape receives rainfall from mid-latitude cyclones, which do not bring uniform rainfall to the entire province. This results in an uneven distribution of rainfall across the region which is further influenced by topography. This result confirms that it would be inappropriate to assign a common threshold defining an extreme event for all of the rainfall stations and each one was calculated separately based on the individual data set as suggested by Li *et al.*, (2005). The outcome supports the method used in this study for determining individual thresholds.

4.2 DECLUSTERING RESULTS

Each rainfall station was declustered with a "run time" of 3 days. This meant that each clustering of 2 or 3 consecutive days of rainfall above the threshold was consigned to one individual extreme event in the data frame. Some of the pertinent results of declustering are described below.

As an example, the Cape Agulhas station between 1900 and 1954 the data set had 94 clusters of threshold exceedances over the threshold set at 15mm. This is substantially different to the period from 1955-2010, where Cape Agulhas had 267 clusters. This indicates that the number of weather systems with high intensity rainfall and a long duration has increased dramatically from 1900-1954 to the more recent time period for that rainfall station. The results of declustering for the full data set are shown in table 4.1 below:

Table 4.1 Changes in the number of long duration, intense storms

Station ID	Number of clusters		
	1900-1954	1955-2010	Difference
0003192_W De Mond	25	304	279
0020838FW Groote Schuur	129	309	180
0003020_W Cape Agulhas	94	267	173
0041533_W Lelyfontein	74	241	167
0062768_W Middeldeurvlei	71	224	153
0041871_W Porterville	77	222	145
0005771_W Bettys Bay	164	294	130
0004762_W Simonstown	159	286	127
0062671_W Eeendekuil	75	199	124
0008813_W Bontebok Park	84	204	120
0107510_W Bulshoek Dam	40	158	118
0042532AW Ceres	100	209	109
0030775_W Keurboomsrivier	145	253	108
0047205_W Martjesvlei	30	133	103

0107759_W Sandvlei	54	154	**100**
0007183_W Greyton	126	225	**99**
0046809_W Zoar	28	126	**98**
0084159_W Graafwater	55	150	**95**
0042588_W Prince Alfred Hamlet	85	176	**91**
0008470_W Plaatjieskraal	75	161	**86**
0005611AW Steenbras	160	245	**85**
0021656AW Stellenbosch	146	231	**85**
0004874_W Rondevlei	147	225	**78**
0084059_W Redelinghuis	81	159	**78**
0107318_W Puts	72	148	**76**
0041279_W Mooreesburg	97	170	**73**
0014393_W Harkerville	187	259	**72**
0042669_W Malabar Farm	76	148	**72**
0006038_A Elgin	156	226	**70**
0041347_A Langgewens	111	179	**68**
0131437_W Ludzville Hotel	36	104	**68**
0006039_W Grabouw	167	234	**67**
0021230_W Altydgedacht	134	201	**67**
0026824_W vanWyksdorp	52	118	**66**
0011617_W Die Eiland	77	141	**64**
0028775_W Witfontein	189	250	**61**
0042358_W Dwarsrivier	102	163	**61**
0010742_W Stilbaai	97	158	**61**
0118029_W Coetzeeskraal	58	119	**61**
0020846_W Atlantis	126	185	**59**
0048384_W Grootkraal	94	153	**59**
0044286_W Jan de Boers	53	112	**59**
0012303_W Sandhoogte	111	169	**58**
0048275_W Zachariasfontein	36	92	**56**
0029624_W Karatara	180	235	**55**
0011065_W Diepkloof	104	157	**53**
0115595_W Gannakraal	53	105	**52**
0090176_W Grootfontein	17	69	**52**
0030297_W Diepwalle	245	296	**51**
0022825_W Kwaggaskloof Dam	64	115	**51**
0008367_W Kleinfontein	79	129	**50**
0117749_W Vleiplaats	63	113	**50**
0085112_W Algeria (BOS)	96	145	**49**
0063452_W Kromriver	63	111	**48**
0050688_W Rooiklip	49	97	**48**
0021778_W Jonkershoek	173	220	**47**
0022038_W Vrugbaar	149	196	**47**
0042621_W Warmbokveld	88	135	**47**
0024110_W Ashton	78	123	**45**
0050327_W Rondekop	64	109	**45**

0094730_W Beeldhouersfontein	80	124	44
0047765_W Damaskus	46	89	43
0047359_W Calitzdorp Dam	43	86	43
0092369_W De Hoop	42	85	43
0070770_W Aardoorns	28	70	42
0029294_W Bergplaats	178	219	41
0004891_W Cape Point	149	190	41
0084558_W Elandsfontein	98	139	41
0021055_W Maitland	128	168	40
0011132_W Albertinia	92	131	39
0025599_W Strawberry Hill	183	220	37
0014633_W Plettenberg Bay	116	152	36
0092386_W Blouboskuil	42	78	36
0045857_W Floriskraal dam	38	74	36
0006612_W Boontjieskraal	117	152	35
0007263_W Boskloof	125	159	34
0006332_W Rustfontein	123	157	34
0008751_W Marloth	168	201	33
0029805_W Goudveld	182	213	31
0117047_W Loskop	52	83	31
0061298_W Langebaanweg	105	135	30
0047436_W Weltevreden	44	74	30
0106880AW Vredendal	51	78	27
0067074_W Anysrivier	37	63	26
0107869_W Kanolvlei	71	96	25
0106603_W Lutzville Hotel	50	74	24
0090196_W Tafelberg	40	64	24
0028150_W Kwepertuin	127	150	23
0028771_W Herold	93	115	22
0049050_W Klaarstroom	48	70	22
0049060_W De Rust	79	99	20
0068547_W Zeekoeivlei	27	47	20
0022539_W Villiersdorp	126	144	18
0106512_W Koekenaap	48	66	18
0048043_W Prince Albert	49	66	17
0045611_W Laingsburg	37	54	17
0006527_W Tussenbeide	139	154	15
0045184_W Dwarsindieberg	49	63	14
0068010_W Merweville	33	47	14
0070735_W Klipkrans	55	67	12
0049372_W Rondawel	44	56	12
0022803_W Bellevue	74	85	11
0085309_W Welbedacht	59	70	11
0014063_W Knysna	184	194	10
0006415_W Hermanus	167	176	9
0027302_W Calitzdorp Pol	64	73	9

0028407_W Groot Doornrivier	68	76	8
0009783_W Blackdown	128	134	6
0107396_W Vanrhynsdorp	69	75	6
0131639_W Nuwerus	64	70	6
0022759_W Worcester	80	85	5
0093074_W Kamferskraal	56	61	5
0021823_W Paarl	152	156	4
0083618_W Elandsbaai	99	101	2
0023597_W McGregor	82	82	0
0084701_W Clanwilliam	81	80	-1
0095006_W Quaggasdrift	90	88	-2
0030265_W Buffelsnek	220	217	-3
0011451_W Herbertsdale	128	125	-3
0159104_W Bitterfontein Kamaboes	77	73	-4
0007669_W Blydskap	140	135	-5
0024197_W Montagu	96	89	-7
0047716_W Kruisrivier	96	88	-8
0046479_W Ladismith	101	90	-11
0086007_W Reenen	48	37	-11
0062444_W Piketberg	131	117	-14
0028415_W Jonkersberg	210	194	-16
0009815_W Heidelberg	131	115	-16
0042227_W Tulbagh	124	108	-16
0042789_W Odessa	110	90	-20
0063005_W Citrusdal	137	102	-35
0040604_W Hopefield	131	95	-36
0029542_W Rooirivier	110	69	-41
0040682_W Darling	178	113	-65
0004734_W Klaasjagersberg	228	162	-66
0029692_W Buffelsklip	111	43	-68
0025450_W Dun Donald	222	150	-72

Of the 137 rainfall stations analysed, 115 (84%) showed an increase in the number of clusters in the more recent segment of the datasets. There are only 22 of the 137 rainfall stations that show a decrease in the number of high intensity, long duration rainfall events across the two time periods. This non-parametric test of change is a strong indicator of an increase in the frequency of long duration, high intensity storms across the Western Cape. On average, there was a 43% increase (13448 such storms in 1900-1954 and 19229 for 1955-2010) in the occurrence of 2 to 3 day extreme events.

For the De Mond rainfall station, the number of clusters of threshold (14mm) exceedances from the period of 1900-1954 was 25 while this increased to 304 during the 1955-2010 period, once again indicating an increase in the number of severe storms. Elgin has a higher threshold of 39.1mm. The number of clustered threshold exceedances for that rainfall station increased from 154, between 1900 and 1954, to 226 clusters between 1955 and 2010; although the increase was not as marked as that of Cape Agulhas and De Mond, the results still display an increase in long duration, high intensity storms. Beeldhouersfontein, with a threshold of 27.4, has 80 clustered threshold exceedances from 1900-1954, while 124 clusters are found between 1955 and 2010. The results indicate that the change in the number of high intensity storms is prevalent across the Western Cape and is not dependent on threshold values.

Figure 4.2, below, shows the increase of extreme storms spanning 2 or 3 consecutive days between the time periods of 1900-1954 and 1955-2010 for the Western Cape. The red points indicate a rainfall station that has shown a decrease in the number of long duration, extreme storm events over time, while the blue rainfall stations are the stations that have shown a significant increase in the number of such storms.

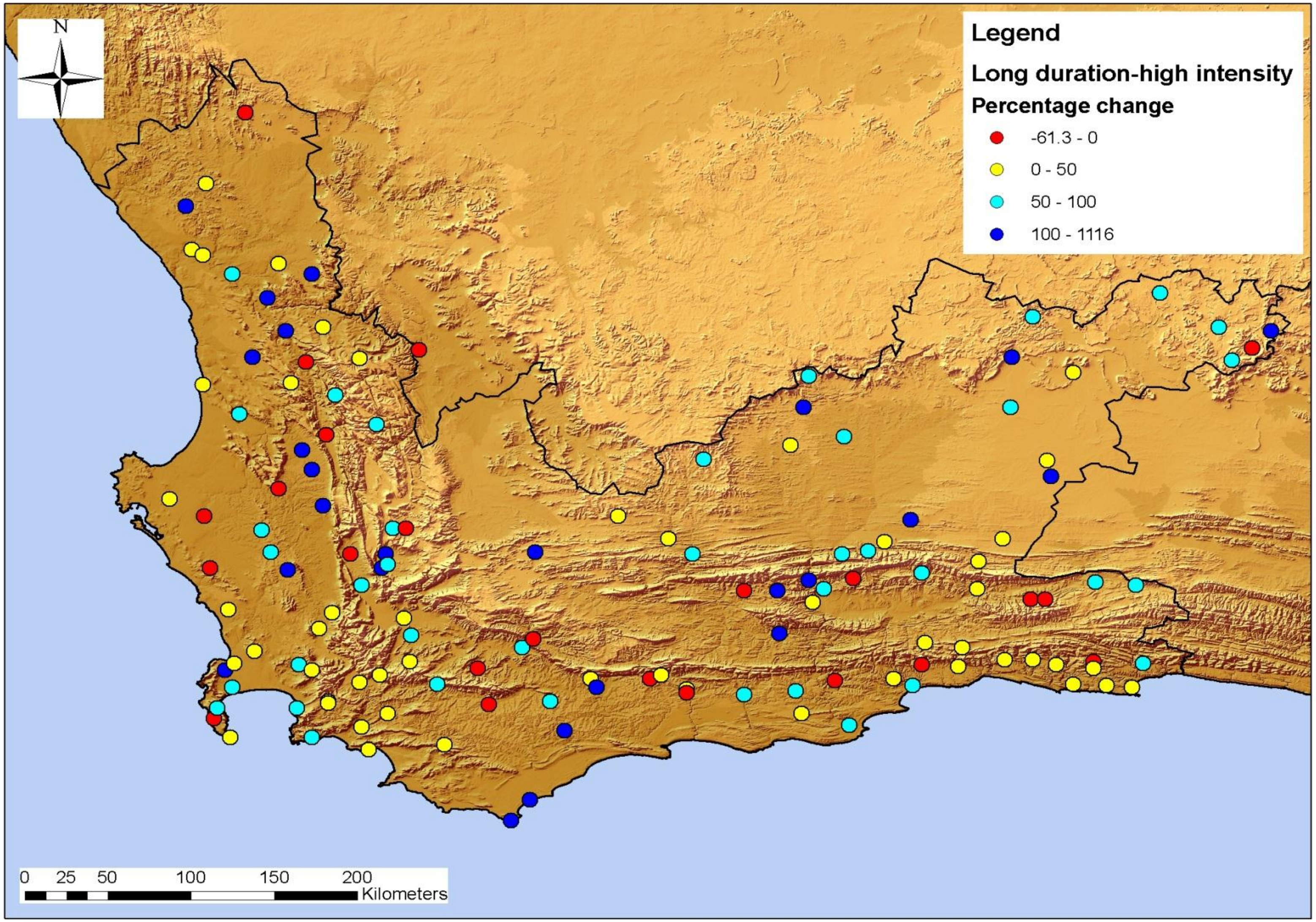

Figure 4.2 Percentage change in long duration, high intensity rainfall

The image suggests that there may be an increase in the number of long duration, high intensity rainfall events over the escarpment up the West Coast, while there appears to be a slight increase in the region near Elgin (the mountainous area indicating a high density of yellow dots just east of Cape Town) and along the South Coast near Knysna. This result in particular is surprising, due to the well-documented floods occurring in the area over the past decade (see DiMP, 2010). The rest of the province seems to display little spatial conformity, suggesting that there is no pattern emerging as to the distribution of changing long duration storm events.

Though the degree to which the number of clusters increased is different for each rainfall station above, the results suggest a strong general trend of increasing storm depth-duration-frequency for the region. However, there is a high spatial variability to the results and in Figure 4.2, the close juxtaposition of different signs (increase and decrease) of some stations warrants further research and attention. On closer analysis, the scale of the map confuses the picture, two widely differing stations are on different sides of a mountain but this is not obvious from the map. In other areas the colour ramp used in the Figure 4.2 is not sufficiently graded to show the relatively small actual difference between stations.

4.3 FITTING GENERALISED PARETO DISTRIBUTION TO DATA

Dual GPDs were fitted to each segment of the data for each of the 137 rainfall stations. For each station a graph was produced comparing return intervals and levels for the period of 1900-1954 and 1955-2010. The results show significant variation from station to station. Of the 137 stations analysed, 85 displayed an increase in the amount of rainfall expected (50-year return level) for a specific return interval over time, 30 showed a decrease and 22 stations remained reasonably similar from one period to the next. These differences vary spatially over the Western Cape (discussed later). The 50-year and 20-year return level values are shown in Appendix F.

4.3.1 Increases in 50-year Return Level

The rainfall stations displaying an increase in return level from 1900-1954 and 1955-2010 are listed below:

Table 4.2 Rainfall stations displaying an increase in return level

Station ID	Coordinates	
0003020_W Cape Agulhas	-34.83	20.01
0003192_W De Mond	-34.71	20.11
0004734_W Klaasjagersberg	-34.24	18.40
0004874_W Rondevlei	-34.06	18.50
0004891_W Cape Point	-34.35	18.49
0005771_W Bettys Bay	-34.35	18.93
0007183_W Greyton	-34.04	19.61
0007669_W Blydskap	-34.16	19.89
0008367_W Kleinfontein	-34.14	20.22
0008470_W Plaatjieskraal	-34.31	20.30
0008813_W Bontebok Park	-34.06	20.47
0009783_W Blackdown	-34.07	20.96
0010742_W Stilbaai	-34.1	21.27
0011132_W Albertinia	-34.21	21.58
0011451_W Herbertsdale	-34.02	21.76
0011617_W Die Eiland	-34.28	21.84
0012303_W Sandhoogte	-34.05	22.18
0014393_W Harkerville	-34.05	23.23
0020838FW Groote Schuur	-33.96	18.46
0020846_W Atlantis	-33.61	18.48
0021055_W Maitland	-33.92	18.51
0021230_W Altydgedacht	-33.85	18.62
0021656AW Stellenbosch	-33.93	18.86
0022038_W Vrugbaar	-33.63	19.04
0022539_W Villiersdorp	-33.99	19.30
0022759_W Worcester	-33.66	19.43
0022825_W Kwaggaskloof Dam	-33.76	19.47
0024110_W Ashton	-33.83	20.07
0024197_W Montagu	-33.78	20.13
0026824_W vanWyksdorp	-33.75	21.46
0028407_W Groot Doornrivier	-33.8	22.25
0028771_W Herold	-33.83	22.45
0028775_W Witfontein	-33.94	22.43
0029624_W Karatara	-33.9	22.83
0030297_W Diepwalle	-33.95	23.16
0040604_W Hopefield	-33.07	18.35
0040682_W Darling	-33.37	18.38
0041279_W Mooreesburg	-33.15	18.66

0041533_W Lelyfontein	-33.38	18.80
0041871_W Porterville	-33.01	18.99
0042358_W Dwarsrivier	-33.47	19.20
0042532AW Ceres	-33.37	19.31
0042588_W Prince Alfred Hamlet	-33.29	19.33
0042621_W Warmbokveld	-33.35	19.34
0044286_W Jan de Boers	-33.28	20.14
0045184_W Dwarsindieberg	-33.07	20.59
0045611_W Laingsburg	-33.2	20.86
0046809_W Zoar	-33.5	21.45
0047205_W Martjesvlei	-33.44	21.62
0047359_W Calitzdorp Dam	-33.49	21.70
0047436_W Weltevreden	-33.29	21.80
0047765_W Damaskus	-33.27	21.94
0048043_W Prince Albert	-33.22	22.03
0048275_W Zachariasfontein	-33.09	22.17
0061298_W Langebaanweg	-32.97	18.16
0062444_W Piketberg	-32.91	18.75
0062671_W Eeendekuil	-32.69	18.88
0062768_W Middeldeurvlei	-32.8	18.93
0063452_W Kromriver	-32.54	19.28
0068010_W Merweville	-32.66	21.52
0070770_W Aardoorns	-32.84	22.93
0084059_W Redelinghuis	-32.48	18.54
0084159_W Graafwater	-32.15	18.61
0085112_W Algeria (BOS)	-32.37	19.06
0085309_W Welbedacht	-32.16	19.19
0090176_W Grootfontein	-32.44	21.59
0090196_W Tafelberg	-32.26	21.62
0092369_W De Hoop	-32.15	22.72
0092386_W Blouboskuil	-32.44	22.71
0093074_W Kamferskraal	-32.24	23.05
0094730_W Beeldhouersfontein	-32.17	23.91
0106512_W Koekenaap	-31.53	18.28
0106603_W Lutzville Hotel	-31.56	18.34
0107318_W Puts	-31.81	18.69
0107396_W Vanrhynsdorp	-31.61	18.75
0107510_W Bulshoek Dam	-32	18.79
0107759_W Sandvlei	-31.67	18.93
0107869_W Kanolvlei	-31.98	18.99
0115595_W Gannakraal	-31.92	22.83
0117047_W Loskop	-31.78	23.52
0117749_W Vleiplaats	-31.98	23.84
0118029_W Coetzeeskraal	-32	24.12
0131437_W Ludzville Hotel	-31.28	18.25
0131639_W Nuwerus	-31.15	18.36

0159104_W Bitterfontein Kamaboes	-30.74	18.57

Figure 4.3 below shows the return level plot for rainfall station 0005771_W Betty's Bay:

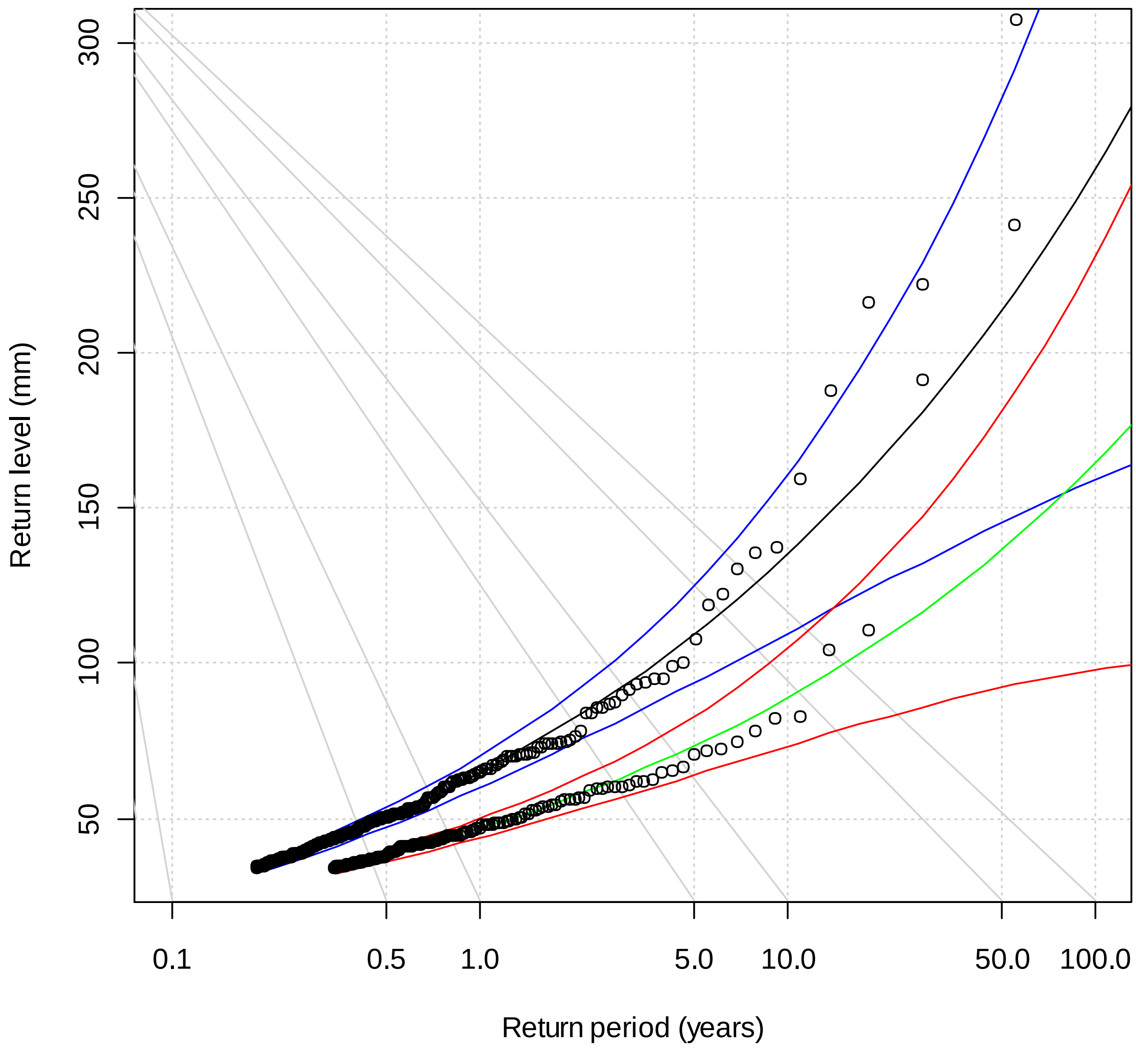

Figure 4.3 Return level plot for 0005771_W Betty's Bay

The blue lines on the graph indicate 95% confidence intervals for the period 1955-2010, while the black line is the curve indicating return level for the same period. The red lines plotted on the graph indicate the 95% confidence intervals for the period of 1900-1954. The green line shows the return level of the period 1900-1954 against the corresponding return period/interval. From the graph one is able to determine that there is an increase of return level for a constant return interval (period) from the first period (1900-1954) to the second (1955-2010). The 50-year return level for 1900-1954 is approximately 137mm, which increases substantially to 214mm for 1955-2010. This graph can also be used to show that from 1900-1954, a storm at the 50-year return period would be at a level of approximately 137mm while, in the later period, the same intensity is achieved by storms at the 10-year return period. This clearly indicates an increase in depth-duration-frequency of extreme rainfall events over the historical record for this rainfall station. It is, however, important to note that as the return interval increases, so the 95% confidence intervals get wider. The 95% confidence intervals for both time periods at the 5- and 10-year return periods are relatively small when compared to the broad margin for error at the 50-year return period. The 95% confidence interval indicates that there is a 95% probability that the return level sits between the upper and lower bounding confidence interval brackets. Therefore, as the 95% confidence intervals get wider, the uncertainty as to where the actual return level is located increases. Narrow confidence interval brackets translate to high confidence. It should be noted that the confidence intervals expand rapidly due to the logarithmic scale used on the x-axis.

Figure 4.4 (below) displays the return level plots for various rainfall stations in the Western Cape that show an increase in return levels over the historical record.

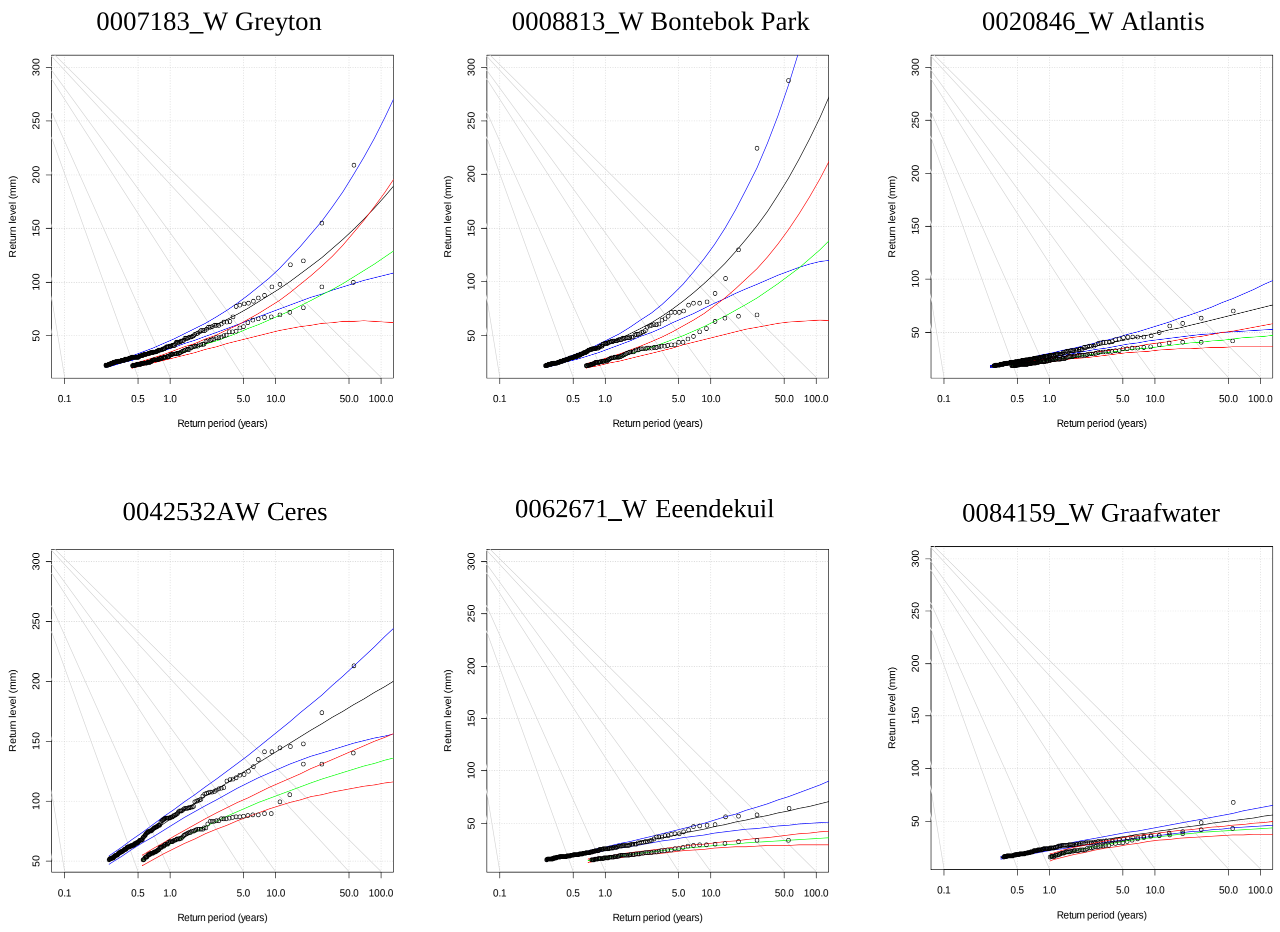

Figure 4.4 Return level plots for various stations showing an increase in return level over the historical record

Figure 4.4 shows the changes in return level and return intervals for:

- 0007183_W Greyton
- 0008813_W Bontebok Park
- 0020846_W Atlantis
- 0042532AW Ceres
- 0062671_W Eeendekuil
- 0084159_W Graafwater.

Similar to Figure 4.3, one can clearly establish that there is an increase in return level for the 50-year return period for each rainfall station. For the 0008813_W Bontebok Park rainfall station, the 1900-1954 period 50-year return level is 103mm. This return level increases substantially to approximately 190mm for the 1955-2010 period. There is an approximate 87mm change in return level for the same (50-year) return period, suggesting an increase in the intensity of storm systems affecting the region over the record. The associated return interval for a certain magnitude storm has decreased as well. From the graph one can determine that the approximate maximum rainfall intensity for a 1 in 50-year event between 1900 and 1954 (103mm) has a similar magnitude to the maximum rainfall event expected in 10 years for the 1955-2010 period. This result shows that the intensity and frequency of extreme events has increased at the rainfall station over the historical record. The minimum bound of the 95% confidence intervals for the 1955-2010 period crosses over the maximum for the 1900-1954 period.

The return level plot for 0007183_W Greyton once again shows an increase in return level over the data record. The 95% confidence intervals for each time period at the 50-year return interval are slightly narrower than the confidence intervals for 0008813_W Bontebok Park, but do, however, remain quite far apart. At the 50-year return interval there is a return level increase from approximately 102mm to 145mm, which is accompanied by a decrease in the return intervals of extreme events. At the 0020846_W Atlantis station, the 95% confidence interval is very narrow for each period, where the minimum for 1955-2010 and maximum for 1900-1954 only cross after the 50-year return interval. While the 5-year return levels are comparable in magnitude, there is an increase in return level from approximately 43mm to 65mm for the 50-year return period as well as a substantial increase in the probability of occurrence of extreme events.

For 0042532AW_Ceres, the 95% confidence intervals widen as the return interval increases. For the 5-year return period, the return interval has increased from approximately 90mm to

125mm from 1900-54 to 1955-2010. This return level differential increases even further for the 50-year return period from 125mm to 178mm. This indicates an increase in the intensity of a rainfall event with the same probability of occurrence. The 50-year return levels at 0062671_W Eeendekuil for both time periods are not as intense as those of Ceres and Greyton, but there is a clear increase in return level between the 1900-1954 and 1955-2010 period. The 95% confidence intervals for both periods are small at the 5- and 10-year return periods, and widen only slightly at the 50-year return period. The return level at the 20-year return period increased from 31mm to 52mm, while the 50-year return level increased from approximately 34mm to 60mm. This represents an 81% increase in return level from 1900-1954 to 1955-2010 and clearly shows an increase in return level for the rainfall station over the historical record as the minimum boundary of the 1955-2010 95% confidence interval is still greater than the maximum of the 1900-1954 95% confidence interval.

For 0084159_W Graafwater station the 95% confidence intervals for both periods are of a similar size while the data points fit the distribution curve well. The return level increase for the 50-year return period was from 41mm to 50mm. The return level curves follow a similar gradient; however, the 1955-2010 period return levels show an increase from the calculated return levels for the 1900-1954 period, indicating an increase in intensity of rainfall events over the data record.

4.3.2 Decreases in 50-year Return Level

The rainfall stations that displayed a decrease in return levels over the historical record are:

Table 4.3 Rainfall stations displaying a decrease in return level

Station ID	Coordinates	
0006039_W Grabouw	-34.15	19.02
0006332_W Rustfontein	-34.03	19.19
0006415_W Hermanus	-34.42	19.24
0006527_W Tussenbeide	-34.29	19.2
0007263_W Boskloof	-34.39	19.65
0008751_W Marloth	-34.01	20.44
0009815_W Heidelberg	-34.09	20.96
0014063_W Knysna	-34.04	23.05
0014633_W Plettenberg Bay	-34.06	23.37
0022803_W Bellevue	-33.91	19.46
0023597_W McGregor	-33.95	19.83

0027302_W Calitzdorp Pol	-33.57	21.64
0028150_W Kwepertuin	-34.01	22.08
0028415_W Jonkersberg	-33.93	22.23
0029294_W Bergplaats	-33.9	22.68
0029542_W Rooirivier	-33.55	22.82
0029692_W Buffelsklip	-33.55	22.9
0041347_A Langgewens	-33.28	18.71
0042669_W Malabar Farm	-33.14	19.37
0046479_W Ladismith	-33.5	21.27
0047716_W Kruisrivier	-33.43	21.86
0048384_W Grootkraal	-33.4	22.23
0049060_W De Rust	-33.49	22.53
0050688_W Rooiklip	-33.47	23.39
0063005_W Citrusdal	-32.6	19.01
0067074_W Anysrivier	-32.74	21.05
0070735_W Klipkrans	-32.75	22.91
0086007_W Reenen	-32.11	19.51
0095006_W Quaggasdrift	-32.1	24.02
0106880AW Vredendal	-31.67	18.5

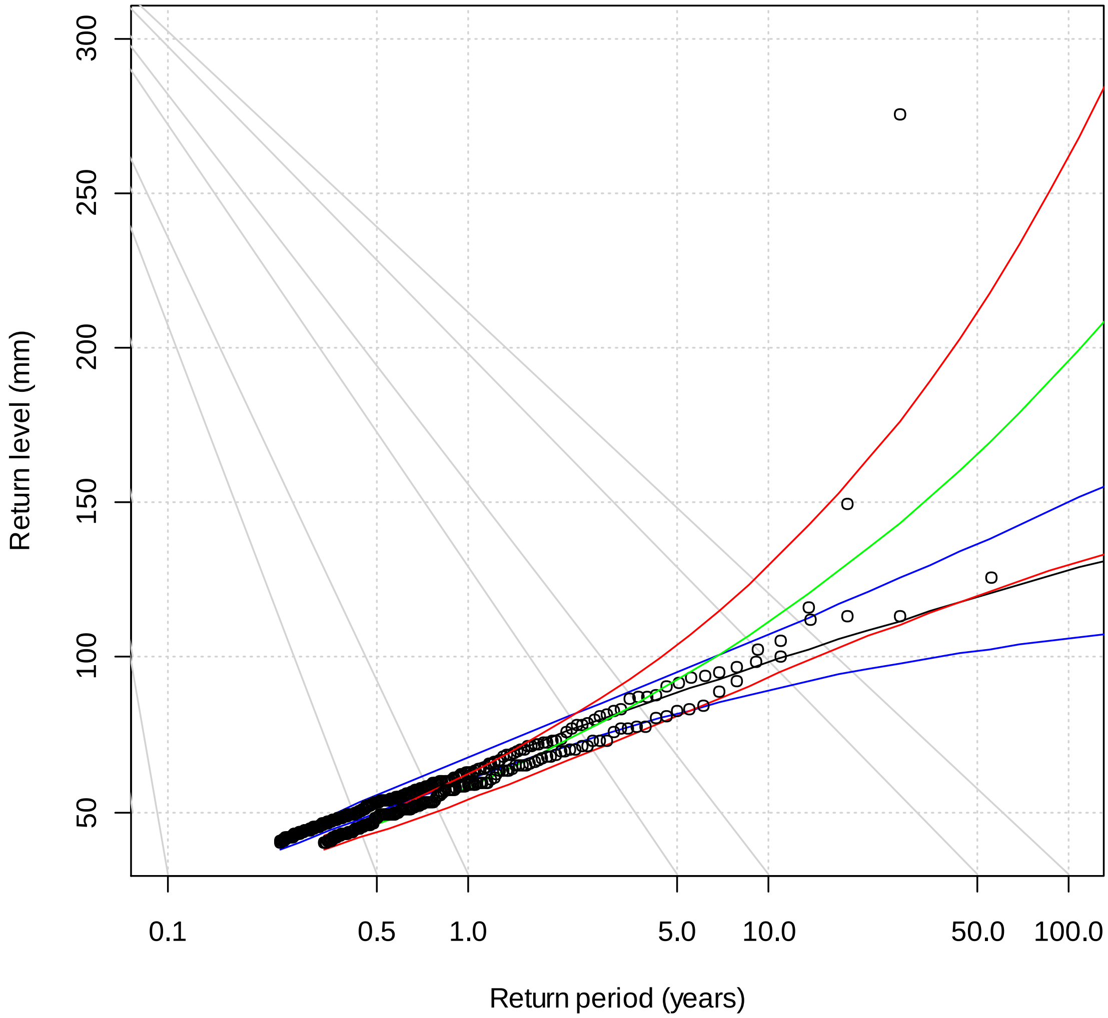

Figure 4.5 Return level plot for 0006039_W Grabouw

Figure 4.5 shows the return level plot for the rainfall station in Grabouw. The 95% confidence interval for the 1900-1954 period is significantly wider than that of the 1955-2010 period. This may be due to the extreme outlier point at approximately 275mm, which does not fit the distribution curve. From the graph, one can determine that there has been a significant decrease in the return level for the 50-year return period from 166mm to 119mm. This is in stark contrast to the difference in 5-year and 10-year return intervals, where the return levels for both periods are comparable. This sudden increase may be caused by the two maximum data points for the 1900-1954 period, which do not fit the distribution well. Figure 4.6 (below) shows return level plots for three rainfall stations in the Western Cape with decreasing return levels over the data record.

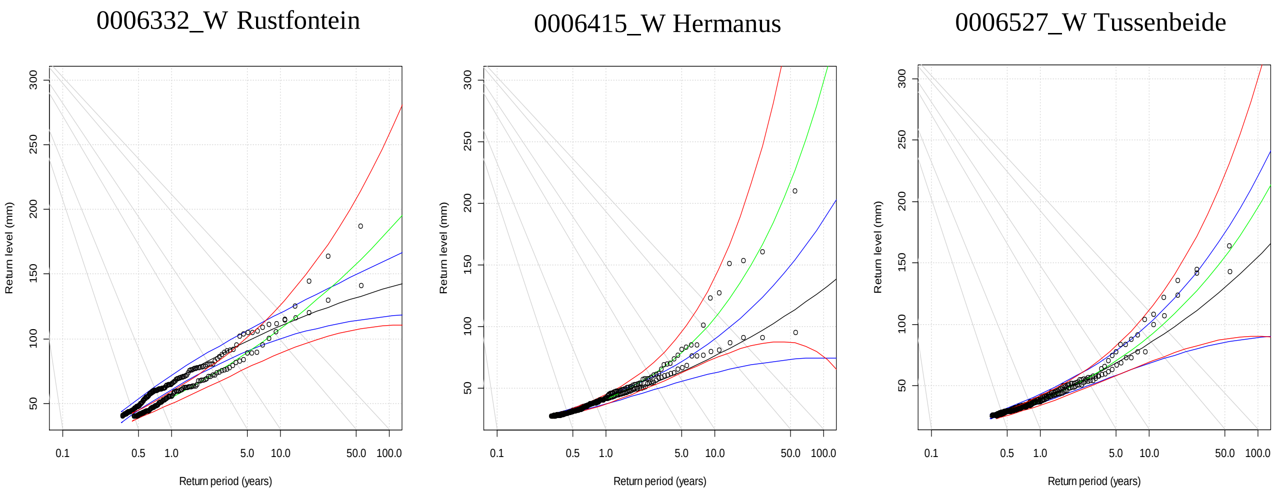

Figure 4.6 Return level plots for various stations showing a decrease in return level over the historical record

All of the return level plots showing decreasing return levels show large 95% confidence interval ranges. These ranges seem to be largest for the 1900-1954 period. For 0006332_W Rustfontein, the 95% confidence envelope (1900-1954) is much wider than that of the 1955-2010 distribution curve. As the return period increases, the curve fits the points (for 1900-1954) less well, while the curve fits the 1955-2010 points well, resulting in a smaller 95% confidence interval. For the rainfall station at Rustfontein, the 1955-2010 return level is greater for the 5-year return period. This, however, changes by the 50-year return period where the 1900-1954 return level (158mm) is greater than that of the 1955-2010 period (131mm). The graph shows that the two distribution curves do not differ substantially until after the 10-year return period. It is important to remember that there may be a great deal of error associated with the 1900-1954 period.

The return level plot for 0006415_W Hermanus, once again, shows a large 95% confidence interval for the 1900-1954 period at the 50-year return interval. At the 5-year return interval, the 95% confidence interval is comparable in size to that of the 1955-2010 period, but increases in size as the curve fits the data points less well as the return period increases. One can clearly see the data points begin to tail away toward the horizontal at the 5-year return period, but there is a large jump in return level by the following data points at the 10-year return period. The 95% confidence interval for the more recent period is also wide, but much narrower than the 1900-1954 95% confidence intervals. At the 50-year return interval, the 1900-1954 return level is approximately 217mm, which is 106mm greater than that of the 1955-2010 time period – 111mm.

The 0006527_W Tussenbeide rainfall station 95% confidence interval for the 1900-1954 period is once again broader than that of the 1955-2010 period and widens rapidly after the 10-year return interval. For the 5- and 10-year return intervals, the return levels for both periods are almost the same, but the 50-year return interval shows a decrease in return level over time from approximately 155mm to 130mm. The close proximity of Tussenbeide, Hermanus, Grabouw and Rustfontein to one another suggests that there is a decrease in return levels, for the 50-year return period over the historical record, in the area. The significant uncertainty associated with these rainfall stations must, however, be noted.

The rainfall stations that show a decrease in storm intensity for the 50-year return period over the historical record, display significant potential for error. The rainfall stations are also predominantly grouped in similar areas and suggest that there may be some degree of spatial autocorrelation to these results and that climate in those regions is not stationary.

4.3.3 Stable 50-year Return Level

Rainfall stations that displayed less than a 5% increase or decrease in 50-year return level have (for this study) been considered as stable rainfall stations. The rainfall stations showing stability in climate (stationarity) are:

Table 4.4 Rainfall stations displaying no noticeable change in return level

Station ID	Coordinates	
0004762_W Simonstown	-34.18	18.42
0005611AW Steenbras	-34.18	18.85
0006038_A Elgin	-34.14	19.02
0006612_W Boontjieskraal	-34.21	19.34
0011065_W Diepkloof	-34.08	21.55
0021778_W Jonkershoek	-33.96	18.93
0021823_W Paarl	-33.72	18.97
0025450_W Dun Donald	-34.01	20.76
0025599_W Strawberry Hill	-33.99	20.82
0029805_W Goudveld	-33.93	22.96
0030265_W Buffelsnek	-33.91	23.16
0030775_W Keurboomsrivier	-33.92	23.43
0042227_W Tulbagh	-33.29	19.14
0042789_W Odessa	-33.14	19.44
0045857_W Floriskraal dam	-33.29	20.99
0049050_W Klaarstroom	-33.33	22.54
0049372_W Rondawel	-33.2	22.67
0050327_W Rondekop	-33.45	23.17

0068547_W Zeekoeivlei	-32.61	21.81
0083618_W Elandsbaai	-32.31	18.34
0084558_W Elandsfontein	-32.3	18.82
0084701_W Clanwilliam	-32.18	18.9

Figure 4.7 shows the return level change for the rainfall station in Simon's Town through the historical record. The gradients of both the 1900-1954 and 1955-2010 curves are very similar and the two curves hardly separate from each other. The size of 95% confidence interval for both time periods is similar, while the data points become increasingly scattered around the distribution curves as return interval increases. The results suggest that there is little change in extreme rainfall in Simon's Town over the last 110 years.

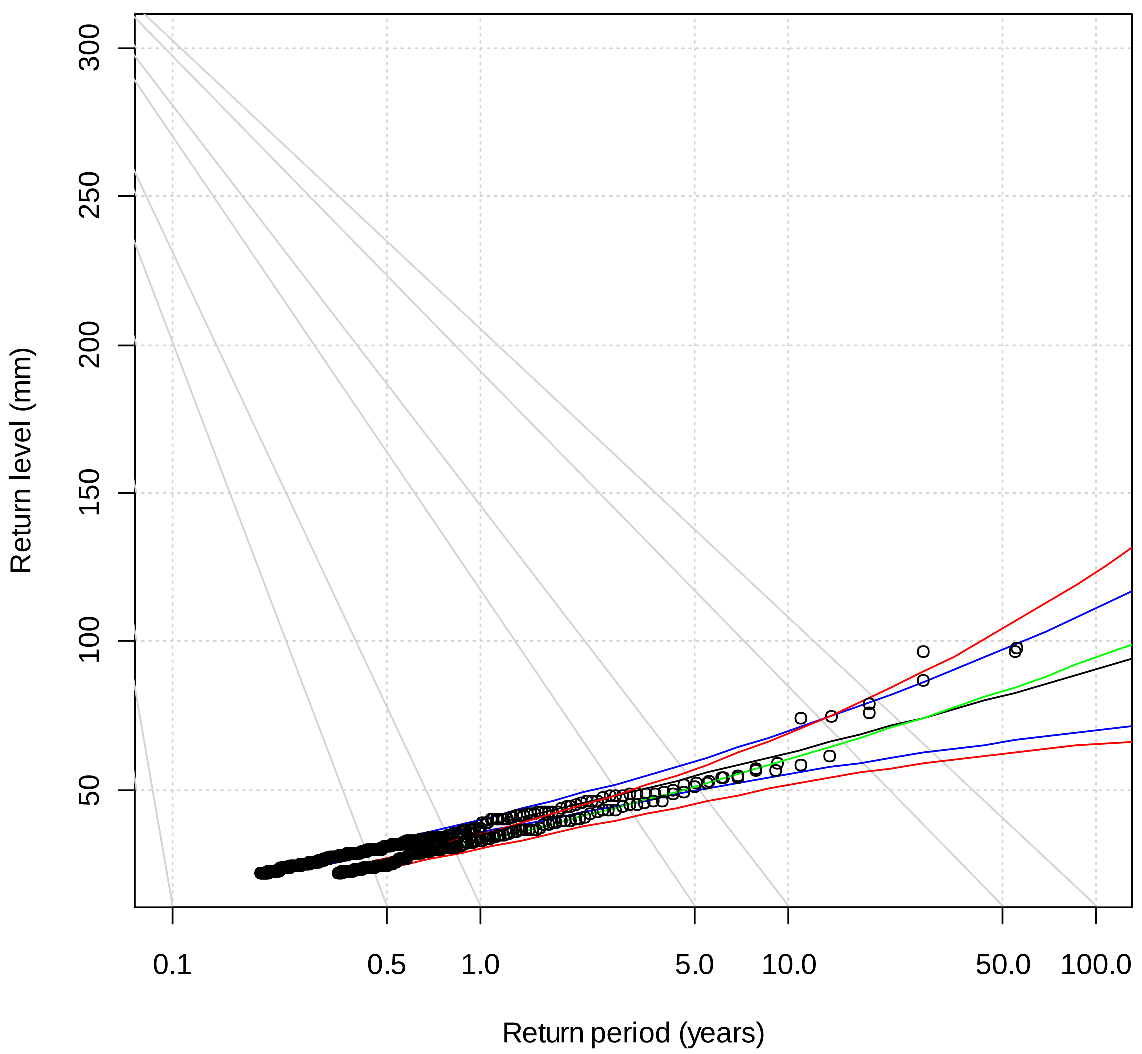

Figure 4.7 Return level plot for 0004762_W Simonstown

The return level plots for 0021823_W Paarl, 0025599_W Strawberry Hill and 0084701_W Clanwilliam are shown in Figure 4.8.

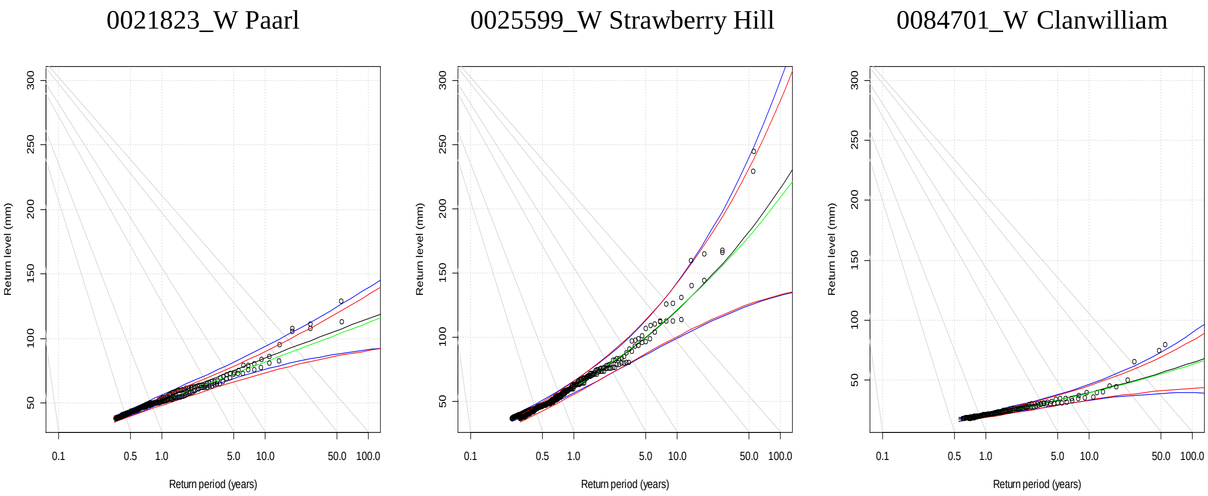

Figure 4.8 Return level plots for various stations showing no change in return level over the historical record

For the 0021823_W Paarl rainfall station the error margins for both time periods are small and the return level curves for both periods track each other. The 50-year return level for both time periods is roughly 105mm, which suggests that the climate with regard to extreme rainfall distribution in the area is reasonably stationary. The 0025599_W Strawberry Hill rainfall station shows significantly higher return levels for the 50-year return interval than the rainfall station in Paarl. The return level curves for 1900-1954 and 1955-2010, however, track each other very closely. There is a slight increase in 50-year return level from 1900-1954 (179mm) to 1955-2010 (182mm) representing a small 2% change in return level over the historical record. The rainfall station 0084701_W Clanwilliam shows a 1.6% change in 50-year return level from 1900-1954 (55mm) to 1955-2010 (56mm) as well as a 1.1% change in 20-year return level over the same period.

4.4 SPATIAL DISTRIBUTIONS

4.4.1 20-year Return Level Changes

Figure 4.9 shows the distribution of 20-year return levels across the Western Cape for the 1900-1954 period. Each point on the map represents a rainfall station analysed using a GPD for the 1900-1954 period. From the map one can clearly determine areas of strong clustering in the magnitude of 20-year return levels. The west coast of the Western Cape is shown to be an area of relatively lower return levels for the 20-year return interval between 1900 and 1954. The results for the interior of the province show that the area is also one of lower 20-year return levels for the same time period. These results are consistent with the mean annual precipitation levels for these regions (shown in Figure 2.2). Towards the south-east of the province there is a large clustering of intense 20-year return levels. Overall, there appears to be an increase in 20-year return level for the 1900-1954 period from west to east as well as a strong topographical influence on the magnitude of these return levels. Mountainous regions are subjected to higher 20-year return levels, while the coastal regions along the southern coast receive medium to high 20-year return levels. The distribution pattern of 20-year return levels for 1900-1954 for the entire province closely follows the spatial distribution of mean annual precipitation.

The spatial distribution of 20-year return levels for the 1955-2010 is shown in Figure 4.10. The map clearly shows that the distribution pattern for 1955-2010 is similar to that of 1900-1954, though the magnitudes of these events have changed. Once again it can be seen that lower 20-year return levels are found along the west coast of the province as well as the interior. The magnitude of these return levels is, however; generally larger than the magnitude of the 20-year return levels for the 1900-1954 period. The map, once again, clearly displays the influence of topography on the magnitude of 20-year return levels, where high altitude regions display larger return levels than those of lower altitude, as well as the west-east rainfall intensity gradient.

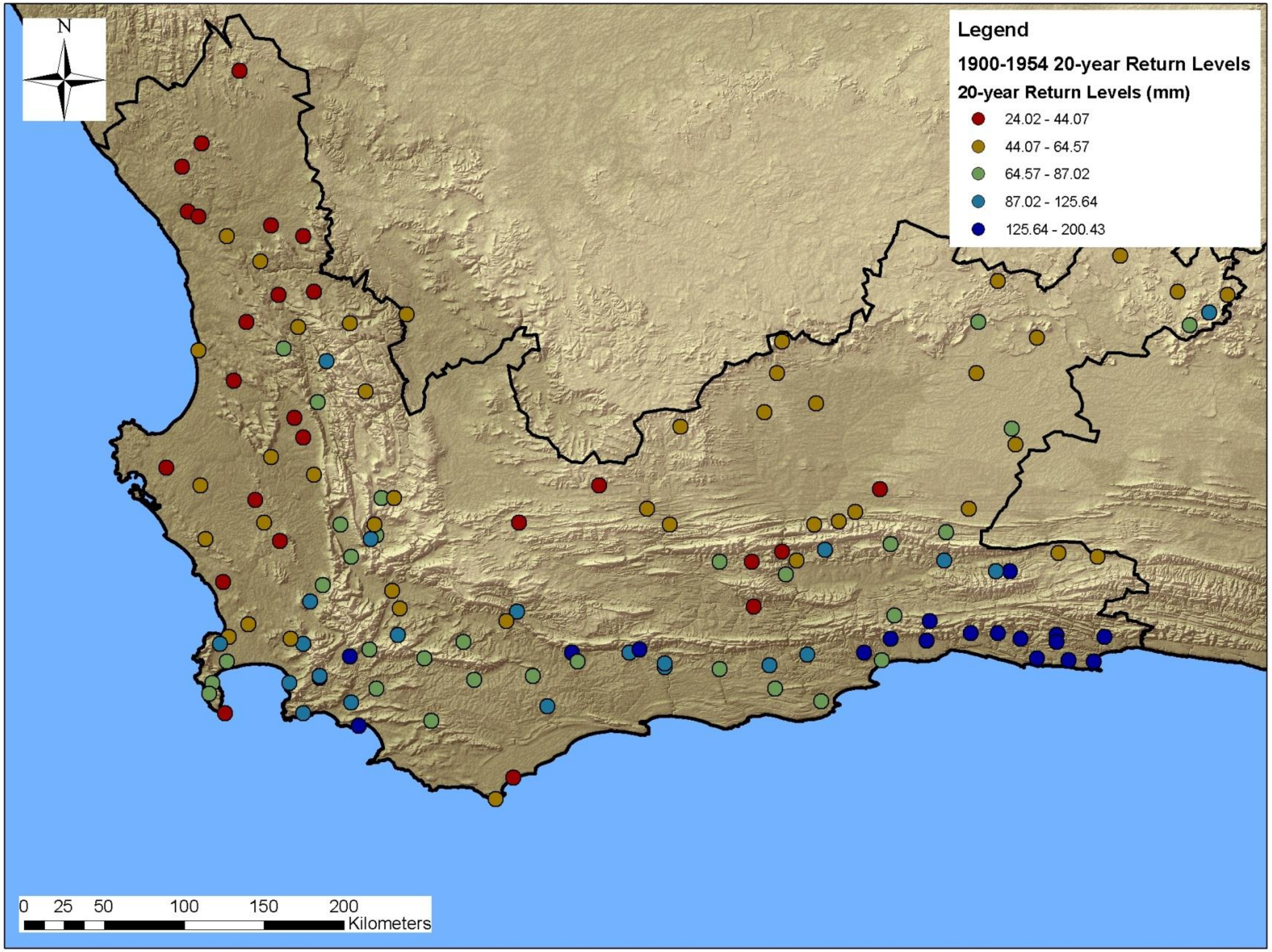

Figure 4.9 20-year Return Level magnitudes for 1900-1954

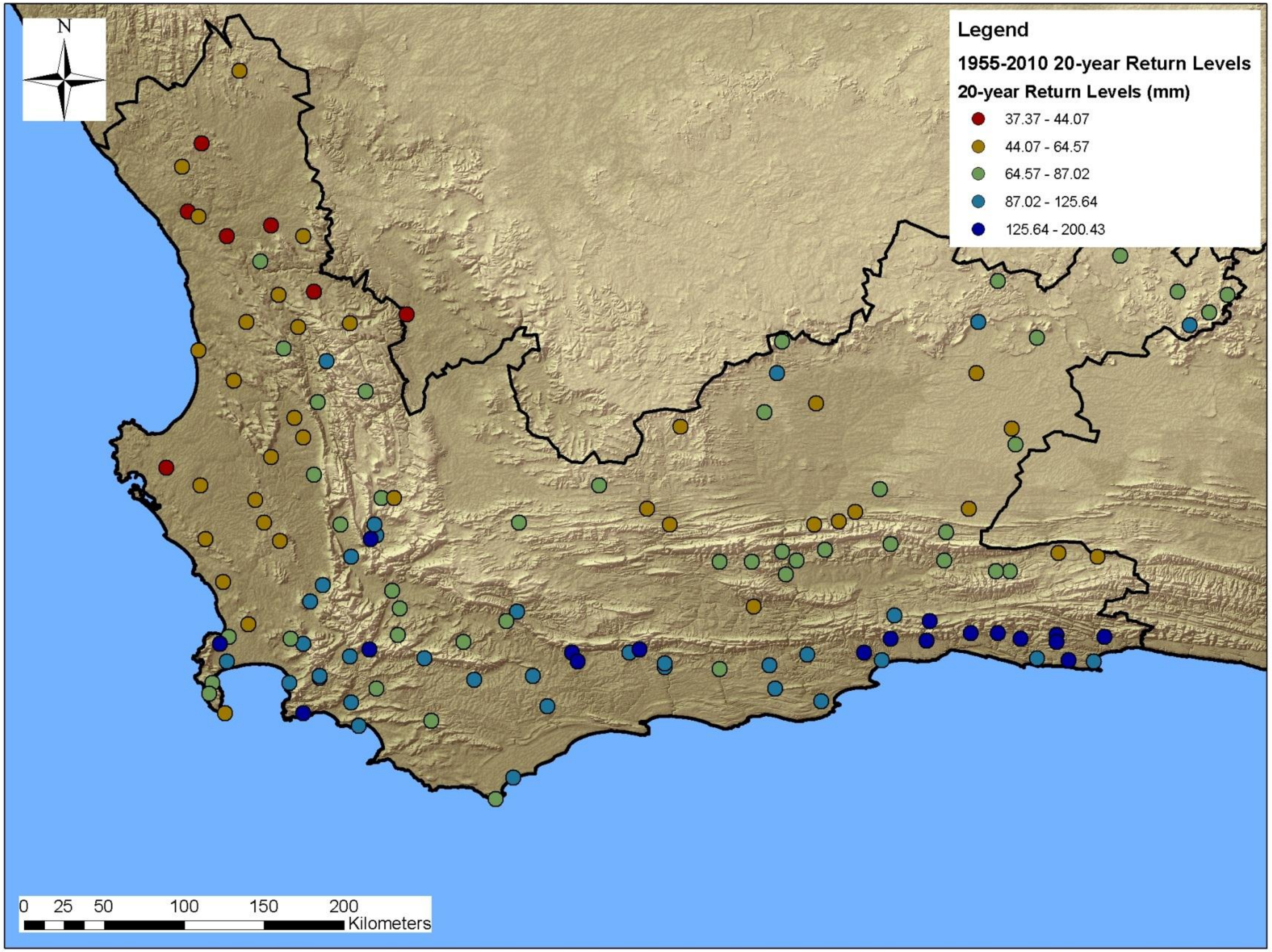

Figure 4.10 20-year Return Level magnitudes for 1955-2010

The percentage change of 20-year return levels is shown in Figure 4.11. Of the 137 rainfall station analysed, 88 showed an increase (> 5% change) in 20-year return levels over the historical record, 28 remained stationary (between -5% and 5%) while 21 stations showed a decrease (< -5%) in 20-year rainfall return levels. The magnitude of these percentage changes ranges from -57% to 180%. Figure 4.11 does not show any strong clustering in the magnitude of the percentage changes to 20-year return levels.

Figure 4.12 displays this pattern by dividing the changes into three classes: increasing, decreasing or stationary. From the map one can determine that most of the province has experienced increases in 20-year rainfall return levels from 1900-1954 to 1955-2010. The distribution of stations showing an increase is quite even throughout the province. Areas displaying a decrease in 20-year return level appear to be predominantly in mountainous areas (high altitude), that have relatively higher return level magnitudes. The results of the spatial auto-correlation run using ArcGIS indicate that there is strong clustering in the percentage change of 20-year return level with a "less than 1% likelihood that this clustered pattern could be the result of random chance".

Figure 4.13 shows the interpolation of the percentage change in 20-year return levels from point data to the rest of the province. The results indicate that there are two main regions in the province where 20-year return levels may be decreasing, including the south-east of the province near George and Knysna. The rest of the province is shown to be a region of increasing 20-year return levels over the historical record, with the biggest increase occurring at the southern-most point of the province (Cape Agulhas).

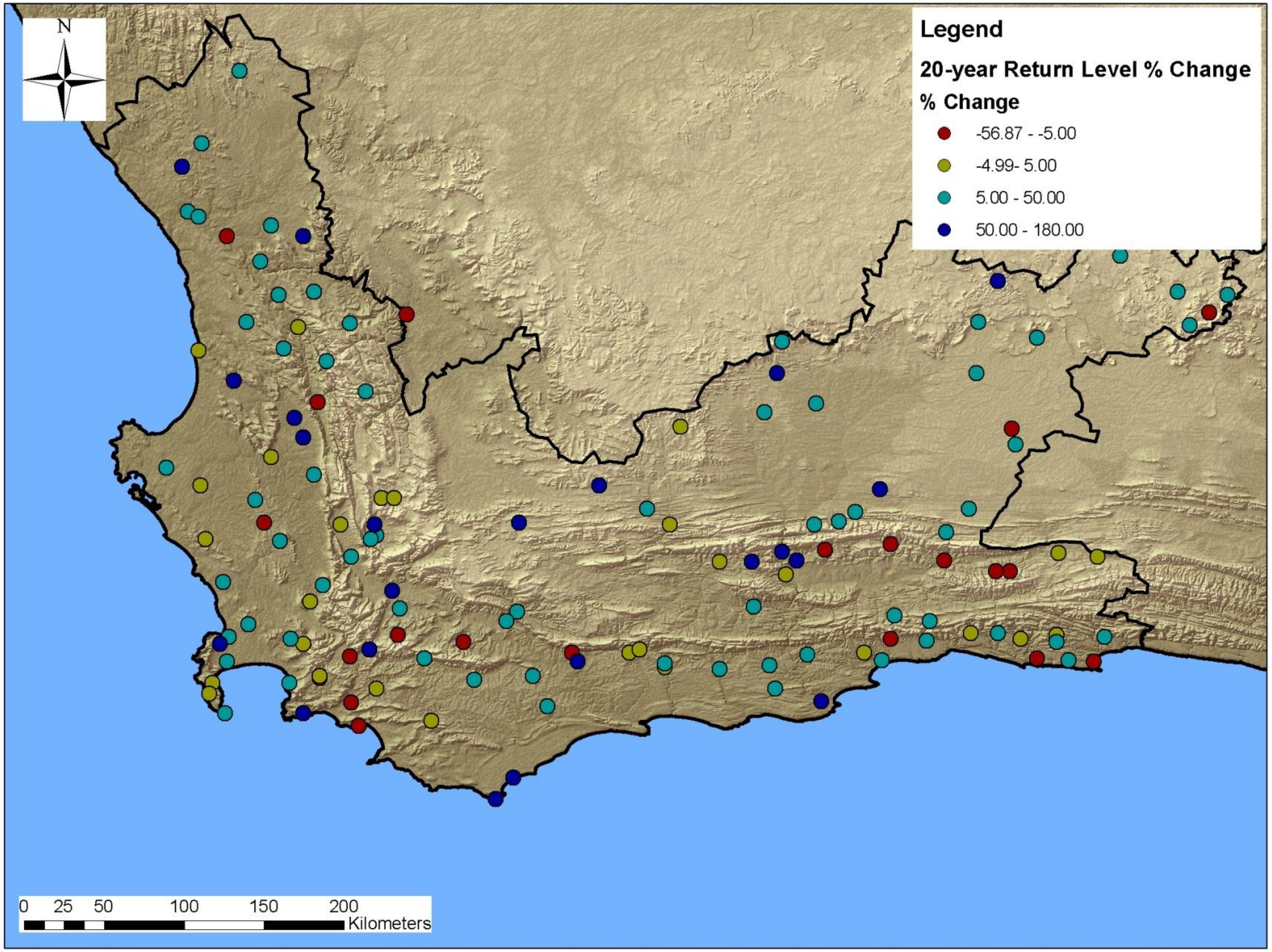

Figure 4.11 20-year Return Level percentage change from 1900-1954 to 1955-2010

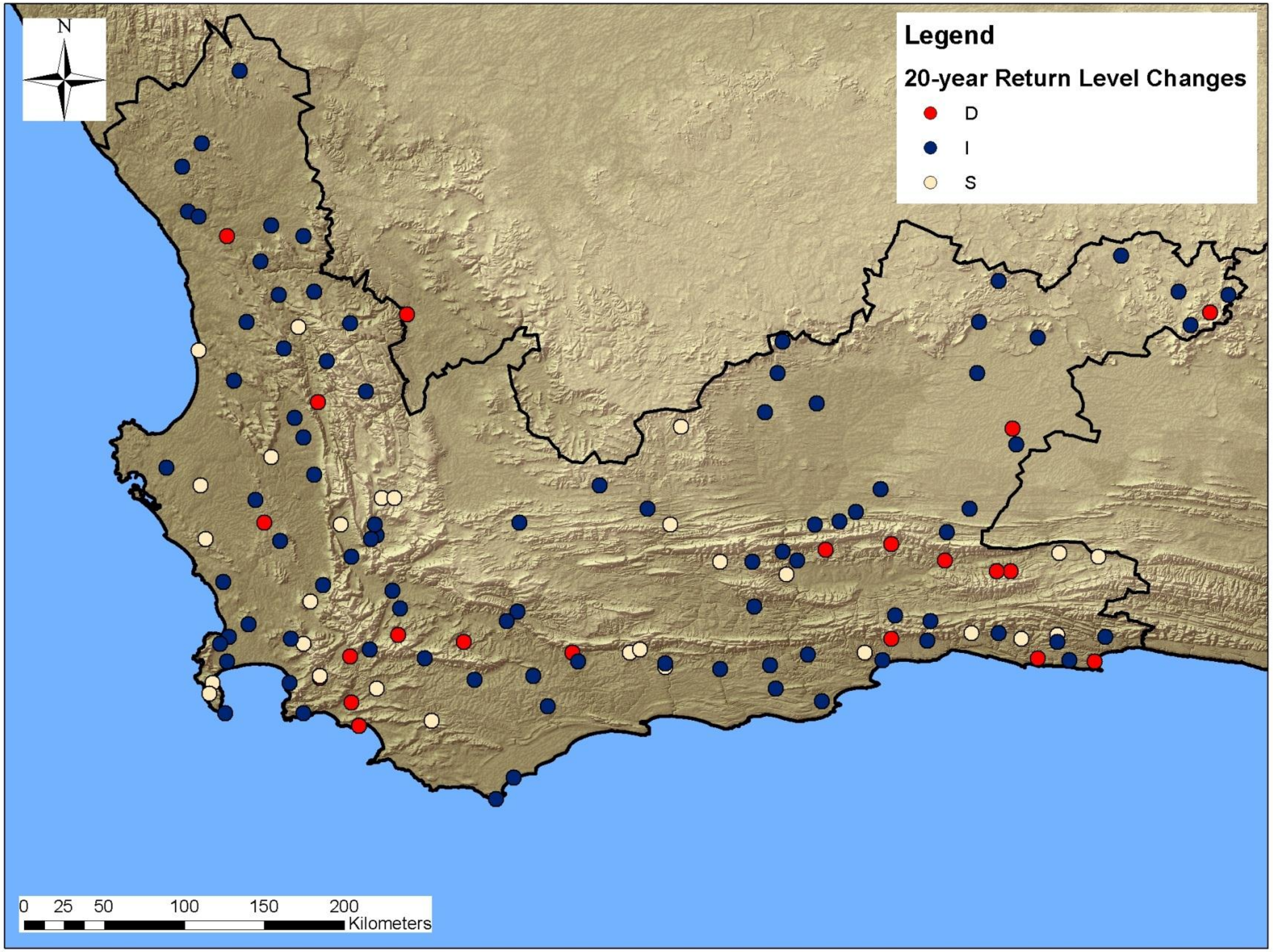

Figure 4.12 20-year Return Level changes from 1900-1954 to 1955-2010

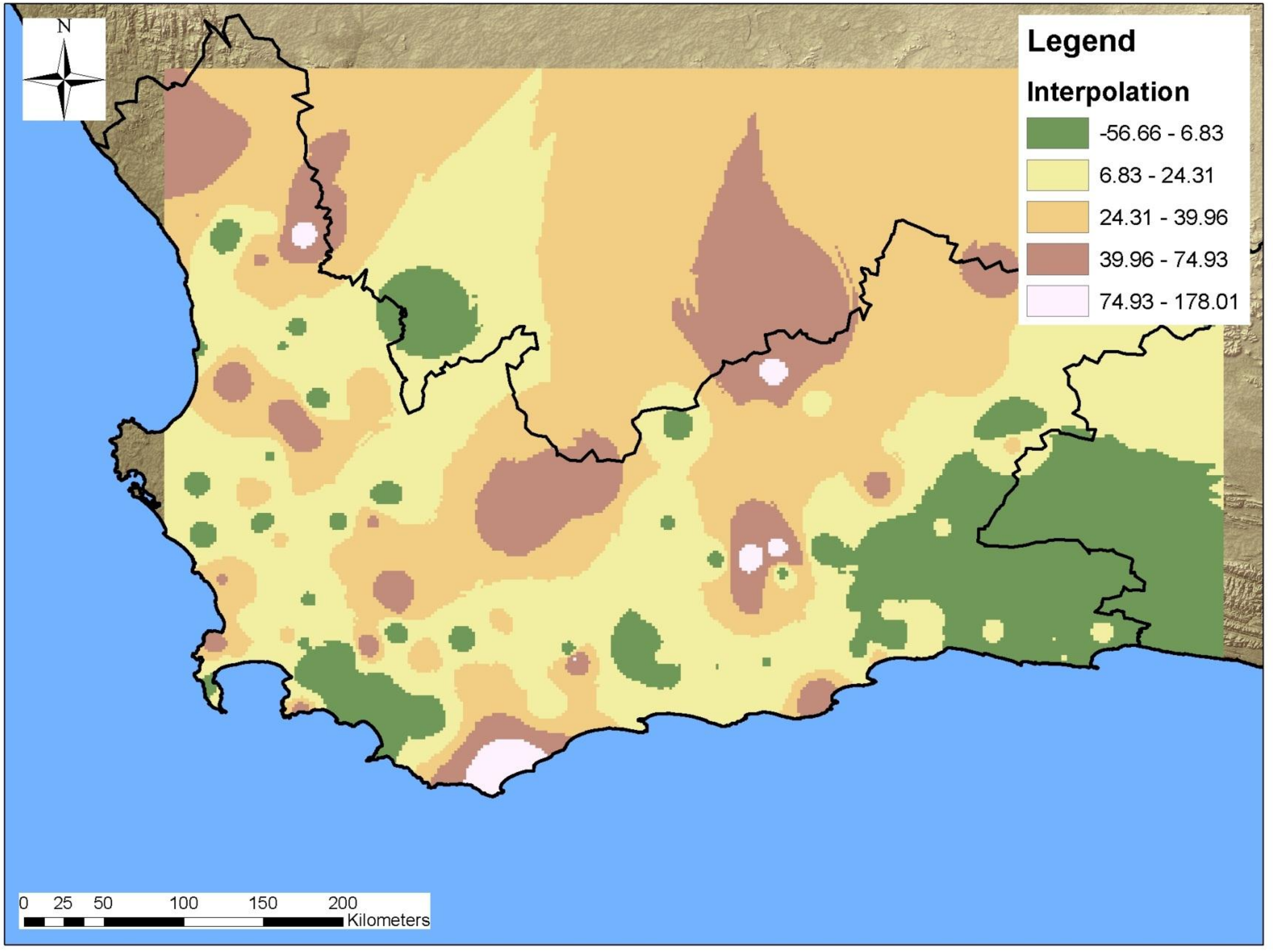

Figure 4.13 Inverse Distance Weighted interpolation of 20-year Return Level percentage change

4.4.2 50-year Return Level Changes

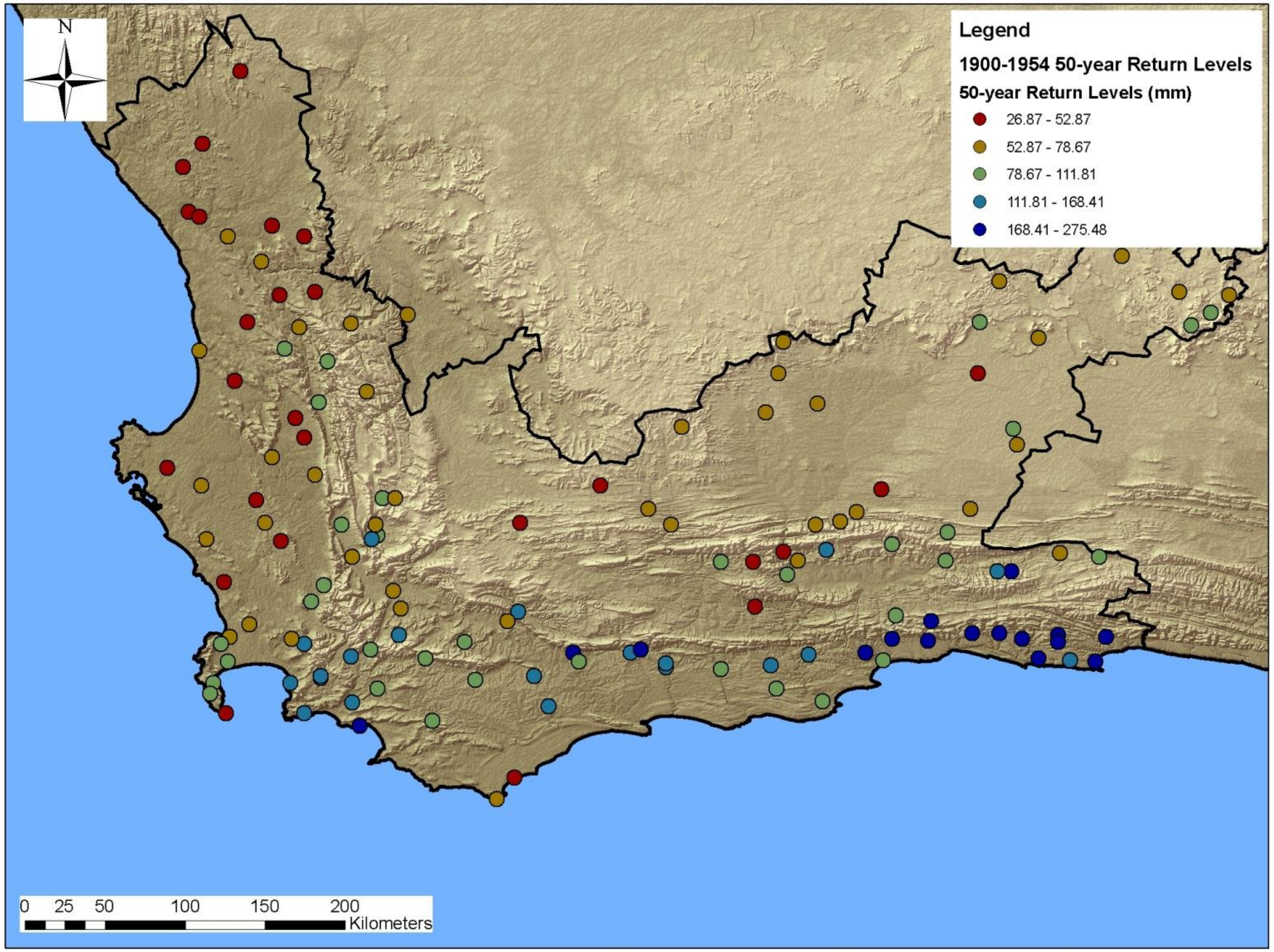

Figure 4.14 50-year Return Level magnitudes for 1900-1954

Figure 4.14 shows the distribution of 50-year return levels for 1900-1954 across the Western Cape. The spatial distribution of these return levels is similar to that of the 20-year return level distribution, however, the magnitude of these events has changed. The west coast and interior of the province are regions of relatively lower 50-year return levels in comparison with the rest of the province. The range of 50-year return levels is between 26.87mm and 275.48mm where, once again, the regions of more intense 50-year return levels are found at higher altitudes (particularly towards the east of the province). The 50-year return levels for the 1955-2010 period (Figure 4.15) follow a similar pattern to those of the 1900-1954 period. There is, however, a substantial increase in the magnitude of these events, particularly in the interior of the province. This indicates that the interior of the Western Cape may be experiencing an increase in 50-year return levels over the data record. There is strong clustering of high intensity 50-year return levels at high altitudes, which follows a similar pattern to the mean annual precipitation distribution for the region (Figure 2.2).

The percentage change in 50-year return levels between the two periods is shown in Figure 4.16. 30 of the rainfall stations show a decrease in 50-year return level while 85 stations show an increase and 22 have remained stationary over the historical record. Like the 20-year return level changes, the 50-year percentage change is highly clustered with a less than 1% likelihood that the pattern is a result of random chance. The distribution of station's 50-year return level change is shown in Figure 4.17. The results indicate that most of the Western Cape is experiencing varying degrees of increasing 50-year return levels (a similar pattern to changes in 20-year return levels) from 1900 to 2010. Areas that show a decrease in 50-year return levels are the south east of the province and possibly the mountainous region near Elgin and Grabouw. This distribution pattern is similar to the distribution of 20-year return levels. The Inverse Distance Weighted interpolation of 50-year return level changes is shown in Figure 4.18. The figure shows two distinct areas in the Western Cape of decreasing 50-year return levels – the south-east and mountainous area east of Cape Town (the Elgin-Grabouw area). The rest of the province appears to be increasing in 50-year return level.

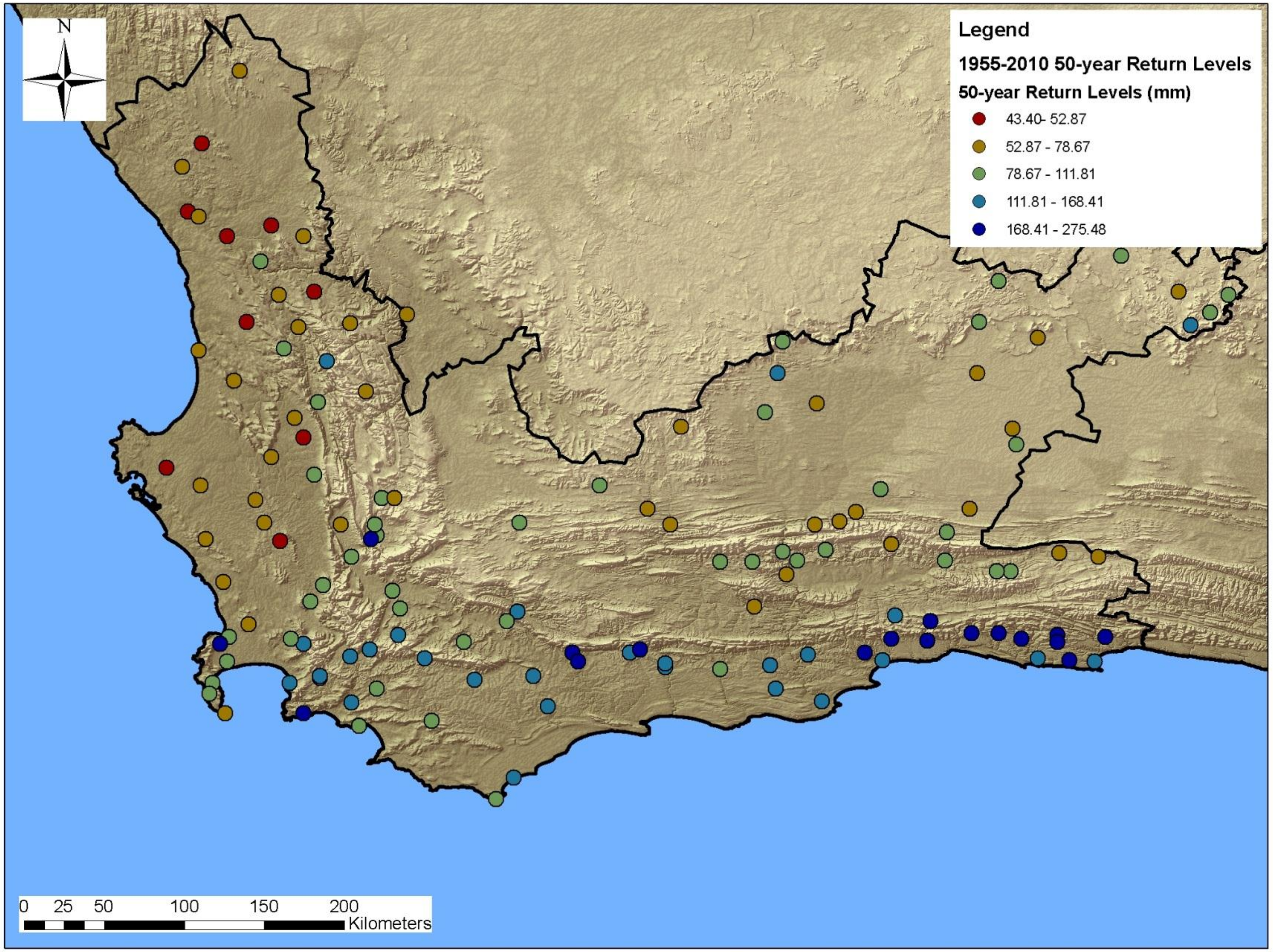

Figure 4.15 50-year Return Level magnitudes for 1955-2010

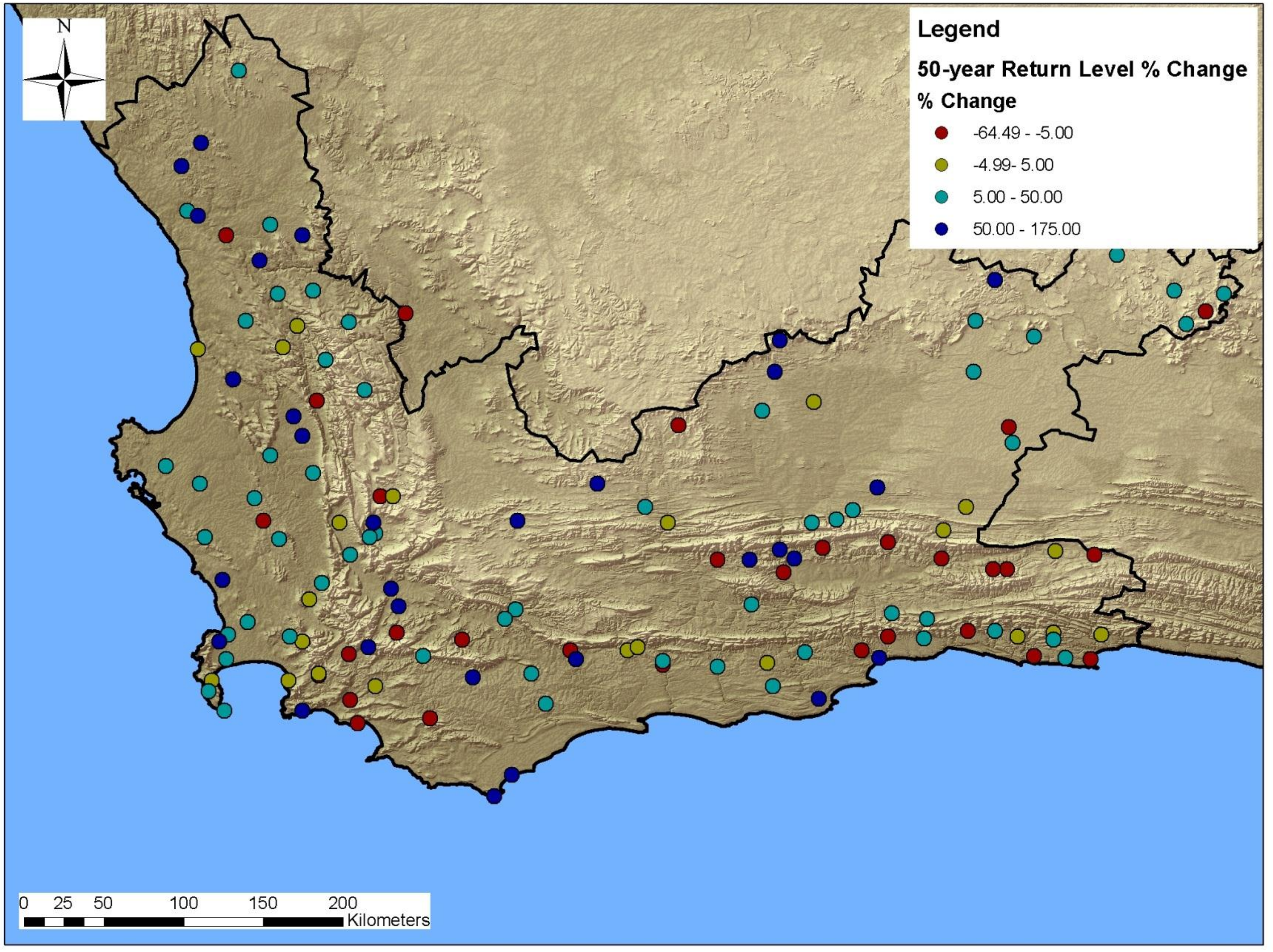

Figure 4.16 50-year Return Level percentage change from 1900-1954 to 1955-2010

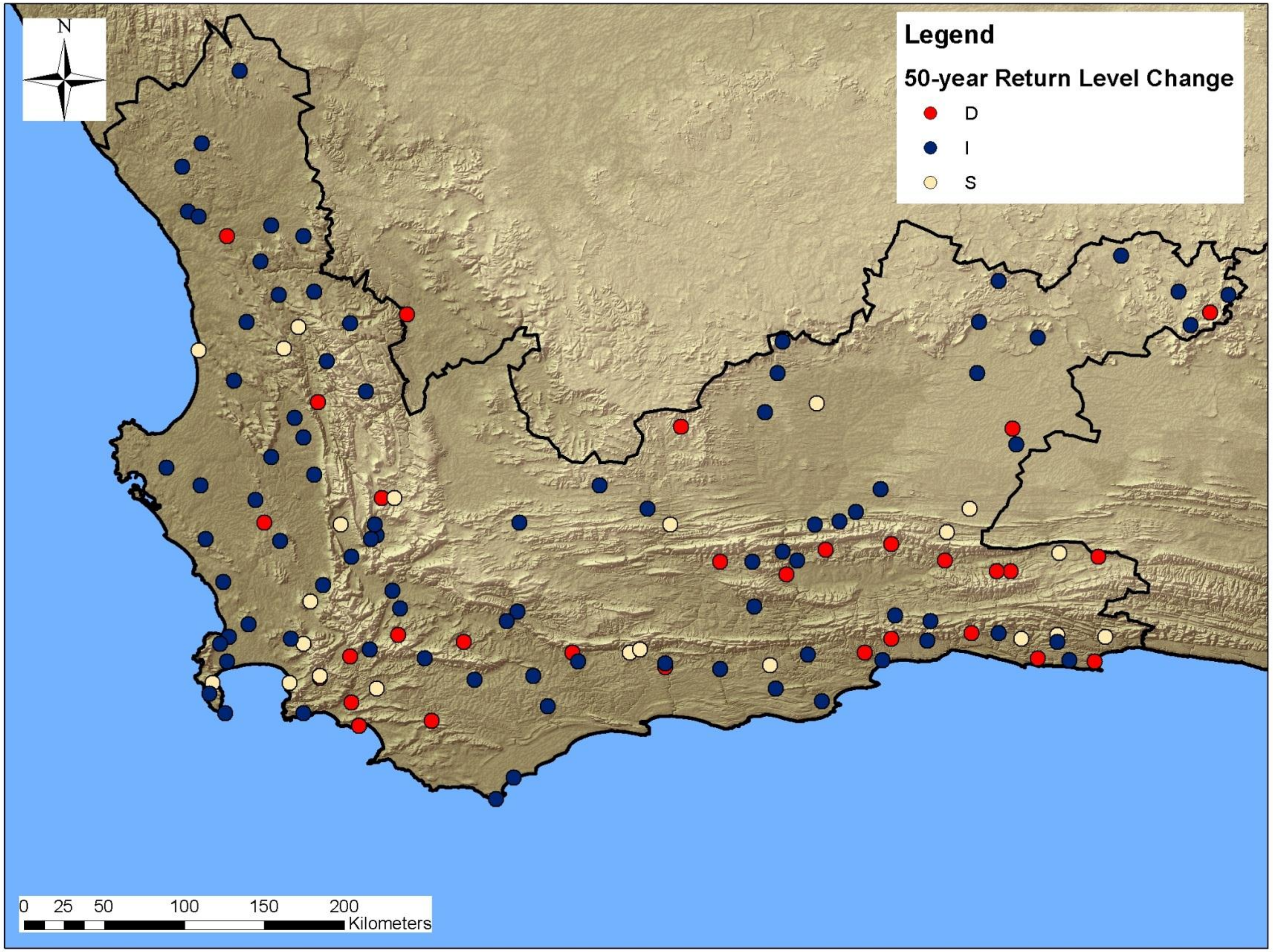

Figure 4.17 50-year Return Level changes from 1900-1954 to 1955-2010

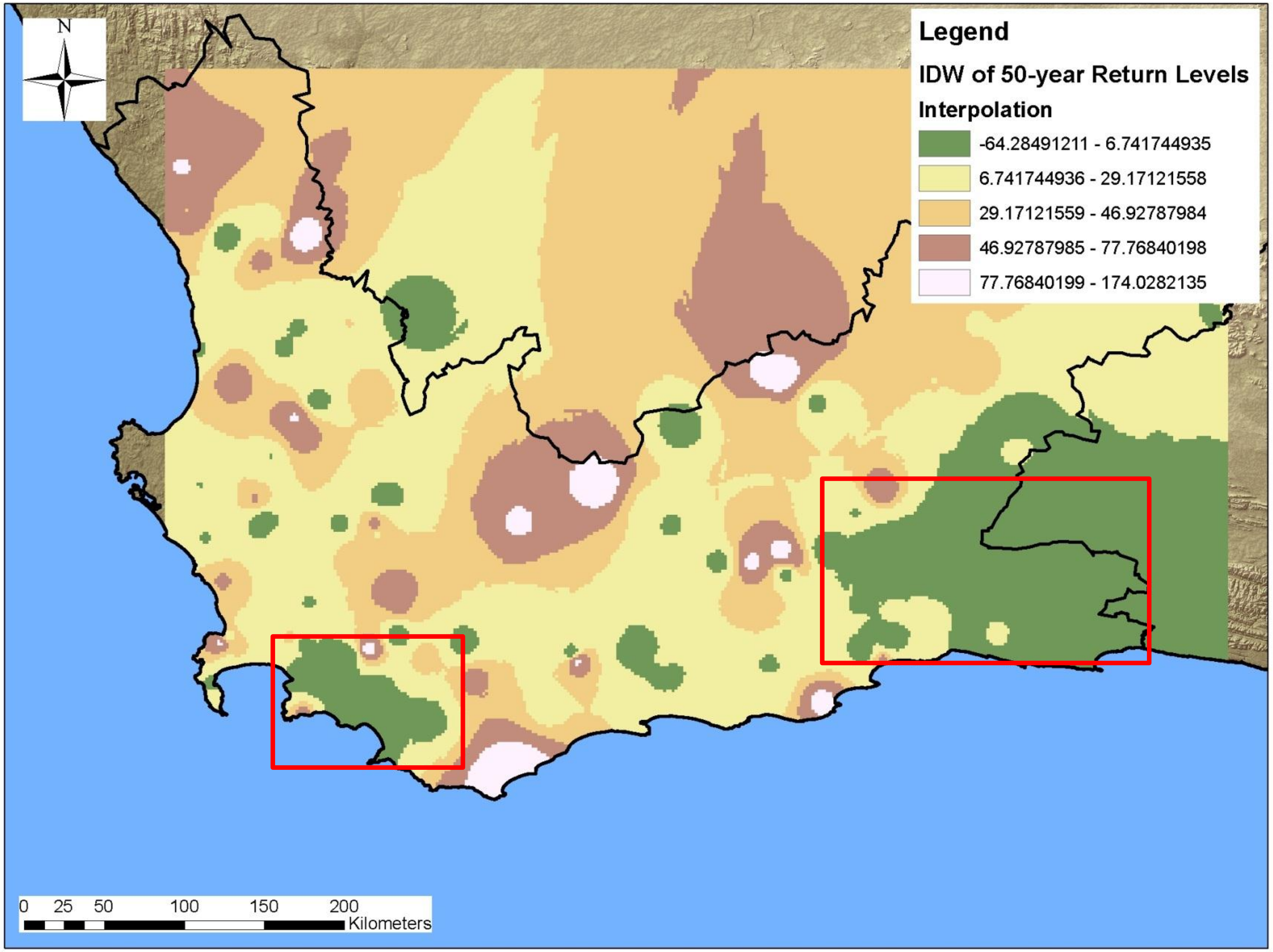

Figure 4.18 Inverse Distance Weighted interpolation of 50-year Return Level percentage change

4.4.3 95th Percentiles

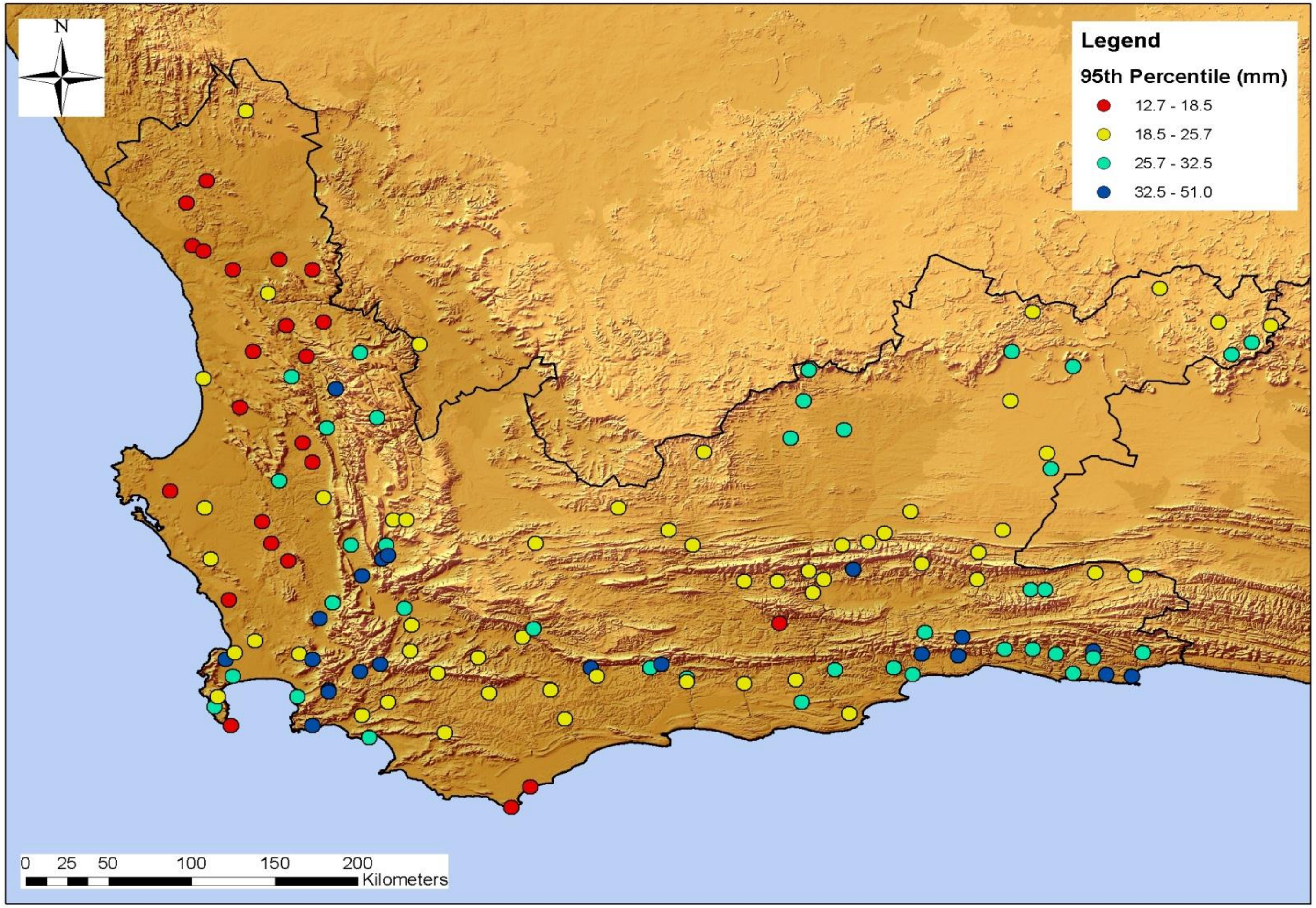

Figure 4.19 Distribution of 95th percentiles over the Western Cape

Figure 4.19 (above) shows the distribution of 95th percentiles, calculated for the entire 110 year data record) for each rainfall station across the Western Cape. The distribution of high intensity rainfall seems to follow a similar pattern to the mean annual precipitation for the region shown in Figure 2.2. The West Coast has many rainfall stations depicting lower 95th percentiles, indicating that rainfall extremes in this region are not as high as those in the rest of the Western Cape. This corresponds with the low mean annual precipitation for the region (Figure 2.2), which is to be expected, due to the proximity of the region to the cold Benguela current. Regions with extreme topography, such as the mountainous regions of the Overberg and Outeniqua (near George) mountain ranges, display an occurrence of larger extremes of rainfall. This is also expected, due to the influence of topography on rainfall; however the upper scale of 95th percentiles is not only confined to mountainous regions.

The area surrounding Knysna and George (south-east coast) experiences, on average, higher levels of extreme precipitation than most of the Western Cape region. The results from the return level calculations indicate that the same region is experiencing a decrease in 50-year return levels. These decreased return levels may still be greater than the increased return levels for the West Coast.

5 DISCUSSION

5.1 50-year Return Level Results

The results of this analysis show that there is substantial change in the intensity of extreme rainfall events over the whole of the Western Cape. Over 62% of the rainfall stations analysed displayed an increase in return level for a 50-year return interval between the 1900-1954 and 1955-2010 periods. A further 22% showed a decrease in the return levels for the same return period, while only 16% of the stations showed no change in 50-year return level. This clearly shows that it cannot be assumed that the nature of extreme rainfall for an individual rainfall station conforms to the idea of stationarity, as set out by Milly *et al.* (2008). The magnitude of the 50-year return levels for both time periods follow a similar spatial distribution to the mean annual precipitation for the Western Cape and a strong topographical influence is shown, where rainfall stations at higher altitudes generally display higher 50-year return levels. The west coast and interior of the province are regions of lower intensity 50-year events. The south-eastern coast has larger magnitude extreme events, which may be influenced by the region receiving both winter (frontal) as well as summer rainfall. The spatial distribution of 50-year return level changes across the Western Cape region shows two distinct regions where 50-year extreme rainfall may be changing. The south-east region of the Western Cape and the mountainous region east of Cape Town (both denoted by red boxes in Figure 4.18) show decrease in 50-year return levels over the data record. The south-east part of the province is an interesting case in that it a clearly a region of high intensity 50-year return levels, however, the magnitude of these return levels, though remaining high, is decreasing over the historical record. This decrease in rainfall intensity may have a significant impact on water management in the area, where high intensity cut-off low pressure systems have replenished dam and ground water levels. A decrease in the magnitude of these extreme events may reduce the amount of water flowing into these reservoirs and thus, decrease water security in the region. The rest of the Western Cape shows an increase in 50-year return levels. The maps also show individual rainfall stations with decreasing 50-year return levels in the middle of a region of general increase. There are also examples of rainfall stations close together that show a decrease and an increase in 50-year return levels. Either, the data quality of these stations should be questioned, or, they are subject to more local scale influences on rainfall intensity. Spatial techniques (such as Inverse Distance Weighted Interpolation) are useful for assessing the data quality of these stations by highlighting stations that are different to the overall trend.

Areas with high 50-year return levels correspond with areas shown to have extremely high 95^{th} percentiles and are largely influenced by their extreme topography. The intensity of these extreme events in the mountainous regions of the Overberg (Grabouw and Elgin) and Outeniqua (George and Knysna region) are decreasing over the historical record, which does not agree with the generalised projections made by Midgley *et al.* (2005) which suggest that rainfall intensity in mountainous regions is expected to increase in the future. If projections are accurate then the areas of decrease are expected to increase with time, which implies that the increasing frequency and intensity of extremes has not yet reached all areas of the Western Cape. There is therefore substantial variability in the measures of extremes, which can be characterised by the wide 95% confidence intervals. The regions analysed, however, do not have an extremely long data record and the results could have significant error. It is also important to note that the projections made by Midgley *et al.* (2005) are future projections for the region, while the results of this study are from already-realized rainfall events. The pattern from the data record, however, suggests that extreme rainfall in those regions (south-east of the Western Cape and just east of Cape Town) is currently decreasing in intensity over time.

The stations showing little change in return levels through the historical record are distributed evenly across the Western Cape. As well as changes to 50-year return levels in the Western Cape, there is also significant change to the amount of long duration, high intensity storms over the region. Of the rainfall stations analysed, 16% showed a decrease in the number of two to three day storms with consecutive threshold exceedances. The rest of the rainfall stations (84%) show an increase in the number of consecutive threshold exceedances over the region.

5.2 20-year Return Level Results

The 20-year return level changes show a similar pattern to the changes in 50-year return level. 64% of the rainfall stations showed an increase in 20-year return level, while approximately 15% had a decrease and the remaining 21% had no change in 20-year return level. The magnitude of 20-year return levels is not as high as those of the 50-year return interval, however, the spatial distribution of intensity levels is similar to that of the 50-year return levels. The results indicate that, even for the less intense return levels, stationarity is not a valid assumption to make when calculating extremes. Once again, there are two major regions showing a decrease in return levels (the south-east of the province and the mountainous regions near Grabouw). There are fewer rainfall stations showing a decrease in 20-year return levels than there are rainfall stations showing a decrease in 50-year return levels.

5.3 Implications for Changing Risk Profile of the Western Cape

The Western Cape is a water scarce area. The change in extreme rainfall has significant implications for flood risk in the province, which, in turn, should inform flood management and dam level management practices. Flood risk is driven predominantly by extreme rainfall. As the intensity of rainfall increases, so does the potential maximum flood peak due to increased amounts of water being in the system. If we can accept that there is a general trend to increasing intensity and frequency of rainfall, the flood risk in the region should increase substantially. Flood peak maxima are expected to increase due to an increase in extreme rainfall in the region. An increase in the volume of water in a river system during a flood should increase the river’s flood plain extent and flow rate. This potential in flood size will affect built-up areas on or within the flood plain margins. This increases the exposure of infrastructure and development to flood events as well as increasing the potential for damage due to increased river flow rates.

The overall increase in long duration, intense rainfall systems across the region can result in increased flood risk. Long duration storms can potentially increase flood risk. As more rainfall falls over the river catchment the ground becomes saturated, which increases the depth of surface runoff from the same quantity of rainfall. This surface runoff flows directly into the river channel, increasing the amount of water flowing in the river. An important implication is that flood risk calculations and design hydrology, which often assumes a standard catchment wetness index for estimating flood peaks for a given return period, is increasingly likely to be at odds with the changes that appear to be occurring.

As vulnerability is a function of exposure, resistance and resilience (Pelling, 2003), it is important to offset the increased exposure in order to reduce vulnerability. This entails increasing the resistance and resilience of the affected to flood risk by promoting effective management. The Disaster Management Act (Act no. 57 of 2002) aims to increase the levels of risk prevention and reduction as well as developing strategies to mitigate the possible outcomes of a disaster event (such as flooding). The act promotes the idea of pre-emptive management and risk prevention over that of post-event response.

In order to meet the aims of this act it is important to realize how flood risk in the region is changing. By acknowledging the increase in potentially flood-causing events due to increased return levels and long duration-high intensity storms, it is possible to install systems, management practices and readdress design criteria as well as identify regions with high vulnerability and increased risk. Areas which have observed an increase in the 50-year return levels should reassess the extent and location of their flood zoning, when subject to a 50-year rainfall event. The resultant change in flood plain extent could place buildings and infrastructure, built along the boundaries of the flood plain, at risk to flooding.

Efforts to reduce the potential damage of floods need, therefore, to be focused on mitigation and pre-flood planning. Mitigation measures are, in a sense, increasing resistance to the effects of damaging floods. Factors which may increase resistance to damaging floods should include:

- improved flood zone identification
- the enforcement of legal restrictions on infrastructure emplacement
- the recalculation of design flows
- flood control measures in high risk areas
- improved usage of flood plains for their original purpose – temporary storage of flood water.

In order to plan for increases in flood risk, the identification of “high risk” areas is important as well as the understanding of general trends and future rainfall projections for that area.

There are many examples of extreme rainfall events causing dams to overtop and further exacerbate the impacts of flood events (DiMP, 2010). In the 2008 November flood event in the Cape Winelands, the N2 close to Heidelberg was flooded as a result of the overtopping of the Vleidam. In the same rainfall event, the Duiwenhoks, Buffelsjags and Korentepoort dams were already overflowing due to the magnitude of rainfall depth-duration (DiMP, 2010). During July 2008, an extreme rainfall event increased the water stored in the Clanwilliam Dam from 55% (two weeks prior to the event) to peak capacity (DiMP, 2010). The water began to overtop the dam wall and 11 of 13 sluice gates were used to release water downstream (DiMP, 2010). This resulted in a significant volume of water flooding the

Oliphants River downstream of the Clanwilliam Dam, causing significant damage and a great risk to infrastructure and human life.

Similarly, The Department of Water Affairs experienced direct damage costs of approximately R40 732 941 resulting from six cut-off low systems over the Western Cape between 2003 and 2008 (DiMP, 2010). Dam level management is a significant factor when aiming to mitigate the effects of flooding. It is also important to note that extreme rainfall events are also responsible for washing away smaller farm dams, as many cases in the southern Cape suggest, which drives up drought vulnerability of local farmers (DiMP, 2012). The over-topping of a dam can greatly increase the damage potential further downstream. It is therefore important to acquire further knowledge on the projected magnitude and frequency of extreme rainfall events so as to improve the operation of large dams. Storm early warning systems need to be put in place both up and down stream.

The appropriate management of dams needs to account for the fact that the Western Cape is a water scarce area (Midgley *et al*., 2005) as well as prone to extreme, high depth-duration rainfall events. Keeping dam levels too high can greatly increase the risk of over-topping if an extreme event, such as a cut-off low, were to fall over the catchment area. In a region where the expected intensity of rainfall events is shown to have increased and is projected to increase even further, the management of dam levels becomes even more difficult. Dam management faces a tight-rope walk of maintaining appropriate dam levels in a region prone to drought, yet also accounting for the potential for increased severity of extreme storm systems. The potential damage to DWA gauging structures also increases with increasing return levels. Damage costs for DWA gauging stations for three storm events in March 2003, August 2006 and November 2007 in the George-Mossel Bay region add up to approximately R8 449 173 (DiMP, 2010). The damage to DWA structures and gauging stations due to extreme rainfall events is significant. An increase in the severity of these events is likely to increase the magnitude of flood events that these structures are subjected to. As a result, the risk of flood damage to dams and gauging structures increases with the increase in return levels over time.

Rosenzweig *et al*. (2002) state that there has been a significant increase in severe rainfall events globally, which has led to wide-spread damage to crops and agricultural produce. This damage can be attributed to flooding as well as crop damage due to increased soil moisture. Flood events can delay the planting of crops, wash away existing crops and damage expensive equipment used for planting and harvesting (Rosenzweig *et al*., 2002). This damage is potentially compounded by the influence of extreme rainfall, which increases soil moisture and the potential for increased disease and pest damage (Rosenzweig *et al*., 2002). Increased soil moisture can reduce the yield of certain crops. Intense rainfall falls with high intensity and hits the ground with high energy. This high energy impact is responsible for the detachment and erosion on top soil (Quansah, 1981). An increase in intense rainfall, as shown in many rainfall stations in the Western Cape, will increase the risk of top-soil erosion over time as well as increase the risk of losing crops and farm machinery to damaging flood events. The potential increase in soil moisture needs to be taken into account. Bates *et al*. (2008) state that increased intensity of precipitation, flooding and increased soil moisture has significantly impacted agricultural production on a global scale. In the Western Cape, the potential reduction in productivity and post-flood and intense rainfall recovery costs poses a significant risk to the livelihoods of the rural, agricultural population.

5.4 Stationarity and Calculating Extremes

As stated earlier, flood peaks can be calculated in various ways:

- Statistical
- Rational
- Alternative Rational Method
- Unit Hydrograph
- Standard design flood
- Empirical method.

(SANRAL, 2007)

The assumption made in the statistical method is that return periods and levels are not changing over the historical record. The statistical method also uses a block maxima approach (SANRAL, 2007), where the peak annual flow rate is used to calculate the annual series. Thus the 2nd and 3rd highest flow rates for a particular year (which may be higher than the peak flow of subsequent years) are omitted from the calculation. This calculation can result in a skewed picture of the Extreme Value Distribution of the peak flood, and can potentially result in the failure to notice a decrease in return period for a certain magnitude flood. Similarly, if rainfall return levels are increasing over time (resulting in an increase in peak runoff), it is inappropriate to assume that climate is stationary. A calculation made for the entire historical record does not establish whether there is a trend toward an increase, decrease or stability in return levels for the catchment area. Thus, the use of the GEV method for statistical analyses of extremes in order to determine return levels and intervals may be inappropriate. Similarly, the assumption of climate stationarity is not valid, as it is clearly shown that climate may be changing at individual rainfall stations over the historical record. It can also be argued that using flow rate data from "comparable" neighbouring catchment areas is also inappropriate as it is clearly shown that changes in precipitation extremes differ significantly for individual rainfall stations, even when close together.

The GPD approach used for this study required the use of a threshold value to define an extreme event. The magnitude of this threshold was the 95th percentile for each rainfall station. This was based on a search of the literature and the number of rainfall stations being analysed. Adjusting the threshold value higher or lower does change the distribution and further research should be conducted as to what the best value would be.

The method for calculating peak flow in the Rational Method assumes that rainfall intensity is constant for the duration of the storm (SANRAL, 2007). However, this value is assumed not to be changing in the region. When assessing the rainfall intensity, the method does not take into account that the rainfall intensity may be increasing or decreasing in the future. As a result, the rational method may produce robust results (for small catchments) in the short term, but it is imperative that the long-term trend and future projections be taken into account when inputting "rainfall intensity" into the calculations. The 50-year return level for today's climate may differ significantly from that of 2030. By determining the design life for the proposed structure, one can determine the extreme rainfall trend and project the return level for the catchment at the end of the design life and input that result as the rainfall intensity value for peak flow rate calculations. The rational method as it stands may be inappropriate for future, longer-term peak flow calculations and should take the potential change in rainfall intensity into account.

The Alternative Rational Method for determining peak flow incorporates the calculation of the return period for the extreme storm event. This variable, however, is inputted assuming stationarity in the catchment area. The calculation does not consider whether return periods for certain level storms may be increasing or decreasing over time. An increase in return level will alter the calculated precipitation depth output. The calculation should therefore take into account the potential change in return levels and periods when in order to provide a better, more robust estimate of rainfall depth for future time periods in the catchment.

When using the Unit Hydrograph method, designers and engineers have assumed that the severity of intense rainfall remains constant through time (SANRAL, 2007). As this project shows, this can clearly not be assumed and one should project future values of rainfall return levels for a particular return period and use those as the input for rainfall intensity when calculating peak flow rates.

The Standard Design Flood method is based around and developed from the Rational Method. As most of the damaging floods in South Africa occur when the storm in question has a longer duration than the "response time" for the catchment (SANRAL, 2007), the SDF method takes into account the effect of saturation on increasing peak flow rates, which is a good assumption, especially when the frequency of long duration, high intensity rainfall events is shown to be changing for the Western Cape through the historical record. The method, however, is still based on the assumption that climate is stationary.

The methods for calculating peak flow rates should account for changes in return level and return period for the specific catchment area. A failure to do so could potentially result in inappropriate estimates for rainfall intensity, which are reasonably accurate for the present day, but are invalid for future time periods. This could result in an increase in the number for severe, damaging floods in the Western Cape, which is a region having already shown significant change to return levels and is projected to show more drastic changes in the future. The IPCC (2012) projects substantial decreases in return intervals of extreme rainfall under all SRES conditions for southern Africa. In the light of such projections, it would be appropriate for peak flow calculation methods to assume that climate is not stationary for the region in question.

The calculations should also account for the changes in long duration, high intensity rainfall in the historical record. It has been noted that particularly damaging floods occur when the ground becomes saturated (SANRAL, 2007). Peak rainfall intensity is often preceded by extended durations of high magnitude rainfall (SANRAL, 2007). As it is shown that the frequency of two- to three-day, intense rainfall events is changing over time, it would be appropriate to assume that, in certain cases, the ground may be approaching saturation.

6 SUMMARY AND CONCLUSIONS

This study used a Generalized Pareto Distribution approach to assess changes in the frequency and intensity of extreme rainfall events across the Western Cape over the historical record. A GPD approach requires the definition of a high threshold for the data series (determining a level that defines an extreme event) and then fits a GPD model to the data above that threshold. In order to do this, daily rainfall data for 137 gauging stations dating back to 1900 were obtained and the data records were divided up into two time periods: 1900-1954 and 1955-2010. By dividing up the data record it was possible to compare the return levels and intervals calculated by the GPD and assess the differences between the time periods.
The 95th percentile for each individual rainfall station was calculated and used as the threshold value (necessary for a GPD). A GPD was fitted to all of the data exceeding the defined threshold and resulted in an output of return level plots comparing the 1900-1954 and 1955-2010 time periods. This analysis was performed using a freeware statistical language called R. R is a software programme that allows for the manipulation, calculation and graphical representation of data (Venables & Smith, 2012). A package called 'ismev' within R was used to fit a GPD to the data and output the return level plots.

Problems were faced in the definition of the threshold for fitting the GPD. Eventually the 95th percentile was chosen as suggested by Karl *et al.* (1995) as well as by fitting a GPD to the data using a range of thresholds. Further study into threshold definition could be undertaken. Importing data into R was a challenge, as the formatting of the input data had to be perfect in a txt. File. When working with such large data files, it is difficult to determine where missing data lies, or a space, which may result in the programme rejecting the input data. It also took a long time for the code to process the data and perform the analysis – approximately five to seven minutes per station.

A non-parametric analysis of rainfall change was also performed on the data by calculating the number of rainfall events that occurred where three consecutive days exceeded the threshold (95th percentile). This allows for a comparison of changes in the number of high intensity-long duration storms between the two time periods. Overall, 22 of the 137 rainfall stations displayed a decrease in the number of high intensity-long duration rainfall events from 1900-1954 to 1955-2010, while the rest (approximately 84%) of the stations either remained the same or had a substantial increase in the number of such events. The largest increase in the number of intense events was in De Mond, where there was an increase of 279 three-day, high intensity events between the two time periods. This is a substantial increase in the number of these events and was much higher than the second highest increase of 180 at Groote Schuur.

The results of the extreme value distribution analysis show that approximately 84% of the rainfall stations analysed have had an increase or decrease in 50-year return level over the historical record. 62% of the rainfall stations showed a substantial increase in rainfall intensity for the 50-year return period, while 22% of the stations showed a decrease in the magnitude of such events. The 95% confidence intervals for the 50-year return levels were wide; however it should be noticed that they were wider for stations showing a decrease in rainfall intensity. There was little discernible spatial pattern to the changes in rainfall intensity; however there did appear to be a slight decrease in return levels for the mountainous regions in the Eden District Municipality (DMA) and Overberg DMA – particularly around Elgin and Grabouw (see red boxes in Figure 4.18). This is a surprising result as it does not agree with future projections made by authors such as Midgley *et al.* (2005), which suggest that rainfall intensity is likely to increase in mountainous areas. This may be due to the use of a relatively long rainfall record (55 years), which could be broken up into shorter periods to determine whether there is more recent change.

The results of the study strongly indicate that rainfall return levels and intervals are changing in the Western Cape. There is very little discernible spatial pattern to this change; however, the results do support the statement made by Milly *et al.* (2008) that 'stationarity is dead'. An increase in the intensity and frequency of high intensity rainfall has increased the exposure of the Western Cape population and infrastructure to damaging flooding. As the magnitude and probabilities of occurrence of rainfall events are changing, there is a need for a review of the definition of flood set back lines and the calculations of peak flows. Further study needs to be undertaken into the changing seasonality of extreme events. If non-stationarity is not accounted for in calculations of flood peaks, etc., the Western Cape is likely to witness an increase in the damage to infrastructure and development across the province, as well as increased risk of deaths due to large floods. Rainfall records should be divided up into time periods and a GPD fitted to each data series in order to determine changes in extreme event magnitude and frequency and inform better design practices.

Extreme Value statistics are a very important tool in the analysis and study of changing rainfall conditions. These statistical techniques allow for the appropriate analysis of changing frequency and intensity and can add great value to the design and decision making process by accounting for changing flood risk. This study has generated a robust methodology for the analysis of changes in extreme events over time that can be replicated by further studies in a variety of regions.

The concept of stationarity in rainfall processes needs to be abandoned by hydrological modellers, engineers, disaster managers and insurance actuaries.

7 RECOMMENDATIONS

Further research should be undertaken into the appropriate definition of a threshold for the GPD as well as the determination of the statistical significance of such results. A study of the changing seasonality (i.e. time of occurrence) of extreme events would help to describe changing risk conditions in the Western Cape.

A review of the flood peak calculation methods should be made, taking into account the fact that climate cannot be assumed to be stationary. The statistical methods for this should abandon the AMS approach (which discards many data points) and adopt a 'Peaks over Threshold' approach to determine changing extreme conditions. Flood set back lines should be reassessed based on the assumption that rainfall intensity is changing and the flood set back lines may not be appropriate under these conditions. Water management and disaster management practices need to account for the changing rainfall intensity and adopt appropriate flood mitigation measures as well as monitor dam levels very closely. Early warning systems for extreme events such as cut-off lows can be implemented to aid dam managers in managing the risk of over-topping.

REFERENCES

Adamson PT (1981): *Southern African Storm Rainfall*. Department of Environment Affairs, Directorate of Water Affairs, Technical Report No. TR 102.

Alexander W (1990): 'Flood hydrology for Southern Africa', *Southern African Committee for Large Dams.* Pretoria, Republic of South Africa.

Alexander D (1993): Natural Disasters. UCL Press Ltd: London.

Bates BC, Kundzewicz ZW, Wu S and Palutikof JP (Eds.) (2008): Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 Pp.

Bronstert A, Niehoff D & Burger G (2002): Effects of climate and land-use change on storm runoff generation: present knowledge and modelling capabilities. *Hydrological Processes,* Vol. 16, Pp. 509-529.

Coles S (2001): *An introduction to statistical modelling of extreme values*. Springer.

Crimp S & Mason S (1999): 'The Extreme Precipitation Event of 11 to 16 February 1996 Over South Africa', *Meteorological and Atmospheric Physics*, Vol.70, Pp. 29-42.

de Waal J (2010): The Duiwenhoks River: An analysis of flood causation. Unpublished B.Sc (Hons.) thesis. University of Cape Town.

DiMP (2010): *RADAR Western Cape Review: Risk and Development Annual Review.* PeriPeri Publications. University of Cape Town.

DiMP (2012): *Southern Cape Drought Disaster: "The Scramble for Water".* A report Commissioned by the PDMC. Stellenbosch University.

Eagleson PS (1981). Some limiting forms of the poisson distribution of annual station precipitation. *Water Resources Research*, Vol. 17(3), Pp. 752-757. doi: 10.1029/WR017i003p00752

Eliazar I & Klafter J (2010): Randomized central limit theorems: A unified theory. *Physical Review*, Vol. 82, Pp. 1-15.

Fauchereau N, Trzaska S, Rouault M & Richard Y (2003): Rainfall Variability and Changes in Southern Africa during the 20th Century in the Global Warming Context. *Natural Hazards,* Vol. 29, Pp.139–154.

Gilleland E & Katz RW (2006): Analysing Seasonal to Interannual Extreme Weather and Climate Variability with the Extremes Toolkit. Research Applications Laboratory, National Center for Atmospheric Research.

Groisman P, Knight R, Easterling D, Karl T, Hegerl G & Razuvaev V (2005): Trends in intense precipitation in the climate record. *Journal of Climate,* Vol. 18, Pp. 1326-1350.

IPCC (2012): *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. A Special Report of Working Groups I and II of the

Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker,D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen,M. Tignor, and P.M. Midgley(eds.)]. Cambridge University Press, Cambridge, UK,and New York, NY, USA, 582 pp.

Katz R, Parlange M & Naveau P (2002): 'Statistics of extremes in hydrology', *Advances in Water Resources.* Vol. 25, Pp. 1287–1304.

Katz R, Brush G & Parlange M (2005): Statistics of extremes: Modeling ecological disturbances. *Ecology*, Vol. 86(5), Pp. 1124–1134.

Katz RW (2010): Statistics of extremes in climate change. *Climatic Change*, Vol. 100, Pp. 71-76.

Karl TR, Derr VE, Easterling DR, Folland CK, Hofmann DJ, Levitus S, Nicholls N, Parker DE & Withee GW (1995): Critical issues for long-term climate monitoring. *Climatic Change,* Vol. 31, Pp. 185–221.

Kjeldsen T, Smithers J & Schulze R (2002): 'Regional flood frequency analysis in KwaZulu Natal Province, South Africa, using the index method'. *Journal of Hydrology.* Vol. 255, Pp. 194 - 211.

Kruger AC (2006): Observed trends in daily precipitation indices in South Africa: 1910-2004. *International Journal of Climatology,* Vol. 26, Pp. 2275-2285.

Li Y, Cai W & Campbell EP (2005): Statistical Modeling of Extreme Rainfall in Southwest Western Australia. *Journal of Climate,* Vol. 18, Pp. 852-863.

Lynch SD (2003): Development of a Raster Database of Annual, Monthly and Daily Rainfall for Southern Africa. Water Research Commission. Pretoria, South Africa. WRC Report no. 1156/1/03. Pp. 78.

Parker SP (2002): *McGraw-Hill dictionary of scientific and technical terms.* McGraw-Hill Book Company. New York. 6th Ed.

Mason SJ & Joubert AM (1997): Simulated Changes in Extreme Rainfall Over Southern Africa. *International Journal of Climatology*. Vol. 17, Pp. 291-301.

Mason SJ, Waylen PR, Mimmack GM, Ajaratnam B & Harrison JM (1999): Changes in Extreme Rainfall Events in South Africa. *Climatic Change.* Vol.41, Pp. 249–257.

Matalas NC (1998): Note on the Assumption of Hydrologic Stationarity. *Universities Council on Water Resources.* Vol. 112, Pp. 64-72.

Midgley GF, Chapman RA, Hewitson B, Johnston P, de Wit M, Ziervogel G, Mukheibir P, van Niekerk L, Tadross M, van Wilgen BW, Kgope B, Morant PD, Theron A, Scholes RJ & Forsyth GG (2005): A Status Quo, Vulnerability and Adaptation Assessment of the Physical and Socio-economic Effects of Climate Change in the Western Cape. Report to the Western Cape Government, Cape Town, South Africa. CSIR Report No.ENV-S-C 2005-073, Stellenbosch.

Milly PCD, Wetherald RT, Dunne KA & Delworth TL (2002): Increasing risk of great floods in a changing climate. Nature, Vol. 415, Pp. 514-517.

Milly P, Betancourt J, Falkenmark M, Hirsch R, Kundzewicz Z, Lettenmaier D & Stouffer R (2008): Stationarity Is Dead: Whither Water Management?. *Science*, Vol. 319, Pp. 573-574.

Mukheibir P (2008): Water Resources Management Strategies for Adaptation to Climate-Induced Impacts in South Africa. *Water Resource Management*, Vol. 22, Pp.1259–1276.

New M (2002): Climate change and water resources in the southwestern Cape, South Africa. *South African Journal of Science*, Vol. 98, Pp. 1-8.

New M, Hewitson B, Stephenson D, Tsiga A, Kruger A, Manhique A, Gomez B, Coelho C, Masisi D, Kululanga E, Mbambalala E, Adesina F, Saleh H, Kanyanga J, Adosi J, Bulane L, Fortunata L, Mdoka M & Lajoie R (2006): Evidence of trends in daily climate extremes over southern and west Africa. *Journal of Geophysical Research*, Vol.111, D14102 (Pp. 1-11).

Pelling M (2003): *Social Vulnerability in the City*, *The Vulnerability of Cities: Natural disasters and social resilience*. Earthscan. Pp. 46-67.

PROVIDE (2005): *A profile of the Western Cape province: Demographics, poverty, inequality and unemployment.* Elsenburg.

Quansah C (1981): The Effect of Soil Type, Slope, Rain Intensity and their interactions on Splash Detachment and Transport. *Journal of Soil Science*, Vol. 32. Pp. 215-224.

Republic of South Africa (2002): Disaster Management Act (57/2005). Government Gazette 24252, Pretoria.

Rosenzweig C, Tubiello FN, Goldberg R, Mills E & Bloomfield J (2002): Increased crop damage in the US from excess precipitation under climate change. *Global Environmental Change*, Vol. 12, Pp. 197-202.

SANRAL (2007): *Drainage Manual.* South African National Roads Agency Ltd. Pretoria. 5thed.

Schilling E & Stakhiv K (1998): What Can Water managers Do About Global Warming?. *Universities Council on Water Resources.* Vol. 112, Pp. 33-40.

Singleton AT & Reason CJC (2006): Variability in the characteristics of cut-off low pressure systems over subtropical southern Africa. *International Journal of Climatology.* Vol. 27, Pp. 295-310.

Smith RL (2003): Statistics of Extremes with Applications in Environment, Insurance and Finance. Available at: http://www.stat.unc.edu/postscript/rs/semstatrls.ps. Accessed on 4 February 2011.

Smithers JC & Schulze RE (2004): The Estimation of Design Rainfalls for South Africa Using a Regional Scale Invariant Approach. *Hydrology: Science and Practice for the 21st Century*, Vol. 1, Pp. 221-228.

StatsSA (2011): Mid-year population estimates. Statistical Release P0302. Stats SA, Pretoria.

Stedinger JR, Lettenmaier DP & Vogel RM (1985): Multisite ARMA(1,1) and Disaggregation Models for Annual Streamflow Generation. *Water Resources Research.* Vol. 21(4), Pp. 497-510.

Stephenson AG & Gilleland E (2005): Software for the analysis of extreme events: The current state and future directions. *Extremes.* Vol. 8, Pp. 87-109.

Stephenson A (2011): Package 'ismev'. Online at: http://cran.r-project.org/web/packages/ismev/ismev.pdf. Accessed on: September 2011

Trenberth KE, Dai A, Rasmussen RM & Parsons DB (2003): The Changing Character of Precipitation. *American Meteorological Society. Pp.* 1205-1217.

Tyson PD & Preston-Whyte RA (2000): *The Weather and Climate of Southern Africa*. Oxford University Press, Oxford.

UCAR (2010): Statistics of Weather and Climate Extremes. Available at: http://www.isse.ucar.edu/extremevalues/back.html. Accessed on: 20 February 2012.

UNISDR (2009): Terminology on DRR. Available at: http://www.unisdr.org/we/inform/terminology. Accessed on: 20 February 2012.

Van Aalst MK (2006): The impacts of climate change on the risk of natural disasters. *Disasters*, Vol. 30(1), Pp. 5−18.

Venables WM & Smith DN (2012): *An Introduction to R.* R Development Core Team. Available at: http://cran.r-project.org/doc/manuals/R-intro.pdf. Accessed on: January 2012

Viljoen MF & Booysen H J (2006): Planning and Management of Flood Damage Control: The South African Experience. *Irrigation and Drainage*, Vol. 55, Pp 83-91.

Wisner B, Blaikie P, Canon T & David I (2004): The Disaster Pressure and Release Model. At Risk: Natural Hazards, people's vulnerability and disasters. Routledge. Pp 49-86.

PERSONAL COMMUNICATIONS

Jan de Waal

Email: janniedw@sun.ac.za

Phone: (+27)   021 8089401

APPENDICES

8 APPENDIX A

R Code

CALCULATING PERCENTILES

```
### CALCULATING PERCENTILES

# percentile=rain$PPT[rain$PPT > 1]    # read PPT in table saved as "rain" and call it
percentile
# quantile(percentile, c(.95))
```

OUTPUT PLOTS

```
### OUTPUT PLOTS

setwd ("C:/Thesis Data")
library(extRemes)
rain1 <- read.table("0004734_W Klaasjagersberg 1900-1954.txt", header=TRUE, sep="\t")
P1 <- dclust(rain1$PPT, 26.1, 3, cluster.by = NULL, verbose=getOption("verbose"))
sink("list_of_data")
P1
sink()

clust1 <- P1[["ncluster"]]

rain2 <- read.table("0004734_W Klaasjagersberg 1955-2010.txt", header=TRUE, sep="\t")
P2 <- dclust(rain2$PPT, 26.1, 3, cluster.by = NULL, verbose=getOption("verbose"))
sink("list_of_data")
P2
sink()

# (not entirely neccessary)
clust2 <- P2[["ncluster"]]
#Output[["clust"]]
#Output[["xdat.dc"]]

z <- gpd.fit(P2[["xdat.dc"]], 26.1)
y <- gpd.fit(P1[["xdat.dc"]], 26.1)

gpd.dg2 <- function()
  {
      gpd.rl(z$mle, z$threshold, z$rate, z$n, z$npy, z$cov,
         z$data, z$xdata)

      gpd.rl1(z$mle, z$threshold, z$rate, z$n, z$npy, z$cov,
         z$data, z$xdata)
```

```
        gpd.rlP150(y$mle, y$threshold, y$rate, y$n, y$npy, y$cov,
            y$data, y$xdata)

  }



gpd.rlP150 <- function (a, u, la, n, npy, mat, dat, xdat)
{
    a <- c(la, a)
    eps <- 1e-06
    a1 <- a
    a2 <- a
    a3 <- a
    a1[1] <- a[1] + eps
    a2[2] <- a[2] + eps
    a3[3] <- a[3] + eps
    jj <- seq(-1, 3.75 + log10(npy), by = 0.1)
    m <- c(1/la, 10^jj)
    q <- gpdq2(a[2:3], u, la, m)
    x <- m[q > u - 1]/npy
    y <- q[q > u - 1]
    d <- t(gpd.rl.gradient(a = a, m = m))
    mat <- matrix(c((la * (1 - la))/n, 0, 0, 0, mat[1, 1], mat[1,
        2], 0, mat[2, 1], mat[2, 2]), nc = 3)
    v <- apply(d, 1, q.form, m = mat)
#    plot(m/npy, q, log = "x", type = "n", xlim = c(0.1, max(m)/npy),
#       ylim = c(u, max(xdat, q[q > u - 1] + 1.96 * sqrt(v)[q >
#           u - 1])), xlab = "Return period (years)", ylab = "Return level",
#       main = "Return Level Plot")
    lines(m[q > u - 1]/npy, q[q > u - 1], col = "green")
    lines(m[q > u - 1]/npy, q[q > u - 1] + 1.96 * sqrt(v)[q >
        u - 1], col = "red")
    lines(m[q > u - 1]/npy, q[q > u - 1] - 1.96 * sqrt(v)[q >
        u - 1], col = "red")
    nl <- n - length(dat) + 1
    sdat <- sort(xdat)
    points((1/(1 - (1:n)/(n + 1))/npy)[sdat > u], sdat[sdat >
        u])
    z <- approxfun(x,y)
    z(50)
}

gpd.rl1 <- function (a, u, la, n, npy, mat, dat, xdat)
{
    a <- c(la, a)
    eps <- 1e-06
    a1 <- a
    a2 <- a
    a3 <- a
    a1[1] <- a[1] + eps
    a2[2] <- a[2] + eps
```

```
    a3[3] <- a[3] + eps
    jj <- seq(-1, 3.75 + log10(npy), by = 0.1)
    m <- c(1/la, 10^jj)
    q <- gpdq2(a[2:3], u, la, m)
    d <- t(gpd.rl.gradient(a = a, m = m))
    mat <- matrix(c((la * (1 - la))/n, 0, 0, 0, mat[1, 1], mat[1,
        2], 0, mat[2, 1], mat[2, 2]), nc = 3)
    v <- apply(d, 1, q.form, m = mat)
    plot(m/npy, q, log = "x", type = "n", xlim = c(0.1, 100),
       ylim = c(u, 300), xlab = "Return period (years)", ylab = "Return level (mm)")
#        main = "Return Level Plot")
    grid(equilogs = FALSE)

    lines(m[q > u - 1]/npy, q[q > u - 1])
    lines(m[q > u - 1]/npy, q[q > u - 1] + 1.96 * sqrt(v)[q >
        u - 1], col = "blue")
    lines(m[q > u - 1]/npy, q[q > u - 1] - 1.96 * sqrt(v)[q >
        u - 1], col = "blue")
    nl <- n - length(dat) + 1
    sdat <- sort(xdat)
    points((1/(1 - (1:n)/(n + 1))/npy)[sdat > u], sdat[sdat >
        u])
}

gpd.dg3 <- function()
  {
        gpd.rlP250(z$mle, z$threshold, z$rate, z$n, z$npy, z$cov,
        z$data, z$xdata)

  }


gpd.rlP250 <- function (a, u, la, n, npy, mat, dat, xdat)
{
    a <- c(la, a)
    eps <- 1e-06
    a1 <- a
    a2 <- a
    a3 <- a
    a1[1] <- a[1] + eps
    a2[2] <- a[2] + eps
    a3[3] <- a[3] + eps
    jj <- seq(-1, 3.75 + log10(npy), by = 0.1)
    m <- c(1/la, 10^jj)
    q <- gpdq2(a[2:3], u, la, m)
    x <- m[q > u - 1]/npy
    y <- q[q > u - 1]
    d <- t(gpd.rl.gradient(a = a, m = m))
    mat <- matrix(c((la * (1 - la))/n, 0, 0, 0, mat[1, 1], mat[1,
        2], 0, mat[2, 1], mat[2, 2]), nc = 3)
    v <- apply(d, 1, q.form, m = mat)
#    plot(m/npy, q, log = "x", type = "n", xlim = c(0.1, max(m)/npy),
```

```
#     ylim = c(u, max(xdat, q[q > u - 1] + 1.96 * sqrt(v)[q >
#          u - 1])), xlab = "Return period (years)", ylab = "Return level",
#     main = "Return Level Plot")
    lines(m[q > u - 1]/npy, q[q > u - 1], col = "green")
    lines(m[q > u - 1]/npy, q[q > u - 1] + 1.96 * sqrt(v)[q >
        u - 1], col = "red")
    lines(m[q > u - 1]/npy, q[q > u - 1] - 1.96 * sqrt(v)[q >
        u - 1], col = "red")
    nl <- n - length(dat) + 1
    sdat <- sort(xdat)
    points((1/(1 - (1:n)/(n + 1))/npy)[sdat > u], sdat[sdat >
        u])
    z <- approxfun(x,y)
    z(50)
}

gpd.dg4 <- function()
  {
        gpd.rlP120(y$mle, y$threshold, y$rate, y$n, y$npy, y$cov,
        y$data, y$xdata)

  }


gpd.rlP120 <- function (a, u, la, n, npy, mat, dat, xdat)
{
    a <- c(la, a)
    eps <- 1e-06
    a1 <- a
    a2 <- a
    a3 <- a
    a1[1] <- a[1] + eps
    a2[2] <- a[2] + eps
    a3[3] <- a[3] + eps
    jj <- seq(-1, 3.75 + log10(npy), by = 0.1)
    m <- c(1/la, 10^jj)
    q <- gpdq2(a[2:3], u, la, m)
    x <- m[q > u - 1]/npy
    y <- q[q > u - 1]
    d <- t(gpd.rl.gradient(a = a, m = m))
    mat <- matrix(c((la * (1 - la))/n, 0, 0, 0, mat[1, 1], mat[1,
        2], 0, mat[2, 1], mat[2, 2]), nc = 3)
    v <- apply(d, 1, q.form, m = mat)
#   plot(m/npy, q, log = "x", type = "n", xlim = c(0.1, max(m)/npy),
#     ylim = c(u, max(xdat, q[q > u - 1] + 1.96 * sqrt(v)[q >
#          u - 1])), xlab = "Return period (years)", ylab = "Return level",
#     main = "Return Level Plot")
    lines(m[q > u - 1]/npy, q[q > u - 1], col = "green")
    lines(m[q > u - 1]/npy, q[q > u - 1] + 1.96 * sqrt(v)[q >
        u - 1], col = "red")
    lines(m[q > u - 1]/npy, q[q > u - 1] - 1.96 * sqrt(v)[q >
        u - 1], col = "red")
```

```
    nl <- n - length(dat) + 1
    sdat <- sort(xdat)
    points((1/(1 - (1:n)/(n + 1))/npy)[sdat > u], sdat[sdat >
        u])
    z <- approxfun(x,y)
    z(20)
}


gpd.dg5 <- function()
  {
        gpd.rlP220(z$mle, z$threshold, z$rate, z$n, z$npy, z$cov,
        z$data, z$xdata)

  }


gpd.rlP220 <- function (a, u, la, n, npy, mat, dat, xdat)
{
    a <- c(la, a)
    eps <- 1e-06
    a1 <- a
    a2 <- a
    a3 <- a
    a1[1] <- a[1] + eps
    a2[2] <- a[2] + eps
    a3[3] <- a[3] + eps
    jj <- seq(-1, 3.75 + log10(npy), by = 0.1)
    m <- c(1/la, 10^jj)
    q <- gpdq2(a[2:3], u, la, m)
    x <- m[q > u - 1]/npy
    y <- q[q > u - 1]
    d <- t(gpd.rl.gradient(a = a, m = m))
    mat <- matrix(c((la * (1 - la))/n, 0, 0, 0, mat[1, 1], mat[1,
        2], 0, mat[2, 1], mat[2, 2]), nc = 3)
    v <- apply(d, 1, q.form, m = mat)
#   plot(m/npy, q, log = "x", type = "n", xlim = c(0.1, max(m)/npy),
#     ylim = c(u, max(xdat, q[q > u - 1] + 1.96 * sqrt(v)[q >
#         u - 1])), xlab = "Return period (years)", ylab = "Return level",
#     main = "Return Level Plot")
    lines(m[q > u - 1]/npy, q[q > u - 1], col = "green")
    lines(m[q > u - 1]/npy, q[q > u - 1] + 1.96 * sqrt(v)[q >
        u - 1], col = "red")
    lines(m[q > u - 1]/npy, q[q > u - 1] - 1.96 * sqrt(v)[q >
        u - 1], col = "red")
    nl <- n - length(dat) + 1
    sdat <- sort(xdat)
    points((1/(1 - (1:n)/(n + 1))/npy)[sdat > u], sdat[sdat >
        u])
    z <- approxfun(x,y)
    z(20)
}
```

```
gpd.dg2()
gpd.dg3()
gpd.dg4()
gpd.dg5()
```

9 APPENDIX B

95th Percentiles

Station ID	95th Percentile
0002885_W Zoetendalsvallei	20
0003020_W Cape Agulhas	15
0003192_W De Mond	14
0004734_W Klaasjagersberg	26.1
0004762_W Simonstown	21.95
0004874_W Rondevlei	26
0004891_W Cape Point	14.8
0005611AW Steenbras	32.5
0005771_W Bettys Bay	34
0006038_A Elgin	39.1
0006039_W Grabouw	40
0006332_W Rustfontein	40.24
0006415_W Hermanus	27.38
0006527_W Tussenbeide	25.5
0006612_W Boontjieskraal	21.6
0007183_W Greyton	22
0007263_W Boskloof	23.6
0007669_W Blydskap	23.4
0008367_W Kleinfontein	21.28
0008470_W Plaatjieskraal	21.6
0008751_W Marloth	36.24
0008813_W Bontebok Park	21.885
0009783_W Blackdown	26
0009815_W Heidelberg	25
0010742_W Stilbaai	24.76
0011065_W Diepkloof	23
0011132_W Albertinia	28
0011451_W Herbertsdale	26.45
0011617_W Die Eiland	23.5
0012303_W Sandhoogte	26.5
0014063_W Knysna	31
0014393_W Harkerville	35.6
0014633_W Plettenberg Bay	38
0020838FW Groote Schuur	33.6
0020846_W Atlantis	18.51
0021055_W Maitland	23.4
0021230_W Altydgedacht	24
0021656AW Stellenbosch	24.9
0021778_W Jonkershoek	37.6
0021823_W Paarl	38.1
0022038_W Vrugbaar	31.8
0022539_W Villiersdorp	35.8
0022759_W Worcester	26.7

0022803_W Bellevue	24.4
0022825_W Kwaggaskloof Dam	23.135
0023597_W McGregor	21.1
0024110_W Ashton	20
0024197_W Montagu	25.9
0025450_W Dun Donald	28.5
0025599_W Strawberry Hill	36.8
0026824_W vanWyksdorp	18
0027302_W Calitzdorp Pol	25
0028150_W Kwepertuin	30
0028407_W Groot Doornrivier	26.325
0028415_W Jonkersberg	37
0028771_W Herold	33.3
0028775_W Witfontein	33.345
0029294_W Bergplaats	32
0029542_W Rooirivier	27.805
0029624_W Karatara	28
0029692_W Buffelsklip	32
0029805_W Goudveld	31.8
0030265_W Buffelsnek	36.8
0030297_W Diepwalle	30
0030775_W Keurboomsrivier	30
0040604_W Hopefield	21
0040682_W Darling	24.935
0041279_W Mooreesburg	18.2
0041347_A Langgewens	18.5
0041533_W Lelyfontein	14.2
0041871_W Porterville	20.6
0042227_W Tulbagh	30.5
0042358_W Dwarsrivier	37.18
0042532AW Ceres	51
0042588_W Prince Alfred Hamlet	31
0042621_W Warmbokveld	35.9
0042669_W Malabar Farm	25
0042789_W Odessa	22
0044286_W Jan de Boers	20.78
0045184_W Dwarsindieberg	22.705
0045611_W Laingsburg	22.9
0045857_W Floriskraal dam	20
0046479_W Ladismith	25.5
0046809_W Zoar	19.5
0047205_W Martjesvlei	22
0047359_W Calitzdorp Dam	24.76
0047436_W Weltevreden	22.515
0047716_W Kruisrivier	33.465
0047765_W Damaskus	21.59
0048043_W Prince Albert	23.795
0048275_W Zachariasfontein	21.215
0048384_W Grootkraal	20.2
0049050_W Klaarstroom	25

0049060_W De Rust	25.7
0049372_W Rondawel	23.13
0050327_W Rondekop	20.035
0050688_W Rooiklip	21.3
0061298_W Langebaanweg	14
0062444_W Piketberg	26
0062671_W Eeendekuil	15
0062768_W Middeldeurvlei	12.7
0063005_W Citrusdal	26.065
0063452_W Kromrivier	27.6
0067074_W Anysrivier	24.06
0068010_W Merweville	29.92
0068547_W Zeekoeivlei	27.5
0070735_W Klipkrans	23
0070770_W Aardoorns	26
0083618_W Elandsbaai	22
0084059_W Redelinghuis	17
0084159_W Graafwater	15.5
0084558_W Elandsfontein	30.2
0084701_W Clanwilliam	18.05
0085112_W Algeria (BOS)	41
0085309_W Welbedacht	27.9
0086007_W Reenen	23.1
0090176_W Grootfontein	31.8
0090196_W Tafelberg	26.905
0092369_W De Hoop	30
0092386_W Blouboskuil	24
0093074_W Kamferskraal	28.5
0094730_W Beeldhouersfontein	27.4
0095006_W Quaggasdrift	30.5
0106512_W Koekenaap	16.5
0106603_W Lutzville Hotel	16.5
0106880AW Vredendal	14.74
0107318_W Puts	23.325
0107396_W Vanrhynsdorp	15.555
0107510_W Bulshoek Dam	16.5
0107759_W Sandvlei	13
0107869_W Kanolvlei	15.445
0115595_W Gannakraal	25.1
0117047_W Loskop	25.4
0117749_W Vleiplaats	25
0118029_W Coetzeeskraal	25.5
0131437_W Ludzville Hotel	15.2
0131639_W Nuwerus	16
0159104_W BitterfonteinKamaboes	20

10 APPENDIX C

Station Locations

Station ID	Co-ordinates		Altitude
	lat	long	
0003020_W Cape Agulhas	-34.83	20.01	11
0003192_W De Mond	-34.71	20.11	2
0004734_W Klaasjagersberg	-34.24	18.4	31
0004762_W Simonstown	-34.18	18.42	30
0004874_W Rondevlei	-34.06	18.5	8
0004891_W Cape Point	-34.35	18.49	228
0005611AW Steenbras	-34.18	18.85	380
0005771_W Bettys Bay	-34.35	18.93	34
0006038_A Elgin	-34.14	19.02	311
0006039_W Grabouw	-34.15	19.02	283
0006332_W Rustfontein	-34.03	19.19	320
0006415_W Hermanus	-34.42	19.24	24
0006527_W Tussenbeide	-34.29	19.2	189
0006612_W Boontjieskraal	-34.21	19.34	125
0007183_W Greyton	-34.04	19.61	273
0007263_W Boskloof	-34.39	19.65	128
0007669_W Blydskap	-34.16	19.89	155
0008367_W Kleinfontein	-34.14	20.22	168
0008470_W Plaatjieskraal	-34.31	20.3	182
0008751_W Marloth	-34.01	20.44	247
0008813_W Bontebok Park	-34.06	20.47	110
0009783_W Blackdown	-34.07	20.96	109
0009815_W Heidelberg	-34.09	20.96	84
0010742_W Stilbaai	-34.1	21.27	128
0011065_W Diepkloof	-34.08	21.55	205
0011132_W Albertinia	-34.21	21.58	199
0011451_W Herbertsdale	-34.02	21.76	78
0011617_W Die Eiland	-34.28	21.84	49
0012303_W Sandhoogte	-34.05	22.18	159
0014063_W Knysna	-34.04	23.05	30
0014393_W Harkerville	-34.05	23.23	213
0014633_W Plettenberg Bay	-34.06	23.37	73
0020838FW Groote Schuur	-33.96	18.46	53
0020846_W Atlantis	-33.61	18.48	121
0021055_W Maitland	-33.92	18.51	13
0021230_W Altydgedacht	-33.85	18.62	151
0021656AW Stellenbosch	-33.93	18.86	109
0021778_W Jonkershoek	-33.96	18.93	239

0021823_W Paarl	-33.72	18.97	109
0022038_W Vrugbaar	-33.63	19.04	175
0022539_W Villiersdorp	-33.99	19.3	345
0022759_W Worcester	-33.66	19.43	222
0022803_W Bellevue	-33.91	19.46	347
0022825_W Kwaggaskloof Dam	-33.76	19.47	315
0023597_W McGregor	-33.95	19.83	229
0024110_W Ashton	-33.83	20.07	168
0024197_W Montagu	-33.78	20.13	223
0025450_W Dun Donald	-34.01	20.76	194
0025599_W Strawberry Hill	-33.99	20.82	427
0026824_W vanWyksdorp	-33.75	21.46	216
0027302_W Calitzdorp Pol	-33.57	21.64	238
0028150_W Kwepertuin	-34.01	22.08	220
0028407_W Groot Doornrivier	-33.8	22.25	442
0028415_W Jonkersberg	-33.93	22.23	325
0028771_W Herold	-33.83	22.45	592
0028775_W Witfontein	-33.94	22.43	258
0029294_W Bergplaats	-33.9	22.68	351
0029542_W Rooirivier	-33.55	22.82	606
0029624_W Karatara	-33.9	22.83	297
0029692_W Buffelsklip	-33.55	22.9	639
0029805_W Goudveld	-33.93	22.96	216
0030265_W Buffelsnek	-33.91	23.16	724
0030297_W Diepwalle	-33.95	23.16	519
0030775_W Keurboomsrivier	-33.92	23.43	305
0040604_W Hopefield	-33.07	18.35	40
0040682_W Darling	-33.37	18.38	120
0041279_W Mooreesburg	-33.15	18.66	149
0041347_A Langgewens	-33.28	18.71	179
0041533_W Lelyfontein	-33.38	18.8	299
0041871_W PORTERVILLE	-33.01	18.99	142
0042227_W Tulbagh	-33.29	19.14	163
0042358_W Dwarsrivier	-33.47	19.2	265
0042532AW Ceres	-33.37	19.31	457
0042588_W Prince Alfred Hamlet	-33.29	19.33	450
0042621_W Warmbokveld	-33.35	19.34	491
0042669_W Malabar Farm	-33.14	19.37	983
0042789_W Odessa	-33.14	19.44	957
0044286_W Jan de Boers	-33.28	20.14	840
0045184_W Dwarsindieberg	-33.07	20.59	923
0045611_W Laingsburg	-33.2	20.86	650
0045857_W Floriskraal dam	-33.29	20.99	610
0046479_W Ladismith	-33.5	21.27	545
0046809_W Zoar	-33.5	21.45	471
0047205_W Martjesvlei	-33.44	21.62	285

0047359_W Calitzdorp Dam	-33.49	21.7	293
0047436_W Weltevreden	-33.29	21.8	475
0047716_W Kruisrivier	-33.43	21.86	592
0047765_W Damaskus	-33.27	21.94	666
0048043_W Prince Albert	-33.22	22.03	619
0048275_W Zachariasfontein	-33.09	22.17	823
0048384_W Grootkraal	-33.4	22.23	593
0049050_W Klaarstroom	-33.33	22.54	728
0049060_W De Rust	-33.49	22.53	436
0049372_W Rondawel	-33.2	22.67	838
0050327_W Rondekop	-33.45	23.17	635
0050688_W Rooiklip	-33.47	23.39	793
0061298_W Langebaanweg	-32.97	18.16	31
0062444_W Piketberg	-32.91	18.75	274
0062671_W Eeendekuil	-32.69	18.88	150
0062768_W Middeldeurvlei	-32.8	18.93	175
0063005_W Citrusdal	-32.6	19.01	230
0063452_W KROMRIVER	-32.54	19.28	914
0067074_W Anysrivier	-32.74	21.05	1135
0068010_W Merweville	-32.66	21.52	714
0068547_W Zeekoeivlei	-32.61	21.81	633
0070735_W Klipkrans	-32.75	22.91	830
0070770_W Aardoorns	-32.84	22.93	835
0083618_W Elandsbaai	-32.31	18.34	5
0084059_W Redelinghuis	-32.48	18.54	61
0084159_W Graafwater	-32.15	18.61	148
0084558_W Elandsfontein	-32.3	18.82	457
0084701_W Clanwilliam	-32.18	18.9	75
0085112_W Algeria (BOS)	-32.37	19.06	517
0085309_W Welbedacht	-32.16	19.19	381
0086007_W Reenen	-32.11	19.51	270
0090176_W Grootfontein	-32.44	21.59	808
0090196_W Tafelberg	-32.26	21.62	1067
0092369_W De Hoop	-32.15	22.72	1043
0092386_W Blouboskuil	-32.44	22.71	870
0093074_W Kamferskraal	-32.24	23.05	945
0094730_W Beeldhouersfontein	-32.17	23.91	1509
0095006_W Quaggasdrift	-32.1	24.02	1585
0106512_W Koekenaap	-31.53	18.28	45
0106603_W Lutzville Hotel	-31.56	18.34	24
0106880AW Vredendal	-31.67	18.5	35
0107318_W Puts	-31.81	18.69	592
0107396_W Vanrhynsdorp	-31.61	18.75	115
0107510_W Bulshoek Dam	-32	18.79	93
0107759_W Sandvlei	-31.67	18.93	192
0107869_W Kanolvlei	-31.98	18.99	180

0115595_W Gannakraal	-31.92	22.83	1311
0117047_W Loskop	-31.78	23.52	1219
0117749_W Vleiplaats	-31.98	23.84	1326
0118029_W Coetzeeskraal	-32	24.12	1448
0131437_W Ludzville Hotel	-31.28	18.25	245
0131639_W Nuwerus	-31.15	18.36	379
0159104_W BitterfonteinKamaboes	-30.74	18.57	600

11 APPENDIX E

Station ID	Number of clusters		
	1900-1954	1955-2010	Difference
0003192_W De Mond	25	304	**279**
0020838FW Groote Schuur	129	309	**180**
0003020_W Cape Agulhas	94	267	**173**
0041533_W Lelyfontein	74	241	**167**
0062768_W Middeldeurvlei	71	224	**153**
0041871_W Porterville	77	222	**145**
0005771_W Bettys Bay	164	294	**130**
0004762_W Simonstown	159	286	**127**
0062671_W Eeendekuil	75	199	**124**
0008813_W Bontebok Park	84	204	**120**
0107510_W Bulshoek Dam	40	158	**118**
0042532AW Ceres	100	209	**109**
0030775_W Keurboomsrivier	145	253	**108**
0047205_W Martjesvlei	30	133	**103**
0107759_W Sandvlei	54	154	**100**
0007183_W Greyton	126	225	**99**
0046809_W Zoar	28	126	**98**
0084159_W Graafwater	55	150	**95**
0042588_W Prince Alfred Hamlet	85	176	**91**
0008470_W Plaatjieskraal	75	161	**86**
0005611AW Steenbras	160	245	**85**
0021656AW Stellenbosch	146	231	**85**
0004874_W Rondevlei	147	225	**78**
0084059_W Redelinghuis	81	159	**78**
0107318_W Puts	72	148	**76**
0041279_W Mooreesburg	97	170	**73**
0014393_W Harkerville	187	259	**72**
0042669_W Malabar Farm	76	148	**72**
0006038_A Elgin	156	226	**70**
0041347_A Langgewens	111	179	**68**
0131437_W Ludzville Hotel	36	104	**68**
0006039_W Grabouw	167	234	**67**
0021230_W Altydgedacht	134	201	**67**
0026824_W vanWyksdorp	52	118	**66**
0011617_W Die Eiland	77	141	**64**
0028775_W Witfontein	189	250	**61**
0042358_W Dwarsrivier	102	163	**61**
0010742_W Stilbaai	97	158	**61**
0118029_W Coetzeeskraal	58	119	**61**

0020846_W Atlantis	126	185	**59**
0048384_W Grootkraal	94	153	**59**
0044286_W Jan de Boers	53	112	**59**
0012303_W Sandhoogte	111	169	**58**
0048275_W Zachariasfontein	36	92	**56**
0029624_W Karatara	180	235	**55**
0011065_W Diepkloof	104	157	**53**
0115595_W Gannakraal	53	105	**52**
0090176_W Grootfontein	17	69	**52**
0030297_W Diepwalle	245	296	**51**
0022825_W Kwaggaskloof Dam	64	115	**51**
0008367_W Kleinfontein	79	129	**50**
0117749_W Vleiplaats	63	113	**50**
0085112_W Algeria (BOS)	96	145	**49**
0063452_W KROMRIVER	63	111	**48**
0050688_W Rooiklip	49	97	**48**
0021778_W Jonkershoek	173	220	**47**
0022038_W Vrugbaar	149	196	**47**
0042621_W Warmbokveld	88	135	**47**
0024110_W Ashton	78	123	**45**
0050327_W Rondekop	64	109	**45**
0094730_W Beeldhouersfontein	80	124	**44**
0047765_W Damaskus	46	89	**43**
0047359_W Calitzdorp Dam	43	86	**43**
0092369_W De Hoop	42	85	**43**
0070770_W Aardoorns	28	70	**42**
0029294_W Bergplaats	178	219	**41**
0004891_W Cape Point	149	190	**41**
0084558_W Elandsfontein	98	139	**41**
0021055_W Maitland	128	168	**40**
0011132_W Albertinia	92	131	**39**
0025599_W Strawberry Hill	183	220	**37**
0014633_W Plettenberg Bay	116	152	**36**
0092386_W Blouboskuil	42	78	**36**
0045857_W Floriskraal dam	38	74	**36**
0006612_W Boontjieskraal	117	152	**35**
0007263_W Boskloof	125	159	**34**
0006332_W Rustfontein	123	157	**34**
0008751_W Marloth	168	201	**33**
0029805_W Goudveld	182	213	**31**
0117047_W Loskop	52	83	**31**
0061298_W Langebaanweg	105	135	**30**
0047436_W Weltevreden	44	74	**30**
0106880AW Vredendal	51	78	**27**
0067074_W Anysrivier	37	63	**26**
0107869_W Kanolvlei	71	96	**25**

0106603_W Lutzville Hotel	50	74	**24**
0090196_W Tafelberg	40	64	**24**
0028150_W Kwepertuin	127	150	**23**
0028771_W Herold	93	115	**22**
0049050_W Klaarstroom	48	70	**22**
0049060_W De Rust	79	99	**20**
0068547_W Zeekoeivlei	27	47	**20**
0022539_W Villiersdorp	126	144	**18**
0106512_W Koekenaap	48	66	**18**
0048043_W Prince Albert	49	66	**17**
0045611_W Laingsburg	37	54	**17**
0006527_W Tussenbeide	139	154	**15**
0045184_W Dwarsindieberg	49	63	**14**
0068010_W Merweville	33	47	**14**
0070735_W Klipkrans	55	67	**12**
0049372_W Rondawel	44	56	**12**
0022803_W Bellevue	74	85	**11**
0085309_W Welbedacht	59	70	**11**
0014063_W Knysna	184	194	**10**
0006415_W Hermanus	167	176	**9**
0027302_W Calitzdorp Pol	64	73	**9**
0028407_W Groot Doornrivier	68	76	**8**
0009783_W Blackdown	128	134	**6**
0107396_W Vanrhynsdorp	69	75	**6**
0131639_W Nuwerus	64	70	**6**
0022759_W Worcester	80	85	**5**
0093074_W Kamferskraal	56	61	**5**
0021823_W Paarl	152	156	**4**
0083618_W Elandsbaai	99	101	**2**
0023597_W McGregor	82	82	**0**
0084701_W Clanwilliam	81	80	**-1**
0095006_W Quaggasdrift	90	88	**-2**
0030265_W Buffelsnek	220	217	**-3**
0011451_W Herbertsdale	128	125	**-3**
0159104_W Bitterfontein Kamaboes	77	73	**-4**
0007669_W Blydskap	140	135	**-5**
0024197_W Montagu	96	89	**-7**
0047716_W Kruisrivier	96	88	**-8**
0046479_W Ladismith	101	90	**-11**
0086007_W Reenen	48	37	**-11**
0062444_W Piketberg	131	117	**-14**
0028415_W Jonkersberg	210	194	**-16**
0009815_W Heidelberg	131	115	**-16**
0042227_W Tulbagh	124	108	**-16**
0042789_W Odessa	110	90	**-20**
0063005_W Citrusdal	137	102	**-35**

0040604_W Hopefield	131	95	**-36**
0029542_W Rooirivier	110	69	**-41**
0040682_W Darling	178	113	**-65**
0004734_W Klaasjagersberg	228	162	**-66**
0029692_W Buffelsklip	111	43	**-68**
0025450_W Dun Donald	222	150	**-72**

12 APPENDIX F

Station ID	50 year Return Levels (mm)			20 year Return Levels (mm)		
	1900-1954	1955-2010	% Change	1900-1954	1955-2010	% Change
0003020_W Cape Agulhas	54.3	105.8	**94.8**	45.5	83.5	**83.4**
0003192_W De Mond	51.3	140.7	**174.3**	37.0	102.9	**178.3**
0004734_W Klaasjagersberg	82.3	89.2	**8.4**	74.2	77.0	**3.7**
0004762_W Simonstown	83.3	81.7	**-2.0**	69.7	70.6	**1.2**
0004874_W Rondevlei	86.7	104.8	**20.9**	74.2	89.9	**21.1**
0004891_W Cape Point	49.9	69.0	**38.3**	42.9	56.0	**30.6**
0005611AW Steenbras	130.0	134.4	**3.4**	104.7	112.3	**7.3**
0005771_W Bettys Bay	136.6	213.6	**56.4**	107.0	164.9	**54.2**
0006038_A Elgin	145.2	141.7	**-2.4**	115.8	119.8	**3.5**
0006039_W Grabouw	165.8	119.4	**-28.0**	132.6	107.6	**-18.9**
0006332_W Rustfontein	157.7	131.8	**-16.5**	127.5	120.0	**-5.9**
0006415_W Hermanus	217.5	111.5	**-48.7**	144.5	90.0	**-37.7**
0006527_W Tussenbeide	155.1	129.9	**-16.2**	114.1	102.2	**-10.5**
0006612_W Boontjieskraal	102.9	99.2	**-3.6**	78.7	78.2	**-0.7**
0007183_W Greyton	102.1	145.2	**42.2**	81.0	112.1	**38.4**
0007263_W Boskloof	99.6	92.4	**-7.2**	81.0	77.1	**-4.7**
0007669_W Blydskap	87.2	141.1	**61.8**	73.9	99.8	**35.0**
0008367_W Kleinfontein	119.8	151.7	**26.6**	86.3	105.1	**21.8**
0008470_W Plaatjieskraal	126.2	140.8	**11.6**	91.9	103.9	**13.0**
0008751_W Marloth	214.3	189.3	**-11.7**	162.6	147.2	**-9.5**
0008813_W Bontebok Park	102.6	190.0	**85.3**	76.9	135.1	**75.6**
0009783_W Blackdown	127.3	150.1	**18.0**	100.6	115.2	**14.6**
0009815_W Heidelberg	124.8	116.6	**-6.5**	96.3	94.8	**-1.5**
0010742_W Stilbaai	102.2	111.5	**9.1**	81.1	86.6	**6.7**
0011065_W Diepkloof	139.4	140.2	**0.5**	100.9	106.2	**5.2**
0011132_W Albertinia	107.1	127.5	**19.1**	87.0	102.1	**17.3**
0011451_W Herbertsdale	131.0	145.9	**11.4**	101.9	110.1	**8.0**
0011617_W Die Eiland	80.2	158.5	**97.5**	67.6	116.6	**72.6**
0012303_W Sandhoogte	100.4	155.2	**54.5**	86.7	119.1	**37.4**
0014063_W Knysna	200.4	143.4	**-28.4**	149.0	119.9	**-19.5**
0014393_W Harkerville	164.4	173.0	**5.3**	131.2	141.4	**7.8**
0014633_W Plettenberg Bay	181.1	132.7	**-26.7**	137.1	111.7	**-18.5**
0020838FW Groote Schuur	111.4	205.1	**84.1**	94.8	162.7	**71.5**
0020846_W Atlantis	43.4	65.3	**50.5**	39.4	55.8	**41.6**
0021055_W Maitland	78.3	96.8	**23.6**	64.6	80.1	**24.0**
0021230_W Altydgedacht	58.1	71.7	**23.3**	53.2	63.4	**19.2**
0021656AW Stellenbosch	66.7	91.0	**36.4**	58.6	77.8	**32.7**

0021778_W Jonkershoek	135.2	136.0	**0.6**	111.9	115.5	**3.3**
0021823_W Paarl	102.9	106.3	**3.3**	90.8	94.2	**3.7**
0022038_W Vrugbaar	81.7	101.6	**24.4**	72.8	87.1	**19.8**
0022539_W Villiersdorp	84.1	165.9	**97.2**	76.6	130.2	**70.0**
0022759_W Worcester	59.5	101.4	**70.5**	52.6	80.7	**53.5**
0022803_W Bellevue	138.2	112.6	**-18.6**	95.5	81.7	**-14.5**
0022825_W Kwaggaskloof Dam	55.0	84.6	**53.9**	47.2	69.8	**47.9**
0023597_W McGregor	97.9	86.1	**-12.1**	75.8	71.9	**-5.1**
0024110_W Ashton	69.9	90.1	**28.9**	55.7	73.8	**32.5**
0024197_W Montagu	118.9	139.6	**17.4**	93.0	101.7	**9.3**
0025450_W Dun Donald	146.9	147.8	**0.6**	120.0	114.8	**-4.3**
0025599_W Strawberry Hill	178.5	182.1	**2.0**	144.0	144.7	**0.5**
0026824_W vanWyksdorp	47.6	68.4	**43.7**	40.4	57.9	**43.4**
0027302_W Calitzdorp Pol	82.2	76.4	**-7.0**	68.0	65.0	**-4.3**
0028150_W Kwepertuin	188.8	171.6	**-9.1**	134.6	136.4	**1.3**
0028407_W Groot Doornrivier	103.6	116.6	**12.6**	81.0	89.8	**10.9**
0028415_W Jonkersberg	217.2	170.5	**-21.5**	171.7	141.9	**-17.4**
0028771_W Herold	197.7	252.4	**27.7**	145.5	169.7	**16.7**
0028775_W Witfontein	193.1	219.9	**13.9**	152.1	172.4	**13.4**
0029294_W Bergplaats	220.5	201.3	**-8.7**	165.3	158.2	**-4.3**
0029542_W Rooirivier	168.4	84.1	**-50.1**	125.6	72.9	**-42.0**
0029624_W Karatara	194.7	233.3	**19.8**	145.1	171.2	**18.0**
0029692_W Buffelsklip	226.7	80.5	**-64.5**	161.8	69.8	**-56.9**
0029805_W Goudveld	224.8	220.2	**-2.1**	165.6	158.9	**-4.0**
0030265_W Buffelsnek	275.5	268.2	**-2.6**	200.4	199.4	**-0.5**
0030297_W Diepwalle	191.3	201.6	**5.4**	146.0	157.2	**7.7**
0030775_W Keurboomsrivier	182.0	185.3	**1.8**	135.3	152.3	**12.6**
0040604_W Hopefield	61.2	65.2	**6.5**	52.0	53.3	**2.6**
0040682_W Darling	66.9	70.6	**5.6**	60.5	61.1	**1.1**
0041279_W Mooreesburg	46.3	69.3	**49.7**	41.6	57.8	**39.0**
0041347_A Langgewens	62.9	53.4	**-15.2**	51.6	48.1	**-6.9**
0041533_W Lelyfontein	43.7	52.0	**19.0**	35.6	45.4	**27.5**
0041871_W PORTERVILLE	68.8	90.4	**31.4**	59.2	75.5	**27.6**
0042227_W Tulbagh	80.4	77.5	**-3.6**	71.8	70.2	**-2.2**
0042358_W Dwarsrivier	76.7	107.3	**39.8**	71.8	95.4	**32.9**
0042532AW Ceres	125.5	178.1	**41.9**	114.0	157.1	**37.8**
0042588_W Prince Alfred Hamlet	68.4	109.1	**59.4**	63.4	95.4	**50.5**
0042621_W Warmbokveld	84.5	105.2	**24.5**	72.9	92.0	**26.1**
0042669_W Malabar Farm	90.1	83.6	**-7.2**	75.2	73.9	**-1.7**
0042789_W Odessa	60.8	61.8	**1.6**	52.5	53.3	**1.6**
0044286_W Jan de Boers	49.2	90.8	**84.7**	43.8	71.6	**63.5**
0045184_W Dwarsindieberg	45.1	94.5	**109.4**	42.1	68.7	**63.3**
0045611_W Laingsburg	57.1	68.6	**20.2**	49.2	57.5	**16.7**
0045857_W Floriskraal dam	60.3	61.1	**1.2**	50.5	52.9	**4.8**
0046479_W Ladismith	85.8	80.4	**-6.3**	71.9	70.6	**-1.7**

0046809_W Zoar	41.9	79.8	**90.3**	31.7	66.7	**110.1**
0047205_W Martjesvlei	44.8	95.3	**112.8**	38.2	76.9	**101.2**
0047359_W Calitzdorp Dam	59.3	92.9	**56.6**	50.4	76.7	**52.0**
0047436_W Weltevreden	59.9	69.8	**16.6**	49.2	59.6	**21.0**
0047716_W Kruisrivier	147.9	96.7	**-34.6**	114.9	81.7	**-28.9**
0047765_W Damaskus	58.9	63.8	**8.3**	47.9	57.5	**20.1**
0048043_W Prince Albert	71.6	75.4	**5.3**	58.2	63.5	**9.2**
0048275_W Zachariasfontein	47.3	83.9	**77.2**	44.1	67.6	**53.4**
0048384_W Grootkraal	102.0	77.0	**-24.5**	76.4	65.3	**-14.6**
0049050_W Klaarstroom	94.2	94.0	**-0.2**	69.2	76.5	**10.4**
0049060_W De Rust	111.8	88.2	**-21.2**	90.4	72.9	**-19.4**
0049372_W Rondawel	65.5	67.7	**3.2**	52.6	55.6	**5.6**
0050327_W Rondekop	77.8	74.0	**-4.9**	61.1	61.1	**0.0**
0050688_W Rooiklip	95.8	76.0	**-20.6**	64.1	62.3	**-2.8**
0061298_W Langebaanweg	45.6	51.4	**12.6**	38.6	41.5	**7.3**
0062444_W Piketberg	65.7	69.6	**5.9**	58.4	61.0	**4.5**
0062671_W Eeendekuil	33.6	61.0	**81.4**	30.8	52.3	**69.6**
0062768_W Middeldeurvlei	31.0	52.4	**69.2**	28.1	45.8	**63.0**
0063005_W Citrusdal	90.6	78.9	**-12.9**	74.6	67.5	**-9.6**
0063452_W KROMRIVER	54.2	78.4	**44.7**	50.5	68.6	**35.7**
0067074_W Anysrivier	78.7	69.9	**-11.1**	60.0	59.9	**-0.1**
0068010_W Merweville	73.4	96.0	**30.7**	58.1	78.2	**34.7**
0068547_W Zeekoeivlei	68.8	68.7	**-0.1**	51.2	60.5	**18.0**
0070735_W Klipkrans	99.6	62.8	**-36.9**	72.8	56.4	**-22.5**
0070770_W Aardoorns	64.6	80.8	**25.2**	52.0	69.8	**34.3**
0083618_W Elandsbaai	66.2	68.5	**3.3**	57.2	58.9	**2.9**
0084059_W Redelinghuis	41.2	69.8	**69.6**	37.0	58.9	**59.1**
0084159_W Graafwater	41.0	49.8	**21.7**	37.8	44.2	**17.0**
0084558_W Elandsfontein	93.7	95.1	**1.4**	76.4	80.8	**5.8**
0084701_W Clanwilliam	55.3	56.2	**1.6**	45.8	46.4	**1.1**
0085112_W Algeria (BOS)	103.2	113.7	**10.2**	90.6	101.9	**12.4**
0085309_W Welbedacht	56.8	73.7	**29.6**	53.0	63.1	**19.1**
0086007_W Reenen	66.8	52.9	**-20.8**	57.2	43.4	**-24.1**
0090176_W Grootfontein	62.3	144.1	**131.3**	55.0	106.3	**93.5**
0090196_W Tafelberg	67.1	105.1	**56.5**	54.6	79.3	**45.1**
0092369_W De Hoop	80.6	102.4	**27.0**	67.3	87.5	**30.1**
0092386_W Blouboskuil	52.9	76.8	**45.3**	47.1	63.9	**35.8**
0093074_W Kamferskraal	71.1	77.1	**8.4**	57.0	67.6	**18.7**
0094730_W Beeldhouersfontein	89.3	113.9	**27.5**	76.6	90.7	**18.4**
0095006_W Quaggasdrift	105.2	92.9	**-11.7**	90.0	80.1	**-11.0**
0106512_W Koekenaap	32.2	47.2	**46.4**	30.0	40.6	**35.5**
0106603_W Lutzville Hotel	35.6	59.1	**65.8**	32.8	46.0	**40.2**
0106880AW Vredendal	54.8	43.4	**-20.8**	47.5	37.4	**-21.3**
0107318_W Puts	57.4	89.7	**56.3**	50.7	72.4	**42.9**
0107396_W Vanrhynsdorp	48.0	52.0	**8.3**	36.9	43.1	**16.9**
0107510_W Bulshoek Dam	43.0	53.7	**24.8**	36.6	48.2	**31.7**

0107759_W Sandvlei	26.9	57.8	**115.0**	24.0	47.4	**97.4**
0107869_W Kanolvlei	38.2	48.0	**25.7**	33.0	41.5	**25.6**
0115595_W Gannakraal	60.0	97.3	**62.3**	54.1	81.5	**50.5**
0117047_W Loskop	60.6	83.4	**37.6**	51.4	69.7	**35.4**
0117749_W Vleiplaats	62.5	74.3	**18.9**	51.8	66.5	**28.3**
0118029_W Coetzeeskraal	65.2	90.7	**39.1**	54.9	79.0	**44.0**
0131437_W Ludzville Hotel	35.3	64.5	**83.1**	30.5	52.1	**70.7**
0131639_W Nuwerus	32.5	50.4	**55.2**	30.5	43.9	**43.9**
0159104_W Bitterfontein Kamaboes	45.9	63.2	**37.7**	40.8	55.0	**34.7**