SCHOOL OF ENVIRONMENTAL SCIENCES

DEPARTMENT OF HYDROLOGY AND WATER RESOURCES

Influence of climate change on flood and drought cycles and implications on rainy season characteristics in Luvuvhu River Catchment, South Africa

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DECLARATION

I, Dagada Khumbudzo (11574149) hereby declare that this dissertation is submitted by me and has never been submitted to this University of Venda for Masters's degree of Earth Science in Hydrology and Water Resources (MESHWR), and has never been submitted to any other University. I declare that, this is my own work. Quotations in this proposal from other people's work have been correctly cited and referenced.

Signature……………………….. **Date…………………………….**

ABSTRACT

This study dealt with the influence of climate variability on flood and drought cycles and implications on rainy season characteristics in Luvuvhu River Catchment (LRC) in Limpopo of South Africa. Extreme weather events resulting in hazards such as floods and droughts are becoming more frequent due to climate change. Extreme events affect rainy season characteristics and hence have an influence on water availability and agricultural production. Annual temperature was obtained from Water Research Commission for stations 0723485W, 0766628W and 0766898W from 1950-2013 were used to show/or confirm if there is climate variability in LRC. Daily rainfall data was obtained from SAWS for stations 0766596 9, 0766563 1, 0723485 6 and 0766715 5 were used to detect climate variability and determine the onset, duration and cessation of the rainy season. Streamflow data obtained from the Department of Water and Sanitation for stations A9H004, A9H012, and A9H001 for at least a period of 30 years for each station were used for climate variability detection and determination of flood and drought cycles. Influence of climate variability on floods and droughts and rainy season characteristic were determined in the area of study. Trends were evaluated for temperature, rainfall and streamflow data in the area of study using Mann Kendall (MK) and linear regression (LR) methods. MK and LR detected positive trends for temperature (maximum and minimum) and streamflow stations. MK and LR results of rainfall stations showed increasing trends for stations 0766596 9, and 0766563 1 whereas stations 0723485 6 and 0766715 5 showed decreasing trends. Standardized precipitation index (SPI) was used to determine floods and droughts cycles. SPI results have been classified either as moderately, severely and extremely dry or, moderately, very and extremely wet. This SPI analysis provides more details of dominance of distinctive dry or wet conditions for a rainy season at a particular station. Mean onset of rainfall varied from day 255 to 297, with 0766715 5 showing the earliest onset compared to the rest of the stations. Cessation of rainfall for most of the hydrological years was higher than the mean days of 88, 83 and 86 days in 0766596 9, 0766563 1 and 0723485 6 stations. Mean duration of rainfall varied from 102 to 128, with station 0766715 5 showing shortest duration of rainfall. The results of the study showed that the mean onset, duration and cessation were comparable for all stations except 0766715 5 which had lower values. The study also found that climate variability greatly affects onset, duration and cessation of rainfall during dry years. This led to late onset, early cessation and relatively short duration of the rainfall season. Communities within the catchment must be educated to practice activities such as conservation of indigenous plants, reduce carbon dioxide emissions.

DEDICATION

This project is dedicated to God the Almighty. I dedicate this work also to my dad who never lived to see it, my mom Dagada Gloria Maria, my children Makhado Gundo, Makhado Waamanda and my husband Makhado Azwifarwi Ronald for guiding me, supporting me and advising me throughout the course of this study.

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LIST OF ABBREVIATIONS/ SYMBOLS

ADM = Amathole District Municipality

AFRA = Association for Rural Advancement

ARC = Agricultural Research Council

AWC = Available water content

CCCSN = Canadian Climate Change Scenarios Network

CO_2 = Carbon dioxide

CSM = Climate System Model

CUSUM = Cumulative sum

CV = Coefficient of Variation

CZMS = Coastal Zone Management Subgroup

DEA = Department of Environmental Affairs

ENSO = El Nino – Southern Oscillation

FIG = Figure

GCMs = Global Climate Models

PDSI = Palmer drought severity index

PWMs = Probability weighted moments

IFRC = International Federation of the Red Cross

IPCC = Intergovernmental Panel on Climate Change

ISDR = International Strategy for Disaster Reduction

IWMI = International Water Management Institute

KM^2 = Square Kilometer

KNP = Kruger National Park

KZN = Kwazulu – Natal

LGP = Length of Growing Period

LGS = Length of growing season

LRC = Luvuvhu River Catchment

MAP = Mean Annual Precipitation

MAE = Mean Annual Evaporation

MK = Mann Kendall

MNCFC = Mahalanobis National Crop Forecast Centre

Msl = Mean sea level

NCEP = National Center for Environmental Prediction

NRC = National Research Council

PET = Potential evapotranspiration

SADC = Southern African Development Community

SA DIB = South African Drought Information Bulletin

SAWS = South African Weather Services

SDM = Statistical Downscaling Model

SPI = Standardized precipitation index

SK = Seasonal Kendall

SREs = scenarios

SR = Spearman rho

TAR = Third assessment report

USA = United States of America

WMA = Water Management Agency

WMO = World Meteorological Organization

WRC = Water Research Commission of South Africa

WWAP = World Water Assessment Programme

X = Rainfall

CHAPTER ONE: INTRODUCTION

1.1 Background

Climate change is a long- term shift in the climate of a specific location, region or planet. The shift is measured by changes in features associated with average weather such as temperature, wind patterns and precipitation (IPCC, 1996). It refers to a change in the state of the climate that can be identified (for example, by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period such as 50 years or above (Berliner *et al.,* 2000). Climate change is a serious and dangerous concern in South Africa (Dilley *et al.,* 2005). Both natural and anthropogenic activities are responsible for climate change, which causes trends and variations in water resources (NRC, 2010). Climate change will lead to an intensification of the global hydrological cycle and can have major impacts on regional water resources, affecting both ground and surface water supply for domestic and industrial uses, irrigation, hydropower generation, navigation, in stream ecosystems and water based recreation (Mukheibir and Sparks, 2006).

Climate change may further reduce water availability for global food production, as a result of mean changes in temperature and precipitation regimes, as well as due to increases in the frequency of extreme events, such as droughts and flooding (Rosenzweig *et al.,* 2001). There is a direct influence of global warming on changes in precipitation and heavy rains. Increased heating leads to greater evaporation and thus surface drying, thereby increasing intensity and duration of drought (Trenberth, 1999).

In the current dispensation in South Africa and elsewhere in the world, the climate variability influencing flood and drought cycles and rainy season characteristics is common. Scientists predict that the rate of climate change will be more rapid than previously expected. Drought, floods and other extreme weather events are projected to become more intense and frequent. If the occurrence of drought were to increase, the impact on water resources, and consequently people's livelihoods and health, would become serious (Mukheibir and Sparks, 2006).

1.2 Statement of the problem

Luvuvhu River Catchment (LRC) is experiencing increase in temperature (Dagada, 2013) causing a warming trend, which will lead to changes in many aspects of weather, such as wind patterns, amount and type of precipitation, and frequency of severe weather events (for example, floods and droughts). Such climate change could have far-reaching and/or unpredictable environmental, social and economic consequences (IPCC, 1996). Water plays a crucial role in food production regionally and worldwide. Changes in water demand and availability under climate change will significantly affect agricultural activities and food security. Climate change increases irrigation demands in the majority of world regions due to a combination of decreased rainfall and increased evaporation arising from increased temperature (FAO, 2003).

In LRC climate change poses a serious problem in many different sectors such as agricultural, domestic, industrial, and recreational, amongst others. Water availability is the main constraint to poverty alleviation, public health, economic development and environmental improvement (WWAP, 2003). Extreme weather events pose direct risks to human health and safety. Climate change increases the frequency or severity of flood and drought cycles. Climate change also causes uncertainties in water supply and demand and this challenges the management practices that are in place for the catchment area. For example, it has been shown that the area of study including the northern region of Limpopo Province as a whole experiences drought, which has an impact on the water resources, agriculture and livestock (Kabanda, 2004). A study done by Odiyo and Maluleke (2005) showed the impact of floods on agriculture in LRC. Climate change affects the amount of precipitation received in LRC. For example, LRC experienced reduction in mean annual precipitation (MAP) by 14% in the period 1991 - 1992 (ARC and IWMI, 2003).

Extreme weather resulting in hazards such as floods and droughts is becoming more frequent due to climate change. Climate change affects agriculture in LRC due to high temperature and more variable rainfall, with substantial reductions in precipitation. Rising temperature, rising potential transpiration rates and declining rainfall conspire to increase the severity, frequency and duration of droughts. Droughts and floods cause or threaten to cause death, injury or diseases; floods can also damage property, infrastructure or the environment and both floods and droughts can disrupt the life of a community such as through affecting agricultural production. For example, South

Africa suffered from reduction in water resources, significant reduction in rainfall and reduced crop yields and livestock due to droughts in 2004 (SA DIB, 2004). The magnitude and severity of the 2004 drought became evident in Nkonkobe when 1 063 farmers submitted applications for drought relief (ADM, 2004). The previous scientific studies focused solely on hazard risks, leaving behind the source of the disaster called climate change because it strongly affects the occurrences of floods and droughts and has implication on rainy season characteristics in LRC (Red Cross International Federation of Red Cross and Red Crescent Societies, 2002). Climate variability, which includes erratic and unpredictable seasonal rainfall, floods and cyclones, contributes to the risk of farming across most of Southern Africa (AFRA, 1993). Warm temperatures caused by climate change will lead to increased drying of the land surface in LRC, and thus increase incidences and severity of droughts and floods, and reduce rainfall received.

1.3 Motivation

It is important to investigate the influence of climate change on flood and drought cycles and implications on rainy season characteristics in Luvuvhu River Catchment because South Africa has been experiencing serious climate change related disasters. IPCC (2013) studied the detection and attribution of climate change from global to regional scale. The results showed that there is high confidence in attributing many aspects to changes in climate (IPCC, 2013). None of the studies in LRC including Nkuna *et al*. (2011) who studied the influence of temperature on rainfall variability, Nkuna (2012) who studied the hydrological variations and trends and links to climate change and land use, and Dagada (2013) who studied changes of evaporation and links to climate change and land use, were on the influence of climate change linked to flood and drought cycles and rainy season characteristics. This creates the need for the current study since climate change is increasing intensity of floods and droughts.

Investigating the influence of climate change on flood and drought cycles in LRC will aid in estimating the occurrence and frequency of flood and drought cycles. This information is crucial in agricultural production studies. Agriculture is more vulnerable today than ever before due to increasing population, high input costs and changing climate across the whole of South Africa. Water is among the most important elements affecting agriculture as it is one of the limiting resources for crop growth in most semi-arid conditions including Southern Africa (Barron *et al.*, 2003).

The management of risks such as floods and droughts is one of the great challenges of the 21st century. The ever-growing population, economic and environmental losses due to natural or human-made disasters, provide the necessity for a systematic approach to the management of risks. Thus, information on influence of climate change on floods and droughts, can aid in disaster risk management. This study will be useful to the decision-makers and resource managers because they require information regarding future changes in climate and variability to better anticipate potential impacts of climate change by the application of both statistical models and Global Circulation models (GCMs) (Zhu *et al.*, 2008).

The results of the study will be used by water managers and other stakeholders involved in water resources management and/or hydrological modelling. Information on rainy season characteristics can help the farmers to plan farming activities such as planting of crops since they will have information on the start, duration and end of a rainy season. This information will save them from wasting money and getting nothing in return. The results of the study will also be useful in developing strategies to minimize climate change. This will ensure the long-term sustainability of the water supplies and the local resources. The results of the study will also assist in the development of early warning system that allows detection and forecasting of impending extreme events.

1.4 Objectives

1.4.1 Main objective

- The main objective of the study is to investigate the influence of climate variability on flood and drought cycles and implications on rainy season characteristics.

1.4.2 Specific objectives

The study sets out to achieve these specific objectives:

- To determine climate variability based on statistical methods.

- To determine variability of the rainy season characteristics (onset, cessation and duration).
- To determine influence of climate variability on flood and drought cycles.
- To determine the implications of flood and drought cycles on rainy season characteristics.

1.5 Research questions

These research questions have been formulated to help achieve the research objectives:

- What are the climatic trends of the study area?
- How has climate variability influenced the onset, cessation and duration of rainfall season in the study area?
- To what extent has climate variability influenced floods and drought cycles?
- What are the implications of changes in flood and drought cycles on rainy season characteristics?

1.6 Characteristics of the study area

1.6.1 Location

The Luvuvhu River Catchment (LRC) is located in the northern Limpopo Province of South Africa. The Luvuvhu River Catchment is located between the longitudes 29 ^{o} 49′ 46.16″ E and 31 ^{o} 23′32.02″ E and latitudes 22 ^{o} 17′33.57″ S and 23 ^{o} 17′57.31″S. It covers approximately a catchment area of 5 941 km^2.

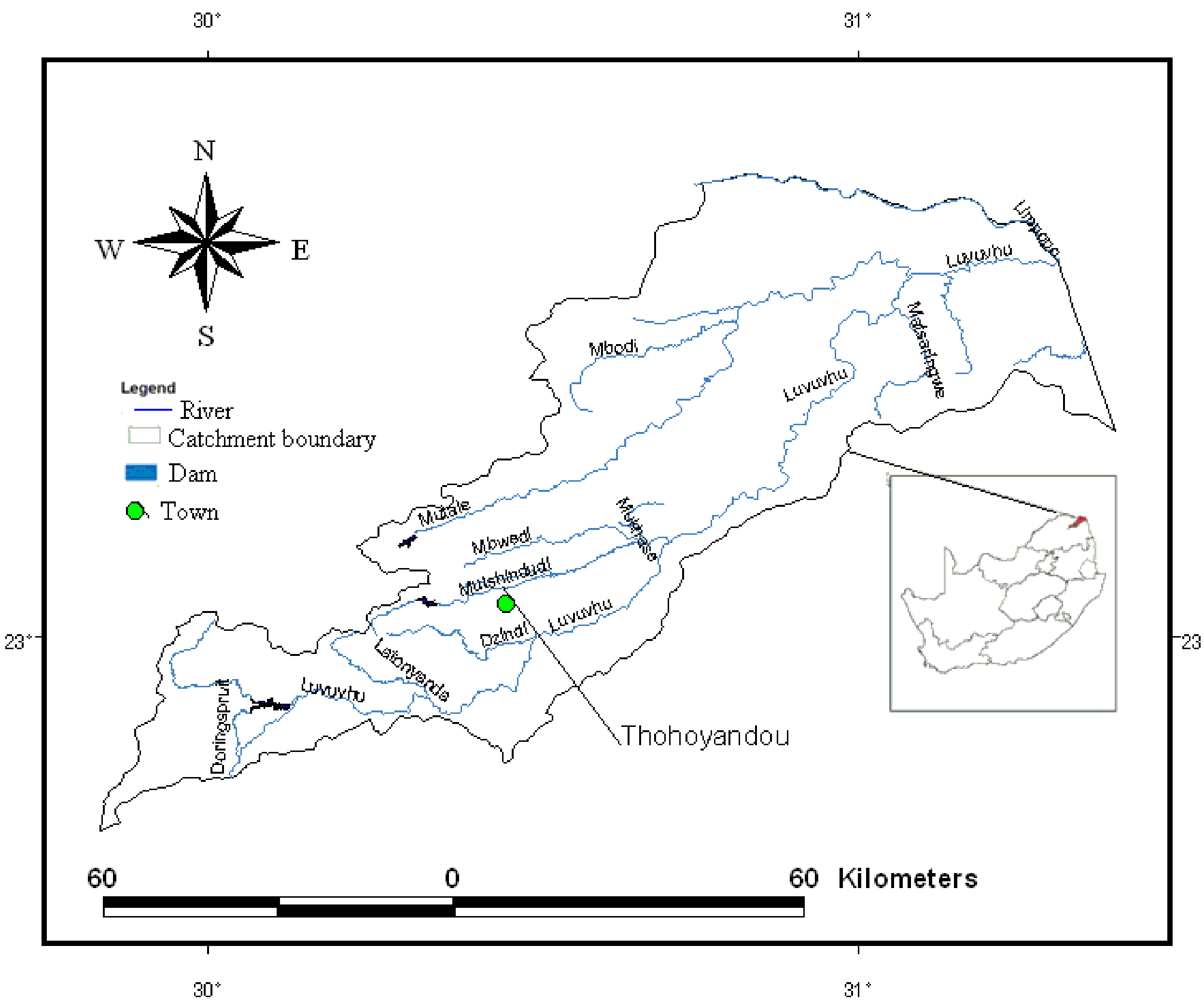

Figure 1.1: Location of the Luvuvhu River Catchment

1.6.2 Hydrology

The LRC and most of its tributaries flow throughout the year. Albasini, Mambedi, Tshakhuma, Damani, Vondo, Nandoni and Phiphidi Dams are found in Luvuvhu River Catchment. Vondo and Phiphidi Dams lie in the Mutshundudi River while Nandoni Dam is found in the middle section of the Luvuvhu River east of the confluence with the Dzindi tributary. Water from the dams in the LRC is mainly used for agriculture, industrial, recreational and household purposes. There are also smaller rivers like Tshirovha, Tshiombedi, Mukhase, Mbwedi, Madanzhe and Sterkstroom. The upper Luvuvhu, Sterkstroom, Latonyanda, Dzindi, Mukhase, Mbedi, Tshinane and

Mutshundudi are steep, narrow rivers dominated by cobblestones and occasional pools with few bedrock rapids. The Tshirovha and Tshiombedi tributaries of the Mutale River are steep with both bedrock and fixed boulder rapids. Near the KNP border, in the Steep Lanner Gorge, the Mutale River joins the Luvuvhu River. Luvuvhu River then joins the Limpopo River near Pafuri at Crook's Corner on the Mozambique border (State of Rivers Report, 2001).

The climatic condition within the Luvuvhu River Catchment varies in different parts of the catchment area. The catchment area is generally semi-arid and becomes arid as it progresses eastward towards the KNP (Mudau, 2002). The mean annual precipitation (MAP) of 608 mm and mean annual evaporation (MAE) of 1 678 mm show high spatial and temporal variation with highest rainfall and lowest evaporation over the Soutpansberg mountain range and lowest rainfall with highest evaporation to the Kruger National Park (DWAF, 2004).

Rainfall occurs seasonally in the LRC and mostly starts in October and end in March, and its distribution is strongly influenced by topography. The highest or peak rainfall months are January and February. More than 85% of the rain falls during the rainfall months (Maluleke, 2003). The other amounts are received during the dry season (May and September) due to frontal systems (Kabanda, 2004). Within the LRC, evaporation increases gradually from 1 400 mm to 1 900 mm per annum (State of Rivers Report, 2001).

Some of its tributaries such as the Mutshundudi River and Mutale River rise from Soutpansberg Mountains. The Luvuvhu River flows for about 200 km through a diverse range of landscapes before it joins the Limpopo River near Pafuri in the Kruger National Park. Towns in the study area include Thohoyandou, Giyani and Tzaneen (Jenkins, 2007). Most of the development in the study area is agriculturebased, with strong contributions by irrigated agriculture and afforestation. Approximately 80 to 90% of the population can be considered as rural (DWA, 2013).

1.6.3 Topography

Climate patterns such as rainfall intensity and distribution, and water drainage patterns such as surface and subsurface waters are commonly affected by topographic features of a region (Ayoade, 1988). The topography of the Luvuvhu/Letaba WMA varies from a zone of high mountain in the west through low mountains and foot hills in the central part of the WMA to the low lying plains in the east (DWAF, 2004). The mountains zone or great Escarpment includes the northern portion of the Drakensberg mountain range and the eastern Soutpansberg, which both extend to the western parts of the management area, and the characteristic wide expanse of the Lowveld to the east of the escarpment (DWAF, 2004). The highest peaks have an elevation of more than 2000 m above mean sea level (msl). This zone is deeply incised by the major tributaries draining the WMA. The low lying plains cover most of the WMA and have gentle flat slopes (DWAF, 2004).

1.6.4 Vegetation

The vegetation is mostly influenced by rainfall, especially the length of wet season (Jackson, 1989). Alien vegetation is found in upper reaches of the LRC from which the vegetation is estimated to cover an area of 168 km^2 (DWAF, 2004). Alien vegetation within the LRC tends to absorb a considerable amount of water from the soil thus creating water scarcity and reducing indigenous vegetation. Alien vegetation such as Lantana Camara and Castor Oil are common along Luvuvhu River. The Luvuvhu River also supports an important ecosystem which is in reasonably good condition. The riparian zone (area adjacent to the river bank), consists of acacia woodland species. Riparian vegetation in large areas has been removed to accommodate orchards for both commercial and subsistence farming. Alien vegetation such as Eucalyptus poplars and Mauritius Thorns are found along the riparian zone. During floods, riparian zone helps absorb water. Riparian vegetation helps prevent the river from down cutting or cutting a straight path, thus promoting the meandering nature of channels, increasing groundwater recharge, and maintaining an elevated water table (Maluleke, 2003).

1.6.5 Land use

Land use in the LRC includes commercial forestry (4%), commercial dry land agriculture (10%), commercial irrigation agriculture (3%), range land (50%), conservation areas (30%) and urban areas (3%) (Hope *et al.*, 2003). Irrigation farming is intensively practiced in LRC and it is the biggest consumer of the Luvuvhu freshwater (Hope *et al.,* 2003). Vegetables, citrus and a variety of fruits such as avocadoes, mangoes, banana and nuts are grown in LRC. Large areas have been planted with commercial forests in the high rainfall parts of the Soutpansberg.

Forests, poor agricultural practices and deforestation along the LRC affect rainwater run-off from the land. Human impacts on the landscape are often observed with synchronous changes in erosion and suspended sediments concentrations in rivers. For example, within the LRC in some area where land use practices are poor and where riparian vegetation has been or is being removed; floods accelerate bank and donga erosion. Widespread clearing, particularly of the riparian vegetation and in areas vulnerable to soil erosion, results in higher than natural sediment loads to many rivers (State of Rivers Report, 2001).

CHAPTER TWO: LITERATURE REVIEW

2.1 Preamble

This chapter reviews literature on influence of climate change on flood and drought cycles. The study will also review implications on rainy season characteristics caused by climate change. Types of floods and droughts as well as impacts of floods and droughts will also be reviewed including methods to determine droughts and floods.

2.2 Influence of climate change on flood and drought cycles

Climate change is having a multitude of immediate and long-term impacts in African countries. These include flooding, drought, sea level rise in estuaries, drying up of rivers, poor water quality in surface and groundwater systems, precipitation and water vapour pattern distortions (Urama, and Ozor, 2010). Global climate change consequences include redistribution of precipitation, rising sea levels, change in the carbon dioxide (CO_2) absorption of the oceans and increases in extreme precipitation events (German Advisory Council, 2004; Stolberg *et al*., 2003). IPCC stated that an increase in the frequency of extreme precipitation events is very likely to expand and the area of the globe affected by increased drought is likely to expand due to natural climate variability (ISDR, 2006).

There is increasing evidence that human- induced climate change, “global warming’’, is changing the hydrological cycle, especially the extremes such as floods and droughts (Trenberth, 1999). It has been observed in many places worldwide that when warming accelerates, land- surface drying occurs due to evaporation of moisture, and this increases the potential incidence of severity of drought (Dai *et al*., 2004). Increasing intensity and frequency of droughts in various parts of Asia and southern Africa are due to rise in temperature and El Nino – Southern Oscillation (ENSO) (Kashyapi, 2008). At the sub- regional scale, Africa is vulnerable to ENSO and related extreme events (droughts, floods, changed patterns) shown by Arnell (1999). An increasing trend in temperature has been noted in recent decades in southern and central India in all seasons and during post monsoon season (Kashyapi, 2008). Bouraoui *et al*. (1999) stated that evidence is mounting that the world is experiencing the period of climate change brought about by increasing atmospheric concentrations of greenhouse gases. Atmospheric carbon dioxide levels have continually increased since the 1950s. The continuation of this phenomenon may significantly alter global and local climate characteristics, including temperature and precipitation. Climate change can have profound effects on the hydrologic cycle through precipitation, evapotranspiration and soil moisture with increasing temperature. The hydrologic cycle will be intensified with more evaporation and more precipitation (Bouraoui *et al.,* 1999). Climate change is expected to amplify climate variability and hence the occurrence of extreme events such as floods and droughts (FAO, 2003). Floods and droughts are typical hydrological extreme events. Globally, evidence indicates that there is strong influence of climate change on the strength and frequency of climate variables such as storms, cyclones, floods and droughts (IPCC, 2007).

The frequency and severity of extreme weather events and natural disasters has increased in the past decades worldwide (Diffenbaugh *et al.,* 2005; Solomon *et al.,* 2007). In Southeast Asia climate change models projected that the region would experience prominent increases in the intensity and/or frequency of extreme events such as tropical cyclones, droughts, floods as well as rising sea levels (ADB, 2009). The increasing frequency and severity of floods and droughts further amplify the water resource tension because these will affect rainy season characteristics.

Although floods are common during the monsoon season, and droughts are common in the summer, climate variability in the past decade has resulted in fluctuating rainfall, which increases the risk of severe droughts and floods in rural Thailand. Changes in rainfall patterns, frequency and intensity of rainfall will result in a higher frequency of severe floods and droughts (Chinvanno *et al*., 2009). This can cause substantial damage, not only to property and human life, but also to the ecosystem, agriculture, and other economic activities, such as food processing and tourism industries that rely heavily on agriculture and natural resources. Bates *et al*. (2008) reported that warming over several decades has been linked to changes in the large-scale water cycle such as increasing atmosphere water vapour content, changing precipitation patterns, intensity and extremes, reduced snow cover and widespread melting of ice, and changes of soil moisture and runoff.

Droughts are the absence of rain, and this grows and retreats in severity at rates paced by the climatological ('normal') precipitation in an area (ISDR, 2006). Floods are often fairy local and develop on short timescale, while droughts are extensive and develop over months or years. The distribution and timing of floods and droughts is most profoundly affected by the cycle of El Nino events, particularly in the tropics and over much of the midlatitudes of pacific-rim countries (Trenberth, 1999). According to statistics from the United Nations, during 1970 - 2005 over 30% of natural disasters were floods and nearly 15% were drought-related (wild fires and extreme high temperatures). During the 30-year period 1980 - 2009, floods accounted for more deaths in the United States while droughts were the main cause of agricultural distress (Torrence and Webster, 1999).

Drought is a normal recurring event that affects the livelihoods of millions of people around the world. Extreme drought in the Limpopo River Basin is a regular phenomenon and has been recorded for more than a century at intervals of 10 - 20 years (Benson and Clay, 1998). Clear cycles of approximately 9 - 10 years below average rain followed by above average rain have been observed in summer rainfall areas in South Africa (Tyson, 1987). For example in the period 1980 - 2000, the Southern African Development Community (SADC) region was struck by four major droughts, notably in the seasons 1982/83, 1987/88, 1991/92 and 1994/95 (FAO, 1994). This corresponds to an average frequency of once every four or five years, although the periodicity of droughts is not necessarily so predictable. FAO (1994) identified three drought cycles in the SADC region during the years 1960 to 1993. In southern Africa, drought occurred in cycles, for example drought occurred in 1800 - 1850, 1840 - 1850, 1895 - 1910, 1921 - 1930, 1930 - 1950, 1967 - 1973, 1981 - 1995 and 2001 - 2007 (Drought Risk Management in Southern Africa, 2011).

Bruwer (1990) stated that South Africa has long been recognized as a country subjected to recurring droughts of varying spatial and temporal dimensions. For example, South Africa experienced drought in early 2004 which led to six provinces, which are Kwazulu Natal, Free state, Northern Cape, Eastern Cape, Mpumalanga and North West being declared disaster zones, with an estimated 15 million people being affected nationwide (IFRC and Red Crescent Societies, 2004). Based on the climate projections for South Africa, Hewitson *et al*. (2005) stated that the most severe drought impacts are likely to occur in the western part, where small towns and subsistence farmers are most vulnerable.

A study done by Gbetibouo, (2009) in Limpopo Basin, on which Luvuvhu is a sub-catchment, shows an increasing trend in temperature mostly in summer. The study showed that the temperature of the Limpopo Province has increased by 1°C over the past fifty years (Gbetibouo, 2009). Regardless of the fact that the above study focused on the whole Limpopo Basin in South Africa, it can also be used as evidence of climate change in the study area. Examples of drought years in LRC include 1980/81 and 1991/92, which were exacerbated by water abstractions, and resulted in the downstream reaches of the river drying up, with the death of large numbers of mature riparian trees, as well as local hippo and crocodiles (Hughes *et al*., 1997). In LRC floods mostly occur after dry periods (Kabanda, 2004). Thus, floods and droughts are common features of the LRC. Floods are associated with extremes in rainfall (from tropical storms, thunderstorms, orographic rainfall, widespread extra tropical cyclones, etc.). Different parts of South Africa experienced floods in the years 1977 and 2000 (Smithers *et al.*, 2001 and Odiyo and Maluleke, 2005). The latter study by Odiyo and Maluleke (2005) has established that these floods were a threat to crops grown in the riparian zone of the Luvuvhu River at Makovha village.

The distribution and timing of droughts and floods is most profoundly affected by the cycle of El Nino events. Limpopo Province has experienced a range of climate related disasters in the past. During the period 2000 - 2009, inhabitants suffered from severe floods (February 2000 and December 2001) and drought in February 2005 (DEA, 2010). Floods in the Limpopo Basin are further complicated by the disparities in climatic and rainfall distribution with most of its catchment area under semi-arid conditions. However, the catchment is occasionally influenced by tropical cyclones that can dump significant amounts of rain causing phenomenal floods in Limpopo River. Thus, it is highly prone to flood disasters. Examples of floods that have occurred in Limpopo basin include 2008, 2001, 2000, 1999, 1997, 1996, 1985 and 1981; these disasters took place in Zambezi, Pungue, Buzi, and Save Rivers in Mozambique (INGC, 2009).

DHI (2005) stated that floods in Limpopo River Basin are caused by heavy rainfall from tropical depression formation as well as cyclone induced rainfall in the catchment area. These disasters were experienced in 2000, 1999, 1996, 1985 and 1981 (DHI, 2005).

2.3 Influence of climate change on rainy season characteristics

The rainfall season over South Africa is unimodal, mainly occurring in the summer months, generally with low precipitation. The overall feature of the mean annual precipitation is that it decreases fairly uniformly westwards from the northern reaches of the Drakensberg Escarpment across the interior plateau (Tennant and Hewitson, 2002). The dates which correspond to the onset of rainy season in South Africa are from mid-October to mid-February (Levey and Jury, 1996). The core rainy season of the Limpopo region occurs from (December - February) (Cook *et al.*, 2004).

The onset (start of rainy season), cessation, Length of Growing Period (LGP), and dry spell are the major rainy season characteristics. Several studies have adopted different definitions for the onset and cessation of the rainy season (Stern *et al.*, 1982; Sivakumar, 1988; Morel, 1992, amongst others). The onset of rainy season, by most agroclimatological definitions (Stern *et al.*, 1982*)* requires as precondition, a certain amount of rainfall over a number of days, complemented by that of a maximum number of dry days within a period of time, following the potential start. Onset of the rainy season over Limpopo Basin has been defined as the date of the first two pentads with at least 25 mm of rainfall, provided this is followed by four pentads within which at least 20 mm of rainfall occurs (Stern *et al*., 1982). This definition is the same as that used by AGRHYMET (1996) and is based on the rainfall needed for successful germination of maize in the first month after planting.

Sivakumar *et al.* (1993) stated that the end of the rainy season corresponds to the date after 15th August, when the soil (able to hold 60 mm of available water) is completely depleted, assuming a daily evaporation rate of 5 mm in central Burkina Faso and central Niger. The date after 1st September, following which no rain occurs for a period of 20 days is also designated as the end of season (Sivakumar *et al*., 1993). According to Traore *et al*. (2000), the cessation of the rainy season occurs after 1st September when a soil (able to hold 80 mm of available water) is depleted up to 4.5 mm, corresponding to 90% of a daily evaporation rate of 5 mm in Burkina Faso, Chad and Niger. All these criteria are particularly adapted to the semi-arid zone (Traore *et al*., 2000). In addition, the onset of rains can be defined as the last day in which rainfall of 25 mm or above has been accumulated over the previous 10 days and at least 20 mm accumulated in the subsequent 20 days (Tadross *et al*., 2005; Hachigonta *et al*., 2008). The end of the rain or cessation is obtained by searching for the last day on which the cumulative 25 mm over 10 days occurs (Tadross *et al*., 2005; Hachigonta *et al*., 2008).

The length of the growing season is the difference between the end of season and the onset (Omotosho *et al*., 2000). FAO (1978) stated that the length of the growing season or growing period (LGS or LGP) is the period (in days) during a year when precipitation exceeds half the potential evapotranspiration (PET). A period required to evapotranspire an assumed 100 mm of water from excess precipitation stored in the soil profile is sometimes added (FAO, 1978). LGP is useful in determining crop cycle lengths and calendars under average conditions. Dry spell is a prolonged period of dry weather. The timing of breaks in rainfall (dry spells) relative to the cropping or plant physiological calendar is of great importance to the eventual yield.

Wet (dry) spell is the number of consecutive days of rain above (below) a prescribed threshold. The distributions of wet (dry) spells appear to exhibit universality. Ocean and land regions which receive ‘‘high’’ rainfall (rainy regions; e.g. India, Amazon, Pacific Ocean) show predominance of 2 - 4 day wet spells. The main contribution to the dry part of the season appears to come from 3 – 4 day spells in the non-rainy regions as opposed to 1 - day dry spells in the rainy regions (Ratan and Venugopal, 2012).

Gornall *et al*. (2010) showed that climate variability which result to late onset of rainfall, high temperatures and increased potential evapotranspiration will make farming systems more highly vulnerable to climate change. Araya and Stroosnijder (2011) asserted that rainfall and rainy season characteristics (onset, dry spells and length of growth production) have significant effects on food production. In most cases, the causes of crop failure in the semi-arid areas of Africa are attributed mainly to dry spells, shorter LGP due to late onset and/or early cessation of rain and decrease in total rain.

Lumsden *et al*. (2009) indicated that for South Africa, key climate variables relate to changes in temperature and rainfall patterns. Sharp increases in temperature are expected, with rates of increase higher in the interior of the country than along the coast (Lumsden *et al*., 2009). With regards to projections of rainfall, an imaginary line divides the country in two. Significant increases in the average annual rainfall are projected for the central and eastern regions (Lumsden *et al*., 2009). Contrasting sharp decreases are expected for the west. More importantly, significant changes in rainfall variability and intensity are projected throughout the country, with consequences for the incidence of floods and droughts (Trenberth, 1999). Rainy season characteristics will be affected by these changes due to the fact that precipitation is intermittent, and the nature of the precipitation, depends greatly on temperature and weather conditions. The latter determines the storms and supply of moisture through winds and surface evaporation, and how it is gathered together to form clouds (Trenberth, 1999).

Long term changes in observed rainfall in South Africa have been noted in a number of studies. Some of these studies were focused on localized areas while others were focused at a national level. Lynch *et al*. (2001) noted a gradual increase in annual rainfall in the Potchefstroom area from 1925 to 1998, while Van Wageningen and Du plessiss (2007) noted a reduction in annual rainfall (with accompanying increase in rainfall intensity) over the latter half of the 20^{th} century at Table Mountain, Cape Town.

Mackellar *et al*. (2007) reported both wetting (central coastal belt, north-eastern areas) and drying (escarpment) over the Namaqualand region during the latter half of the 20^{th} century. At a national level, Richard *et al.* (2001) and Fauchereau *et al*. (2003) noted no overall wetting or drying, but reported an increase in inter-annual rainfall variability during the 20^{th} century. Warburton and Schulze (2005) reported that over the latter half of the 20^{th} century, median annual rainfall decreased markedly over the Limpopo, North-West and into Northern Cape provinces.

2.4 Review of climatic trends studies in South Africa

Mean annual precipitation (MAP) in South Africa is highly variable from year to year, few spatially coherent or statistically significant trends in this quantity have been observed. However, of more relevance than MAP are characteristics of how rainfall is distributed throughout the year. These characteristics include the timing of the onset and end of the rainy season, the typical durations of wet and dry periods and the occurrence of extreme heavy rainfall events. A review by Easterling *et al.* (2000) indicated a tendency for increased extreme precipitation in the southwestern and eastern parts of South Africa during most of the 20^{th} century. The results of Groisman *et al*. (2005) showed a significant increase in the annual frequency of very heavy rainfall events over eastern South Africa from 1906 to 1997. Furthermore, Mason *et al.* (1999) demonstrated increases in the intensity of high rainfall events in the 1961 - 1990 periods relative to 1931 - 1960 over much of South Africa. Kruger (2006) shows increases in extreme rainfall indices over the southern Free State and parts of the Eastern Cape from 1910 to 2004.

New *et al*. (2001) also showed some evidence of increased rainfall extremes over parts of South Africa for the 1961 – 2000 periods. Nel (2009) demonstrated a shift in seasonality for stations in the Kwazulu-Natal (KZN) Drakensberg for 1955 - 2000. The MAP showed no significant trend, but an increase in summer rainfall, accompanied by decreased autumn and winter rainfall, resulted in shorter wet season and a more pronounced season cycle (Nel, 2009). These findings are consistent with results from Thomas *et al*. (2007) for northwest KZN, which showed an increase in early - season rainfall along with a decrease in late-season rainfall between 1950 and 2000. Seasonal shifts were also observed in Limpopo for the same period, where there has been a tendency for a later seasonal rainfall onset accompanied by increased dry spells and fewer rain days (Thomas *et al*., 2007). A trend towards later onset of rainfall in Limpopo between 1979 and 1997 was also identified by Tadross *et al*. (2005) but they noted that this trend is likely part of low-frequency variability rather than, long-term change. Increased dry spell duration is also evident for much of the Free State and Eastern Cape, and decreases in wet spell duration have been observed in parts of the Eastern Cape and north- eastern parts of South Africa during 1910 - 2004 (Tadross *et al*., 2005).

2.5 Types of floods and droughts

2.5.1 Floods

Floods can happen on flat or low-lying areas when the ground is saturated and water either cannot runoff or cannot runoff quickly enough to stop accumulating (Werner *et al*., 2006). Flood can also occur if water falls on an impermeable surface, such as concrete, paving or frozen ground, and cannot rapidly dissipate into the ground. Flood is also an overflow of water that submerges land which is usually dry (Werner *et al*., 2006).

- **River floods**

A river flood occurs when the level of water overtops the river banks, albeit it is a natural or artificially made. However, such an event is not a hazard unless it threatens human life and property (Burby, 2001). For a hydrologist, flood magnitude is best expressed in terms of instantaneous peak river flow (discharge), whilst the hazard potential will relate more to the maximum height (stage), that the water reaches. Flooding along rivers is a natural and inevitable part of life (Burby, 2001).

Overbank flooding of river and streams is the increase in volume of water within a river channel and the overflow of water from the channel onto the adjacent floodplain – represents the classic flooding event that most people associate with the term flood (Alexander *et al*., 1994).

When surface water runoff introduced into streams and rivers exceeds the capacity of the natural or constructed channels to accommodate the flow, water overflows the stream banks, spilling out into adjacent low lying areas. Riverline flooding occurs as a consequence (Alexander *et al*., 1994).

The dynamics of riverline flooding vary with terrain (Ives, 1989). In relatively flat areas, land may stay covered with shallow, slow-moving floodwater for days or even weeks. In hilly and mountainous areas, floods may come minutes after a heavy rain (Ives, 1989). The short notice, large depths, and high velocities of flash floods make these types of floods particularly dangerous. Riverline floodplains range from narrow confined channels (as steep river valleys in hilly and mountainous areas) to wide, flat areas. In the steep narrow valley, flooding usually occurs quickly and is of short duration, but is likely to be rapid and deep. In relatively flat floodplains, areas may remain inundated for days or even weeks, but floodwaters are typically slow-moving and shallow.

- **Coastal flood**

Winds generated from tropical storms and cyclones or intense offshore low-pressure systems, can drive ocean water inland and cause significant flooding in coastal zones or river deltas and floodplains (Abbott, 1996). Coastal flooding can also be produced by sea waves (Abbott, 1996).

Coastal flooding and erosion are serious problems along much of the nation's coasts, although the frequency and magnitude of flooding and severity of the erosion vary considerably (IPCC 1990). They result from storm surges and wave actions. Storm surge is the increase in water surface elevation above normal tide levels due primarily to low barometric pressure and the piling up of waters in coastal areas as a result of wind action over a long stretch of open water (IPCC 1990). Storm surge causes sea levels to rise for a relatively short period of time (typically four to eight hours, though some areas may take much longer to recede to their pre storm levels) – often resulting in extensive coastal flooding that can weaken or destroy coastal structures (Zhang *et al*., 2004).

- **Urban floods**

Urban development creates a number of areas, which cannot absorb natural rainfall, for example: parking lots, roads, building etc (Ramachandra *et al*., 2009). Urbanization increases runoff 2 to 6 times over what would occur on natural terrain (Ramachandra *et al*., 2009).

Urban flooding is the inundation of land or property in a built environment, particularly in more densely populated areas, caused by rainfall over whelming the capacity of drainage systems, such as storm sewers (Carter and Nick, 1991). Although sometimes triggered by events such as flash flooding or snowmelt, urban flooding is a condition, characterized by its repetitive and systemic impact on communities that can happen regardless of whether or not affected communities are located within formally designated floodplains or near a body of water (Carter and Nick, 1991). Urban flooding can lead to chronically wet houses, which are linked to an increase in respiratory problems and other illnesses. Urban flooding also has significant economic implications for affected neighborhoods (Thompson, 1964).

- **Flash floods**

Flash floods occur when an excessive amount of rain falls within a short period of time (in dried upstream and wetlands, river valleys and also urban areas), or when a massive amount of water is suddenly released by dams or the release of blockages in rivers (Abbott, 1996). A flash flood is a rapid flooding of geomorphic low-lying areas: washes, rivers, dry lakes and basins. It may be caused by heavy rain associated with a severe thunderstorm, hurricane, tropical storm, or melt water from ice or snow flowing over ice sheets or snowfields (Weather, 2007). Flash flooding occurs when precipitation falls rapidly on saturated soil or dry soil that has poor absorption ability (Weather, 2007). The runoff collects in gullies and stream and, as they join to form larger volumes, often forms a fast flowing front of water and debris. Flash floods most often occur in normally dry areas that have recently received precipitation, but may be seen anywhere downstream from the source of the precipitation, even many miles from the source (Schmittner and Pierre, 1996).

2.5.2 Droughts

Drought is a normal feature of any climate. Drought has many facets in any single region and it always starts with the lack of precipitation, but may affect soil moisture, streams, groundwater, ecosystem and human beings (Smakhtin, 2001). This leads to the identification of different types of drought (meteorological, agricultural, hydrological and socioeconomic), which reflect the perspectives of different sectors on water shortages. These drought types are in effect different stages (different extremes) of the same natural and recurring process (Smakhtin, 2001).

- **Meteorological drought**

Meteorological drought is defined solely on the degree of dryness expressed as a departure of actual precipitation from an expected average or normal amount based on monthly, seasonal/ or annual time scales (Palmer, 1965). Definitions of meteorological drought must be considered as region-specific since the atmospheric conditions that result in deficiencies of precipitation are highly variable from region to region (Sinha Ray and Shewale, 2000). For example, some definition of meteorological drought identify periods of drought on the basis of the number of days with precipitation less than some specified threshold (Hounam *et al.,* 1975). This measure is only appropriate for regions characterised by a year-round precipitation regime such as a tropical rainforest, humid subtropical climate, or humid mid-latitude climate (Alley, 1984). Meteorological droughts are temporary, recurring disasters, which originate from lack of precipitation and can bring significant economic losses. It is not possible to avoid meteorological droughts, but they can be predicted and monitored, and their adverse impacts can be alleviated (Smakhtin and Hughes, 2004).

Meteorological droughts, only express a deficit of rainfall relative to an expected amount over a given time regardless of association with an activity. This drought happens when dry weather patterns dominate an area. Meteorological drought can begin and end rapidly (Keyantash and Dracup, 2002).

- **Agricultural drought**

Agricultural drought is defined principally in terms of moisture deficiencies relative to water demands of plant life, usually crops (Paulson *et al*., 1991). Plant water demand depends on prevailing weather conditions, biological characteristics of the specific plant, its stage of growth, and the physical and biological properties of the soil (Agricultural Drought Assessment Report, 2012). A good definition of agricultural drought should be able to account for the variable susceptibility of crops during different stages of crop development, from emergence to maturity (Wilhite and Glantz, 1985).

Agricultural drought is specifically related to the availability of rainfall measured against the requirement of crops within the course of growing season (Keyantash and Dracup, 2002). They are therefore short term, encompass the amount as well as the distribution of the rainfall received, and could be described as associated more with the quality rather than the quantity of rainfall. This drought happens when crops become affected (Keyantash and Dracup, 2002).

- **Hydrological drought**

Hydrological drought is related to the effects of precipitation shortfalls on streamflows and reservoir, lake, and groundwater levels (Paulson *et al*., 1991). The frequency and severity of hydrological drought is often defined on a watershed or river basin scale. Although all droughts originate with a deficiency of precipitation, hydrologists are more concerned with how this deficiency plays out through the hydrologic system.

Hydrological droughts are the hydrological system such as soil moisture, streamflow, and groundwater and reservoir levels (Keyantash and Dracup, 2002). Hydrological droughts differ in that they are related to reduction of discharge in rivers and streams as manifestation of sustained, long-term water (rainfall) deficits. This drought occurs when low water supply becomes evident, especially in streams, reservoirs, and groundwater levels, usually after many months of meteorological drought and it takes much longer to develop and then recover (Keyantash and Dracup, 2002).

2.6 Statistical methods used to detect climate change in hydrological data

Change in a data series can occur in numerous ways: for example, gradually (a trend), abruptly (a step – change), or in a more complex form. It may affect the mean, median, variance, autocorrelation, or almost any other aspect to the data. In order to carry out a statistical test, it is necessary to define the null and alternative hypothesis; these are statements that describe what the test is investigating. For example, to test for trend in the mean of a series, the null hypothesis (H_o) would be that there is no change in the mean series and the alternative hypothesis (H_1) would be that the mean is either increasing or decreasing over the time (WMO, 1988).

Climate variability can easily give rise to apparent trends when records are short. These are trends that would be expected to disappear once more data has been collected. Because of climatic variability, records of 30 years or less are almost certainly too short; at least 50 years of record is necessary for climate change detection (Kundzewicz and Robson, 2000). The best way to improve understanding of change is to gather as much information as possible, using for example information about changes in the catchment (land - use, amongst others) (Kundzewicz and Robson, 2000).

There are many approaches that can be used to detect trends and other forms of non- stationarity in hydrological data. In deciding which approach to take it is necessary to be aware of which test procedures are valid (i.e. the data meets the required test assumptions) and which procedures are most useful (likely to correctly find change when it is present).

2.6.1 Parametric methods

Parametric testing procedures are widely used in classical statistics. In parametric testing, it is necessary to assume an underlying distribution for the data (often the normal distribution), and to make assumptions that data observations are independent of one another. For many hydrological series, these assumptions are not appropriate. Parametric tests also assume that the time series data and the errors (deviations from the trend) follow a particular distribution. Most parametric tests are useful as they also quantify the change in the data (e.g. change in mean or gradient of trend). Hydrological series rarely have a normal distribution and there is often temporal dependence in hydrological series; particularly if the time series interval is short (Cavadias, 1992). If parametric techniques are to be used, it may be necessary to (a) transform data so that its distribution is nearly normal and (b) restrict analyses to annual series, for which independence assumptions are acceptable, rather than using the more detailed monthly, daily or hourly flow series (Cavadias, 1992).

Generally speaking parametric methods make more assumptions than non-parametric methods. If those extra assumptions are correct, parametric methods can produce more accurate and precise estimates. They are said to have more statistical power. However, if assumptions are incorrect, parametric methods can be very misleading. For that reason they are often not considered. On the other hand, parametric formulae are often simpler to write down and faster to compute (Geisser and Johnson, 2006).

- **Cumulative deviations and other CUSUM tests**

The cumulative deviation test is a parametric method (Buishad, 1982) that is based on the rescaled cumulative sum of the deviations from the mean. The test is relatively powerful in comparison with other tests (for example, Worsely likelihood ratio test) (Buishad, 1982). This is the change point that occurs towards the centre of the time series. The basic test assumes normally distributed data.

This procedure was implemented by Wayne (2000) for performing a change-point analysis. A cumulative deviation is a technique used to determine an average value for sub group and determine the expected variability about the mean. Cumulative sum (CUSUM) charts are used for performing change point analysis and detection. Change point analysis – an analysis used to determine whether a change has taken place or not.

Procedure

Let X_1, X_2………Xn represent the n data points. The cumulative sums S_0, $S_{1……}S_n$ are calculated iteratively in the following three steps:

1. First calculate the average $\bar{X} = (x_1 + x_2 + x_3 ....x_n)/n$
2. Start the cumulative sum at zero by setting $S_0 = 0$.
3. Calculate the other cumulative sums by adding the difference between the current value and the average to the previous sum.

$$S_i = S_{i-1} + (x_i - \bar{X}) \quad \text{……………………………………………………………….. (2.1)}$$

The cumulative sums are not the cumulative sums of the values. Instead they are the cumulative sums of differences between the values and the average.

A sudden change in the direction of the Cumulative sum (CUSUM) indicates a sudden shift in the average. A period where CUSUM chart follows a relatively straight path indicates a period where the average does not change. Most of the values added to the cumulative sum will be positive and the sum will steadily increase. A segment of the CUSUM chart with an upward slope indicates a period when the values tend to be above the overall average. Likewise a segment with a downward slope indicates a period of time when the values tend to be below the overall average.

To estimate the location of the change point, define m such that:

$$|S_m| = \max_{i=0,\ldots n} |Si| \quad \text{…………………………………………………………………………….. (2.2)}$$

S_m is the point noted furthest from zero in the CUSUM chart. The point m estimates the last point before the occurrence of the change point. The point m+1 estimate the first point after the change. Another estimator that can be used to estimates when the change occurred is the mean square error (MSE) estimator. The MSE (m) is defined as

$$\text{MSE (m)} = \sum_{i=1}^{m} (x_i - \bar{x}_1)^2 + \sum_{i=m+1}^{n} (x_i - \bar{x}_2)^2 \quad \text{……………………………………………………….... (2.3)}$$

Where $\bar{X}_1 = \frac{\sum_{i=1}^{m} x_i}{m}$ and $\bar{X} = \frac{\sum_{i=m+1}^{n} x_i}{n-m}$

The MSE error estimator is based on the idea of splitting the data into two segments 1 to m and m+1 to n, estimating the average of each segment, and then seeing how well the data fits the two estimated averages. The value m that minimises MSE (m) is the best estimator of the last point before the change. The point m+1 estimate the first point after the change.

Advantages of cumulative deviations and other CUSUM tests

1. It is more powerful at detecting smaller sustained change.
2. It better characterises such changes including detection of multiple changes
3. It reduces the number of false detections by controlling the change-wise error rate
4. It is robust to outliers and can be made even more robust by performing a change-point analysis on the ranks.
5. It is more flexible. The same procedure works for all types of data including attribute data, individual values, counts, averages and standard deviations. Further, a change-point analysis can be performed on ill-behaved data like particle counts and complaint data, which do not follow any of the traditional control charting distribution and may contain numerous outliers.
6. It is simpler to use and interpret, especially for large data sets and when multiple changes have occurred.

Disadvantages of CUSUM tests

This method does not detect isolated abnormal points. Change-point analysis should be supplemented with a Shewhart control chart when such points are of concern. Box and Luceno (1997) demonstrated that Shewhart control charts are optimal at detecting isolated abnormal points while CUSUM charts are optimal at detecting shifts of the mean. If one is concerned with both types of changes, both procedures can be used to complement each other.

- **Student's t test**

This is a standard parametric test for testing whether two samples have different means. In its basic form it assumes normally distributed data and a known change – point time. The t test requires that observations area drawn from a normally distributed population and the two – sample t – test requires that the two populations have the same variance (de Winter, 2013). According to Siegel (1956), these assumptions cannot be tested when the sample size is small. The student's t test statistic is (critical test statistic values for various significance levels can be obtained from student's t statistic table):

$$t = \frac{\left(x^{-} - y^{-}\right)}{s\sqrt{\frac{1}{n} + \frac{1}{m}}} \quad \text{(2.4)}$$

Where x^{-} and $\bar{y}$ are the means of the first and second periods, respectively, m and n are the number of observations in the first and second periods, respectively, and s is the sample standard deviation (of the entire m and n observations). For applying the t- test, the series is divided into a number of subseries, and t-test is performed to check whether the statistical character of each subseries is significantly different from that of the original series.

- **Worsley likelihood ratio test**

This method tests whether the means in two parts of a record are different (for an unknown time of change). The test assumes that the data are normally distributed. It is similar to the Cumulative Deviation Test but weights the values of S_k depending on their position in the time series (Kundzewicz and Robson, 2000). This test is designed to detect a change in the mean of a time series. The values of S_k are weighted according to their positions in the time series to form the sequence $Z_{k.}$

$$Z_k = [k(n-k)]^{0.5} S_k$$

$$Z_k = Z_k / D_x$$

The test statistic W is

$$W = \frac{(n-2)^{0.5} V}{(1-V^2)^{0.5}} \quad \text{.......} (2.5)$$

Where $V = \max |Z_k|$

Where n = No. of observations, k = weight assigned, v = any convenient statistic and W = worsley likelihood. Worsley likelihood ratio locates a change point and tests whether the means in the two parts of the data set are statistically different (Kundzewicz and Robson, 2000).

- **Linear regression**

The test statistic for linear regression is the regression gradient. This is one of the most common tests for trend and, in its basic form, assumes that data are normally distributed. Linear regression can be used to describe linear relationships (Sheather, 2009). The setting for this is a bivariate data set (i.e. a list of cases/ subjects for which two variables have been measured for each case) with both variables being quantitative. They use graphs (scatterplots and residual plots), using horizontal axis for explanatory (*x*) variable and the vertical axis for the response (*y*) variable to help discern whether there is, in fact, a linear relationship $y = b_0+b_1x$ between variables. The correlation r provides a quantitative (objective) measure of whether there is such a relationship, with *r* close to ± 1 indicating a strong linear relationship, and $r \sim 0$ indicating little linear relationship (Sheather, 2009).

2.6.2 Non - parametric methods

In non- parametric and distribution – free methods, fewer assumptions about the data need to be made. With such methods it is not necessary to assume a distribution. However, many of these methods still rely on assumptions of independence. More advanced approaches must therefore be used for daily or hourly series. Very useful classes of non-parametric tests are permutation tests.

They are based on changing the order (shuffling) of data points, calculating statistics, and comparing these with the observed test statistics (Cavadias, 1992).

Mann Kendall (MK)

Mann Kendall (MK) test is used to test the trend significance. It is a non-parametric test for identifying trends in time series data. The test compares the relative magnitudes of sample data rather than the data values themselves (Gilbert, 1987). MK is the most common method used in detection of trend in a time series, particularly environmental time series (Kundzewicz and Robson, 2000); the reason being that MK does not require a continuous record, and is suitable for hydrological time series with gaps. This technique has been widely used to test for randomness against trend in climatological time series (Zhang *et al*., 2001).

In the MK test, the null hypothesis H_0 states that the deseasonalised data ($x_{1 \ldots} x_n$) are a sample of n independent and identically distributed random variables (Yu *et al*., 1993). Deseasonalisation of data is done by dividing the mean value of the individual records by the standard deviation (Hisdal and Tallaksen, 2003) in order to remove the increases and decreases in values due to time of the year. The alternative hypothesis H_1 of a two-sided test is that the distribution of x_k and x_j are not identical for all k, j<n with k. The test statistic S is calculated with Equations 2.6 and 2.7.

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \qquad (2.6)$$

$$\operatorname{sgn}(x_j - x_k) = \begin{cases} +1 \; if \; (x_j - x_k) > 0 \\ 0 \; if \; (x_j - x_k) = 0 \\ -1 \; if \; (x_j - x_k) < 0 \end{cases} \qquad (2.7)$$

Which has mean zero and variance of S, computed by

$$\operatorname{Var}(S) = \frac{\left[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5) \right]}{18} \qquad (2.8)$$

Hirsch and Slack (1984), stated that this equation is asymptotically normal, where t is the extent of any given time and $\sum_t$ denotes the summation over all ties. For cases where n is larger than 10, the standard normal variate z is computed by using the following equation (Dougkas *et al*., 2000).

$$Z=\begin{Bmatrix} \frac{s-1}{\sqrt{\operatorname{var}(s)}} \, if \; s>0 \\ 0 \, if \; s=0 \\ \frac{s-1}{\sqrt{\operatorname{var}(s)}} \, if \; s<0 \end{Bmatrix} \quad \text{(2.9)}$$

Thus, in a two-sided test for trend, the H_0 should be accepted if $|z| \leq z_{\alpha/2}$ at the level of significance. A very high positive value of S is an indicator of an increasing trend, and a very low negative value indicates a decreasing trend. Yue and Wang (2002) conducted a study that demonstrated that when a trend exists in a time series, the effect of positive/negative serial correlation on the MK test is dependent on the sample size, magnitude of the serial correlation and magnitude of the trend. When a sample size and magnitude of trend are large enough, the effect of serial correlation no longer significantly affect the MK test.

Many studies that have applied the MK technique have been done in different study areas, including Canada (Burn and Hag Elnur, 2002), Zimbabwe (Chingombe *et al.*, 2005), South Africa (Ndiritu, 2005, Nkuna, 2012, Dagada, 2013 and Odiyo *et al*., 2015), among others. All of them have concluded that MK can be successfully applied in detecting trends in hydro meteorological data, depending on the availability of data. A study by Burn and Hag Elnur (2002) has indicated that some parts of Canada have experienced variations and trends in hydrology. In Southern Africa variations and trends were also found to have occurred in the Mazowe Catchment in Zimbabwe (Chingombe *et al.*, 2005). These were similarly attributed to changes in the meteorological variables (Chingombe *et al*., 2005).

MK has been used by Gilbert (1987) to test for long-term trend analysis of surface insolation and evaporation over selected climate types in India. Gilbert (1987) concluded that the increasing trend in diffuse component was not significant at all the stations except arid and wet-dry tropical climates. Simultaneous reduction in global insolation and atmospheric thermal regime led to substantial reduction in pan evaporation. MK has also been used by Warburton *et al.* (2005) to detect trends in temperature in South Africa using daily records of 51 years long. This technique was able to detect trends in some parts of South Africa. Warburton *et al*. (2005) concluded that there is a change in temperature across South Africa, though it is not uniformly distributed. MK was also used by Liepert (2002) to detect the effect of radiation trend on pan evaporation; the results show that reduction in global insolation and atmospheric thermal regime lead to substantial reduction in pan evaporation. The limitations of this trend test are frequently associated with its own null hypothesis (H_0), which assumes that the data are independently and identically distributed.

Spearman rho (SR)

SR is also a non-parametric statistic test used to detect trends in a time series. This is because SR provides results almost identical to those provided by the MK test (Yue and Wang, 2002). Strength of such non parametric test depends upon pre-assigned significance level, magnitude of trend, sample size and the amount of variation within time series (Yue *et al*., 2002).

Spearman's rho (SR) test has been applied for the detection of trends in many studies such as Gellens (2000), Kahya and Kalayci (2004) and Gadgil and Dhorde (2005). Their results showed the power of SR to detect monotonic trends (Yue and Wang 2004). The SR test is a simple method with uniform power for linear and non-linear trends and is also commonly used to verify the absence of trends (Dahmen and Hall, 1990; Tonkaz *et al*., 2007). The SR test statistic D and the standardized test statistic Z_{SR} are expressed as follows:

$$D = 1- \frac{6\sum_{i=1}^{n}(R_i - i)^2}{n(n^2-1)} \quad \ldots\ldots (2.10)$$

$$Z_{SR} = D\sqrt{\frac{n-2}{1-D^2}} \quad \ldots\ldots (2.11)$$

Where R_i is the rank of i^{th} observation X_i in the time series and n is the length of the time series. Positive values of Z_{SR} indicate upward trends, while negative Z_{SR} indicate downward trends in the time series.

Seasonal Kendall test (SK)

The Seasonal Kendall test (SK) is a version of the Mann – Kendall test that allows for seasonality in the data (Hirch *et al*., 1982). It is the most popular trend test in environmental studies. It was developed by Hirsch, Smith and Slack at the USGS in the 1980s. It is now used throughout the world. It is a nonparametric test which detects monotonic trends, not just linear. SK provides an overall slope (rate of change) and it conducts trend test within each season then combines to form one overall test. SK test statistic is computed by performing a Mann – Kendall calculation for each season, then combining the results for each season. The SK test is highly robust and relatively powerful. The SK statistic is computed as the sum of the S from each season.

$$S_K = \sum_{i=1}^{m} s_i \qquad (2.12)$$

Where s_i is the s from the i^{th} season and m is the number of seasons.

2.7. Review of drought indices

Drought indices are normally continuous functions of rainfall and/or temperature, river discharge or other measurable variables. Rainfall data is widely used to calculate drought indices, because long-term rainfall records are often available. Rainfall data alone may not reflect the spectrum of drought-related conditions, but they can serve as a pragmatic solution in data- poor region (Smakhtin and Hughes, 2004).

- **Palmer drought severity index (PDSI)**

Palmer (1965) developed a soil moisture algorithm (a model) which uses precipitation, temperature data and local available water content (AWC) of the soil. AWC is a 'model parameter', which has to be set at the start of calculations. Calculations result in an index (PDSI), which indicates standardized moisture conditions and allows comparisons to be made between locations and between months. Details of a PDSI calculation may be found in Palmer (1965) and in many subsequent publications (for example, Alley, 1984; Kim *et al*., 2002). PDSI varies roughly between -6.0 to +6.0. More wet conditions are indicated by positive values of PDSI, and more dry conditions are indicated by negative values. Classification of PDSI values is given in (Table 2.1).

Table 2.1: Ranges of drought using PDSI

PDSI	Condition	PDSI	Condition
4.0 or more	Extremely wet	0.49 to -0.49	Near normal
3.0 to 3.99	Very wet	-0.5 to -0.99	Incipient dry spell
2.0 to 2.99	Moderately wet	-1.0 to 1.99	Mild drought
1.0 to 1.99	Slightly wet	-2.0 to -2.99	Moderate drought
0.5 to 0.99	Incipient wet spell	-3.0 to -3.99	Severe drought
		-4.0 or less	Extreme drought

PDSI values are normally calculated on a monthly basis. Further interpretation of monthly PDSI allows drought duration to be taken into account as well. A drought sequence is interpreted as a sequence of three or more consecutive months with a PDSI value ≤ -2.0. A series of six or more months is a major drought event. The end of a drought sequence is taken as the last month where the PDSI is ≤ -2.0. Kogan (1995) suggested that PDSI had little acceptance except in the USA. Tests in other countries (for example, Du pisani, 1990; Bruwer, 1990) found PDSI to be poor indication of short-term (e.g., periods of several weeks) changes in moisture status affecting crops and farming operations. Some of the limitations of PDSI (for example, sensitivity to AWC, arbitrary thresholds, no account of river flow, liquid precipitation only, amongst others) may be overcome by appropriate modifications of the calculation procedures (Du pisani, 1990; Bruwer, 1990). However, PDSI values may lag behind emerging droughts by several months (Alley, 1984). This limits its application in areas of frequent climatic extremes, like Southwest Asia, where large areas are dominated by monsoonal climates, for example. Also the major problem associated with PDSI is that its computation is complex and requires substantial input of meteorological data. PDSI is used for a quantitative description of droughts and wet periods (Alley, 1984). PDSI can determine the beginning and end of drought or a wet spell (Alley, 1984). Thus, it can be used to determine drought cycles.

- **Standardized precipitation index (SPI)**

SPI was developed in Colorado by McKee *et al*. (1993) and is based just on precipitation and, therefore requires less input data and calculation effort than PDSI. A long-term precipitation record at the desired station is fitted to a probability distribution (e.g. gamma distribution), which is then transformed into a normal distribution so that the mean SPI is zero (Edwards and McKee, 1997). SPI may be computed with different time steps (for example 1 month, 3 month…., 48 month) and is reported to be able to identify emerging drought sooner than the palmer index. The use of different time scales under the umbrella of the same index allows the effects of a precipitation deficit on different water-resources components (groundwater, reservoir, and soil moisture, streamflow) to be assessed.

Positive SPI values indicate greater than mean precipitation and negative values indicate less than mean precipitation. Similarly, to the PDSI, SPI may be used for monitoring both dry and wet conditions (McKee *et al*., 1993). A drought event starts when SPI value reaches -1.0 and ends when SPI becomes positive again. The positive sum of the SPI for all the months within a drought event is referred to as drought magnitude. To date, SPI is finding more applications in Southwest Asia than other drought indices due to its limited input data requirements, flexibility and simplicity of calculations. SPI has become a popular measure of drought across the globe. SPI can be used in annual period of time to survey on drought. Also it can be used in zonation frequency of drought (McKee *et al*., 1993). SPI can be used to determine drought and flood cycles. It measures meteorological flood and drought and uses only precipitation. SPI can determine whether a specific year of an area is a flood or a drought year when compared with historical records (McKee *et al*., 1993). It compares the precipitation of a year with historical records and uses probabilities to indicate if the precipitation of the year is greater or less than the median precipitation of the historical records (Hayes *et al*., 1999). The SPI was designed to quantify the precipitation deficit for multiple timescales. These timescales reflect the impact of drought on the availability of the different water resources (McKee *et al*., 1993). This shows how SPI can be used to determine drought cycles.

Table 2.2: Ranges of drought using SPI

2.0+	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to 1.99	Moderately dry
-1.5 to -1.99	Severely dry
-2 and less	Extremely dry

CHAPTER THREE: METHODOLOGY

3.1 Preamble

This chapter highlights the types of data required in this study, and where and how the data was collected. It also describes data analysis methods that were used to achieve the objectives of the study.

3.2 Data collection

3.2.1 Temperature data

Maximum and minimum temperature data were obtained from the Water Research Commission (WRC) temperature data base (Schulze and Maharaj, 2003), which consists of quality controlled daily temperatures from the South African Weather Services (SAWS). Temperature stations in the LRC are mostly centered around the upper reaches. As a result, three stations with consistent records from each other were selected. Their details are in Table 3.1. These include 0723485 W (Levubu), 0723664 6 (Thohoyandou) and 0766628 W (Tshivhase). This data was used to show or confirm if there is climate variability in the study area. Figure 3.1 shows the distribution of temperature, streamflow and rainfall stations in LRC.

Table 3.1: Temperature stations in the study area

Station number	Station name	Latitude (◦S)	Longitude (◦E)	Altitude (m)	Start year	End year	Record length (years)
0723485 W	Levubu	-23.094	30.29	1130	1952	2013	61
0723664 6	Thohoyandou	-22.96	30.47	1250	1952	2013	61
0766628 W	Tshivhase	-22.97	30.48	610	1952	2013	61

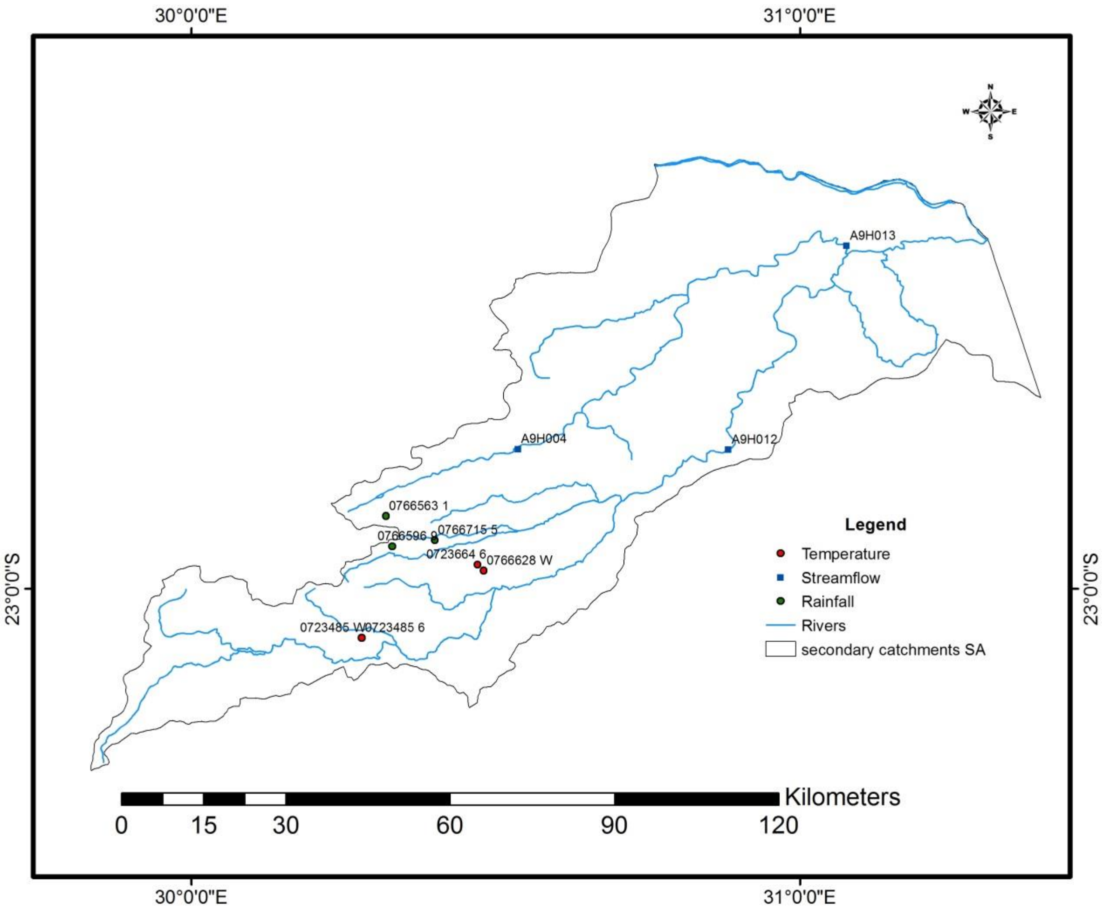

Figure 3.1: Temperature, streamflow and rainfall stations in the LRC

3.2.2 Rainfall data

The study area has quite a number of rainfall stations, and rainfall data from these stations was obtained from SAWS. The stations that were selected were the ones with long term data (Table 3.2 and Figure. 3.1). The record length of rainfall data that was used was from 1952 - 2013 years. Rainfall data was used for climate variability detection and to determine the onset, duration and cessation of the rainy season. Rainfall data was also used for determination of flood and drought cycles.

Table 3.2: Rainfall stations in the study area

Station number	Station name	Latitude (◦S)	Longitude (◦E)	Altitude (m)	Start year	End year	Record length (years)
0766596 9	Vondo	-22.93	30.33	1130	1964	2013	49
0766563 1	Thathe Vondo	-22.88	30.32	1250	1963	2000	37
0723485 6	Levubu	-23.08	30.28	610	1952	2013	61
0766715 5	Mukumbani	-22.92	30.40	811	1986	2013	27

3.2.3 Streamflow data

Streamflow data was obtained from the Department of Water and Sanitation (DWS) of South Africa. The streamflow gauging stations that were selected should have data for a period of at least 50 years. Due to climatic variability, records of 30 years or less are almost certainly too short; at least 50 years of record is necessary for climate change detection (Kundzewicz and Robson, 2000). The distribution of streamflow gauging stations in the study area is displayed in Table 3.3 and Figure 3.1. Streamflow data was used for climate change detection in order to compare the trends obtained from both rainfall and streamflow data.

Table 3.3: Streamflow stations in the study area

Station number	Station Name	Latitude ($^{\circ}_{S}$)	Longitude ($^{\circ}_{E}$)	Start year	End year	Record length (years)
A9H004	Mutale	22.771	30.5389	1933	2004	71
A9H012	Mhinga	22.69	30.889	1987	2004	17
A9H013	Mutale	22.437	31.077	1913	2006	93

3.3 Data analysis methods

3.3.1 Detection of climate change

- **Mann Kendall test and linear regression**

A non-parametric method, Mann Kendall, test described in sub – section 2.8.2 was used to detect changes in temperature, rainfall and streamflow data. A parametric method which is linear regression was also used to detect trends in temperature, rainfall and streamflow data. Minimum and maximum temperatures, rainfall and streamflow data were used for trend analysis. Mann Kendall test was run using XLSTAT which is an add – in component of Excel Spreadsheet. Linear regression was conducted in Excel spread sheet. The trends were tested at a significance level (α) of 5%.

3.3.2 Determination of onset, cessation and duration of the rainfall

The onset and cessation of rainfall were defined following Tadross *et al*. (2005) and Hachigonta *et al*. (2008). These definitions were selected because they only depend on rainfall to detect onset, cessation and duration, whereas other methods require soil moisture and evaporation. There was no long term soil moisture data in the study area that could aid in defining onset and cessation of rainfall. The length or duration of the rainy season was obtained by counting the number of days between onset to cessation. Mean variability of onset, cessation and duration of rainfall were determined using mean and standard deviation.

3.3.3 Determination of flood and drought cycles

SPI model was used to determine flood and drought cycles. Long-term rainfall records for a period of 61 years for similar stations used for MK and linear regression analyses were used. The long-term rainfall records were fitted to a probability distribution, which was then transformed into a normal distribution so that the mean SPI for the location and desired period was zero. SPI – 6 which presents time scale of 6 months from October to March of the following year, was selected for the study to capture rainfall departures in the wet/rainy season and allow appropriate determination of flood and drought cycles. A drought event was considered to occur any time the SPI was continuously negative and reaches an intensity of -1.0 or less. The event ends when the SPI becomes positive (WMO, 2012). Floods were considered to occur anytime when the SPI was continuously positive and reaches an intensity of 2.0 or more following WMO (2012). Thus, hydrological years with SPI below zero were considered as dry years while those above zero were considered as wet years. The reason for selecting this SPI was because this model requires less input and is effective to check emerging droughts and floods. SPI compared the precipitation of a year with historical records and it used probabilities to indicate if the precipitation of the year was greater or less than the median precipitation of the historical records. The standardization procedure was used to transform rainfall data in order to come up with standardized anomalies using Equation 3.1.

$$Z = \frac{x_i - \bar{x}}{\sigma} \quad \text{...} (3.1)$$

Where, $\bar{x}$ = sample mean, Z = normalized standardised departure, x_i = rainfall value

σ = sample standard deviation

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Preamble

This chapter presents the results obtained from the analyzed data using the methods highlighted in chapter three. The Mann Kendall (MK) method was used to detect trend in temperature data, rainfall data and streamflow data.

4.2 Detection of climate variability using Mann Kendall test and linear regression

Table 4.1 presents MK test results for all temperature stations for both minimum and maximum temperatures at a significance level (α) of 5% (Table 4.1). Data used in Mann Kendall and linear regression is presented in Appendix A1 to A13. In stations 0723485 W, 0723664 6 and 0766628 W, MK method detected values of 750, 398 and 434 for maximum temperatures while the values for minimum temperatures were 645, 213 and 710 for all stations, respectively (Table 4.1). Positive MK values show significant increasing positive trends (Yue and Wang, 2002). The trend test revealed that there were significant increasing trends for maximum and minimum temperatures in stations 0723485 W, 0723664 6 and 0766628 W. The results obtained from LR also showed increasing trends in all stations for both minimum and maximum temperatures (see Figures 4.1 and 4.2). Gbetibouo (2009) reported that Limpopo Province has experienced increased temperature by 1°C over the past fifty years. Nkuna *et al.* (2011) and Dagada (2013) also showed increasing temperature trends in the study area.

Table 4.1: MK results for maximum and minimum temperatures for stations considered in the area of study

Station name	Mann Kendall Statistic for maximum temperature	Direction of trend	Mann Kendall Statistic for minimum temperature	Direction of trend	Significance
0723485 W	750	Increasing	645	Increasing	Significant
0723664 6	398	Increasing	213	Increasing	Significant
0766628 W	434	Increasing	710	Increasing	Significant

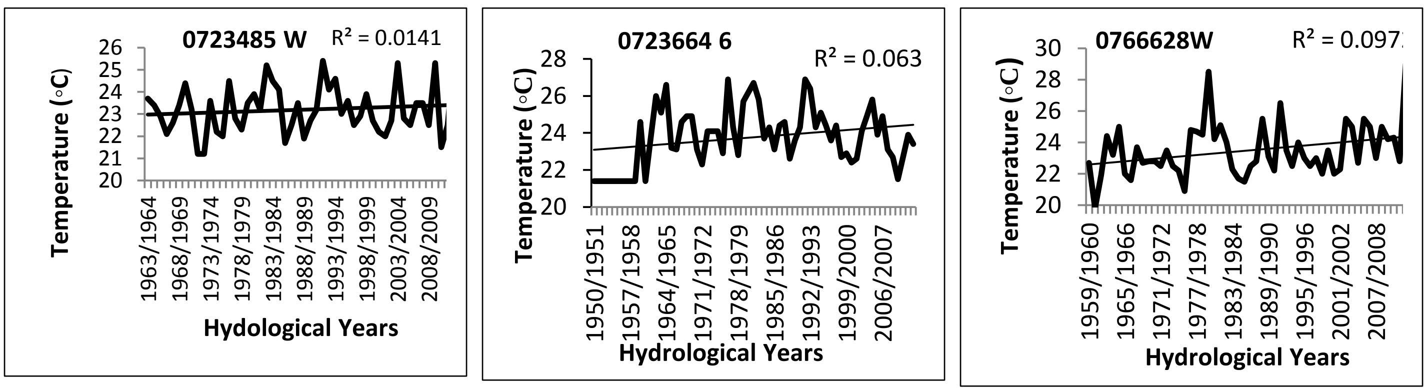

Figure 4.1: Linear regression for minimum temperatures

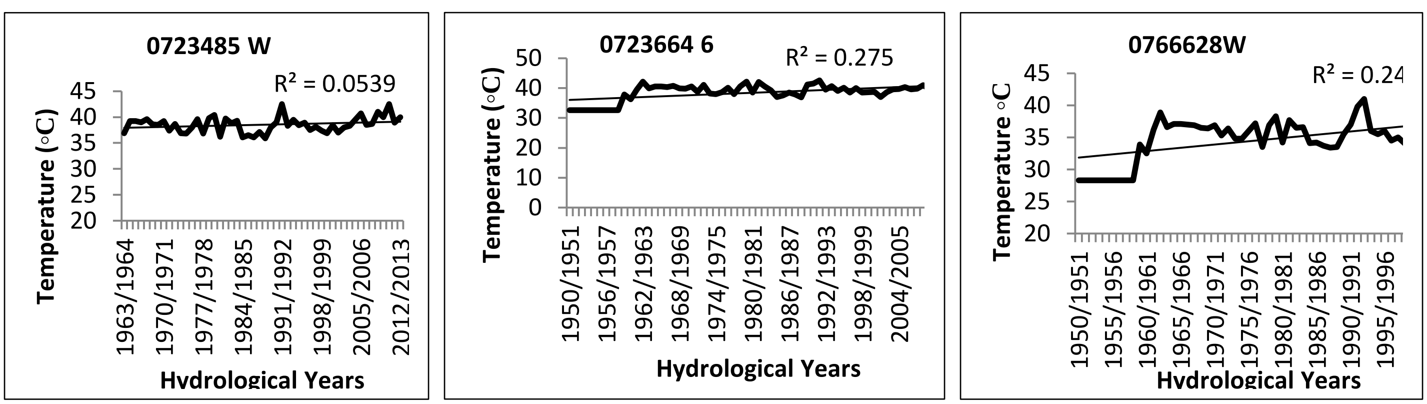

Figure 4.2: Linear regression for maximum temperatures

In rainfall stations, 0766596 9, 0766563 1, 0723485 6 and 0766715 5 MK method detected values of 198, 80, -184 and -56, respectively, with α of 5% in all stations (Table 4.2). MK results showed significant increasing trend for stations 0766596 9 and 0766563 1 and this implies that rainfall was increasing in these stations whereas station 0723485 6 and 0766715 5 showed significant decreasing trend which implies that rainfall was decreasing in these stations. A study by Yue and Wang (2002) showed that negative MK values indicate decreasing trends. Similarly, the results obtained through linear regression also showed an increasing trend in stations 0766596 9 and 0766563 1 whereas in stations 0723485 6 and 0766715 5 decreasing trends were detected (see Figure 4.3). The differences in the rainfall trends may be attributed to spatial variability of climate within the LRC. The consistency in the trends obtained from MK and LR verified the results obtained in the current study.

Table 4.2: MK results for rainfall stations

Station name	Mann Kendall	Direction of trend	Significance
0766596 9	198	Increasing	Significant
0766563 1	80	Increasing	Significant
0723485 6	-184	Decreasing	Significant
0766715 5	-56	Decreasing	Significant

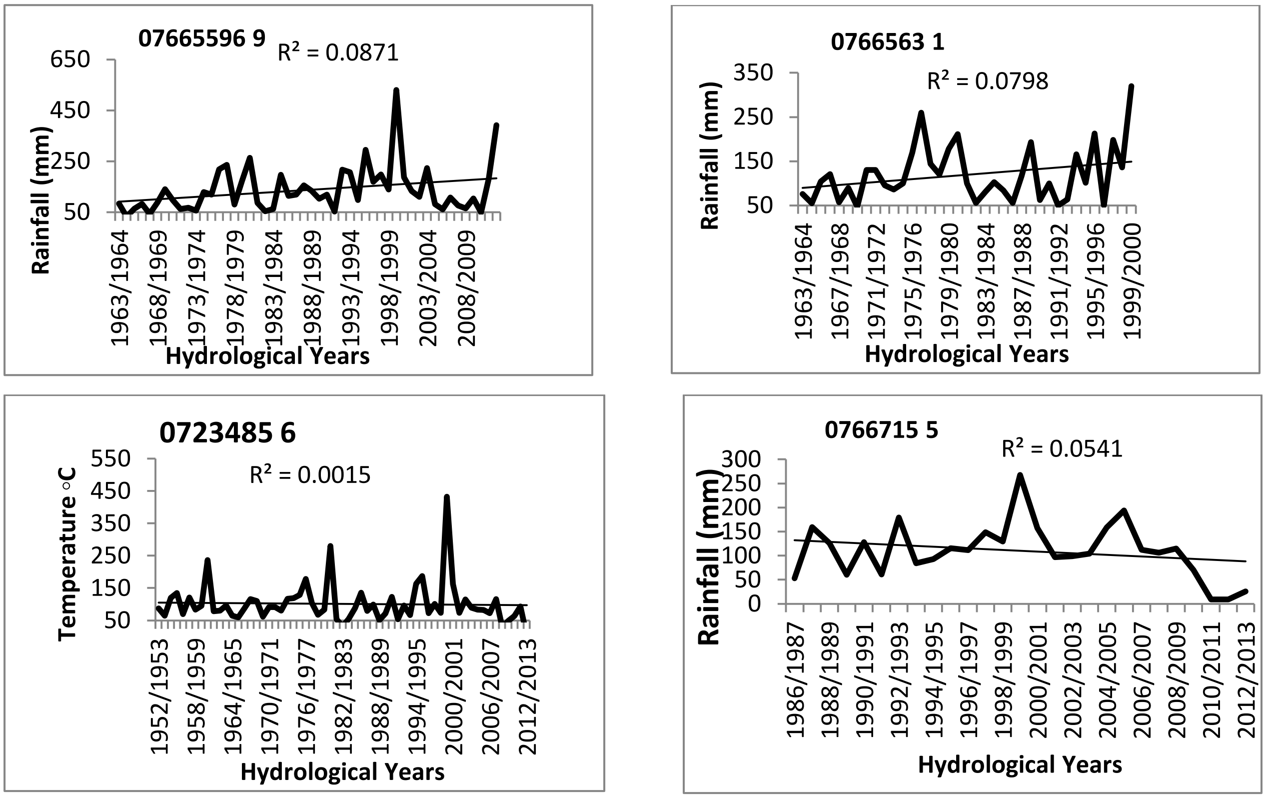

Figure 4.3: Linear regression for rainfall stations

Stations 0766596 9 and 0766563 1 are located at high altitudes of 1130 and 1250 m, respectively, (Table 3.2), within the Soutpansberg Mountains. These constitute some of the areas where highest rainfall occurs within the Soutpansberg Mountains (Odiyo *et al.*, 2015). Thus, the increasing trends may be associated with high rainfall received in this area. Decreasing rainfall in stations 0723485 6 and 0766715 5 may be associated with climate variability influencing drought. Climate variability amplify occurrence of extreme events such as floods and droughts (FAO, 2003). Nenwiini and Kabanda (2013) studied trends and variability assessment of rainfall using data for the period 1970 - 2009 in Vhembe District where the study area is also found. The study also identified increasing and decreasing rainfall trends in stations 0766596 9 and 0723485 6, respectively. The study concluded that a continuous decrease in rainfall can be explained by lack of strong local influences on rainfall formation like vegetation on mountains. Climate variability effects at global to local scale might also be playing a role. The findings of the study by Nenwiini and Kabanda (2013) are similar to the current study. This, thus, further validates the findings of this study.

In streamflow stations A9H004, A9H012 and A9H013, MK method detected values 267, 14 and 207, respectively, with a significance level of 5% in all stations (Table 4.3). These values imply that these stations experienced increased streamflow. Similarly, the results obtained through linear regression also showed significant increasing trends in all stations (see Figure 4.4).

Table 4.3: MK results for streamflow stations

Station name	Mann Kendall	Direction of trend	Significance level
A9H004	267	Increasing	Significant
A9H012	14	Increasing	Significant
A9H013	207	Increasing	Significant

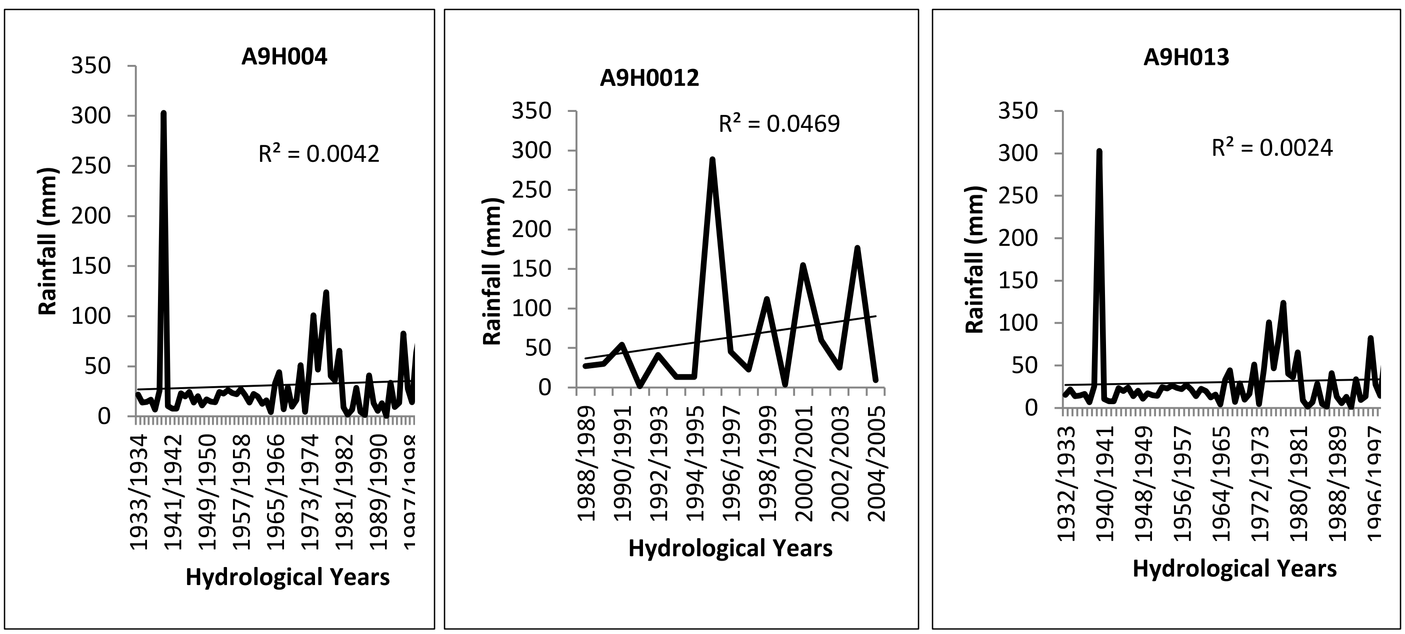

Figure 4.4: Linear regression for streamflow stations

4.3 Standardized precipitation index (SPI) for determining floods and drought cycles

Figures 4.5 to 4.8 show SPI results for the rainfall stations in the study area and a summary of the classification of hydrological years, as per the classifications given in Tables 4.4 to 4.7, is provided in Table 2.2. Some climate extreme phenomenona have been observed in Luvuvhu River Catchment (LRC). Out of the many reflections of those events, precipitation extremes are usually associated with physical and then socio economic damages whenever they occur. The occurrence of those events results in damaging floods and severe drought of different types. The most notable occurrences of precipitation extremes in LRC are related to droughts but some years experience extreme wet events causing different types of floods. For example, extreme cycles of precipitation deficit were observed on SPI-6 time scale in station 0766596 9 (Table 4.4), with the results clearly illustrating that the years 1964/1965 and 1973/1974 were characterized by severely dry conditions while 1992/1993 was extremely dry. This could be due to decreasing trend of annual rainfall. The long term precipitation analysis based on SPI for the same station showed that there has been moderately wet, very wet and extremely wet years which included 1985/1986, 1988/1989, 1999/2000, 2001/2002, 1977/1978, 1978/1979, 1996/1997, 2000/2001 (Table 4.4).

In stations 0766563 1 and 0766596 9 the SPI-6 time scale detected that wet years dominated during the period of study (Tables 4.4 and 4.5). This indicates the shift towards the wet conditions within the vicinity of the stations. The results on the long term precipitation analysis based on SPI showed that there have been more wet years. Examples include the years 1996/1997, 2000/2001 (Table 4.4) and 1977/1978, 1996/1997 (Table 4.5).

In stations 0766715 5and 0723485 6 the SPI-6 time scale detected that dry years dominated during the period of study (Tables 4.6 and 4.7). This indicates the shift towards the dry conditions within the vicinity of the stations. The results on the long term precipitation analysis based on SPI showed that there have been more dry years. Examples include the years 2010/2011, 2012/2013 (Table 4.6) and 1977/1978, 1996/1997 (Table 4.7). Due to climate variability parts of LRC are experiencing wet conditions while others are experiencing dry conditions. A study by Arnell (2004) has indicated that climate change is contributing to frequent occurrence of extreme rainfall events including floods and droughts in Limpopo Province.

Table 4.4: SPI results for 0766596 9 (Vondo) station

Year	SPI	Condition	Year	SPI	Condition
1964/1965	-1.76	Severely dry	1991/1992	0.64	Near normal
1965/1966	-1.08	Moderately dry	1992/1993	-2.05	Extremely dry
1966/1967	-0.45	Near normal	1993/1994	0.78	Near normal
1967/1968	-0.05	Near normal	1994/1995	0.48	Near normal
1968/1969	-1.04	Moderately dry	1995/1996	-0.50	Near normal
1969/1970	-0.26	Near normal	1996/1997	2.00	Extremely wet
1970/1971	-1.23	Moderately dry	1997/1998	0.03	Near normal
1971/1972	-0.83	Near normal	1998/1999	-0.22	Near normal
1972/1973	-0.23	Near normal	1999/2000	1.09	Moderately wet
1973/1974	-1.49	Severely dry	2000/2001	2.67	Extremely wet
1974/1975	-0.17	Near normal	2001/2002	1.21	Moderately wet
1975/1976	1.00	Moderately dry	2002/2003	0.11	Near normal
1976/1977	0.90	Near normal	2003/2004	-0.29	Near normal
1977/1978	1.85	Very wet	2004/2005	0.73	Near normal
1978/1979	1.98	Very wet	2005/2006	-0.78	Near normal
1979/1980	-0.11	Near normal	2006/2007	0.17	Near normal
1980/1981	0.81	Near normal	2007/2008	-0.23	Near normal
1981/1982	0.64	Near normal	2008/2009	0.20	Near normal
1982/1983	-0.30	Near normal	2009/2010	-0.50	Near normal
1983/1984	-0.93	Near normal	2010/2011	-0.08	Near normal
1984/1985	-0.41	Near normal	2011/2012	-1.34	Moderately dry
1985/1986	1.08	Moderately wet	2012/2013	-1.10	Moderately dry
1986/1987	-0.49	Near normal	2013/2014	-0.33	Near normal
1987/1988	-0.80	Near normal			
1988/1989 1.34		Moderately wet			
1989/1990 -0.47		Near normal			
1990/1991 -0.24		Near normal			

Table 4.5: SPI results for 0766563 1 (Thathe) station

Year	SPI	Condition	Year	SPI	Condition
1964/1965	-0.43	Near normal	1983/1984	-0.83	Near normal
1965/1966	-0.29	Near normal	1984/1985	-0.42	Near normal
1966/1967	0.26	Near normal	1985/1986	0.41	Near normal
1967/1968	0.58	Near normal	1986/1987	-0.41	Near normal
1968/1969	-0.25	Near normal	1987/1988	-0.94	Near normal
1969/1970	0.25	Near normal	1988/1989	1.23	Moderately wet
1970/1971	-1.01	Moderately dry	1989/1990	0.47	Near normal
1971/1972	0.25	Near normal	1990/1991	-0.12	Near normal
1972/1973	0.82	Near normal	1991/1992	0.20	Near normal
1973/1974	-0.91	Near normal	1992/1993	-1.93	Severely dry
1974/1975	0.35	Near normal	1993/1994	-1.92	Severely dry
1975/1976	-0.11	Near normal	1994/1995	-0.17	Near normal
1976/1977	1.29	Moderately wet	1995/1996	-0.47	Near normal
1977/1978	2.28	Extremely wet	1996/1997	2.14	Extremely wet
1978/1979	1.18	Very wet	1997/1998	-1.23	Moderately dry
1979/1980	-0.09	Near normal	1998/1999	-0.59	Near normal
1980/1981	-0.16	Near normal	1999/2000	0.39	Near normal
1981/1982	0.60	Near normal	2000/2001	0.83	Near normal
1982/1983	-0.47	Near normal			

Table 4.6: SPI results for 0766715 5 (Mukumbani) station

Year	SPI	Condition
1987/1988	-0.41	Near normal
1988/1989	0.63	Near normal
1989/1990	0.04	Near normal
1990/1991	0.10	Near normal
1991/1992	0.89	Near normal
1992/1993	-0.82	Near normal
1993/1994	0.93	Near normal
1994/1995	0.11	Near normal
1995/1996	-0.74	Near normal
1996/1997	0.81	Near normal
1997/1998	-1.45	Moderately dry
1998/1999	0.12	Near normal
1999/2000	0.82	Near normal
2000/2001	2.38	Extremely wet
2001/2002	0.92	Near normal
2002/2003	0.54	Near normal
2003/2004	-0.22	Near normal
2004/2005	0.49	Near normal
2005/2006	-0.49	Near normal
2006/2007	1.01	Moderately wet
2007/2008	-0.21	Near normal
2008/2009	0.62	Near normal
2009/2010	0.34	Near normal
2010/2011	-1.15	Moderately dry
2011/2012	-1.45	Moderately dry
2012/2013	-1.40	Moderately dry
2013/2014	-1.16	Moderately dry

Table 4.7: SPI results for 0723485 6 (Levubu) station

Year	SPI	Condition	Year	SPI	Condition	Year	SPI	Condition
1953/1954	-1.42	Moderately dry	1975/1976	0.79	Near normal	1997/1998	0.25	Near normal
1954/1955	-0.10	Near normal	1976/1977	1.16	Moderately wet	1998/1999	-0.13	Near normal
1955/1956	-0.27	Near normal	1977/1978	1.35	Moderately wet	1999/2000	0.99	Near normal
1956/1957	0.83	Near normal	1978/1979	1.38	Moderately wet	2000/2001	2.10	Extremely wet
1957/1958	0.08	Near normal	1979/1980	0.00	Near normal	2001/2002	0.62	Near normal
1958/1959	0.57	Near normal	1980/1981	0.61	Near normal	2002/2003	0.32	Near normal
1959/1960	0.32	Near normal	1981/1982	1.45	Moderately wet	2003/2004	-0.26	Near normal
1960/1961	-0.07	Near normal	1982/1983	-0.63	Near normal	2004/2005	0.71	Near normal
1961/1962	1.05	Moderately wet	1983/1984	-0.95	Near normal	2005/2006	-0.50	Near normal
1962/1963	-0.29	Near normal	1984/1985	-0.57	Near normal	2006/2007	0.90	Near normal
1963/1964	-2.13	Extremely dry	1985/1986	0.39	Near normal	2007/2008	-0.97	Near normal
1964/1965	-2.13	Extremely dry	1986/1987	-0.49	Near normal	2008/2009	0.65	Near normal
1965/1966	-0.39	Near normal	1987/1988	-0.10	Near normal	2009/2010	-1.52	Severely dry
1966/1967	0.06	Near normal	1988/1989	0.80	Near normal	2010/2011	-0.70	Near normal
1967/1968	0.69	Near normal	1989/1990	-0.31	Near normal	2011/2012	-0.88	Near normal
1968/1969	-0.29	Near normal	1990/1991	-0.06	Near normal	2012/2013	-0.38	Near normal
1969/1970	0.74	Near normal	1991/1992	0.60	Near normal	2013/2014	-2.14	Extremely dry
1970/1971	-0.35	Near normal	1992/1993	-1.25	Moderately dry			
1971/1972	-0.17	Near normal	1993/1994	0.43	Near normal			
1972/1973	1.10	Moderately wet	1994/1995	0.00	Near normal			
1973/1974	-0.23	Near normal	1995/1996	0.20	Near normal			
1974/1975	0.48	Near normal	1996/1997	1.30	Moderately wet			

Table 4.8 gives an indication of dry and wet cycles in the study area. The dry cycles ranged from 1 – 12, 1 – 4, 1 – 4 and 1 – 5 years in stations 0766596 9, 0766563 1, 0766715 5 and 0723485 6, respectively. Most of the dry cycles are below the range of 9 – 10 years which was identified by Tyson 1987. Tyson (1987) noted cycles of 9 – 10 years of below average rainfall in South Africa. Benson and Clay (1998) reported that extreme drought in Limpopo River Basin has interval of 10 – 20 years. Most of the dry cycles are below the range of 9 – 10 years which shows the increase in frequency of dry conditions which may be attributed to increase in temperature trends as identified in the current study. As it has been observed in many places worldwide that when warming accelerates, land- surface drying occurs due to evaporation of moisture, and this increases the potential incidence of severity of drought (Groisman and Knight, 2008). The wet cycles ranged from 1 – 4, 1 – 3, 1 – 5 and 1 – 8 years in stations 0766596 9, 0766563 1, 0766715 5 and 0723485 6, respectively.

Table 4.9 shows the frequency of hydrological years with SPI-6 values < -1 and > 1 for dry and wet years, respectively. These have been classified either as moderately, severely and extremely dry or, moderately, very and extremely wet in Table 2.2. This analysis provides more details on dominance of distinctively dry or wet conditions for a rainy season at a particular station. These are likely to have more impacts as compared to near normal conditions. It is only station 0766715 5 which had high frequency of dry years indicating that the rainy season is mostly characterized by dry conditions (Table 4.9). Station 0766596 9 had equal number of dry and wet years while 0723485 6 and 0766563 1 had more wet years.

It is important to note it is difficult to compare the SPI results and those obtained from MK and LR trend analysis. This is because MK and LR analysis were based on total annual rainfall for each hydrological year. In addition the MK result for each station is a single value which indicates an overall trend for the entire period of study. In contrast, SPI analysis were based on rainfall data for the wet season (October-March) and thus its analysis are more focused on the rainfall behaviour during wet season of each hydrological year in record. SPI-6 gives an indication of the amount of rainfall received in a particular rainy season (WMO, 2012). This means that the seasonal analysis from SPI gives results which differ from those based on annual data (MK and LR results.

Table 4.8: Dry and wet cycles

Station	Dry cycle (Years)	Wet cycle (Years)
0766596 9	12	3
	1	2
	3	1
	2	1
	2	1
	1	2
	1	2
	1	4
	1	1
	1	1
	1	1
	5	1
0766563 1	2	2
	1	1
	1	2
	1	1
	1	3
	2	1
	3	1
	2	2
	1	1
	4	1
	2	2
0766715 5	1	4
	1	2
	1	1
	1	5
	1	1
	1	1
	1	2
	4	-
0723485 6	3	4
	1	1
	4	2
	1	1
	2	1
	1	8
	3	1
	2	1
	2	1
	1	5
	1	4
	1	1
	1	1
	1	1
	5	-

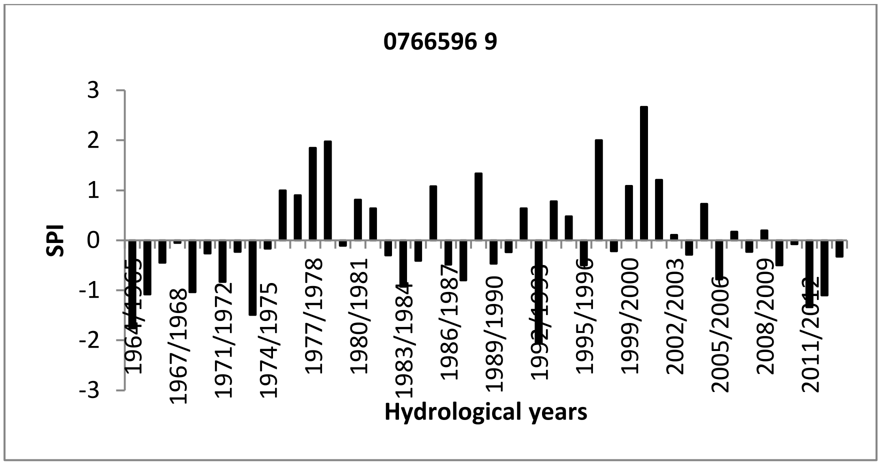

Figure 4.5: SPI cycles for all rainfall station 0766596 9

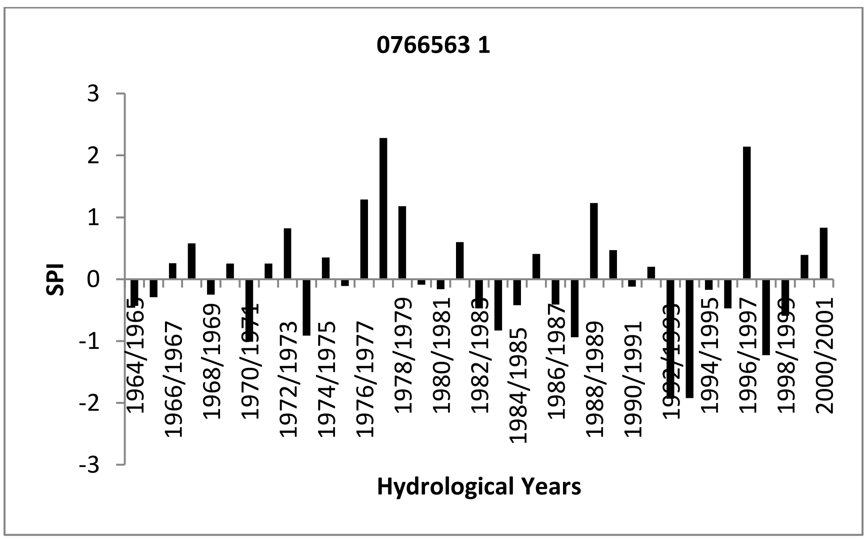

Figure 4.6: SPI cycles for all rainfall station 0766563 1

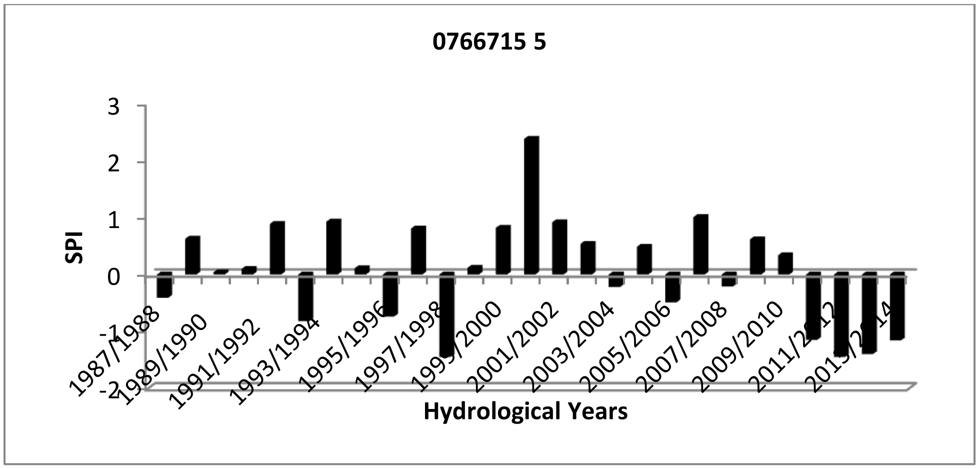

Figure 4.7: SPI cycles for all rainfall station 0766715 5

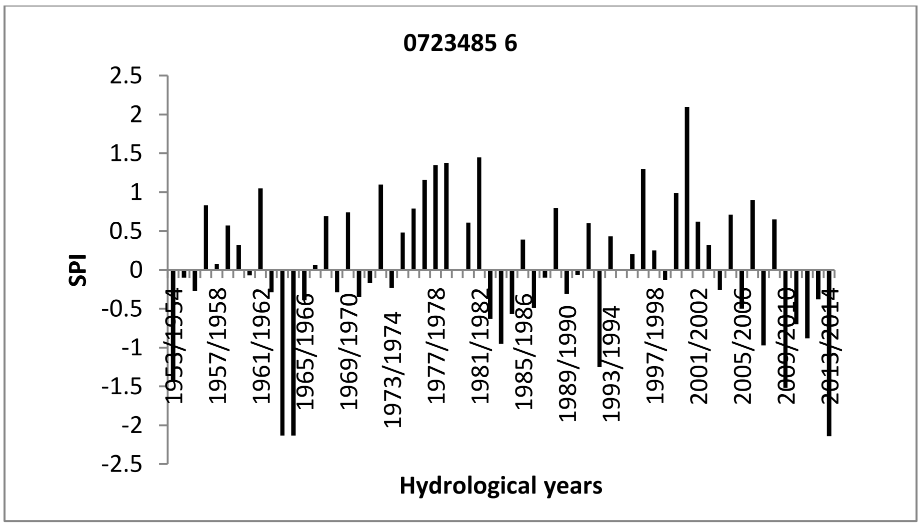

Figure 4.8: SPI cycles for 0723485 6

Table 4.9: Frequency of occurrence of dry and wet years

Station	Dry	Wet
0766596 9	8	8
0766563 1	4	5
0766715 5	6	2
0723485	6	8

4.4 Computed onset, cessation and duration of rainfall

Computed onsets, duration and cessation for all stations are presented in Appendix B1 to B4. Their mean and standard deviations are in Table 4.13. Mean onset of rainfall varied from day 255 to 297, with station 0766715 5 showing the earliest onset compared to the rest of the stations (Table 4.13). Days 255 and 297 correspond to 12 September and 25 October of the year, respectively. The results show that rainfall started in October for 3 of the 4 rainfall stations. Reason *et al.* (2005) noted mean onset ranging from 23–27 October in Limpopo region of southern Africa calculated over the 1979/80–2001/02 summers. A study by Moeletsi (2010) showed the earliest onsets occurring between 20 September and 10 October in Free State Province, South Africa. In the current study, it is only station 0766715 5 which had an earlier mean onset of 12 September.

Mean cessation of rainfall varied from day 69 to 88 which corresponds with the dates 10 to 29 March. Rainfall also ceased earlier at day 69 and had a shorter duration of 102 days at station 0766715 5 (Table 4.13). The onset and cessation of rainfall in the study area still correspond to the typical rainfall season in South Africa which starts from October to March. The standard deviation of rainfall onset varied from 88 to 137. Station 0766563 1 had the smallest standard deviation for onset and duration of rainfall compared to other stations. Low standard deviation is an indicator of low rainfall variability in onset and duration of rainfall for this station as compared to the rest of the stations (Figure 4.13). Station 0766596 9 had the lowest standard deviation for cessation, thus it had low variability of rainfall cessation throughout the period of record. Rainfall cessation and duration had standard deviations which ranged from 19 – 44 and 26 – 41, respectively, for all stations.

Table 4.10: Onset, day of cessation and duration of rainfall for stations 0766596 9, 0766563 1, 0766715 5 and 0723485 6

Station Name	Mean					Standard Deviation				
	Onset		Cessation		Duration	Onset		Cessation		Duration
	Day	Date	Day	Date	Day	Day	Date	Day	Date	Day
0766596 9	284	11 Oct	88	29 Mar	117	110	20 Apr	19	19 Jan	36
0766563 1	297	25 Oct	83	24 Mar	128	88	29 Mar	26	26 Jan	26
0766715 5	255	12 Sept	69	10 Mar	102	137	17 May	36	6 Feb	41
0723485 6	295	22 Oct	86	27 Mar	115	91	1 Apr	44	13 Feb	35

Generally, the onset of rainfall for most of the years was higher than the mean of 284 in 0766596 9 station (Figure 4.13). In the hydrological years 1966/1967, 1971/1972 and 2008/2009 among others, the onset days were far much lower than the mean (Figure 4.13). This indicated delay in onset of rainfall during these years as compared to that of the rest of the years in the period of record. When there is drought, rainfall start late and end quickly resulting in a shorter duration. The hydrological years 1964/1965, 1992/1993 and 2011/2012 were characterized as dry years in Table 4.4. In station 0766563 1 the onset of rainfall for most of the hydrological years was generally higher than the mean of 297 days except in 1972/1973 and 1994/1995 (Figure 4.13 and Table 4.10). Similarly onset of rainfall for most of the hydrological years was higher than the mean of 255 for station 0766715 5 except in 1997/1998, 2010/2011, 2011/2012, 2012/2013, 2013/2014 with these hydrological years characterized as moderately dry (Table 4.6 and Figure 4.13). In station 0723485 6, the onset of rainfall for most of the hydrological years was generally higher than the mean of 295 days except in 1963/1964, 1981/1982, 1985/1986, 1993/1994, 2009/2010 and 2010/2011 (Figure 4.13). These hydrological years were characterized as moderate dry years in Table 4.7.

The onset, duration and cessation of rainfall differ with those identified in a study by Tadross *et al*. (2005) in Limpopo Province, which showed a trend towards later onset (December) of rainfall in Limpopo between 1979 and 1997. This means that due to climate change the trends of late onset were recognized in most of the years in the study by Tadross *et al*. (2005).

Cessation of rainfall for most of the hydrological years was higher than the mean days of 88, 83 and 86 days for stations 0766596 9, 0766563 1 and 0723485 6, respectively (Figure 4.14). In 1978/1979, the cessation day was far much lower than the mean in station 0766563 1 (Figure 4.14). In 2009/2010, the rain ceased early in station 0766715 5. In station 0723485 6, in most of years the rainfall cessation was lower than the mean of 86 days. Most parts of the Free State Province have their mean/average dates for the cessation of rain between 21 April and 30 April (Moeletsi, 2010). Tadross *et al.* (2009) also showed earlier cessation of rain with negative implications for agriculture. The onsets dates of the current study are similar to those of Moeletsi (2010) whereas the cessation of the current study differs from Moeletsi (2010) and Tadross *et al*. (2009). In the current study early and late onset differ because of the climate variability taking place in the area of study. Extreme events are occurring more often due to climate change (such as low rainfall and high rainfall).

Mean duration of rainfall varied from 102 to 128, with station 0766715 5 showing shortest duration of rainfall (Table 4.13). Stations 0766563 1 and 0766596 9 also had the highest duration (Figure 4.15). Stations 0766596 9 and 0723485 6 had the highest cessation of rainfall (Figure 4.15). Station 0766563 1 also had the smallest standard deviation for onset and duration of rainfall (Table 4.10). The results of the study showed that the onset, duration and cessation were mostly higher than the mean for all stations except for 0766715 5 which had the lowest mean values indicating prevalence of early onset, cessation and low duration, for this station.

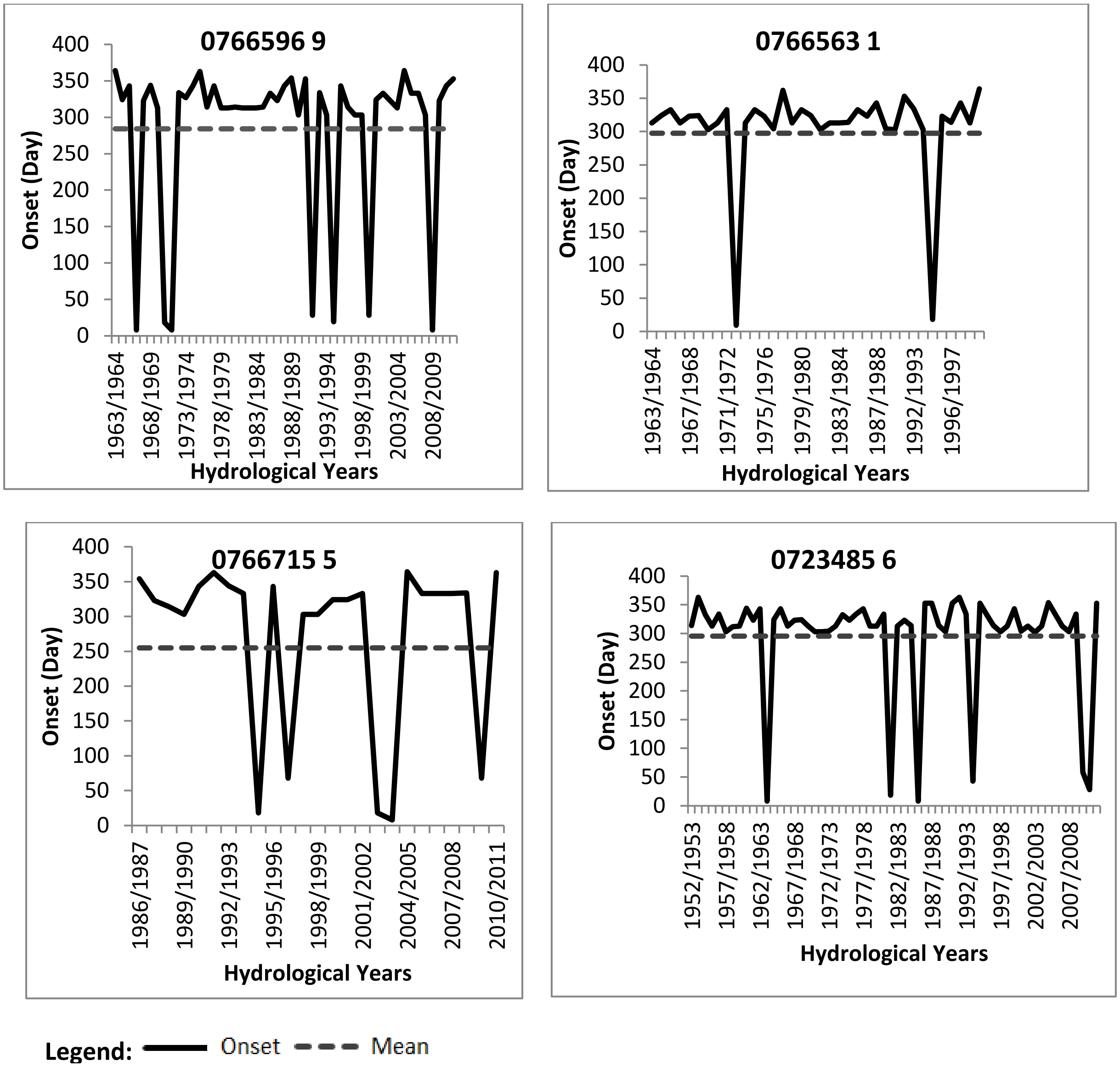

Figure 4.13: Onset of rainfall for 0766596 9, 0766563 1, 0766715 5 and 0723485 6

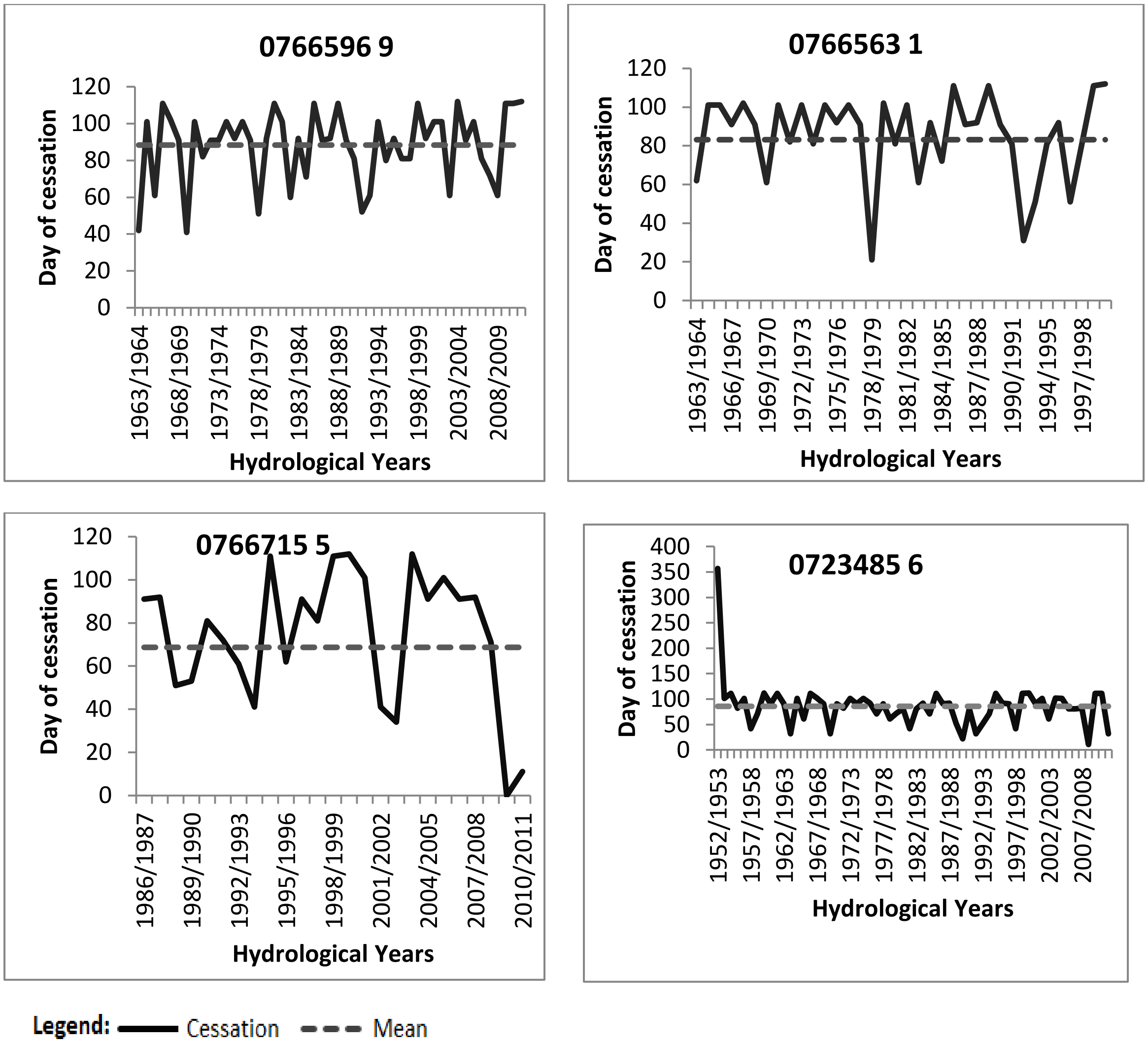

Figure 4.14: Rainfall cessation for 0766596 9, 0766563 1, 0766715 5 and 0723485 6

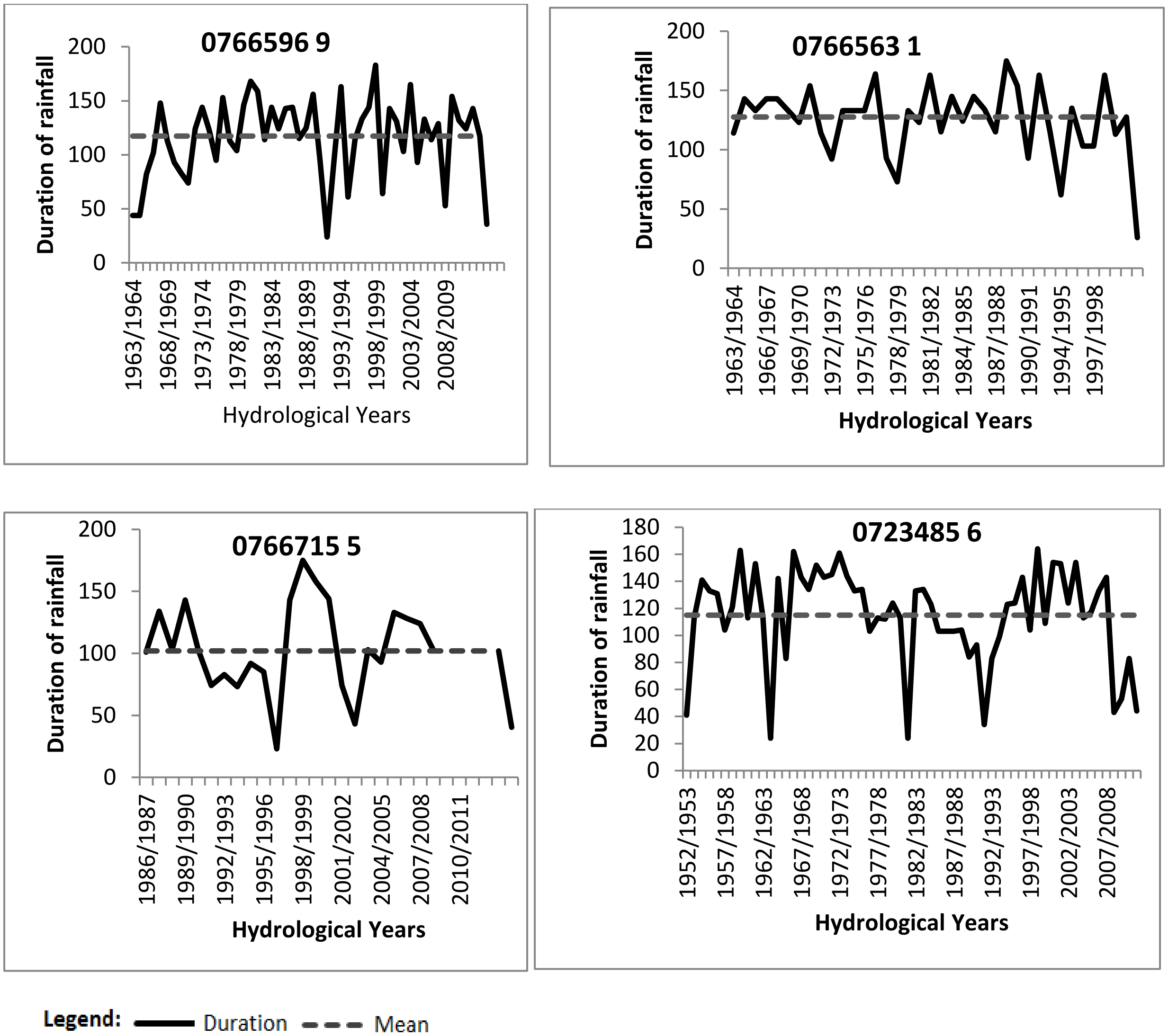

Figure 4.15: Duration of rainfall for 0766596 9, 0766563 1, 0766715 5 and 0723485 6

4.5 Influence of climate variability on flood and drought cycles and implications on rainy season characteristics

Trends analysis showed both increasing and decreasing rainfall trends, and increasing temperature trends. There was dominance of dry cycles with most of them below the range of 1 – 10 years identified by Tyson (1987). This indicated the possibility of increased frequency of dry years which can be linked to increasing temperature trends. Breashears *et al.* (2005) noted that future drought was projected to occur under warmer temperature conditions as climate change progresses in Southern Africa. The results of the study showed that the mean onset, duration and cessation were comparable for all stations except 0766715 5 for which had lower values. However, onset and duration of rainfall was mostly lower than the mean for most of the dry years which is an indication of delay of rainfall. In 1992/1993, the cessation day was far much lower than the mean in station 0766563 1 (Figure 4.14). The hydrological year 1992/1993 was categorized as severely dry year in Table 4.5. In 2009/2010, 2011/12, 2012/2013 and 2013/2014, the rain ceased early in station 07665969 9. These hydrological years are also dry years with conditions varying from near normal to moderately dry (Table 4.4). Dry years are associated with El Nino years in South Africa (Edossa *et a*l., 2014). Tadross *et al.* (2003) reported that onset of rain occurs later than normal in El Nino years. Thus, climate variability greatly affect onset, duration and cessation of rainfall during dry years.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study was focused on investigating the influence of climate variability on flood and drought cycles and implications on rainy season characteristics. MK and LR methods were used to analyze the trends in rainfall, temperature and streamflow. In all temperature and streamflow stations, MK detected increasing trends which were statistically significant. Increasing rainfall trends detected by MK were found in stations 0766596 9 and 0766563 1 whereas in stations 0723485 6 and 0766715 5 decreasing rainfall trends were detected. This shows that the first specific objective of the study was achieved.

Mean and variability of onset, cessation and duration of rainfall were determined using mean and standard deviation. Mean onset of rainfall varied from day 255 to 297 (12 September and 25 October), with station 0766715 5 showing the earliest onset compared to the rest of the stations. Rainfall also ceased earlier and had a shorter duration at station 0766715 5 station. Stations 0766563 1 and 0723485 6 had the longest mean duration and cessation of rainfall, respectively. The standard deviation of cessation of rainfall varied from day 88 to 137 (29 March and 17 May), with station 0766563 1 showing the smallest standard deviation compared to other stations. Low standard deviation is an indicator of low rainfall variability in this station as compared to the rest of the stations because it received very low rainfall. Station 0766563 1 also showed smaller standard deviation for cessation and duration. Generally the onset of rainfall for most of the years was higher than the mean of 284 days in station 0766596 9. In the hydrological years 1966/1967, 1971/1972 and 2008/2009, the onset days were far much lower than the mean. This indicated that in these years the area within the vicinity of this station was experiencing drought caused by climate variability. In station 0723485 6 the onset of rainfall for most of the hydrological years was generally higher than the mean of 295 days except in 1963/1964, 1981/1982, 1985/1986, 1993/1994, 2009/2010 and 2010/2011 in which there was drought. This shows that the second specific objective of the study was achieved.

Determination of flood and drought cycles was done using SPI. The results of SPI analysis showed that the study area is dominated by dry years. Extreme wet conditions occurred in the hydrological years 1977/1978 and 1996/1997 in station 0766563 1 and in 2000/2001 in station 0766596 9. In station 0766596 6 SPI time scale observed dominating near normal conditions. In the years 1964/1965 and 1973/1974 this station experienced severely dry conditions while 1992/1993 was extremely dry. This may be associated with reduced rainfall that was received. Station 0766596 6 experienced moderate wet, very wet, and extremely wet conditions in the hydrological years 1985/1986, 1988/1989, 1999/2000, 2001/2002, 1977/1978, 1978/1979, 1996/1997 and 2000/2001. The findings of station 0766563 1 indicated that most of the hydrological years were experiencing drought cycles. This station also experienced some extreme precipitation cycles in the years 1976/1977, 1977/1978, 1978/1979, 1988/1989 and 1996/1997. SPI results identified dry and wet years, for example, Levubu (0723485 6), Thathe (0766563 1), Vondo (0766596 9) and Mukumbani (0766715 5) stations experienced rare floods in the hydrological years 2000/2001, 1996/1997, 2000/2001 and 2000/2001, respectively. In some years it is clear that the stations experienced dry years whereas some of the years were wet years, for example 1964/1965 to 1974/1975 and the rest of the years were fluctuating from dry years to wet years. These results may lead to the conclusion that some parts of the area of study experienced dry cycles whereas other parts experienced wet cycles influenced by climate variability. This shows that both third and fourth objective of the study were achieved.

The study identified dry cycles ranging from 1 – 12, 1 – 4, 1 – 4 and 1 – 5 years in stations 0766596 9, 0766563 1, 0766715 5 and 0723485 6, respectively. This indicated the possibility of increased frequency of dry years which can be linked to increasing temperature trends. The study also identified wet cycles ranging from 1 – 4, 1 – 3, 1 – 5 and 1 – 8 years in stations 0766596 9, 0766563 1, 0766715 5 and 0723485 6, respectively. The results of the study showed that the mean onset, duration and cessation were comparable for all stations except for station 0766715 5, which had lower values. The study also found that climate variability greatly affects onset, duration and cessation of rainfall during dry and wet years. This led to late onset, early cessation and relatively short duration of the rainfall season.

5.2 Recommendations

Due to the fact that minimum and maximum temperatures showed increasing trend in the area of study, water resources should be managed and used sustainably to avoid future shortages due since climate change will affect water resources availability. A study on the impacts of climate variability on water resources availability for domestic and agricultural uses should be undertaken in the study area.

Strategies to minimise and adapt to climate change should also be developed for LRC. Water conservation awareness should be implemented to alert the water managers, farmers and other stakeholders involved in water resources management and/or hydrological modelling on the risks that may occur if temperature trends keep on increasing.

Global warming and/or climate change must be minimised by educating communities within the LRC due to the fact that they have influence on flood and drought cycles and implications on rainy season characteristics. Communities within the catchment must be educated to practice activities that reduce carbon dioxide emissions and minimise warming and/or climate change. These may include reducing deforestation, use of green energy, appropriate industralisation.

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LIST OF APPENDICES

APPENDIX A: DATA USED IN MANN KENDALL AND LINEAR REGRESSIONS

Appendix A1: Data used in Mann Kendall and linear regression analysis for minimum temperatures in the study area.

Station 0723485 W

Year	Temperature ($^{\circ}$C)	Year	Temperature (^{0}C)	Year	Temperature (^{0}C)	Year	Temperature (^{0}C)
1950/1951	20.7	1967/1968	22.6	1984/1985	24.1	2001/2002	22
1951/1952	20.7	1968/1969	23.4	1985/1986	21.7	2002/2003	22.7
1952/1953	20.7	1969/1970	24.4	1986/1987	22.5	2003/2004	25.3
1953/1954	20.7	1970/1971	23.2	1987/1988	23.5	2004/2005	22.8
1954/1955	20.7	1971/1972	21.2	1988/1989	21.9	2005/2006	22.5
1955/1956	20.7	1972/1973	21.2	1989/1990	22.7	2006/2007	23.5
1956/1957	20.7	1973/1974	23.6	1990/1991	23.2	2007/2008	23.5
1957/1958	20.7	1974/1975	22.2	1991/1992	25.4	2008/2009	22.5
1958/1959	20.7	1975/1976	22	1992/1993	24.1	2009/2010	25.3
1959/1960	20.7	1976/1977	24.5	1993/1994	24.6	2010/2011	21.5
1960/1961	20.7	1977/1978	22.8	1994/1995	23	2011/2012	22.5
1961/1962	20.7	1978/1979	22.3	1995/1996	23.6	2012/2013	25.4
1962/1963	20.7	1979/1980	23.5	1996/1997	22.5		
1963/1964	23.7	1980/1981	23.9	1997/1998	22.9		
1964/1965	23.4	1981/1982	23.2	1998/1999	23.9		
1965/1966	22.9	1982/1983	25.2	1999/2000	22.7		
1966/1967	22.1	1983/1984	24.5	2000/2001	22.2		

Appendix A2: Data used in Mann Kendall and linear regression analysis for minimum temperatures in the study area.

Station 0723664 6

Year	Temperature (^{0}C)	Year	Temperature (^{0}C)	Year	Temperature (^{0}C)	Year	Temperature (^{0}C)
1950/1951	21.4	1967/1968	24.6	1984/1985	24.3	2001/2002	22.6
1951/1952	21.4	1968/1969	24.9	1985/1986	23.1	2002/2003	24.1
1952/1953	21.4	1969/1970	24.9	1986/1987	24.4	2003/2004	24.9
1953/1954	21.4	1970/1971	23.1	198719/88	24.6	2004/2005	25.8
1954/1955	21.4	1971/1972	22.3	1988/1989	22.6	2005/2006	23.9
1955/1956	21.4	1972/1973	24.1	1989/1990	23.6	2006/2007	24.9
1956/1957	21.4	1973/1974	24.1	1990/1991	24.3	2007/2008	23.1
1957/1958	21.4	1974/1975	24.1	1991/1992	26.9	2008/2009	22.7
1958/1959	21.4	1975/1976	22.9	1992/1993	26.4	2009/2010	21.5
1959/1960	23.8	1976/1977	26.9	1993/1994	24.3	2010/2011	22.7
1960/1961	26	1977/1978	24.3	1994/1995	25.1	2011/2012	23.9
1961/1962	25.1	1978/1979	22.8	1995/1996	24.4	2012/2013	23.4
1962/1963	26.6	79/80	25.7	1996/1997	23.6		
1963/1964	25.1	1980/1981	26.2	1997/1998	24.4		
1964/1965	26.6	1981/1982	26.7	1998/1999	22.7		
1965/1966	23.2	1982/1983	25.8	1999/2000	22.9		
1966/1967	23.1	1983/1984	23.7	2000/2001	22.4		

Appendix A3: Data used in Mann Kendall and linear regression analysis for minimum temperatures in the study area.

Station 0766628 W

Year	Temperature (^{0}C)	Year	Temperature (^{0}C)	Year	Temperature (^{0}C)	Year	Temperature (^{0}C)
1950/1951	19.5	1967/1968	23.7	1984/1985	21.7	2001/2002	22.3
1951/1952	19.5	1968/1969	22.7	1985/1986	21.5	2002/2003	25.5
1952/1953	19.5	1969/1970	22.8	1986/1987	22.5	2003/2004	25
1953/1954	19.5	1970/1971	22.8	1987/1988	22.8	2004/2005	22.7
1954/1955	19.5	1971/1972	22.5	1988/1989	25.5	2005/2006	25.5
1955/1956	19.5	1972/1973	23.5	1989/1990	23.1	2006/2007	25
1956/1957	19.5	1973/1974	22.5	1990/1991	22.2	2007/2008	23
1957/1958	19.5	1974/1975	22.2	1991/1992	26.5	2008/2009	25
1958/1959	19.5	1975/1976	20.9	1992/1993	23.5	2009/2010	24.2
1959/1960	22.7	1976/1977	24.8	1993/1994	22.5	2010/2011	24.3
1960/1961	19.8	1977/1978	24.7	1994/1995	24	2011/2012	22.8
1961/1962	21.9	1978/1979	24.5	1995/1996	23	2012/2013	29
1962/1963	24.4	1979/1980	28.5	1996/1997	22.5		
1963/1964	23.2	1980/1981	24.2	1997/1998	23		
1964/1965	25	1981/1982	25.1	1998/1999	22		
1965/1966	22	1982/1983	24	1999/2000	23.5		
1966/1967	21.6	1983/1984	22.3	2000/2001	22		

Appendix A4: Data used in Mann Kendall and linear regression analysis for maximum temperatures in the study area.

Station 0723485 W

Year	Temperature (⁰C)	Year	Temperature (⁰C)	Year	Temperature (⁰C)	Year	Temperature (⁰C)
1950/1951	31	1967/1968	39.6	1984/1985	36.1	2001/2002	37
1951/1952	31	1968/1969	38.6	1985/1986	36.5	2002/2003	38
1952/1953	31	1969/1970	38.5	1986/1987	36.1	2003/2004	38.3
1953/1954	31	1970/1971	39.2	1987/1988	37.1	2004/2005	39.5
1954/1955	31	1971/1972	37.4	1988/1989	35.9	2005/2006	40.7
1955/1956	31	1972/1973	38.7	1989/1990	38	2006/2007	38.5
1956/1957	31	1973/1974	36.9	1990/1991	39	2007/2008	38.7
1957/1958	31	1974/1975	36.8	1991/1992	42.5	2008/2009	41
1958/1959	31	1975/1976	38	1992/1993	38.3	2009/2010	40
1959/1960	31	1976/1977	39.6	1993/1994	39.5	2010/2011	42.5
1960/1961	31	1977/1978	36.8	1994/1995	38.4	2011/2012	38.9
1961/1962	31	1978/1979	39.8	1995/1996	38.9	2012/2013	40
1962/1963	31	1979/1980	40.4	1996/1997	37.5		
1963/1964	36.9	1980/1981	36.2	1997/1998	38.1		
1964/1965	39.2	1981/1982	39.7	1998/1999	37.4		
1965/1966	39.2	82/83	38.8	1999/2000	36.9		
1966/1967	39	1983/1984	39.3	2000/2001	38.4		

Appendix A5: Data used in Mann Kendall and linear regression analysis for maximum temperatures in the study area.

Station 0723664 6

Year	Temperature (^{0}C)	Year	Temperature (^{0}C)	Year	Temperature (^{0}C)	Year	Temperature (^{0}C)
1950/1951	32.6	1967/1968	40.8	1984/1985	37	2001/2002	37
1951/1952	32.6	1968/1969	39.9	1985/1986	37.5	2002/2003	38.6
1952/1953	32.6	1969/1970	39.8	1986/1987	38.5	2003/2004	39.6
1953/1954	32.6	1970/1971	40.6	1987/1988	37.9	2004/2005	39.7
1954/5195	32.6	1971/1972	38.7	1988/1989	36.9	2005/2006	40.3
1955/1956	32.6	1972/1973	41.1	1989/1990	41.2	2006/2007	39.6
1956/1957	32.6	1973/1974	38.2	1990/1991	41.5	2007/2008	39.8
1957/1958	32.6	1974/1975	38	1991/1992	42.6	2008/2009	41
1958/1959	32.6	1975/1976	38.6	1992/1993	39.5	2009/2010	39.7
1959/1960	37.9	1976/1977	40.1	1993/1994	40.7	2010/2011	41.6
1960/1961	36.3	1977/1978	38	1994/1995	39.1	2011/2012	38.3
1961/1962	39.5	1978/1979	40.5	1995/1996	40.1	2012/2013	39.4
1962/1963	42.2	1979/1980	42.2	1996/1997	38.5		
1963/1964	39.9	1980/1981	38.5	1997/1998	40		
1964/1965	40.5	1981/1982	42	1998/1999	38.5		
1965/1966	40.5	1982/1983	40.5	1999/2000	38.6		
1966/1967	40.3	1983/1984	39.3	2000/2001	38.7		

Appendix A6: Data used in Mann Kendall and linear regression analysis for maximum temperatures in the study area.

Station 0766628 W

Year	Temperature (^{0}C)	Year	Temperature (^{0}C)	Year	Temperature (^{0}C)	Year	Temperature (^{0}C)
1950/1951	28.3	1967/1968	36.9	1984/1985	34.1	2001/2002	33
1951/1952	28.3	1968/1969	36.5	1985/1986	34.2	2002/2003	35.5
1952/1953	28.3	1969/1970	36.4	1986/1987	33.7	2003/2004	35.5
1953/1954	28.3	1970/1971	36.9	1987/1988	33.4	2004/2005	36
1954/1955	28.3	1971/1972	35.3	1988/1989	33.5	2005/2006	37
1955/1956	28.3	1972/1973	36.4	1989/1990	35.5	2006/2007	40
1956/1957	28.3	1973/1974	34.8	1990/1991	37	2007/2008	35.7
1957/1958	28.3	1974/1975	34.8	1991/1992	39.8	2008/2009	35
1958/1959	28.3	1975/1976	36	1992/1993	41	2009/2010	24.8
1959/1960	33.9	1976/1977	37.2	1993/1994	36	2010/2011	38.2
1960/1961	32.5	1977/1978	33.5	1994/1995	35.5	2011/2012	36.1
1961/1962	36.2	1978/1979	36.9	1995/1996	36	2012/2013	43.4
1962/1963	38.9	1979/1980	38.3	1996/1997	34.5		
1963/1964	36.6	1980/1981	34.2	1997/1998	35		
1964/1965	37.1	1981/1982	37.7	1998/1999	34		
1965/1966	37.1	1982/1983	36.5	1999/2000	34.5		
1966/1967	37	1983/1984	36.6	2000/2001	35		

Appendix A7: Data used in Mann Kendall and linear regression analysis for rainfall in the study area.

Station 0766596 9

Year	Rainfall (mm)	Year	Rainfall (mm)	Year	Rainfall (mm)
1963/1964	84	1980/1981	264	1997/1998	198.5
1964/1965	33.1	1981/1982	87	1998/1999	140
1965/1966	63.5	1982/1983	54.5	99/2000	531
196619/67	83	1983/1984	63	2000/2001	187.5
1967/1968	44.5	1984/1985	197	2001/2002	133.5
1968/1969	87.5	1985/1986	114	2002/2003	110.5
1969/1970	141	1986/1987	120	2003/2004	224
1970/1971	97.5	1987/1988	155.5	2004/2005	82
1971/1972	63	1988/1989	134	2005/2006	61.5
1972/1973	67.5	1989/1990	103	2006/2007	108.5
1973/1974	57	1990/91	119	2007/2008	77
1974/1975	130	1991/92	53	2008/2009	65
1975/1976	120	1992/1993	218	2009/2010	104
1976/1977	218.5	1993/1994	208	2010/2011	49
1977/1978	237	1994/1995	98	2011/2012	182
1978/1979	81	1995/1996	296	2012/2013	392
1979/1980	175	1996/1997	169.5		

Appendix A8: Data used in Mann Kendall and linear regression analysis for rainfall in the study area.

Station 0766563 1

Year	Rainfall (mm)	Year	Rainfall (mm)	Year	Rainfall (mm)
1963/1964	76	1980/1981	211	1997/1998	198
1964/1965	55	1981/1982	99.5	1998/1999	136
1965/1966	104	1982/1983	55.5	1999/2000	320
1966/1967	120.6	1983/1984	80		
1967/1968	57.5	1984/1985	103		
1968/1969	89.5	1985/1986	84		
1969/1970	47	1986/1987	56		
1970/1971	130.5	1987/1988	117.5		
1971/1972	130	1988/1989	193		
1972/1973	95.5	1989/1990	62.5		
1973/1974	86	1990/1991	100		
1974/1975	100	1991/1992	50		
1975/1976	169	1992/1993	64		
1976/1977	260	1993/1994	166		
1977/1978	144	1994/1995	101.3		
1978/1979	120	1995/1996	213		
1979/1980	178	1996/1997	50		

Appendix A9: Data used in Mann Kendall and linear regression analysis for rainfall in the study area.

Station 0723485 6

Year	Rainfall (mm)	Year	Rainfall (mm)	Year	Rainfall (mm)	Year	Rainfall (mm)
1952/1953	87.1	1970/1971	91.4	1988/1989	50.5	2006/2007	72
1953/1954	64	1971/1972	90.7	1989/1990	71.4	2007/2008	116
1954/1955	120	1972/1973	80	1990/1991	122.5	2008/2009	29.4
1955/1956	135	1973/1974	116.4	1991/1992	54	2009/2010	49
1956/1957	69	1974/1975	119	1992/1993	96.3	2010/2011	63.8
1957/1958	121	1975/1976	128.3	1993/1994	66	2011/2012	93.2
1958/1959	83.5	1976/1977	178	1994/1995	163.3	2012/2013	2.6
1959/1960	95	1977/1978	104	1995/1996	187.3		
1960/1961	236.6	1978/1979	67.4	1996/1997	72.4		
1961/1962	78.2	1979/1980	83.4	1997/1998	101		
1962/1963	80.2	1980/1981	280.2	1998/1999	73.5		
1963/1964	96.4	1981/1982	53.4	99/2000	432.6		
1964/1965	64.5	1982/1983	31.9	2000/2001	162.8		
1965/1966	59.8	1983/1984	54.8	2001/2002	73.5		
1966/1967	87	1984/1985	87.7	2002/2003	114.4		
1967/1968	116	1985/1986	136.1	2003/2004	88.7		
1968/1969	110	1986/1987	79	2004/2005	83		
1969/1970	61.3	1987/1988	99	2005/2006	82.5		

Appendix A10: Data used in Mann Kendall and linear regression analysis for rainfall in the study area.

Station 0766715 5

Year	Rainfall (mm)	Year	Rainfall (mm)
1986/1987	53	2003/2004	104
1987/1988	159	2004/2005	158.5
1988/1989	126	2005/2006	194
1989/1990	60.3	2006/2007	112
1990/1991	128	2007/2008	106
1991/1992	61	2008/2009	115
1992/1993	179	2009/2010	70
1993/1994	84	2010/2011	9
1994/1995	93	2011/2012	9
1995/1996	115.5	2012/2013	25.7
1996/1997	111.7		
1997/1998	148.5		
1998/1999	129.5		
1999/2000	268		
2000/2001	157.5		
2001/2002	97		
2002/2003	99		

Appendix A11: Data used in Mann Kendall and linear regression analysis for streamflow in the study area.

Station A9H004

Year	Streamflow	Year	Streamflow	Year	Streamflow
1933/1934	21.7	1957/1958	27.1	1981/1982	9
1934/1935	13.7	1958/1959	21.6	1982/1983	1.58
1935/1936	14.5	1959/1960	13.9	1983/1984	6.7
1936/1937	16.5	1960/1961	22.5	1984/1985	28.5
1937/1938	6.8	1961/1962	20	1985/1986	4.6
1938/1939	25.5	1962/1963	12.4	1986/1987	1.3
1939/1940	303	1963/1964	15.9	1987/88	40.9
1940/1941	10.4	1964/1965	4.22	1988/1989	13
1941/1942	7.8	1965/1966	32.9	1989/1990	5.5
1942/1943	7.8	1966/1967	44.2	1990/1991	13
1943/1944	23.1	1967/1968	7	1991/1992	0.4
1944/1945	20	1968/1969	29.1	1992/1993	33.7
1945/1946	24.2	1969/1970	9.7	1993/1994	9.5
1946/1947	13.7	1970/1971	16.3	1994/1995	13.6
1947/1948	20.2	1971/1972	51	1995/1996	82.6
1948/1949	10.9	1972/1973	4.5	1996/1997	27.5
1949/1950	17.1	1973/1974	44.9	1997/1998	14.1
1950/1951	14.8	1974/1975	101	1998/1999	63.7
1951/1952	14.2	1975/1976	46.5	1999/2000	88.8
1952/1953	24.3	1976/1977	84.7	2000/2001	90.7
1953/1954	22.8	1977/1978	124	2001/2002	20.9
1954/1955	26.3	1978/1979	40.2	2002/2003	10.4
1955/1956	23.5	1979/1980	35.9	2003/2004	73.4
1956/1957	22.2	1980/1981	65.5		

Appendix A12: Data used in Mann Kendall and linear regression analysis for streamflow in the study area.

Station A9H012

Year	Streamflow
1988/1989	27
1989/1990	30.1
1990/1991	54.4
1991/1992	1.6
1992/1993	41.3
1993/1994	13.5
1994/1995	13.4
1995/1996	289
1996/1997	45.4
1997/1998	22.8
1998/1999	112
1999/2000	3.48
2000/2001	155
2001/2002	59.9
2002/2003	25
2003/2004	177
2004/2005	9.3

Appendix A13: Data used in Mann Kendall and linear regression analysis for streamflow in the study area.

Station A9H013

Year	Streamflow	Year	Streamflow	Year	Streamflow
1932/1933	15.3	1956/1957	22.2	1980/1981	65.5
1933/1934	21.7	1957/1958	27.1	1981/1982	9
1934/1935	13.7	1958/1959	21.6	1982/1983	1.6
1935/1936	14.5	1959/1960	13.9	1983/1984	6.7
1936/1937	16.5	196019/61	22.5	1984/1985	28.5
1937/1938	6.8	1961/1962	20	1985/1986	4.6
1938/1939	25.5	1962/1963	12.4	1986/1987	1.3
1939/1940	303	1963/1964	15.9	1987/1988	40.9
1940/1941	10.4	1964/1965	4.2	1988/1989	13
1941/1942	7.8	1965/6196	32.9	1989/1990	5.5
1942/1943	7.8	1966/1967	44.2	1990/1991	13
1943/1944	23.1	1967/1968	7	1991/1992	0.6
1944/1945	20	1968/1969	29.1	1992/1993	33.7
1945/1946	24.2	1969/1970	9.7	1993/1994	9.5
1946/1947	13.7	1970/1971	16.3	1994/1995	13.6
1947/1948	20.2	1971/1972	51	1995/1996	82.6
1948/1949	10.9	1972/1973	4.5	1996/1997	27.5
1949/1950	17.1	1973/1974	44.9	1997/1998	14.1
1950/1951	14.8	1974/1975	101	1998/1999	63.7
1951/1952	14.2	1975/1976	46.5	1999/2000	88.8
1952/1953	24.3	1976/1977	80.6	2000/2001	90.7
1953/1954	22.8	1977/1978	124	2001/2002	20.9
1954/1955	26.3	1978/1979	40.2	2002/2003	10.4
1955/1956	23.5	1979/1980	35.9		

APPENDIX B: COMPUTED ONSET, CESSATION AND DURATION OF RAINFALL

Appendix B1: Computed onset, duration and cessation for station 0766596 9.

Year	Onset	Duration	Cessation	Year	Onset	Duration	Cessation
1963/1964	364	44	42	1997/1998	303	144	81
1964/1965	324	44	101	1998/1999	303	183	111
1965/1966	343	82	61	1999/2000	28	64	92
1966/1967	8	102	111	2000/2001	324	143	101
1967/1968	323	148	102	2001/2002	333	131	101
1968/1969	344	113	91	2002/2003	323	103	61
1969/1970	313	93	41	2003/2004	313	165	112
1970/1971	18	83	101	2004/2005	364	93	91
1971/1972	8	74	82	2005/2006	333	133	101
1972/1973	334	124	91	2006/2007	333	114	81
1973/1974	327	144	91	2007/2008	303	129	72
1974/1975	343	123	101	2008/2009	8	53	61
1975/1976	363	95	92	2009/2010	323	154	111
1976/7197	314	153	91	2010/2011	343	132	111
1977/1978	343	113	51	2011/2012	353	123	112
1978/1979	313	104	92	2012/2013	314	144	101
1979/1980	313	146	111				
1980/1981	314	168	101				
1981/1982	313	159	60				
1982/1983	313	144	92				
1983/1984	313	144	71				
1984/1985	314	124	111				
1985/1986	333	143	91				
1986/1987	323	144	92				
1987/1988	343	115	111				
1988/1989	354	125	92				
1989/1990	303	156	81				
1990/1991	353	94	52				
1991/1992	28	24	61				
1992/1993	334	95	101				
1993/1994	303	163	80				
1994/1995	19	61	92				
1995/1996	343	114	81				
1996/1997	314	113	81				

Appendix B2: Computed onset, duration and cessation for station 0766563 1.

Year	Onset	Duration	Cessation
1963/1964	313	114	62
1964/1965	324	143	101
1965/1966	333	133	101
1966/1967	313	143	91
1967/1968	323	143	102
1968/1969	324	133	91
1969/1970	303	123	61
1970/1971	313	154	101
1971/1972	333	114	82
1972/1973	9	92	101
1973/1974	313	133	81
1974/1975	333	133	101
1975/1976	323	164	92
1976/1977	304	93	101
1977/1978	362	73	91
1978/1979	313	133	21
1979/1980	333	123	81
1980/1981	324	163	101
1981/1982	303	115	61
1982/1983	313	145	92
1983/1984	313	124	72
1984/1985	314	145	111
1985/1986	333	134	91
1986/1987	323	115	92
1987/1988	343	175	111
1988/1989	304	154	91
1989/1990	303	93	81
1990/1991	353	163	31
1991/1992	334	115	51
1992/1993	303	62	81
1993/1994	18	135	92
1994/1995	323	135	51
1995/1996	314	103	81
1996/1997	343	103	111
1997/1998	313	143	112
1998/1999	364	163	112

Appendix B3: Computed onset, duration and cessation for station 0766715 5.

Year	Onset	Duration	Cessation
1986/1987	354	101	91
1987/1988	323	134	92
1988/1989	314	103	51
1989/1990	303	143	53
1990/1991	343	103	81
1991/1992	363	74	72
1992/1993	344	83	61
1993/1994	333	73	41
1994/1995	18	92	111
1995/1996	343	85	62
1996/1997	68	23	91
1997/1998	303	143	81
1998/1999	303	175	111
1999/2000	303	158	112
2000/2001	324	144	101
2001/2002	324	74	41
2002/2003	333	43	34
2003/2004	18	103	112
2004/2005	8	93	91
2005/2006	364	133	101
2006/2007	333	128	91
2007/2008	333	124	92
2008/2009	333	103	71
2009/2010	334		0
2010/2011	68	13	11
2011/2012	363		0
2012/2013	0		0

Appendix B4: Computed onset, duration and cessation for station 0723485 6.

Year	Onset	Duration	Cessation	Year	Onset	Duration	Cessation
1952/1953	314	41	357	1988/1989	314	103	52
1953/1954	363	113	101	1989/1990	303	104	22
1954/1955	333	141	111	1990/1991	353	84	81
1955/1956	313	133	82	1991/1992	363	93	32
1956/1957	334	131	101	1992/1993	334	34	51
1957/1958	303	104	42	1993/1994	43	83	71
1958/1959	312	121	71	1994/1995	353	99	111
1959/1960	313	163	112	1995/1996	333	123	92
1960/1961	344	113	91	1996/1997	314	124	91
1961/1962	323	153	111	1997/1998	303	143	42
1962/1963	343	113	91	1998/1999	313	104	111
1963/1964	8	24	32	1999/2000	343	164	112
1964/1965	324	142	101	2000/2001	304	109	91
1965/1966	343	83	61	2001/2002	313	154	101
1966/1967	313	162	111	2002/2003	302	153	61
1967/1968	323	143	102	2003/2004	313	124	102
1968/1969	324	134	91	2004/2005	354	154	101
1969/1970	313	152	32	2005/2006	333	113	81
1970/1971	303	143	91	2006/2007	313	117	81
1971/1972	303	145	82	2007/2008	303	133	82
1972/1973	304	161	101	2008/2009	334	143	11
1973/1974	313	144	91	2009/2010	58	43	111
1974/1975	333	133	101	2010/2011	28	83	111
1975/1976	323	134	92	2011/2012	353	44	32
1976/1977	334	103	71				
1977/1978	343	113	91				
1978/1979	313	112	61				
1979/1980	313	124	72				
1980/1981	334	113	81				
1981/1982	18	24	42				
1982/1983	313	133	81				
1983/1984	323	134	92				
1984/1985	314	123	71				
1985/1986	8	103	111				
1986/1987	353	103	91				
1987/1988	353	103	92				