Drought analysis with reference to rain-fed maize for past and future climate conditions over the Luvuvhu River catchment in South Africa

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ELISA TEBOHO MASUPHA

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DECLARATION

Name: Elisa Teboho Masupha

Student number: 58563660

Degree: Master of Science in Agriculture

I declare that "DROUGHT ANALYSIS WITH REFERENCE TO RAIN-FED MAIZE FOR PAST AND FUTURE CLIMATE CONDITIONS OVER THE LUVUVHU RIVER CATCHMENT, SOUTH AFRICA" is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references. I further declare that I have not previously submitted this work, or part of it, for examination at Unisa for another qualification or at any other higher education institution. The turnitin report has been attached in line with the College of Agriculture and Environmental Sciences requirements.

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DEDICATION

This thesis is dedicated to my mother Nkgetheleng Masupha for her unfailing emotional support, encouragement and for taking care of my precious son Bohlokoa throughout my years of study. This one is for you Motloung wa Seleso sa Lekgunuana, wa ha Mmanape!

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ABSTRACT

Recurring drought conditions have always been an endemic feature of climate in South Africa, limiting maize development and production. However, recent projections of the future climate by the Intergovernmental Panel on Climate Change suggest that due to an increase of atmospheric greenhouse gases, the frequency and severity of droughts will increase in drought-prone areas, mostly in subtropical climates. This has raised major concern for the agricultural sector, particularly the vulnerable small-scale farmers who merely rely on rain for crop production. Farmers in the Luvuvhu River catchment are not an exception, as this area is considered economically poor, whereby a significant number of people are dependent on rain-fed farming for subsistence. This study was therefore conducted in order to improve agricultural productivity in the area and thus help in the development of measures to secure livelihoods of those vulnerable small-scale farmers.

Two drought indices viz. Standardized Precipitation Evapotranspiration Index (SPEI) and Water Requirement Satisfaction Index (WRSI) were used to quantify drought. A 120-day maturing maize crop was considered and three consecutive planting dates were staggered based on the average start of the rainy season. Frequencies and probabilities during each growing stage of maize were calculated based on the results of the two indices. Temporal variations of drought severity from 1975 to 2015 were evaluated and trends were analyzed using the non-parametric Spearman's Rank Correlation test at α (0.05) significance level. For assessing climate change impact on droughts, SPEI and WRSI were computed using an output from downscaled projections of CSIRO Mark3.5 under the SRES A2 emission scenario for the period 1980/81 – 2099/100. The frequency of drought was calculated and the difference of SPEI and WRSI means between future climate periods and the base period were assessed using the independent t-test at α (0.10) significance level in STATISTICA software.

The study revealed that planting a 120-day maturing maize crop in December would pose a high risk of frequent severe-extreme droughts during the flowering to the grain-filling stage at Levubu, Lwamondo, Thohoyandou, and Tshiombo; while planting in

October could place crops at a lower risk of reduced yield and even total crop failure. In contrast, stations located in the low-lying plains of the catchment (Punda Maria, Sigonde, and Pafuri) were exposed to frequent moderate droughts following planting in October, with favorable conditions noted following the December planting date. Further analysis on the performance of the crop under various drought conditions revealed that WRSI values corresponding to more intense drought conditions were detected during the December planting date for all stations. Moreover, at Punda Maria, Sigonde and Pafuri, it was observed that extreme drought (WRSI <50) occurred once in five seasons, regardless of the planting date.

Temporal analysis on historical droughts in the area indicated that there had been eight agricultural seasons subjected to extreme widespread droughts resulting in total crop failure i.e. 1983/84, 1988/89, 1991/92, 1993/94, 2001/02, 2002/03, 2004/05 and 2014/15. Results of Spearman's rank correlation test revealed weak increasing drought trends at Thohoyandou (ρ = of 0.5 for WRSI) and at Levubu and Lwamondo (ρ = of 0.4 for SPEI), with no significant trends at the other stations. The study further revealed that climate change would enhance the severity of drought across the catchment. This was statistically significant (at 10% significance level) for the near-future and intermediate-future climates, relative to the base period.

Drought remains a threat to rain-fed maize production in the Luvuvhu River catchment area of South Africa. In order to mitigate the possible effects of droughts under climate change, optimal planting dates were recommended for each region. The use of seasonal forecasts during drought seasons would also be useful for local rain-fed maize growers especially in regions where moisture is available for a short period during the growing season. It was further recommended that the Government ensure proper support such as effective early warning systems and inputs to the farmers. Moreover, essential communication between scientists, decision makers, and the farmers can help in planning and decision making ahead of and during the occurrence of droughts.

Key terms: Climate change, Crop water requirements, Drought trends, Hargreaves method, Maize growing period, Planting dates, Probability distributions, Relative drought frequency, Small-scale farming, Water balance.

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ABBREVIATIONS

A-D	Anderson-Darling
AR4	Assessment Report Four
ARC	Agricultural Research Council
CA	Conservation agriculture
CASP	Comprehensive Agricultural Support Progamme
CCAM	Conformal-Cubic Atmospheric Model
CGCM	Coupled Global Climate Model
CMI	Crop Moisture Index
CMIP3	Coupled Model Intercomparison Project Phase 3
CO_2	Carbon dioxide
CSDI	Crop Specific Drought Index
DAFF	Department of Agriculture, Forestry and Fisheries
Dek	Dekad
Dekad	Ten-day period
ENSO	El Niño Southern Oscillation
ET0	Reference Evapotranspiration
EWS	Early warning systems
GCM	Global Climate Model
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
Kc	Crop Coefficient
NDVI	Normalized Difference Vegetation Index
PDSI	Palmer Drought Severity Index
PET	Potential Evapotranspiration
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
SADC	Southern African Development Community
SAWS	South African Weather Service
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardized Precipitation Index

SRES	Special Report on Emission Scenarios
SST	Sea Surface Temperature
SWHC	Soil Water Holding Capacity
SWSI	Surface Water Supply Index
WRSI	Water Requirement Satisfaction Index

CHAPTER 1 INTRODUCTION

1.1 Background

Maize (*Zea mays* L) is a tall grain plant classified under the genus *Zea*, belonging to the grass family called *Gramineae* which includes other grain crops such as Oats, Rice, Sorghum and Wheat (CFIA, 2014; Wratt and Smith, 2015). This leafy plant produces separate pollen and ears, yielding edible kernels/seeds on a thickened, almost woody cob (CFIA, 2014). According to Verheye (2010), cultivation of the maize crop is presumed to have originated from a wild grass called Teosinte in the subtropics of Central America more than 7,000 years ago. Since its introduction in the West and East Africa by Portuguese and Arab explorers about 500 years ago, maize cultivation is evident in all the corners of the continent due to its wide climatic adaptability (McCann, 2005; Verheye, 2010). In South Africa, it is the most important grain crop serving as a staple food, livestock feed and an export crop (DAFF, 2012). Commercial farming, mainly in the Free State, North West, Mpumalanga and KwaZulu-Natal provinces is responsible for approximately 98% of maize production, while, developing farmers supply about 2% (DAFF, 2012). Moreover, small-scale and subsistence farmers contribute toward food security and job creation in rural areas, although these are at times harder to quantify (National Treasury, 2015).

Maize is produced under diverse environments responding well to warm temperatures and a significant amount of water (du Plessis, 2003). However, increasing recurrences of extreme weather events such as extreme temperatures and severe droughts, pose a serious threat to the country's natural resources and socio-economic development (COP17, 2011). Researchers thus face the necessity to study aspects of climate variability and climate change effects on agriculture in order to identify the challenges faced by farmers. For the attainment of optimum productivity, adequate water is required throughout the physiological development (Emergence to Maturity) of a maize crop, as the yield of which is sensitive to the occurrence of drought (Moeletsi and Walker, 2012; Wetterhall *et al.*, 2014). Under rain-fed conditions, which is the most common practice in South African smallholder cropping systems, crops can be susceptible to mild-extreme drought conditions due to the variability of rainfall (DAFF, 2012; Bouagila and Sushama, 2013).

Drought serves as one of the three abiotic factors primarily responsible for limiting maize development and productivity in the developing world in addition to problems of waterlogging and low soil fertility (Khalili *et al.*, 2013). Drought occurs when soil water in the root zone is reduced to an extent that a plant is not able to absorb enough water coupled with water loss from the plant through transpiration (Das, 2012). Furthermore, the severity of a drought event can generally be attributed to various climatic factors such as high temperatures, strong winds, and low relative humidity (Wilhite and Svoboda, 2000).

Crop responses to drought conditions vary in all stages of development and the effects of the event could affect the rate of germination and emergence; development of root, leaf and stem; flowering, pollination, grain-filling as well as the quality of the grains (Prasad *et al.*, 2008). Moreover, Khalili *et al.* (2013) stated that the severity of drought damage could be influenced by various factors including the duration of the event, its intensity, crop growth stage, different responses of the various crop varieties and soils to water stress. The effects of drought on the on the development and growth of a medium maturing maize crop (120-day) are summarised in Table 1.1.

Table 1.1: The effects of drought on the development and growth of a medium maturing (120-day) maize crop.

Maize phenological stages (Days after planting)	Drought effects
Emergence – Early Vegetative (1-30)	Slowed seedling growth
Vegetative – Tasselling (31-60)	Reduced stem height and smaller ear size
Silking – Grain-filling (61-90)	Delayed silking, pollination failure and shorter gran-filling period
Maturity (91-120)	Drying of leaf (No further effect on final yield)

Source: (Lauer, 2003)

Identifying potential drought risk prior planting and during the development of the crop is essential, as it allows decision makers to make timely, informed decisions on how to eliminate the accompanying drought impacts (Wu *et al.*, 2004). However, it is important to identify this risk during the crop's early growth stages, as drought occurrence at the wrong time (sensitive crop stage), might be too late to take relevant action. Thus, knowledge on the evolution of drought in the study area, coupled with drought preparedness and mitigation plans might reduce the risk associated with the occurrence of damaging droughts.

1.2 Research problem and objectives

1.2.1 Research problem

In South Africa, recurring drought conditions have always been an endemic feature of climate, affecting all sectors of society, with agriculture being the first sector to feel the effects as it primarily depends on precipitation for crop growth and production (Vogel *et al.*, 2000; Woli, 2010). Thus, drought serves as one of the major environmental factors resulting in large reductions in agricultural production, contributing toward food insecurity (Vogel *et al.*, 2000; Wilhelmi *et al.*, 2002; Khalili *et al.*, 2013).

A study conducted by Kruger (2006) over the period 1910 – 2004 reported significant decreases in annual precipitation in the northern regions of the Limpopo Province, which is where the Luvuvhu River catchment is located. Climate change predictions presented in the IPCC (2014), have indicated a decrease in mean precipitation and an increase in temperature over mid-latitude and subtropical dry climate regions, suggesting a possible increase in future drought occurrences. Furthermore, a study conducted by Li *et al.*, (2009) stated that due to climate change, drought risk would increase in drought-prone areas, particularly in subtropical climates, placing stress on food security systems.

Pretorius and Smal (1992) demonstrated that long-term downtrends in South Africa's crop production were often associated with periods of meteorological drought. Various studies assessing drought impacts on agriculture have also shown a high confidence in predictions that climate change will have adverse effects on crop yields (IPCC, 2014). It is evident that future droughts pose a threat to the agricultural sector and this has raised major concern, particularly for the vulnerable small-scale farmers who merely rely on rain for crop production. For this reason, drought serves as one of a large number of risks that a farmer must be prepared for.

In order to improve agricultural productivity and assist in the development of measures to secure livelihoods of vulnerable farmers in any given region, it is critical to conduct relevant investigations on the timing, frequency, intensity and perceived impacts of drought on production. This will also reduce agricultural vulnerability and deliver food security for those small-scale farmers who are dependent on rain–fed agriculture (Mishra and Singh, 2010). However, such assessments require an understanding of past droughts and their impacts in the region under investigation (Mishra and Singh, 2010). Research questions presented here are thus, 1) what is the ideal planting date for maize, based on the evolution of drought? and 2) how is the frequency and severity of drought expected to change under future regional climate projections?

1.2.2 Objectives of the study

This study set out to assess impacts of past and future agricultural drought events in relation to the development of the maize crop. The main objectives of the study were to investigate:

1. Probable impacts of drought occurrence in relation to different planting dates on maize production, and
2. The variability and severity of drought during each physiological stage of the maize growing period;

The specific objectives were to:

a) Apply the selected indices to assess the climatology of drought based on historical data, during the maize growing season.
b) Determine the temporal variation and drought trends.
c) Investigate future occurrences of drought during the growing period of maize utilizing climate change projected data.

1.3 Organisation of the thesis

- The thesis comprises of five chapters.
- Chapter 1 describes the background of the research project, problem statement, and objectives.
- The second chapter outlines a review of literature such as general drought concepts, the history of drought in the Limpopo province and the use of drought indices in the context of their application to agriculture.
- Following the literature review, Chapter 3 provides an overview of the Luvuvhu River catchment as well as the methodology used for assessing drought conditions.
- The results and discussion are presented in Chapter 4, and lastly,
- Conclusions are drawn and recommendations are provided in Chapter 5.

CHAPTER 2 LITERATURE REVIEW

2.1 The concept of drought

Drought recurrence is one of the most common climate disasters affecting most economic sectors (Sonmez *et al.*, 2005; Li *et al.*, 2009). Drought occurs in nearly all parts of the world, even in different climate regimes, i.e. high and low rainfall areas (Mniki, 2009). This is generally due to drought being considered a prolonged precipitation deficiency, relative to a region's long-term average (Dai, 2011). It is thus essential to note that unlike aridity or desertification where low rainfall is a permanent climatic feature of a specific region, drought is merely a temporary phenomenon (Das, 2012).

Droughts are unique in their climatic characteristics, and each event can be differentiated from the other by intensity, duration and spatial coverage (Wilhite and Svoboda, 2000). Intensity refers to the degree of precipitation deficit and/or the severity of its impacts (Dlamini, 2013). However, Das (2012) mentioned that drought intensity forms gradually, such that droughts are not easily detected, thus, making this phenomenon difficult and complex. Duration is another important characteristic of drought, as it is interrelated to the timing and the effectiveness of rains such as delays in the onset of the rainy season and occurrence of rainfall in relation to crop growth stages (Wilhite and Svoboda, 2000). It is closely associated with intensity, as it determines the impact of drought (Dlamini, 2013). According to Wilhite and Svoboda (2000), the duration required to establish a drought event commonly starts from two months and can even last for years.

It is rare to determine areas over which drought evolution is homogeneous due to the differences in their spatial characteristics. Droughts of different intensities and duration can occur over a large geographical region covering a few hundred square kilometers (Das, 2012). This implies that a region can be subjected to a severe drought, while concurrently the neighbouring regions experience normal or even above normal rainfall conditions (Vicente-Serrano, 2006). Such variation is caused by complex atmospheric circulation patterns; hence, it is important not to associate droughts with a single type of atmospheric condition (Vicente-Serrano, 2006).

2.1.1 Drought definitions

To better understand the various concepts associated with drought, it is important for its definition to provide a clear understanding of how it can be quantified (Sun, 2009). There is, however, no generally accepted definition partly because it is viewed in different ways by different multiple users; hence definitions should be region and impact specific in order to be used in a meaningful manner for decision makers (Vogel *et al.* 2000; Austin, 2008; Das, 2012). Drought definitions can be described as either conceptual or operational (Wilhite and Glantz, 1987).

Conceptual definitions refer to the general definitions commonly found in the dictionary such as:

- "Drought is when the actual rainfall is less than the rainfall which is climatically appropriate for the existing conditions" (Palmer, 1965).
- "Drought is a decrease of water availability over a particular period and area" (Beran and Rodier, 1985).
- "Drought is a prolonged deficiency of rainfall that results in a water shortage for some activity" (IPCC, 2007).

These definitions help to understand the meaning of drought, however, they can be fairly vague and do not provide quantitative answers to when, how long and how severe a drought is. Operational definitions, on the other hand, provide the degree of departure from the average precipitation over a certain period (Das, 2012). These type of definitions specify the characteristics and thresholds that define the onset, severity, development and the end of a drought event (Wilhite, 2000). In South Africa, a commonly used operational signal for drought alert in several drought monitoring and assistance schemes is that provided by the South African Weather Service (SAWS, 2016), stating that "any amount of precipitation less than 75% of the mean annual precipitation constitutes a drought.

2.1.2 Types of drought

Drought has many characteristics – it always starts with a deficiency of precipitation, affecting soil moisture, stream flows, groundwater, ecosystems and human beings depending on its duration and intensity (Smakhtin and Hughes, 2004). Based on these biophysical, socio-economic and socio-political attributing factors, Vogel and van Zyl (2016) explained drought as a 'wicked problem and challenge'. Thus, drought was classified into four different categories viz. meteorological, agricultural, hydrological and socioeconomic. Figure 2.1 shows the interrelation between the different types of drought and generally, the significance of each type of drought to a given region mainly depends on its agroclimatic features and socioeconomic characteristics.

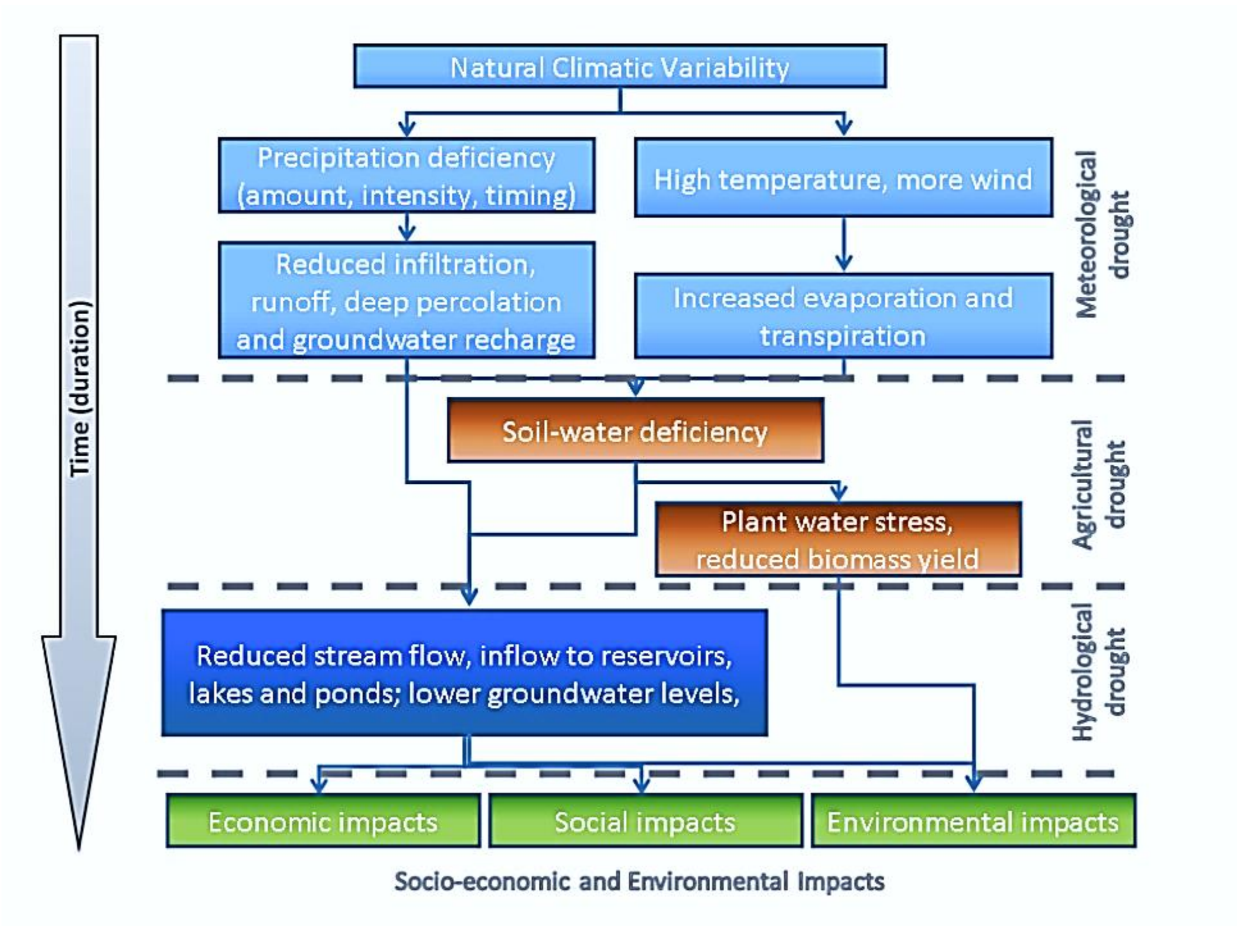


Figure 2.1 Types of drought and their impacts in relation to the duration of the event (Source: NDMC, 2006).

a) Meteorological drought

A meteorological drought is defined solely based on the degree of dryness and the duration of the dry period due to precipitation deficiency (Lourens, 1995; Wilhite, 2000; Smakhtin and Hughes, 2004). This type of drought focuses on the physical characteristics of drought, such as the departure of precipitation from normal, rather than on the impacts associated with it. It also depends on what the normal climatic conditions of the area being investigated are, merely due to the high variation of atmospheric conditions resulting in precipitation deficiencies from region to region (Sun, 2009). Thus, a modification of a definition developed in one part of the world is necessary prior to application elsewhere (Mniki, 2009).

b) Agricultural drought

Agricultural drought occurs when there is a deficiency in soil water content over a particular period, significantly affecting crop production, pasture yields and livestock holdings (Bordi and Sutera, 2007). It is linked to several characteristics of meteorology such as precipitation deficits and high evapotranspiration, often leading to soil water deficits, thus affecting agricultural processes (Das, 2012). It is worthy to note that plant water needs are dependent on the crop variety, environment and stage of plant growth thus; agricultural drought does not only depend on the amount of precipitation received but also on the timing and duration of the drought (Fraisse *et al.*, 2011).

c) Hydrological drought

Hydrological drought refers to below normal amounts of inland surface water bodies such as lakes, dams, streams, rivers as well as groundwater levels (Fraisse *et al.*, 2011). It normally follows prolonged meteorological and agricultural droughts, due to a considerable time lag between precipitation deficiencies and hydrological system elements (Sun, 2009). This type of drought could also be aggravated by the rate of water losses through factors such as evapotranspiration as well as social activities that include extracting water for irrigation or domestic use and this could further lead to a reduction of streamflow levels and discharge from reservoirs (Kusangaya *et al*., 2013).

d) Socioeconomic drought

Socioeconomic drought occurs when the deficiency of precipitation starts to affect human health, wellbeing, and quality of life (Sun, 2009). This is due to the reliance of food grains and livestock grazing on precipitation (Sun, 2009). Socioeconomic drought reflects the interrelation of meteorological, agricultural and hydrological drought to the vulnerability of human beings (Wilhite and Buchanan-Smith, 2005). Moreover, the occurrence of this type of drought can increase due to a change in the frequency of other drought types, a change in societal vulnerability to water shortages, or both (Dlamini, 2013). Population growth can also further intensify the impacts of socioeconomic drought due to increased demand of certain economic goods (Dlamini, 2013).

2.2 Causes of drought

In South Africa, the El Niño Southern Oscillation (ENSO) phenomenon serves as one of the main causes of drought (Tyson and Preston-Whyte, 2000). ENSO refers to the interaction of the global atmosphere with the eastern and central Pacific Ocean, which results in variability in many ocean and climate patterns (Holloway *et al.*, 2012). During an El Niño event, clouds that are generally the source of high rainfall, move offshore and thus cause warm and dry conditions over the south eastern parts of the subcontinent (Tyson and Preston-Whyte, 2000; Austin, 2008). Contrary to El Niño, a La Niña event is associated with above-normal rainfall, although not always resulting in floods (Nicholson and Selato, 2000). However, not all drought events in South Africa can be explained by the ENSO (Tyson and Preston-Whyte, 2000; Vogel *et al.*, 2000). Wright *et al.* (2015) explained that the frequent drought occurrences over South Africa could also be linked to regular climate variability and global warming due to climate change.

Intra- and inter-annual climate variability and droughts form part of the earth's natural climate dynamics and to some extent caused by oscillations and complex patterns of global and regional climate systems (Wright *et al.*, 2015). Moreover, climate change varies from climate variability, such that it is based on changes in the climate system, resulting from global warming which is caused by natural forcings and human activities (IPCC, 2014). These forcings alter the composition of the global atmosphere, together with natural climate variability, ultimately leading to the occurrences or intensity of extreme weather events (Cubash *et al.*, 2013).

Meteorological drought occurs when irregular tropical sea surface temperatures (SSTs) or other conditions trigger persistent anomalies such as high-pressure systems in large-scale atmospheric circulation patterns (Hoerling *et al.*, 2006). Agricultural drought, on the other hand, occurs when the atmospheric anomalies are enhanced by local feedbacks (reduced evaporation and humidity) related to dry soils and high temperatures, thus causing crop failure (Dai, 2011). Similar to meteorological and agricultural drought, precipitation deficiency is the main cause of hydrological drought. However, irregularities in the frequency of more intense precipitation, erosion, and poor water management can cause or further intensify this type of drought (Dai, 2011). A socioeconomic drought is then said to occur when there is an imbalance between the supply of a certain economic product and the demand, as a result of the above-mentioned drought types (Sun, 2009).

Drought can occur naturally due to a prolonged dry spell, as well as artificially as a result of increasing water demand caused by human activities such as increasing population, irrigation and environmental awareness (Tessema, 2007). Thus, policy makers should not only consider ENSO-related variations in precipitation as part of drought management but should also incorporate all aspects of climate variability, agricultural management and societal behaviours (Wilhite, 2000).

2.3 Determination of drought

The most commonly used methods to detect the onset, intensity, duration, as well as to study drought's spatial and temporal patterns are drought indices (Wu *et al.*, 2004). They have been developed over the years to detect and monitor the occurrence and impacts of droughts and due to the differing concepts of drought to various users, the criteria for measuring drought severity cannot be captured by a single index. (Heim 2002; Song *et al.*, 2013). Some of the widely used drought indices are briefly explained in Table 2.1.

Table 2.1: Description of various drought indices

	Drought index	Description
a)	**Palmer Drought Severity Index (PDSI)** - Palmer (1965)	Calculates water supply and demand, incorporating soil moisture.
b)	**Crop Moisture Index (CMI) -** Palmer (1968)	Observes short-term (weekly) moisture conditions during crop development.
c)	**Water Requirement Satisfaction Index (WRSI)** - Frere and Popov (1979)	Monitors available water to the crop during the growing phase.
d)	**Normalized Difference Vegetation Index (NDVI)** - Tucker (1979)	Monitors vegetation behavior in the invisible and infrared range of the electromagnetic spectrum.
e)	**Surface Water Supply Index (SWSI)** - Shafer and Dezman (1982)	Measures drought in high elevation river basins depending on snow melt for water.
f)	**Crop Specific Drought Index (CSDI)** - Meyer *et al*. (1993)	Based on the ratio of calculated and potential evapotranspiration.
g)	**Standardized Precipitation Index (SPI)** - McKee *et al.* (1993)	Monitors precipitation probabilities for any time scale.
h)	**Standardized Precipitation Evapotranspiration Index (SPEI)** - Vicente-Serrano *et al.* (2010)	Monitors precipitation deficits, incorporating the effects of evapotranspiration
i)	**Dry spells assessment**	Calculates a number of dry days during the growing season.

a) Palmer Drought Severity Index (PDSI)

The Palmer Drought Severity Index (PDSI) was initially developed as a meteorological index by Palmer (1965) and modified in 1989, to calculate drought based on precipitation, soil water content, runoff, stream flow and evapotranspiration. It links the severity of drought to accumulated weighted variances between actual precipitation and water requirements (Das, 2012). Due to this concept, the PDSI is more relevant for hydrogeological use and can further be referred to as the Palmer Hydrological Drought Index (Hayes *et al*., 1999). This index was designed to ignore other water balance factors such as irrigation (Hayes *et al*., 1999). Furthermore, the PDSI takes into consideration that a wet month during a prolonged drought and near-normal precipitation following a severe drought does not imply the end of a drought (Barua, 2010).

The formulation of the Palmer Drought Severity Index is centered on zero and ranges from ≤ -4 to ≥ 4, with values with negative values indicating drought and wet conditions represented by negative values (Smakhtin and Hughes, 2004). This index has further been proven useful as a drought-monitoring tool across the United States as it was originally based on data limited to U.S. regions (Hayes *et al*., 1999). However, this index has little acceptance elsewhere, such as in Australia and South Africa due to its poor performance in regions with high rainfall variability (Dai, 2011). Moreover, research also indicated that this index is inappropriate to measure agricultural drought conditions, as it does not reflect short-term changes in the water status (Hayes *et al*., 1999).

b) Crop Moisture Index (CMI)

Palmer (1968) later designed the Crop Moisture Index (CMI) based on similar formulations of the PDSI. Following the PDSI shortfall of not capturing potential agricultural droughts, the CMI was developed to evaluate meteorological dry and wet spells for short-term (weekly) periods (Jordaan, 2012). It uses weekly precipitation, temperature and a CMI value of the previous week as inputs (Jordaan, 2012). The resultant CMI is the sum of the evapotranspiration anomaly represented by slight positive to negative values, whereas water surplus is reflected by positive values (Das, 2012).

This index was designed for monitoring short-term drought conditions affecting crop development (Hayes *et al*., 1999). However, it cannot be used to monitor long-term droughts as captures near-normal precipitation with a drought as adequate, thus underestimating prolonged drought conditions (Das, 2012). Jordaan (2012) stated that the CMI's application is therefore limited to the growing season of a specific crop and cannot be used to monitor droughts outside a specific growing season (longer-term droughts).

c) Water Requirement Satisfaction Index (WRSI)

In 1979, the Food and Agriculture Organization (FAO) developed the Water Requirement Satisfaction Index (WRSI) to assess drought stress to a crop. It is defined as the proportion of actual evapotranspiration to crop water requirement corresponding to maximum evapotranspiration (Senay and Verdin, 2002).

Formulation of the index requires input data of rainfall, evapotranspiration, soil water holding capacity and crop coefficients (Kc). The use of soil water holding capacity determines the amount of potential stored soil water, while Kc values are used to adjust for the growth stage and land cover condition (Martin *et al.*, 2000). The index is calculated after each dekad and WRSI at the end of the growing period shows the degree of water stress to the crop throughout development. The interpretation of WRSI corresponding to drought starts at 100 (no drought) and a decrement in the index indicates an increase in the severity of drought. A seasonal WRSI value <80 specifies a drought episode and <50 indicates total crop failure (FAO, 1986).

Due to its ability to integrate meteorological components to crop and soil factors, the index can further be used as a proxy for crop performance (Jayanthi and Husak, 2013). It has been widely used to monitor agricultural drought and forecast crop yield across the world, including in the Southern African Development Community (SADC) (Martin *et al.*, 2000; Rafi and Ahmad, 2005; Jayasree *et al.*, 2008; Senay *et al.*, 2011).

d) Normalized Difference Vegetation Index (NDVI)

The most prominent vegetation index used for monitoring drought is the Normalized Difference Vegetation Index (NDVI), developed by Tucker (1979). The index monitors vegetation reflectance in the invisible and infrared range of the electromagnetic spectrum. According to Padhee (2013), the formulation of NDVI is given as the ratio of the difference between near-infrared and red wavelengths to their sum.

NDVI values range between -1 to +1 and a large NDVI value represents dense vegetative cover, permeable soil and extensive soil moisture (Eden, 2012). Meanwhile smaller NDVI reflect little or no vegetation, moderate impermeable soil and minimal soil moisture (Padhee, 2013). The mean of NDVI is used for overall greenness, maximum of NDVI for peak greenness, NDVI amplitude for real time greenness and multi-temporal NDVI for vegetation monitoring (Padhee, 2013). This index is not crop specific and therefore, it accounts for the entire vegetated area. However, it is to date one of the most commonly used index for drought monitoring, based on remote sensing data (Anyamba *et al.*, 1996; Legesse, 2010; Eden, 2012; Padhee, 2013).

e) Surface Water Supply Index (SWSI)

Shafer and Dezman (1982) developed the Surface Water Supply Index (SWSI) to complement the PDSI focusing mainly on non-irrigated areas. The index incorporates both climatological and hydrological components for high elevation river basins (Shafer and Dezman, 1982). The application of the SWSI is important in areas with heavy snowfall, where snowpack becomes more significant during winter months with stream flow replacing the importance of snowpack during warm summer months (Jordaan, 2012). The SWSI is calibrated such that it accounts for relatively homogeneous regions, and does not consider snow accumulation and subsequent runoff (Hayes *et al*., 1999).

The SWSI is standardized and ranges between -4.2 and +4.2 (Jordaan, 2012). One of the main limitations of the SWSI is that it cannot compare values between basins and regions, simply due to the fact that any changes in a basin would require a re-developed of the whole SWSI algorithm in order to account for changes in stream flow and the weighting of other components (Hayes *et al*., 1999).

f) Crop Specific Drought Index (CSDI)

Meyer *et al*. (1993) originally designed the Crop Specific Drought Index (CSDI) based on assessing agricultural drought for specific crops, specific soils and the growth stage during which the drought stress occurs. The authors developed the CSDI initially for maize and then extended to soybeans, then wheat and later sorghum (Wu and Wilhite, 2004). The index is based on computing actual evapotranspiration to potential evapotranspiration (Jordaan, 2012).

The index calculates the degree of drought stress to a specific crop of interest using daily meteorological data, soil, and information on the growth stage of the specific crop of interest (Meyer *et al*., 1993). It can, therefore, be used as a proxy for predicting crop yield and it has advantages over other drought indices such as PDSI and CMI (Wu and Wilhite, 2004; Jordaan, 2012).

g) Standardized Precipitation Index (SPI)

McKee *et al*. (1993) developed the Standardized Precipitation Index (SPI) based on the probability of precipitation for 3, 6, 12, 24, and 48-month time scales. Calculation of SPI is based on precipitation data, which is fitted to a probability distribution and then transformed to follow a normal distribution (McKee *et al*., 1993). This index uses a classification system whereby wet conditions are indicated by positive values and negative values represent drought conditions (Sonmez *et al.*, 2005).

The SPI is limited to long-term seasonal precipitation datasets, and using small historical records might lead to falsely large positive or negative SPI values (Hayes *et al*., 1999). Due to its standardized nature, wet and dry periods can be monitored in the same way (Das, 2012). This index finds more applications of monitoring drought conditions around the world than other drought indices, as it requires fewer input data and the calculations are flexible (Smakhtin and Hughes, 2004; WMO, 2006).

h) Standardized Precipitation Evapotranspiration Index (SPEI)

An extension of the widely used SPI is the Standardized Precipitation Evapotranspiration Index (SPEI), which is designed to take into account both precipitation and evapotranspiration in determining drought (Vicente-Serrano *et al*., 2015). This index was developed by Vicente Serrano *et al*. (2010) based on a climatic water balance i.e., the difference between actual precipitation and potential evapotranspiration.

The Standardized Precipitation Evapotranspiration Index uses the same classification system as that of the SPI, with evapotranspiration incorporated. Due to the inclusion of temperature, the main advantage of this index above other indices is in its ability to combine the effects of temperature variability and evapotranspiration in assessing drought risk (Vicente-Serrano *et al.,* 2010; Potop *et al.*, 2012). However, one major disadvantage of this index is in the calculation of evapotranspiration as lack of reliable data for all the parameters might lead to errors (Vicente-Serrano *et al.*, 2010). Therefore, in order to reduce this sensitivity to error, Vicente-Serrano *et al*. (2015) added two more methods for calculating evapotranspiration in addition to the Thornthwaite method.

i) Dry spells assessment

Dry spells assessment is based on calculating consecutive dry days depending on the users' aims and area under investigation (Mathugama and Peiris, 2011). In addition to the occurrence, the length (short, medium and long) of each dry spell can be analysed to determine the frequency of dry days as well as the longest spell occurrence during the growing season.

A dry spell was initially defined as a period of at least 15 consecutive dry days in which none of those days received ≥1.0 mm (Sivakumar, 1992). Thereafter, numerous modifications have been done to this definition (Stern *et al.*, 2003; Mathugama and Peiris, 2011; Masupha *et al*., 2015), whereby different threshold values were introduced according to the researcher's interest and climatic conditions of the study area. Dry spell values are then fitted to a probability distribution, in order to investigate the dry spell behaviour at a particular region. Among the most preferred probability models, the following still find more application, viz. Markov Chains of different orders (Martin-Vide and Gomez, 1999), Negative Binomial model (Deka *et al.*, 2010), Weibull distribution (Mzezewa *et al.*, 2010) and Log normal distribution (Muita, 2013).

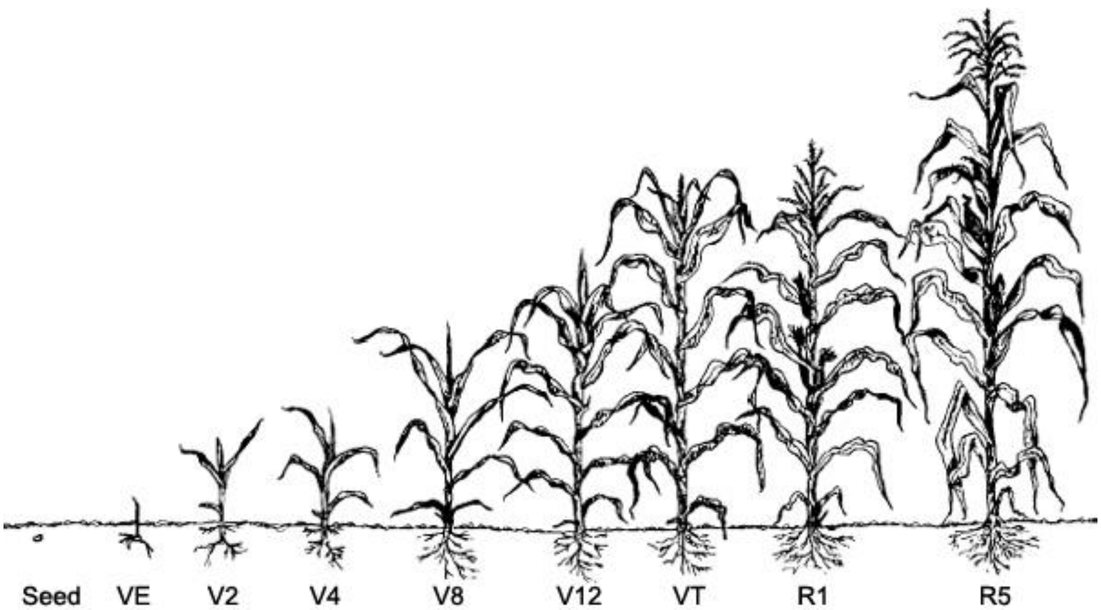
Similar to the SPI, dry spell analysis can be performed over a range of climatic regions at different time scales, however, it is based solely on precipitation and does not take into account soil water and crop factors. However, in order to assess potential drought stress to the crop, calculations can be done in accordance with the crop's phenological cycle (Sivakumar, 1992).

2.4 Effects of drought on the physiology and development of maize

Drought stress on crops is primarily caused by a deficiency of water in the root zone as well as increased evapotranspiration rates, particularly, referred to as an imbalance between crop water requirements and the amount a rainfall received during the growing season (Sun, 2009; Lisar *et al*., 2012). This is due to the simultaneous occurrence of droughts and heat stress resulting from an increase in air temperature, affecting the physiology, development, and yield of crops (Prasad *et al.*, 2008). Crop water requirements can be explained as the amount of water needed for optimal growth and development (FAO, 1986). In South Africa, maize water requirements are estimated at between 450 mm and 600 mm depending on the local environment (du Plessis, 2003). Consequently, the ability and extent of crops to withstand drought stress vary with crop variety, climate and soil type of a given area (Akıncı and Lösel, 2012; Lisar *et al*., 2012).

The identification system by Ritchie *et al.* (1996) divides crop development into two main stages, viz. vegetative and reproductive (Figure 2.2). The “E” in the first vegetative stage represents emergence, while the numbers in the subsequent stages symbolize the number of leaves with visible collars. The last vegetative stage is the labelled as VT, with the “T” representing tasselling. Whereas the reproductive stages are all labelled in a numerical order, from Silking – Maturity.

The moisture condition during crop establishment is largely attributed to the amount of water received prior to planting (Sun, 2009). At this stage, soil moisture conditions for crop establishment is important because sufficient soil moisture conditions encourage good germination and early root growth (Whitmore, 2000). It was reported by Aslam *et al.* (2013) that these early stages are very sensitive to drought, and thus seedling growth could stop when exposed to drought conditions due to an expansion of cells and cessation of elongation. It was also found that shoot weight could be reduced by 40% and root weight by 58% during drought stress (Aslam *et al.*, 2013).



Vegetative Stages		Reproductive Stages	
Stage	**Description**	**Stage**	**Description**
VE	Emergence	R1	Silking - silks visible outside the husks
V1	One leaf with collar visible	R2	Blister - kernels white
V2	Two leaves with collars visible	R3	Milk - kernels yellow with milky inner fluid
V(n)	(n) leaves with collars visible	R4	Dough - milky inner fluid thickens
VT	Last branch of tassel is	R5	Dent - nearly all kernels are denting
	completely visible	R6	Physiological maturity

Figure 2.2 Developmental stages of the maize crop (Source: Ritchie *et al*., 1996).

Plant and leaf size is commonly determined during emergence to V8, and thus, drought stress during this stage could result in reduced plant height and leaf area (Heiniger, 2001; Aslam *et al.*, 2013). The reduction in leaf area will thus reduce the area available for photosynthesis to occur and this could have harmful effects on the final yield (Heiniger, 2001; Lauer, 2003). Drought stress can further influence the process of photosynthesis by means of stomatal closure and slowed carbon dioxide (CO_2) uptake (Prasad *et al.*, 2008). In addition to the negative effects of photosynthesis, drought stress also inhibits chlorophyll synthesis in the leaves (Lisar *et al*., 2012).

From V8 to VT (tasseling), ear size is determined and kernel rows are initiated (Heiniger, 2001). Drought stress during this stage may result in smaller ear size and a reduction of potential kernels (Lauer, 2003). Moreover, potential yield could be reduced by up 30% depending on the length and severity of drought stress (Heiniger, 2001). Beyond these development phases, drought stress starts to have far adverse effects on the potential final yield (Lauer, 2003).

For the maize plant, the reproductive stages are considered the most sensitive, as inadequate soil water level, coupled with high temperatures, and low relative humidity during this period can either alter the initiation or shorten the duration of the developmental phase (Prasad *et al.*, 2008; Aslam *et al.*, 2013). During flowering, drought stress could delay the process and cause pollination failure due to decreased pollen or ovule function (Drexler, 2008). Aslam *et al.*, 2013 mentioned that drought stress a week before and after silking might lead to an abortion of ovules, ears, and kernels. Severe drought may also cause silks to become non-receptive to pollen and even result in 100% loss (Heiniger, 2001; Lauer, 2003). Drought stress during this phase can further delay silking, reduce silk elongation, and inhibit embryo development after pollination (Lauer, 2003). During this stage, maize grain yield could be reduced by up to 8% for each day of stress and this may cause serious challenges for farmers, as there would be no chance for re-planting or recover for the yield lost (Lauer, 2003; Kamara *et al.*, 2007).

Drought conditions that continue during silking and into the grain-filling period will have detrimental effects on severe maize yield losses (Heiniger, 2001). Drought stress effects during stage include faster drying up of leaves, shorter grain-filling period, and low kernel weight due to a decreased flow of CO_2 (Lauer, 2003; Kamara *et al.*, 2007). Drought stress can further have profound effects on the development of grains, such that they change the composition and nutritional quality (Prasad *et al.*, 2008). Furthermore, a premature black layer may form in the kernels once they have reached the dough stage and this will ease dry weight accumulation, thus leading to further yield losses (Heiniger, 2001; Lauer, 2003). Once the grain has reached physiological maturity, the growth rate decreases and therefore, the effects of drought stress on the yield cease (Heiniger, 2001).

2.5 Previous droughts and its impacts on agriculture

The Southern African Development Community (SADC) region is identified as one of the regions in Africa that are prone to frequent occurrences of drought with extreme droughts observed at intervals of 10-20 years for more than a century (FAO, 2004). The Limpopo River Basin is no exception, with notable agricultural seasons subjected to severe drought recorded during 1982/83, 1987/88, 1991/92, 1994/95, 2002/03, 2008/09 and 2015/16 (Agricultural Disaster Management Policy, 2011; BFAP, 2016).

Vogel *et al.* (2000) indicated that the 1982/83 and 1991/92 were the worst droughts, as compared to other severe droughts, in which most of the Southern and central areas of Africa were affected. However, during the 2015/16 the country experienced one of the most extreme droughts of the past century that affected the summer agricultural production adversely (BFAP, 2016).

During the 1982 drought, widespread livestock deaths were reported and water restrictions were enforced (Dlamini, 2013). In1991/92, compared to pre-drought levels, crop production failed significantly, even in community and household gardens (Dlamini, 2013). Furthermore, a report conducted by Pretorius and Smal (1992) indicated estimates of a decline in the gross value added by the agricultural sector based on summer crop estimates for 1991/92 as compared to the previous agricultural season (Figure 2.3). As a result, these food shortages caused malnutrition and increased vulnerability to disease (Nyabeze, 2004).

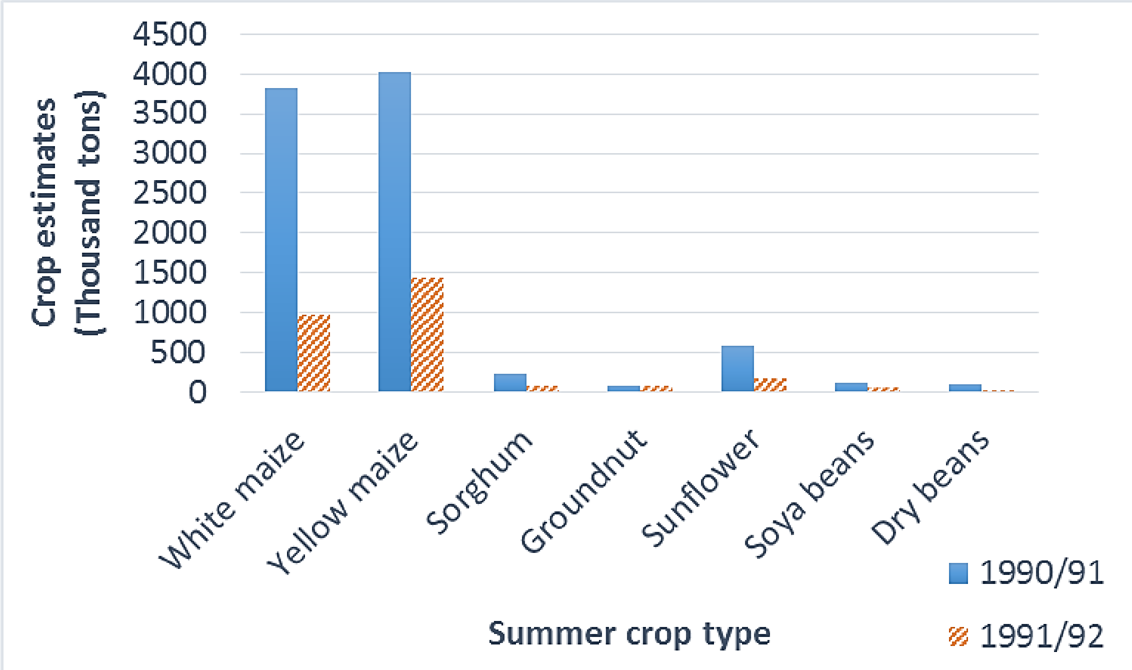


Figure 2.3 Production estimates for summer crops during the 1990 – 1992 seasons (Source: Pretorius and Smal, 1992).

In the 1994/95 season, crop yields in South Africa were less seriously affected, as the eastern and north-eastern parts received 75 – 100% of normal rainfall (Vogel *et al.* 2000). The rainfall proved inadequate to supplement water reserves but was sufficient only for crops to yield enough to supply home consumption (Vogel *et al.* 2000). This then necessitated the drilling of boreholes in the Limpopo province (Dlamini, 2013).

For the 2015/16 season, a significant share of the maize area was planted in January due to severe drought conditions experienced during the optimal planting window (October – December), while other farmers opted not to plant (BFAP, 2016). Figure 2.4 presents the total maize production of the area planted from 2010 to 2016 in South Africa and the season 2015/16 revealed the lowest production in the seven years. During this season, maize was imported instead of being exported to earn foreign revenue as common practice, and thus, the agricultural sector shifted to a negative trade position (BFAP, 2016).

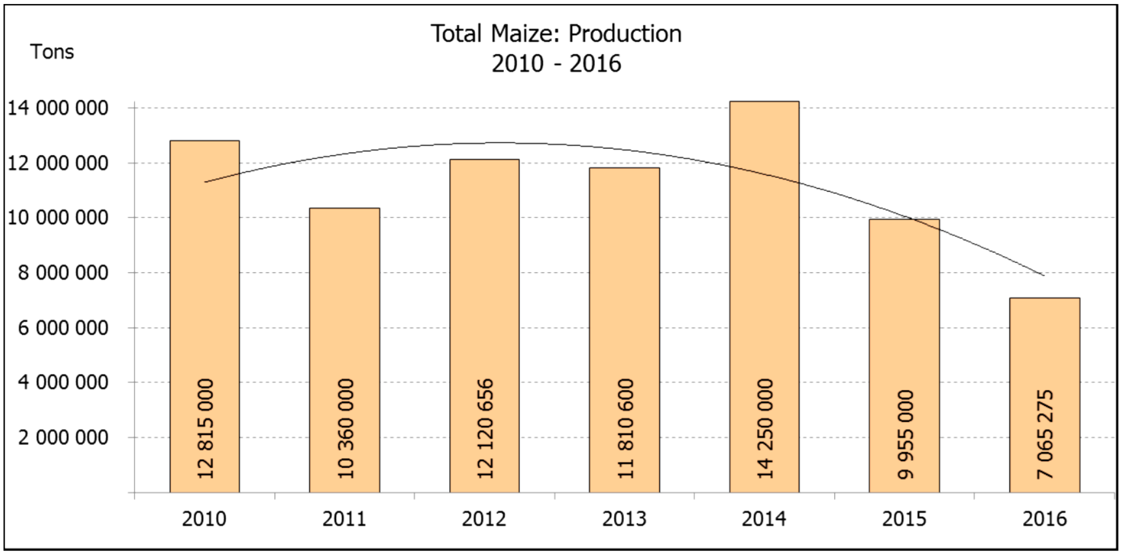


Figure 2.4 Total maize production from 2010 to 2016 in South Africa (Source: DAFF, 2016).

2.6 Impacts of projected climate change on droughts

Climate change projections are based on future changes in the climate system, attributed to past or current forcings as well as natural climate variability (IPCC, 2014). These forcings, whether natural or human-driven, can cause variation in the occurrence or intensity of extreme weather events such as heatwaves, droughts, floods, and wildfires (Cubash *et al.*, 2013). Hence, Mishra and Singh (2010) described climate change as one of the major threats to sustainable development in the 21st century.

The most commonly used method for predicting future climate change and its impacts is by utilizing global climate models (GCMs) employing different emission scenarios. These emissions scenarios have been developed since 1990 (Table 2.2) by the Intergovernmental Panel on Climate Change (IPCC) to analyse the possibility of climate change, its impacts and probable mitigation methods (IPCC, 2000). They have been updated from using schematic representations of annual percentage increases in global average concentrations of greenhouse gases (GHG) to including, future trends in energy demand, population increases, economic and technological developments, emitted greenhouse gases, changes in land use and behaviour of climate system over a long period of time (IPCC, 2001; Bjørnæs, 2013). The most recently developed set of scenarios (Representative Concentration Pathways - RCPs) improved from the previously used ones in a sense that it can provide information about the location of numerous emissions and land use changes at a resolution of approximately 60 Kilometres (Bjørnæs, 2013).

Table 2.2: History of emission scenarios used as input to climate models as per contribution to the Intergovernmental Panel on Climate Change (IPCC) Assessments reports to provide (Bjørnæs, 2013).

Year	**Name**	**Assessment report contributed**
1990	SA90	First
1992	IS92	Second
2000	SRES - Special Report on Emission Scenarios	Third and Forth
2009	RCP - Representative Concentration Pathways	Fifth

Assessments on drought projections are often based on computing drought indices using outputs from different climate models (Ujeneza, 2014). However, the spatial resolution of these models is rather coarse (300 km × 300 km) and at that scale, their outputs cannot be used directly at a local level due to their inability to capture local topographical features and cloud dynamics, etc. (Coulibaly, *et al.*, 2005). Therefore, downscaling techniques should be used to convert the coarse spatial resolution of GCM outputs to high-resolution projections over local areas under investigation (CSIR, 2010).

These downscaled scenarios have been applied over South Africa, for various scenarios using regional climate models (RCMs) and when considering the Limpopo Province, the following climate conditions were noted, relative to the baseline period 1971-2005 (CSIR, 2010; DEA, 2013a):

- With an assumption that there will be moderate to high increases in greenhouse gas (GHG) emissions, temperatures are likely to increases by about 2°C to 2.5°C by 2040-2060, reaching about 3°C by the far future (2080-2100). Similar changes can be expected for minimum and maximum temperatures.

- Rainfall is expected to increase in the mid-future by more than 20 mm/month – 90th percentile. However, for the far-future, when the climate change signal is best developed, most ensemble members project modest to significant drying for this region, for both summer and autumn seasons.
- Other ensemble members project increases in average annual rainfall of more than 40 mm/year for the far-future in the median of projections.
- For the ensemble members that project general drying, the biggest rainfall reductions are projected to occur over this region.
- Evaporation rates are estimated to increase by the end 2100.

It is worthy to note that these model projections provide contrasting indications of future climatic conditions associated with drought in the region. According to DEA (2013a), most modelling approaches indicate that there is less uncertainty on the increase of temperatures, while there is no agreement on the possibility of both drying and wetting trends in almost all parts of South Africa, as rainfall is more challenging to predict. Furthermore, an increase in evaporation rates was projected and this could increase drought occurrences and intensity, possibly even in regions where total rainfall might increase (CSIR, 2010).

The prediction of future droughts is possible, provided that reliable future projections of climatic elements impacting the occurrence of drought are available (Mishra and Singh, 2010). The relationship between temperature and rainfall to drought is quite complex, however, recent studies have indicated how temperature affects the occurrence of droughts (Ujeneza, 2014; Vicente-Serrano *et al.*, 2015).

2.7 Drought policy and preparedness

2.7.1 National drought policy

The recurrence of drought in South Africa has in the past caused serious implications for the agricultural sector, vulnerable communities and the overall economy of the country (WMO, 2006; Austin, 2008). Thus, in order to reduce risk, the South African Government has developed and implemented relevant policies to plan for and respond effectively to drought's far-reaching effects (Austin, 2008). According to Wilhite *et al.* (2005), it is essential for a national drought policy to comprise of a clear set of functional principles, reflecting regional, population and economic variances. Moreover, the policy should be able to create awareness and understanding of the drought concept as well as its impacts on social vulnerability (Wilhite *et al*., 2014).

Over time, drought policies have been modified and the approach has shifted from focusing on relief-response to risk-reduction (Austin, 2008). Before the year 1990, stock farming was considered the best in South Africa due to its ability to adapt to rainfall variability, and thus the drought policy focused on this type of farming, placing much emphasis on climatically marginal areas (Smith, 1993; Monnik, 2000). Thereafter, during the early 1990s, this policy underwent several amendments due to unpremeditated results that caused serious implications on farmer development in the country (Austin, 2008).

Following this period, farmers were obligated to change management practices such that they encourage conservation of natural resources and promote long-term economic sustainability (Austin, 2008). The government then placed more emphasis on the management of disaster risk by introducing the 'Disaster Management Act of 2002'. Moreover, the Government developed an agricultural risk insurance bill in 2002 to reduce the vulnerability of farmers to natural disasters such as drought (Wilhite *et al.*, 2005). In 2005, much significance occurred for agriculture and drought risk management following the introduction of the 'National Disaster Risk Management Framework of 2005' that primarily focused on a more proactive response to natural disasters (Austin, 2008).

In 2004/05, Department of Agriculture, Forestry, and Fisheries (DAFF) implemented a Comprehensive Agricultural Support Programme (CASP), by which monthly early warning climate advisories from the South African Weather Service (SAWS) are obtained to help farmers manage climate-related risks. The Department further launched a "broad risk and disaster management" campaign whereby 52 259 small-scale farmers participated in the drought relief scheme (DAFF, 2017).

More recently, the Department (DAFF) issued the 2015/16 to 2019/20 Strategic Plan which intends on maintaining a comprehensive structure of internal controls and risk management by implementing the "Risk Management Plan" as part of its "Programme And Subprogramme Plans", incorporated in the Strategic objectives (DAFF, 2015). Moreover, adequate consideration of risk management associated with climate change has been set and DAFF plans of focusing on an adaptation intervention category for the next five years, addressing initiatives such as research on climate change vulnerability mapping, crop suitability and biogas production for various farming systems (DAFF, 2015).

2.7.2 Drought monitoring, early warning, and mitigation

Previously, preparedness, early warning, and mitigation of climate disaster risk were given less consideration and this placed a greater need to plan and improve operational capabilities as communities became increasingly vulnerable to risks associated with these risks (Batisani, 2011). As this vulnerability increased globally, drought policy makers started to develop strategies that could assist to mitigate future drought impacts (Wilhite *et al*., 2014). However, if an emphasis is placed in all portions of the disaster management cycle (Figure 2.5), the effects of drought and the need for emergency relief measures from the government would be lessened substantially (Wilhite *et al*., 2014). Continuous drought monitoring, early warning and mitigation serve as the three key components to planning for drought (Wilhite *et al*., 2014). Due to the slow onset nature of drought over time, these components are necessary at a local to national level, as they will allow for early detection of potential impacts over any region (Hayes *et al*., 1999).

A drought monitoring system could ideally be based on various indicators that generally characterize droughts such as precipitation, soil water, crop water requirements and water supply indicators for better decision making and implementation of effective strategies prior and during drought events (Hayes *et al*., 1999). Generally, there are two types of monitoring systems, i.e. surface observation and remote sensing networks (Das, 2012). However, in order to provide a more comprehensive system for decision making and planning, the two systems can be combined to establish a three-dimensional monitoring system comprising of ground, space and mobile-based observations (Wu *et al.*, 2004).

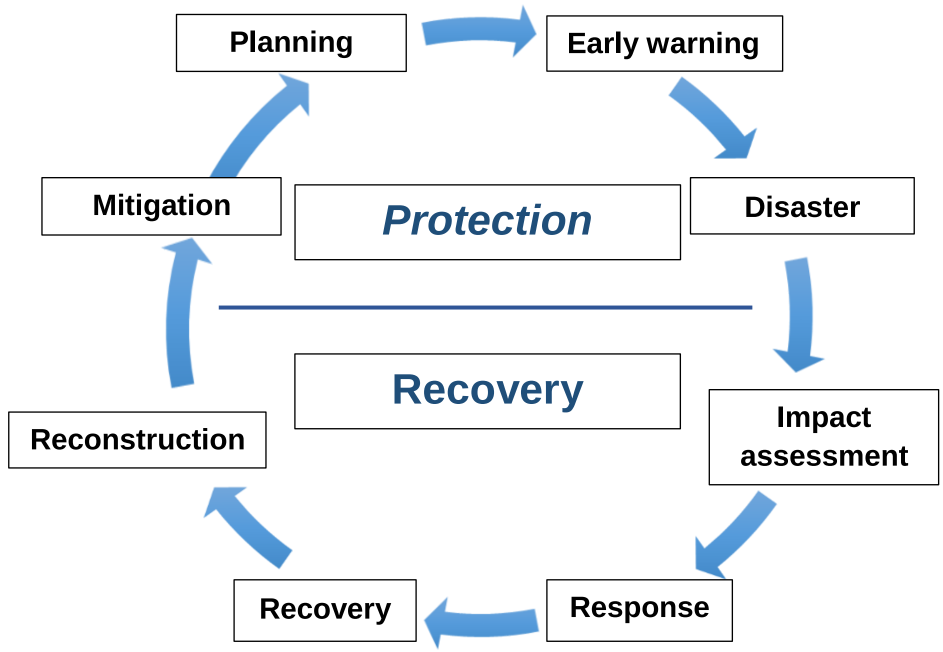


Figure 2.5 Disaster management cycle (Source: NDMC, 2013).

Early warning systems (EWS) as another key factor to drought preparedness, link the information on risk to a communication system that provides a lead-time for implementing possible mitigation measures (Pulwarty and Sivakumar, 2014). According to the United Nations International Strategy for Disaster Reduction (UNISDR, 2006), such systems should provide risk information, technical monitoring service, effective dissemination and awareness to relevant decision makers. In addition, during drought recovery, these systems should also provide information on the status of recovery and detect the end of the event (Hayes *et al*., 1999).

It is evident that the use of the media (newspapers, television, radio and social media platforms) in this regard, is important as it would educate and inform the public on the drought status as well as probable coping mechanisms available (Wilhite *et al*., 2000; Austin, 2008). In South Africa, several institutions have established climate information dissemination systems such as the drought monitoring desk by SAWS (http://www.weathersa.co.za/city-pages/); Umlindi by the ARC (http://www.arc.agric.za/Pages/Newsletters.aspx); DroughtSA by WRC (http://www.droughtsa.org.za/) and eNCAWeather (http://www.enca.com/weather), to provide an easy access to forecasts, current status and impacts of drought and other extreme climate conditions.

The management of drought risk on agriculture should further comprise of coping strategies that mitigate the impact of this hazard on crop production. Drought mitigation refers to a proactive approach that focuses on minimizing the severity and impacts of drought by implementing measures prior an event (van Zyl, 2006). Adaptation can also be linked to these mitigation measures in order to reduce vulnerability to drought prone areas (Thomas, 2008). More often, the rural areas are the most vulnerable to risks associated with drought on crop production systems, due to abandonment, an absence of investment, lack of information, insufficient or lack of quality climate and hydrological data (Austin, 2008; Thomas, 2008; Pulwarty and Sivakumar, 2014). Therefore, proper knowledge on drought mitigation measures and adaptation practices could increase the resilience of such communities and thus improve livelihoods and food security (DEA, 2013b).

However, there is no particular strategy that can be adopted universally, as the impacts of drought are region specific. Some strategies believed to mitigate drought impacts at farm level are (Thomas, 2008; Das, 2012; DEA, 2013b):

- Practice conservation agriculture - CA (e.g. Intercropping, mulching, rainwater harvesting, crop rotation, amongst others),
- Crop diversification,
- Shifting planting dates and
- Groundwater exploitation.

Apart from farm level, strategies can also be adopted on a national level for effective mitigation and adaptation; such as (Das, 2012, DEA, 2013b):

- Monitoring, early warning systems, and decision support tools,
- Promote sustainable crop management and stocking densities to ease pressure on vulnerable ecosystems,
- Implement relevant financial schemes, and
- Expansion of research on drought management.

CHAPTER 3 METHODOLOGY

3.1 Overview of the study area

Figure 3.1 displays the location of the Luvuvhu River catchment and the eight weather stations utilized in this study. The catchment is found within the Vhembe district, in the north-eastern corner of the Limpopo Province in South Africa; between longitudes 29.49 and 31.23 and latitudes -22.17 and -23.17. It covers an area of 5941 km^2 subdivided into 14 quaternary catchments (Nkuna and Odiyo, 2011).

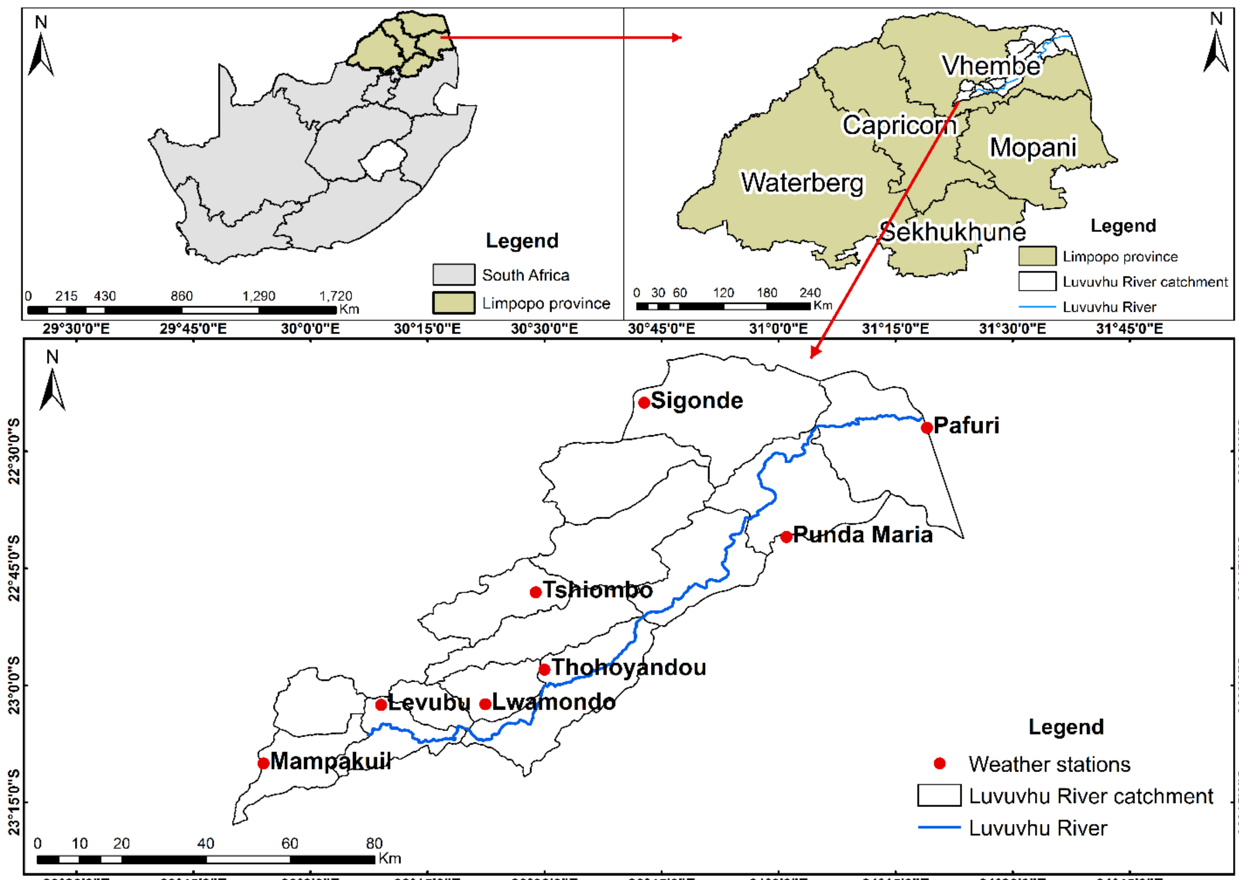


Figure 3.1 Location of the Luvuvhu River catchment with the distribution of the eight weather stations used in the study.

The catchment has a humid subtropical climate, that is fairly warm to hot during summer and dry in winter (FAO, 2005). Precipitation varies greatly (Figure 3.2) and it is mostly determined by orographic patterns, with the topography in the catchment ranging from

200m to 1300m. The highest rainfall occurs in the south-western regions of the catchment where the Soutpansberg Mountains are located. Meanwhile, the north-eastern regions are regarded as the driest and sparsely populated. The mean annual temperature ranges from <18°C in the mountainous regions to >24°C in the north-eastern plains of the catchment (Figure 3.2). The catchment is characterized by a wide spectrum of soils, with sandy loam soils being the most prevalent and soil water-holding capacity ranging from 21 mm to 80 mm (DWAF, 2004; ARC, 2016).

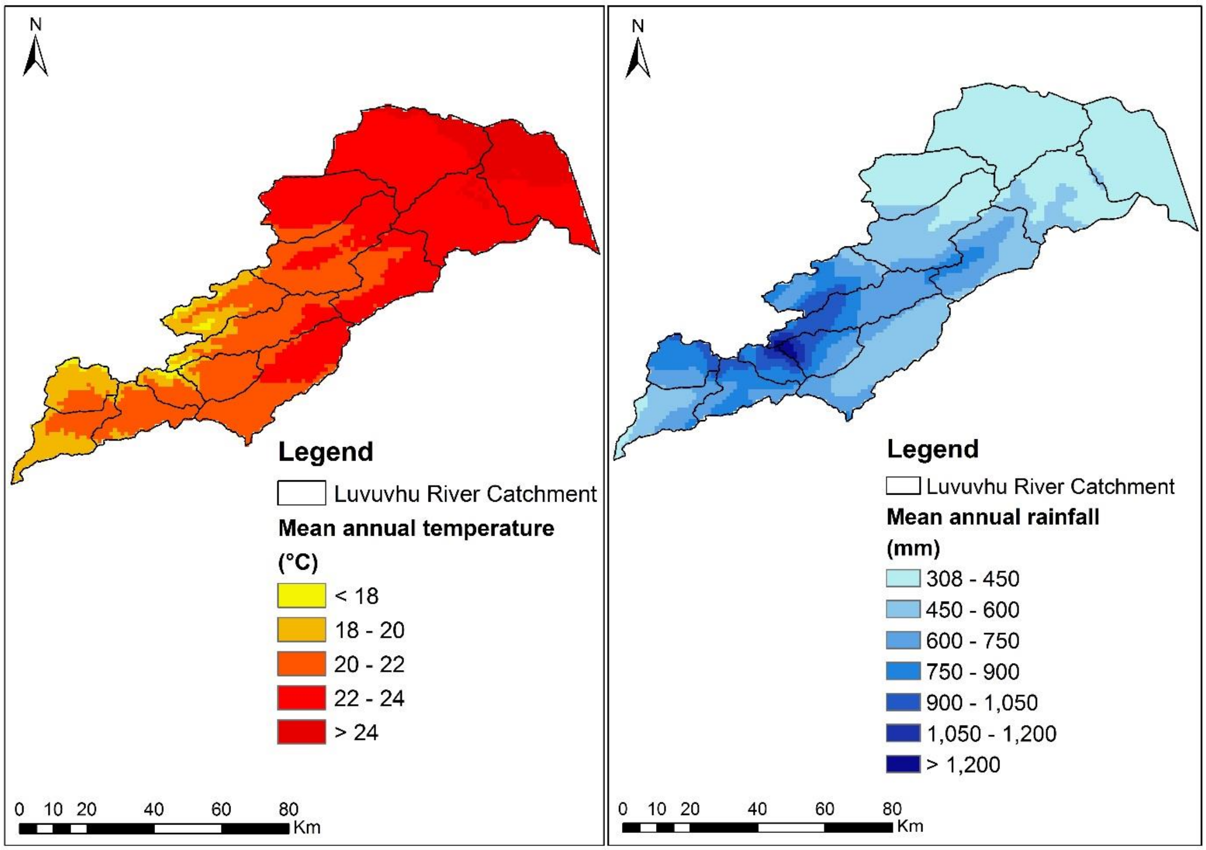


Figure 3.2 Long-term mean annual temperature and mean annual rainfall at the Luvuvhu River catchment.

Although large-scale commercial forests, fruits, and vegetable farms are dominant in the high rainfall regions of the catchment, small-scale and subsistence livestock and rain-fed maize farming controlled by regional Venda and Tsonga Chiefs, play a crucial role in the improvement of livelihoods and food security in most parts of the catchment (Griscom *et al.*, 2009; DWAF 2012). However, a great number of people in the catchment acquire their income from remittances, livestock and rain-fed maize farming (DWAF, 2004). Moreover, a change in land cover, whereas forests and shrubs were cleared for the provision of fuelwood, maize fields, and pasture, has been noted since 1978 due to a swift increasing population in the catchment (WRC, 2001; DWAF, 2004; Jewitt *et al*., 2004).

3.2 Data

The geographical description of the eight weather stations representative of the cultivated dryland regions within the catchment, comprising datasets of ≥30 years is given in Table 3.1. The dataset (daily rainfall, minimum, maximum temperature, and soil water holding capacity) was obtained from Agricultural Research Council (ARC, 2015). For data quality, the climate data was inspected and the ARC stand-alone patching tool, which uses the Inverse Distance Weighting and the Multiple Linear Regression methods using neighbouring stations was used to fill missing values (Shabalala and Moeletsi, 2015; Moeletsi *et al*., 2016).

Table 3.1: Details of the eight weather stations utilized in the study

Station Name	Latitude (°S)	Longitude (°E)	Altitude (m)	Timeframe (Rainfall)	Timeframe (Temperature)	SWHC (mm)
1. Mampakuil	-23.167	29.900	945	1945-2004	-	21-40
2. Levubu	-23.042	30.151	880	1945-2014	1983-2014	61-80
3. Lwamondo	-23.044	30.374	648	1954-2014	1983-2014	61-80
4. Thohoyandou	-22.967	30.500	600	1982-2014	1983-2014	41-60
5. Tshiombo	-22.801	30.481	653	1954-2014	1983-2014	41-60
6. Punda Maria	-22.683	31.017	457	1945-2004	1975-2004	41-60
7. Sigonde	-22.397	30.713	428	1983-2014	1983-2014	21-40
8. Pafuri	-22.450	31.317	305	1945-2004	1975-2004	21-40

Projected climate data of daily rainfall and temperature at a resolution of 0.5° × 0.5° for the period 1981 – 2100 was obtained from the Council for Scientific and Industrial Research (CSIR). The data is an output of detailed projections of a regional climate model titled the Conformal-Cubic Atmospheric Model (CCAM), which was downscaled from the projections of a coupled global climate model (CGCM) called the CSIRO Mark3.5, to a high resolution over southern Africa. These CGCM projections formed part of the Coupled Model Intercomparison Project Phase 3 (CMIP3) and contributed to Assessment Report Four (AR4) of the Intergovernmental Panel on Climate Change (IPCC). The simulations are for the SRES-A2 emission scenario, which assumes the highest CO_2 emissions, moderate economic growth, high population increase, focusing on self-reliance and local identity (IPCC, 2000).

3.3 Drought index selection

Each index provides a different measure of drought; therefore, one drought index cannot be utilized for monitoring this complex phenomenon completely (Heim, 2002). Drought risk studies that employ numerous indices are meaningful, as they may provide a comprehensive representation of the drought conditions (Heim, 2002).

Agricultural drought links meteorological drought and soil moisture deficits to crop growth and production (Wilhite and Glantz, 1987). As a result, an assessment of agricultural drought requires joint analyses of rainfall, temperature and soil moisture conditions (Hao and Aghakouchak, 2013). For the purpose of this study, various meteorological and agricultural drought indices were reviewed and the two drought indices, i.e. Standardized Precipitation Evapotranspiration Index (SPEI) and Water Requirement Satisfaction Index (WRSI) were selected based on the following criteria:

1. Quantify precipitation deficit at multiple time scales (Gocic and Trajkovic, 2014).
2. Account for the role played by the soil in regulating moisture in the crop root zone (Jayanthi and Husak, 2013).
3. Integrate crop factors such as potential evapotranspiration (Meyer *et al.*, 1993).
4. Be applied in areas where there are limited weather and yield data (Wu *et al.*, 2004).
5. Be computed in accordance with the phenological cycle of the crop (Wu *et al.*, 2004).

3.4 Formulation of drought indices

3.4.1 Standardized Precipitation Evapotranspiration Index (SPEI)

For calculating the Standardized Precipitation Evapotranspiration Index, the algorithm developed by Vicente-Serrano *et al.* (2010) was applied using the R package SPEI version 1.6 developed by Bergueria and Vicente-Serrano (2013). The package calculates potential (PET) or reference evapotranspiration (ET0) using three methods, viz. the Thornthwaite, Penman-Monteith and Hargreaves method (Vicente-Serrano *et al.*, 2015).

For the present study, the Hargreaves method was applied, using geographic coordinates of the station, minimum and maximum air temperature as inputs. This method was selected for the reason that it has been demonstrated as the best alternative for quantifying evapotranspiration in large-scale studies where data on certain climate variables were missing (see e.g. Droogers and Allen, 2002; Moeletsi *et al.*, 2013; Trambauer *et al.*, 2014). Moreover, Hargreaves and Allen (2003) indicated that this method leads to a remarkably smaller sensitivity to error in climatic inputs as it calculates ET0 based on the minimum and maximum air temperature and extra-terrestrial radiation. The Hargreaves method is given by (Hargreaves and Samani, 1985):

$$ET0 = 0.0023 \times Ra \times TD^{0.5} (Tm + 17.8) \quad (3.1)$$

where:

$ET0$ = Daily reference evapotranspiration

TD = Difference between maximum and minimum temperatures

Tm = Average monthly temperature

Ra = The water equivalent of the extra-terrestrial radiation in mm/day:

$$Ra = \frac{1440}{\pi} (G_{sc}.d_r)[\Psi_s sin(\varphi)\, sin(\delta) + cos(\delta)\, sin(\Psi_s)] \quad (3.2)$$

where:

G_{sc} = solar constant (0.0820 MJ/m^2/min)

d_r = inverse relative distance from earth to the sun, given by:

d_r $= 1 + 0.033\cos[\frac{2\pi(JD)}{365}]$

JD = Julian day of year

Ψ_s = sunset hour angle (rad)

δ = solar declination (rad), given by:

$0.409\sin(2\pi.\frac{JD}{365} - 1.39)$

φ = latitude of the location

To convert of MJ/m^2/d to mm/d, multiply MJ/m^2/d value by 2.43

The next step was to compute the climatic water balance (D), i.e. the difference between precipitation (P) and $ET0$ for a given month:

$$D = P - ET0 \quad (3.3)$$

where:

D = Climatic water balance

P = Precipitation

$ET0$ = Reference evapotranspiration

A log-logistic probability function was then fitted to the data series of D, where the log-logistic is the distribution of a random variable whose logarithm follows a logistic distribution. The probability density function $F(x)$ of a log-logistic distribution is given by (Vicente-Serrano *et al.*, 2015):

$$F(x) = \frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1}\left[1 + \left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right]^{-2} \text{, with } \gamma \leq x < \infty,\ \alpha < 0,\ \beta < 0 \text{ and } \gamma < 0 \quad (3.4)$$

where:

α = scale parameter

β = shape parameter

γ = location parameter

The function $F(x)$ was then transformed to a normal variable following the classical approximation of (Abramowitz and Stegun, 1965):

$$Z = U - \frac{c_{0+} c_1 U + c_2 U^2}{1 + d_1 U + d_2 U^2 + d_3 U^3} \tag{3.5}$$

where:

$U = \sqrt{2\ln(H(x))}$ for 0 < $H(x)$ ≤ 0.5 with $H(x)$ = 1 – $G(x)$ as the probability of exceeding D. The constants are given as c_0 = 2.515517; c_1 = 0.802853; c_2 = 0.010328; d_1 = 1.432788; d_2 = 0.189269 and d_3 = 0.001308.

The Standardized Precipitation Evapotranspiration Index (SPEI) value is the obtained variable *Z* and it ranges from ≥ +2 (extremely wet) and ≤ -2 (extremely dry). Negative SPEI values specify drought conditions (Table 3.2) and the larger the negative value, the more intense the drought.

Table 3.2: SPEI classification representing drought conditions.

SPEI	Drought category
>0	No drought
0 to -0.99	Mild drought
-1.0 to -1.49	Moderate drought
-1.5 to -1.99	Severe drought
≤-2.0	Extreme drought

(Source: McKee *et al.*, 1993).

3.4.2 Water Requirement Satisfaction Index (WRSI)

A crop water balance model in Instat+ software was used to generate WRSI. In this model, the seasonal WRSI was calculated a proportion of actual evapotranspiration (AET) to crop water requirement (WR), expressed by (Senay and Verdin, 2002):

$$WRSI = \frac{AET}{WR} \times 100 \tag{3.6}$$

The crop water requirement (WR) was taken as the product of reference evapotranspiration (ET0) and crop coefficient (Kc), given by Allen *et al.* (1998):

$$WR = ET0 \times Kc \tag{3.7}$$

Reference evapotranspiration was estimated using the Hargreaves method (see Section 3.4.1). The crop coefficient (Kc) was calculated using the single Kc approach developed by Allen *et al.* (1998). This approach of calculating Kc values was based on the four growing stages of the maize crop, i.e. initial stage; development stage; mid-season stage and late season stage. The crop coefficient (Kc) values for initial and end were obtained from Allen *et al.* (1998) and adjusted according to the area's climatic conditions. Thereafter, intermediate Kc values were linearly interpolated to obtain the crop coefficients during the whole growing period (Figure 3.3).

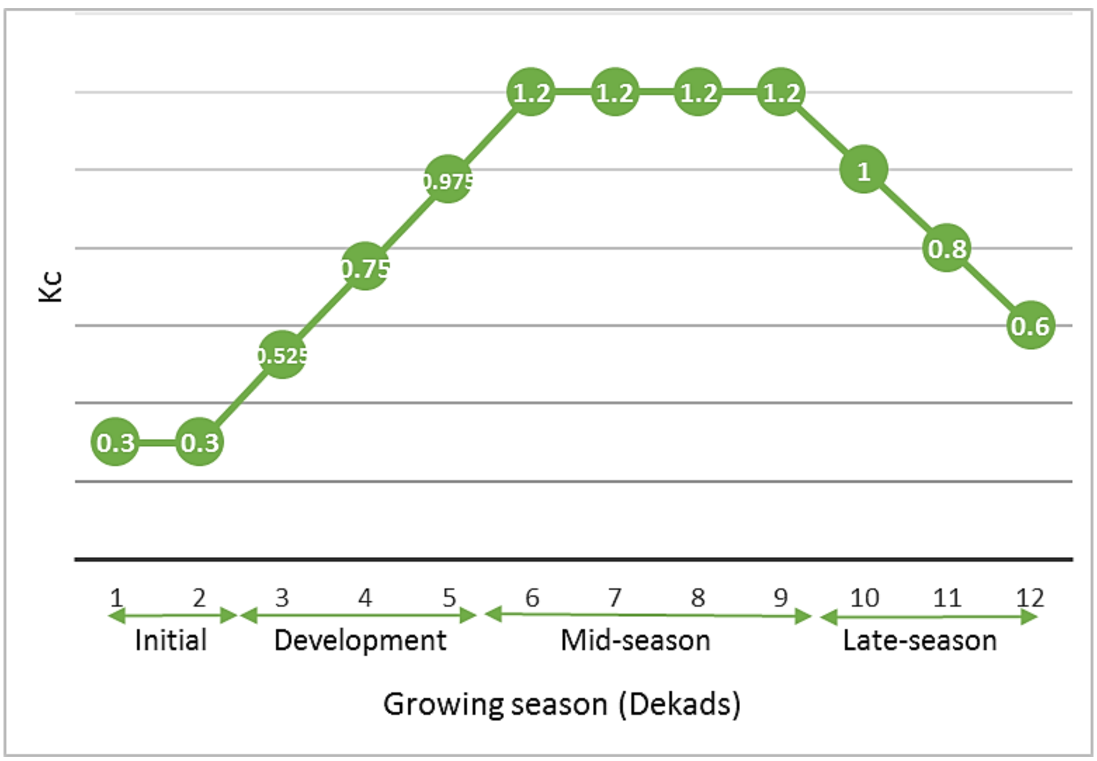


Figure 3.3 Dekad crop coefficient (Kc) curve during each growing phase of maize.

After determining the water requirements (WR), the AET, representing the actual amount of water lost from the soil water reservoir was estimated using the soil water balance method incorporated within the model. In order to determine AET for the maize crop, rainfall (PPT) was added to the soil water content to produce a plant-available-water (PAW) value:

$$PAW_i = SW_{i-1} + PPT \qquad (3.8)$$

Where:

SW_{i-1} = soil water content at the end of the previous i^{th} time interval (mm/dekad).

Depending on the PAW in the soil reservoir, the value of AET was estimated using the following equations (Senay and Verdin, 2002):

$$AET = WR \quad when\ PAW \geq SWC \qquad (3.9)$$

$$AET = \frac{WR}{SWC} \times PAW \quad when\ PAW < SWC \qquad (3.10)$$

$$AET = PAW \quad when\ AET > PAW \qquad (3.11)$$

where:

WR = crop water requirement

SWC = critical soil water level in the soil reservoir

WRSI is calculated after each consecutive dekad and cumulative water stress experienced by the maize crop throughout the growing period is then given at the end of the growing season (FAO, 1986). The index starts with a value of 100 and a reduction occurs as the crop undergoes water stress in a form of water deficit and if the water surplus is greater than 100 mm (Allen *et al*., 1998). Therefore, as illustrated in Table 3.3, a WRSI value <80 specifies a drought episode and a decrement in the index indicates an increase in the severity of the drought, with a seasonal WRSI value less than 50 indicating total crop failure (FAO, 1986).

Table 3.3: WRSI classification for drought conditions and crop performance.

WRSI	Drought classification	Crop performance description
80 – 100	No drought	Good
70 – 79	Mild	Satisfactory
60 – 69	Moderate	Average
50 – 59	Severe	Poor
<50	Extreme	Total crop failure

(Source: FAO, 1986; Legesse, 2010).

3.5 Analysis of drought under historic and future climates

To assess the possible impact of climate change on drought characteristics in relation to maize, a medium maturing (120-day) maize crop was considered. Analysis of drought was conducted following three consecutive planting dates, based on the mean start of the rainy season in the area (Masupha *et al*., 2015). A drought was categorized according to the definition of each index and the output series were arranged starting from 1st July to 31st June (signifying agricultural year).

Assessment of drought was conducted during the whole growing period of maize as well as for each phenological stage. The outputs were then analysed using the following statistical methods: frequency analysis, probability distributions, non-parametric Spearman's correlation test and independent t-test. For future drought projections, drought indices were computed using outputs from the CGCMs and time series variations were evaluated. These steps are elaborated in the subsequent sections.

3.5.1 Analysis of drought by SPEI

A drought episode was defined as any month with a SPEI value ≤ 0 as presented in Table 3.3. The four drought categories (mild, moderate, severe and extreme) were used to designate drought severity and drought frequency was considered as the number of times in which SPEI was ≤ 0. To analyse drought during the maize growing period, SPEI was analysed based on selected the planting dates.

Relative frequencies of the different drought categories for each growing stage of a 120-day maturing crop was calculated using the 1-month SPEI series. The frequencies were calculated by dividing the total number of drought events during the analyzed period by the number of drought events for each agricultural season. The frequency distributions were then calculated at each station and plotted using STATISTICA software. This method has effectively been applied in several studies (Potop and Možný, 2011; Edossa *et al*., 2014; Ujeneza, 2014) for investigating the climatology of droughts over various regions.

3.5.2 Analysis of drought by WRSI

The crop water balance model in Instat+ software was run using nine planting dekads as the starting period, i.e. from the first dekad of October (Oct_dek1) until the last dekad of December (Dec_dek3). Dekadal WRSI values were then obtained and drought severity was interpreted according to the classes in Table 3.4.

To investigate crop performance in relation to drought occurrence during each growing season, probabilities of WRSI following the 9 planting dekads were analysed and plotted for each station using STATISTICA software. Based on the WRSI series, it was determined that the Normal and Johnson SB distributions (Table 3.4) generated the best-fitting curves for the different stations randomly. The Johnson SB distribution is related to the Normal distribution and in this regard, it was applied to transform data points which did not follow a standard normal curve (Dell Inc., 2015). These distributions were selected from over 23 different types of probability distributions according to the Anderson-Darling (A-D) goodness-of-fit test at 5% significance level.

Table 3.4: Normal and Johnson SB distribution models used to formulate WRSI cumulative distribution functions (Dell Inc., 2015).

Probability model	Density function	Parameters
Johnson SB	$F(x) = \frac{\delta}{\lambda\sqrt{2\pi}\, z(1-z)} exp\left[-0.5\left(\gamma + \delta \ln(\frac{2}{1-z})\right)^2\right],\ for\ \xi \leq x \leq \xi + \lambda$	γ = shape parameter δ = shape parameter ($\delta > 0$) λ = scale parameter ($\lambda > 0$) ξ = location parameter
Normal	$F(x{:}\, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} exp\left[-0.5\left(\frac{x-\mu}{\sigma}\right)^2\right], for\ 0 \leq x \leq \infty$	μ = mean of x σ = standard deviation of x

3.5.3 Temporal variability and trends analysis

Outputs from the drought indices were analysed to investigate the evolution of drought occurrences and severity during the whole study period. Thereafter, the Spearman's Rank Correlation test was conducted at α (0.05) significance level, to determine trends in droughts. This non-parametric correlation test quantifies the strength and direction between two variables using the coefficient ρ values ranging from -1 to 1. In this regard, zero indicates no trend, while a decreasing and increasing trend is represented by a negative and positive ρ value, respectively. Moreover, the closer the coefficient ρ value to the absolute value specifies a stronger decrease or increase in trend (Gitau, 2011). The following method is used for calculating the coefficient ρ to determine trends (Gitau, 2011):

$$\rho = -6 \sum_{i-1}^{n} \left(\frac{d_i}{n(n^2-1)}\right)^2 \quad (3.12)$$

where:

d_i = difference between each rank of *x* and y values

n = number of data pairs

3.5.4 Evaluation of extreme widespread dry and wet agricultural seasons

Three stations representing the different rainfall regions in the catchment, from high to low (Lwamondo, Tshiombo, and Sigonde) were randomly selected and analysis was conducted using December results, as this was identified as the period in which the drought was more intense compared to other planting dates.

Notable agricultural seasons subjected to extreme widespread drought given by SPEI (<-2) were assessed by studying the actual rainfall and evapotranspiration during the summer rainfall season in the catchment i.e. from October to April (ARC, 2016). Subsequently, seasons reflecting WRSI values corresponding to extreme drought (<50) were evaluated to measure the extent to which the crop water requirement had been satisfied during each growing stage. On further analysis, the seasons in which there was no drought (wet seasons) and whereby there was mild to moderate drought at low rainfall regions (due to high risk of recurrent drought occurrence) were also evaluated to inspect the intra-seasonal variability of rainfall throughout the growing season.

3.5.5 Simulations of drought under future projected climates

Future drought events in the catchment were generated from time series of SPEI and WRSI, for four 30-year periods, viz. base period 1980/81-2009/10, near-future 2010/11-2039/40, intermediate-future 2040/41-2069/70 and far-future 2070/71-2099/100. A drought was analysed according to the definition of each index, based on the average onset of significant rains in the area (November) as indicated by Masupha *et al*. (2015).

Drought frequencies were obtained by calculating the ratio of the number of drought events corresponding to each drought category to the total number of agricultural seasons analyzed. The independent t-test was performed in STATISTICA software at 10% significance level to assess significant changes in the projected drought indices reflecting drought frequency and severity. The test was defined as:

H0: ($\mu_1 = \mu_2$) - the means of the drought indices for future climate periods are equal to the base period.

H1: $(\mu_1 \neq \mu_2)$ - the means of the drought indices for future climate periods are different from the base period.

Test statistic (NIST/SEMATECH, 2013):

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{s_1^2/N_1 + s_2^2/N_2}} \tag{3.13}$$

where:

$\bar{X}_1$ and $\bar{X}_2$ = sample means

N_1 and N_2 = sizes of the samples

s_1^2 and s_2^2 = variances of the samples

Rejection or failure to reject the null hypothesis would then be on the basis that the corresponding p-value is less or greater than the significance level of 0.10, respectively. This statistical test assumes normal distributions. However, this is a reasonable assumption, given that SPEI values are transformed into normal variables during the calculations and WRSI values revealed to be normally distributed (see Section 3.5.2). This method has been widely used to measure the differences between the means of drought indices for investigating historical and future droughts (Ngaka, 2012; Stagge *et al.*, 2015; Wanders and Lanen, 2015; Westphal, 2016).

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Analysis of drought on maize using Standardized Precipitation Evapotranspiration Index (SPEI)

4.1.1 Relative frequency of drought by SPEI for each growth stage of maize

It can be depicted from Figure 4.1 that mild droughts occur most frequently (100%) during all growth stages, following the three planting dates (October, November, and December). During the first stage of the crop, considering the first planting date, it can be noted that the highest frequency (47%) was at Tshiombo, while other stations revealed a frequency of ≤ 30%. Severe drought conditions were observed at six of the seven stations, with Tshiombo being the only station revealing no occurrence at this stage. Extreme drought was observed only at Sigonde, giving a frequency of 6%. Relative to planting in November, it can be seen that moderate droughts were most frequent at Punda Maria (44%), followed by Levubu (40%). Severe drought frequency was the highest (13%) at Levubu and Sigonde, while Lwamondo and Punda Maria revealed no occurrences. Similarly, planting in November resulted in extreme drought conditions only at Sigonde. When looking at December planting date, results indicate that moderate drought conditions were most frequent at Sigonde (53%) and Tshiombo (47%), giving a return period of once in two drought events. The highest frequency (16%) of severe droughts was observed at Levubu, with Tshiombo revealing no occurrence; while extreme droughts were identified only at Thohoyandou, with a 6% frequency.

During the vegetative stage (stage 2), moderate drought conditions were most frequent (44%) at Punda Maria, while the lowest frequency (27%) was observed at Pafuri, following planting in October. Severe droughts were observed at five of the seven stations, while extreme drought was noted only at Sigonde. For planting in November, Sigonde revealed the highest frequency (53%) of moderate drought conditions, with the least frequency (22%) observed at Lwamondo. Severe droughts during this stage were detected most frequently at Levubu, while an occurrence of extreme drought was noted only at Thohoyandou. Relative to planting in December, high frequencies of moderate drought conditions were observed at Lwamondo (54%), Thohoyandou (67%), Tshiombo (44%)

and Sigonde (47%). Frequencies of severe drought during this stage ranged from 6% at Tshiombo to 20% at Punda Maria, while there was no occurrence of extreme droughts observed at all stations following this planting date.

When considering planting in October for stage 3, it can be observed that moderate drought was most frequent at Sigonde (53%), followed by Tshiombo and Pafuri with 44% and 43%, respectively. Severe drought conditions were most frequent at Levubu (16%), with Tshiombo revealing no occurrence of drought during this stage. Extreme drought conditions were noted only at Thohoyandou, giving a frequency of 3%. Relative to the second planting date, high frequencies of moderate drought conditions were observed at Lwamondo (54%), Thohoyandou (67%), Tshiombo (50%) and Sigonde (47%). This implies that moderate drought was observed once in two drought events during this stage. Severe drought conditions were most frequent at Punda Maria (20%), while a non-occurrence of extreme drought during this stage was observed. When looking at planting in December during this stage, the highest frequency of moderate drought conditions was observed at Thohoyandou (40%), with Punda Maria revealing the least (21%). For severe droughts, Tshiombo indicated the highest frequency (15%), with extreme droughts observed only at Levubu (6%) and Punda Maria (11%) during this stage.

During stage 4, moderate drought (≥ 50%) conditions were noted at three stations (Lwamondo, Thohoyandou, and Tshiombo) following October planting date. Severe drought conditions were most frequent at Punda Maria (20%), with no occurrence of extreme drought during this stage. Following the second planting date, Thohoyandou recorded the highest frequency (40%) of moderate droughts with severe drought conditions noted to be most frequent (15%) at Tshiombo, followed by Levubu, Lwamondo, Thohoyandou, and Sigonde with a frequency of 13%. Furthermore, extreme drought was noted only at Levubu and Punda Maria. While, December planting date revealed the highest frequency (40%) of moderate drought during stage 4 was at Lwamondo, with Sigonde being the least at 22%. Severe drought conditions were most frequent (12%) at Punda Maria as compared to other stations, while extreme drought conditions were observed only at Lwamondo.

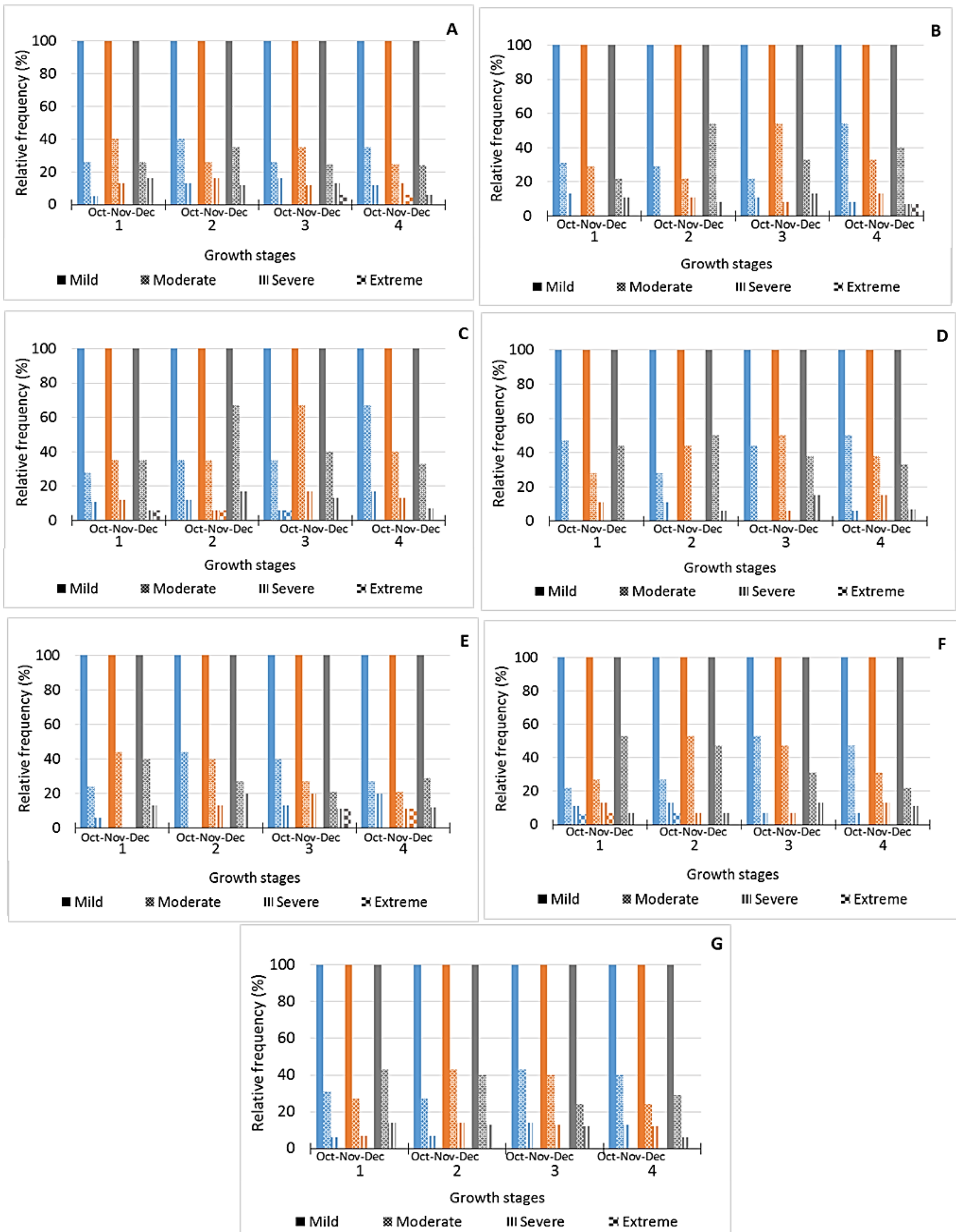


Figure 4.1 Relative frequency of SPEI drought categories during each growing stage of maize with reference to planting in October, November and December for stations Levubu (A), Lwamondo (B), Thohoyandou (C), Tshiombo (D), Punda Maria (E), Sigonde (F), and Pafuri (G).

Relative frequencies (Figure 4.1) varied among stations for all the planting dates. It was noted that mild drought conditions revealed a 100% frequency for all the growing stages as expected. This is due to the comparable classification of mild drought to the definition of drought as presented in Table 2. For the first stage of the crop, high frequencies of moderate drought were recorded following the first planting date at Lwamondo and Tshiombo, while other stations indicated a higher risk relative to planting in November-December. At this stage, drought delays imbibition and thus can lead to decreased germination rates and total germination percentage (Prasad *et al.*, 2008). Results during the vegetative stage indicate that stations located in regions receiving annual precipitation of 600-900 mm (Lwamondo, Thohoyandou, and Tshiombo) are at higher risk of moderate drought conditions following planting in December, while the other stations indicated a higher risk following October-November planting.

Results during the 3rd stage of maize showed that stations located in the middle-lower catchment are at a higher risk of moderate drought during stage 3, relative to planting in November. Additionally, these areas were more frequent to severe-extreme droughts following December planting date, implying that planting in October at Levubu, Lwamondo, Thohoyandou, and Tshiombo could place crops at a lower risk of reduced yield and even total crop failure. Furthermore, a return period of one extreme drought (SPEI <2) in 17 drought events, was noted for Thohoyandou relative to planting in October. In contrast, stations located in the low-lying plains of the upper catchment (Punda Maria, Sigonde, and Pafuri) were exposed to frequent moderate droughts following planting in October, with favourable conditions noted following December planting date.

For a maize crop, this reproductive phase (stage 3) is considered the most sensitive to drought stress as it can result in serious implications for the yield. Therefore, it is crucial for farmers to adapt to planting at proper times in environments where drought stress is observed to be more frequent during late vegetative, flowering and grain-filling phase. However, proper education on mitigation and adaptation methods is needed for most small-scale farmers, as they still prefer traditional planting dates (Mabhaudhi *et al*. 2014).

This shift in planting date could also imply the probable need to diversify crops as an effort to adapt to the climate conditions and this might be a challenge to many small-scale farmers, due to unavailability to inputs.

4.1.2 Temporal evolution of drought and trends based on SPEI

Noticeable seasons subjected to drought conditions were noted in Figure 4.2 as 1981-84, 1986/87, 1988/89, 1991/92, 1994/95, 1997/98, 2000/01, 2002/03, 2004/05, 2006/07, 2009/10, 2011/12 and 2014/15. Corresponding to a typical frequency of once every two to three seasons. The 1983/84 drought reached severe conditions at five of the seven stations, while the worst drought was detected during the 1991/92 season, reaching severe to extreme conditions at all the stations. When considering this drought season, extreme conditions were identified following planting in November at four of the seven stations. Previous findings recorded by LDA (2011) stated the 1991/92 drought was one of the most severe across the whole country and other parts of the SADC region. Austin (2008) reported that in 2001, maize prices had dramatically increased within five months in the season. This increase could have been due to different influential factors such as maize world price, exchange rate, and maize accessibility in other southern African countries (Chabane, 2002). By 2002, the average farming output of the country was recorded to have decreased by 75% of the previous output.

Spearman's rank correlation test for drought trends (Figure 4.2) show that at Levubu and Lwamondo, noticeable upward trends (ρ values of 0.4) occurred relative to planting in November and October, respectively. Whereas, the same trend was observed at Thohoyandou for all the planting dates. This implies a slight decrease in the severity of drought during the growing period of maize in the regions that receive $\geq$ 750 mm of annual precipitation. It can also be noted at other stations (Tshiombo, Punda Maria, Sigonde, and Pafuri) that there was no significant change in the severity of drought. A similar study on simulating the characteristics of droughts in southern Africa (Ujeneza, 2014) showed a slight significant downward trend, implying an increase in the intensity of drought over the area. However, the study was conducted at a country level, using monthly gridded climatic data for the period 1940-2004.

Figure 4.2 Observed SPEI time series and trends per growing season relative to the three planting dates for stations Levubu (A), Lwamondo (B), Thohoyandou (C), Tshiombo (D), Punda Maria (E), Sigonde (F) and Pafuri (G).

4.1.3 Observed extreme widespread dry and wet agricultural seasons using SPEI

As per SPEI results, notable seasons subjected to extreme widespread drought were identified as 1983/84 and 1991/92. Monthly distribution of rainfall and evapotranspiration during these seasons (Figure 4.3) indicate that during the 1983/84 drought, evapotranspiration reached a peak of about 200mm in January at all stations, while accumulated rainfall was recorded as <100mm at Tshiombo and <50mm at Lwamondo and Sigonde. This indicates that adequate rain was not available for crop use due to an imbalance between crop water demand and supply. Furthermore, these conditions improved by March, whereby at the high and moderate rainfall regions, amounts of rain were recorded to be higher than the accumulated evapotranspiration rates. It can also be noted that at Sigonde (low rainfall region), the highest rainfall amount during this rainfall season was also recorded in March, however, due to the region experiencing fairly high temperatures as compared to other regions in the catchment, the evapotranspiration remained higher.

Drought conditions during the 1991/92 agricultural season can clearly be described by the low rainfall amounts together with high evapotranspiration rates throughout the rainfall season. Similar to 1983/84 season, the month of January experienced the highest accumulated evapotranspiration as compared to the other months of the season. At Sigonde, there was no rainfall during October, January, and February, with the highest amount recorded as 75mm in November, suggesting that rainfall was not enough to meet evapotranspiration demands, thus the prevalence of water deficit during this season. This shows that even though the catchment was struck by widespread droughts, conditions in the low rainfall regions seemed to be more severe when compared to other parts that receive fairly good rains in summer. In order to minimise additional water losses due to increased evaporative demand, various mulching techniques can be employed (Thomas, 2008). However, such information on mitigation actions needs to be disseminated effectively to farmers (Archer, 2003); suggesting the need to capacitate extension services to advise farmers, for better drought preparedness.

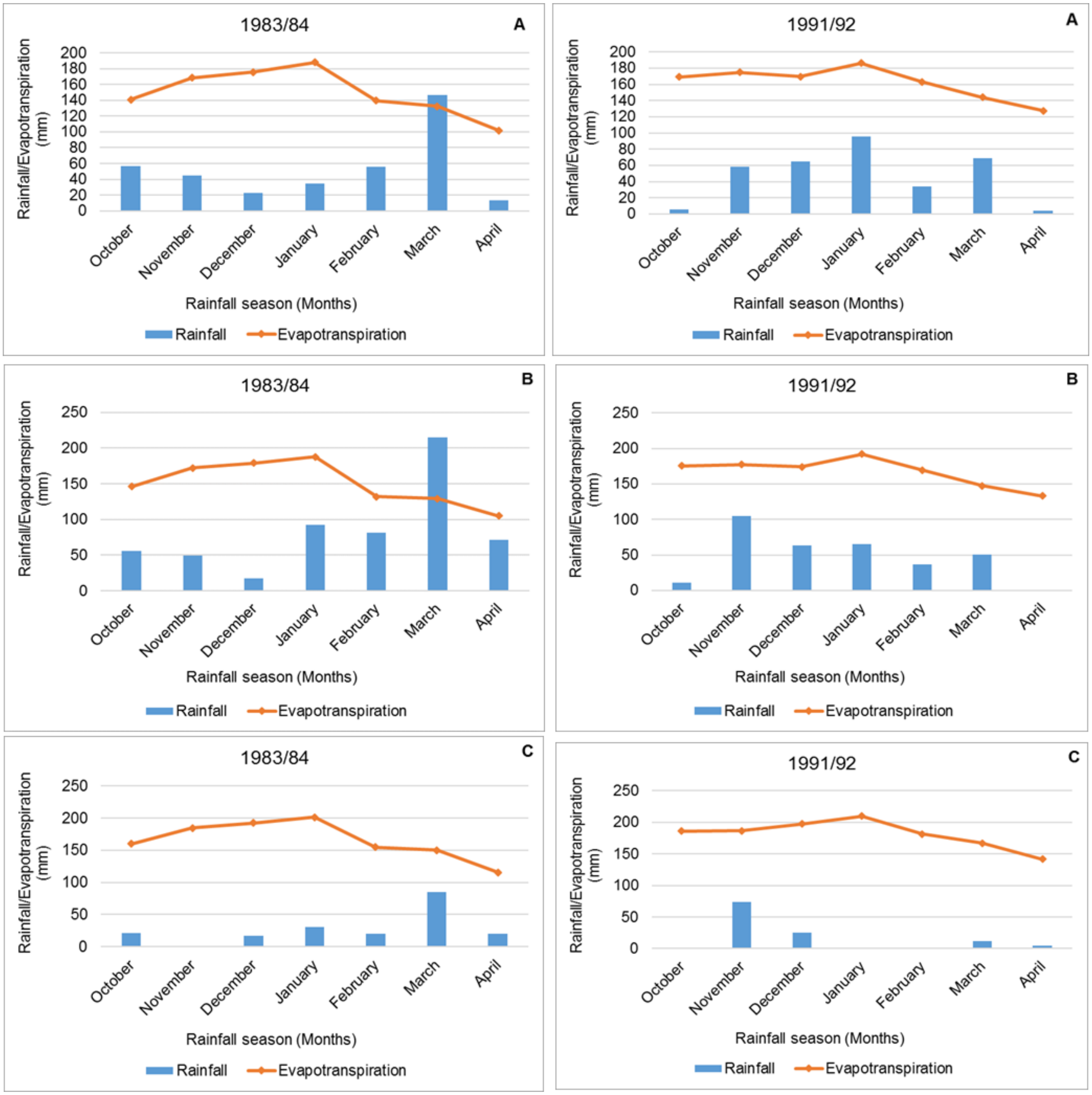


Figure 4.3 Monthly distribution of rainfall and evapotranspiration during 1983/84 and 1991/92 extreme widespread droughts, for stations Lwamondo (A), Tshiombo (B) and Sigonde (C).

Results further revealed 1999/00 and 2012/13 as being the extreme wet seasons in the area for the analysis period. The potential water balance presented in Figure 4.4 shows that in general there was a marginal difference between the actual amount of rainfall received and evapotranspiration rates as compared to the drought seasons. It is also evident that in January 2000, the area received considerably high rainfall, which continued to increase in February, recording values of about 1000mm at the high and moderate rainfall regions. At Sigonde, the weather station recorded 550mm of rain in February, and this is substantially high considering that the area is situated in a region that receives mean annual rainfall of <450mm. These heavy rains resulted in flooding across the Limpopo province, filling the Luvuvhu River channels and catchment basins (DWAF, 2004). The strength of the water resulted in the removal of soil, vegetation, and rocks that led to crop failure in several regions of the catchment (Khandlhela and May, 2006). Reason and Keibel (2004) explained that the main cause of these floods was due to the occurrence of tropical cyclone Eline, which to date lasted for the longest time in southern Africa.

For the 2012/13 season, rainfall of up to 900mm at Lwamondo and 590mm at Sigonde was observed in January, while at Lwamondo rainfall amounts of between 90mm and 210mm were experienced from November to February. This implies that crops that were planted in November were at an advantage of receiving significant amounts of rain during the most critical stages of growth and development. Furthermore, the distribution of rainfall and evapotranspiration amounts noted during the four months at Lwamondo showed a good water balance. Hence, the resulting SPEI indicated values corresponding to ‘no drought’ conditions suggesting the probability of good agricultural productivity during that season.

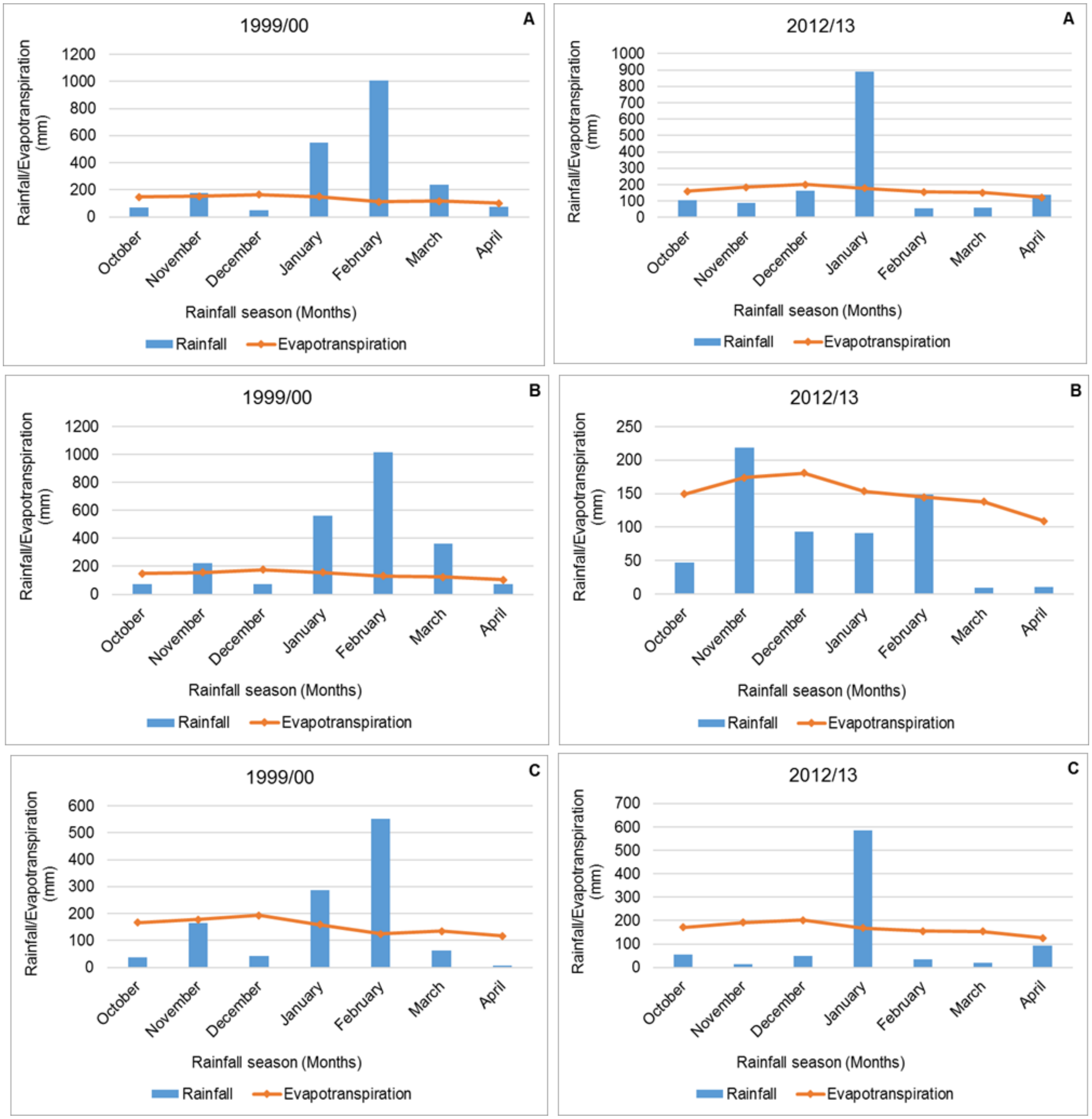


Figure 4.4 Monthly distribution of rainfall and evapotranspiration during 1999/00 and 2012/13 extreme widespread wet seasons, for stations Lwamondo (A), Tshiombo (B) and Sigonde (C).

4.1.4 Drought conditions under projected future climates using SPEI

Figure 4.5 shows the projected changes in drought conditions given by SPEI under the SRES A2 scenario, while Table 4.1 clearly shows the expected changes in drought frequency.

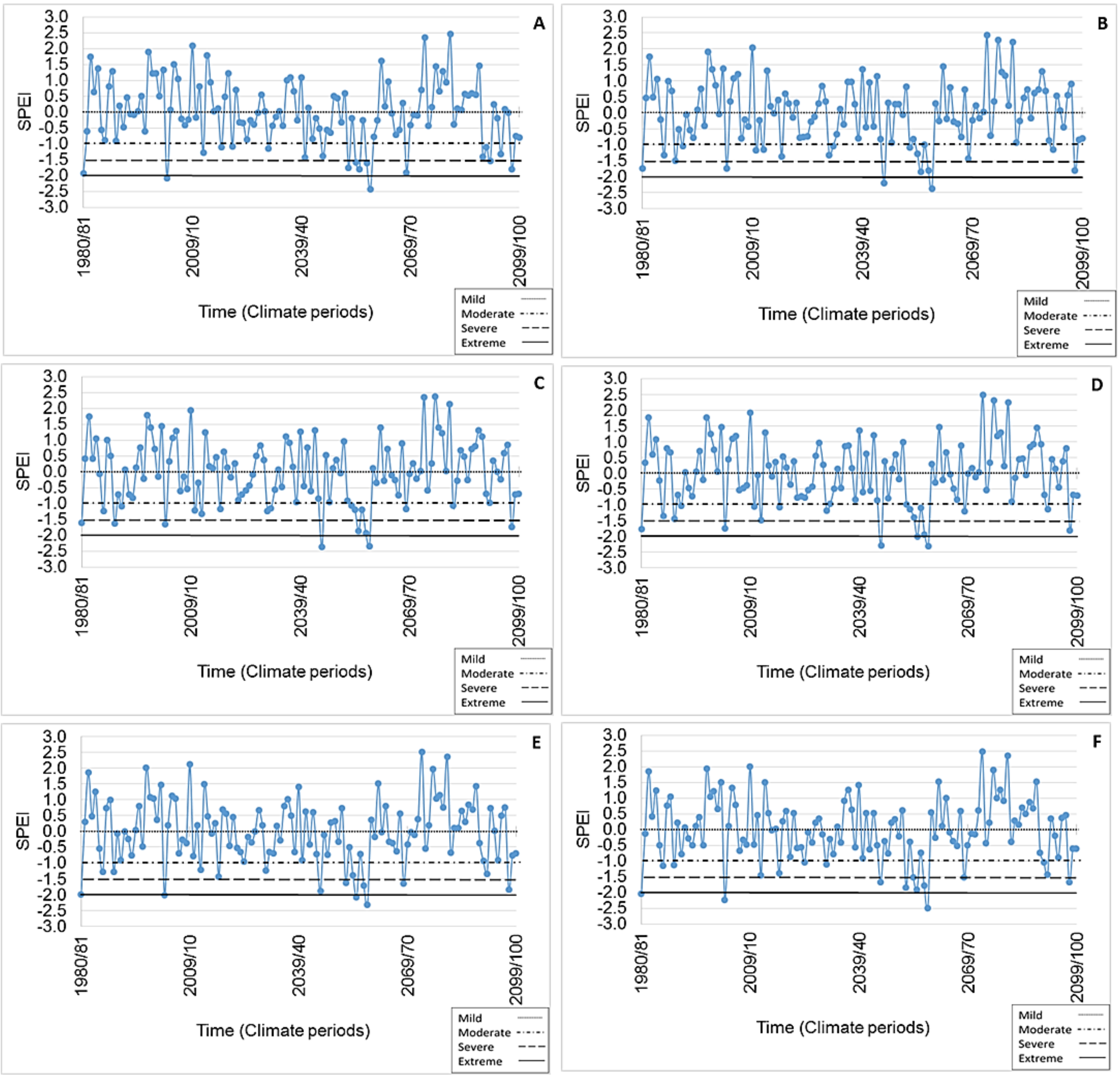


Figure 4.5 Simulated SPEI time series per growing season relative to the four climate periods for stations Mampakuil (A), Sigonde (B), Pafuri (C), Punda Maria (D), Tshiombo (E) and Levubu (F).

Results show that 43 – 50% of the agricultural seasons during the base period projected mild drought conditions (SPEI 0 to -0.99), corresponding to a recurrence of once in two seasons. These conditions are then expected to change during the future climate periods. Mild drought can be expected to increase by up to 27% at Mampakuil, followed by 20%, 16% and 13% at Tshiombo, Pafuri, and Sigonde, respectively, during the intermediate-future period. At Punda Maria, the frequency of mild drought occurrence is expected to remain the same during the near-future and intermediate-future and then decrease by 4% towards the end of the century. It is also notable at Levubu that the frequency is not expected to change from the base during the near-future climate period; however, there will be an increase of 3% during the intermediate-future and far-future climate periods. Similarly, the highest increase in the frequency of moderate drought (SPEI -1 to -1.49) from the base period can be expected during the intermediate-future as compared to other climate periods. This reflects an increase of 20% at Mampakuil, Punda Maria, and Levubu, while at the other stations a 10% frequency increase can be expected. However, the only station that revealed a statistically different mean in SPEI ($p = 0.09$) as compared to the base period was Sigonde, with a decrease in SPEI values during the near-future period.

It is clear (Table 4.2) that droughts are likely to intensify during the intermediate-future, where nearly all the stations (except Punda Maria) were significantly different ($p < 10\%$) from the base period. Projections also showed expected occurrences of extreme droughts (SPEI values of <-2) during the 2045/46 and 2058/59 agricultural seasons, whereby the 2045/46 drought will be expected to reach this severity level only at Mampakuil, Sigonde, Pafuri and Punda Maria. This could be beneficial if crops are at a mature stage whereby the water demand is lower, but could also be harmful if water is unavailable during the reproductive stages (Kraemer, 2015). These drought conditions can be explained by the expected increases in temperature in the Limpopo province by 2040-2060; and along with projected decreases in precipitation, given by (Lobell and Gourdji, 2012), this could lead to the soil significantly drying and thus increasing the risk of experiencing agricultural drought. Furthermore, the frequency of drought is projected to slightly decrease during the beginning of the far-future climate period as compared to previous climates. However, severe to extreme drought (SPEI values of -1.5 to -2) can then be expected towards the end of the century at all stations. This agrees with findings by CSIR (2010), that evaporation rates (aggregating the degree of drought) are expected to increase by the end of 2100. Seasonal forecasts during drought seasons would be beneficial for local rain-fed maize growers especially in regions where there is a constant shortage of water during the growing season. Moreover, Winsemius *et al*. (2014) highlighted that these forecasts should be timely, easily accessible and simple to interpret.

Table 4.1: Frequency (in %) of the different levels of drought (by SPEI) for future climates, relative to the base period, at the Luvuvhu River catchment

Station	**Drought category**	**Climate period**			
		Base	**Near-future**	**Intermediate-future**	**Far-future**
Mampakuil	Mild	**43**	50	70	43
	Moderate	**7**	13	27	17
	Severe	**7**	0	20	7
	Extreme	**3**	0	3	0
Sigonde	Mild	**50**	53	63	37
	Moderate	**17**	17	27	7
	Severe	**7**	0	13	3
	Extreme	**0**	0	7	0
Pafuri	Mild	**47**	50	63	37
	Moderate	**17**	17	27	7
	Severe	**10**	0	13	3
	Extreme	**0**	0	7	0
Punda Maria	Mild	**47**	47	47	43
	Moderate	**17**	7	37	17
	Severe	**7**	0	17	7
	Extreme	**3**	0	0	0
Tshiombo	Mild	**47**	53	67	37
	Moderate	**13**	10	23	7
	Severe	**7**	0	20	3
	Extreme	**3**	0	7	0
Levubu	Mild	**47**	47	50	50
	Moderate	**13**	13	30	23
	Severe	**3**	0	13	10
	Extreme	**3**	0	0	3

Table 4.2: Independent t-test for mean SPEI for future climates, relative to the base period, at the Luvuvhu River catchment.

Station	Stats	Base	Near-future	Intermediate-future	Far-future
Mampakuil	Mean	**0.30**	0.04	-0.52	0.17
	t-value	**0.00**	1.16	3.31	0.48
	p	**1.00**	0.13	0.00	0.32
Sigonde	Mean	**0.17**	-0.14	-0.39	0.33
	t-value	**0.00**	1.35	2.14	-0.60
	p	**1.00**	0.09	0.02	0.28
Pafuri	Mean	**0.16**	-0.15	-0.40	0.35
	t-value	**0.00**	1.32	2.09	-0.75
	p	**1.00**	0.10	0.02	0.23
Punda Maria	Mean	**0.12**	0.15	-0.18	0.00
	t-value	**0.00**	-0.14	1.16	0.48
	p	**1.00**	0.44	0.13	0.32
Tshiombo	Mean	**0.20**	-0.09	-0.44	0.31
	t-value	**0.00**	1.29	2.51	-0.41
	p	**1.00**	0.10	0.01	0.34
Levubu	Mean	**0.18**	0.19	-0.18	-0.10
	t-value	**0.00**	-0.06	1.40	1.13
	p	**1.00**	0.48	0.08	0.13

*values highlighted in red differ statistically at α (0.10).

Results also show that SPEI averages can be expected to decrease from the base period during the near-future at Sigonde, Pafuri, and Tshiombo, while for the intermediate-future this change is detectable at all stations. It is worthy to note that although there is a variation from the base (at other stations except for Mampakuil); the difference is not statistically significant. The standard deviation values range from 0.82 at Tshiombo to 1.07 at Punda Maria. These are somewhat realistic, as by definition the average SPEI value is zero, and the standard deviation is one; thus values strongly greater than one would imply more extreme values towards both drier and wetter conditions (Vicente-Serrano *et al.*, 2010).

4.2 Assessment of maize crop performance using the Water Requirement Satisfaction Index (WRSI)

4.2.1 Probabilities of WRSI during the growing season of maize

The WRSI probability plots showing drought-proneness, relative to planting in October, November, and December are presented in Figure 4.6 – 4.8. At the 20th percentile mark, results show that mild conditions (WRSI 70 - 79) can be expected at Levubu, following October and November planting dates, while December planting reflected WRSI values corresponding to moderate-severe droughts. At Lwamomdo and Tshiombo, probabilities of severe droughts (WRSI <60) were observed relative to planting during the 2nd dekad of October to the 1st dekad of November, with the drought intensifying to extreme conditions (WRSI <50) in December. Moreover, at Thohoyandou, the least risk can be expected during the 1st dekad of October, while at Punda Maria, Sigonde and Pafuri, extreme droughts can be expected once in five seasons, regardless of the planting date.

When observing at the 50% probability of non-exceedance, it was evident that at Levubu, WRSI reflected values of ≥80 during all planting dates. This implies that once in two seasons, the farmers in this region can expect no drought conditions, resulting in good crop performance. At Lwamondo, it can be seen that planting in the 1st dekad of October could results in severe drought while the risk may possibly be reduced if planting occurs during the 3rd dekad of October to the 3rd dekad of December, with WRSI values ranging from 70 – 79 during this period. At Tshiombo and Thohoyandou, planting during the 1st dekad and 2nd – 3rd dekad of December, respectively, gave a risk of severe droughts, while planting in October to November could result in better crop produce at both stations. Similar to the 20th percentile, it can also be seen at 50% probability (with a return period of once every two seasons), that Punda Maria, Sigonde, and Pafuri can expect to receive extreme drought conditions following all the planting dates. This implies an imbalance between the distribution of rainy days and the rainfall amount when compared to the crop requirements (Yengoh *et al.*, 2010).

At 80% probability of non-exceedance, conditions of no drought can be expected at Levubu and Lwamondo following all planting dates. A similar pattern can be observed at Thohoyandou and Tshiombo, however, cases of mild drought were observed following planting in December. This shows that the risk of experiencing drought every season in these regions is very low. On contrary, given the same return period, drought conditions can be expected at stations that are located in the upper catchment (Punda Maria, Sigonde, and Pafuri). At Punda Maria, planting in the 1st dekad of October to the 1st dekad of December could result in mild to moderate drought, while planting later(2nd dekad onwards) in December suggests probabilities of severe droughts (WRSI <60). Results further indicated that delay in planting at Sigonde and Pafuri could result in probable crop failure as compared to the other planting dates.

The WRSI results indicate that the optimal planting date for rain-fed maize crop in the catchment ranges from October to November, with WRSI values relative higher than other growing periods. Although early planting can be advised, it is important to note that at Thohoyandou, planting too early (1st dekad of October) might place crops grown in this area under drought stress. This indicates that there is a risk that water requirements of the crop will slightly be met during critical periods of the growing season, following this planting date. Dryland farmers can be advised to change their cropping patterns, rotations, and switch to crop varieties that are more tolerant to drought (Thomas, 2008). However, numerous subsistence and small-scale farmers in South Africa count on their indigenous knowledge for climate change resilience and prefer to use traditional maize varieties (Mabhaudhi and Modi, 2010; Ubisi 2016); therefore convincing them to switch to ‘unknown’ drought-tolerant varieties might be a challenge. Another critical factor is the inaccessibility and unaffordability of these inputs. Therefore, in order to improve the livelihoods of small-scale farmers, the Government need to put in place support initiatives to improve access to inputs (Belt *et al*., 2015).

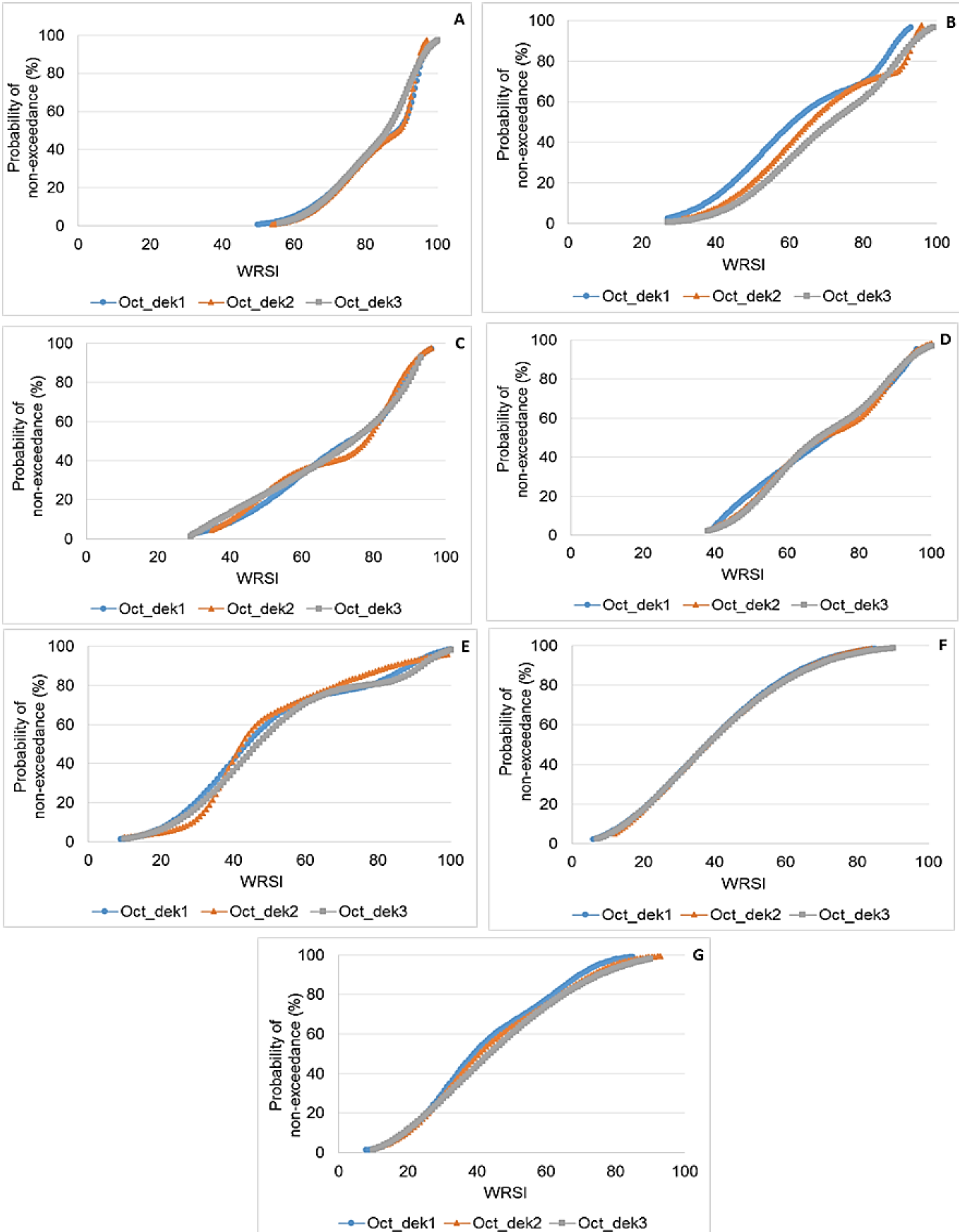


Figure 4.6 WRSI cumulative distribution function for the maize growing season with reference to planting in October for stations Levubu (A), Lwamondo (B), Thohoyandou (C), Tshiombo (D), Punda Maria (E), Sigonde (F) and Pafuri (G).

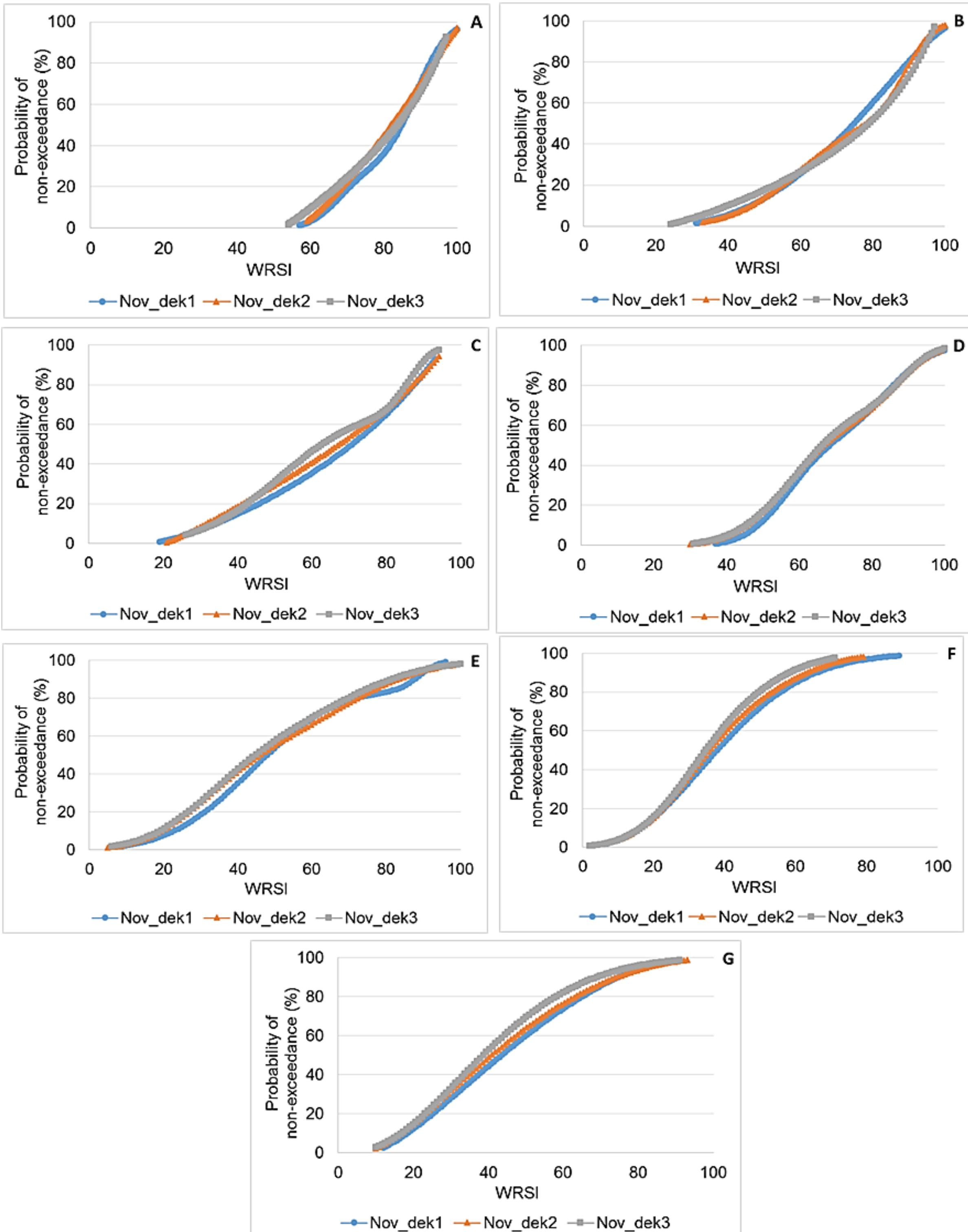


Figure 4.7 WRSI cumulative distribution function for the maize growing season with reference to planting in November for stations Levubu (A), Lwamondo (B), Thohoyandou (C), Tshiombo (D), Punda Maria (E), Sigonde (F) and Pafuri (G).

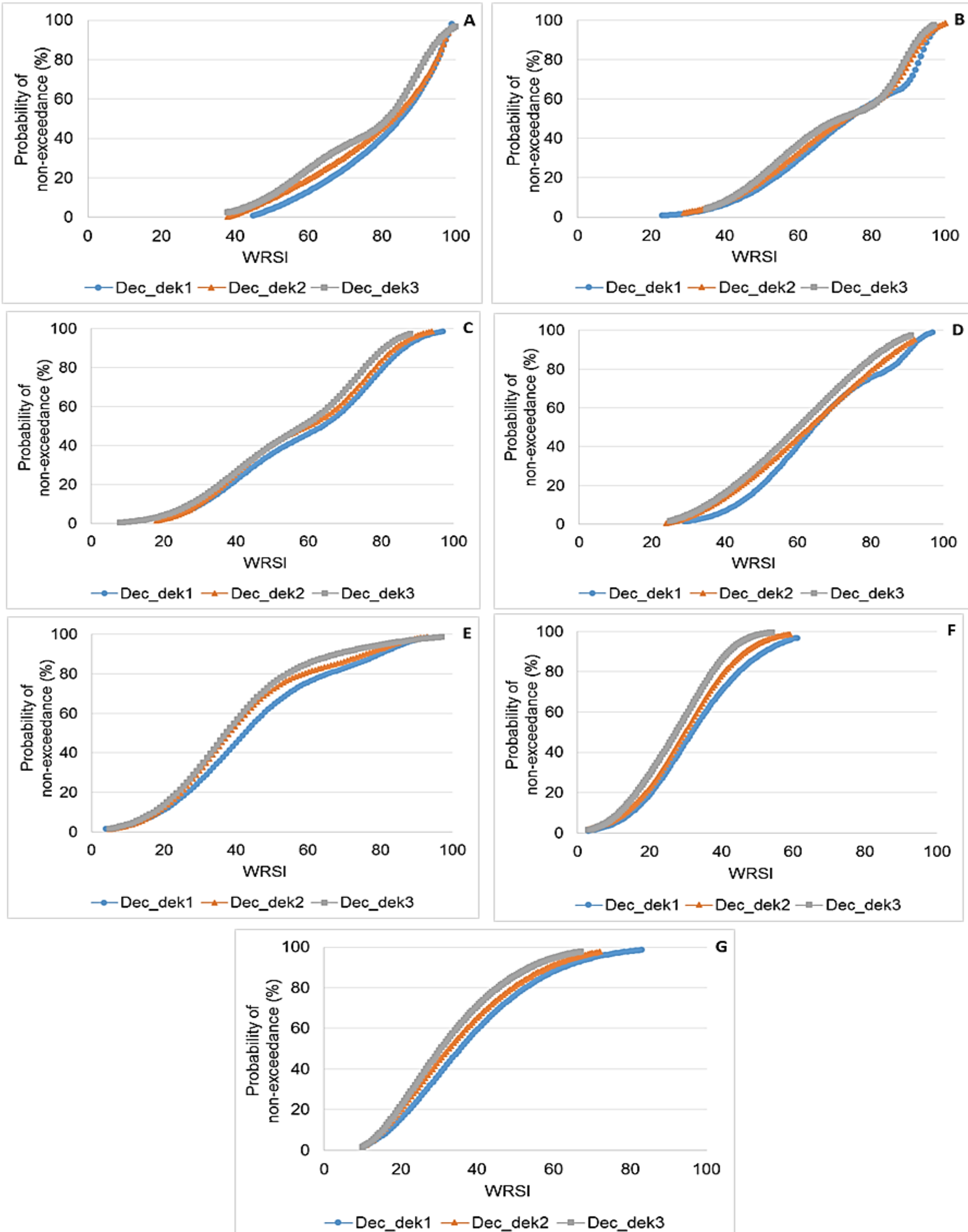


Figure 4.8 WRSI cumulative distribution function for the maize growing season with reference to planting in December for stations Levubu (A), Lwamondo (B), Thohoyandou (C), Tshiombo (D), Punda Maria (E), Sigonde (F) and Pafuri (G).

4.2.2 Temporal evolution of drought and trends based on WRSI

The temporal patterns of WRSI (Figure 4.9 – 4.11) revealed that the catchment encountered notable drought conditions at different severity during the analyzed agricultural seasons. WRSI values corresponding to mild and moderate droughts showed to be more frequent at Levubu, Lwamondo, Thohoyandou, and Tshiombo. This was commonly observed once every two to three seasons. As mentioned previously, there have also been notable widespread extreme droughts in the past, including 1983/84, 1988/89, 1991/92, 1993/94, 2001/02, 2002/03, 2004/05 and 2014/15. These historical droughts were recorded at all stations except Levubu, where the drought was observed to be less intense. Previous findings by Pretorius and Smal (1992) indicated estimates of a decline in the gross value added by the agricultural sector based on summer crop estimates for 1991/92 as compared to previous agricultural seasons. These reductions resulted in the loss of foreign exchange normally derived from agricultural exports (FAO, 2004).

Planting in December resulted in more seasons as being exposed to the occurrence of extreme droughts as compared to planting in October and November. This is evident for all stations analyzed. A previous study conducted by Mzezewa *et al.* (2010), using a station in Thohoyandou, indicated that the probability of receiving high rainfall (>100 mm) was greatest in December (58%) and lowest in the month of October (20%). It is worthy to note that these findings do not imply December as being the optimum planting date and can, therefore, suggest that planting prior this month can place crops at a good probability of receiving considerable amounts of rainfall as the crop develops.

Furthermore, the least potential risk of crop damage was observed at Levubu with no occurrences of extreme droughts (WRSI <50) following planting during the 2nd dekad of October to the 3rd dekad of November, while an occurrence of extreme drought was noted only three times following planting in Dec_dek3. When looking at the occurrence of severe drought, it was seen that only two cases were observed relative to planting in October, followed by four and nine cases should planting occur in November and December, respectively. This implies that late planting could increase the risk of possible total crop failure in the region; therefore planting in October to November could be advised. However, other factors such as switching crop varieties should be considered, as certain crops might not be suitable to the durations of the new season (Tom, 2014). Another evident observation is that at Punda Maria, Sigonde and Pafuri, extreme drought episodes (WRSI<50) were generally predominant in these regions during the growing period, irrespective of the different planting dates. This implies a high risk of total crop failure, making the upper regions of the catchment unsuitable for rain-fed maize production.

WRSI time series trends provided by the Spearman's rank correlation test did not show any significant increase or decrease. This implies that although the Luvuvhu River catchment has experienced several drought events in the past, the area has not become drier since the 1980's. Earlier findings have reported significant decreases in annual precipitation as well as a strong warming trend in the northern regions of Limpopo Province (Kruger and Shongwe, 2004; Kruger, 2006). However, these studies were carried out over long periods (1910-2004 for rainfall and 1960-2003 for temperature), over the whole province. Contrary to these findings, weak increasing trends were noted at Lwamondo following December planting date, whereas at Thohoyandou the trend (ρ values of 0.5) was observed following planting in the 1st dekad of October. This increase in WRSI suggests that there has been a gradual decrease in drought severity following the respective planting dates; implying improved precipitation patterns at those regions.

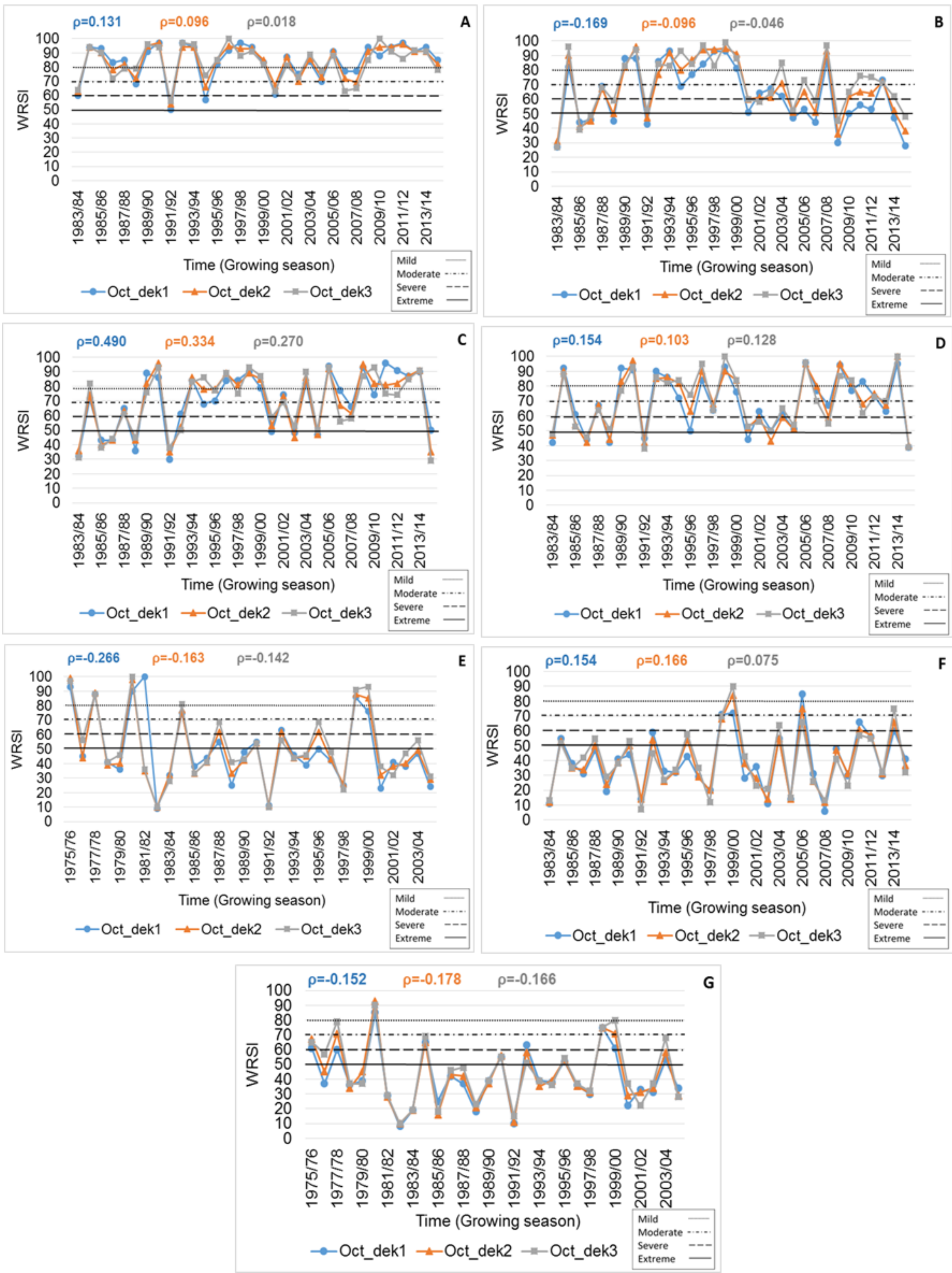


Figure 4.9 Observed WRSI time series and trends per growing season relative to planting in October for stations Levubu (A), Lwamondo (B), Thohoyandou (C), Tshiombo (D), Punda Maria (E), Sigonde (F) and Pafuri (G).

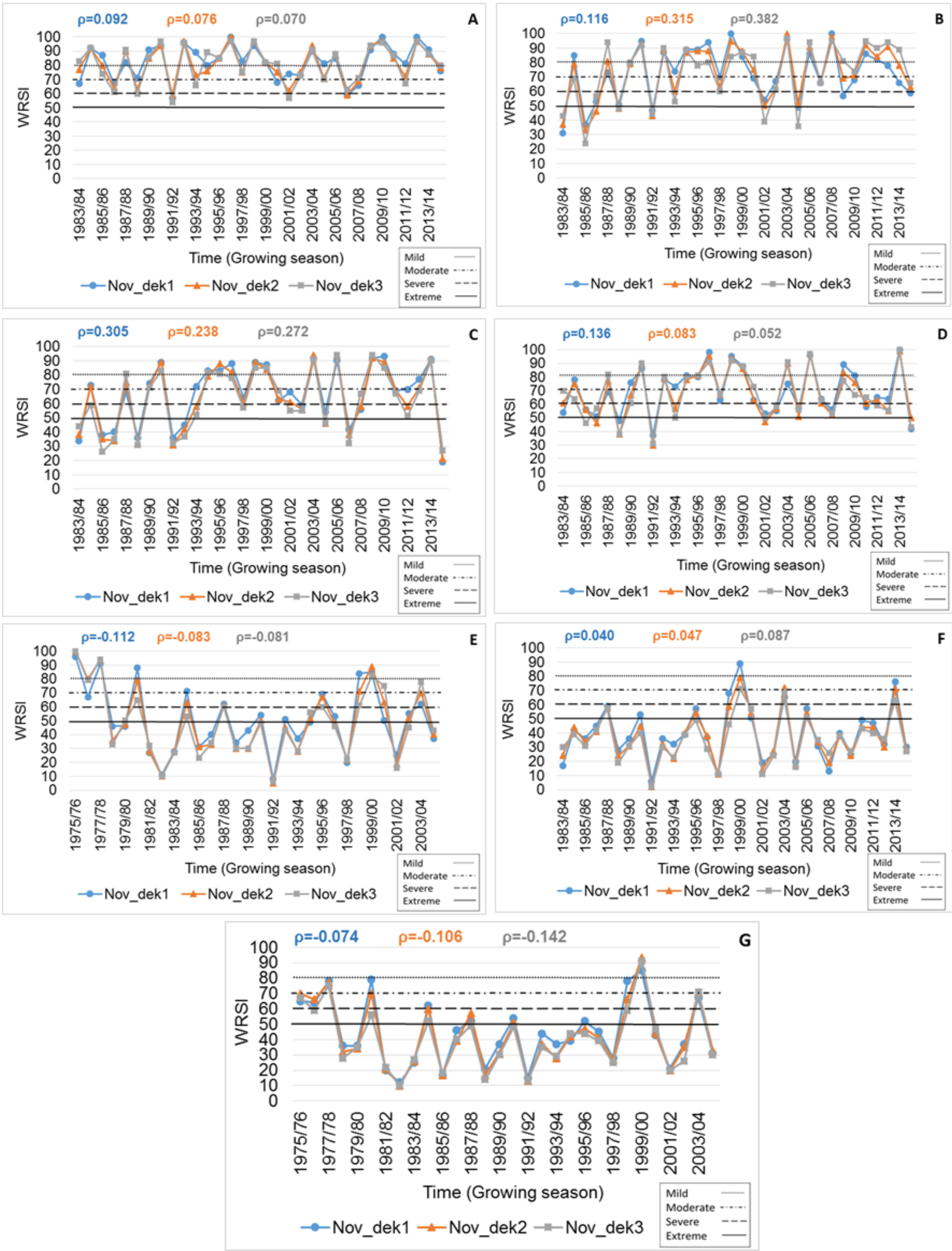


Figure 4.10 Observed WRSI time series and trends per growing season relative to planting in November for stations Levubu (A), Lwamondo (B), Thohoyandou (C), Tshiombo (D), Punda Maria (E), Sigonde (F) and Pafuri (G).

Figure 4.11 Observed WRSI time series and trends per growing season relative to planting in December for stations Levubu (A), Lwamondo (B), Thohoyandou (C), Tshiombo (D), Punda Maria (E), Sigonde (F) and Pafuri (G).

4.2.3 Observed extreme widespread dry and wet agricultural seasons using WRSI

The widespread drought events and wet seasons were evaluated to measure drought severity on crop performance. It appears (Figure 4.12 – 4.13) that the droughts were due to a deficit of water starting from the 5th dekad to the 12th dekad of the growing period. This implies that the rainfall experienced during that period did not meet the crop water requirements and therefore crops did not get sufficient water during the most critical stages (7th – 9th dekad), explaining the decrement of WRSI values. This is consistent with the literature, as it has been revealed that the maize crop is unable to resume growth and development after a severe drought at tasselling to silking stage (Whitmore, 2000). Another interesting finding is that at Sigonde, the extreme drought of 1991/92 was caused by lack of water throughout the growing season, with only four dekads receiving rainfall of less than 10mm per dekad. The resulting WRSI during that season was zero.

During the 1993/94 season, it is interesting to note that apart from the good start to the season, with fairly good rainfall occurring during the 1st to 4th dekad, conditions at the end of the season resulted in WRSI values of <50. A similar study has shown that the 1991/92 drought effects worsened until the end of 1993, correspondingly affecting the hydrological water supply (Trambauer *et al.*, 2014). This prolonged drought was widely experienced throughout the country as well as in other parts of southern Africa, including Botswana, Zimbabwe, and Mozambique, causing widespread crop failure and livestock mortalities (FAO, 2004). After the year 2000, the area experienced an extreme drought for two consecutive seasons (2001/02 and 2002/03), and again during 2004/05 at Lwamondo and Sigonde. Thereafter the area was then struck by extreme drought again after a decade (2014/15) at the moderate and low rainfall regions.

In contrast, results showed extreme wet seasons as being 1987/88, 1999/00, 2003/04 and 2013/14. Figure 4.14 shows that during the course of these seasons, rainfall was equal and/or more than the correspondent water requirements for a considerable number of dekads including the critical stage of the crop. It was further noted that for some dekads the index was reduced despite the high rainfall amounts that were received. This is because according to Allen *et al.* (1998), the index is also reduced when the water surplus is >100mm. However, the WRSI value at the end of these seasons reflected good crop performance at the high and moderate rainfall regions and average crop performance at the low rainfall regions.

The total crop failure during the notable seasons could be explained by the lack of rainfall during the growing season at the low rainfall regions as well as during the sensitive stages at the high and moderate rainfall regions. This intra-seasonal variability of rainfall could result in deficient uptake of the required water by crops due to a reduction of moisture in the root zone (Das, 2012). However, during the wet seasons, it was observed that the rainfall was fairly distributed, thus resulting in WRSI values corresponding to good crop performance, implying satisfactory yields.

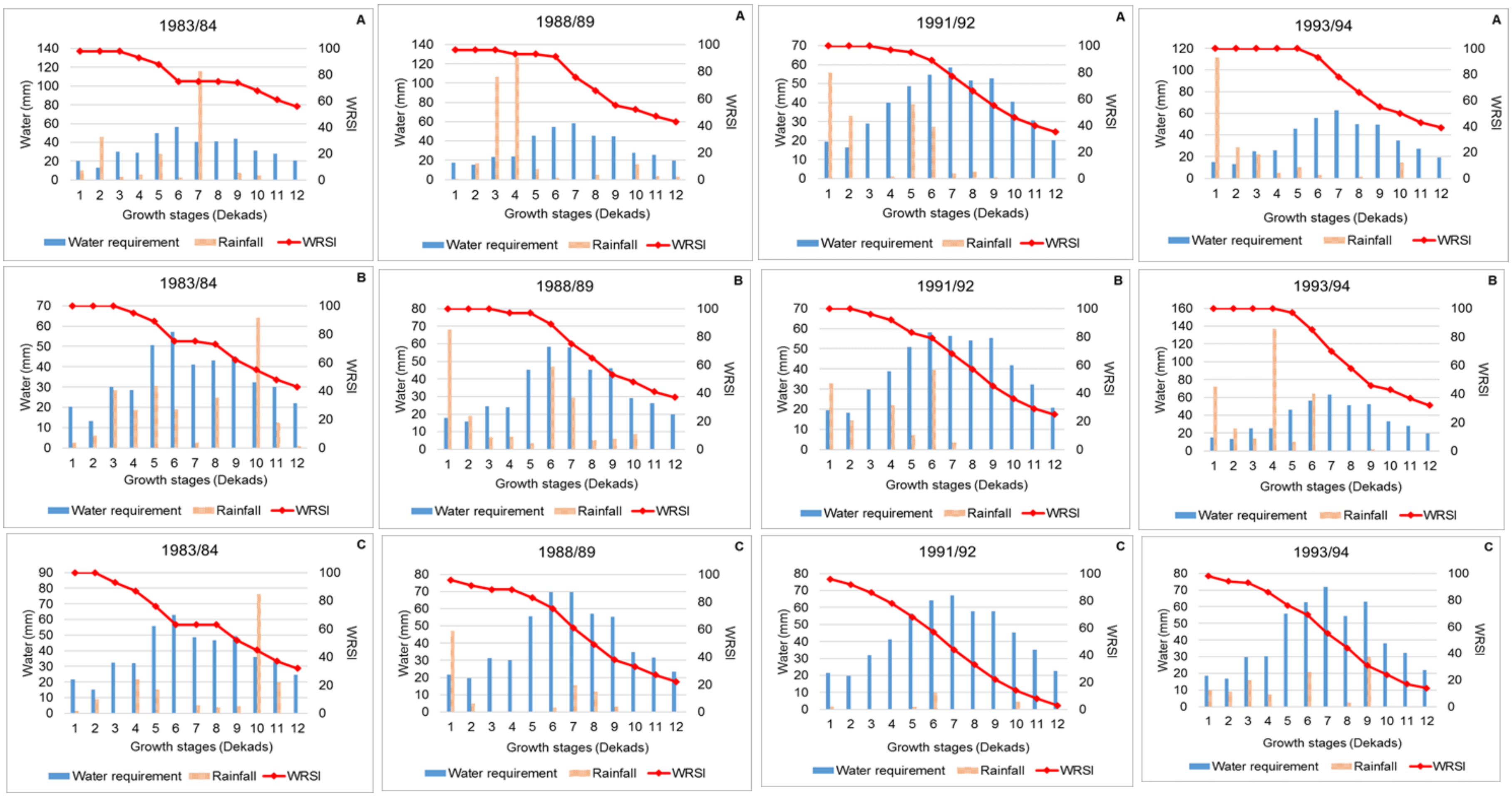


Figure 4.12 Water balance and WRSI for each dekad of the growing period, during notable widespread drought seasons (1983/84, 1988/99, 1991/92 and 1993/94), for stations Lwamondo (A), Tshiombo (B) and Sigonde (C).

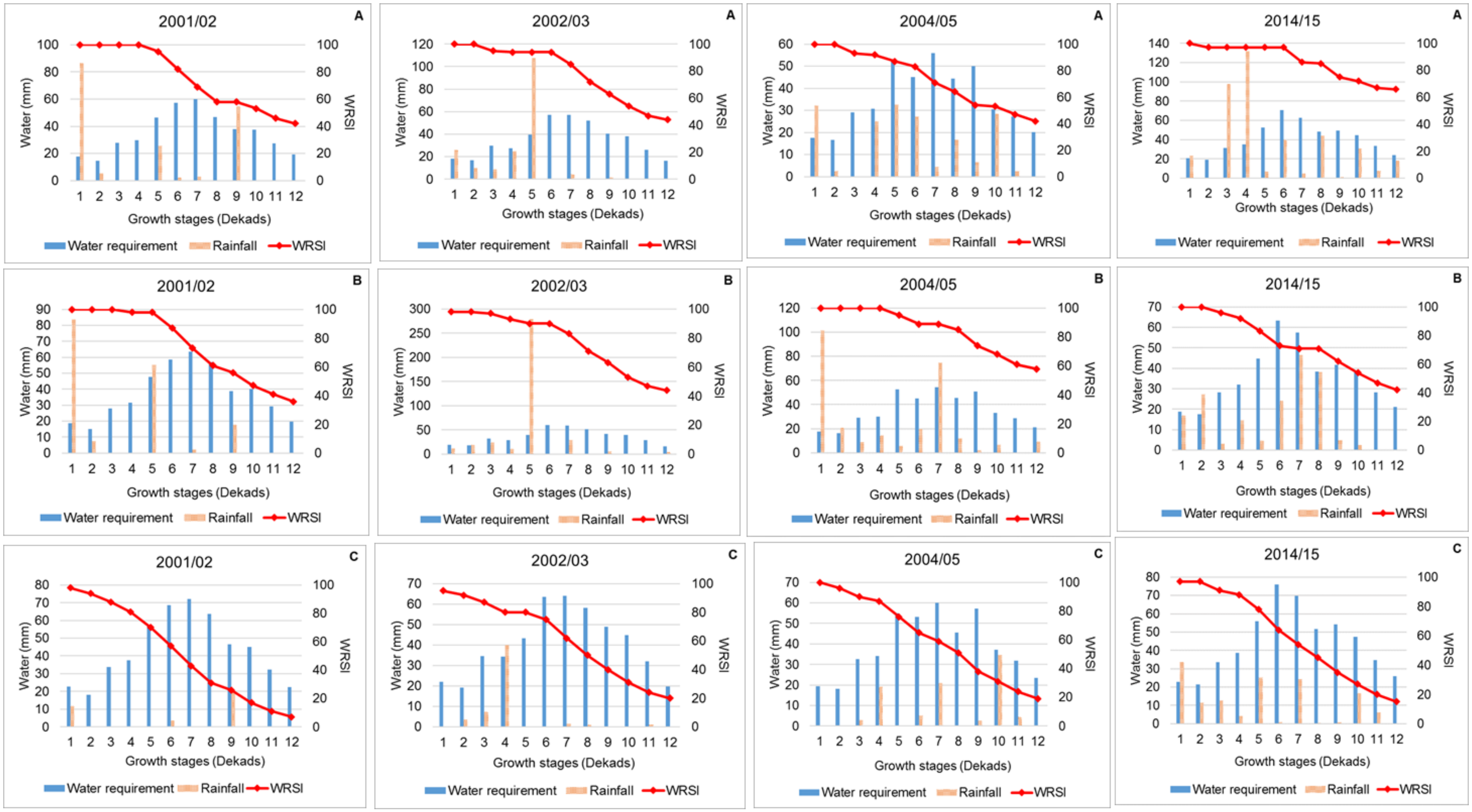


Figure 4.13 Water balance and WRSI for each dekad of the growing period, during notable widespread drought seasons (2001/02, 2002/03, 2004/05 and 2014/15), for stations Lwamondo (A), Tshiombo (B) and Sigonde (C).

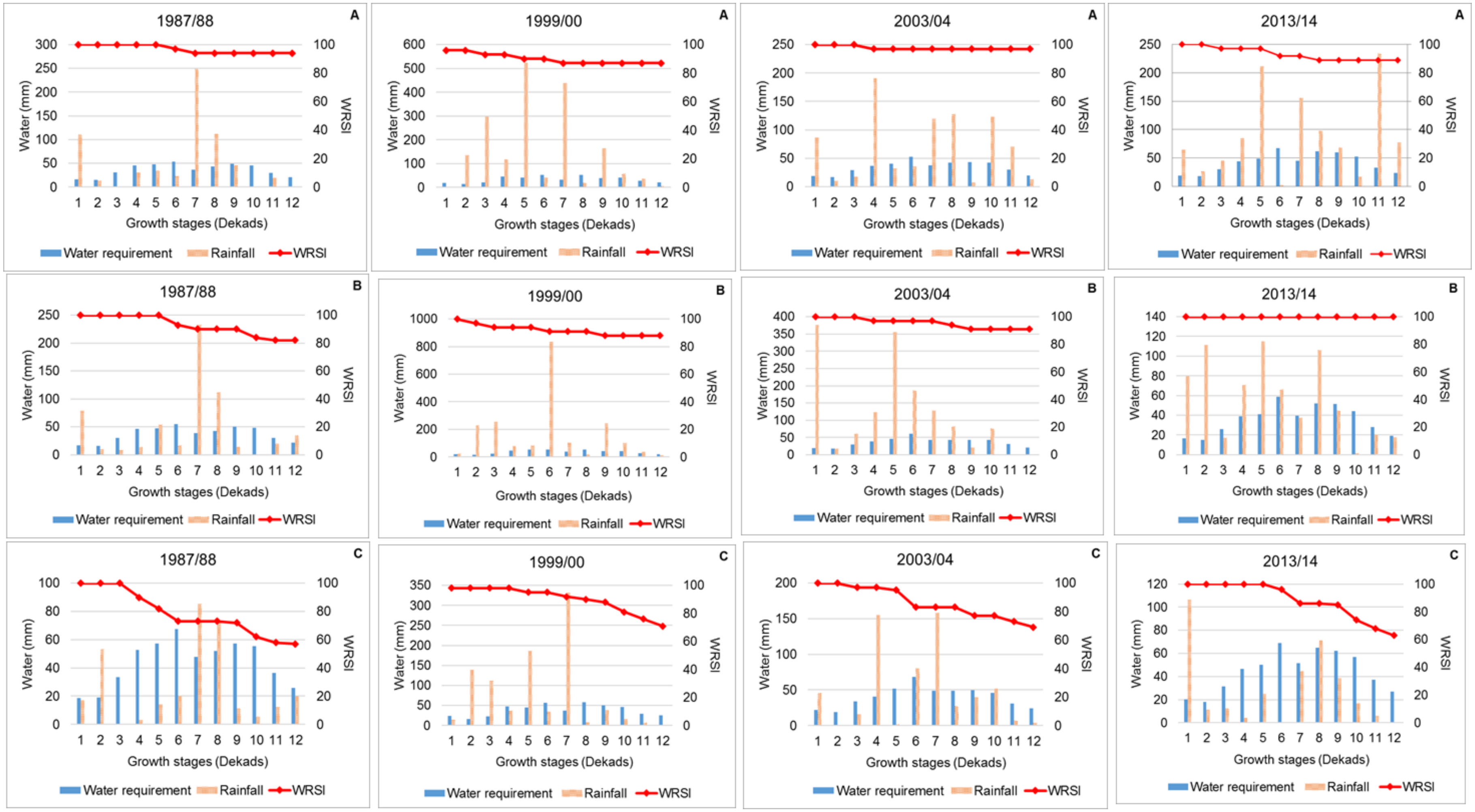


Figure 4.14 Water balance and WRSI for each dekad of the growing period, during widespread wet seasons, for stations Lwamondo (A), Tshiombo (B) and Sigonde (C).

4.2.4 Drought conditions under projected future climates using WRSI

Figure 4.15 presents results on projected drought conditions by means of the WRSI, with the variation between the three dekads clearly seen in Table 4.3. Generally, mild drought conditions showed to be more frequent compared to other drought categories, as expected. Results also showed the 3rd dekad to being more drier as compared to the 1st and 2nd dekad. Moreover, mild droughts are expected to occur during all seasons of the future periods at Sigonde and Pafuri, whereas at Mampakuil a 100% frequency was only noted for the intermediate-future climate period. The average frequency of observed moderate drought conditions during the base period was 60%, with the highest (97%) noted at Sigonde and Pafuri following the 3rd dekad, while a low of 10% was seen at Levubu during the 1st dekad. The frequency of this level of drought at Sigonde and Pafuri are expected to remain the same during the near-future climate period, with a decrease of 4% seen for the far-future climate period. This indicates a high risk of crop damage caused by drought in these regions, suggesting that stations located in the drier regions of the catchment could not be suitable for growing the maize crop.

It is also evident that stations located in the high rainfall regions have a low variability in the increase of moderate drought frequency, with the highest (23%) increase noted at Tshiombo during the 3rd dekad of the intermediate climate period. These findings coincide with a study by Zhu and Ringler (2012), which predicted that under the SRES A1b scenario, the most prominent significant reductions in the annual precipitation were noted by the year 2050, expecting to worsen the water supply availability in the Limpopo River basin.

Results also indicated severe to extreme drought conditions (WRSI <60), that often lead to poor crop performance and failure, during the intermediate-future period, except for Sigonde and Pafuri, whereby 80% of the near-future climate period can be expected to experience extreme drought conditions. This is an increase of 30% and 33%, respectively, relative to the base period and by far the highest as compared to other climate periods. Furthermore, it appears that the WRSI mean during the near-future to the intermediate-future period (Table 4.4) can be expected to be lower than the other future climate period, suggesting more intense drought events. This is evident at all stations, with a resultant p-value <10%, agreeing on a statistically significant shift towards drier conditions during these respective climate periods. This will plausibly have an adverse impact on rain-fed maize farmers in the Luvuvhu River catchment since they solely rely on maize as a staple food and are considered economically poor according to South African standards (DWAF, 2004).

Results further indicated that at Levubu, there will be no occurrence (0% frequency) of extreme droughts during the far-future period, for all the analyzed dekads. It can also be observed that the severity of drought is expected to lessen in the beginning of the far-future climate period (Figure 4.15) and then intensify towards the end of the far-future period. These results suggest that previous seasons' water content does not impact crop growth and development, as each season is unique. A study by Sun (2009) indicated that moisture condition during crop establishment is largely attributed to the amount of water received prior to planting. At this stage, soil moisture conditions for crop establishment is important because sufficient soil moisture conditions encourage good seed establishment and early root growth (Whitmore, 2000).

Moreover, findings reported by Engelbrecht *et al*. (2015) projected a significant reduction in rainfall over the subtropics, as well as a temperature increase of 4-7°C towards the end of the 21st century relative to present-day climate under the SRES A2 (a low mitigation) scenario. However, it is interesting to notice that the expected conditions resulting in total crop failure by the end of the century might be due to the projected high evapotranspiration rates, which may also intensify the drought more quickly during the growing period regardless of the high precipitation rates experienced in the previous seasons (Törnros and Menzel, 2014).

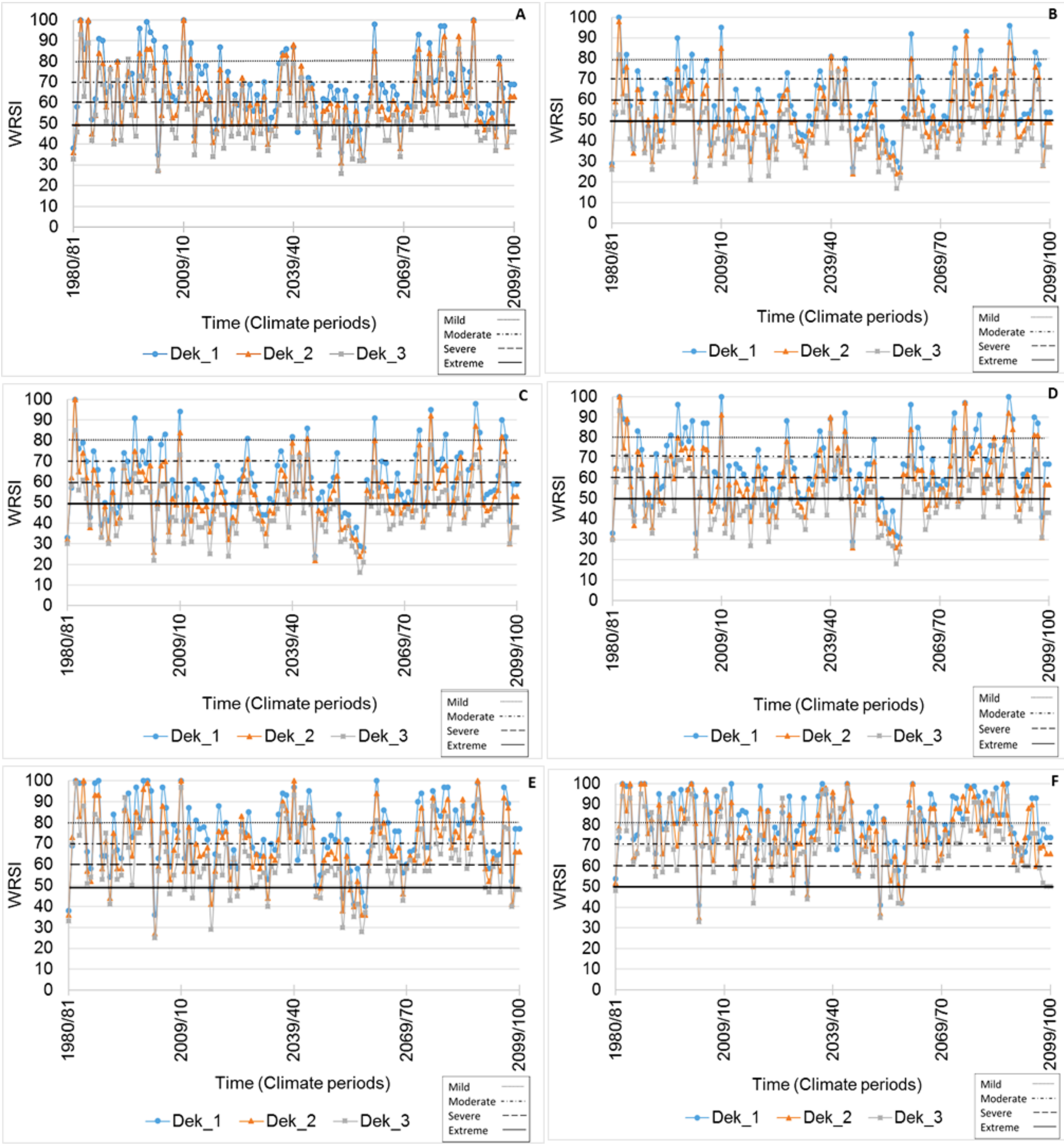


Figure 4.15 Simulated WRSI time series per growing season relative to the four climate periods for stations Mampakuil (A), Sigonde (B), Pafuri (C), Punda Maria (D), Tshiombo (E) and Levubu (F).

Table 4.3: Frequency (in %) of the different levels of drought (by WRSI) for future climates, relative to the base period, at the Luvuvhu River catchment.

Station	Drought category	Climate period (Dekad 1)				Climate period (Dekad 2)				Climate period (Dekad 3)			
		Base	**Near-future**	**Intermediate-future**	**Far-future**	**Base**	**Near-future**	**Intermediate-future**	**Far-future**	**Base**	**Near-future**	**Intermediate-future**	**Far-future**
Mampakuil	Mild	**63**	83	93	73	**73**	87	93	80	**90**	93	100	90
	Moderate	**50**	63	87	53	**57**	77	90	73	**70**	87	87	80
	Severe	**20**	40	37	33	**40**	43	73	43	**47**	73	87	73
	Extreme	**7**	13	23	3	**13**	27	27	10	**30**	43	50	37
Sigonde	Mild	**87**	97	90	80	**97**	97	93	93	**97**	100	100	100
	Moderate	**67**	90	87	63	**90**	97	87	77	**97**	97	90	93
	Severe	**50**	67	77	50	**60**	83	80	60	**87**	97	83	77
	Extreme	**33**	33	40	17	**40**	60	50	40	**50**	80	77	60
Pafuri	Mild	**87**	93	90	77	**97**	97	93	90	**97**	100	100	100
	Moderate	**60**	90	83	63	**87**	93	87	77	**97**	97	90	93
	Severe	**40**	63	63	47	**50**	80	80	57	**83**	93	87	77
	Extreme	**27**	30	30	10	**37**	53	47	33	**47**	80	73	60
Punda Maria	Mild	**67**	90	87	70	**90**	97	90	77	**97**	97	97	97
	Moderate	**50**	80	80	50	**60**	90	87	63	**90**	97	87	80
	Severe	**33**	43	43	30	**43**	70	47	43	**53**	90	83	63
	Extreme	**20**	17	23	3	**30**	30	43	10	**43**	57	47	37
Tshiombo	Mild	**50**	70	73	47	**60**	87	80	67	**77**	90	87	87
	Moderate	**40**	40	43	37	**40**	57	63	47	**57**	80	80	63
	Severe	**17**	13	30	7	**33**	30	30	17	**40**	57	63	37
	Extreme	**7**	3	13	0	**10**	10	27	3	**13**	23	27	17
Levubu	Mild	**33**	50	50	37	**43**	67	63	47	**60**	80	67	73
	Moderate	**10**	20	23	10	**23**	27	37	20	**40**	60	57	37
	Severe	**7**	7	13	0	**7**	13	17	0	**20**	17	37	13
	Extreme	**3**	0	7	0	**3**	3	7	0	**7**	10	13	0

Table 4.4: Independent t-test for mean WRSI for future climates, relative to the base period, at the Luvuvhu River catchment.

Station	Stats parameters	Base	Near-future	Intermediate-future	Far-future
Mampakuil	Mean	**67**	59	54	64
	t-value	**0.00**	2.11	3.50	0.76
	p	**1.00**	0.02	0.00	0.22
Sigonde	Mean	**54**	47	47	57
	t-value	**0.00**	2.15	1.84	-0.67
	p	**1.00**	0.02	0.04	0.25
Pafuri	Mean	**57**	49	49	59
	t-value	**0.00**	2.36	1.96	-0.55
	p	**1.00**	0.01	0.03	0.29
Punda Maria	Mean	**62**	54	53	65
	t-value	**0.00**	2.39	2.10	-0.65
	p	**1.00**	0.01	0.02	0.26
Tshiombo	Mean	**73**	66	63	73
	t-value	**0.00**	1.99	2.43	0.10
	p	**1.00**	0.03	0.01	0.46
Levubu	Mean	**81**	74	72	80
	t-value	**0.00**	1.91	2.22	0.40
	p	**1.00**	0.03	0.02	0.35

*values highlighted in red differ statistically at α (0.10).

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Results given by the two drought indices can be summarized as follows:

- The frequency analysis of drought given by the Standardized Precipitation Evapotranspiration Index (SPEI) revealed that for the emergence and early vegetative stage, a high risk of frequent droughts was observed following planting in November-December at five of the seven stations, while for stage 2 (Vegetative), the risk was noted for October-November planting. Furthermore, results for stage 3 (flowering to grain-filling) showed that severe-extreme droughts were mostly observed at Levubu, Lwamondo, Thohoyandou, and Tshiombo relative to planting in December, while this planting period gave lower risks for stations in the low-lying plains of the upper catchment (Punda Maria, Sigonde, and Pafuri).
- Water Requirements Satisfaction Index (WRSI) values corresponding to more intense drought conditions were reflected during the December planting date for all stations. Moreover, at Punda Maria, Sigonde and Pafuri, it was seen that extreme droughts occurred once in five seasons, regardless of the planting date.
- As per SPEI results, notable seasons subjected to extreme widespread drought were identified as 1983/84 and 1991/92; while WRSI reflected the following seasons as having experienced extreme widespread droughts: 1983/84, 1988/89, 1991/92, 1993/94, 2001/02, 2002/03, 2004/05 and 2014/15.
- Generally, there were no significant trends noted, with the exception of some stations revealing weak decreasing drought trends (ρ = of 0.5 for WRSI at Thohoyandou; Levubu and Lwamondo with ρ = of 0.4 for SPEI).
- Analysis of water balance during the widespread droughts given by SPEI showed that the occurrence and the severity of drought were aggravated by the low rainfall amounts together with high evapotranspiration rates throughout the rainfall season.
- WRSI results also showed the 1991/92 drought as being the worst, however, unlike the SPEI, it was noted that the drought effects of this drought worsened until the end of 1993.

- SPEI results further revealed 1999/00 and 2012/13 as being the extreme wet seasons in the area for the analysis period; while, WRSI results showed extreme wet seasons as being 1987/88, 1999/00, 2003/04 and 2013/14.
- Future climates analysis by both SPEI and WRSI projected increased frequency of droughts that would often lead to poor crop performance and failure, by the near-future to the end of the intermediate-future period. These conditions are then expected to return to normal at the beginning of the far-future climate period with a slight intensification of drought detected towards the end of the analysis period.
- Independent t-test results further revealed that the mean SPEI and WRSI during the near-future and intermediate-future climates were significantly different from the base period. This was observed at all stations based on WRSI results, while SPEI results revealed this change at only five of the six stations for the intermediate-future period only.

5.2 Conclusions and recommendations

The main objective of this study was to assess the past and future occurrences of drought in relation to its effects on the development of maize in the Luvuvhu River catchment area of South Africa. The study utilized the Standardized Precipitation Evapotranspiration Index (SPEI) and Water Requirement Satisfaction Index (WRSI) in order to detect the onset, severity and temporal variations of drought. Variations in how these two indices were able to identify drought occurrences. The SPEI was used to account for the influence of evapotranspiration in determining the possible effects of drought for each stage of the crop. While the WRSI captured the crop's vulnerability to the occurrence of droughts by indicating the extent to which the crop water requirements have been dis/satisfied during the growing season.

Results indicated that stations receiving moderate to high annual rainfall were at a higher risk of recurrent SPEI values of -1 to -1.99 (moderate to severe drought) during the crop's most sensitive stage following planting in December, while the upper catchment experienced more frequent droughts relative to October planting date. Moreover, results given by WRSI on the performance of the maize crop subjected to drought conditions revealed a high risk of crop water requirements not being met during critical periods of the growing season, following planting in December at all stations.

Furthermore, analysis on previous droughts led to a recommendation of using October-November as the optimum planting date in the catchment. For minimizing the risk of damaging drought conditions on maize, planting in October can be recommended at stations Levubu, Lwamondo, Thohoyandou, and Tshiombo, however, planting too early (1st dekad of October) might place crops grown in these areas under drought stress. It can also be advised for farmers located near stations Punda Maria, Sigonde and Pafuri to plant in November. However, these three regions have shown (by the WRSI results) to be unsuitable for rain-fed maize production, with the number of seasons subjected to extreme drought conditions being >50% out of all the analysed seasons. Farmers located in these areas can be advised to supplement rain-fed farming with irrigation should they be located nearby to rivers. Moreover, for the improvement of agricultural productivity, the Government needs to ensure that proper support such as effective early warning systems and input provision is provided.

Generally, Spearman's correlation test revealed that there was a regularity in the behaviour of drought and that the area did not become drier or wetter over time. Overall features of drought conditions in the future given by both the SPEI and WRSI showed that all stations could become significantly drier ($p < 0.10$) during the near-future to intermediate-future relative to the base period, resulting in poor crop performance and crop failure. Drought conditions can then be expected to weaken during the beginning of the far-future climate period.

This study provided information that agricultural decisions can be improved and better supported if the probability of drought occurrences is computed following effective planting dates. The timing of drought, also highlighted that, although farmers would rather want a fair distribution of rainfall throughout the season, in reality, this is not ideal, thus the necessity of assessing drought relative to the different stages of the crops. Therefore, sustainable water management measures (such as conservation agriculture) should be planned in order to mitigate the possible drought effects under climate change. Moreover, essential communication between scientists, decision makers, and the farmers can help in planning and decision making ahead of and during the occurrence of droughts.

5.3 Future studies

For future research, assessments on adapting to climate change on different staple crops as well as suitability studies can also be considered in the area. Future work could also consider using crop modelling to estimate maize yields, taking into consideration different management practices, crop varieties and seasonal variations of climate. In addition, for a more comprehensive assessment of climate change, future studies may also consider using emission scenarios provided by the IPCC fifth assessment report (AR5).

5.4 Publications

The following three manuscripts from this study have been submitted for review:

1. "Use of Standardized Precipitation Evapotranspiration Index to investigate drought relative to maize, in the Luvuvhu River catchment area, South Africa" has been accepted for publication in an international Journal "Physics and Chemistry of the Earth".
2. "The use of Water Requirement Satisfaction Index for assessing agricultural drought on rain-fed maize, in the Luvuvhu River catchment, South Africa" has been submitted for publication in an international Journal titled "Theoretical and applied climatology" and currently being reviewed.
3. "Analysis of potential future droughts limiting maize production, in the Luvuvhu River catchment area, South Africa" has been submitted for publication in an international Journal "Physics and Chemistry of the Earth" and currently being reviewed.

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