CLIMATE VARIABILITY AND EXTREME EVENTS ANALYSIS IN THE ZAMBEZI RIVER BASIN USING STANDARDIZED PRECIPITATION EVAPOTRANSPIRATION INDEX AND L-MOMENTS

REPORT

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1 INTRODUCTION

1.1 BACKGROUND AND SIGNIFICANCE

The Zambezi River is an important water resource with its catchment area covering most parts of Southern Africa (Figure 1). It is a habitat to a wide range of plant and animal species. Humanity in this region just like other animals depends on water from the Zambezi River and its tributaries. Its dependence ranges from provision of potable water, agriculture, power, manufacturing, mining, tourism and many other sectors (World Bank 2010). With such benefits from the river, the human population is proved to be rapidly increasing. For example, an annual increase of 3.9% in Africa (the highest in the world) has been recorded with most of the increase in the Southern part of the continent, which is mostly covered by this basin (World Bank, 2010). Despite the population boom, industrialization and urbanization, not all Africans have access to clean water and sanitation. Water availability varies from country to country as some parts of Southern Africa receive very low mean annual rainfall (Namib and Kalahari deserts) and low river flows with others receiving very high precipitation (areas in the sub tropics) hence high river flows. With this in mind, more water is needed to meet the increasing demands for clean water, sanitation, irrigation, and power (Hydroelectric).

According to the Intergovernmental Panel on Climate Change (IPCC), Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events (IPCC, 2014). Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability) (ibid). On the contrary, climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer (IPCC, 2014). Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use. Climate change, and or variability are known to be impacting water availability in the Zambezi River Basin (IPCC, 2007; Beilfuss, 2012). For example, the IPCC has categorized the Zambezi as the river basin exhibiting the "worst" potential effects of climate change among 11 major African river basins due to the projected increase in temperature and decrease in rainfall (IPCC, 2007). It is estimated that overall, the basin is expected to experience a significant warming trend of 0.3-0.6^{o} C, which in turn will lead to increased open-water evaporation, while rainfall and runoff are likely to decrease by 10-15%, and 26-40%, respectively by 2050 (IPCC, 2007; Beilfuss, 2012). These changes will increase the vulnerability of the basin in the future particularly affecting water security of the basin.

Other studies however, predict a high increase in the mean annual temperature of about 4ºC due to global warming and a reduction in the mean annual rainfall (by up to about 20%) by the end of the 21st Century (Engelbrecht et al (2011). These different projections (as a result of using different models and assumptions) bring in uncertainties surrounding the actual changes brought in by climate change. In some cases, there is evidence of marginal increase in precipitation in some parts of the basin and across the entire continent (Schlosser and Strzepek, 2015; Engelbrecht et al, 2011), with more extreme events (droughts, floods, heat waves and veld fires) occurring very often (Kenabatho et al., 2012).

The projected aridity changes indicated by the Aridity Index also show a strong deterioration towards more arid conditions due to low rainfall in the Southern part of Africa (Serdeczny et al., 2016). These factors are going to impact negatively on the already existing water resources and low and unreliable rainfall together with prolonged droughts will result in low surface water flows and low groundwater recharge rate (Kenabatho et al., 2012). Increasing temperatures cause high evaporation rates. In combination with loss of vegetation cover due to overstocking, overgrazing and deforestation there is an accelerated rate of loss of soil moisture that will cause a low agricultural production impacting negatively on food security in Southern Africa.

). The climate of an area is closely tied to its location relative to the Intertropical Convergence Zone (ITCZ) often called the 'climate equator'. This is an area around the geographic equator where north and south trade winds converge, rise and circulate back. As the winds converge, moist air rises. It then cools causing water vapor to convert to rainfall. Areas closest to the ITCZ receive the highest, frequent and reliable rainfall with a reduction as you go further south and north of the ITCZ. Because the earth is tilted on its axis relative to its orbit around the sun, the amount of heat received from the sun is not equal (in the north and southern hemisphere) and that gives rise to seasonal climatic changes. In January most of the precipitation is in the southern part of the equator and shifts to the north as the year progresses (around June). Although these climatic variables show a very close link between the geographical location of an area relative to the ITCZ position, many studies predict a general change in precipitation patterns, temperature and dryness in Southern Africa, most of which is within the Zambezi River Basin.

Researchers also reveal that in the Zambezi River Basin, a slight climatic change case results in a 32% fall in energy production (Beilfuss R., 2012) affecting other sectors such as mining and manufacturing which are much reliant on power. Taking all the issues above into consideration, there is a rapid rise in water demand due to population increase, urbanization and irrigation which automatically expands the human dependence on the Zambezi River Basin.
Despite this increasing dependence, water availability is decreasing due to climate change, which implies the current abundance of water on most parts of the Zambezi River Basin is not likely to last (Beck and Bernauer, 2011).

Although studies may have assessed the implications of water demand and climate change collectively (Beck and Bernauer T, 2011), and predict dryness across the region (Kenabatho et al., 2012), they do not reveal the dryness distribution across basin's riparian countries. This study therefore, focuses on the dryness characteristics of the basin as a result of increased water demand, increasing temperatures and change in precipitation patterns due to El Nino.

It is therefore in this context that it is proposed to make a holistic study on the changes in the dryness condition across the Zambezi basin so as to assess the trends for the futuristic water resources management for this basin.

1.2 PROBLEM STATEMENT

The rapidly increasing population and economic growth in Southern Africa has a very large impact on water demand. For example, the population of [1]Southern Africa grew from 76 million in 1980 to 171 million in 2015 (more than double), and is projected to rise to 213 million and 344 million by 2025 and 2050, respectively (United Nations Department of Economic and Social Affairs (UN DESA, 2018); United Nations Economic Commission for Africa (UN ECA), 2016).

The impacts are further increased by the climatic variations due to El Nino. This is evident as extreme events (such as droughts and heat waves) have been common in the past three decades with frequent water shortages (potable water) as most water resources have been below normal to almost empty (Dams and rivers) due to unreliable and low precipitation. Scientifically, if the rate of loss of soil moisture exceeds the amount of precipitation, dryness is said to occur, in that case leading to droughts. With most of Southern African population heavily dependent on the Zambezi for critical economic activities such as agriculture, Hydro power, fishing, it is necessary to study the dryness and wetness conditions based on historical data and project the future so as to inform the relevant policies and decision makers on adaptive measures to increase resilience of the Zambezi ecosystem and its people. According to the IPCC, resilience of an ecosystem means its ability either to resist change or to recover after a disturbance (Allen et al, 2018). Knowing the wetness/dryness dynamics of the basin under future climate change will go a long way in developing policies and strategies that are geared towards strengthening resilience and adaptive capacity to address these extreme events as espoused in SDG 13, which calls for urgent action to address climate change and its impacts (United Nations, 2015).

1.3 DESCRIPTION OF STUDY AREA

The area under study is the Zambezi River Basin (*Figure 1)*. The river basin drains about 1.4 million km^2 across Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe. The river starts from a small spring in the Northwestern Zambia and stretches for

[1] Comprising of Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Zambia and Zimbabwe

approximately 3000 km across Zimbabwe, Malawi, through Mozambique into the Indian Ocean, sustaining a population of 40 million people (projected to be 51 million by 2025) (SADC 2013).. It hosts numerous urban areas including most of Zambian cities and Harare (Zimbabwean Capital City). The natural environment is characterized by lakes (Nyasa, Malawi), gorges, water falls (including the famous Victoria Falls in Zambia) and a very diverse flora and fauna species. The ecology and natural environment has a socio-economic influence on humanity since it directly hosts (facilitates) human activities such as mining, fishing, agriculture, forestry, manufacturing and tourism all relying on the hydropower electricity utilizing river water (WMO, 2009). The Zambezi River Basin map shows all riparian countries, sub basins and catchment areas (highlighted) (*Figure 1)* and *Table 1.*

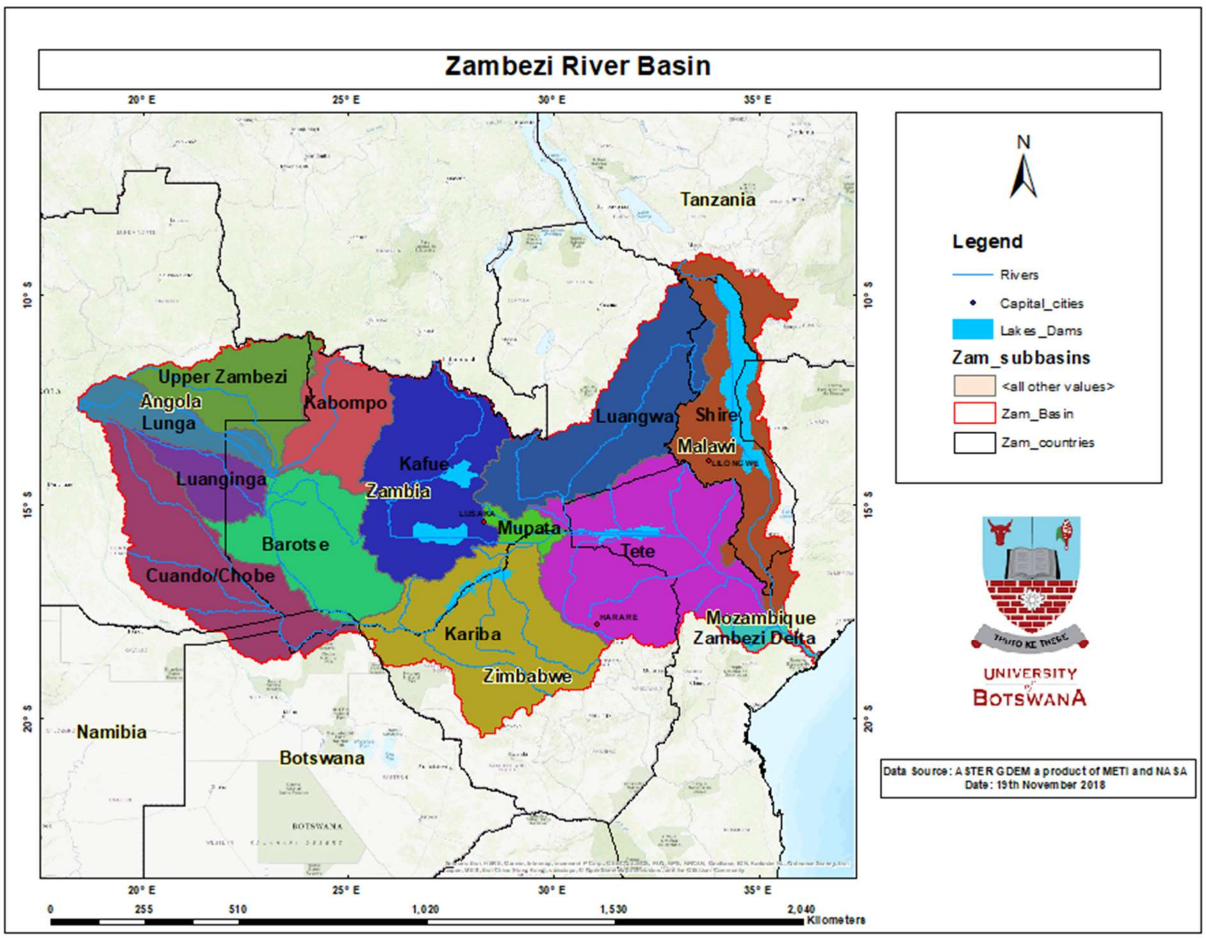

Figure 1: Zambezi River Basin Map

Table 1: Zambezi River sub-basin and their areas

Number	**Sub_basin Name**	**Sub_basin area (Km^2)**
1	Zambezi Delta	14,539.23
2	Tete	219,390.68
3	Shire	156,916.18
4	Mupata	16,362.28
5	Luanga	157,119.03
6	Kariba	185,569.44
7	Kafue	163,753.95
8	Cuando/Chobe	159,032.44
9	Barotse	116,278.43
10	Luanginga	44,440.64
11	Lunga	49,328.69
12	Upper Zambezi	89,907.97
13	Kambompo	73,130.23

The hydrology of the basin is dependent on a number of variables. The variation in precipitation (Table *2*) in summer is due to Inter Tropical Convergence zone between the North east Monsoon and the South east trade winds for the middle and lower Zambezi and the Congo air boundary between the South West Monsoon and the South east Trades for the upper Zambezi (Moore at al., 2007). The further south the boundaries move, the more the precipitation as seen in Table *2*. Drier conditions are experienced in winter as the ITCZ shifts to the north, and so most of the flow contribution is from the North (Moore at al., 2007). The mean monthly changes in flow are depicted in Table *3*.

Table 2: Precipitation data for the Zambezi River Basin (Source: WMO, 2009)

	Sub basin	Mean annual precipitation (mm)
1	Kapombo	1211
2	Upper Zambezi	1225
3	Lungue Bungo	1103
4	Luanginga	958
5	Barotse	810
6	Cuando/Chobe	797
7	Kafue	1042
8	Kariba	701
9	Luangwa	1021
10	Mupata	813

11	Shire River and Lake Malawi/Niassa/Nyasa	1125
12	Tete	887
13	Zambezi Delta	1060
	Zambezi River Basin, mean	956

Table 3: Zambezi River mean monthly flows in m^3s^{-1} (Source: Moore et al., 2007)

Station Period (Years)	Chavuma 1959/60-2001/02	Lukulu 1950/51-2001/02	Katima Mulilo 1967/68-2001/02	Victoria Falls 1951/52-2001/02
Oct	68	271	306	293
Nov	94	310	320	297
Dec	228	468	430	438
Jan	655	803	678	686
Feb	1411	1294	1211	1184
Mar	2031	1645	2374	2175
Apr	1770	1523	3129	3007
May	684	944	2427	2613
Jun	310	575	1326	1621
Jul	188	434	691	845
Aug	124	361	467	519
Sep	83	306	364	376
Mean annual	637	745	1144	1171

1.4 RESEARCH OBJECTIVE

How is the Zambezi River Basin changing in terms of climate variability and extreme events?

1.4.1 SPECIFIC RESEARCH OBJECTIVES

- To evaluate the trends of climatic variables in the Zambezi River basin
- To analyze dryness/wetness conditions of the Zambezi River Basin (ZRB) based on historical data
- To produce a dryness/wetness severity map for the ZRB based on the analysis

1.5 RESEARCH QUESTIONS

Table 4: Research objectives and questions

Objectives	Research Questions	Methodology
To evaluate the trends of climatic variables between 1970 and 2015	Are there any trends in the climatic variables and if any, how significant are they?	Mann-Kendall trend test (for direction of trend) and Sen's slope estimator (for magnitude of trend)
To analyze dryness/wetness conditions of the ZRB based on historical data.	What is the rate of increase of the dryness or wetness?	Use of Standardised Precipitation Evapotranspiration Index (SPEI) and L-moments
	What is the seasonal outlook of the basin using available data?	
To produce a dryness/wetness severity map for the ZRB based on the analysis	Which areas are wetting and which ones are drying?	Use of Maps based on Geographic Information System (GIS)
	What is the rate of drying/wetting per location?	
	How severe is the drying/wetting per location?	

1.6 SCOPE OF RESEARCH

The study covers the Zambezi river basin using the subcatchments shown in *Figure 1*. In addition, due to paucity of data, the study utilized the Climatic Research Unit (CRU) gridded data extracted from each sub catchment (Harris et al, 2014). No historical data has been used in this report. However, it should be noted that the CRU datasets have been interpolated based on available historical data (Harris et al, 2014). During this project, no validation nor bias correction were performed due to data limitation.

For the Standardized Precipitation Evapotranspiration (SPEI), this study adopted the analysis described by Vicente-Serrano et al., 2010, as recently applied by Byakatonda et al (2018). In addition, related analysis such as trends, and change point/intervention analyses were undertaken.

1.7 BENEFITS AND BENEFICIARIES

The study is expected to reveal the dryness/wetness conditions of the study area in response to climate change. This information is beneficial in the sense that it will inform future decision making for policy makers in various organizations and enterprises on adaptive measures to take within the context of climate change. These are shown in *Table 5*.

Table 5: Benefits and beneficiaries of this study

Beneficiary sector	**Benefits**
Agriculture	Development of climate adaptive technologies in plant and animal production.
	Prediction of likelihood climate borne plant and animal diseases.
	Forecasting of possibility of low agricultural produce so as to take necessary measures.
Political	Development of policies regarding water supply, agriculture and other sectors affected by dryness/wetness of the land.
Manufacturing	Development of better manufacturing techniques in response to raw material quality (for example, the quality of timber may be influenced by the availability of soil moisture where it was grown).

Education	Dissemination of information so as to inform the society on dryness/wetness adaptation measures in different sectors such as agriculture (for example, new planting technologies).
Forestry	Understanding of how forestry resources may change in future.

1.8 COLLECTION AND COLLATION OF EXISTING DATA

Since the study was conducted within the auspices of the NEPAD Southern African Network of Centres of Excellence (SANWATCE), the hub at Stellenbosch University played a role in facilitating the collection of historical data from the Zambezi Watercourse Commission (ZAMCOM) through a non-disclosure agreement (NDA). However, since the process was still ongoing during the execution of the project, the study adopted to use freely available datasets from the Climatic Research Unit known as the CRU data. Precipitation, maximum and minimum data were downloaded from the CRU databases and processed for analysis. No validation of datasets was done due to unavailability of historical data as explained earlier, so the results should be interpreted with caution.

2 METHODOLOGICAL APPROACH

2.1 CLIMATE VARIABILITY

In assessing climate variability, this report adopted the use of trend analysis methods and drought indices assessment mainly the standardized precipitation evapotranspiration (SPEI). These approaches are discussed in this chapter, whose results are presented and discussed in chapter 3.

2.1.1 TREND ANALYSIS

2.1.1.1 MONOTONIC TREND TEST

Tests for the detection of significant trends in climatologic time series can be categorized as parametric and non-parametric. Parametric trend tests require data to be independent and normally distributed, while non-parametric trend tests require only that the data be independent (Gocic and Trajkovic, 2013). Non-parametric methods such as Mann-Kendall (MK) will be used to detect trends in the data for the basin.

The method has been used extensively across different climatic zones to assess the significance of trends in hydro-meteorological time-series data like in (Modarres and de Paulo Rodrigues da Silva, 2007; Kampata et al., 2008; Parida and Moalafhi, 2008; Petrow and Merz, 2009; Wang et al., 2015; Byakatonda et al., 2018). The Mann-Kendall test statistic has been shown to be more robust than parametric tests when dealing with skewed data and outliers in a data series (Helsel and Hirsch, 1992). The Mann-Kendall statistic S is given by;

$$S = \sum_{i}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_k) \qquad (2.3)$$

Where n is the number of data points, x_k and xj are the data values in time series k and j (j>k), respectively and $sgn(x_j - x_k)$ is the sign function as:

$$sgn(x_j - x_k) = \begin{cases} +1 & if\ (x_j - x_k) > 0 \\ 0 & if\ (x_j - x_k) = 0 \\ -1 & if\ (x_j - x_k) < 0 \end{cases} \qquad (2.4)$$

The test statistic represents the number of positive differences minus the number of negative differences for all the differences between adjacent points in the time series.

For circumstances where the sample size n>10, the standard normal test statistic Z_S is computed using

$$Z_s = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}\ if\ S > 0 \\ 0\ if\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}\ if\ S < 0 \end{cases} \qquad (2.5)$$

Where Var(s) is the variance of the sample also given by

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i}^{m} t_i(t_i-1)(2t_i+5)}{18} \qquad (2.6)$$

Where n is the number of data points, m is the number of tied groups and t_i denotes the number of ties of extent i. A tied group is a set of sample data having the same value. Taking a data set of 2, 3, 1, 3, 1 and 3 ,
t_3=1(one set of three values), t_2=1(one set of two value) and t_1=1 (one set of untied values)
Positive values of Z_s designate an upward trend and negative values otherwise.
Testing trends is done at the specific α significance level. When $|Z_S| > Z_{1-\alpha/2}$, the null hypothesis of no trend is rejected and a significant trend exists in the time series. $Z_{1-\alpha/2}$ is obtained from the standard normal distribution table. In this research, significance levels α=0.01 and α=0.05 will be used.

2.1.1.2 SEN'S SLOPE ESTIMATOR

2.1.1.2.1 The Sen's Slope

The Mann-Kendall's trend test is only able to indicate the direction of the trend and as such does not reveal the significance of the trend. The test for significance of a linear dependence between two continuous variables, the meteorological data and time (Y and X) will be investigated by determining whether the regression slope coefficient for the explanatory variable is significantly different from zero by applying the Sen's slope criteria (Helsel and Hirsch, 1992).

Testing the significance of the slope of trend in the sample of N pairs of data will be accomplished using the non-parametric procedure developed by Sen (1968). The slope of N pairs of data sets is given by:

$$Q_i = \frac{x_j - x_k}{j-k} \; for \; i = 1, 2, \ldots.., N \qquad (2.7)$$

Where x_j and x_k are the data values at times j and k (j>k), respectively.

Should there be single measurements for each time period, then $N = \frac{n(n-1)}{2}$;
Where n is the number of time periods. If there are multiple measurements in one or more time periods, then $N < \frac{n(n-1)}{2}$

The N values of Q_i are ranked in ascending order with the median of slope or Sen's slope estimator computed as

$$Q_{med} = \begin{cases} Q_{\frac{(N+1)}{2}} \; if \; N \; is \; odd \\ \dfrac{Q_{\left(\frac{N}{2}\right)} + Q_{\left[\frac{(N+2)}{2}/2\right]}}{2} \; if \; N \; is \; even \end{cases} \qquad (2.8)$$

The Q_{med} sign reflects data trend reflection, while its value indicates the steepness of the trend (Gocic and Trajkovic, 2013). To determine whether the median slope is statistically different than zero, a confidence interval of Q_{med} at specific probability will be obtained.
The confidence interval about the time slope as applied in Gocic and Trajkovic (2013) while they were analyzing significance of trends is given by

$$C_\alpha = Z_{\left(1-\frac{\alpha}{2}\right)} \sqrt{Var(S)} \qquad (2.9)$$

Where Var(S) is defined earlier and $Z_{1-\alpha/2}$ is the statistic obtained from the standard normal table. In this study, confidence intervals will be established at two significance levels (α=0.01 and α=0.05).

From C_α above, the $M_1 = \frac{N-C_\alpha}{2}$ and $M_2 = \frac{N+C_\alpha}{2}$ are obtained. The lower and upper limits of the confidence interval, Q_{min} and Q_{max}, are the M_1^{th} largest and the $(M_2+1)^{th}$ largest of the N ordered slope estimates. The slope Q_{med} statistically differs from zero if the two limits (Q_{min} and Q_{max}) have similar sign (Gocic and Trajkovic, 2013)..

The Sen's slope estimator method has found use in a number of analyses of hydro-meteorological time series, including recent studies (Petrow and Merz, 2009; Tabari et al., 2011; Gocic and Trajkovic, 2013).

2.1.1.2.2 Percentage change in magnitude based on Sen's slope

To evaluate the percentage change in magnitude, an approach based on Yue and Hashino (2003) was implemented as:

$$\%Change = \frac{\beta\ X\ length\ of\ data(years)}{mean} X\ 100 \qquad (2.10)$$

Where β is the Sen's slope.

2.2 DRYNESS/WETNESS INDICES

Two indices were considered, being:

(i) Standardized Precipitation Index (SPI), or
(ii) Standardized Precipitation Evapotranspiration Index (SPEI).

However, in this report the focus was on SPEI, mainly because it incorporates temperature, which is valuable when considering climate variability or climate change.

2.2.1 STANDARDIZED PRECIPITATION EVAPOTRANSPIRATION INDEX (SPEI)

The SPEI (Vicente-Serrano et al., 2010) method will be used. It has been credited for incorporating evapotranspiration into the standard SPI thereby allowing for inclusion of water balance. The method has found wide application across many areas of different climatic zones (Vicente-Serrano et al., 2010; Yu et al., 2014; Wang et al., 2015, Byakatonda et al., 2016). The following procedure is adopted for computation of SPEI:

i) Determination of the Potential Evapotranspiration ETo
ii) Accumulation of climate water balance (D_i) at different time scales (i.e. P_i-ETo_i)
iii) Normalization of the water balance into a probability distribution function to obtain the SPEI index series.

2.2.1.1 DETERMINATION OF THE POTENTIAL EVAPOTRANSPIRATION (ET_0)

From the numerous existing ETo equations, the FAO-56 application of the Penman-Monteith (PM) equation (Allen et al., 1998) has received wide application. The method is widely used and recommended by the Food and Agricultural organization FAO Statistics (1998), the International Commission on Irrigation and Drainage (ICID) and the American Society of Civil Engineers (ASCE) as a robust procedure because it is predominately a physically based method (Vicente-Serrano et al., 2010). A major limitation to the application of the PM however, is the relatively high data demand in the form of air temperature, wind speed, relative humidity, and solar radiation. These datasets are not always available for the desired case studies.

An alternative approach was developed by Hargreaves (1994) where only mean maximum and mean minimum air temperature and extraterrestrial radiation are required. The extraterrestrial radiation in the computation can be calculated for a certain day and location. Due to the limited data availability, the Hargreaves (1994) method offers a better alternative. The study will follow the approach as implemented by Droogers and Allen (2002), and Byakatonda et al (2018). The following equation will be used to compute ET_o:

$$\boldsymbol{ET_0 = 0.0023(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} * 0.408R_a} \tag{2.1}$$

Where,

T_{mean} is the mean air temperature (^0C),

T_{max} is the maximum air temperature (^0C),

T_{min} is the minimum air temperature (^0C)

R_a is extraterrestrial radiation [MJ m^{-2} day^{-1}] and is given by:

$$\boldsymbol{R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)]} \tag{2.2}$$

Where,

G_{sc} is solar constant = 0.0820 MJ m^{-2} min-1,

d_r is inverse relative distance Earth-Sun (Equation 2.3),

ω_s is sunset hour angle (Equation 2.6) [rad],

φ is latitude [rad],

δ is solar declination (Equation 2.4) [rad].

The inverse relative distance Earth-Sun, d_r, and the solar declination, δ, are given by:

$$\boldsymbol{d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right)} \tag{2.3}$$

$$\boldsymbol{\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right)} \tag{2.4}$$

Where ***J*** is the average Julian day of the month given by

$$J = \begin{cases} \left(\frac{275M}{9} - 30 + D\right) - 2 & M > 3 \\ \left(\frac{275M}{9} - 30 + D\right) & M < 3 \\ \left(\frac{275M}{9} - 30 + D\right) + 1 & M > 2 \; for \; leap \; year \end{cases} \quad (2.5)$$

D=15 for average month

The sunset hour angle, ω_s, is given by:

$$\omega_s = cos^{-1}[-tan(\varphi)tan(\delta)] \quad (2.6)$$

2.2.1.2 ACCUMULATION OF CLIMATE WATER BALANCE (D_I) SERIES

With ETo established, the monthly water balance will be calculated as a difference between Precipitation (P_i) and evapotranspiration (ET_{oi}) as follows:

$$D_i = P_i - ET_{0i} \quad (2.7)$$

Where,
P is monthly precipitation from the CRU datasets
i is month under consideration

The calculated D_i values will be aggregated at different time scales, following the same procedure as that for the SPI. The difference $D^k_{j,i}$ in a given month j and year i depends on the chosen time scale k. For example, the accumulated difference for one month in a particular year i with a 12-month time scale is calculated using

$$X^k_{j,i} = \sum_{l=13-k+i}^{12} D_{i-1,l} + \sum_{l=1}^{j} D_{i,l} \; if \; j < k \; and \quad (2.8)$$

$$X^k_{j,i} = \sum_{l=j-k+1}^{j} D_{i,l} \; if \; j \geq k \quad (2.9)$$

Where $D_{i,l}$ is $P_i - ET_{0i}$ the difference in the first month of year j, in millimeters and $D^k_{j,i} = X^k_{j,i} = D_i$ series.

2.2.1.3 NORMALIZATION OF THE WATER BALANCE SERIES

In quantifying SPEI a three parameter distribution will be used, since in the two parameter distributions the variable (D_i) has a lower boundary of zero ($0 > D < \infty$) which is the case in SPI that uses precipitation series with a lower minimum of 0.0 mm (Potop et al., 2010; Vicente-Serrano et al., 2010), whereas in three parameter distributions x in this case D_i series can take values in the range $\gamma > D < \infty$, where γ is the parameter of origin of the distribution, consequently D can have negative values, in an event of a deficit climate balance. The water balance series were normalized as twelve independent series. The method of L-Moments in combination with probability weighted moments (PWMs) will be used for parameter estimation of the probability distribution functions fitting the D_i series. Parameters resulting from this procedure are more stable against possible outliers in the series data (Haktanira and Bozduman, 1995). The unbiased probability weights as suggested by (Hosking et al., 1985) and presented in Haktanira and Bozduman (1995) is given by;

$$\boldsymbol{P_i}^{\boldsymbol{r}} = \frac{(\boldsymbol{i}-\mathbf{1})(\boldsymbol{i}-\mathbf{2})\ldots\ldots(\boldsymbol{i}-\boldsymbol{r})}{(\boldsymbol{n}-\mathbf{1})(\boldsymbol{n}-\mathbf{2})\ldots\ldots(\boldsymbol{n}-\boldsymbol{r})} \quad (2.10)$$

Where,

P_i^r is the probability weight,
i is the rank assigned to the data series arranged in ascending order,
n are number of observations,
r is the order

The L-moments permit the comparison of various candidate distributions frequency (Hosking and Wallis, 2005). To identify the candidate distributions, L-moment ratios (L-Skewness τ_3 and L-Kurtosis τ_4) will be calculated as follows;

$$\tau_3 = \frac{\lambda_3}{\lambda_2} \quad (2.11)$$

$$\tau_4 = \frac{\lambda_4}{\lambda_2} \quad (2.12)$$

and note that the *L*-coefficient of variance, $L - C_v(\tau_2)$; is given by:

$$\tau_2 = \frac{\lambda_2}{\lambda_1} \quad (2.13)$$

λ_2, λ_3 and λ_4 are L-moments of the of the D_i series computed from probability weighted moments (PWMs) as indicated in equations below:

$$\lambda_1 = M_0 \quad (2.14)$$

$$\lambda_2 = 2M_1 - M_0 \quad (2.15)$$

$$\lambda_3 = 6M_2 - 6M_1 + M_0 \quad (2.16)$$

$$\lambda_4 = 20M_3 - 30M_2 + 12M_1 - M_0 \quad (2.17)$$

These four moments are analogous to the first four conventional moments of X (i.e. mean, variance, skewness and kurtosis).

The PWMs of order r are given by,

$$M_r = \frac{1}{N}\sum_{i=1}^{N} {P_i}^r . X_i \qquad (2.18)$$

$$SPEI = W - \frac{C_0 + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3} \qquad (2.19)$$

Where

$W = \sqrt{-2\ln(P)}$ for $P \leq 0.5$ and P is the probability of exceeding a determined D value. The P value is obtained from $P = 1 - F(x)$. If P>0.5, then P is replaced by 1-P and the sign of the resultant SPEI is reversed. The constants are C_0=2.515517, C_1=0.802853, C_2=0.010328, d_1=1.432788, d_2=0.189269, d_3=0.001308

The average value of SPEI is 0, and the standard deviation is 1. The SPEI is a standardized variable, and it can therefore be compared with other SPEI values over time and space. For each time scale, each drought event (period in which SPEI is continuously negative and SPEI ≤ -1), will be defined through its *(i) duration* (time from the beginning to the end), (ii) *severity* (SPEI value for each month following a given classification), *(iii) magnitude* (SPEI sum for each month and for the duration of the severity), *(iv) intensity* (magnitude/duration ratio of the event).

2.3 MAPPING OF DRYNESS INDICES

The results obtained for SPI/SPEI and AI will be compiled and mapped to obtain spatially interpolated indices over the Zambezi basin, as well as time series for selected stations representative of the basin. In addition, other variables such as trends, variability will be plotted for the basin.

3 RESULTS AND DISCUSSION

3.1 TREND ANALYSIS USING MANN-KENDALL TEST

As discussed in Section 2.1.1, the MK and Sen's slope tests were used to detect the direction and magnitude of trend, respectively. In addition, percentage change in magnitude was also computed. The results are presented in Table *6* to Table *8* for rainfall, maximum and minimum temperature, respectively.

3.1.1 Rainfall trends in the study area

Starting with rainfall, the results (Table *6*) show that out of the twenty (20) [2]stations, fifteen (15) stations exhibited decreasing trends (i.e.75% of the stations in the basin). Of these fifteen, only

[2] Station here means virtual station, i.e. CRU data downloaded at the centroid of the subcatchment. In some subcatchments, two virtual stations were established based on the extent or significance of the subcatchment.

three stations showed statistically significant trends, i.e. Harare (Zimbabwe: p-value of 0.041), Mzuzu (Malawi: p-value of 0.024) and Tete1 (Mozambique: p-value of 0.0023). In terms of percentage change, Harare represents the highest percentage decrease of -25%, followed by Mzuzu (-21%) and Tete (-16%). The remaining five (5) stations displayed positive trends, with only one station having a significant positive trend at 5% level. The statistics for rainfall averaged across the entire basin indicate that rainfall has generally decreased, with MKZ of -0.58, and the Sen's slope of -1.59, and percentage change of -8.7%.

3.1.2 Maximum temperature trends

The results for maximum temperature are recorded in Table *7*. Based on the MKZ statistic and the Sen's slope, the results indicate that all stations recorded positive trends for the period under assessment. In addition, all the stations showed that the trends are significant at 5% level. High percentage changes for temperature over the last 46 years (1970-2015) are 6.84% and 6.63% for Kariba and Harare, respectively. It is important to mention that since all the stations recorded significant increasing trends in maximum temperature (as per the p-values), these increases however indicate that the changes occurred recently as shown by low percentage changes across the stations (2.4% to 6.8%: Table *7*). In general, maximum has increased, as shown by the positive basin statistics, with MKZ of 5.11, Sen's slope of 0.03 and percentage change of 4.8% across the basin.

3.1.3 Minimum temperature trends

The minimum temperature trends (Table *8*) also show increasing trends that are statistically significant at all the stations. However, the percentage changes over the period of assessment are slightly higher than those of maximum temperatures, with the highest being 12.14% (Cuando), followed by 11.49% (Victoria Falls). The statistics for the Zambezi basin shows an increase in minimum temperature with a MKZ of 4.1, Sen's slope of 0.03 and percentage change of 8.6%.

Table 6: MK trend and Sen's slope estimator for rainfall in the Zambezi River basin

Sub-Catchment	Station	MKZ	P-value	Sen's slope	% Change in magnitude	MAR (mm)
Barotse(Zambia)	Barotse	-0.167	0.87	-0.22	-1.23	822
Shire(Malwi)	Blantyre	-1.192	0.23	-2.494	-9.88	1161
Cuando/Chobe (Angola)	Cuando	0.095	0.92	0.168	-1.23	665
	Harare	-2.042	***0.041**	-4.405	**-24.65**	822
Kafue(Zambia)	Kafue	-0.275	0.78	-0.884	-5.01	811
Kapombo (Zambia)	Kapombo	0.795	0.43	1.167	-1.23	973
Kariba(Zimbabwe)	Kariba	-1.235	0.22	-2.228	-14.56	704

Cuando/Chobe (Botswana)	Kasane	-1.25	0.21	-2.208	-1.23	604
Shire (Malawi)	Lilongwe	-1.629	0.10	-2.3	-12.55	843
Luangwa(Zambia)	Luangwa	-1.037	0.30	-1.697	-12.08	646
	Luena	6.82	***0.0000**	0.177	0.70	1162
Lunga(Angola)	Lunga	1.022	0.31	1.454	6.29	1064
Mupata(Zambia)	Lusaka	-0.985	0.32	-1.668	-9.46	811
Mupata(Zambia)	Mupata	-1.155	0.25	-2.476	-16.68	683
	Mussuma	0.317	0.75	0.517	2.59	917
Shire(Malawi)	Mzuzu	-2.244	***0.024**	-5.526	**-21.41**	1187
Tete (Mozambique)	Tet1	-1.612	0.11	-2.056	-10.75	880
Tete (Mozambique)	Tet2	-3.048	***0.0023**	-2.382	**-15.95**	687
Kariba (Zimbabwe)	VictoriaFalls	-1.231	0.22	-2.031	-14.69	636
ZambeziDelta (Mozambique)	Zambezidelta	-1.52	0.13	-2.797	-10.49	1226
	Zambezi Mean	**-0.58**	**0.31**	**-1.59**	**-8.7**	**865**

Table 7: MK trend and Sen's slope estimator for Maximum temperature in the Zambezi River basin

Sub-Catchment	**Station**	**MKZ**	**P-value**	**Sen's slope**	**% change in magnitude**	**Mean Max Temp**
Barotse(Zambia)	Barotse	6.56	0.0000	0.037	5.59	30.47
Shire(Malwi)	Blantyre	4.50	0.0000	0.026	4.42	27.07
Cuando/Chobe (Angola)	Cuando	7.15	0.0000	0.037	5.55	30.69
	Harare	5.01	0.0000	0.038	6.63	26.37
Kafue(Zambia)	Kafue	4.85	0.0000	0.032	5.11	28.78
Kapombo (Zambia)	Kapombo	6.50	0.0000	0.032	4.84	30.39

Kariba (Zimbabwe)	Kariba	5.24	0.0000	0.043	6.84	28.93
Cuando/Chobe (Botswana)	Kasane	6.58	0.0000	0.038	5.63	31.04
Shire (Malawi)	Lilongwe	4.16	0.0000	0.025	4.29	26.79
Luangwa(Zambia)	Luangwa	5.31	0.0000	0.033	4.83	31.44
	Luena	4.38	0.0000	0.015	2.41	28.67
Lunga(Angola)	Lunga	3.83	0.0001	0.019	2.89	30.22
Mupata(Zambia)	Lusaka	5.95	0.0000	0.031	5.08	28.08
Mupata(Zambia)	Mupata	4.17	0.0000	0.032	4.79	30.70
	Mussuma	5.22	0.0000	0.033	4.92	30.86
Shire(Malawi)	Mzuzu	4.16	0.0000	0.019	3.26	26.85
Tete (Mozambique)	Tet1	4.10	0.0000	0.027	4.12	30.15
Tete (Mozambique)	Tet2	4.72	0.0000	0.03	4.37	31.60
Kariba (Zimbabwe)	VictoriaFalls	4.80	0.0000	0.039	5.90	30.42
ZambeziDelta (Mozambique)	Zambezidelta	5.12	0.0000	0.028	4.27	30.15
	Zambezi Mean	**5.11**	**0.0000**	**0.03**	**4.8**	**29.48**

Table 8: MK trend and Sen's slope estimator for Minimum temperature in the Zambezi River basin

Sub-Catchment	**Station**	**MKZ**	**P-value**	**Sen's slope**	**% Change in magnitude**	**Mean Min Temp (°c)**
Barotse(Zambia)	Barotse	3.57	0.000	0.035	10.59	15.20
Shire(Malwi)	Blantyre	4.74	0.000	0.021	5.85	16.51
Cuando/Chobe (Angola)	Cuando	6.65	0.000	0.040	12.14	15.16
	Harare	3.62	0.000	0.027	9.99	12.43
Kafue(Zambia)	Kafue	3.79	0.000	0.034	10.43	15.00
Kapombo (Zambia)	Kapombo	4.38	0.000	0.035	10.82	14.88

Kariba (Zimbabwe)	Kariba	3.20	0.001	0.032	9.04	16.29
Cuando/Chobe (Botswana)	Kasane	3.08	0.002	0.038	10.63	16.44
Shire (Malawi)	Lilongwe	4.05	0.000	0.022	6.81	14.87
Luangwa(Zambia)	Luangwa	4.24	0.000	0.030	7.52	18.35
	Luena	3.72	0.000	0.021	6.80	14.21
Lunga(Angola)	Lunga	3.44	0.001	0.024	7.48	14.76
Mupata(Zambia)	Lusaka	3.92	0.000	0.034	10.45	14.96
Mupata(Zambia)	Mupata	4.65	0.000	0.033	8.52	17.82
	Mussuma	4.65	0.000	0.033	9.72	15.62
Shire(Malawi)	Mzuzu	5.68	0.000	0.024	6.96	15.86
Tete (Mozambique)	Tet1	4.19	0.000	0.024	5.88	18.77
Tete (Mozambique)	Tet2	4.02	0.000	0.026	6.21	19.26
Kariba (Zimbabwe)	VictoriaFalls	2.75	0.006	0.039	11.49	15.61
ZambeziDelta (Mozambique)	Zambezidelta	3.70	0.000	0.022	5.18	19.52
	Zambezi Mean	**4.10**	**0.0006**	**0.03**	**8.6**	**16.08**

3.1.4 Spatial trends for the Zambezi basin

3.1.4.1 Mean annual rainfall, maximum and minimum temperature

The spatial distribution of climate variables is presented in *Figure 2* to Figure *4*. The inverse distance weighing method was used for interpolation. The mean annual rainfall varied from 600 to 1225 mm, with high rainfall occurring at the headwaters in Angola and downstream in Malawi and Mozambique and low rainfall values shown in the middle of the basin, particularly in the southern part of the basin. Maximum temperature generally decreases from the west to the eastern side of the basin, with high values recoded in Angola and Zimbabwe, and lower values in Malawi and some parts of Mozambique. As for minimum temperature, high temperature values are recorded towards the downstream part of the basin, with relatively low temperatures found in the headwaters. Considering both maximum and minimum temperatures, it is clear particularly in the headwaters that there is high temperature difference (i.e. between minimum and maximum temperature). This scenario may have implications on potential evaporation, which in most cases depend on this difference (Hargreaves and Samani (1982).

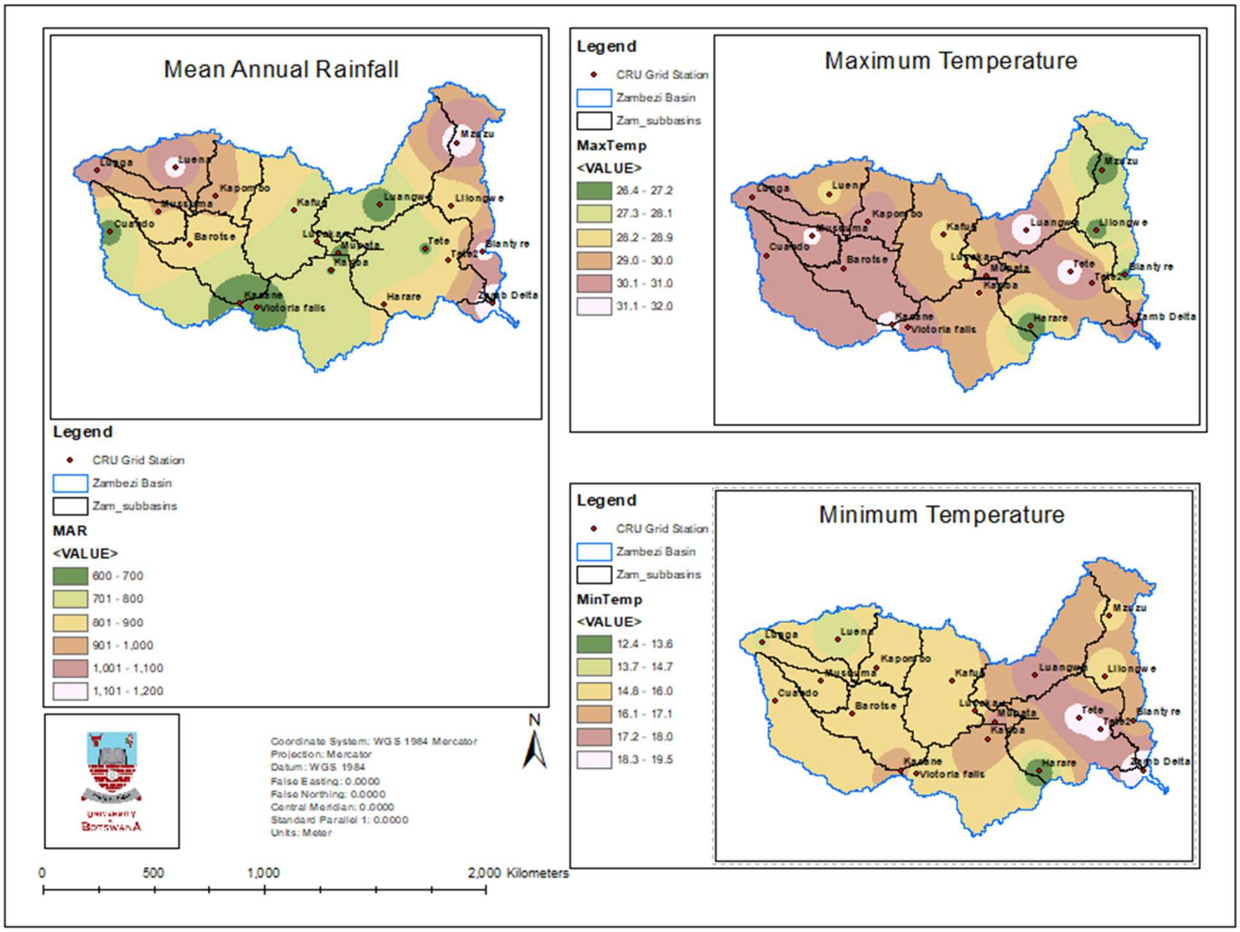

Figure 2: Spatial distribution of mean annual rainfall, mean maximum and minimum temperature in the Zambezi River basin

3.1.4.2 The Mann-Kendall (MKZ) statistic for rainfall, maximum and minimum temperature

The MKZ statistic was used to evaluate the direction of trend (Figure *4*) for rainfall, maximum and minimum temperature. For rainfall, positive values (increasing trend) of MKZ are found in the upstream of the basin while negative values (decreasing trend) are clustered from the middle of the basin towards the downstream side, with a high percentage of the basin depicting a decreasing trend for rainfall. For maximum temperature, it is worth noting that all the MKZ values are positive (increasing trend), and a good number of stations in the western part of the basin, as well as the central part, have high MKZ values. This signifies that the basin is increasingly become hot and dry over time. The distribution of minimum temperature trend is irregular and random. However, it is also clear that the basin is becoming hot due to positive values of the MKZ values even for minimum temperatures. The regions around the Cuando/Chobe sub-basin and Mzuzu show high MKZ values and these regions represent headwaters of the basin. In general, the MKZ statistic for rainfall and temperature (minimum and maximum) point to a hot and dry Zambezi basin. This has negative implications for water availability in the basin due to decreasing rainfall and increasing temperatures. This is likely to affect water security in the basin in the future, particularly when considering climate variability and change. For example, high temperatures could lead to increased evaporation from open water bodies such as dams, or from shallow alluvial aquifers.

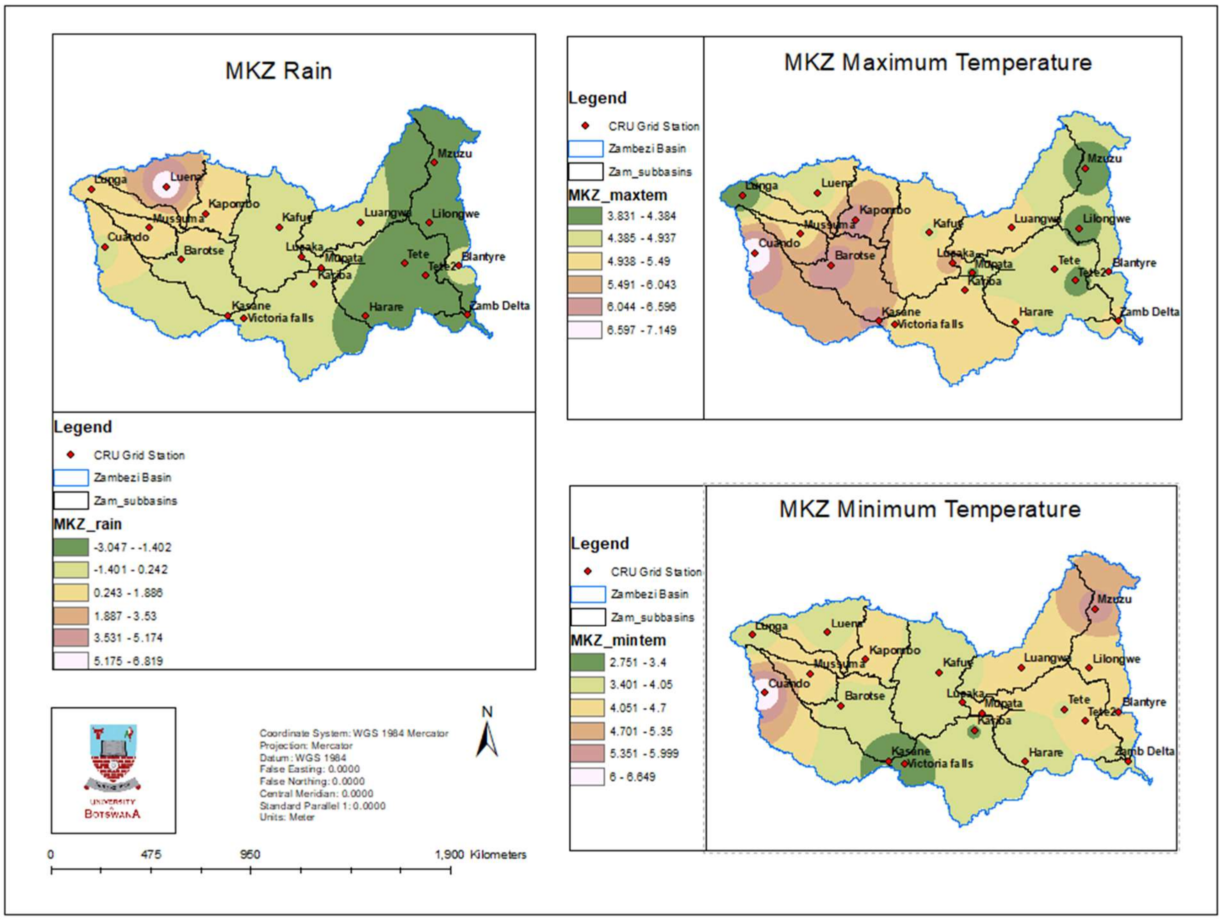

Figure 3: Spatial distribution of MKZ for rainfall, maximum and minimum temperature in the Zambezi River basin

3.1.4.3 The Sen's slope estimator for rainfall, maximum and minimum temperature

3.1.4.3.1 Magnitude and direction of Sen's slope

As discussed in section 2.1, the Sen's slope estimator indicates the magnitude of the trend. The spatial distribution of Sen's slope is presented in Figure *4*. In general, for rainfall series, the downstream part of the basin shows higher (negative) values compared to the upstream part, where the values are small (and positive). This observation implies that the basin is highly likely to experience reduced rainfall, and by extension reduced inflows and recharge in the future. This scenario may trigger water shortage which may render the basin into a water stressed place in the future when considering, among others population growth and climate variability/change.

Regarding maximum and minimum temperature, it is evident that the strength of the slope is higher in the central part of the basin, particularly on the southern part, which includes mainly southeastern Angola, northern Botswana, southern Zimbabwe and Zambia. Should this continue into the future, this part of the basin is likely to experience high rates of evaporation particularly from open water bodies such as dams, waterfalls and rivers.

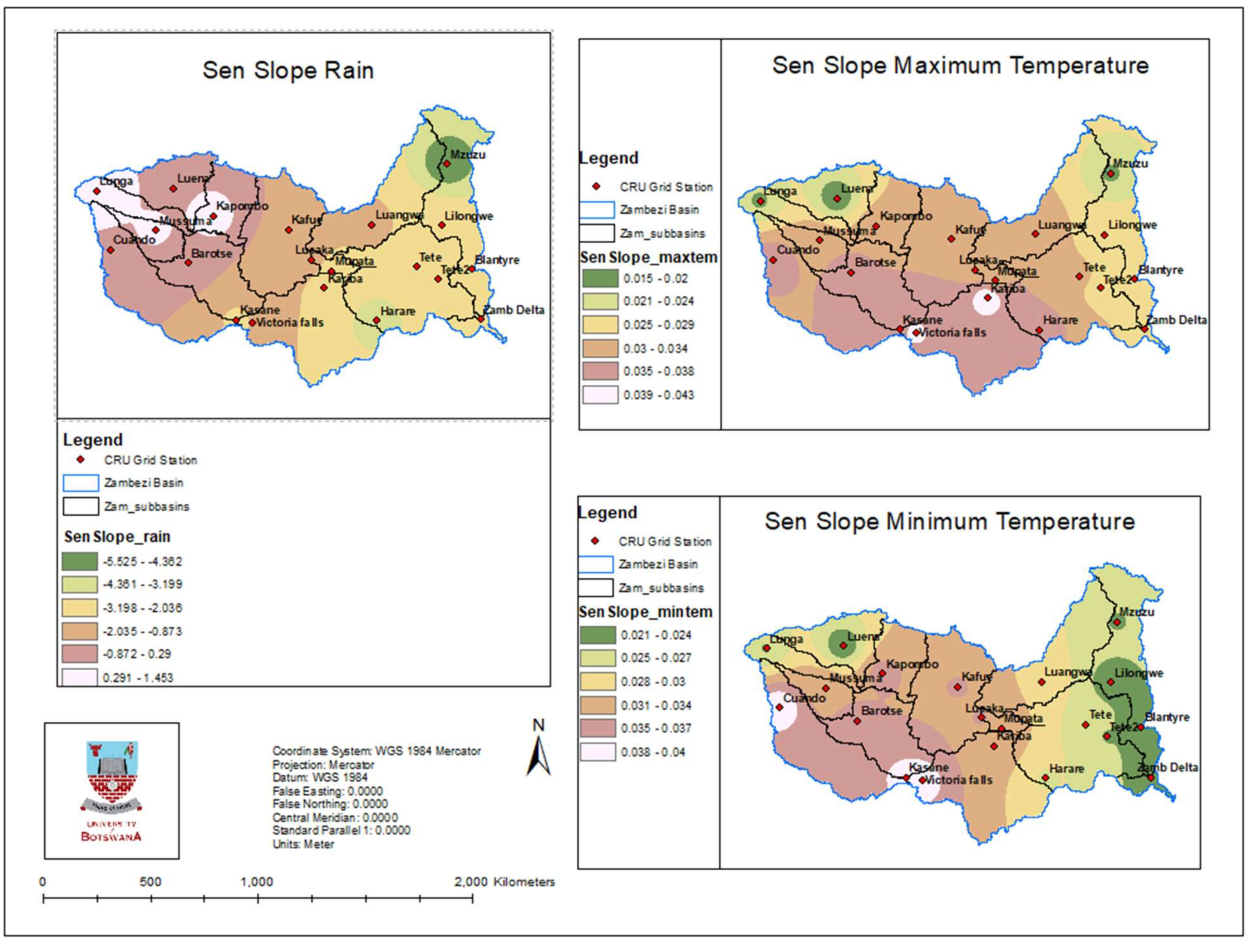

Figure 4: Spatial distribution of Sen's slope for rainfall, maximum and minimum temperature in the Zambezi River basin

3.1.4.3.2 Percentage change in magnitude

By using Equation (2.10), percentage in magnitude for each station was computed and the results are presented in Figure *5* to Figure *7* . Starting with rainfall, the station with highest rainfall change is Harare, Zimbabwe (-24%) followed by Mzuzu, in Malawi (-22%). Only three stations recorded an increase in precipitation, with the highest found at Lunga station (+6%), followed by Mussuma (+3%), and Luenga (1%), all in Angola. The rest show decreased rainfall over the period under assessment. For maximum temperature, all the changes are positive, ranging between +6.5 % (Kariba, Zambia) and +2% (Luenga, Angola), while for minimum temperature the changes range between +12% (Cuana, Angola) and +5% (Zambezi delta, Mozambique). In general, minimum temperature has increased more than the maximum temperature across all the stations in the basin. This increase is likely to affect many sectors of the economy such as agriculture, where, for example, majority of crops (and their yields) such as wheat and maize are influenced by temperature differences (Rosenzweig and Tubiello, 1996; Chauhan et al, 2015).

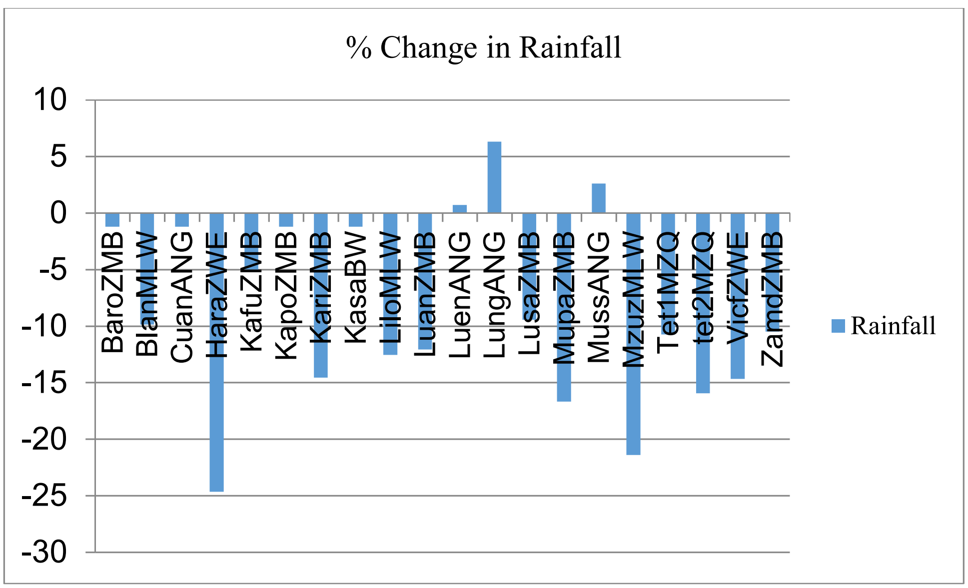

Figure 5: Percentage change in Rainfall magnitude

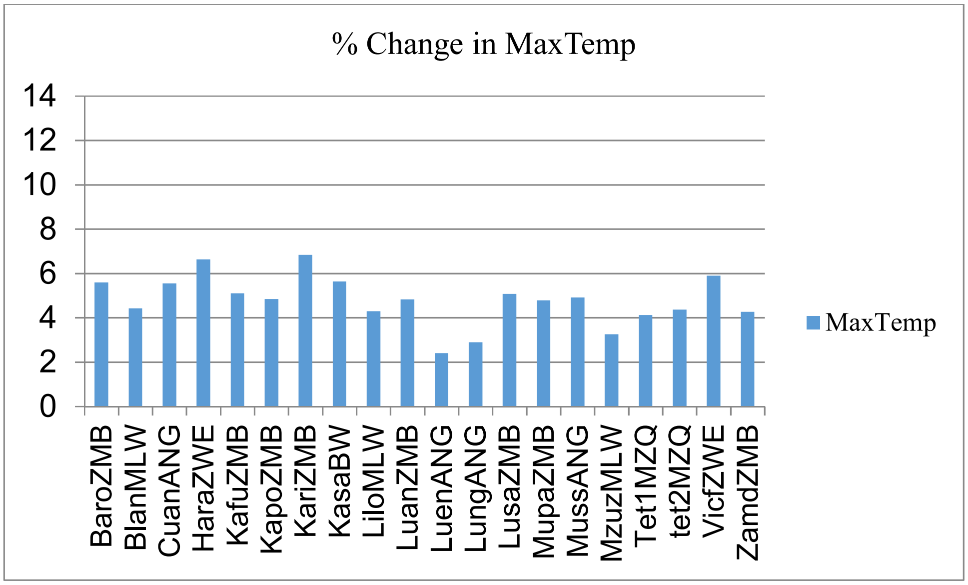

Figure 6: Percentage change in Maximum Temperature

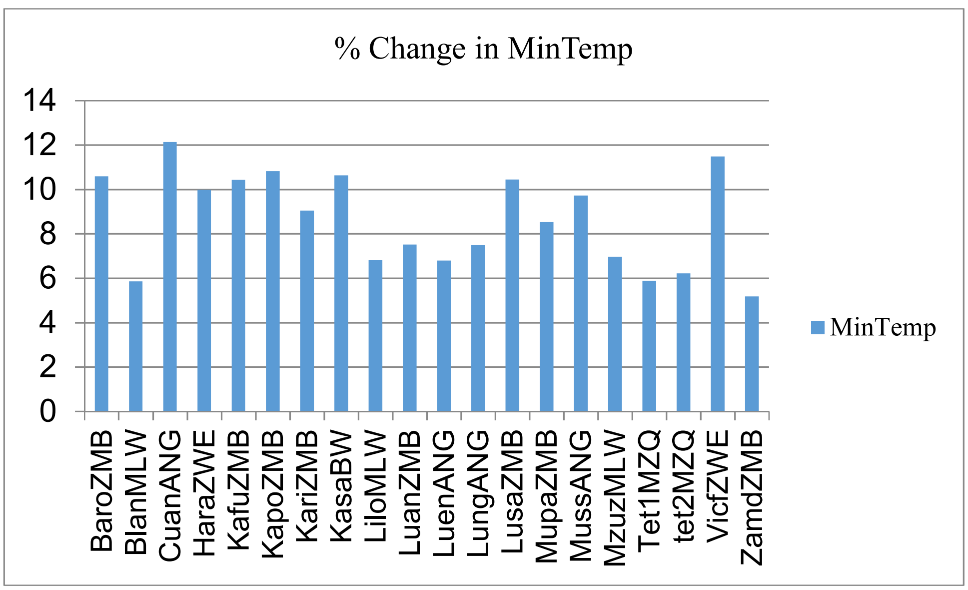

Figure 7: Percentage change in Minimum temperature

3.2 Standardised Precipitation Evapotranspiration Index (SPEI) Results

Based on the procedure developed in section 2.2, the SPEI were computed for the stations under consideration and the results are presented in *Figure 8 to Figure 12* . Based on the recent work done in Botswana (Byakatonda et al 2018), where the SPEI of between 12 and 15 months timescales were found to adequately model drought in the Limpopo and Okavango basins, this study adopted the SPEI-12 for analysis in the Zambezi River Basin. The assumption for using SPEI-12 was that in general, the basin is considered to have sufficient carryover storage particularly during periods of mild drought. However, this assumption will be evaluated based on the findings of the SPEI in the basin. The SPEI results are presented together with details of SPEI trend for the 1970-2015 period.

3.2.1 Overall indications from the SPEI values

The results from *Figure 8 to Figure 12* show that in general, the SPEI are clustered between -1 to 1, except for one station (Tete1), which recorded values beyond -2 and 1.5. A summary of the SPEI and moisture category is displayed in Table *9*. This results show that 95% of the SPEI fall within the near normal category, followed by moderately wet (2%) and moderately dry (1.4%). However, there are cases of extremely dry conditions (0.3%) and severely dry (0.5%), occurring in some parts of Mozambique. Regarding the overall trends, out of the twenty (20) stations, eleven (11) of them displayed downward SPEI trends, representing 55% of the stations. The remaining nine (9) showed increasing SPEI trends. Despite these changes, the magnitude of the slope is low, i.e. ranging from $-4.1x10^{-6}$ to $8.9x10^{-5}$ which indicates that in general the basin is not experiencing any major shifts in terms of drought patterns. It is also worth mentioning that while drought frequency seems to have increased in recent years, the duration and magnitude are generally low compared to the former years.

Table 9: SPEI category and characteristics for the Zambezi River basin

Moisture Category	**SPEI Range**	**Distribution of SPEI for Zambezi (%)**
Extremely Wet (EW)	2.00 and above	0.00
Very Wet (VW)	1.50 to 1.99	0.40
Moderately Wet (MW)	1.00 to 1.49	2.02
Near Normal (NN)	**-0.99 to 0.99**	**95.49**
Moderately Dry (MD)	-1.00 to -1.49	1.38
Severely Dry (SD)	-1.50 to -1.99	0.46
Extremely Dry (ED)	-2.00 and less	0.25

3.2.2 Individual plots of the SPEI values

The individual stations were grouped generally to indicate transect from the upper basin to the downstream side. For example, *Figure 8* shows some of the stations within the upper Zambezi catchment located in Angola. The stations located in the headwaters (i.e. the Lunga and Luena) show deceasing SPEI trends (i.e. negative slope and downward trend line) while Cuando and Mussuma show increasing trends. The stations located in the middle of the basin (*Figure 9 and Figure 10*) also display a mixture of decreasing and increasing trends. Out of these eight (8), five display a decreasing trend while 3 show increasing trends. This observation is also noted for stations located downstream of the basin (i.e. *Figure 11 and Figure 12*). It is also noted that only one station (Tete1 in *Figure* 12) display higher values of SPEI going beyond -2 and 1.5. Furthermore, most stations show negative SPEI values which correspond to some of the strong El Nino years such as the 1982-83, 1997-98 and 2014-2016.

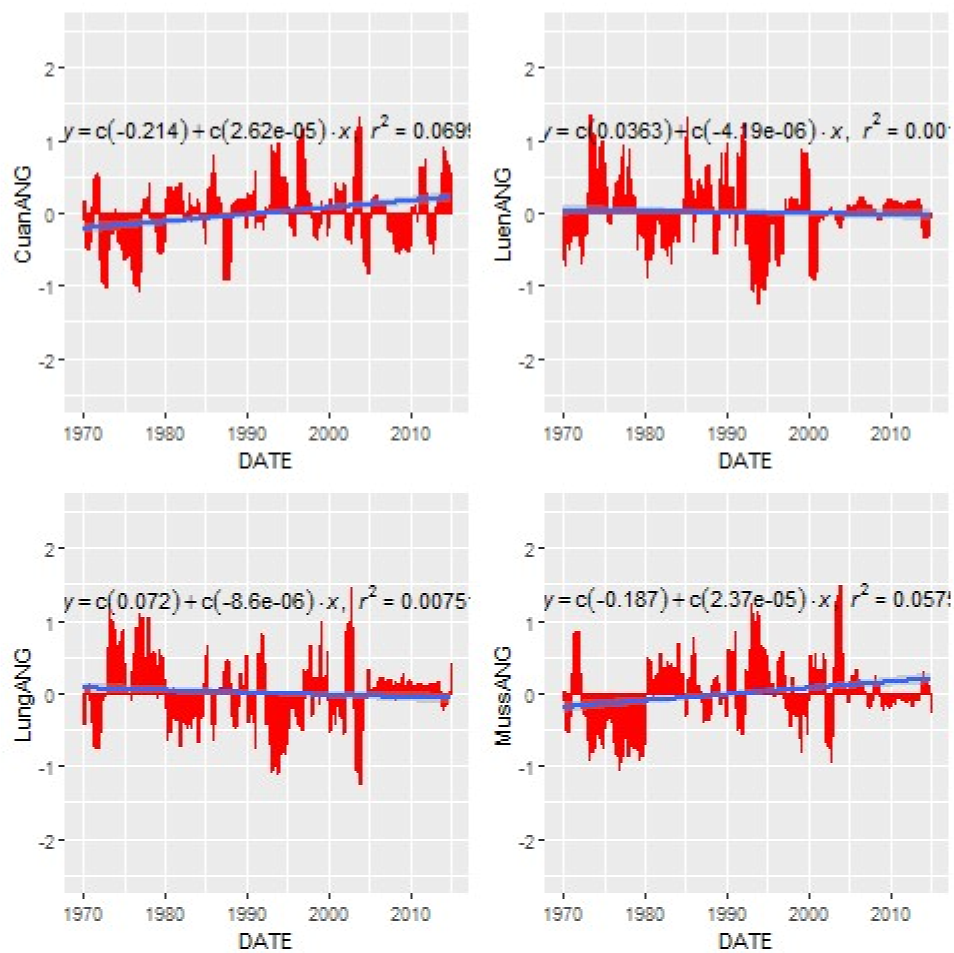

Figure 8: SPEI results for Cuando, Luen, Lunga, Mussuma

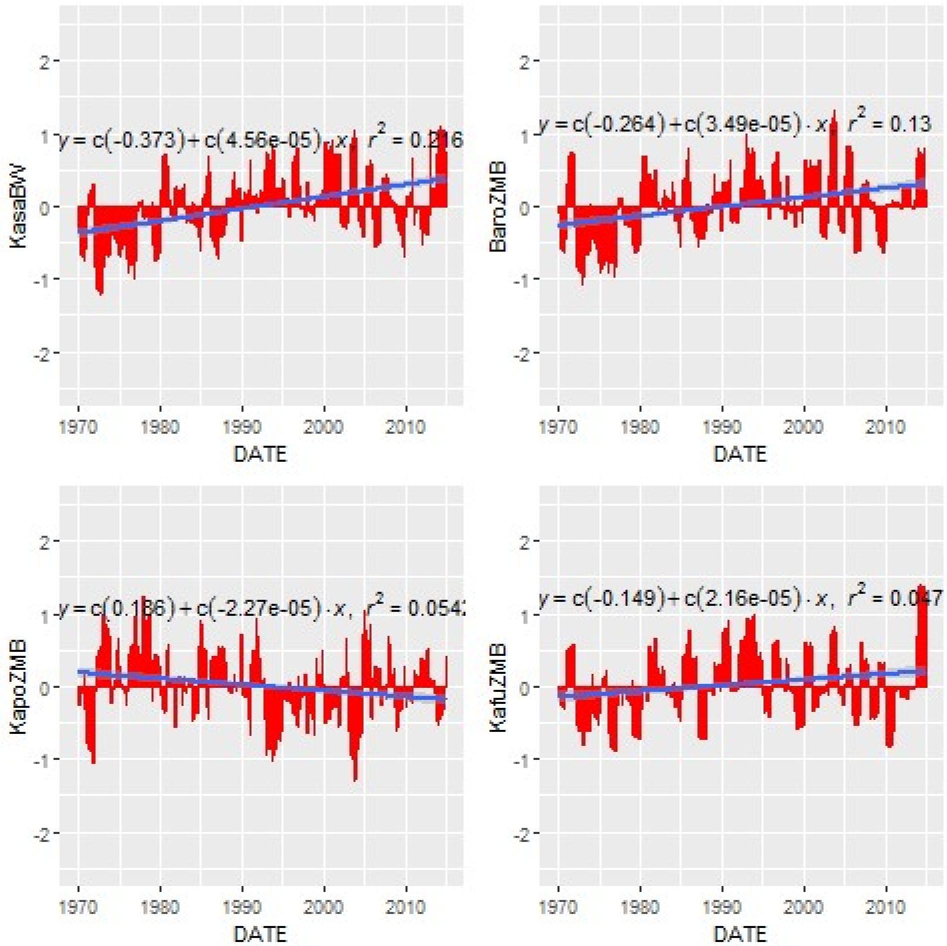

Figure 9: SPEI results for Kasane, Barotse, Kapombo and Kafue.

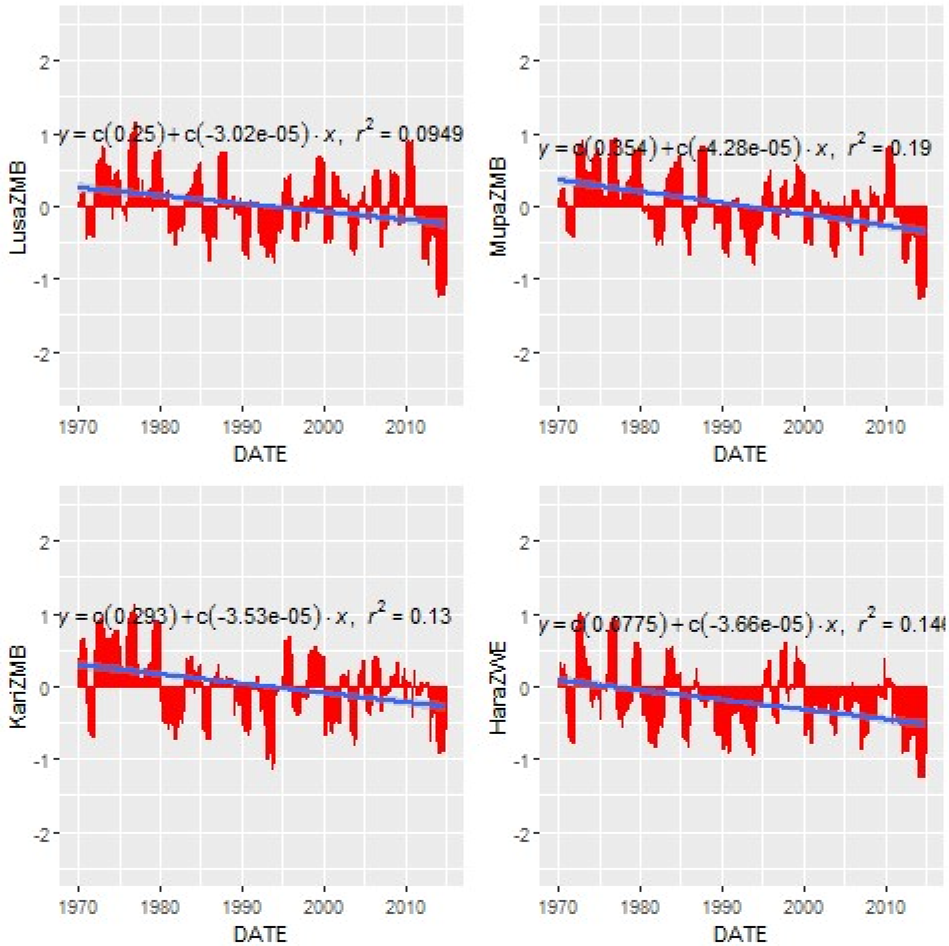

Figure 10: SPEI results for Luangwa, Victoria Falls, Blantyre and Lilongwe

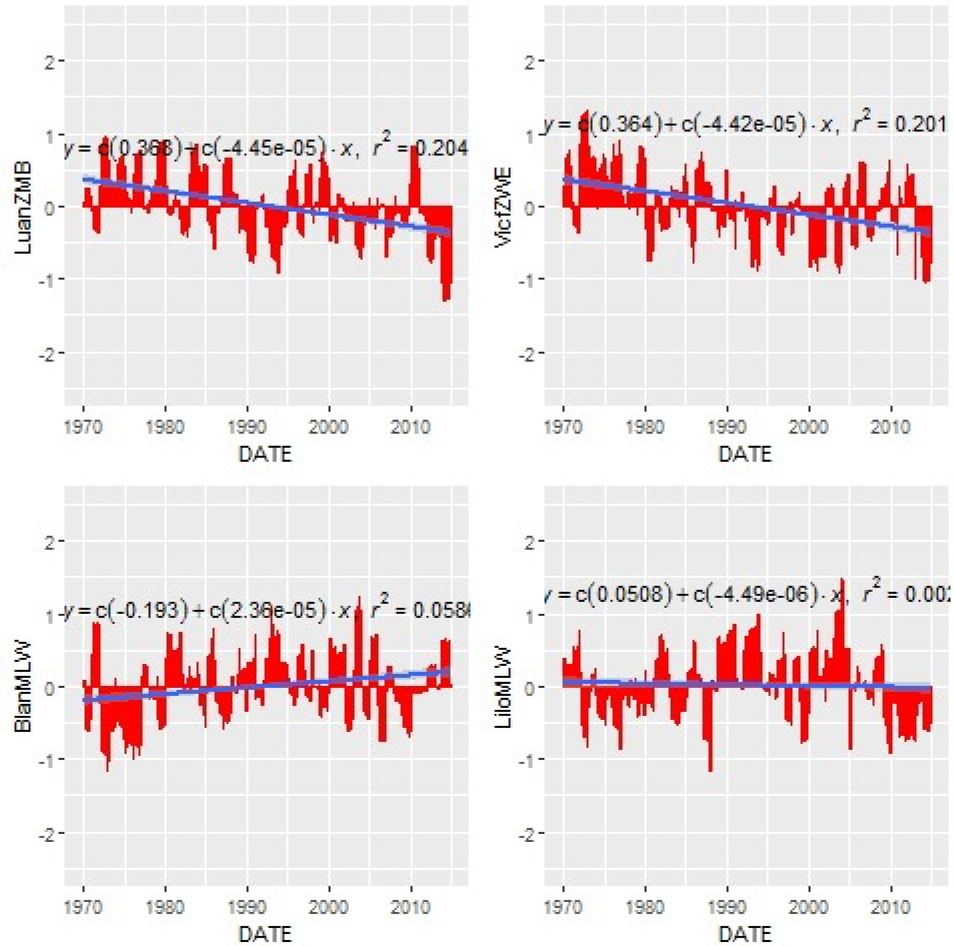

Figure 11: SPEI results for Mzuzu, Tete1, Tete2 and Zambezi Delta

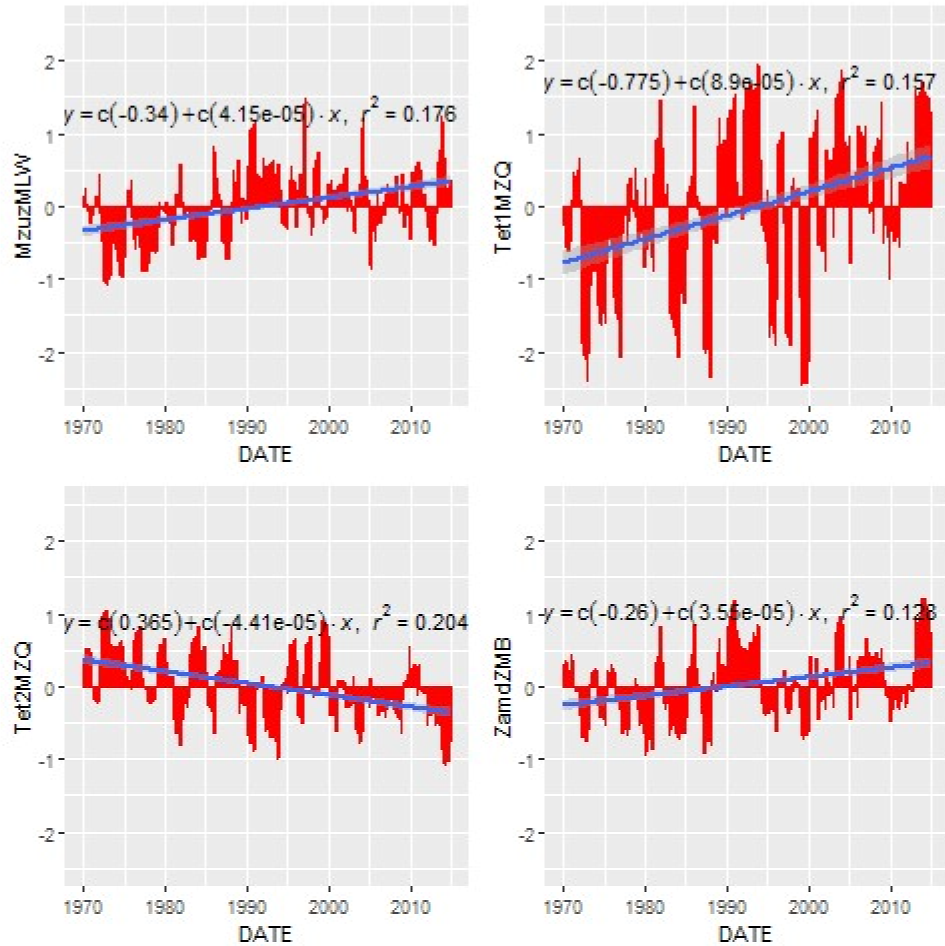

Figure 12: SPEI results for Mzuzu, Tete1, Tete2 and Zambezi Delta

4 SUMMARY AND RECOMMENDATIONS

4.1 Summary

In this report, climate variability and extreme events analyses have been undertaken. It is widely accepted that climate change will lead to increased frequency and magnitude of extreme events such as droughts and floods, and the extent of these changes will vary from place to place and will affect many sectors of the economy, including water resources, agriculture, among others (Jury, 2002). Over the years, many approaches have been developed to evaluate the extent of climate variability (i.e. trends and magnitude of climate variables) as well as magnitude and frequency of extreme events (Pettitt, 1979, Buishand, 1984, McKee et al, 1993; Hamed and Rao (1998); Vicente-Serrano et al, 2010). Trend analysis methods based on Mann-Kendall (MK) statistic (Z), referred to in this report as MKZ, and the Sen's slope (S) have been used to evaluate the direction and magnitude of trend, respectively. On extreme events, the standardised precipitation evapotranspiration index (SPEI) based on L-moments have been used to evaluate the dryness/wetness conditions within the Zambezi River basin covering the period 1970 to 2015. The climate research unit (CRU) gridded database has been used in place of historical observations. This option was taken because of the challenges of obtaining data from the existing data holding agencies within the limit of this project. The results therefore should be treated with caution since no validation of these datasets has been undertaken so far. However, there is a growing usage of these datasets in the scientific community (Harris et al., 2014; McMahon et al., 2015).

In general, the findings from this report indicate the following:

1) Rainfall has decreased over the years in the Limpopo basin. For example, about 75% of the stations showed a downward trend when using the CRU data covering the period 1970 to 2015. In addition, rainfall changes range between +6% and -25% across the basin (Figure *5*).
2) The MKZ statistic for the basin was found to be -0.58 with the Sen's slope of -1.59, and a a percentage change of -8.7% in rainfall values across the basin. This may lead to reduced rainfall and, as a consequence, reduced dam inflows as well as groundwater recharge should these trends persist.
3) However, only 20% of the stations showed a statistically significant trend at 5% significance level.
4) Regarding temperature (minimum and maximum), it was found that these values have generally increased over time and across the basin, indicating a shift towards warmer conditions. . Maximum temperature has increased by between 2% to 6%, while minimum temperature increased by between 5% and 12% (Figure *6* and Figure *7*)
5) All the station showed positive and significant trends when using the MKZ and S statistics.
6) The SPEI values revealed that the river basin has been experiencing near normal conditions representing about 95% of the drought indices, followed by moderate conditions (wet and dry) at about 3.4%, and about 0.7% of severe to extreme dry conditions.
7) The data revealed that some stations experienced decreasing SPEI values (about 55%) while the remaining experienced increasing trends. However, the slopes of these trends

were found to be very low, which further supports the fact that the conditions have been near normal for most of the time.

In general, there are signs that the river basin has experienced reduced rainfall in most parts of the basin leading to negative SPEI values. However these changes were found to be generally non-significant. However, due to increasing temperatures, the basin may become more vulnerable as a result of increased evaporation. This may affect water resources particularly within the context of climate change, land use change and population growth. According to the United Nations Water (UNWater), *"adaptation to climate change is mainly about better water management. Without improved water resource management, the progress towards poverty reduction targets, the SDGs and Sustainable Development in all its economic, social and environmental dimensions will be jeopardized"*.

4.2 Recommendations

In view of the above issues, the following recommendations are suggested:

1) Access to the historical observations is highly desirable. This will allow validation of the CRU datasets to evaluate their reliability in representing the observed data.
2) In spite of this, the general picture revealed by these findings is consistent with studies previously done in the basin, and other similar environments. As a result, the findings are thought to be reasonable and may be used to inform policy and for decision making.
3) Availability of streamflow and flood data will be useful in undertaking regional flood frequency analysis to complete this analysis as well as to establish relationship s between streamflow and rainfall based on the findings emanating from this study, where in some cases significant rainfall decrease were established

5 ACKNOWLEDGEMENT

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