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Trend Analysis of Extreme Rainfall in Zambia and Its Potential Implication on Water Resources Availability and Agricultural Productivity

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Abstract

Extreme events are the major cause of droughts, floods and other associated disasters worldwide. Therefore, understanding trends in extreme rainfall events is important in mitigating their impacts on socioeconomic sectors such as health, agriculture, water resources and the environment. Against this background, a study was undertaken to investigate trends in extreme rainfall events in Kasama, Lusaka and Livingstone (representing agro-ecological regions 1, 2 and 3 of Zambia respectively) and their potential implications on water resources and agriculture. Gridded daily precipitation data from National Oceanic Atmosphere Administration (NOAA) with the spatial coverage of 0.50 - degree latitude x 0.50 - degree longitude grid (720x360) and temporal coverage from 1979 to 2017 were used. Eleven extreme precipitation indices were generated from NOAA precipitation data using the RClimDex package in R software. The data was processed by checking the homogeneity, while the trend for each extreme rainfall index was calculated using the Mann-Kendall, a non-parametric test. Results of the study revealed statistically significant decreasing trends in annual total precipitation, Simple Daily Index (SDII), heavy rainfall (R95P, R99P and RX1DAY) and the persistence of intense rainfall events (R10mm, R20mm and R25mm) in Kasama area. Decreasing trends in total annual precipitation and the persistence of intense rainfall events were also observed in Lusaka and Livingstone although were insignificant at 5% significance level. In Lusaka town, statistically significant trends in consecutive dry days (CDD) and consecutive wet days (CWD) were observed. The trend in CDD increases at the rate of 1.3days per year while that for CWD decreases at 0.17days per year. Decreasing trends in CDD and CWD were also observed in Kasama and Livingstone area although not statistically significant at 5% significant level. These trends point to the change towards drier conditions especially in Lusaka area. This coupled with the decrease in total annual rainfall may in the long run impact negatively on groundwater recharge, soil moisture content and surface water resources, and subsequently agricultural productivity especially rain fed agriculture. Improved natural resources management in Zambia especially water resources will be critical in mitigating the aforementioned potential impacts of extreme precipitation events.

Keywords

Extreme Rainfall, Climate, Water Resources, Agriculture

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1. Introduction

Trends in precipitation have been variable across the globe [1]. It is therefore important to understanding the variability of precipitation trends due to their effects on socioeconomic sectors such as health, agriculture, environment and natural resources management. According to [2], the changes in climate in various parts of the world will likely cause high

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variability in water resources including higher frequencies or intensities of floods and droughts. Extreme climatic events such as floods and droughts threaten sustainable development in terms of agricultural productivity and other sectors, and also the security and stability of many countries. Developing countries with low adaptive capacity coupled with other stresses are expected to suffer the worst effects of climate change [3, 17].

Precipitation trends have been variable across the African continent over the past decades [16]. West Africa experienced a decrease in annual total rainfall from 1950 to 2000 [4]. In terms of extreme daily rainfall, an increase is observed over the central Sahelian region of West Africa [5]. In Southern African region where the study area lies, increased inter-annual rainfall variability such as higher rainfall anomalies and more intense widespread droughts have been observed since 1970 [6]. According to the Zambia Metrological Department (as cited in [7]), an assessment of historical climate data in Zambia revealed a decline in total annual rainfall patterns across the country from 1980 to 2010. Global circulation models of climate change predict that Zambia will experience increasing temperatures with longer dry periods, more intense rainfall and increased storm events over the next 20 to 30 years [8]. Furthermore, the study conducted by National Adaptation Programme of Action (NAPA) (as cited [9]) indicates that increased temperatures in Zambia will result in reduced precipitation in the range of 8% and 30% of the normal average.

The Southern and Central regions (agro-ecological region 1 and 2 respectively) of Zambia have already been identified as the most vulnerable areas to the negative effects of climate change. The Southern region (agro-ecological region 1) of Zambia has been consistently experiencing climatic shocks in terms of floods and droughts, and water scarcity [9] Frequent long dry spells in this region have led to critical water shortages due to the reduction in groundwater recharge, reduced agricultural productivity and lowering of surface water bodies such as the Lake Kariba. For instance, during 1982/83 rainy season, water scarcity caused by frequent dry spells in Southern Province of Zambia which led to poor performance in the agricultural sector and consequently increased the poverty levels among the local communities [10].

As Zambia is divided into three agro-ecological regions with significant differences in annual rainfall amounts [11], there is need to thoroughly explore the trends in extreme rainfall events for each agro-ecological. Against this background, this study intends to determine the trend in extreme rainfall events in Lusaka, Kasama and Livingstone towns in Zambia and its potential implications on water resources availability.

Site Location and Description

According [12] the population of Zambia was estimated at 16.2 million in the year 2015. Zambia has three ecological regions with diverse climatic conditions. Rainfall is brought mainly by wind from the north-west which swing into northern Zambia from Congo DR as the moist Congo air. The north-eastern part of the country receives little rainfall from the north-east trade winds. Rainfall decreases from about 1250m in the north to about 400m in the south. Fluctuations in total rainfall and the length of the dry season increase in areas of low rainfall. Therefore, this study used three major urban centres of Zambia, each located in a single ecological region in order to have an overall clear situation analysis of the country. These are Livingstone located in ecological region one, Lusaka in ecological region two and Kasama in ecological three.

Agro-ecological region I covers mostly Southern and parts of Eastern and Western provinces. It is characterized by annual average rainfall of less than 800 mm and covers 12% of the total land area [11, 12]. The region has maize been grown as well as other drought-tolerant crops like cotton, sorghum, and millet, and has good potential for irrigated crops, including fruits and vegetables. With regards to relief, Livingstone lies on elevation of 986 m (3,235 ft) above sea level, implying that it is located in a low lying region. The climatic features of Livingstone are that, it's hot and dry, with rainfall of less than 800mm per annum hence categorized as semi-arid. Due to a shorter rainy season, the growing period for crops is also short (between 80 and 120 days). Furthermore, the rainfall received is variable and unreliable within one rainy season, and between the years; increasing the risk of crop failure. Livingstone is been the major city in the agro-ecological region I, it is considered as one of the historical cities in Zambia due to the natural wonders such as the Victoria Falls, named after the Queen of Britain by a missionary by the name of David Livingstone. The population growth of Livingstone has been increasing due to its massive economic activities such as tourism, agriculture and both local and international trade, factors which may have either encouraged people to migrate to this city or natural increase of population through birth rates. According to [13], the population of Livingstone was 136, 897 as of 2010, though considering the high population growth rates, this figure may be more currently.

Lusaka is the capital city of Zambia and is considered as one of the fastest developing cities in southern Africa. It is part of the central plateau located an elevation of about 1,279 metres (4,196 ft) above sea level. The city lies in agro-ecological region II which has been identified as the most vulnerable areas to the negative effects of climate change. Agro-ecological region II covers 42% of Zambia's land area [11, 12]. According to [13], Lusaka at Provincial level in Zambia has the highest population of 2,191,225 people with a growth rate of about 4.6 per cent decade. Among the major economic activities in Lusaka include agriculture, mining and quarrying, construction, commerce, transport etc.

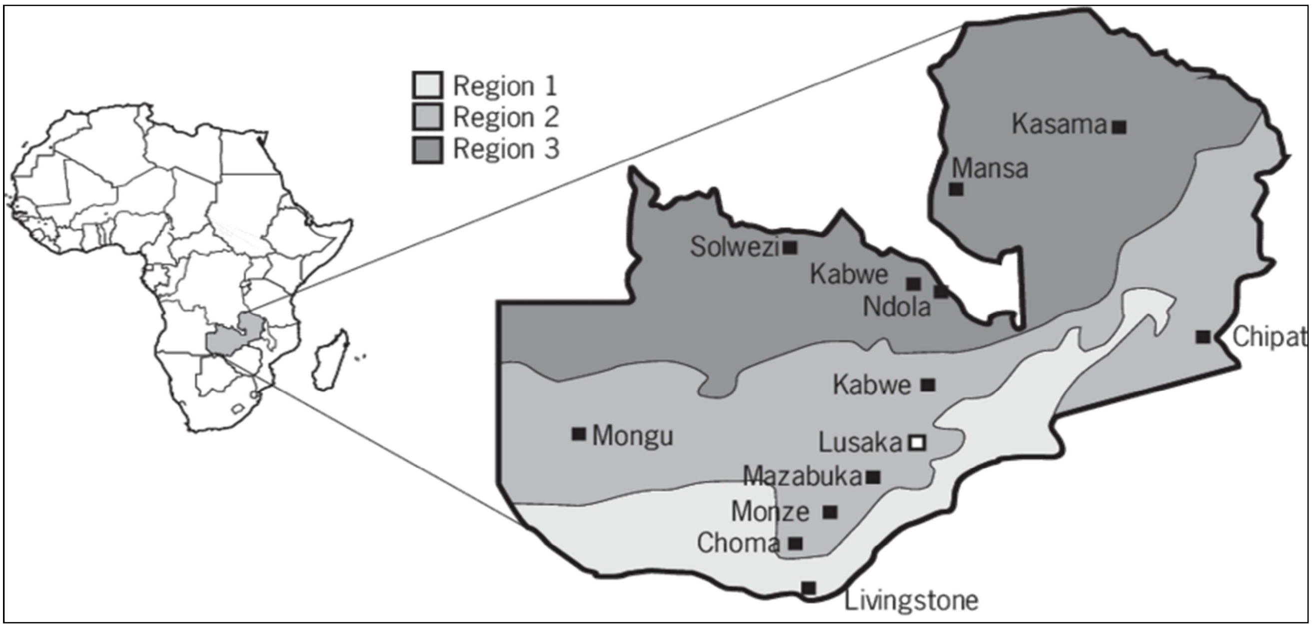

Figure 1. Map showing the agro-ecological regions in Zambia and the study areas (after [14]).

Kasama is the provincial headquarters for the northern province of Zambia; it lies in the ecological region III, a region that receives above 1200mm of rainfall annually. Agro-ecological region III covers 46% of the country's land area. As of year 2010, the population for Kasama stood at 101,845 [13]. Considering high rates of population growth, this statistic may have been adjusted upwards. Unlike the other ecological regions, the physical relief for Kasama town is believed to be 4,508 ft (1,374 m) above sea level with regards to elevation. The major economic activities of around Kasama include agriculture (subsistence in most cases), transport, manufacturing as well as tourism.

2. Methodology

2.1. Data Collection and Analysis

Gridded daily precipitation data from National Oceanic Atmosphere Administration (NOAA) Climate Prediction Center (CPC) was used in this study. CPC data has the spatial coverage is 0.50 - degree latitude x 0.50 - degree longitude grid (720x360) and is available from 1979 to date. In this study, the temporal coverage of the data is from 1979/01/01 to 2017/12/31.

Precipitation data for Lusaka, Kasama and Livingstone representing the three agro-ecological regions of Zambia was extracted from NOAA-CPC based on its latitude and longitude. The extracted data was then used to generate the eleven precipitation indices using the RClimDex package in R software developed by the Climate Research Branch of Meteorological Service of Canada. RClimDex generates indices of climate extremes which are used to monitor and detect climate change [18, 19]. Before calculating the indices, RClimDex firstly identifies errors in the data such as missing values, negative values and wrong dates.

After generating the climate indices, a trend analysis was performed using Mann-Kendall test (a non parametric test) recommended by the World Meteorological Organization (WMO) to explore trends hydroclimatological time series. Since the Mann-Kendall test is non-dimensional and does not quantify the scale or the magnitude of trend, the Sen.'s non-parametric method was used to estimate the slope of the trend [15]. With Mann-Kendall, the Z statistic and p-value were used to test the null hypothesis, H_o, which states that the data come from a population with independent realizations and are identically distributed against the alternative hypothesis, H_1, that there is an increasing or decreasing monotonic trend.

Table 1. List of WMO ETCCDI Indices used in this study.

Index	Description	Unit
prcptot	Annual total precipitation in wet days, e	mm
r95p	Annual total precipitation from daily precipitation >95th percentile	mm
r99p	Annual total precipitation from daily precipitation >99th percentile	mm

Index	Description	Unit
rx1day	Annual maximum 1-day precipitation	mm
r10mm	Annual count of days when precipitation is >=10mm	days
r20mm	Annual count of days when precipitation is >=20mm	days
r25mm	Annual count of days when precipitation is >=25mm	days
SDII	Simple Daily Index, annual mean of daily precipitation Index	mm
CWD	Annual maximum length of wet spell, maximum consecutive number of wet days >= 1mm	days
CDD	Annual maximum length of dry spell, maximum consecutive number of wet days < 1mm	days

2.2. Results of Trend Analysis

Table 2. Climatic Indices of Precipitation for Lusaka, Zambia.

Indices	Z	p-value	Significance level	Sen's slope
CDD	2.43	0.02	0.05	1.33
CWD	-3.42	0.001	0.05	-0.17
RX1DAY	0.12	0.90	0.05	0.06
RX5DAY	-1.43	0.15	0.05	-0.79
R10MM	-1.7966	0.07	0.05	-0.17
R20MM	-0.99584	0.32	0.05	-0.06
R25MM	-0.59617	0.55	0.05	0
R95P	-0.2783	0.78	0.05	-0.2
R99P	0.47529	0.63	0.05	0
SDII	0.84744	0.40	0.05	0.03
PRCPTOT	-1.6694	0.10	0.05	-5.83

Table 3. Climatic Indices of Precipitation for Livingstone.

Indices	Z	p-value	Significance level	Sen's slope
CDD	1.86	0.06	0.05	0.88
CWD	-1.49	0.14	0.05	-0.06
RX1DAY	0.41	0.68	0.05	0.12
RX5DAY	0.46	0.65	0.05	0.21
R10MM	-0.01	0.99	0.05	0
R20MM	-0.66	0.51	0.05	0
R25MM	-0.11	0.91	0.05	0
R95P	0.39	0.70	0.05	0.73
R99P	0.20	0.84	0.05	0
SDII	0.88	0.38	0.05	0.02
PRCPTOT	-0.60	0.55	0.05	-1.28

Table 4. Climatic Indices of Precipitation for Kasama.

Indices	Z	p-value	Significance level	Sen's slope
CDD	-1.03	0.30	0.05	-0.71
CWD	-1.53	0.13	0.05	-0.08
RX1DAY	-2.83	0.004	0.05	-1.14
RX5DAY	-1.91	0.06	0.05	-0.63
R10MM	-3.55	0.0004	0.05	-0.42
R20MM	-2.68	0.0074	0.05	-0.18
R25MM	-2.81	0.005	0.05	-0.17
R95P	-2.77	0.006	0.05	-5.94
R99P	-3.51	0.001	0.05	-3.41
SDII	-2.43	0.015	0.05	-0.07
PRCPTOT	-3.87	0.0001	0.05	-11.79

3. Discussion and Data Analysis

In order to understand the nature of climatic variability within the climate system, it is necessary to study its components in a systematic way. Therefore, results of this study were analyzed in terms of changes in the statistical distribution of the local climatic indices.

3.1. Trend in Total Annual Precipitation

As PRCPTOT is probably the most important climatic index reflecting rainfall variations over the entire year, the discussion of extremes in rainfall events will start with the changes of this parameter across the study area. From the trend analysis results, it can be observed that there is a negative trend in total annual precipitation in all the three towns. The trends are decreasing in Lusaka, Livingstone and Kasama are decreasing at the rate of 5mm/year, 1.28mm/year and 11.8mm/year respectively. For Kasama, the trend in annual total precipitation is significant at 5% significance level. On the other hand, observed trends in annual total rainfall for Lusaka and Livingstone not statistically significant at 5% significance level.

3.2. Trends in Simple Daily Index

One extreme climatic index that does not only take into account the total amount of precipitation throughout the year but also reflects changes in daily rainfall is the Simple Daily Intensity Index (SDII). SDII combines the total amount of annual precipitation and the number of days when rainfall greater than 1mm actually occurs. In this study, it can be observed that there is a statistically significant trend of SDII for Kasama at 5% significance level. This trend decreases at the rate of 0.07mm/year. On the other hand, there is a statistically insignificant trend of SDII for Lusaka and Livingstone at 5% significance level.

3.3. Trends in R95P and R99P

The R95P and R99P indices are used to measure heavy precipitation events that exceed 95^{th} and 99^{th} percentiles. In other words, these indices measure the total rainfall per year from days with rainfall above the 95th and 99th percentile daily rainfall totals. Based on the Mann-Kendall results of this study, there is sufficient evidence for the existence of a trend for both R95P and R99P in Kasama town at 5% significance level. The trends in R95P and R99P are decreasing at the rate 5.9mm/year and 3.4mm/year respectively. For Lusaka and Livingstone, the trends in R95P and R99P are statistically insignificant at the same significance level.

3.4. Trends in RX1DAY and RX5DAY

Very heavy or intense rainfall events are measured using the RX1day and RX5day indices respectively. Based on Mann-Kendall test results, it can be observed that there is no trend in RX5day at 5% significance level for all the three towns. With regard to RX1day index, there is a statistically negative trend decreasing at 1.1mm/year for Kasama while that for Lusaka and Livingstone are not statistically significant at 5% significance level.

3.5. Trends in R10mm, R20mm and R25mm

The persistence of intense precipitation can be measured by the number of cases of daily rainfall exceeding the 10mm, 20mm and 25mm limits, defined as the R10mm, R20mm and R25mm indices respectively. Mann-Kendall test results indicate that there is insufficient evidence of a statistically significant monotonic trend in R10mm, R20mm and R25mm indices at 5% significance level for Lusaka and Livingstone. On the other hand, there is a statistically significant trend at the same significance level in the aforementioned indices in Kasama. The trends in R10mm, R20mm and R25mm are decreasing at the rate of 0.4days/year, 0.2days/year and 0.2days/year respectively. Therefore, the trend in the persistence of intense rainfall in Kasama has been decreasing over the years.

3.6. Trends in Consecutive Wet Days

The Continuous Wet Days (CWD) index indicates the maximum number of continuous wet days per year. This extreme climatic index reflects time-series variations that can lead to wetter conditions. Results of the Mann-Kendall test indicate that there is a decreasing trend in CWD in all the towns. However, the trends in CWD for Kasama and Livingstone are no statistically significant while that for Lusaka is statistically significant at 5% significance level. This trend in Lusaka is decreasing at the rate of 0.17days per year. Therefore, this suggests that there is a decrease in the number of wet days over the 39 years base period in Lusaka. The observed decreasing trends in CWD will likely have negative impact on the amount of soil moisture content and subsequently agricultural productivity in the long run.

3.7. Trends in Consecutive Dry Days

Contrary to CWD, Consecutive Dry Days index defines the length in days of the longest annual period with no significant rain. It is a measure of dryness or an indication of the change to drier conditions. From results of the Mann-Kendall test, it can be observed that indicate that there is an increasing trend in CDD in all the three towns. However, the trends in CDD for Kasama and Livingstone are insignificant while that for Lusaka is statistically significant at 5% significance level. The trend in CDD for Lusaka is decreasing at the rate of 1.33days per year. Therefore, CDD index for Lusaka point to a change to drier conditions. This finding agrees with the World Bank (2009) report which states that global circulation models on climate change predict that Zambia will experience longer dry spells for the next 20 to 30 years.

4. Conclusion

Trend analysis of extreme rainfall events over the period 1979 to 2017 in three towns representing the agro-ecological regions of Zambia revealed statistically significant decreasing trend in annual total precipitation and SDII in Kasama town (agro-ecological 1). Statistically significant decreasing trends in heavy rainfall events as measured by R95P, R99P and RX1DAY were also observed in Kasama town. Furthermore, the study indicates the existence of a statistically significant decreasing trend in the persistence of intense precipitation events in the aforementioned town. In terms of CDD and CWD, statistically significant trends were observed in agro-ecological region two represented by Lusaka town. The trend in CDD was increasing at the rate of 1.33days per year while that for CWD was decreasing at the rate of 0.17days per year. Trends in these two indices point to the change towards drier conditions in Lusaka area. The continuous increase in CDD, the decrease in annual total precipitation and CWD will likely have negative impact on future water resources availability and agricultural productivity in all the three agro-ecological regions of Zambia. The amount of groundwater recharge, moisture content and water storage is surface water bodies are likely to be affected.

Future Work

There is need to relate the observed trends in extreme events with the amount of recharge using a groundwater flow model or soil water mass balance in order to thoroughly understand their impacts on water resources in the three agro-ecological regions.

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